

AES 2025 Tangier - Morocco

The 11th International Conference on Antennas and Electromagnetic Systems

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The 11th International Conference on Antennas and Electromagnetic Systems

Edited by

Andrea Fratalocchi | King Abdullah University of Science and Technology, Saudi Arabia
Said Zouhdi | Paris-Saclay University, France

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PLENARY SPEAKERS



Stefano Maci

University of Siena, Italy

Degrees of Freedom of the Field and Upper Bounds for the Number of MIMO Channels

Stefano Maci received the Laurea Degree cum Laude at University of Florence in 87 and from '97 is a Professor at the University of Siena. His research interest includes high-frequency and beam representation methods, computational electromagnetics, large phased arrays, planar antennas, reflector antennas and feeds, metamaterials and metasurfaces. Since 2000 he was member the Technical Advisory Board of 12 international conferences, member of the Review Board of 6 International Journals. He organized 25 special sessions in international conferences, and he held 10 short courses in the IEEE Antennas and Propagation Society (AP-S) Symposia about metamaterials, antennas and computational electromagnetics. In 2004-2007 he was WP leader of the Antenna Center of Excellence (ACE, FP6-EU) and in 2007-2010 he was International Coordinator of a 24-institution consortium of a Marie Curie Action (FP6). He has been Principal Investigator from 2010 of 6 cooperative projects financed by European Space Agency. In 2004 he was the founder of the European School of Antennas (ESoA), a post graduate school that presently comprises 34 courses on Antennas, Propagation, Electromagnetic Theory, and Computational Electromagnetics and 150 teachers coming from 15 countries. Since 2004 is the Director of ESoA.

Professor Maci is IEEE Fellow since 2004, he has been a former member of the AdCom of IEEE Antennas and Propagation Society (AP-S), associate editor of AP-Transaction, Chair of the Award Committee of IEEE AP-S, and member of the Board of Directors of the European Association on Antennas and Propagation (EurAAP). From 2008 to 2015 he has been Director of the PhD program in Information Engineering and Mathematics of University of Siena, and from 2013 to 2015 he was member of the National Italian Committee for Qualification to Professor. He has been former member of the Antennas and Propagation Executive Board of the Institution of Engineering and Technology (IET, UK). He is presently the director of the consortium FORESEEN, presently involving 48 European Institutions, and principal investigator of the Future Emerging Technology project "Nanoarchitectronics" of the 8th EU Framework program. He was co-founder of 2 Spin-off Company. He is a Distinguished Lecturer of the IEEE Antennas and Propagation Society (AP-S), and recipient of the EurAAP Award in 2014, of the IEEE Sheldkunoff Transaction Prize 2015, and of the Chen-To Tai Distinguished Educator award 2016. In 2020 will be TPC Chair of the METAMATERIAL conference. In the last ten years he has been invited 25 times as key-note speaker in international conferences. The research activity of Professor Maci is documented in 150 papers published in international journals, (among which 100 on IEEE journals), 10 book chapters, and about 400 papers in proceedings of international. These papers have received around 6800 citations with h index 41.

Degrees of Freedom of the Field and Upper Bounds for the Number of MIMO Channels

The talk detail the Embedded Element Patterns (EEPs), their associate Efficiency Correlation Matrix (ECM), Cell Correlation Matrix (CCM), and orthogonal field modes, discussing the practical implications of these concepts for MIMO systems. The findings underscore the significance of sophisticated antenna models in enhancing network capacity, efficiency, and reliability.



Dorota Anna Pawlak

ENSEMBLE3 Centre of Excellence, Poland

Novel optical and functional materials enabled by crystal growth

Dorota Anna Pawlak (DAP) obtained her PhD (1999) and habilitation (2013) degrees at the University of Warsaw, Chemistry Dept. DAP was a Head of the Department of Functional Materials at Ł-ITME/Ł-IMiF, Leader of the Laboratory of Materials Technologies at the Chemistry Dept. at UW, first coordinator of a collaborative NMP FP7 EU-funded Project in Poland, laureate of two TEAM Projects (FNP), holding grants from such foreign institutions as the Air Force Office for Scientific Research in U.S. Currently she leads Teaming for Excellence H2020 and IRAP projects and is the president of the board of the ENSEMBLE3 Centre of Excellence. DAP works on the interface between crystal growth, nanophotonics and new materials concepts. She proposed utilizing the crystal growth techniques for metamaterials and plasmonic materials applications – which is a novel idea within the world research community.

Novel optical and functional materials enabled by crystal growth

Crystal growth is behind many everyday devices. The novel crystal growth approach offers simple and fast fabrication methods for three-dimensional bulk micro/nanocomposites with various functionalities that offer control over the size, shape and chemical composition. While volumetric materials could bring new optical and other phenomena, they have been mostly unavailable.



Marin Soljačić

MIT, USA

Certain intersections of AI and Photonics

Marin Soljačić is a Professor of Physics at MIT. He is a founder of a few companies, including WiTricity Corporation (2007) and Lightelligence (2017). His main research interests are in artificial intelligence as well as electromagnetic phenomena, focusing on nanophotonics, non-linear optics, and wireless power transfer.

He is a co-author of more than 300 scientific articles, more than 100 issued US patents, and he has been invited to give more than 100 invited talks at conferences and universities around the world. He is a recipient of the Adolph Lomb medal from the Optical Society of America (2005), and the TR35 award of the Technology Review magazine (2006). In 2008, he was awarded a MacArthur fellowship “genius” grant. He is an international member of the Croatian Academy of Engineering since 2009. In 2011 he became a Young Global Leader (YGL) of the World Economic Forum. In 2014, he was awarded Blavatnik National Award, as well as Invented Here! (Boston Patent Law Association). In 2017, he was awarded "The Order of the Croatian Daystar, with the image of Ruđer Bošković", the Croatian President's top medal for Science. In 2017, the Croatian President also awarded him with "The Order of the Croatian Interlace" medal. He has been recognized as a Highly Cited Researcher by Web of Science for six consecutive years : 2019, 2020, 2021, 2022, 2023, and 2024. In 2023, he was awarded Max Born award of Optica.

Certain intersections of AI and Photonics

This “vision” talk will explore how photonics can enhance AI hardware and how AI can accelerate photonics research. Topics will include large language models for scientific discovery and robotics for photonics experiments, highlighting key opportunities and challenges at this intersection.

KEYNOTE SPEAKERS



Gabriele Gradoni

University of Surrey & University of Cambridge, UK

Quantum Computational Electromagnetics for Wireless Communications

Gabriele Gradoni received the Ph.D. degree in electromagnetics from Università Politecnica delle Marche, Ancona, Italy, in 2010. He was a Visiting Researcher with the Time, Quantum, and Electromagnetics Team, National Physical Laboratory, Teddington, U.K., in 2008. From 2010 to 2013, he was a Research Associate with the Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD, USA. From 2013 to 2016, he was a Research Fellow with the School of Mathematical Sciences, University of Nottingham, U.K., where he became a Full Professor of applied mathematics and electromagnetics engineering in 2022.

In May 2023, Gabriele joined the Institute for Communication Systems, University of Surrey, as a Full Professor and Chair in Wireless Communications. Currently, he is also an Adjunct Professor with the Department of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign, USA, and a Visiting Fellow with the Department of Computer Science and Technology, University of Cambridge, UK. His research interests include electromagnetic modelling of complex systems, meta-surface modelling, stochastic electrodynamics, wave chaos, and quantum computational electromagnetics, with applications to electro-magnetic compatibility and modern wireless communication systems.

He received several international awards including URSI Commission B. Young Scientist Award in 2010 and 2016, the Gaetano Latmiral Prize in 2015, and the Honorable Mention IEEE TEMC Richard B. Schulz Transactions Prize Paper Award in 2020. From 2014 to 2021, he was the URSI Commission E. Early Career Representative. Since 2020, he has been a Royal Society Industry Fellow at British Telecom, UK.

Quantum Computational Electromagnetics for Wireless Communications

This talk explores quantum computational electromagnetics, focusing on Hamiltonian-based optimization for arrays and metasurfaces in future wireless networks. We also highlight variational eigensolvers and Riemann-Silberstein time-domain solvers for NISQ architectures, enabling the simulation of high-dimensional problems and enhancing quantum-assisted design. These methods are of interest in future wireless communication systems.



Xiao Hu

Shanghai University, China

Harness light in honeycomb topological photonic crystal

Tommaso Isernia is a Full Professor of Electromagnetic Fields at Università Mediterranea di Reggio Calabria (Italy) where he leads the "LEMMA" Group, ranked amongst the best research groups in Italy according to the last national evaluation of the quality of research (all "class A" products). From October 2018 to January 2023 he has been the Head of "Dipartimento di Ingegneria dell'Informazione, delle Infrastrutture e della Energia Sostenibile" (DIIES), which has been included in the restricted list of "Dipartimenti di eccellenza" by the Italian Ministry for Research. The scientific activities of Tommaso Isernia have considered non linear inverse scattering problems in electromagnetics, with particular reference to the problem of the possible occurrence of false solutions when solving the considered non-linear retrieval problems. He is an IEEE Fellow since 2022 for contributions to Antenna Synthesis and inverse scattering solution methods. Main research results include definitive solution procedures for a number of antenna synthesis problems, for the 2D phase retrieval problem, as well as the introduction of a number of effective approaches for the solution of inverse scattering problems.

Harness light in honeycomb topological photonic crystal

It is observed that electromagnetic modes in honeycomb photonic crystals exhibit Dirac-type frequency dispersions. I will discuss how this system can be exploited for harnessing light efficiently and deriving novel optic features after an introduction on basic notions of topological crystalline insulator and photonic topology.



Lingling Huang

Beijing Institute of Technology, China

Heterogeneously integrated metasurface for achieving switchable Pancharatnam–Berry phase

Lingling Huang is a professor in Beijing Institute of Technology, China. She received her Double B.S. degree (both Science and Engineering B.S. degree) in Optoelectronics from Tianjin University and Nankai University, Tianjin, China, in 2009. And she received Ph. D. degree in Optical Engineering from Tsinghua University, Beijing, China, in 2014. Her research activities are focused on optical metasurfaces, nanophotonics and holographic-related technique. She has published more than 120 SCI papers. She has received Friedrich Wilhelm Bessel Research Award from the Alexander von Humboldt Foundation, Youth Science Prize from Ministry of Education, China, et al.

Heterogeneously integrated metasurface for achieving switchable Pancharatnam–Berry phase

The geometric phase has attracted enormous interest and has played a pivotal role for metasurfaces, which can be encoded into the orientation angles of antennas. However, once the metasurface is fabricated, the orientation arrangement of the antenna arrays is fixed, resulting in limitations of such approach to realize dynamic functionalities.



Renato Lombardi

Huawei Fellow, Director of Italy Research Center, VP Microwave Product Line

The importance of the research in Advanced Electromagnetics for 5G and 6G wireless communication systems : an industry view

Renato Lombardi is the Director of the Huawei Italy Research Center and Vice President of Huawei's Microwave Product Line. In these roles, he oversees the research and development of microwave and millimeter-wave technologies for wireless communications, as well as the implementation of innovative mobile broadband backhaul solutions worldwide. He joined Huawei in 2008, founding the Huawei Research Center in Milan, Italy. In 2011, he was honored with the title of "Huawei Fellow for Microwave."

Renato Lombardi has more than 30 years of experience in the microwave and millimeter-wave industry. He previously led Siemens' Microwave Business and Product Management and, in 2006, was appointed Director of Research and Development. In 2015, he was elected Chair of the ETSI Industry Study Group mWT (millimeter-Wave Transmission). He also serves as an industry representative on the Board of the European Microwave Association.

Renato Lombardi holds a Master's Degree in Electronic Engineering from Politecnico di Milano, the largest and most prestigious technical university in Italy.

The importance of the research in Advanced Electromagnetics for 5G and 6G wireless communication systems : an industry view

The keynote talk starts by analyzing the key requirements of mobile networks evolving from 5G to 6G, and how these drive trends and technologies for radio access and wireless backhaul products and solutions.



Konstantinos Makris

University of Crete - FORTH , Greece

Fluctuations and correlations in optical thermodynamics

Konstantinos Makris is Associate Professor in the Department of Physics, of the University of Crete and Affiliated Researcher at the Institute of Electronic Structure and Laser (IESL) of Foundation for Research and Technology Hellas (FORTH). He obtained his PhD in Theoretical Photonics from the School of Optics and Photonics (CREOL-FCPE) at the University of Central Florida, Orlando (USA) in 2008. From 2008 until 2010 he was a postdoctoral researcher at Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland. During 2011 he was Lecturer at Institute for Theoretical Physics of Vienna University of Technology (TU-Wien), Austria. From 2012 until 2015 he was a Marie Curie fellow between Princeton University, USA and TU-Wien, Austria. His current research interests lie on non-Hermitian physics, nonlinear optics, photonics lattices and wave propagation in complex media. He has more than 100 publications in refereed journals and more than 60 invited talks-colloquia at international conferences/schools and Institutions. In 2022 he was awarded an ERC consolidator grant related to open disorder systems. He was also elected as a 2023 Fellow of OPTICA (former OSA).

Fluctuations and correlations in optical thermodynamics

Direct study of nonlinear multimode systems is a highly complex problem, due to the large number of the involved supermodes. Following a classical statistical mechanics approach, a thermodynamic theory for optical supermodes can be formulated. Recent theoretical and experimental advances will be presented, in this new direction of Optical Thermodynamics.



Masaya Notomi

NTT Basic Research Labs., Japan

Complex Photonic Crystals and Complex Perturbation

Masaya Notomi received his B.E., M.E. and Ph.D. degrees in applied physics from The University of Tokyo, Japan in 1986, 1988, and 1997, respectively. He joined NTT Optoelectronics Laboratories, Nippon Telegraph and Telephone Corporation in 1988 and moved to NTT Basic Research Laboratories in 1999. Since then, his research interest has been to control the optical properties of materials and devices by using artificial nanostructures, and engaged in research on quantum wires/dots and photonic crystal structures. In 1996-1997, he was a visiting researcher of Linköping University, Sweden. He was a guest associate professor of Applied Electronics in 2003-2009 and is currently a guest professor of Physics in Tokyo Institute of Technology. He was appointed as Senior Distinguished Scientist of NTT since 2010. He is currently a director of NTT Nanophotonics Center. He received IEEE/LEOS Distinguished Lecturer Award in 2006, Japan Society for the Promotion of Science (JSPS) prize in 2009, Japan Academy Medal in 2009, the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology (Prize for Science and Technology, Research Category) in 2010, and IEEE Fellow grade in 2013. He served as a member of National University Corporation Evaluation Committee in the Japanese government. He is a research director of JST CREST program from 2015. He is also a member of the Japan Society of Applied Physics, APS, IEEE, and OSA.

Complex Photonic Crystals and Complex Perturbation

We have recently fabricated several types of complex photonic crystals where the real and imaginary parts of refractive index have independent periodic modulation, leading to interesting properties, such as non-Hermitian skin-effect. We also discuss the effect of tiny complex perturbations to Hermitian systems to induce large changes in optical properties.



Willie Padilla

Duke University, USA

A Large Language Model Agentic System for Autonomous Metamaterials Research

Willie Padilla is the Dr. Paul Wang Distinguished Professor of Electrical & Computer Engineering and the Director of the Metamaterials Center with a master's degree and doctorate in physics. He received a Young Investigator Award from the Office of Naval Research and a Presidential Early Career Award for Scientists and Engineers. Padilla is a fellow of the IEEE, American Physical Society, Optical Society of America and Kavli Frontiers of Science. He is also a Web of Science Highly Cited Researcher in physics for 2018 and 2019. He heads a group working in the area of metamaterials with a focus on machine learning, computational imaging, spectroscopy and energy, and has published more than 250 peer-reviewed journal articles.

A Large Language Model Agentic System for Autonomous Metamaterials Research

Large language models (LLMs) have expanded the capabilities of deep neural networks (DNNs). LLMs utilize training knowledge to perform basic reasoning tasks. We show the construction of an agentic LLM system (ALS), capable of performing metamaterials simulation, deep learning, and analysis autonomously. We highlight the future of this exciting field.



Hrvoje Petek

University of Pittsburgh, USA

Design and Nanofemto Imaging PT Symmetric E.B Topological Plasmonic Fields

Hrvoje Petek received B.S. (MIT ; 1980), and PhD degrees in Chemistry from the (University of California, Berkeley 1985). He was a postdoctoral researcher and research associate at the Institute for Molecular Science in Japan from 1985 to 1993. From 1993 to 2000, he was a group leader at the Hitachi Advanced Research Laboratory, where he established his research on ultrafast photoemission spectroscopy. In 2000 he moved to the University of Pittsburgh, where he is the R. K. Mellon Chair in Physics and Astronomy, and Professor of Chemistry. There he broadened his research to include ultrafast photoemission electron microscopy of coherent plasmonic fields. He has received awards relating to his national and international activities including the Alexander von Humboldt Award (Germany ; 2000), Morino Award (Japan ; 2014) Ahmed Zewail Award in Ultrafast Science and Technology (USA ; 2019), and President's International Fellowship Initiative (China ; 2022). He is a Fellow of the American Physical Society and the American Association of Arts and Sciences, as well as the Editor-in-Chief of Progress in Surface Science.

Design and Nanofemto Imaging PT Symmetric E.B Topological Plasmonic Fields

We perform imaging of surface plasmon polariton fields with nanometer spatial and femtosecond temporal resolution by photoemission electron microscopy. We find that plasmonic vortices host E.B fields that can drive magnetoelectric interactions or probe synthetic axion responses on 10 nm spatial scale.



Gennady Shvets

Cornell University, USA

Electromagnetic waves in time-varying media : the first 35 years

Gennady Shvets received his Ph.D. in Physics from MIT in 1995. Previously he has held research positions at the Princeton Plasma Physics Laboratory and the Fermi National Accelerator Laboratory, and was on the faculty of the Illinois Institute of Technology. His research interests include nanophotonics, optical and microwave metamaterials and their applications (including bio-sensing, optoelectronic devices, and vacuum electronics), and plasma physics. He is the author or coauthor of more than 180 papers in refereed journals, including Science, Nature Physics, Nature Materials, Nature Photonics, Nature Communications, Physical Review Letters, and Nano Letters. Dr. Shvets was a Department of Energy Postdoctoral Fellow in 1995-96. According to the ISI Web of Science, his work was cited over 7,000 times, giving him an h-factor of 45. He was a recipient of the Presidential Early Career Award for Scientists and Engineers in 2000. He is a Fellow of the American Physical Society (APS) and Optical Society of America (OSA).

Electromagnetic waves in time-varying media : the first 35 years

The earliest developments in the field of time-varying media – specifically, plasmas – will be reviewed, with the emphasis on the underlying microscopic description of the media and the resulting conservation laws. I will then discuss how dielectric metasurfaces can be used to produce a wide range of optical phenomena, including : time-steps, negative refraction, and phase front reversal.



Ventsislav K. Valev

University of Bath, UK

Nonlinear chiroptical scattering for photochemistry and enhanced surface sensing

Ventsislav K. Valev is a Professor in the Physics Department of the University of Bath (UK). He received his PhD from the Radboud University Nijmegen (the Netherlands). Subsequently, he was a post-doc and a Research Fellow at the KU Leuven University (Belgium), and in the Cavendish Laboratory at the University of Cambridge (UK). He joined the University of Bath as a Research Fellow of the Royal Society. In 2019, he was promoted to professor, in 2021 he became the Director of Research for the Department of Physics, and in 2022 he was appointed Head of Department. Valev's research team focuses on the interaction between powerful laser light and nanostructured materials. He builds laser experiments to study novel materials, such as plasmonic nanostructures, metamaterials, 2D materials and quantum optical materials. He explores the physics of photons, electrons and magnetism confined to tiny volumes of space – nanoparticles or 2D sheets. He aims to discover new properties and to test theoretical predictions, seeking out new and useful intersections between classical electromagnetism and quantum mechanics. His investigations are both fundamental and applied. Valev's work is very interdisciplinary; it has been distinguished with the Thomas Young Medal of the Institute of Physics, the Horizon Prize from the Faraday Division of the Royal Society of Chemistry. He is a Fellow of Optica, SPIE, and the Institute of Physics.

Nonlinear chiroptical scattering for photochemistry and enhanced surface sensing

We present the first demonstration of second-harmonic hyper-Mie optical activity and show that this effect can both induce and probe nonlinear chiroptical photochemical reactions. We also show that nonlinear chiroptical scattering can reveal surface states at the SiO₂/Si interface of nanoparticles.



Rachel Won

Nature Photonics, UK

Publishing in Nature Journals : Some Facts and Trends

Rachel Won is an International Editor of Nature Photonics. She joined the journal in June 2006 as one of four Founding Editors. Before that, Rachel worked for Aston University's Business Partnership Unit in Birmingham, UK, as a Medici Fellow commercializing research output of the university, particularly that of photonics research. She obtained her PhD in microwave photonics and nonlinear optics as a member of Aston's Photonics Research Group. She worked for Philips Optical Storage in Singapore as an Optics Engineer after completing her Master's degree study in Nanyang Technological University of Singapore doing research in optical fibre sensing. She holds a Bachelor's degree from the National University of Malaysia. She is a Fellow of OPTICA and the International Society of Optics and Photonics (SPIE).

Publishing in Nature Journals : Some Facts and Trends

In this talk, Rachel will give you an overview on Nature journals and Nature Photonics, before detailing their editorial and peer review processes. She will also share some facts and recent trends in scientific publishing.



Anatoly V. Zayats

King's College London, UK

Ultrafast, Nonlinear and Chiral Nanoplasmonics

Anatoly V. Zayats is a Chair in Experimental Physics and the head of the Photonics & Nanotechnology at the Department of Physics, King's College London, where he also leads Nano-optics and Near-field Spectroscopy Laboratory (www.nano-optics.org.uk). He is a Co-Director of the London Centre for Nanotechnology and the London Institute of Advanced Light Technologies. His current research interests are in the areas of nanophotonics, plasmonics, metamaterials, optical spin-orbit coupling, plasmonically-derived hot carriers, scanning probe microscopy, nonlinear and ultrafast optics and spectroscopy, and optical properties of surfaces, thin films, semiconductors and low-dimensional structures. He is a founding co-editor-in-chief of Advanced Photonics journal. He is a Fellow of the Institute of Physics, the Optical Society of America, SPIE, the Royal Society of Chemistry and elected Member of Academia Europaea.

Ultrafast, Nonlinear and Chiral Nanoplasmonics

Ultrafast nonlinear and chiral photonic applications are often limited by the available choice of naturally occurring materials and their generally weak responses. Here, we will discuss novel plasmonic nanomaterials and hetero-nanostructures for tailoring hot-electron dynamics, plasmonic nonlinearities, ultrashort pulses and chirality.

TUTORIALS



Rachel Won

Nature Photonics, UK

Wednesday 2nd July

10:15 - 11:15 — Room 2

Writing and submitting your papers : Dos and Don'ts

Rachel Won is an International Editor of Nature Photonics. She joined the journal in June 2006 as one of four Founding Editors. Before that, Rachel worked for Aston University's Business Partnership Unit in Birmingham, UK, as a Medici Fellow commercializing research output of the university, particularly that of photonics research. She obtained her PhD in microwave photonics and nonlinear optics as a member of Aston's Photonics Research Group. She worked for Philips Optical Storage in Singapore as an Optics Engineer after completing her Master's degree study in Nanyang Technological University of Singapore doing research in optical fibre sensing. She holds a Bachelor's degree from the National University of Malaysia. She is a Fellow of OPTICA and the International Society of Optics and Photonics (SPIE).

Writing and submitting your papers : Dos and Don'ts

This talk covers the detailed information and guidelines on scientific paper preparation and submission, including tips for writing an effective cover letter, an informative abstract, a comprehensive introduction and an attractive paper, and editorial and peer-review processes. You will also get to know how to choose a journal for submission, what editors seek, how your papers are reviewed and how to make an appeal.

GUIDELINES FOR PRESENTERS

Oral Presentations

Each session room is equipped with a stationary computer connected to a LCD projector. Presenters must load their presentation files in advance onto the session computer. Technician personnel will be available to assist you.

Scheduled time slots for oral presentations are 15 mn for regular, 20 mn for invited presentations, 30 mn for keynote talks and 35 mn for plenary talks, including questions and discussions. Presenters are required to report to their session room and to their session Chair at least 15 minutes prior to the start of their session.

The session chair must be present in the session room at least 15 minutes before the start of the session and must strictly observe the starting time and time limit of each paper.

Poster Presentations

Presenters are requested to stand by their posters during their session. One poster board, A0 size (118.9 x 84.1 cm), in portrait orientation, will be available for each poster. Pins or thumbtacks are provided to mount your posters on the board. All presenters are required to mount their papers 30mn before the session and remove them at the end of their sessions. Posters must be prepared using the standard AES poster template (available on the conference [website](#)).

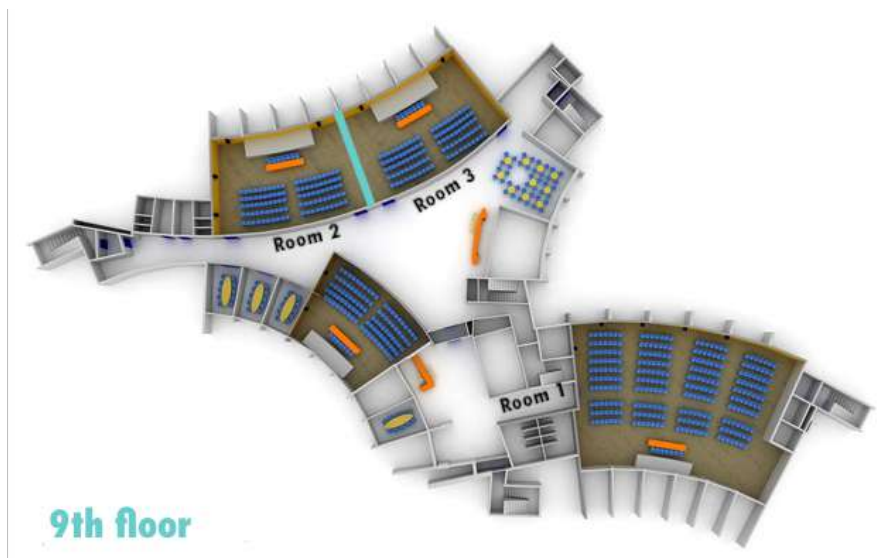
USEFUL INFORMATION

Venue

AES 2024 will be held at :

Kenzi Solazur Hotel
168 Blvd. Mohamed VI
90000, Tangier
Morocco)

<https://www.kenzi-hotels.com/kenzi-solazur>



AES 2025 will take place in the vibrant city of Tangier, Morocco, a historic gateway between Africa and Europe. The conference will be hosted at the modern 4-star Kenzi Solazur Hotel, ideally located along the seafront and within walking distance of the city's main attractions.

Getting to Venue

How to Get to Tangier

By Plane Tangier Ibn Battouta Airport (TNG) is the primary gateway to Tangier, offering direct flights to over 50 destinations. These include major European cities and capitals, as well as key locations in the Middle East and North Africa. The airport is located just 11 km from the city center. Grand taxi prices from the airport to the city are government-regulated, costing 250 dirhams (approximately €25) before 8 PM and 300 dirhams (around €30) after 8 PM.

By Train (from Casablanca) To reach Tangier from Casablanca, you can take the high-speed train, Al Boraq, which offers a comfortable and efficient journey. The train departs from Casa Voyageurs station and takes approximately 2.5 hours to arrive at Tanger Ville station. Once you arrive, the station is conveniently located just a short distance from the city center, making it easy to get around. You can take a petit taxi for less than 40 dirhams (about 4€) to reach your destination in the heart of Tangier.

By Car (from Spain) If you're driving from Spain, take the ferry from Tarifa to the Port of Tangier or from Algeciras to the Tanger-Med port. The Port of Tangier is close to the city while Tanger-Med is 40 km from downtown. Cars can be brought into Morocco for a maximum of six months each year, and you should check this with the rental company if you're renting a car in Spain. You'll need to have 'green card' insurance to drive in Morocco and it can be obtained at the port.

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Plenary presentations

AES 2025, TANGIER - MOROCCO, JULY 1 – 4, 2025

Certain intersections of AI and Photonics

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Abstract: This “vision” talk will explore how photonics can enhance AI hardware and how AI can accelerate photonics research. Topics will include large language models for scientific discovery and robotics for photonics experiments, highlighting key opportunities and challenges at this intersection.

Degrees of Freedom of the Field and Upper Bounds for the Number of MIMO Channels

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Abstract: Massive Multiple Input Multiple Output (M-MIMO) technology has significantly advanced base station antenna design by integrating many transceivers with antenna arrays, improving network capacity and managing complex interference dynamically. Advanced antenna modeling and theory are therefore essential today for the accurate prediction and assessment of system performance of next generation of communication systems. In this paper we propose a theoretical framework that emphasizes the joint design of system algorithms and antennas using exact electromagnetic (EM) field representations. This approach defines novel parameters for the quantification of antenna array performances, and defines design strategies to maximize the number of independent channels, the average efficiency, and the maximum average gain within a specific cell. By exploring the degrees of freedom (DoF) of the EM field, we establish the physical upper bounds for system performance, providing a comprehensive understanding of antenna potential.

The talk detail the Embedded Element Patterns (EEPs), their associate Efficiency Correlation Matrix (ECM), Cell Correlation Matrix (CCM), and orthogonal field modes, discussing the practical implications of these concepts for MIMO systems. The findings underscore the significance of sophisticated antenna models in enhancing network capacity, efficiency, and reliability. This research contributes to the optimization of antenna arrays in next-generation mobile networks.

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Novel optical and functional materials enabled by crystal growth

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Abstract: Crystal growth is behind many everyday devices. The novel crystal growth approach offers simple and fast fabrication methods for three-dimensional bulk micro/nanocomposites with various functionalities that offer control over the size, shape and chemical composition. While volumetric materials could bring new optical and other phenomena, they have been mostly unavailable.

Keynote presentations

Ultrafast, Nonlinear and Chiral Nanoplasmonics

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Abstract: Ultrafast nonlinear and chiral photonic applications are often limited by the available choice of naturally occurring materials and their generally weak responses. Here, we will discuss novel plasmonic nanomaterials and hetero-nanostructures for tailoring hot-electron dynamics, plasmonic nonlinearities, ultrashort pulses and chirality.

Implementation of ultrafast plasmonic nonlinearities across various metamaterial and metasurface configurations revolves around enhancing the nonlinear response to minimize both the required light intensities and switching times, important in nonlinear optics and emerging time-varying functionalities. These challenges can be addressed through material-level improvements, nanostructuring, and leveraging the nuanced properties of nanostructured media, such as quantum confinement effects and nonlocality [1]. The potential of nonlocal spatial dispersion effects also needs further exploration, offering opportunities for customizing the nonlinear response, particularly in the epsilon-near-zero regime [2].

In this context, we will discuss several aspects of nonlinear optics and chirality in plasmonic nanostructures. The nonlinear optical response of ultrathin plasmonic films (in the trans-dimensional limit) and related ultrafast effects in hot-electron gas will be presented [3–5] and the routes towards active control of strong-coupling in plasmonic nanocavities will be overviewed [6]. Hot-carrier dynamics in ultrathin ITO films will be considered which results in counterintuitive modifications of the second-order nonlinear susceptibility [7]. The control over ultrafast pulses in nonlocal plasmonic metamaterials will also be discussed [8]. Tuneable nonlinearity in plasmonic metamaterials, which imprints a specific non-uniform hot-electron population distribution and drives targeted electron and lattice dynamics will be overviewed [9,10].

We will introduce a concept of rotating chiral dipoles in order to achieve unidirectional chiral scattering, which can be implemented by engineering multipole excitations in helicoidal plasmonic nanoparticles to realise enantio-sensitive and highly-directional scattering of circularly polarised light [11]. This concept offers numerous opportunities for engineering scattering from chiral nanostructures and optical nano-antennas paving the way for innovative designs and applications of chiral light-matter interactions.

The capability to manipulate temporal, spectral, chiral and mechanical aspects of light-matter interactions underscores nanophotonic applications where polarisation diversity, spectral selectivity and fast modulation are important. Tailored ultrafast optical and electronic processes are important for applications in nonlinear photonics, photocatalysis, chiral sensing and development of time-varying media.

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Complex Photonic Crystals and Complex Perturbation

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Abstract: We have recently fabricated several types of complex photonic crystals where the real and imaginary parts of refractive index have independent periodic modulation. In this talk, we discuss various interesting properties arising from them, such as non-Hermitian skin effect. We also discuss the effect of tiny complex perturbations to Hermitian systems to induce large changes in optical properties.

It has been clarified that various novel phenomena show up in non-Hermitian photonics where the complex refractive index plays an essential role. This indicates that conventional photonics should be reconsidered by designing the full complex nature of the degree of freedom for the refractive index. In this talk, we discuss two orientations with this scenario, that is, complex photonic crystals and complex perturbation. The concept of non-Hermitian photonics naturally upgrades photonic crystals to complex photonic crystals where the real and imaginary parts of index are both periodically modulated. Recently, we have succeeded in making various types of complex photonic crystals for which we separately control the symmetry and spatial pattern of the real and imaginary parts of index distribution. In this talk, we show that these specially-designed complex photonic crystals exhibit intriguing band structures and wavefunctions, leading to interesting properties including non-Hermitian chiral singular points in the momentum space, reciprocal non-Hermitian skin effect, and chiral responses including orbital angular momentum states. Second, we discuss the impact of complex perturbation to nanophotonic systems. Recently, we found that a very tiny localized complex perturbation to symmetric Hermitian systems produces chiral states. We show that this idea can be extended to various types of resonators and waveguides. These results show that the complex degree of freedom opens up new possibilities in nanophotonic systems in various manners.

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Quantum Computational Electromagnetics for Wireless Communications

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Abstract: This talk explores quantum computational electromagnetics, focusing on Hamiltonian-based optimization for arrays and metasurfaces in future wireless networks. We also highlight variational eigensolvers and Riemann-Silberstein time-domain solvers for NISQ architectures, enabling the simulation of high-dimensional problems and enhancing quantum-assisted design. These methods are of interest in future wireless communication systems.

Harness light in honeycomb topological photonic crystal

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Abstract: Transforming the concept of band topology fostered in electron systems to electromagnetic waves opens a completely new direction for harnessing propagation of light. It is observed that electromagnetic modes in honeycomb photonic crystals exhibit Dirac-type frequency dispersions, which are characterized by emergent spin degree of freedom, and that deforming the honeycomb structure in a designed way gives birth to a photonic analogue of quantum spin Hall effect. I will discuss how this system can be exploited for harnessing light efficiently and deriving novel optic features after an introduction on basic notions of topological crystalline insulator and photonic topology.

Nonlinear chiroptical scattering for photochemistry and enhanced surface sensing

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Abstract: We present the first demonstration of second-harmonic hyper-Mie optical activity and show that this effect can both induce and probe nonlinear chiroptical photochemical reactions. We also show that nonlinear chiroptical scattering can reveal surface states at the SiO₂/Si interface of nanoparticles.

Although theoretically predicted in 1979,¹ nonlinear optical activity effects in scattered light have only recently been experimentally demonstrated. There are three distinct patterns of light scattering, and they mainly depend on the wavelength of light and on the respective size of the scatterers. *Rayleigh scattering* occurs for particles much smaller than the wavelength. *Mie scattering* occurs for particles much larger than the wavelength of light. The intermediate regime is referred to as *Tyndall scattering*. These regimes extend to nonlinear optics. When the scattered light is at a harmonic frequency of the illumination, the effects are referred to as *hyper-Rayleigh*, *hyper-Mie* and *hyper-Tyndall scattering*, respectively. Furthermore, if the scatterers are chiral (i.e. lack mirror symmetry), the polarization of the scattered light can change – a phenomenon known as *optical activity*.

In 2019, we demonstrated the first instance of *hyper-Rayleigh optical activity*, at the second-harmonic wavelength.² Because they obey different selection rules and they typically probe different parts of the materials, even and odd harmonic nonlinear optical effects are very distinct. Our demonstration of third-harmonic hyper-Rayleigh optical activity was therefore another significant advance.³ A year later, we also evidenced third-harmonic hyper-Mie optical activity,⁴ which led to the question of whether hyper-Mie optical activity could perhaps be detected at the second-harmonic as well. Our initial attempts produced inconclusive results and therefore we turned our attention to showing hyper-Tyndall optical activity.⁵

All the light scattering effects mentioned so far correspond to *elastic scattering* – energy is conserved in both light and matter. By contrast, *Raman scattering* is an example of *inelastic scattering*. When the scattered photon is shifted from a harmonic frequency of the illumination, the effect is referred to as *hyper-Raman*. We demonstrated that chiral nanoparticles can confer chirality to achiral molecules, which leads to Raman⁶ and hyper-Raman optical activity, respectively.⁷

Now, we report second-harmonic hyper-Mie optical activity. The reason for the apparent inconsistency of our initial observations is a nonlinear photochemical reaction that transformed CdTe nanoparticles into CdO. As we show, the transformation leads to dramatic changes in the nonlinear optical activity signal. In this work, we compare directly linear and nonlinear optical activity, illustrating that the nonlinear effects are much more sensitive. In addition, we show that these nonlinear optical activity effects can detect surface states in the nanoparticles (e.g. at the SiO₂/Si interface), that are completely absent in the linear optical activity response.

In summary, nonlinear optical activity effects in scattered light took between 40 and 45 years to be experimentally demonstrated. They are now emerging as widely applicable spectroscopic techniques, vastly more sensitive than linear optical counterparts. They can probe tiny volume of analytes, and they can reveal the interactions between surface states and electromagnetic multipoles within nanoparticles.

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The importance of the research in Advanced Electromagnetics for 5G and 6G wireless communication systems: an industry view

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Abstract: The invited talk start analyzing the most important requirements of mobile networks evolving from 5 to 6G and how those drive the trends and technology for radio access and wireless backhaul products and solutions

- Application scenarios and frequency bands for 5G and 6G access and backhaul
 - Low bands and medium bands
 - cm-wave and mmw bands
 - Sub-THz
- Massive MIMO architectures comparison
- How backhaul can meet the demand of capacity and network densification

Industry will face additional challenges to antennas design and fabrication due to the unavoidable need to use high frequencies (starting from above 6 GHz) and antenna architectures that reduce the complexity and the power consumption of the system and the digital processing part. In particular, for high frequency scenarios, the growth of system's frequency corresponds to a growth of antenna complexity and cost, relative bandwidth and losses. Several challenges impact on the antenna design like sensitivity to manufactory accuracy, high integration level and distribute control points. Moreover, new problems like the harmonized co-channel coexistence between the IMT 5G systems and the fixed-satellite services will challenge the designers like never seen before in the wireless industry.

Research in Advanced Electromagnetism is fundamental to find technical and technology directions to solve the above challenges:

- unconventional phased arrays and the use of meta-surfaces to achieve tight emission masks and extended field of view
- new beamforming techniques without phase shifters that exploit the antenna as additional element to improve performance and efficiency
- mm-wave and Sub-THz for Sensing and Communication Integration
- smart electromagnetic environment to enhance the propagation channel

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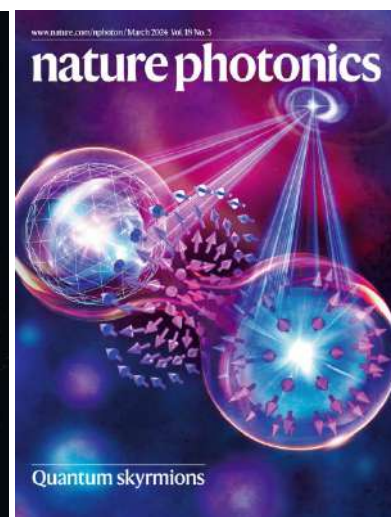
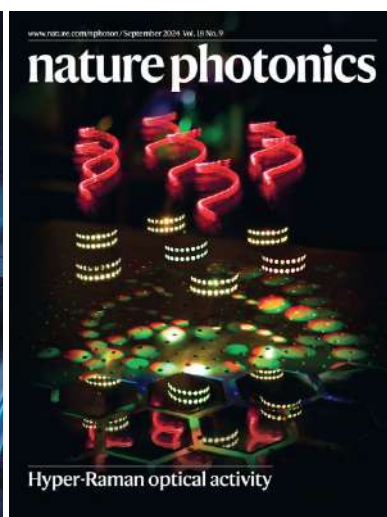
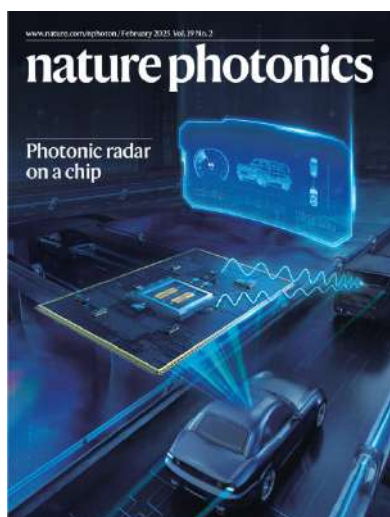
Publishing in *Nature* Journals: Some Facts and Trends

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Abstract: In this talk, Rachel will give you an overview on *Nature* journals and *Nature Photonics*, before detailing their editorial and peer review processes. She will also share some facts and recent trends in scientific publishing.



Design and Nanofemto Imaging PT Symmetric $\mathbf{E} \cdot \mathbf{B}$ Topological Plasmonic Fields

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Abstract: We perform imaging of surface plasmon polariton fields with nanometer spatial and femtosecond temporal resolution by photoemission electron microscopy. We find that plasmonic vortices host $\mathbf{E} \cdot \mathbf{B}$ fields that can drive magnetoelectric interactions or probe synthetic axion responses on 10 nm spatial scale.

The vector transverse $\mathbf{E} \times \mathbf{H}$ electric and magnetic fields and their pseudoscalar $\mathbf{E} \cdot \mathbf{H}$ counterparts are separately finite in vacuum as transverse plane waves and as angular momentum structured light. Current theories of electromagnetic interactions beyond the standard model of particle physics invoke $\mathbf{E} \cdot \mathbf{H} \neq 0$ as the source term of the axion law that describes interactions with the cosmological dark matter axion particles outside of the usual quartet of Maxwell's equations. In condensed matter, the $\mathbf{E} \cdot \mathbf{H} \neq 0$ pseudoscalar also drives relativistic spin-charge magnetoelectric excitations of synthetic axion quasiparticles at a distinctively higher condensed matter scale in magnetic and topological materials. Yet, how to drive coherent $\mathbf{E} \cdot \mathbf{H}$ responses in matter is untested and unknown. By analytical theory and ultrafast coherent photoemission electron microscopy,¹ we image $\mathbf{E} \cdot \mathbf{H}$ fields in surface plasmon polariton vortex cores, where phase singularities focus the magnetoelectric relative to the dipole density on a ~ 10 nm diameter scale.² The spin-orbit interaction of light generates localized nanoscale $\mathbf{E} \cdot \mathbf{H}$ fields, introducing the magnetoelectric class that has parity P and time reversal T symmetry broken, and the joint PT symmetry preserved opening the possibility of inducing and imaging electromagnetic interactions with synthetic axion quasiparticles on nanofemto scale.

We generate nanofemto movies of surface plasmon polariton (SPP) fields by nonlinear two-photon photoemission electron microscopy and simulate their space-time distributions by an analytical vectorial electromagnetic model. SPP fields are imaged with < 15 nm spatial resolution at a 50 attosecond per frame rate (the speed of light) by recording the spatial distribution of two-photon photoemission electron distribution that is generated by illumination of plasmonic coupling structures with a pair of phase correlated ~ 20 fs, 550 nm laser pulses. Lithographically defined structures in polycrystalline Ag films and polarization of the excitation fields define the orbital angular momentum of the generated SPP fields. The SPP orbital and transverse spin angular momenta interact to form vortex fields. Imaging of the interference by time delayed optical pulses images the fields to generate movies of electromagnetic interactions with sub optical space-time resolution.

We design SPP topological fields by spin-orbit interaction of light. Polygonal coupling structures together with illumination with circularly polarized light generate single, polygonal array (Figure 1), and quasicrystalline vortex field and spin textures.³⁻⁶ Imaging of the field space-time evolution with sub-optical cycle precision gives evidence of formation of topological meron or skyrmion spin textures. Closer examination of the generated fields by electromagnetic simulation and vectorial attosecond precision imaging reveals that plasmonic vortices host phase singularities that are a focus of surface parallel or antiparallel $\mathbf{E}$ and $\mathbf{H}$ fields on $< \lambda/2$ length scales for duration of the excitation field. While optical fields in vacuum are transverse electric and magnetic, the possibility of generating structured $\mathbf{E} \cdot \mathbf{H}$ plasmon fields opens the way to Poincaré engineering of topological

light-matter interactions⁷ with goals of driving magnetoelectric interactions and excitation of synthetic axion responses in solid state materials.

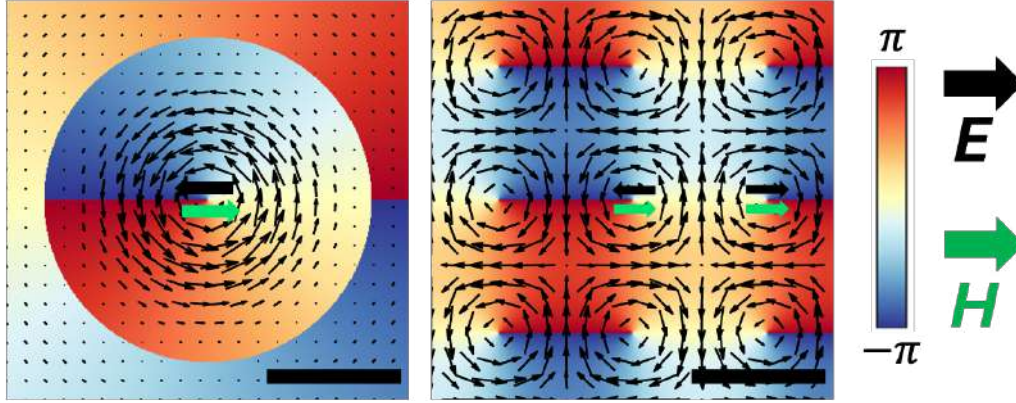


Figure 1. The simulated SPP field phase (color scale), k -vectors (thin black lines) of a single plasmonic vortex with skyrmion spin texture (left), and a meron spin texture vortex array (right), showing the focus of their anti-parallel E and H fields at their vortex cores. The thick black lines mark $\lambda_{SPP}/2=265$ nm.

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A Large Language Model Agentic System for Autonomous Metamaterials Research

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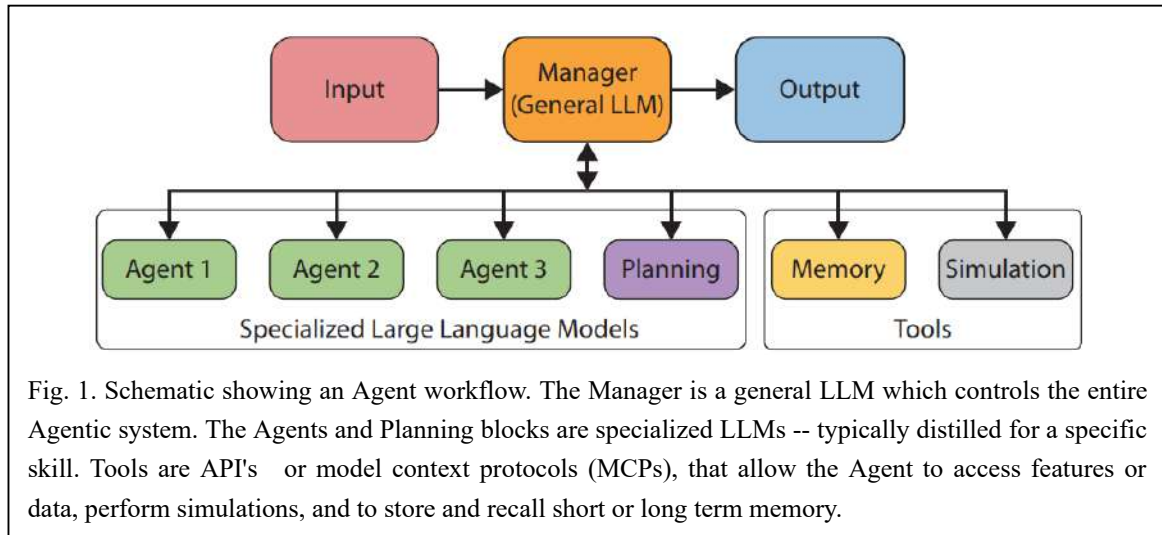
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Abstract: Large language models (LLMs) have expanded the capabilities of deep neural networks (DNNs). LLMs utilize training knowledge to perform basic reasoning tasks. We show the construction of an agentic LLM system (ALS), capable of performing metamaterials simulation, deep learning, and analysis autonomously. We highlight the future of this exciting field.

An agentic system is typically fashioned from distinct large language models (LLMs) and tools. The LLMs may be multi-100's of billions of parameters, e.g. 671 billion parameter deep seek R1, or distilled specialized LLMs, or quantized LLMs. Tools may include long and short-term memory, computational electromagnetic simulators (CEMS), or surrogate electromagnetic solvers (SEMS), i.e. a deep neural network. One particular framework shown in Fig. 1 consists of a general LLM Manager (orange), that controls the entire system. Here a human user provides Input (red) to the Manager, the Manager plans, conducts, compiles, and Outputs (blue) data and information. Such an ALS is termed an augmented LLM. Other common architectures which may be included within an ALS include prompt chaining, routing, parallelization, orchestration, and evaluation / optimization.



We will present initial progress toward achieving a LLM Agent that is capable of autonomous metamaterial design. The ALS can be given a relatively broad research area within the field of electromagnetic metamaterials. Here we show a research area where we have expertise and can therefore judge on the novelty of the proposed and carried out research. For example, an all-dielectric metasurfaces operating in the thermal infrared range from 8-15 μm . Given this relatively broad research area, the ALS can then:

1. Perform a literature search to generate research ideas
2. Use a LLM critic to evaluate if proposed research ideas are truly novel
3. Plan experiments
4. Perform experimental iterations (simulations, analysis, etc.)
5. Generate figures
6. Write manuscript
7. Use an LLM critic to evaluate if generated research paper is novel

A schematic depicting a generic ALS workflow is shown in Fig. 1, and we next summarize some specific Agents and Tools which are critical to the overall goal of the ALS. It is important, however, to clarify that an Agentic system may be a *Workflow*, which we define here as being composed of LLMs and tools which are coordinated with a user defined algorithm. A more complex arrangement, which we term an *Agent*, is a system where LLMs interact on their own and decide whether or not to access tools and other LLMs. Therefore, we can think of a *LLM Workflow* as a deterministic system, and a *LLM Agent* as a stochastic system. Both types of LLM systems will be presented and there can be value in both approaches. Some primary LLMs and Tools that serve specific functions within the Agentic system are: Critic, Planner, Retrieval, Reporter, Reasoner, Memory, and Simulation.

A LLM Agent can be distilled to be an expert *Critic* to judge whether ideas proposed in by the *Planning* LLMA are novel. The *Critic* can be given the capability to search the internet to develop a general and statistical understanding of the types of papers published in the realm of ADMs operating in the thermal infrared. For example the ALS can utilize APIs for Arxiv, Google Scholar, IEEE Xplore, ScienceDirect, SpringerLink, Web of Science, and Semantic Scholar to enable the Critic to search for relevant papers. We note there are other ways in which novelty can be determined more quantitatively through use of similarity metrics including: textual or semantic similarity. The Critic can be designed such that it output a *novelty score*, which indicates the degree of novelty, explains why the idea is novel, and provides relevant papers which support its assessment.

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Fluctuations and correlations in optical thermodynamics

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Abstract: Direct study of nonlinear multimode systems is a highly complex problem, due to the large number of the involved supermodes. Following a classical statistical mechanics approach, a thermodynamic theory for optical supermodes can be formulated. Recent theoretical and experimental advances will be presented, in this new direction of Optical Thermodynamics.

Acknowledgements: This project was funded by the European Research Council (ERC- Consolidator) under the grant agreement No. 101045135 (Beyond Anderson).

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Wave Propagation in Time-Varying Media: The First 35 Years

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Abstract: The earliest developments in the field of time-varying media – specifically, plasmas – will be reviewed, with the emphasis on the underlying microscopic description of the media and the resulting conservation laws. I will then discuss how dielectric metasurfaces can be used to produce a wide range of optical phenomena, including: time-steps, negative refraction, and phase front reversal.

Tutorial

AES 2025, TANGIER - MOROCCO, JULY 1 – 4, 2025

Writing and submitting your papers: Dos and Don'ts

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Abstract: In this tutorial, I will talk you through the detailed information and guidelines on scientific paper preparation and submission. Guidelines and tips for writing an abstract and a paper will be provided. Submission, editorial and peer-review processes will be discussed. At the end of the tutorial, you will walk away knowing how to write an informative cover letter, an outstanding abstract and a comprehensive scientific paper. You will also get to know where to submit your papers to, what editors seek, how your papers are reviewed and how to make an appeal.

Recent Advances in Nanophotonics and Metamaterials

First-principal end-to-end design for achromatic metalens in the visible

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Abstract: This work proposed an end-to-end inverse design scheme for broadband achromatic metalens working in the visible spectrum (380-750nm). The model combines the training of hardware nanostructure and a software reconstruction network, reaching an average peak signal-to-noise ratio (PSNR) of 18.88 dB.

Metalenses manipulate wavefront at the sub-wavelength scale, offering opportunities in various industries such as photography, communication, and medicine [1,2,3]. Compared with bulk refractive lenses, metalenses offer precise control over the impinging beam's amplitude, phase, and polarization. Conventionally, designing metalenses requires optimization of objectives such as modulation transfer function (MTF), Strehl ratio (SR), and depth of focus (DOF). Among common design methodologies, geometric phase metalenses [4] modulate the phase profile by altering the orientation of anisotropic nanostructures, whose phase delay changes in correspondence with the light polarization. Similarly, the propagation phase and resonance phase [5,6] are widely investigated in the development of metalenses. However, the performance of current methods is largely limited by their oversimplification of the light-matter interaction and incomplete optimization objectives.

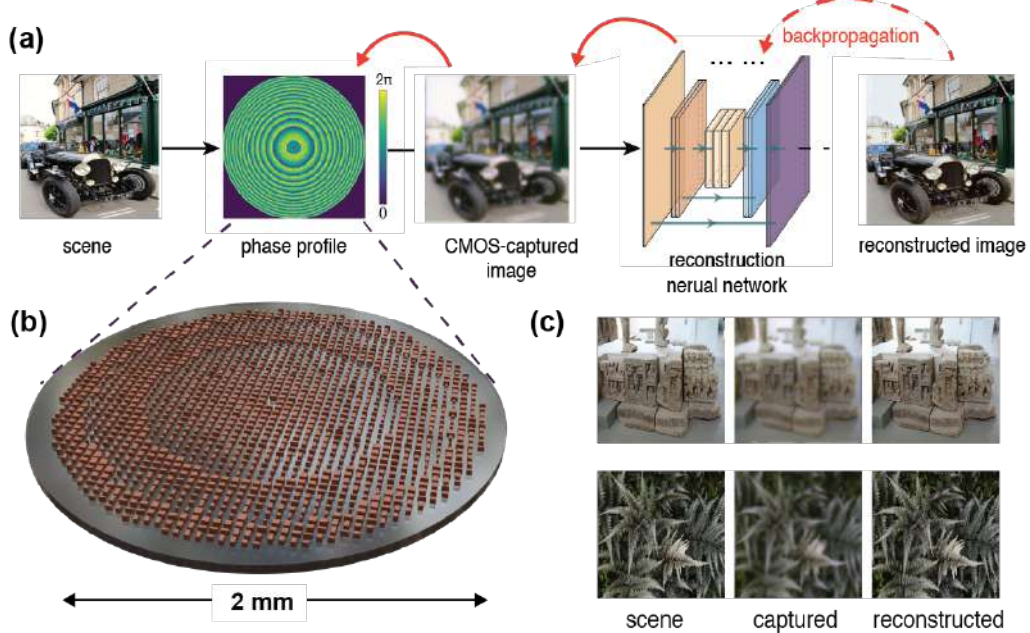


Figure 1: (a) End-to-end training framework for the metalens and reconstruction network. (b) Illustration of the metalens building blocks, designed for working in the visible range. (c) Examples of the original scene, the captured and reconstructed images.

This work addresses this issue by incorporating first-principal simulation (FDTD) into the end-to-end metalens design loop. The design framework focuses on image quality as the optimization objectives. Figure 1a depicts the end-to-end design scheme, where we propagate the light reflected from a scene through the metalens and free space. Numerically, we realize this operation by applying convolution with the metalens point-spread-function (PSF) on the scene image. Then, the framework simulates the photon-electron conversion process in a CMOS camera sensor by applying sensor sensitivity spectra and adding Gaussian noise. With the captured data, the framework implements a pre-trained neural network to reconstruct the image. The end-to-end training of the entire framework defines the image reconstruction loss as the mean absolute error (MAE) between the original scene and the reconstructed image. During training, the loss is first back-propagated by the reconstruction network and, consequently, the metalens phase profile and the metalens unit cell structures. The network's weights and the metalens geometry parameters are updated simultaneously in the same training epoch. We designed an 2mm by 2mm broadband metalens working in 380-750nm. Figure 1a illustrates the metalens building blocks, which are comprised of 1mm-wide unit cells of silicon nanostructure on glass. We build the reconstruction network with a lightweight ResUNet [7] backbone, comprising a total of 13 million parameters. The training is deployed on a single Nvidia RTX A6000 and uses the DIV2K-highres dataset [8].

Figure 1c exemplified part of the reconstruction performance on the validation dataset. One can observe that both the high-level features (objects, shapes) and low-level features (edges, textures) in the original scene are well reconstructed by the metalens and the network. The system reaches an average peak signal-to-noise ratio (PSNR) of 18.88 dB and an average structural similarity (SSIM) of 0.7948 across the validation dataset.

Acknowledgments: For large-scale FDTD simulations, this research used the resources of the Supercomputing Laboratory at King Abdullah University of Science & Technology (KAUST) in Thuwal, Saudi Arabia

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Inverse design of nanophotonic devices using high-order fullwave solvers and statistical learning global optimization algorithms

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Abstract: We present our recent achievements on the development of inverse design strategies for single-objective, multi-objective and robust optimization of nanophotonics devices. The backbone of these strategies consists in a combination of high-order methods for solving Maxwell’s equations and of different variants of a statistical learning-based global optimization algorithm.

In this talk, we will present our recent efforts and achievements toward the development of innovative numerical methodologies for the design of nanoscale photonic devices. Numerical modeling plays a crucial role in this context, in particular for discovering non-intuitive nanostructures or material nanostructuring for harvesting and tailoring the interaction of light with matter at the nanoscale. In our works, we combine two main numerical ingredients: (1) high-order Discontinuous Galerkin (DG) methods for solving the system of time-domain [1] or frequency-domain [2] Maxwell equations in 3D coupled to appropriate differential models of physical dispersion in photonic materials and (2) one of the most advanced optimization techniques that belongs to the class of Bayesian optimization and is known as Efficient Global Optimization (EGO) [3]. The statistical learning framework underlying the EGO method is particularly well adapted to the formulation of single-objective, multi-objective and robust optimization algorithms (optimization under fabrication uncertainties).

On one hand, our high-order fullwave solvers adopt the DG discretization framework. In the last ten years, we have developed two DG-based fullwave solvers that are high-order accurate and able to deal with unstructured meshes for a detailed representation of irregular geometrical features: a DGTG (Discontinuous Galerkin Time-Domain) solver of the time-domain Maxwell equations coupled to a Generalized dispersion Model [1] and a HDGFD (Hybridized Discontinuous Galerkin Frequency-Domain) solver of the frequency-domain Maxwell equation [2]. These fullwave solvers are accurate and particularly well adapted to problems involving multiple scales in space and time or wavelength. However, they are also computationally expensive. More recently, we also addressed this efficiency issue by studying fully data-driven model order reduction. A preliminary contribution in this direction combines a form of PCA (Principal Component Analysis) with a convolutional auto-encoder to devise a non-intrusive reduced-order technique starting from a training dataset, which is built a few fullwave simulations with the DGTG method [4].

On the other hand, for what concern the optimization part of our inverse design strategies, we also take into account the fact that each call to the DGTG or HDGFD fullwave solvers is a costly process by selecting an efficient optimization algorithm that requires a reasonable budget of forward solves to achieve a global optimum for the problem at end. More precisely, the EGO algorithm is a global optimization algorithm that substitutes the complex and costly iterative electromagnetic evaluation process with a simpler and cheaper metamodel. EGO is related to the class of Bayesian optimization. Contrary to the traditional common global optimization strategies like genetic algorithms, EGO is not based on adaptive sampling but on a surrogate model, which is constructed on the basis of available objective function evaluations. This surrogate model utilizes a statistical learning criterion related to the optimization target (usually called *merit function*) in order to identify which design (set of parameters) should be

tested in the next iteration that would provide better results close to the predefined goal. In our works, we have relied on several variants of the EGO algorithm to devise inverse design strategies for single-objective, multi-objective and robust optimization of nanophotonics devices.

We have developed an innovative software suite dedicated to computational nanophotonics, which is named DIOGENeS (<https://diogenes.inria.fr/>) and implements the aforementioned methods. The numerical tools from this software suite are utilized for conducting concrete studies in close collaboration with physicists from laboratories at the national and international levels. We will present several applications of these computational tools for the design of optical metasurfaces, nanostructured solar cells and plasmonic nanostructures (see Figure 1).

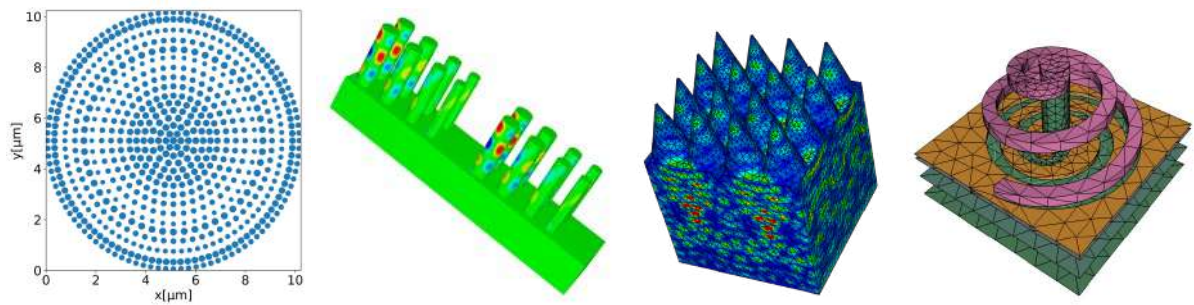


Figure 1. Left: 3D Metasurfaces for light for shaping. Middle left: phase gradient metasurfaces for deflecting light. Middle right: nanostructured solar cell for solar light trapping. Right: chiral plasmonic nanostructures.

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Development of magnetic microwires with high Giant Magneto-Impedance effect

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Abstract: We studied the correlation of the Giant Magneto-Impedance (GMI) effect and magnetic properties in Co-rich magnetic microwires. A remarkable GMI ratio improvement up to 735% is observed after annealing of studied Co-rich microwire. The observed modification of magnetic properties and GMI ratio improvement are discussed considering the internal stresses relaxation and the magnetostriction coefficient sign and value.

The main advantages of amorphous magnetic wires is their excellent magnetic softness that can be obtained directly after preparation [1]. In addition, superior mechanical and corrosion properties are observed in amorphous materials [1,2]. Therefore, studies of amorphous wires have attracted substantial attention owing to several promising applications [1-3]. Aforementioned magnetic softness of amorphous wires is intrinsically related to the Giant Magneto-Impedance, GMI, effect, consisting of a substantial impedance, Z , modification under the applied magnetic field, H [3,4]. The GMI effect is commonly described in terms of the GMI ratio, $\Delta Z/Z$, defined as [3,4]:

$$\Delta Z/Z = [Z(H) - Z(H_{max})] / Z(H_{max}) \cdot 100 \quad (1)$$

where H_{max} – is the maximum applied DC magnetic field (usually below a few kA/m).

A change of the skin depth, δ , of a magnetically soft conductor under effect of magnetic field, H , is assumed as the origin of the GMI effect. The relationship δ and circumferential magnetic permeability, μ_ϕ , of magnetic wire is given as [4]:

$$\delta = \frac{1}{\sqrt{\pi \sigma \mu_\phi f}} \quad (2)$$

being σ -the electrical conductivity.

High μ_ϕ and substantial $\mu_\phi(H)$ dependencies of amorphous magnetic wires are the essentially relevant factors for achievements of high GMI effect [3,4].

The main technological interest in GMI effect is related to the extraordinary high magnetic field sensitivity (few hundred percent change of impedance under low external magnetic field).

Consequently, in this paper we provide our latest attempt on optimization of the magnetic softness and GMI effect in Co-rich glass-coated magnetic microwires.

We studied magnetic properties and GMI effect in amorphous $\text{Co}_{72}\text{Fe}_4\text{B}_{13}\text{Si}_{11}$ glass-coated amorphous microwires with metallic nucleus diameters, d , of about 40 μm and a total diameter, D , of about 45 μm manufactured by the aforementioned by Taylor-Ulitovsky method [3]. Hysteresis loops have been determined by

flux-metric method, as described elsewhere [3]. We measured magnetic field dependences of impedance, Z , and GMI ratio, $\Delta Z/Z$, for as-prepared and annealed samples. We used specially designed micro-strip sample holder. The sample holder was placed inside a sufficiently long solenoid that creates a homogeneous magnetic field, H . The sample impedance Z was measured using vector network analyzer from reflection coefficient S_{11} .

A rather soft magnetic properties with coercivity, H_c , about 21 A/m and magnetic anisotropy field, H_k , about 130 A/m are observed in studied microwire. As shown in Figure 1a, a rather high maximum GMI ratio, $\Delta Z/Z_m$, above 550 % is observed in as-prepared sample.

However, it has previously been shown that appropriate annealing usually allows further improvement in the $\Delta Z/Z_m$ -value [4].

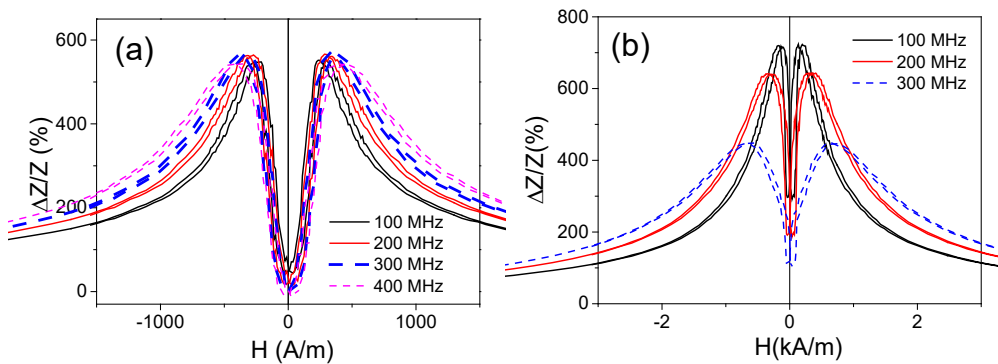


Figure 1. $\Delta Z/Z(H)$ dependencies measured at different frequencies in as-prepared (a) and annealed at 300 °C samples.

Therefore, we studied the magnetic properties and GMI effect after annealing.

A substantial increase in $\Delta Z/Z_m$ up to about 735% is observed after annealing at 300° C (see Figure 1b). This $\Delta Z/Z_m$ improvement

correlates with a change in the hysteresis loops, which consists of a decrease in the value of H_k -value up to $H_k \approx 75$ A/m, and an increase in the remanent magnetization, M_r/M_s , while H_c remains practically unchanged ($H_c \approx 24$ A/m).

The observed change in the hysteresis loop shape, in $\Delta Z/Z$ - value and $\Delta Z/Z(H)$ dependence upon annealing must be attributed to change in λ_s and corresponding change of domain structure of studied microwires after annealing.

Accordingly, the appropriate annealing of Co-rich microwires can substantially improve the GMI ratio.

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Non-uniform wave manipulation in biaxial anisotropic photonic time crystals

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Abstract: We explore the exotic wave dynamics of biaxial anisotropic photonic time crystals (B-APTCs) and examine their interaction with non-uniform waves, focusing on the momentum-bandgap phenomena for evanescent and ghost waves. Our study expands time-varying metamaterials by integrating wave characteristics, shedding new light on extreme manipulation of surface polaritons.

Photonic Time Crystals (PTCs) harness periodic temporal modulation of a uniform medium's material properties to unlock a spectrum of unique wave phenomena. We recently introduced anisotropic photonic time crystals (APTCs) that enable radiation from stationary charges and control emission features through reconfigurable anisotropic band structure in momentum space. PTCs host momentum bandgaps that allow for non-resonant light amplification and exotic light-matter interactions, yet achieving a wide bandgap requires refractive index changes beyond those possible with conventional nonlinear optics.

Here, we introduce momentum bandgaps for non-uniform waves, including evanescent and ghost types, by extending PTCs to biaxial anisotropic photonic time crystals that alternate periodically between uniform biaxial anisotropy and isotropic media. We show that ghost waves, unlike evanescent waves, sustain only momentum bandgaps, opening wide bandgaps at even the smallest modulation depths. Moreover, we demonstrate momentum bandgap effects on non-uniform waves that can be amplified, or through decaying modes, selectively attenuated. We find that ghost wave momentum bandgaps uniquely boost refracted over reflected waves under one-way incidence, in stark contrast to balanced amplification seen in both propagating and evanescent waves. Our approach bridges the gap between traditional nonlinear optics and PTC momentum bandgaps, enriching four-dimensional optics with time-varying metamaterials that integrate wave characteristics, potentially extending to surface polariton manipulation.

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Quantum optics with nonlinear metasurfaces

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Abstract: We demonstrate asymmetric nonlinear responses in quantum metasurfaces for tuning polarization entanglement and engineer biphoton spectra using nonlocal metasurfaces. Additionally, we present the first SPDC demonstration using 3R-MoS₂ metasurfaces, achieving a 20-fold SPDC rate increase. These advancements pave the way for on-demand quantum state generation and advanced quantum applications.

Photon pairs generated by spontaneous parametric down-conversion (SPDC) are pivotal in quantum applications such as quantum computing, imaging, and communication. Metasurfaces, two-dimensional arrays of nanostructures, have been intensively studied to enhance SPDC and provide additional functionalities compared to bulky optical systems. [1].

In the first project, Asymmetric nonlinear responses in quantum metasurfaces enable continuous tuning of polarization entanglement. While asymmetric optical responses have enabled breakthroughs in classical applications like non-reciprocal light transmission, we report the first experimental demonstration of asymmetric nonlinear responses for biphoton entanglement [2]. Using a structurally asymmetric semiconductor metasurface incorporating [110]-InGaP nano-resonators, we realize continuous tuning of polarization entanglement from near-unentangled states to a Bell state by adjusting the pump wavelength. Additionally, our nanoscale entanglement source features an ultra-high coincidence-to-accidental ratio of $\sim 7 \times 10^4$, outperforming existing semiconductor flat optics by two orders of magnitude [2]. Introducing asymmetric nonlinear response in quantum metasurfaces opens new directions for tailoring on-demand quantum states.

We also propose and experimentally demonstrate the comprehensive engineering of the biphoton spectrum from a nonlocal metasurface [3] by spatially shaping a pump beam. The nonlocal metasurface, incorporating silica grating on top of a lithium niobate film, supports optical resonances with tailored angular dispersion across the grating. Following the conservation of energy and transverse momentum, the metasurface can produce photon pairs at specific wavelengths $\lambda_{s,i}$ for a plane-wave pump beam with a given wavenumber k_p . This unique correspondence between k_p and $\lambda_{s,i}$ enables the generation of arbitrary biphoton spectra by spatially shaping the pump beam in k space. We experimentally demonstrate such spectral engineering by modulating the pump beam in the back-focal plane of the metasurface with different masks. The results may pave the way towards on-demand generation of spectral entanglement with nonlinear metasurfaces for applications in quantum information processing.

Van der Waals (vdWs) layered materials have emerged as a promising platform for quantum light sources, owing to their unique properties [4,5]. For example, vdWs materials offer high refractive index, a high nonlinear susceptibility, and compatibility with on-chip integration. In this work, we present the first experimental demonstration of SPDC utilizing a metasurface realized from 3R-MoS₂, a specially stacked van der Waals material. The metasurface supports quasi-bound states in the continuum (qBIC) with a quality factor of 120 at 1540 nm, greatly enhancing light-matter interactions. As a result, we observe a 20-fold increase in SPDC rate, which shows the measured coincidence counts for the metasurface and an

unstructured substrate. The corresponding SPDC spectrum at resonance exhibits a distinct peak corresponding to the resonance wavelength. Furthermore, our metasurface facilitates the generation of nondegenerate quantum photon pairs upon changing the pump wavelength, visible in the SPDC spectrum. This work demonstrates van der Waals metasurfaces as a versatile platform in generating quantum photon pairs, opening avenues for advanced quantum applications.

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This last project was supported by the Australian Research Council (DP190101559, CE200100010), Australian Research Council grant no. DP240101011 (Y.L.), DP220102219 (Y.L.), DP180103238 (Y.L.), LE200100032 (Y.L.) and ARC Centre of Excellence in Quantum Computation and Communication Technology project number CE170100012 and Meta Active IRTG 2675 (437527638). Metasurface fabrication was performed at Prof. Yuerui's group.

Fano line shapes in optical spectra of nonmetallic excitonic nanoparticles

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Abstract: Spectra of light scattering from excitonic nanoparticles are analyzed in the small particle limit and beyond the small particle limit. For various nanoparticles with different shapes, the Fano line shapes are generated by a common mechanism, and a generalized Fano function can generally describe the line shapes.

In this work, we discuss the optical spectra of a single excitonic nanoparticle characterized by a dielectric function $\varepsilon(\omega)$ placed in a surrounding material with a dielectric constant ε_m . The dielectric function of the excitonic particle is assumed to take the following form:

$$\varepsilon(\omega) = \varepsilon_b - \frac{f\omega_{exc}^2}{\omega^2 - \omega_{exc}^2 + i\gamma_{exc}\omega_{exc}}, \quad (1)$$

where ε_b is the background dielectric constant, $\hbar\omega_{exc}$ the energy of exciton transition, γ_{exc} the damping rate, and f the oscillator strength. In numerical calculations of spectra, we use the following set of parameter values that describe the optical properties of the PVA film doped with J-aggregates of TDBC molecules, which is one of the typical excitonic materials: $\varepsilon_b = 2.31$, $\hbar\omega_{exc} = 2.1029$ eV, and $\hbar\gamma_{exc} = 52.70$ meV. With these values of parameters, when $f < 0.115$, the real part of $\varepsilon(\omega)$ takes positive values over the whole range of photon energy considered, implying that the excitonic material is nonmetallic. In this work, we consider nonmetallic excitonic nanoparticles with $f = 0.100$.

In our previous work¹, we analyzed the spectra of light scattering of an excitonic nanosphere, and showed that the Fano line shape is generated by the interference between a broad nonresonant component arising from ε_b and a sharp resonant component arising from the Lorentzian response of exciton [2nd term in Eq. (1)]. Here, we extend the analysis to nanoparticles with various shapes, including ellipsoidal nanoparticles and nanocylinders, and show the similarity of the mechanism of Fano line shape generation and peculiarities of the line shape brought by the difference in the geometrical shape. Findings of the present work are summarized below.

I. Small particle limit

When the nanoparticles are much smaller than the wavelength of light (small particle limit), the retardation effects can be neglected, and the optical properties can be described under the electrostatics approximation. In the small particle limit, the spectra of light scattering from nanoparticles can generally be expressed in the following form²:

$$C_{sca}(\omega) = A(\omega)|F(\omega)|^2, \quad (2)$$

where $C_{sca}(\omega)$ is the scattering cross section, $A(\omega)$ is a prefactor, and $F(\omega)$ is given by

$$F(\omega) = \frac{a\varepsilon(\omega) + b\varepsilon_m}{c\varepsilon(\omega) + d\varepsilon_m}, \quad (3)$$

with constants a , b , c , and d . In the case of an ellipsoidal nanoparticle, the constants are given by $a = -b = 1$, $c = 3L_j$ and $d = 3(1 - L_j)$, where L_j is the depolarization factor along the j^{th} axis of the ellipsoid. For a spherical nanoparticle, $a = -b = 1$, and the values of c and d are retrieved by setting $L_j = 1/3$.

Defining χ_{back} as $\chi_{back} = (a\varepsilon_b + b\varepsilon_m)/(c\varepsilon_b + d\varepsilon_m)$ and the background spectrum as $C_{back}(\omega) =$

$A(\omega)|\chi_{\text{back}}(\omega)|^2$, and writing $F(\omega)$ as $F(\omega) = \chi_{\text{back}}\chi(\omega)$, the spectrum normalized to the background spectrum is obtained by

$$NC_{\text{sca}}(\omega) = \frac{C_{\text{sca}}(\omega)}{C_{\text{back}}(\omega)} = |\chi(\omega)|^2. \quad (4)$$

When the procedures described in Ref. 1 are applied, it is possible to show that $NC_{\text{sca}}(\omega)$ takes the following form of the generalized Fano function:

$$NC_{\text{sca}}(\omega) = |\chi(\omega)|^2 \cong \frac{(X+q)^2+b}{X^2+1}, \quad (5)$$

with $X = (\omega^2 - \omega_F^2)/\omega_{\text{exc}}\gamma_{\text{exc}}$, $\omega_F^2 = \omega_{\text{exc}}^2[1 + fa/(a\epsilon_b + b\epsilon_m)]$, and $b = 1$. The asymmetry factor q is analytically expressed using the parameters as,

$$q = \frac{(bc-ad)\epsilon_m}{(a\epsilon_b+b\epsilon_m)(c\epsilon_b+d\epsilon_m)}. \quad (6)$$

The above equations provide a unified description of the Fano line shape exhibited by small enough excitonic nanoparticles with various geometrical shapes.

II. Beyond the small particle limit

For nanoparticles with sizes beyond the small particle limit, we have to perform electromagnetic calculations that take into account the retardation effects. For spherical particles and infinite cylinders, the Mie theory allows us to obtain spectra of scattering cross-section (or efficiency). Using the dielectric function given by Eq. (1) and the above parameters, we have calculated the spectra of the normalized scattering cross-section for an infinite cylinder by varying the radius R . The spectra obtained for light normally incident on the cylinder are shown in Fig. 1. In contrast to the spherical particle in which the spectra do not depend on the polarization of the incident light, the spectra for the cylinder depend strongly on the polarization [Fig. 1(a) for TE and Fig. 1(b) for TM] and exhibit different dependencies on R . The results shown in Fig. 1 demonstrate that the Fano line shape changes systematically depending on R , and the line shape starts to deviate from the Fano line shape at $R \sim 80$ nm for the TE polarization and at $R \sim 100$ nm for the TM polarization. The present results confirm that the Fano line shape is preserved even beyond the small particle limit provided that R is smaller than the upper bound value.

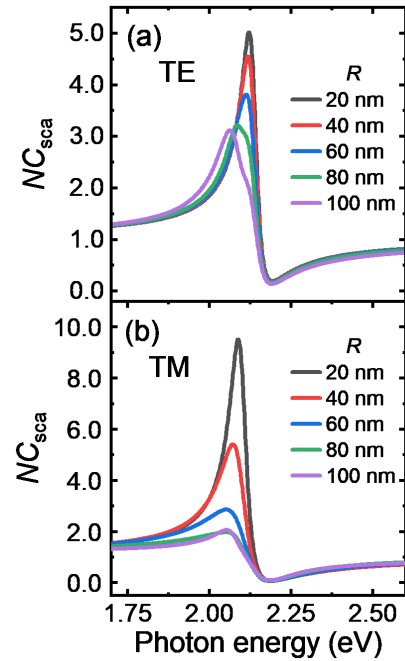


Fig. 1 Normalized scattering cross-section for infinite excitonic cylinder.

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Light-to-matter chirality transfer: growing chiral plasmonic systems using circularly polarized light

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Abstract: Light-to-matter chirality transfer can modify achiral plasmonic structures illuminated with circularly polarized light, inducing chiral growth on achiral plasmonic seeds by photocatalytically imprinting the reduced symmetry of the local fields onto the nanoparticle. We will discuss how different energy-transfer mechanisms can drive such asymmetric geometrical transformations, discussing recent experimental demonstrations.

Plasmonic nanostructures offer strong resonant responses in the UV-to-IR spectral range, which has led to their use in many optical and energy-related applications. Plasmonic photocatalysis stands as a prominent example of the latter, with plasmonic nanostructures serving as nanoscale antennas funneling radiant energy into their local environment. This talk will cover a particular subset of plasmonic photocatalytic setups with two defining characteristics: (i) the light-driven process modifies the geometry of the plasmonic nanoparticle or the optical properties of its immediate environment, and (ii) does so preserving local asymmetries induced by impinging circularly polarized light (CPL). This creates chiral features in initially achiral shapes, hence transferring chirality from light to the nanostructures, and contrasting with common strategies yielding chiral plasmonic systems, where chirality is seeded from molecules or introduced through top-down fabrication methods. The presentation will cover theoretical considerations underpinning light-to-matter chirality transfer in plasmonics,¹ a discussion about the physical energy-transfer mechanisms driving this phenomenon,^{2,3} as well an overview of experimental work going from pioneering examples^{4,5} to recent progress.^{6,7}

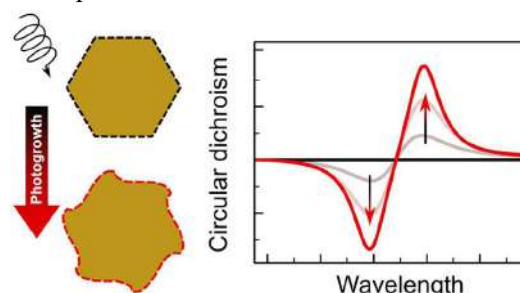


Figure 1. Diagram representing chiral growth of an achiral plasmonic nanostructure under CPL.¹

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Harnessing multiple-scattering electromagnetic environments for wave-control via in-situ adjoint optimization

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Abstract: We develop an in-situ time- and energy-efficient adjoint optimization (AO) methodology for the manipulation of wave scattering in multiple scattering systems and demonstrate wave-driven functionalities like targeted channel emission, coherent perfect absorption and camouflage. Our paradigm leverages these highly multi-path complex environments which dramatically amplify small local system AO-informed variations.

We experimentally demonstrate an in-situ optimization protocol that leverages adjoint sensitivity analysis to control and harness complex wave dynamics. The protocol is built around three components: in-situ measurements, targeted perturbations, and an external control mechanism, which collectively enable the real-time optimization of wave networks through two sequential field propagations -- forward and adjoint. First, local probes are employed to measure both the forward and adjoint wave fields at specific elements within the system. Forward propagation is utilized to compute a desired merit (or cost) function and to determine the excitation profile required for the subsequent adjoint propagation. The adjoint field, in turn, provides a comprehensive and simultaneous measurement of all targeted sensitivities. An external control mechanism evaluates these sensitivities to identify the potential perturbations which could enhance (or diminish) the merit (cost) function. These adjustments are then delivered by local actuators to the targeted components (i.e., the tunable degrees of freedom of the system). The cycle is repeated as many times as necessary to maximize (minimize) the merit (cost) function. To demonstrate the versatility of our protocol we showcase three different modalities, namely, targeted channel emission, coherent perfect absorption, and camouflaging, using a microwave experimental platform. The latter consists of a network of coupled coaxial microwave cables whose wave transport demonstrates features characterizing wave chaotic systems. These networks are frequently used as models for mesoscopic quantum transport, sound propagation, and electromagnetic wave behavior in complex interconnected structures such as buildings, ships, and aircrafts and therefore constitute a simple and versatile platform for experimentally implementing our in-situ optimization protocol.

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Nanoscale optical memory based on aggregation induced emission dye doped photoresist

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Abstract: Optical data storage has been limited by its low capacity due to its areal density. Here, we developed a nanoscale optical recording disk with Petabit-storage capacity based on a photoresist film doped with aggregation-induced emission dye, resulting in recording data spot at three-dimensional super-resolution scale.

Summary

Large amount of data is growing at an exponential rate globally along with the rapid development of information technology including cloud computing, internet of things and artificial intelligence. Conventional green and sustainable optical data storage (ODS) technology is a promising candidate for data storage with advantages of low energy consumption, high data capacity and long life-time. However, the storage capacity of current ODS technology is constrained by the optical diffraction limit¹. To massively increase the storage capacity of ODS is of crucial importance.

We developed a novel ODS medium of dye-doped photoresist with aggregation-induced emission (AIE) luminogens. The nanoscale data recording can be conducted via a dual-beam nanolithography process through a triplet–triplet absorption mechanism that can be inhibited by a donut shaped beam. The nanoscale data read-out process can be realized via employing optically stimulated AIE mechanism through the STED (stimulated emission depletion) microscope with a deactivating beam to distinguish nanoscale recording spots².

We demonstrated the ability of both super-resolution writing and reading up to 100 layers of data with the lateral spot size of 54 nm (about $\lambda/12$) and the lateral track pitch of 70 nm (about $\lambda/9$) inside our newly developed nanoscale optical memory (Figure. 1). The storage capacity of our ODS technology is extended up to 1.6 Petabit within the area of a DVD-sized disk.

These significant advantages indicate the development of next-generation industry-oriented nanoscale ODS that is more cost-effective than current state-of-the-art optical disk libraries and hard disk drives data arrays. Our results can serve as an effective solution to fulfil the vast data storage requirements of the big-data era.

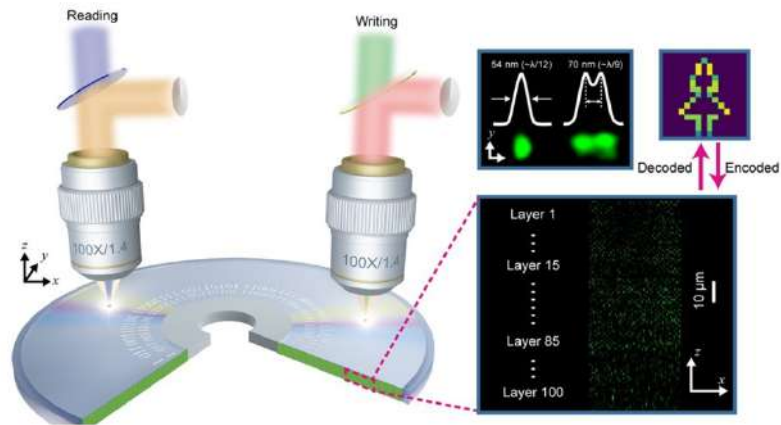


Figure. 1 Dual-beam configuration for super-resolution writing and reading

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Tailoring the emission and the photodynamics of quantum emitters with simple and optimized high-index dielectric nanostructures

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Abstract: Through experimental and theoretical methods, we demonstrate the controllable photodynamics of quantum emitters (NV colored centers in nanodiamonds) precisely positioned near silicon dimer nanoantennas. Then, by designing specific geometries with an evolutionary optimization algorithm, we explore enhancing the directional emission of these quantum sources numerically.

Introduction

Improving the brightness and efficiency of single photon sources by the mean of optically resonant nanostructures is a major stake for the development of efficient nanodevices for quantum communications.

For a couple of decades, these resonant nanostructures have mainly been made of noble metal that sustain strong localized resonances that can be used to manipulate, concentrate or redirect visible light. Such properties have led to numerous actual or potential applications in integrated optics, sensors, nonlinear optics, field-enhanced spectroscopies, or photovoltaics. Recently, an alternative emerged with high refractive index dielectric nanostructures, which offer the same range of applications as plasmonics by manipulating Mie optical resonances [1].

These resonances can be efficiently tuned by modifying the size, shape, and material of those nanostructures (e.g. silicon, $n \sim 4$) [2]. Furthermore, high index dielectric nanostructures offer several key advantages when compared to their metallic counterparts: absorption losses are far weaker for wavelengths longer than the direct band gap, access to semiconductor (CMOS) technology for nanostructure fabrication, and presence of intrinsic strong magnetic and electric resonances, providing an unique opportunity to spatially separate and redistribute the energy of the magnetic and electric parts of the electromagnetic field in the near field, otherwise inextricably connected in the far field [3].

Discussion

We discuss here the effect of simple high index dielectric nanoantennas on the spontaneous emission of model quantum emitters. First, we accurately positioned arrays of nanodiamonds hosting NV colored centers in the gap

of silicon dimer nanoantennas, using atomic force microscopy (AFM – [4]) nanoxerography [5]. The NV center is an ideal model system exhibiting single photon emission properties at room temperature, which is well adapted for proof of concept experiments in quantum nano-optics. Since the emission rate of the emitters, and therefore the local density of photonic states (LDOS), are modified by the nanostructure, we show by the mean of time-resolved photoluminescence acquisitions that the photodynamics of these emitters can be enhanced by the coupling to the nanoantenna down to the single photon emission regime [5]. Our experimental results are in good agreement with multipolar analysis and numerical simulations based on the Green Dyadic Method - GDM.

Next, to go a step further, we numerically investigate controlling the directional emission of quantum dipolar sources using complex Si antennas. These antennas, composed of specific numbers of building blocks, are optimized via an Evolutionary Algorithm (EA). The resulting geometries enable precise tailoring of emission direction, enhancing light intensity within defined solid angles. Our numerical experiments demonstrate the effectiveness of these EA-optimized antennas [6].

Acknowledgements

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Photolithography-compatible large area integrated photonic emitters by translation symmetry breaking: demonstrating full polarization control at 460 nm

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Abstract: A photonic metamaterial antenna emits ≈ 300 μm optical beams with customizable polarization, intensity, and phase at 460 nm. Transverse electric (TE), transverse magnetic (TM), diagonal linear and circular polarizations with smooth intensity profiles are generated from the TE slab mode by superimposing weak continuous perturbations on the translationally-symmetric slab metamaterial.

Photonic integrated circuits (PICs) enable cost-efficient, large-scale fabrication of advanced photonic systems. PIC functionality can be further enhanced by direct coupling with photonic modes in free space, such as wide, collimated Gaussian beams [1]. A promising approach for precise and flexible control of the emitted intensity, wavefront and polarization state is through symmetry-breaking techniques in 2D planar waveguide-based metamaterials. Coupling between a slab mode and free space can be accurately controlled by carefully perturbing the initial symmetry of these materials, as has been shown for 1550 nm light using arrays of discrete deep subwavelength features [2]. However, discrete translational symmetry designs require accurate fabrication of dense 2D arrays of very small structural elements, which is particularly challenging for shorter wavelengths in the blue and even ultraviolet necessary for coupling PICs to miniature atomic systems.

We have developed an alternative design relying on breaking a continuous translational symmetry. In our recent work [3], we demonstrated a fish-bone grating design that emits well-shaped, millimeter-scale, collimated beams at 461 nm and 780 nm directly from a PIC surface. Starting with a dense array of lines, we break translational symmetry by modulating line widths in a "fish-bone" pattern (Fig. 1 (a)), enabling optical emission. This approach produces a TE, s-polarized output from the incident TE slab mode, with modulation strength adjusted to shape the emission profile into an approximately Gaussian beam. Importantly, the ability to create weak modulation without making very small features enables broad and smooth beam profiles while retaining ≈ 100 nm lines and spaces, compatible with 193 nm photolithography. Continuous translation symmetry breaking also affords full polarization control (Figure 1), similar to its discrete counterpart [2], while using significantly larger feature sizes and spacing. Introducing a mirror-anti-symmetric "wiggle" modulation along the walls (Fig. 1(b)) produces pure TM (p-polarized) emission from the TE slab mode, while the TE (s-polarized) emission remains suppressed by symmetry. By superposing two such modulations with a tunable relative phase shift, the device can be made to emit any polarization, including circular (Fig. 1(d)), 45-degree linear (Fig. 1(c)), and customizable elliptical polarizations. Importantly, by spatially varying the modulation across the device surface, it is possible to achieve complex, user-defined spatial distributions of phase, intensity, and polarization in the output. The devices in Figure 1 measured at 460 nm, are made from 100 nm thick SiN_x in a silicon dioxide matrix. The modulation depth of the etched SiN_x regions, shown in dark blue, are spatially apodized to define smooth beam profiles with gradual onsets. The corresponding experimental images depict emission from the devices, with the collimated Gaussian slab mode light incident from the left, as indicated by the blue arrows. Light is outcoupled into collimated free-space beams emitted at small angles near

normal incidence. Emitted polarization is measured using a rotating linear polarizer (Figure 1(e,f)).

To summarize, metamaterials with continuous translational symmetry breaking offer the potential for large-area, flat photonic beam emitters that span the blue to infrared spectrum. It can also provide the ability to generate a wide range of spatial profiles for polarization, intensity, and phase. Furthermore, the devices created from these metamaterials are fully compatible with foundry-scale fabrication techniques, including photolithography, making them scalable and suitable for mass production.

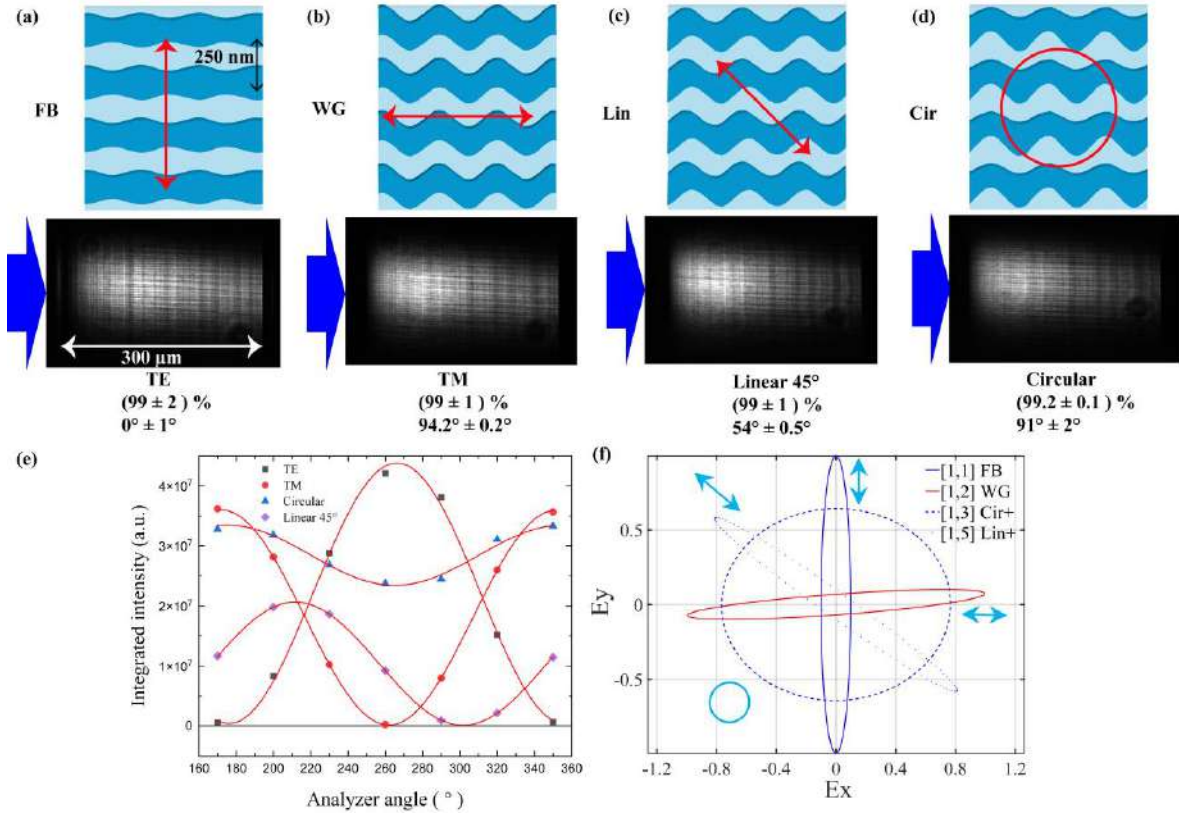


Fig. 1. (a)-(d) Fish-bone (FB) grating design preserving TE polarization, wiggle grating (WG) emitting TM polarization, and two combination grating designs (45° linear and circular). The etched regions of 100 nm thick SiN_x are depicted in dark blue, showing maximum modulations, located at the right-hand side of the spatially apodised gratings. Images show light emission from the corresponding gratings, with the slab mode light incident from the left (indicated by the blue arrow). The numerical values below indicate the estimated fraction of the power emitted into the dominant linear/circular polarizations and polarization major axis orientation. (e) Integrated optical intensity through a linear polarization analyzer (symbols) with sinusoidal fits (f) Reconstructed field ellipses showing the electric field vector trajectory.

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Efficient Diffraction Gratings based on 3D Structured Liquid Crystal

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Abstract: With photoalignment, complex surface patterns of liquid crystal orientation can be defined, to achieve a volume of inhomogeneous anisotropic material. Incident light is diffracted by the 3D volume grating and high diffraction efficiencies can be achieved, even for large diffraction angles.

Liquid crystals (LC) phases spontaneously arrange into anisotropic structures in order to minimize the elastic free energy. Owing to the fact that they are liquid, the self-assembling property can yield complex structures in three dimensions using simple processes that can be extended to large areas at a low cost. Periodic structures for diffraction gratings can be written by interference illumination on a photosensitive layer that contains azo-dye molecules. The average orientation of the long axis of the molecules, also called the director, tends to align parallel to the azo-dye molecules that have been reoriented by the illumination with linearly polarized UV or blue light. When the patterned director orientation near the surface is prescribed, then the liquid crystal director self-organizes into the (or one of the) state with lowest free elastic energy [1,2,3,4]. The structures may have a small period, which leads to diffraction over large angles. When the incident light is polarized, the diffraction efficiency can easily increase above 90%. Similarly as in the case of LC displays, applying a voltage across electrodes on the substrates can reorient the director pattern into an adjusted 3D arrangement, thereby modifying the diffraction properties of the device.

In nematic LC phase the lowest energy state is achieved for homogeneous alignment and any deformation of the homogeneous alignment leads to additional elastic energy. The drawback is that variations on the sub-micrometer scale at the surface are averaged out and the director in the bulk obtains an averaged orientation. Diffraction gratings based on nematic liquid crystal with LC thickness in the order of a few micrometer have limited efficiency if the diffraction angle increases above 10 degrees [4]. Other liquid crystal phases such as chiral nematic liquid crystal or blue phase liquid crystal obtain the lowest elastic energy state when there is an intrinsic periodicity in the 3D structure. This material property can be used to achieve diffraction gratings with period well below 1 μm , where the periodicity extends throughout the volume of the layer, even if the layer is several μm thick.

Recently we have shown that diffraction gratings with chiral LC [5] can be used to realize a one-component spectrometer that simultaneously diffracts and focusses light entering through a slit onto a linear detector array [6,7]. This diffraction grating has very high efficiency in reflection and can be used in outcoupling structures for waveguide-based augmented reality devices.

We have demonstrated that blue phase LC, which has a cubic structure with period in the range of 200 nm to 300 nm can be well aligned by periodic photoalignment [8,9]. Depending on the period written onto the substrate surface, and on detailed pattern that is used, the cubic unit cell may spontaneously orient in different ways, and

may undergo some deformations. The highly periodic 3D structure is revealed by observing Kossel patterns in the optical microscope.

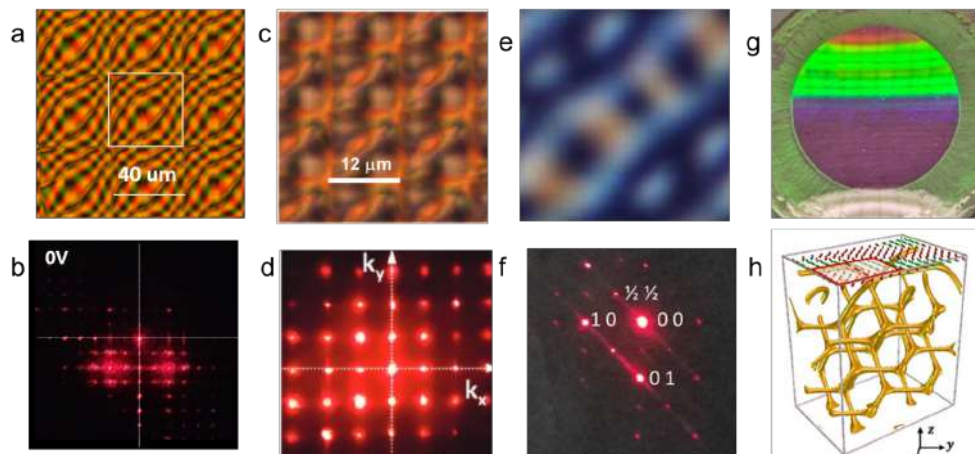


Figure 1: (a) Microscope image of a nematic LC grating with variable periodicity and (b) corresponding diffraction pattern. [2] (c) Microscope image of a long pitch chiral nematic LC grating with variable periodicity and (d) corresponding diffraction pattern [3]. (e) Microscope image of a nematic LC grating with rotating director on top and bottom substrates and (f) corresponding diffraction pattern [1]. (g) Diffraction grating of 20 mm diameter on a curved substrate to be used in spectrometer [7]. (h) Simulated blue phase structure below a periodic photoalignment pattern [9].

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Optomagnetism induced molecular phosphorescence

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Abstract: Subnanometer resolved single-molecule optical spectromicroscopy allows us to observe an intriguing electro-phosphorescence phenomenon of single molecules in a highly confined plasmonic picocavity, leading to the discovery of a new optomagnetic channel to activate the emission from the triplet-to-singlet transition that goes beyond the conventional spin-orbit coupling mechanism.

Aspirations for reaching atomic resolution with light have been a major force in shaping nano-optics, whereby a central challenge is to achieve highly localized optical fields. The plasmonic picocavity defined by the coinage-metal tip and substrate in a scanning tunneling microscope (STM) can provide highly confined and dramatically enhanced electromagnetic fields, which can modify both the excitation and emission of a single molecule inside the picocavity and also improve the spatial resolution of optical imaging down to the subnanometer scale [1]. In this talk, I shall present two aspects of our recent progresses on STM-based single-molecule optical spectromicroscopy. One is single-molecule tip-enhanced Raman spectroscopy (TERS), with spatial resolution down to single-bond resolution [2,3]. By using bond-specific vibrational fingerprints, such an ultrahigh resolution allows to track the bond breaking and making in surface reactions [4] and to spectrally resolve individual nucleobases and their sequence structures within a DNA molecule. A proof-of-principle demonstration of the latter will be presented using artificially designed short single-stranded DNA molecules [5]. The other aspect is single-molecule STM-induced luminescence (STML) with spatial resolution down to subnanometer scale. Unlike the common electric-dipole induced fluorescence via the electric channel [6–9], we recently observe an intriguing electro-phosphorescence phenomenon with an “anomalous” center-bright emission pattern, which unravels a new optomagnetic channel to activate the emission from the triplet-to-singlet transition. The optical-frequency magnetic field is found to be significantly enhanced in a confined plasmonic picocavity, leading to a new observation of optomagnetism induced molecular phosphorescence via the magnetic channel that goes beyond the conventional spin-orbit coupling scheme. The underlying microscopic mechanism involves an anti-symmetric spin exchange effect in a highly inhomogeneous plasmonic field, with the field gradient of the local optical-frequency magnetic field playing a critical role. Our results provide new insights and routes to optical imaging, spectroscopy and engineering of light–matter interactions at the subnanometer scale.

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Plasmonic chiro-optical field for circularly polarized luminescence and chiral structure fabrication

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Abstract: We utilized the plasmonic chiro-optical field to induce chiral light-matter interaction. Here, chiral emission with high luminescence dissymmetry was generated using the chiral nanoparticle. In addition, chiral structures were photofabricated by using the chiro-optical interaction of achiral nanoparticles with circularly polarized light.

The chiro-optical phenomena provide many intriguing optical effects in the sub-wavelength region, encompassing various applications from polarization control to chiral sensing, chiral optical forces, and spin-orbit interactions. Therefore, understanding the chiral light-matter interaction of nanoscale materials is crucial for developing novel chiro-optical materials and devices with desired functionalities. The plasmonic nanoparticles of chiral or achiral structures are capable to generate strongly twisted fields and mediate the absorption and radiation dissymmetries. We utilized the chiro-optical field near plasmonic nanostructures for the generation of circularly polarized luminescence and the creation of photofabricated chiral structures.

Recently, it has been proposed that the localized chiral electromagnetic fields of plasmonic nanostructures and metamaterials can transfer the chirality to other systems. This idea has been applied to generate circularly polarized luminescence (CPL) using additional luminescent materials such as organic dyes or quantum dots. In the present study, we demonstrate a novel approach to generate circularly polarized luminescence using only a chiral nanoparticle synthesized with a bottom-up approach.^{1,2} Despite being composed of a single element, the chiral Au nanoparticles are capable to produce the photoluminescence attributed to the electronic band structure of Au. At the same time, the strong chiro-optical responses in the near-field regime arising from the localized surface plasmon resonance of the nanoscale chiral structure can provide a dissymmetry in the photoluminescence process. We found that chiral Au helicoid nanoparticles exhibit circularly polarized two-photon induced photoluminescence (TPI-PL, Fig. 1), with a very high luminescence dissymmetry factor (g-factor) of ~ 0.7 , as single-component nanoparticles. Using electromagnetic simulations, we confirmed that the characteristic chiral gap structure of the helicoid nanoparticle is the local emission site contributing to the highly chiral light emission.

The capability to transfer the chirality has also been used to fabricate chiral nano-/microstructures. Recent studies have shown that a simple achiral plasmonic nanostructure can induce dissymmetry (chirality) of the electromagnetic field under the excitation with circularly polarized light.³ This principle has been mainly applied to the strong near-field effect near the surface of nanostructures to form chiral structures.⁴ Here, we focused on the effect of the scattering field extending over the few- μm regime, which is relatively weak compared to the near-field and therefore its effect has not been well addressed in previous studies. The secondary field induced by the nanoparticles can interfere with the incident light and give rise to a novel structure of the electromagnetic field at this spatial scale. Such fields can potentially provide unique nano-/micro-structured materials via photochemical reactions. In this study, we have shown that the plasmonic scattering can be coupled with the incident circularly polarized light to generate characteristic chiral interference patterns.⁵ We exploited this phenomenon to create the well-defined double spiral structure from achiral Au@Ag cuboid nanoparticles, by applying the

photopolymerization reaction under the irradiation of visible light (Fig. 2). Our numerical calculation further supports that the experimentally obtained photopolymerized structures are consistent with the interference pattern of the electromagnetic fields.

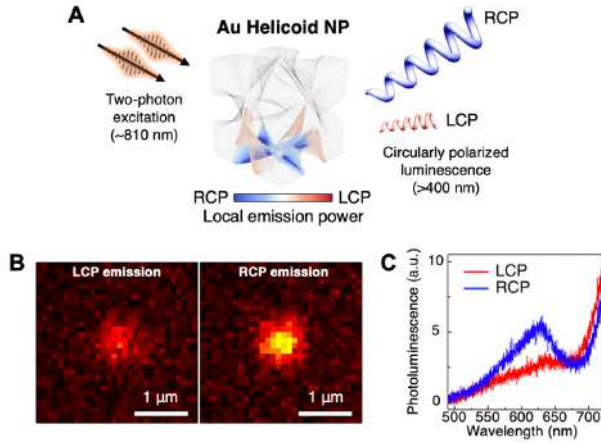


Fig. 1 (A) Schematic illustration of chiral light emission by TPI-PL process of Au helicoid NP. (B) TPI-PL images for left and right circularly polarized emission of a single Au helicoid NP. (C) TPI-PL spectra of the Au helicoid NP.

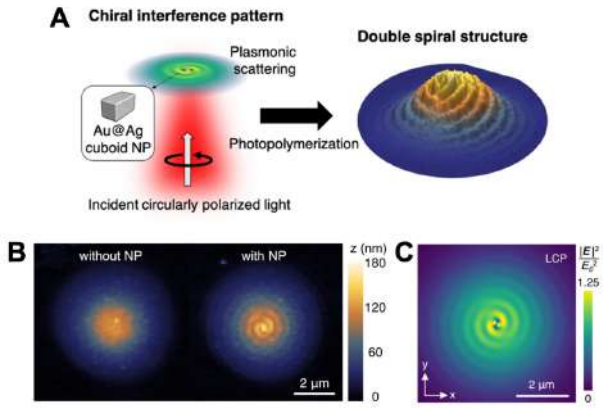


Fig. 2 (A) Schematic illustration of the creation of double spiral structure. (B) AFM images of photofabricated structures with (right) or without (left) Au@Ag NP under LCP irradiation. (C) FDTD simulated electric field near Ag cuboid NP under LCP irradiation.

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Au Enhanced Nanopillar Array for Polarization-Dependent Light-Driven Photocatalysis

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Abstract: A polarization-dependent metasurface of elliptical Au nanopillars was designed to enhance photocatalysis via localized surface plasmonic resonance. Asymmetric nanopillars tuned resonance wavelengths to molecular resonance under x-polarized light, maximizing yield while suppressing the reaction in y-polarization. The ordered array enabled precise optical predictions, with potential applications in multibranch reactions.

Photocatalysis holds immense potential for harnessing clean energy through chemical processes, such as water splitting and CO₂ reduction [1]. These typically encompass multistep electron transfer processes that culminate in the simultaneous generation of diverse products [2,3]. However, achieving high efficiency in collecting solar energy and selective conversion of a specific product remains a challenge. Thus, we concentrated on precisely manipulating a single-step reaction: the N-demethylation of Methylene blue (MB) driven by light with an effective wavelength range of 530-710nm [4]. Here, we designed a polarization-dependent metasurface (as shown in figure 1c)) which exhibits a localized surface plasmonic resonance (LSPR) at a specific wavelength and provides control over the reaction by adjusting the polarization of the incident light [5].

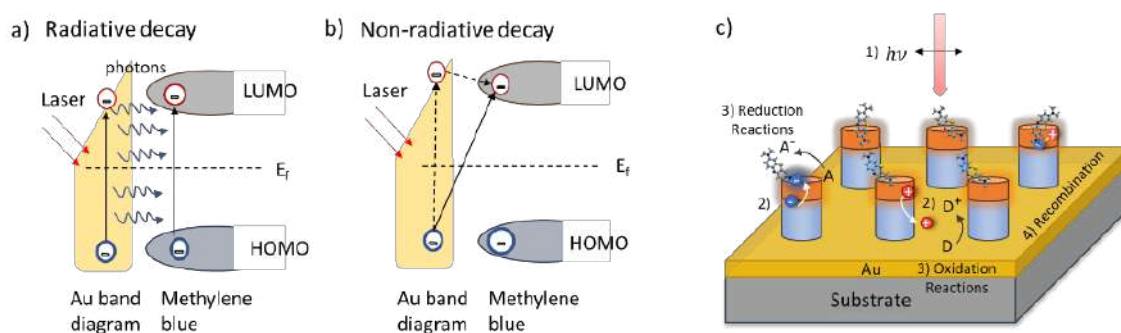


Figure 1. Metasurface nanostructure and photocatalysis mechanisms: a) LSPR radiative decay provides optical near-field enhancement for photocatalysis in MB. b) LSPR non-radiative decay provides direct and indirect hot electrons for reactions. c) Photocatalysis mechanisms on a Au-TiO₂ hybrid nanopillar array.

Metasurfaces have a nanometre scale structure which allows tuning the optical behaviour with tailoring their geometry. Elliptical TiO₂ and Au nanopillars with asymmetric diameters result in polarization-dependent optical properties. A hybrid nanopillar array was simulated with finite elements method (FEM) and fabricated through the top-down approach using electron beam lithography (EBL). For the laser in transverse magnetic (TM) modes, the array absorption has a peak at 620 nm, aligning with the laser wavelength to active the MB reaction. In contrast, the absorption

is reduced for the transverse electric (TE) mode to suppress the reactions, with the peak red-shifting to 800nm due to the asymmetric diameter in this direction.

Furthermore, to assess catalysis capability, surface-enhanced Raman spectroscopy (SERS) was employed to real-time monitor the progression of the N-demethylation reaction. The yield of the reaction is analyzed with the integration of the Raman peak of the reaction product at 480 cm^{-1} , which reveals the reaction rate manipulation. By switching laser polarization, the yield increased from 4.7 to 9.8 over a 10-second period on the same sample under the similar illumination conditions.

Our work highlights the potential for precise control of light-driven reactions using tunable metasurfaces, offering significant applications in selective photocatalytic reactions. We employed advanced nanostructure fabrication techniques to achieve precise nanoscale morphologies, enabling the tuning of optical properties to target specific reactions and pathways. These tunable metasurfaces present a promising approach for selectively catalyzing optical resonance-driven reactions by enabling particular pathways at intermediate steps. Future work will integrate more tunable materials, such as phase-change materials, into these designs, and extend this approach to complex multibranch reactions, such as CO₂ reduction. This method provides an effective solution for producing a broad range of products in multistep reactions, which is essential for achieving highly efficient conversion processes for renewable fuels.

Acknowledgements: This work is supported by the German Research Foundation DFG (Deutsche Forschungsgemeinschaft) through funding of the International Research Training Group IRTG 2675. The authors acknowledge access to NCRIS facilities (ANFF-ACT Node) at the Australian National University.

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Plasmonic properties of non-noble metal nanoparticles

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Abstract: We present an investigation of plasmonic properties of nanostructured non-noble metals at single particle level that establishes the spectral tunability of localized surface plasmon resonances in them. We focus on silver amalgam, gallium and especially bismuth which has been identified as a viable substitute for gold.

In metallic nanostructures, collective oscillations of free electrons are strongly coupled to the electromagnetic field forming the excitations called localized surface plasmons. Their characteristic feature is a strong enhancement of an electromagnetic field within the surrounding dielectric together with its confinement on the subwavelength scale, which can be utilized to control various optical processes even below the free space diffraction limit and is utilized in numerous applications. Despite the considerable promise exhibited by gold-based plasmonic applications, their widespread utilization is impeded by two significant challenges. Firstly, the high fabrication costs associated with these applications pose a substantial obstacle, and secondly, the plasmon energy range is constrained by interband transitions, which limits their effectiveness. These challenges can be addressed by exploring alternative metals such as gallium, bismuth, lead, and tin. Theoretical predictions indicate that these metals could offer comparable plasmonic performance while providing a broader plasmon energy range [1]. In this contribution, we present an experimental investigation of the plasmonic properties of silver amalgam nanoparticles [2], gallium nanoparticles [3], vanadium dioxide nanoparticles [4], and bismuth plasmonic antennas [5] using scanning transmission electron microscopy (STEM) combined with electron energy loss spectroscopy (EELS) [6], which allows for single particle analysis.

Silver amalgam is one of the most suitable solid electrode materials in electroanalysis. An exploration of the plasmonic nature of its nanoparticles has been conducted, resulting in the observation of strong plasmon resonances spanning the ultraviolet to mid-infrared regions for sizes ranging from nano- to micro-scale [2]. These findings establish silver amalgam nanoparticles as promising candidates for applications within photochemistry and spectroelectrochemistry, where the synergy between their plasmonic and electrochemical qualities can be fully utilized.

Gallium is a plasmonic material offering facile and scalable preparation and good stability of nanoparticles. We have grown lens-shaped gallium nanoparticles directly on a silicon nitride membrane using an effusion cell and experimentally proven that their dipole mode can be tuned through their size from the ultraviolet to near-infrared spectral region [3].

Finally, to investigate the plasmonic potential of bismuth, thin polycrystalline bismuth films were sputtered onto silicon nitride membranes. Thereafter, bowtie and bar plasmonic antennas of varying sizes were fabricated using focused ion beam lithography [7,8]. While the fabricated bismuth antennas exhibit lower plasmon resonance intensity than gold ones, the nearly identical plasmon energies across the entire range of tested antenna sizes demonstrate bismuth's potential as a viable alternative in plasmonic applications (see Figure 1). Moreover, the experimentally verified wider interval of bismuth plasmon energies allows applications at shorter wavelengths as well. The plasmonic performance of bismuth antennas has been validated, highlighting their potential as a viable substitute for gold [5].

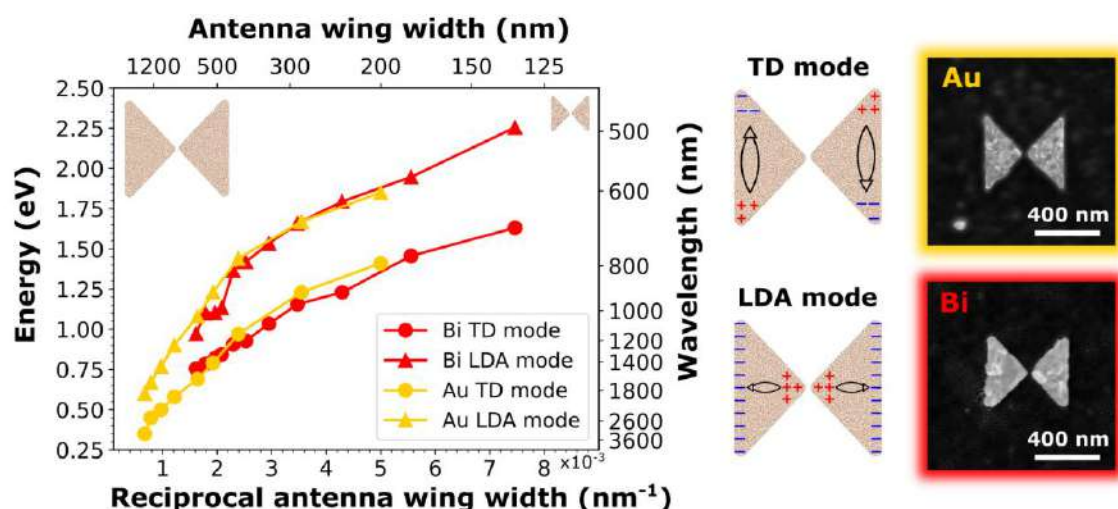


Figure 1: Energy of transverse dipole (TD) and longitudinal antibonding dipole (LDA) mode as a function of the reciprocal antenna width for bismuth and gold antennas. Based on the observed overlap of the two dependencies, bismuth can serve as a cheaper plasmonic alternative to gold. The data for gold bowtie antennas originates from Ref. [9].

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Optical manipulation of plasmonic particles as a promising approach for the fabrication of sensitive sensors based on Raman-enhanced methods

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Abstract: Optical manipulation of plasmonic particles represents a smart approach to the preparation of an active surface, enabling combined enhanced Raman spectroscopy of molecules. Here we introduce a fabrication method for detection platforms based on imprinting of plasmonic nanoparticles within a microfluidic chip, capable of detecting substances at the molecular level, as well as nanoplastics contamination.

Despite significant progress in the sensing strategies, the detection of biomolecules and very small plastic particles still faces problems caused by the limitations of current detection methods and instruments. Herein, we present an optical method for fabricating a substrate using plasmonic particles that can be used as sensors for a broad range of application fields. We summarize recent progress in our experiments using optical nanoimprinting of plasmonics nanoparticles to create the "active" aggregates that can be used for Surface Enhanced Raman Spectroscopy (SERS) detection of biomolecules (see Figure 1) and dyes in microfluidic circuits [1,2]. We applied the same strategy to prepare the active substrate to prepare a plasmon-enhanced thermoplasmonic concentrators for nanoscale particulate matter such as nanoplastics. The principle of nanoimprinting is based on the dominance of the scattering force (compared to the gradient force) for plasmonic particles, that are pushed in the laser beam propagation for the most of common wavelength used in Raman spectroscopy (532, 633 and 785 nm). An aggregate comprising plasmonic particles is produced that can serve as a substrate for SERS and as a source of the temperature gradient attracting dielectric nanoparticles (Figure 2). In both cases, enhanced effect is demonstrated, allowing the detection of nanoplastics/molecules of size/concentration orders of magnitude lower than what can be achieved by ordinary Raman spectroscopy.

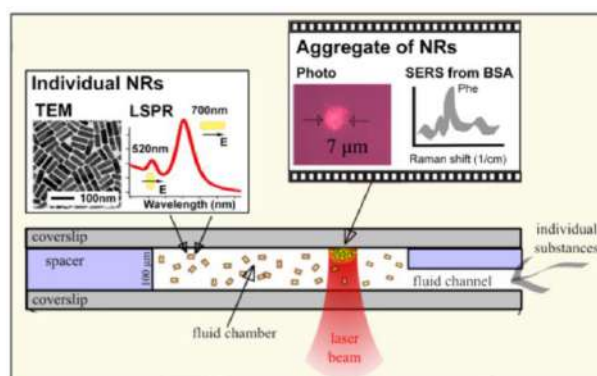


Figure 1: Basic principle of nanoimprinting plasmonic particles by optical forces in a microfluidic chip, followed by the formation of an aggregate that generates a SERS active hot-spots.

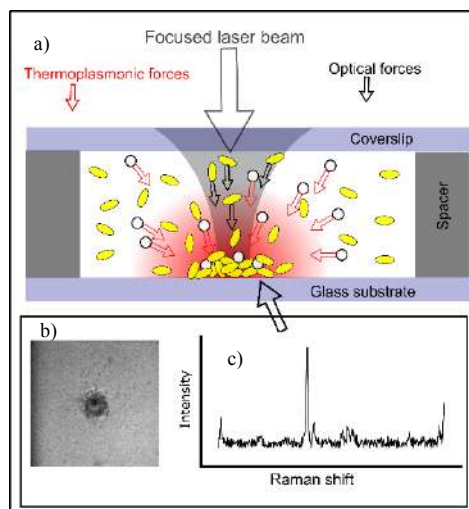


Figure 2: Basic principle of nanoimprinting plasmonic particles by optical forces, followed by the formation of an aggregate that generates a temperature gradient that attracts the dielectric nanoparticles.

a) The image of aggregate formed due to the plasmonic particles imprinting b). Raman spectrum of attracted nanoplastics due to the thermoplasmonic effect of the formed aggregate c).

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Tunable conducting polymer mid-IR microantenna arrays

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Abstract: Actively tunable mid-IR plasmonic antennas show prospects for a broad range of applications, which rely on efficiently switchable materials. Here, we investigate the tunable mid-IR plasmonic response of conducting polymer microantenna arrays and demonstrate efficient and reversible on/off switching capability.

Summary: Although noble metals like gold and silver show strong plasmonic resonances, their tunability is limited due to fixed carrier density. Recently, Chen *et al.*, introduced PEDOT (poly[3,4-ethylenedioxythiophene]) based dynamically tunable conducting polymer nanoantennas exhibiting plasmonic resonances in the near-IR regime. [1] These resonances could be chemically or electrically switched on/off by controlling the polaronic charge carrier concentration of the polymer, which switches the polymer between metallic (oxidized) and dielectric (reduced) states. [2,3]

Here, I will present our recent results on PEDOT microantenna arrays with plasmonic resonances at longer wavelengths in the mid-IR spectral range. [4] We find that the antenna arrays can provide clear asymmetric Fano-type plasmon resonances with peak position controlled by antenna size or array periodicity. Furthermore, we demonstrate complete and reversible chemical on/off switching of the mid-IR plasmonic response. This study can contribute to the developments in applications such as active mid-IR beam steering, thermal sources, and the adaptive radiative cooling technology.

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Bipartite Periodic Arrays as Platforms for Enhanced Absorption

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Abstract: Periodic arrays with bipartite unit cells have emerged as highly promising candidates for a wide range of photonic applications. Here, we show that these systems can be harnessed to achieve strong resonances with exceptional absorbance values and outstanding quality factors, further solidifying their potential within the field of photonics.

Two-dimensional periodic arrays of nanostructures support collective modes known as lattice resonances, which emerge from the coherent multiple interactions between the elements of the array [1]. Owing to their collective nature, these modes exhibit strong and spectrally narrow optical responses, making them valuable for various photonic applications, including biosensing and light emission [2]. More recently, increasing attention has been given to leveraging lattice resonances in applications that require efficient absorption, such as photodetection and photocatalysis [3]. Thus, fully exploiting their potential for this purpose requires strategies to tailor their optical response beyond conventional designs. In this contribution, we demonstrate how different bipartite configurations can be exploited to attain modes with extraordinary absorbance values and exceptional quality factors. In particular, we show that perfect absorption can be achieved in planar, bipartite arrays through the overlap of independent electric- and magnetic-dipolar lattice resonances, resulting in modes with remarkably high quality factors [4]. Beyond this, we also explore a strategy to significantly enhance absorption in weakly absorbing systems [5], further extending the versatility of bipartite arrays of nanostructures.

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A generalized specular scattering model based on susceptibilities

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Abstract

In this talk, we present a generalized solution for the generalized sheet transition conditions considering a metasurface homogenized in terms of susceptibilities. Under this generalization, it is possible to obtain analytical expressions for specular scattering for any polarization, by knowing the susceptibilities that characterize a given metasurface.

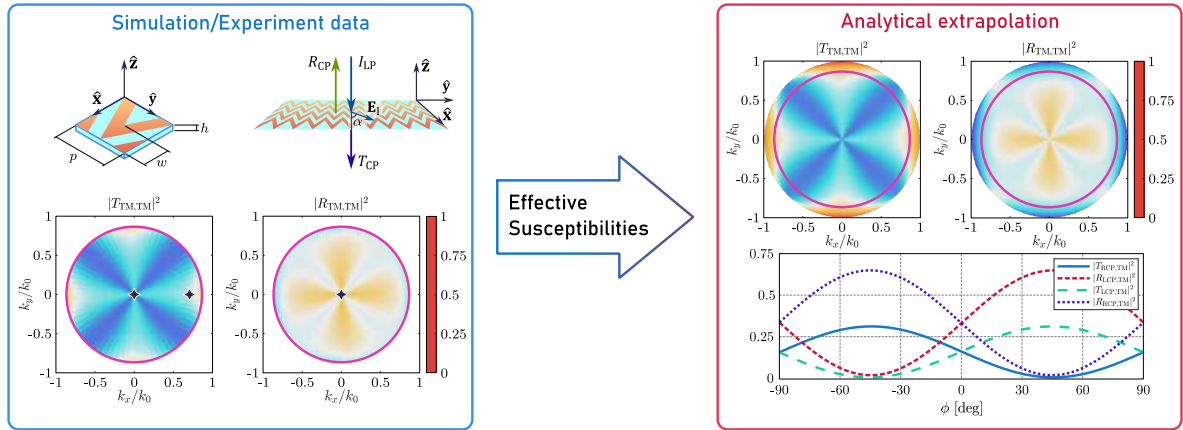


Figure 1: Through the use of the developed analytical model, it is possible to characterize any uniform homogenizable metasurface into a set of effective susceptibilities. With the use of such susceptibilities, the metasurface behavior can be characterized for any polarization and angle of incidence.

In order to analyze, design, and synthesize metasurface, it is relevant to have at hand a model that links the scattering properties of the metasurface with its geometry. The conventional approach to obtain analytical expressions is to solve the generalized sheet transition conditions (GSTCs) [1, 2]

$$\Delta \mathbf{E}_{\parallel} = j\omega \hat{\mathbf{n}} \times \mathbf{M}_{\parallel} - \nabla_{\parallel} P_n / \varepsilon_0 \quad (1a)$$

$$\hat{\mathbf{n}} \times \Delta \mathbf{H}_{\parallel} = j\omega \mathbf{P}_{\parallel} + \nabla_{\parallel} \times (\hat{\mathbf{n}} M_n / \mu_0). \quad (1b)$$

There is a generalized solution for Eqs. (1) for specular scattering, when the metasurface is characterized in terms of polarizabilities $\hat{\alpha}$ [3]. The main drawback of this implementation is that effective polarizabilities are characterized in terms of the unit-cell as a single scatter, and its interaction as part of a periodic array. While the scattering properties of a single particle are, for most cases, easy to characterize; the overall response of a particles array becomes non-trivial due to the interaction between the particle with their neighbors. Because of that, it becomes more beneficial to consider alternative means to homogenize the metasurface.

In this work, we propose an alternative solution to the GSTC, where the surface polarization densities are expressed in terms of susceptibilities

$$\mathbf{P} = \varepsilon_0 \bar{\bar{\chi}}_{ee} \cdot \mathbf{E}_{\text{avg}} + \frac{1}{c_0} \bar{\bar{\chi}}_{em} \cdot \mathbf{H}_{\text{avg}} \quad (2a)$$

$$\mathbf{M} = \mu_0 \bar{\bar{\chi}}_{mm} \cdot \mathbf{H}_{\text{avg}} + \frac{1}{c_0} \bar{\bar{\chi}}_{me} \cdot \mathbf{E}_{\text{avg}}. \quad (2b)$$

The main advantage of using susceptibilities is the use of spatial symmetries to reduce the complexity of the susceptibility tensors, reducing the overall complexity of the analytical expressions [4]. In a susceptibilities context, the GSTCs can be expressed as

$$\Delta \mathbf{E}_{\parallel} = \sum_{F=I,R,T} \left[j\omega \hat{\mathbf{n}} \times \bar{\bar{W}}_{\parallel,F} + j \frac{1}{\varepsilon_0} \mathbf{k}_{\parallel} \mathbf{V}_{n,F} \right] \cdot \mathbf{E}_{\parallel,F} \quad (3a)$$

$$\hat{\mathbf{n}} \times \Delta \mathbf{H}_{\parallel} = \sum_{F=I,R,T} \left[j\omega \bar{\bar{V}}_{\parallel,F} + j \frac{1}{\mu_0} \mathbf{1}_{\parallel} \mathbf{W}_{n,F} \right] \cdot \mathbf{E}_{\parallel,F}, \quad (3b)$$

where the tensors $\bar{\bar{W}}_{\parallel}$, $\bar{\bar{V}}_{\parallel}$, $\mathbf{W}_n$, $\mathbf{V}_n$ relates the susceptibilities with the incident ($F = I$) and scattered ($F = T, R$) waves. The generalized solution provides analytical expressions for co- and cross-polarized scattering

$$\bar{\bar{T}} = \begin{bmatrix} T_{\text{TM,TM}} & T_{\text{TM,TE}} \\ T_{\text{TE,TM}} & T_{\text{TE,TE}} \end{bmatrix}, \quad \bar{\bar{R}} = \begin{bmatrix} R_{\text{TM,TM}} & R_{\text{TM,TE}} \\ R_{\text{TE,TM}} & R_{\text{TE,TE}} \end{bmatrix}. \quad (4)$$

The main advantage of this approach can be utilized to characterize the behavior of a metasurface with given susceptibilities, without having to solve the GSTCs for each scenario [5]. Alternatively, this model can be used to determine the effective susceptibilities of a metasurface from its simulated or measured data, as portrayed in Fig. 1.

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Nonlocal and nonlinear plasmonics in actively tunable atomically thin heterostructures

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Abstract: We theoretically explore possibilities to engineer nonlocal light-matter interactions in graphene heterostructures by leveraging the electrical tunability of their individual components. Specifically, we propose strategies to control plasmon-driven nonlinear optical phenomena and the interaction of charged particles with matter in graphene nanoribbon heterostructures.

Graphene—the atomically-thin carbon monolayer—is now a widely recognized platform for nanophotonics at terahertz (THz) and infrared (IR) frequencies that supports high-quality plasmon resonances when doped with additional charge carriers [1]. The emergence of highly-doped graphene in plasmonics has been further catalyzed by the electrical tunability of its plasmons, which exhibit longer lifetimes and stronger near-field confinement than their noble metal counterparts, thus stimulating explorations across all areas of nanophotonics that capitalize on long-lived, strongly confined, and actively tunable optical resonances spanning the THz and near-IR spectral regimes. In many applications, the patterning of graphene into subwavelength structures facilitates the coupling of light impinging from the far-field to localized plasmon resonances that can be passively tuned by changing the structure size and morphology, while maintaining their active tunability by electrical doping [2]. Typically, localized graphene plasmons are explored in systems comprised of identical units arranged in periodic arrays to accumulate a measurable optical response. However, the independent electrical tuning of individual components in two-dimensional graphene heterostructures offers intriguing possibilities to engineer light-matter interactions on truly nanometer (i.e., ≈ 1 nm) length scales.

Here we theoretically explore plasmon-driven light-matter interactions in graphene heterostructures and novel nanophotonic functionalities enabled by actively tuning individual components. Focusing on one-dimensional systems, we first study the nonlinear plasmonic response of closely-spaced graphene nanoribbons with distinct charge doping levels that allow even-ordered nonlinear optical processes to be triggered in otherwise inversion-symmetric nanostructures, elucidating the role of nonlocal and cascaded effects in the nonlinear optical response [3]. Then, employing the atomistic simulation framework reported in Ref. [4], we show that nonlocal interactions of plasmons in similar electrically tunable nanoribbon heterostructures can drive an extreme nonlinear optical response associated with high harmonic generation. Finally, we propose a novel approach to actively control and tune the emission of Smith-Purcell radiation, arising from the interaction between charged particles and periodic structures [5], that leverages the tunable properties of graphene nanoribbon ensembles. Our findings pave the way for the development of advanced actively tunable nanophotonic light sources based on nonlinear optical phenomena and charged particles interacting with matter.

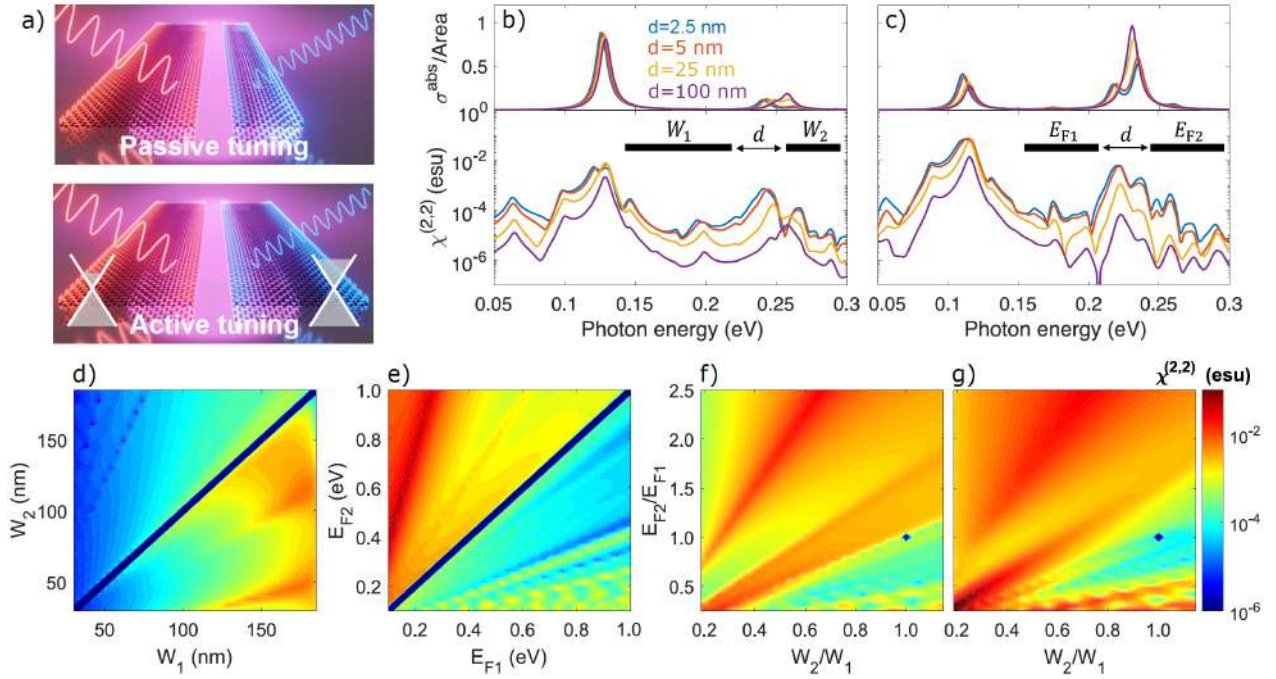


Figure 1: Second-harmonic generation in co-planar asymmetric graphene nanoribbon pairs. (a) Schematic illustration in the upper (lower) panel depicting second-harmonic generation (SHG) in two co-planar graphene nanoribbons separated by a distance d and characterized by unequal (equal) widths W_j and equal (unequal) Fermi energies E_{Fj} for $j \in \{1, 2\}$. (b) For a dimer formed by arranging ribbons of width $W_1=160$ nm and $W_2=40$ nm at the same doping $E_F=0.4$ eV, such that the frequency of the lowest-order dipolar plasmon resonance in ribbon $j=1$ is half of that in ribbon $j=2$, the effect of inter-ribbon interaction is explored in both the linear absorption cross-section (upper panel) and the SHG susceptibility (lower panel) by varying the separation distance d . (c) Similar to (b), but for ribbons of equal width $W_j=100$ nm and different doping $E_{F1}=0.2$ eV and $E_{F2}=0.8$ eV. (d-f) SHG from co-planar ribbons spaced $d=25$ nm apart when: (d) the ribbons have the same doping $E_{F1}=E_{F2}=0.4$ eV and varying widths W_j ; (e) equal widths $W_1=W_2=100$ nm and varying doping E_{Fj} ; (f) both the width and doping of ribbon $j=2$ are changed. (g) Similar to (f), but for a small ribbon separation $d=2.5$ nm. In panels (d-g) the impinging light frequency is maintained at the lowest-order dipolar plasmon resonance frequency.

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Microwave-modulated optomagnet as a tunable nanosource of spin-waves

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Abstract

We demonstrate the tunable excitation of spin waves using nanoscale a modulated optomagnet. The modulated optomagnet is a plasmonic nanoantenna coupled to a modulated continuous wave (CW) infrared laser source. We experimentally demonstrate the conversion of different sinusoidal microwave signals into monochromatic spin waves belonging to different allowed magnon bands in the GHz frequency regime.

Introduction

Optics has enabled efficient and compact sources of propagating magnons by use of femtosecond optical pulses[1, 2], based on the Inverse Faraday effect (IFE) produced with single or periodic light pulses[3, 4]. However, being diffraction limited, the resulting excitation spots have not allowed for ultracompact magnon emitters. Recently, subwavelength gratings have been successfully used to locally excite spin waves beyond the diffraction limit[5]. However, the tightly confined light spots were obtained through coherent scattering across a large array of subwavelength grooves, and the development of a truly nanometer-scale optical source of spin waves has not yet been presented.

Recent studies on IFE report that illumination with circularly polarized light turns the plasmonic nanoantenna into a nanoscale optomagnet i.e generates a static magnetic field around the disk [6–10]. Our approach is to use these optomagnets to generate spin-waves from a compact tunable nanosource. In this approach a microwave-modulated CW laser beam excites spin-waves through optomagnet via resonant IFE. The modulation can be fine tuned which makes optomagnet highly tunable source of spin waves. Here, we report the experimental demonstration of a nanometer-scale optical source of spin waves by coupling a microwave-modulated CW laser to a resonant plasmonic nanoantenna.

Results and discussion

We positioned a 50nm thick gold nanodisk on top of a transparent thin-film yttrium iron garnet (YIG) in a presence of an external static magnetic field ($\mu_0 H$) of 20mT (Fig. 1, (a) blue arrow). The diameter of the nanodisk is set to 130 nm to match its electromagnetic resonance with the frequency of the illuminating modulated infrared (IR) laser ($\lambda=808\text{nm}$). When illuminated with a circularly polarized CW IR laser, the nanodisk generates a static magnetic field around itself, known as the optomagnetic field (Fig. 1, (a) black arrows). The idea now is to illuminate

the nanodisk with a microwave-modulated CW laser source, thereby enabling the modulation of the optomagnetic field around the nanodisk as evidenced in [11, 12]. This way we create a microwave-modulated optomagnet on YIG via resonant IFE. The modulated optomagnetic field couples to the spin-waves in YIG (Fig. 1 (a) red arrows) which are detected by means of inelastic/Brillouin light scattering (BLS) (Fig. 1 (a) green arrows).

Fig. 1 (b) shows that when the modulation is removed spin-waves are not excited. Moreover, in Fig. 1 (c) one can see that the acquired BLS spectra show the enhancement of spin-wave signals at the frequencies corresponding exactly to the modulation frequencies of the IR CW laser: 3.6 GHz (red), 4.5 GHz (green), and 7.4 GHz (blue). The small peak at 6.2 GHz (indicated with a cross) did not depend on H and was attributed to a parasitic line of the green laser.

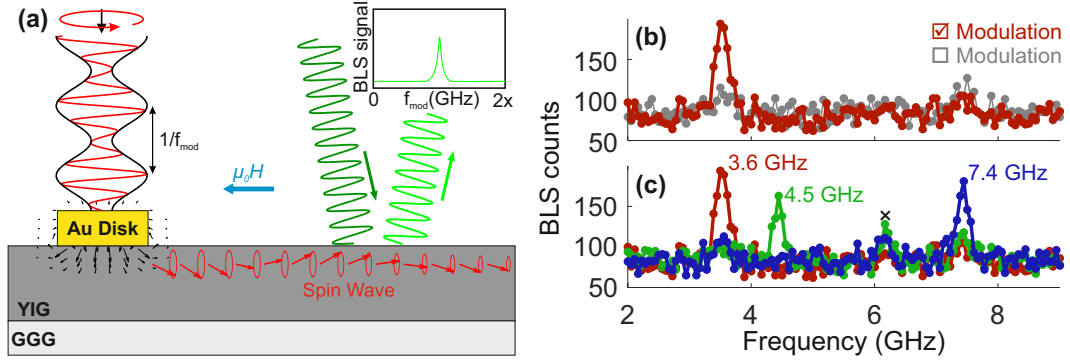


Figure 1: **Excitation of monochromatic spin waves by an optomagnetic nanoemitter.** (a) Experiment depiction. (b) BLS spectra of the probe beam with/without modulation (3.6 GHz) of the IR laser. (c) BLS spectra of the probe beam with different modulations of the IR laser that are indicated in the legend.

Our results show that plasmonic nanoantennas are nanoscale emitters capable of tunably transduce a microwave signal into short-wavelength spin-waves, while avoiding physical and technical constraints inherent to microwave antennas. Particularly, our approach offers a broad spin-wave-frequency bandwidth from MHz to sub-THz depending only on the light-modulation methodology. Spin waves, in turn, serve as a novel probe for investigating plasmon-induced optomagnetic effects at the nanoscale.

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Emission Behavior Control in Triplet-Triplet Annihilation Upconversion Systems Induced by Metal Nanostructures

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Abstract: Triplet-triplet annihilation-based upconversion (TTA-UC) systems have recently attracted significant interest due to their ability to be driven by noncoherent, low-intensity light including sunlight. We have enhanced their performance by leveraging near-field effects induced by localized surface plasmon resonance through hybridization with plasmonic metal nanostructures.

Upconversion is a general term for technologies that convert low-energy, long-wavelength light into high-energy, short-wavelength light. Recently, triplet-triplet annihilation-based upconversion (TTA-UC) systems, composed of sensitizer and emitter molecules, have attracted much attention as a strategy to address the inherent issue of unutilized sunlight wavelengths in solar devices. In particular, the development of high-performance solid-state TTA-UC systems, which offer high weather resistance and are easily integral into solar devices, is highly desired. However, many optimized solid-state TTA-UC systems suffer from both low absorption and quantum yield, necessitating significant performance improvements. Strategies involving modifications to molecular and system structures have improved the performance of solid-state TTA-UC systems. Meanwhile, we are working on performance enhancement through hybridization with metal nanostructures. For example, the upconverted emission was enhanced by approximately eightfold in systems composed of silver nanoprisms-immobilized substrate, overlaid with thin films containing Pd porphyrin as a sensitizer and anthracene derivative as an emitter (**Figure 1**(A) and (B)). This is likely due to the photoexcitation enhancement of sensitizer by the localized surface plasmon (LSP) resonance of silver nanoprisms because the LSP resonance wavelength of the silver nanoprisms generated a significantly enhanced localized electromagnetic fields at the excitation wavelength of the TTA-UC system. This effect significantly improved the threshold

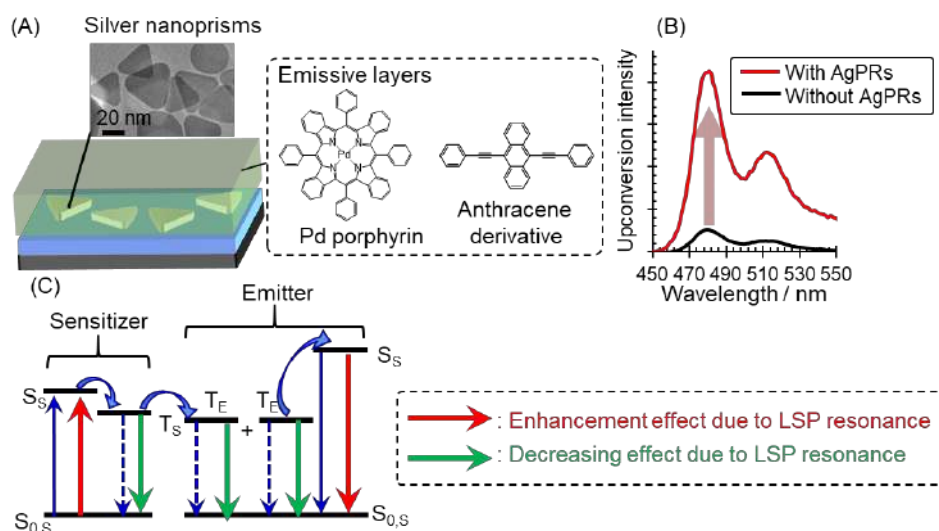


Figure 1. (A) Schematic showing of plasmonic TTA-UC systems. (B) Upconverted emission spectra of systems with and without silver nanoprisms. (C) Energy diagram of plasmonic TTA-UC systems.

excitation light intensity, which is one of the performance indices of the TTA-UC systems. Additionally, the strong local electromagnetic fields induced by LSP resonance enhanced the Purcell effect on singlet-excited emitter molecules, leading to a threefold increase in upconverted emission.[1] This is supported by the fact that the fluorescence lifetime of singlet-excited emitters was shortened by the silver nanoprism. These results indicate that LSP resonance has significant potential for enhancing the performance of TTA-UC systems by increasing upconverted emission intensity (**Figure 1(C)**). Furthermore, it was experimentally confirmed that LSP resonance can rather reduce the upconverted emission. Phosphorescent metal porphyrins, which exhibit strong spin-orbit coupling, are commonly used as sensitizers. The LSP resonance accelerates the radiative decay of triplet-excited sensitizers, competing with triplet energy transfer to the adjacent emitters and ultimately diminishing the upconverted emission (**Figure 1(C)**). Additionally, it was confirmed that the nonradiative decay rate of triplet-excited emitter molecules was accelerated by LSP resonance, thereby reducing triplet-triplet annihilation between competing emissive molecules.[1,2] By elucidating the influence of LSP resonance on the spin dynamics of metal complexes, we aim to contribute to future research for improving TTA-UC performance.

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In-Operando Control of Sum-Frequency Generation in Tip-Enhanced Nanocavities

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Abstract: We demonstrate continuous wave sum frequency generation in nanoparticle-on-mirror cavities filled with a monolayer of molecules when placed beneath a metal scanning probe tip. Tip-enhanced nanocavities enable in-operando control of nonlinear optical signals, achieving enhancements of up to 14 orders of magnitude and covering a broad range of infrared frequencies.

In only a few years, scattering-type scanning near-field optical microscopy (s-SNOM) has transformed into a key actor for the nanoscale imaging and spectroscopy of thin layers materials across the IR and THz spectral ranges. Extension of its abilities to other spectral regions and to properties of vibrational and phononic modes different from the mere absorption would be interesting for researchers in nanooptics but also for a number of technological developments in surface science and chemistry.

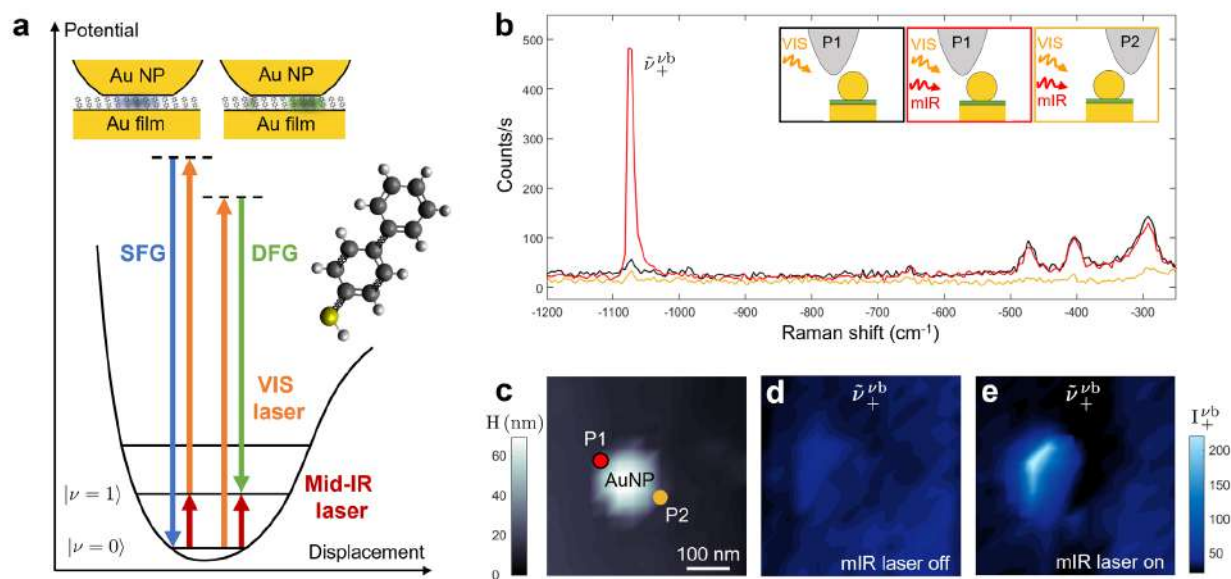


Figure 1: (a) Energy diagram of vibrational nonlinear optical processes. Above the diagram: Field distributions inside the plasmonic gap, where the molecular upconversion signals (SFG and DFG) are generated. (b) Spectra for different tip positions and illumination conditions (VIS or VIS+IR) (c) Topography map and intensity maps at the vibrational sideband of interest with IR illumination on (d) and off (e).

Here, we use s-SNOM to study mid-IR to VIS sum-frequency generation (SFG), in which the sample's SFG cross-section is enhanced by many orders of magnitude by the s-SNOM microscope's tip. By combining

simultaneously mid-IR and VIS illuminations on gold nanostructures, we show the “on-demand” emergence of upconverted infrared signals controlled by the tip’s nanomechanical positioning. Studying several vibrational modes, we additionally evidence and distinguish the tip contribution on both infrared and Raman processes.

Our experiment demonstrates for the first time CW SFG with a near-field microscope, simplifying greatly the requirements on samples that can be addressed via upconversion spectroscopy. Conversely, our work also leads to a novel near-field microscopy modality where the hyperpolarizability of thin molecular films and 2D materials could be probed at the nanoscale.

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Spoof Surface Plasmon Polaritons on MEMS-Integrated Tunable Metasurfaces for Filter and Leaky Wave Antennas Applications

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Abstract: The dispersion properties of MEMS-integrated metasurfaces can be precisely engineered across a broad frequency range. By careful design, these metasurfaces enable effective tunable frequency filtering of spoof surface plasmon polaritons and can function as surface waveguides for beam steering leaky wave antennas.

Advancing on-chip communication at higher frequencies relies heavily on the miniaturization of plasmonic networks. Although various metallic metasurface designs can guide and statically control confined spoof surface plasmon polaritons (SSPPs) at lower frequencies, enabling real-time reconfigurability at microwave or terahertz frequencies remains a significant challenge. Presently, most practical solutions focus on integrating graphene monolayers with metasurfaces [1,2].

Here, we report the design and fabrication of a MEMS-integrated metasurface that allows tunable low-pass filtering of spoof surface plasmon polaritons along with a MEMS design for implementing a leaky wave antenna for microwave beam steering. It is notable that, in principle, the set forth approach is scalable to higher frequency applications, including the terahertz frequency range.

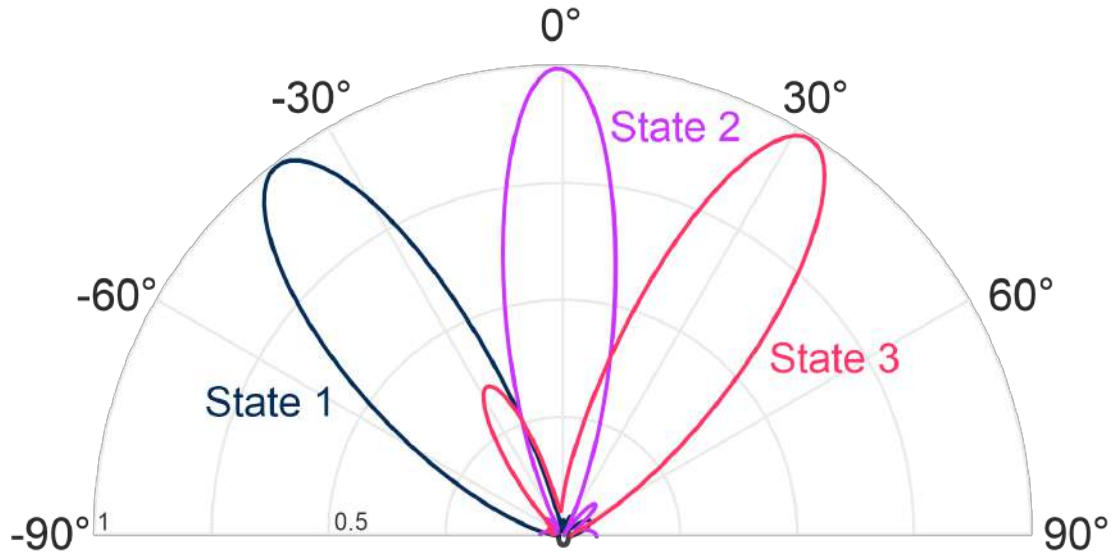


Fig. 1: Simulated beam steering at 57.5 GHz by a MEMS-based metasurface for three different states.

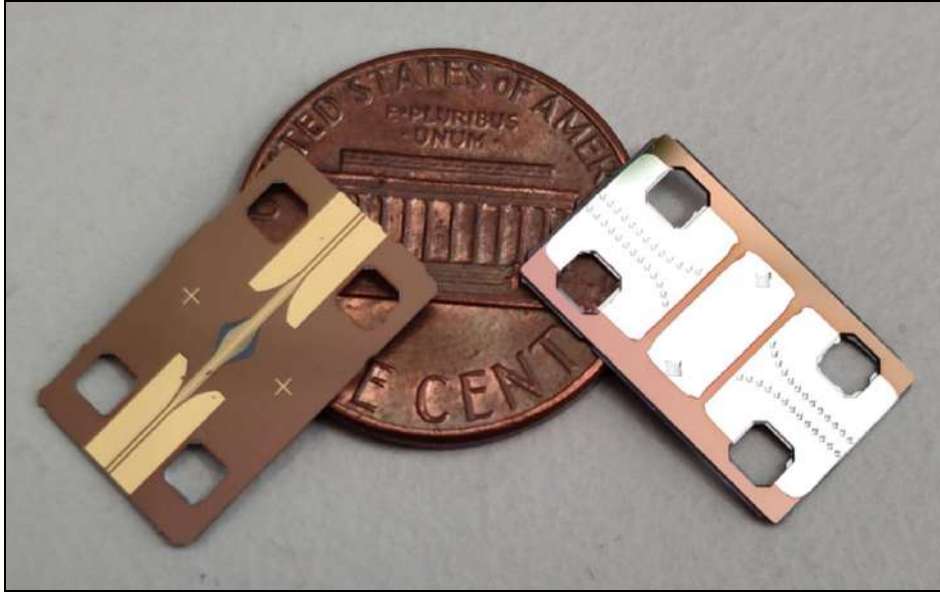


Fig. 2: Photograph of a MEMS-based fishbone metasurface.

Fig. 1 shows the beam steering of a MEMS-based metasurface for three different switching states. The metasurface consists of a fishbone structure with bendable microbridges of varying length. By application of a bias voltage, the microbridges bend dependent on their length and modulate the dispersion, which results in a coupling of the surface plasmon polaritons to propagating modes at a corresponding angle. By changing the bias voltage, the beam can be steered as shown in Fig. 1, in which beam steering has been calculated for three different bias voltages of 0 V (state 1), 105 V (state 2) and 120 V (state 3).

Fig. 2 shows a picture of a fabricated MEMS-based metasurface as used for tunable low-pass filtering of surface plasmon polaritons. The radiation is coupled into the surface plasmon polariton modes by a tapered antenna, propagates along the fishbone metasurface and is detected by a tapered receiving antenna. The microbridges are bent by application of a bias voltage. We achieved continuous tuning of the low-pass filter in the attenuation band by 15 dB with a cut-off frequency at 83 GHz.

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Chiral sensing with silicon nanophotonics

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Abstract: Chiral molecules with opposite handedness can have strongly different biological functionalities. Identifying chirality is, however, limited by low sensitivity, restricting detection to high concentrations and large volumes. We demonstrate a silicon nanophotonics-based technique to enhance the sensitivity of chiral molecular detection.

Detecting the handedness of chiral molecules is critical in biochemistry, where the functionality of biomolecules such as proteins, amino acids, and carbohydrates can strongly differ between enantiomers. Circularly polarized light is commonly used to distinguish enantiomers based on their differential absorption for the two circular polarizations, *i.e.*, circular dichroism (CD). This transmission-based method requires measuring very small changes in absorption, which is inherently difficult due to the large background caused by negligible absorption at low concentrations. As a result, the sensitivity is reduced, requiring a high density of molecules and long measurement times. This makes the conventional method unsuitable for critical applications like detecting protein aggregates linked to various diseases.

Fluorescence-based chiral sensing bypasses some of the difficulties of CD by shifting the wavelength of the light that interacted with the chiral molecules, allowing for separating this signal from the background of the excitation source. However, fluorescence is weak and its polarization very low. Nanophotonics provides routes for enhancing chiral sensitivity [1], [2], [3]. Optical resonators function as antennas, facilitating a more efficient light-matter interaction between the analyte and the excitation light. This effect can be amplified by arranging the resonators in arrays with an appropriate pitch [4]. In addition to excitation enhancement, the fluorescence of the analytes can also be increased thanks to Purcell enhancement, which increases the radiative rate. Furthermore, the resonator array can improve directionality, enabling more efficient detection of the emitted fluorescence. These combined enhancement processes significantly boost the detected fluorescence of chiral molecules. Additionally, for chiral sensing, the polarization component is also critical. Utilizing resonators made from high-refractive-index dielectrics allows for tuning of electric and magnetic resonances, enabling control over optical chirality density, which can even generate local super-chiral fields, enabling a CD greater than that produced by of a circularly polarized plane wave.

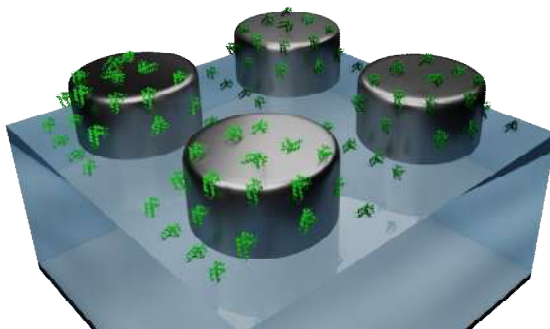


Figure 1. Chiral molecules on a silicon metasurface.

In this presentation, we introduce our recent experimental results on enhancing fluorescence-based chiral sensing using silicon metasurfaces. We fabricate crystalline silicon nanostructures displaying optical resonances in the visible. By combining them with chiral materials, we demonstrate enhanced circularly polarized fluorescence. To this end, we developed a custom-built polarization-sensitive microscope with polarization-modulation and photon-counting capabilities. Our microscope can measure smaller chiral analyte volumes than commercial systems.

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Metasurface System for Quantum Phase Imaging

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Abstract: We present a compact quantum phase imaging system using entangled photon pairs from a nonlinear metasurface. A nonlocal metasurface extracts phase gradients via angle-dependent resonances, enabling phase and amplitude imaging. The system achieves over 94% accuracy in distinguishing phase gradients, offering potential for ultra-compact biomedical and remote sensing applications.

Quantum imaging using entangled photon pairs from spontaneous parametric down-conversion (SPDC) provides fundamental advantages over classical phase imaging in the study of transparent object, such as the operation at ultra-low photon flux and high signal-to-noise ratio [1, 2]. These properties are crucial for the area where low-light condition and non-destructive techniques are critical, such as biomedical imaging and remote sensing. Metasurfaces supporting angle-dependent resonances have recently been employed to achieve phase imaging by extracting phase gradients of incident light [3]. These nanoscale metasurfaces indicate significant potential to replace bulky differential interference contrast microscopes, offering an opportunity for integration into ultra-compact biomedical devices. Together with recent development on metasurface-based quantum light source, this opens up the potential for developing a compact quantum phase imaging device, where metasurfaces serve both generation and detection functions.

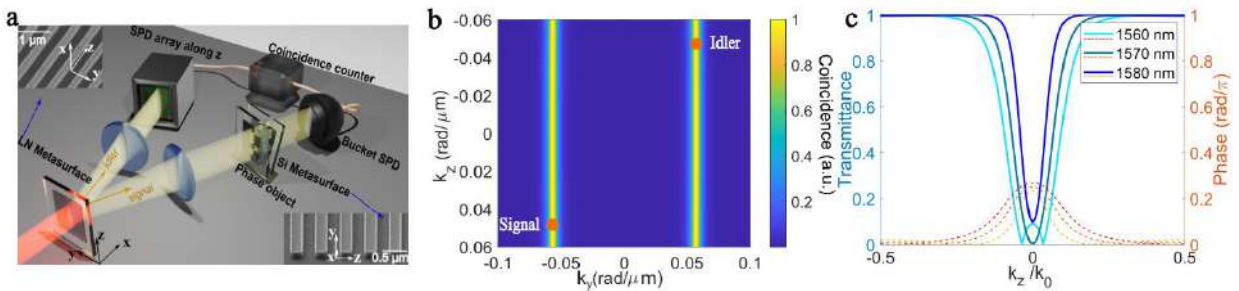


Fig 1: **a.** The sketch of the quantum phase imaging setup. The SEM image of the LiNbO3 metasurface is shown on the top-left corner, and that of Si metasurface is shown at the bottom-right corner. **b.** The wavefield propagation direction is set to x -direction. The transverse directions are z and y . The photon-pair emission pattern from LiNbO3 in the k -space with anti-symmetric uniform z -direction distribution and narrow y -direction distribution. **c.** Optical transfer function produced by the Si metasurface. The blue solid lines show the amplitude transfer function respect to incident angles into the metasurface.

Here we present an approach to achieve metasurface-based quantum phase imaging using photon pairs

produced from a nonlinear metasurface and a nonlocal metasurface. As shown in Fig. 1a, the signal photon illuminates a phase object and is then collected with a bucket single-photon detector while the idler photon is received by a detector array. Biphotons emitted from a nonlinear metasurface where the emission direction is optically tunable via the pump wavelength, facilitating a novel quantum phase imaging protocol combining ghost imaging and all-optical scanning [4]. The ghost imaging protocol along the z -direction based on the uniform emission (Fig. 1b) is also associated with the uniform phase profile, which opens up the potential for quantum phase imaging.

A metasurface incorporating a silicon grating is placed immediately after the phase object. This metasurface supports an optical non-local resonance at the signal wavelength (~ 1570 nm), where the transmittance depends on the incident angle of light (Fig. 1c). This metasurface is tilted with a small angle, producing a linear optical transfer function in k -space that can be used to perform the first derivative operation of the phase object profile. As a result, the correlation measurement between signal and idler photons can be used to reconstruct the phase gradient of the object.

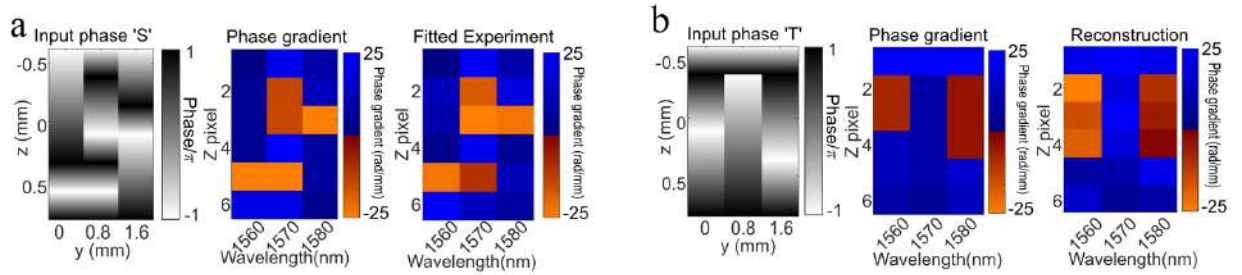


Fig 2: **a.** Phase gradient extraction by nonlinear fitting of object “S” and served as calibration reference.

b. Reconstructed phase gradient of phase object “T” through biphoton correlation measurement and calibrated according to the result in “S”.

An example of phase gradient extraction for input “S” and “T” shaped phase pattern, formed through multiple distinct linear phase modulation sections, was experimentally demonstrated. By employing the coincidence of the “S” (Fig. 2a) object as a calibration reference to reconstruct the “T” object (Fig. 2b), the system effectively distinguishes between positive and negative phase gradients within the range of -25 rad/mm to 25 rad/mm with a success rate above 94%. Besides phase imaging, this device can directly perform quantum amplitude imaging without any modification, making it a switchable quantum imaging system. This work will establish metasurfaces as miniaturized devices for ultra-compact quantum imaging.

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From Catalysis to Sensing: Plasmon-Driven Conversion of pATP and its Application in Fe²⁺ Detection

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Abstract: Plasmon-driven catalysis exploits localized surface plasmon resonance (LSPR) to enhance reaction efficiency via hot carrier generation and thermoplasmonic effects. This study reveals a three-phase mechanism in the photocatalytic conversion of pATP into DMAB and demonstrates its application as a selective Fe²⁺ sensor, highlighting its potential for environmental analysis.

Catalysis plays a crucial role in accelerating chemical reactions by lowering activation energy, with broad applications in pharmaceuticals, environmental protection, and energy conversion [1]. Photocatalysis extends this principle by harnessing light energy, yet conventional photocatalysts often suffer from limited absorption spectra and inefficient charge carrier dynamics [2]. In contrast, plasmon-driven catalysis leverages the unique optical properties of noble metal nanoparticles (e.g., Au, Ag), where localized surface plasmon resonance (LSPR) generates hot carriers that enhance reaction efficiency [3].

The photocatalytic conversion of p-aminothiophenol (pATP) into 4,4'-dimercaptoazobenzene (DMAB) has emerged as a model system, extensively studied via Surface-Enhanced Raman Scattering (SERS) to monitor reaction dynamics in real time [4]. This study systematically investigates the influence of pATP concentration, incubation temperature, and LED irradiation wavelength on spherical silver nanoparticles (AgNPs), revealing a distinct three-phase mechanism. By examining the relationship between pATP density on AgNP surfaces and photocatalytic performance under 405 nm LED irradiation, we elucidate the fundamental mechanisms governing plasmon-driven conversion and identify optimal conditions for maximum efficiency. Furthermore, analysis of photocatalytic activity at different irradiation wavelengths confirms that plasmon excitation generates hot charge carriers, particularly hot holes, which drive the oxidation of pATP into DMAB. The study also highlights the contribution of localized heating (thermoplasmonic effects) to the reaction, demonstrating that both hot carriers and thermal effects play a role in plasmon-driven catalysis.

A key distinction of this work is the use of LED excitation instead of traditional laser sources, leading to a slower reaction rate. This controlled reaction environment enabled the clear identification of three distinct phases in the plasmon-driven conversion of pATP into DMAB, offering new insights into reaction kinetics and nanoparticle-mediated catalysis.

Beyond fundamental studies, we further exploit this plasmon-mediated oxidation reaction as a sensitive and selective sensor for Fe²⁺ ion detection. The presence of Fe²⁺ near the surface of pATP-functionalized AgNPs disrupts the plasmon-driven reaction, reducing conversion efficiency as ion concentration increases. This behavior arises from a competitive

oxidation process in which Fe^{2+} preferentially oxidizes to Fe^{3+} due to its lower redox potential compared to pATP-to-DMAB conversion. As a result, pATP oxidation occurs only after complete Fe^{2+} oxidation. By monitoring the intensity of DMAB-specific SERS bands as a function of Fe^{2+} concentration, a linear dependency was established, enabling quantitative metal ion detection. This work underscores the potential of plasmonic nanostructures for metal ion sensing and expands the applicability of plasmon-driven reactions in environmental and analytical chemistry.

Acknowledgements

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Non-Hermitian gapped states inside topological gapless states

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Abstract: Using a gap structure intrinsic to non-Hermitian systems, we introduce new topological phases from topological gapless states and argue relevant physical phenomena.

Although non-Hermiticity is ubiquitous in nature, including metamaterials, its implications for topological physics have not been fully understood yet. In this talk, I will explain our recent results on non-Hermitian topological physics. In particular, I will show that non-Hermiticity enables new gap structures and the corresponding new topological numbers even for topological gapless states in Hermitian systems. These new topological numbers predict detachable boundary states and the anomalous scattering analogs to the Callan-Rubakov effect [1-3].

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Direct laser written polymeric fiber-coupled metasurfaces for achromatic imaging and light structuring in the near-infrared

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Abstract: 3D nanoprinting based on direct laser writing via two-photon polymerization was used to fabricate metasurfaces and couple them to optical fibers aiming at combining functionalities of both structures to achieve achromatic lensing/imaging across the entire S, C and L telecommunication bands and generating cylindrical vector- and circularly polarized vortex beams.

Metasurfaces, thin engineered materials composed of subwavelength structures, are designed to manipulate electromagnetic waves in unique and highly controllable ways [1]. These surfaces allow for the customization of optical properties, such as reflection, refraction, and polarization, at scales smaller than the wavelength of light. By carefully designing the shape, arrangement, and material composition of these structures, metasurfaces have enabled groundbreaking advancements in optical technologies, including the development of ultra-thin lenses, holograms, beam shaping, and even invisibility cloaks [2]. The ability to control light with unprecedented precision has opened new possibilities in fields such as telecommunications, imaging, and quantum computing, driving innovations that were once thought to be the realm of science fiction [3].

Optical fibers are thin, flexible strands of glass or plastic that transmit light signals over long distances with minimal loss. Their key characteristics include high bandwidth, allowing rapid data transmission [4], low attenuation, and immunity to electromagnetic interference, making them ideal for environments with electrical noise [5]. Optical fibers are also used in industrial sensors and military applications due to their lightweight, flexibility, and security against signal interception. In medical imaging applications, flexible fiber endoscopes use bundles of optical fibers to transmit light and capture images from inside the body. A light source at one end illuminates the target area, while a separate bundle of fibers carries the reflected light back to an eyepiece or a digital sensor. At the tip of the fiber, normally a graded-index (GRIN) lens or a convex lens collects light from the target area and focuses it into the fiber bundle. Although compact, GRIN lenses suffer from chromatic and spherical aberrations, which can distort colors and image sharpness, especially in broadband illumination. Ordinary convex lenses, while simpler, can introduce optical aberrations if not precisely aligned. Both lens types may also face light loss at fiber coupling, reducing overall imaging efficiency in endoscopic applications. Achromatic polymeric metalenses incorporate nanostructured metasurfaces to precisely control phase delays across different wavelengths, eliminating chromatic aberration presented by GRIN lenses. Their flat, ultrathin design ensures better light coupling into optical fibers, reducing alignment issues and minimizing light loss.

There are several different nanofabrication techniques which can be used to produce metasurfaces [6]. One of them is the direct laser writing (DLW) via photopolymerization by two-photon absorption (TPA), that uses a focused fs laser to induce localized polymerization or material modification in a photosensitive medium. Because TPA occurs only at the focal point, this method enables high-precision 3D nanostructuring with minimal damage to surrounding areas and higher spatial resolution when compared to linear DLW.

In the first part of this work, we use DLW via TPA to 3D nanoprint a polarization-insensitive achromatic metalens and at the output of a commonly used telecommunication SMF-28 single-mode fiber (an achromatic “metafiber”). The 3D achromatic metalens is composed by subwavelength nanopillar meta-atoms exhibiting strong birefringence, capable of imprinting a hyperbolic lens profile to the incident wavefront via a geometric phase. As a result, the 3D achromatic metalens fabricated on the single-mode fiber enables achromatic and diffraction-limited focusing over the entire near-infrared telecommunication band ranging from 1.25 to 1.65 μm , which represents the whole single-mode operation regime of this particularly type of fiber. Moreover, we employed the achromatic metafiber for fiber-optic confocal scanning imaging without involving a standard microscope, demonstrating that our approach offers an unprecedented solution to establish an ultracompact and ultrabroadband confocal imaging system [7], which additionally can very easily be coupled to a spectrometer.

In the second part of this work, we demonstrate how metafibers can be used for generating structured light. Structured light refers to light with controlled phase, polarization, or intensity patterns, such as vortex or Bessel beams [8]. These beams can resist diffraction, carry orbital angular momentum [9], and enhance imaging or communication, finding applications in microscopy, optical trapping, and quantum optics for precise light control [10]. However, the use of structured light in optical fiber science and technology remains highly constrained due to mode mixing and the absence of integrated optical components on fiber end-faces for wavefront shaping. As a result, structured light generation still relies on bulky free-space optics outside the fiber. We present a metafiber platform capable of generating arbitrarily structured light on the hybrid-order Poincaré sphere (HOPS), a geometric representation used to describe structured light fields that combine spatial modes and polarization states. Unlike the conventional Poincaré sphere, which maps only polarization, HOPS encodes higher-order modes, such as the already mentioned vector vortex beams, enabling a more comprehensive classification of complex light fields [11]. Utilizing the same fabrication approach as in the initial study, multiple metasurfaces were integrated onto optical fiber end-faces, shaping the metafiber output into various structured-light fields, such as cylindrical vector beams, circularly polarized vortex beams, and arbitrary vector fields [12].

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Quantum photonic sources based on nanophotonics

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Abstract: I will introduce our recent works about quantum photonic sources based on nanophotonic structures, such as 2D materials, metalens array.

Integrated quantum photonics has attracted intensive attention due to the compactness, scalability, and stability. Quantum photonic source, especially an on-chip entangled photon source, is a basic device for realizing quantum photonic integrated circuits (QPICs). I will introduce our recent works about quantum photonic sources based on nanophotonic structures and materials, such as metalens array [1] and 2D materials [2-4].

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Fluctuation-induced forces with optical gain

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Abstract: We discuss quantum fluctuation-induced forces in photonic systems with optical gain. We focus on how the fluctuation-dissipation relation must be modified to account for optical gain and exemplify how engineering optical gain can enhance and control fluctuation-induced forces.

Non-Hermiticity (loss and/or gain) may dramatically modify the system’s response and produce unique phenomena without Hermitian counterparts, such as exceptional points and non-trivial topology around them [1]. Their uniqueness has helped pioneer various applications in optics and photonics: enhanced lasing, unidirectional transmission, and perfect absorption. In this talk, we will discuss how the non-hermiticity interplays with quantum fluctuations to induce unusual forces. In particular, two types of optical gain will be discussed:

1. Direction-dependent gain in moving media

First, we consider a moving metal slab. When the slab is at rest, it is described by the Drude dielectric function $\epsilon(\omega) = 1 - \omega_p^2/(\omega^2 + i\omega\gamma)$, which satisfies the passivity condition—ensuring that its imaginary part remains positive for all positive frequencies, $\text{sgn}\{\epsilon''(\omega)\} = \text{sgn}\{\omega\}$. However, once the slab is set in motion, the Doppler shift is applied [i.e., $\epsilon(\omega) \rightarrow \epsilon(\omega - k_x v/2)$], potentially leading to a *negative* imaginary part in the dielectric function. Specifically, short-wavelength, right-going waves experience this negative imaginary part,

$$\epsilon''(\omega - k_x v/2) < 0 \quad (0 < \omega < |k_x|v/2, k_x > 0). \quad (1)$$

In essence, this corresponds to optical gain. As the Doppler shift is direction-dependent, so too is the induced optical gain [2, 3].

2. Polarisation-dependent gain in low-symmetry materials

As demonstrated in previous studies, drift electric currents emulate mechanical motion, giving rise to optical gain [4]. When combined with a class of low-symmetry materials, these drift currents can induce non-Hermitian electro-optic effect, leading to non-trivial off-diagonal elements in the dielectric tensor [5],

$$\epsilon := \begin{pmatrix} \epsilon_d & 0 & 0 \\ 0 & \epsilon_d & -i\epsilon_g \\ 0 & +i\epsilon_g & \epsilon_d \end{pmatrix}, \quad (2)$$

where ϵ_d represents the conventional Drude type response, while ϵ_g accounts for the electro-optic effect. The non-Hermitian part of the dielectric tensor $\epsilon'' := (\epsilon - \epsilon^\dagger)/(2i)$ can be *negative* for left-handed polarisation $\mathbf{u}_- = (\mathbf{u}_y - i\mathbf{u}_z)/\sqrt{2}$ if the electro-optic contribution is dominant

$$(\epsilon''_g > \epsilon''_d),$$

$$\mathbf{u}_-^* \cdot \epsilon'' \cdot \mathbf{u}_- = \epsilon''_d - \epsilon''_g < 0. \quad (3)$$

In contrast, for other polarisations, the non-Hermitian part remains positive (i.e., $\mathbf{u}_+^* \cdot \epsilon'' \cdot \mathbf{u}_+ > 0$ and $\mathbf{u}_x^* \cdot \epsilon'' \cdot \mathbf{u}_x > 0$). Consequently, this system exhibits polarisation-dependent optical gain.

In the presentation, we shall discuss how the fluctuation-dissipation relation (FDR) must be modified to account for optical gain. Utilising the modified FDR, we will explore how the aforementioned optical gain enhances and controls fluctuation-induced forces [2, 3, 6].

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Pillared elastic plates for precise artificial modulation of flexural wave

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Abstract: Precise artificial manipulation of elastic devices is a major topic for the purpose of practical applications. Hereby, we investigated on-demand broadband bound states, robust chiral bound states and vortex modes theoretically. The proposed elastic wave devices are expected to enable fast design and fabrication of mechanical devices.

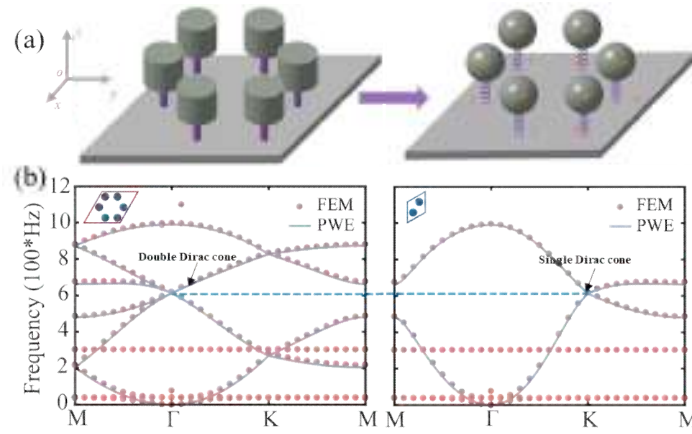


Figure 1. (a) Two-dimensional resonant structure (left panel) and corresponding simplified theoretical model (right panel). (b) Band structures of the phononic plates with unit cells contain six (left panel) and two scatterers (right panel), respectively ¹.

Thin plate structures are widely used in dynamic platforms, such as aerospace, ships and high-speed trains. The artificial modulation of elastic waves in thin plates has always been one of the most important factors affecting the dynamic performance of devices ². Dynamic platforms require vibration modulation of flexural waves to ensure the stability of the overall structural vibration characteristics, while also ensuring the comfort of the internal working environment. Hereby, we proposed the simplified theoretical model for the thin plate structures for the precise artificial manipulation of elastic waves and given some applications in the on-demand broadband bound states ¹, strongly robust chiral bound states ³ and topological vortex modes ^{4,5}.

To artificial modulate the flexural waves in thin plate, we need to simplify the 3D solid model into the Kirchhoff thin plate assumption and the mass-spring model for thin plate and neck-mass. In this case, the 3D model must follow the hypotheses: The radius of the neck should be much smaller than the lattice constant in which the effect of the thin neck on the plate can be equivalent to the point load. The thin neck mass is much smaller than the mass, so the model is simplified into a mass-spring model in Fig. 1(a). Following the hypotheses, we used the plane wave expand method to calculate the dispersion curves of the unit cell with two and six resonators in Fig. 1(b), which were verified by FEM.

We further explored engineered lattice systems where double Dirac cones emerge via the zone-folding effect of single Dirac cone dispersion curves. Furthermore, we verified that machine learning models could be used to predict bandgap behavior, with dispersion analysis confirming distinct bandgap widths at 100 Hz and 230 Hz.

Corresponding waveguide displacement fields reveal enhanced broadband bound states, critical for high-performance waveguiding.

Chiral resonant and C_{6v} -symmetric topological structures demonstrate remarkable robustness against scatterer defects, preserving bound states even in perturbed configurations. 3D schematics and displacement field visualizations highlight how progressive chirality and selective scatterer removal (e.g., near boundaries) tailor wave localization. The robustness of chiral structures against the defects are stronger than C_{6v} systems, the harvesting power is about two orders of magnitude higher than the latter ³.

Furthermore, Position-dependent Kekulé modulation induces tunable bandgap distributions in primitive and disturbed lattices ⁵. Symmetry-preserving defects, such as resized central scatterers, enable precise control of topological cavity modes, with power maps and wave patterns (e.g., at critical expansion points) showcasing defect-driven mode tuning. The energy harvesting system based on the topological cavity of the phononic plate is designed with highly robust against symmetry-preserving defects ⁴.

These findings advance strategies for defect-tolerant topological systems and dynamically reconfigurable metamaterials, with direct applications in photonics, phononics, and resonant sensing. To extend these systems to real-world scenarios—such as nonlinear elastic wave devices and real-time energy harvesting—key challenges remain. These include enhancing energy density and broadening the operational frequency range of elastic resonant metaplates. Designing energy-capture systems that integrate competing objectives (e.g., robustness, high power density, broadband operation, and lightweight architectures) demands extensive parameter optimization, often requiring prohibitive computational resources ². To address these barriers, we propose on-demand intelligent structural design frameworks with real-time feedback, enabling adaptive tuning of metaplates under dynamic conditions.

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On-Chip Quantum Correlations Measurements with In-Line SNSPDs

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Abstract: In-line on-chip single-photon detection offers a powerful means to miniaturize complex integrated circuits, but the lack of suitable integration strategies has so far hindered its demonstration. Here, we introduce a novel integration method for SNSPDs, enabling in-line detection and demonstrating one of the most compact quantum correlation setups to date.

Integrated photonics offers a scalable platform for quantum computing and networking, enabling complex photonic circuits with enhanced reliability and miniaturization. One of the critical components in these systems is the superconducting nanowire single-photon detector (SNSPD), which has established itself as the preferred choice for integrated quantum photonics due to its unmatched sensitivity at telecommunication wavelengths, low noise, high timing precision, and compatibility with various integration platforms [1]. However, conventional waveguide-integrated SNSPDs [2], typically positioned on top of the photonic circuit, are constrained to waveguide terminations. This placement limits their potential, preventing inline detection schemes necessary for advanced protocols such as quantum tomography [3], photon subtraction [4] and correlation measurements. It also hinders the scalability of architectures that require multiple detectors, such as photon number resolution schemes [5].

In this work, we introduce a novel integration approach in which SNSPDs are positioned at the bottom of the photonic circuit [6]. This configuration offers enhanced flexibility for detector placement within the circuit, enabling more complex and scalable architectures. Our integrated detectors achieve on-chip detection efficiencies exceeding 70%, low dark count rates, and ultrafast recovery times below 2 ns, demonstrating performance comparable to standard approaches. As a proof of concept, we implement an inline autocorrelation measurement scheme on-chip, validating its operation with a heralded single-photon source. These results demonstrate the potential of our approach to support scalable and functional quantum photonic circuits.

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Integrate and fiber-based photonics for quantum and machine learning signal processing

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Abstract: We demonstrate an integrated photonic platform enabling optical signal processing and quantum key distribution. Leveraging silicon-based nonlinear devices and programmable on-chip interferometers, our optimized platform performs ultrafast machine learning tasks and facilitates secure, high-rate quantum communication using high-dimensional photon entanglement over telecom-compatible fiber networks.

Introduction

Integrated photonics has garnered considerable attention due to its significant potential for advancing smart technologies, particularly in classical and quantum information processing. On-chip photonic circuits support high-speed parallel operations and benefit from established semiconductor fabrication processes and existing telecom infrastructure. Traditional electronic hardware and processors increasingly face limitations in terms of speed and energy efficiency, prompting the exploration of photonic computing as a compelling alternative [1]. Likewise, quantum communication systems operating over fiber networks encounter fundamental limitations such as photon losses and scattering, constraining achievable transmission distances and data rates.

Leveraging the inherent advantages of photonics, including parallelism, substantial bandwidth, and the unparalleled speed of light, programmable photonic hardware can effectively mitigate these challenges. This approach offers substantial benefits, including reduced power consumption, enhanced processing speeds, and significantly lower latency[2].

To address these critical issues, we propose an integrated, CMOS-compatible platform designed for reconfigurable reservoir computing (RC) and ultrafast signal processing applications. Additionally, the same unified silicon-based integrated photonic platform facilitates the implementation of secure, high-speed quantum key distribution (QKD)[3]. This integrated platform uniquely combines nonlinear silicon photonic sources with programmable interferometric structures, providing a versatile and efficient solution for next-generation information processing tasks.

Results

Our work leverages an integrated photonic platform fully compatible with CMOS fabrication processes and standard optical fiber links. This platform comprises two core components: silicon-based nonlinear optical devices—including spiral waveguides and microring resonators (MRRs) [4]—and cascaded programmable interferometers. The Silicon-based sources generate classical and quantum frequency combs, characterized by broad spectral bands with equally spaced frequencies, and serve as artificial neurons within our reservoir

computing (RC) system. Programmable interferometers precisely shape optical pulses required for photon pair generation and quantum state processing.

Our RC system addresses distortions in telecom signals arising from fiber propagation effects such as dispersion and nonlinearity. Preliminary results demonstrate that our integrated photonic platform achieves ultrafast waveform reconstruction at speeds exceeding GHz rates, nanosecond latency, and a bit error rate as low as 10^{-4} . This performance represents a significant advancement over traditional electronic and software-based machine learning solutions reliant on the von-Neumann architecture.

The embedded MRRs, can effectively scale data capacity through advanced multiplexing techniques, enhancing their suitability for telecom applications. Microcombs generated by MRRs can significantly boost data processing rates; however, their spectral properties are highly sensitive to pump conditions and detuning, complicating stable generation and information encoding. To overcome these challenges, we employ a genetic algorithm (GA)-based optimization scheme[5]. This method designs microcombs targeting specific spectral characteristics such as comb line spacing, intracavity power, and spectral envelope uniformity. Iterative GA optimization has successfully achieved exceptional spectral stability, maintaining power-per-line stability for durations exceeding one day and coherence values of approximately 86% over three-photon lifetimes.

In parallel, the platform's spiral waveguides and programmable interferometers produce high-dimensional, time-bin entangled photon pairs ideal for quantum key distribution (QKD). Input laser pulses are divided by interferometers into coherent pulse trains, subsequently converted into entangled photon pairs via spontaneous four-wave mixing within spiral waveguides across the telecom C-band. When integrated with external high-speed fiber-based phase modulators, these interferometers support sophisticated quantum state processing and tomography. Using this integrated platform, we have successfully implemented an entanglement-based QKD scheme, achieving quantum bit error rates below 12% and secret key rates on the order of a few kbit/s. Incorporating time multiplexing into our QKD system further enables multi-user communication within the telecom C-band. Additionally, increasing photonic qudit complexity—either through higher-dimensional quantum states or by involving additional photons—offers an enhancement in secret key rates and robustness of security.

Conclusions

The CMOS compatibility, minimal spatial footprint, low power consumption, and thermal efficiency of our photonic platform align directly with energy-efficiency goals crucial to current and future telecom and smart processing technologies, including optical computing and photonic optimization. Ultimately, our research paves the way for breakthroughs in digital signal processing, ultra-dense data encoding suitable for 5G and 6G networks, and advances in quantum communication with unprecedented processing speeds and security performance over existing fiber telecom networks.

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Passive Radiative Cooling and other Photonic Strategies for Enhanced Photovoltaics Performance

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Abstract: We present our recent studies exploring Passive Radiative Cooling and other photonic cooling strategies, such as sub-bandgap and UV reflection engineering, for demonstration of reduced temperature and enhanced efficiency in different types of solar cells (silicon, organic, perovskite).

The efficient management of heat in photovoltaic (PV) systems is crucial for improving their performance and longevity. Passive radiative cooling (PRC) has emerged as a highly effective technique for mitigating excessive heat accumulation, enabling enhanced efficiency and stability in PV devices without requiring additional energy input. This talk reviews our recent studies on passive radiative cooling and other photonic strategies for reducing the temperature and enhancing the efficiency of photovoltaic cells, including Si commercial-like cells, thin Si cells and next generation organic and perovskite PVs. The investigated strategies include, besides enhanced thermal emission in the atmospheric transparency window of 8-13 μm , also enhanced sub-bandgap radiation reflection, controlled UV reflection, enhanced IR emission, and enhanced optical transparency. For the assessment of those strategies, we have developed a combined opto-electro-thermal modelling approach able to evaluate the PV temperature and efficiency under different radiation reflection/absorption/emission conditions and different environmental conditions.

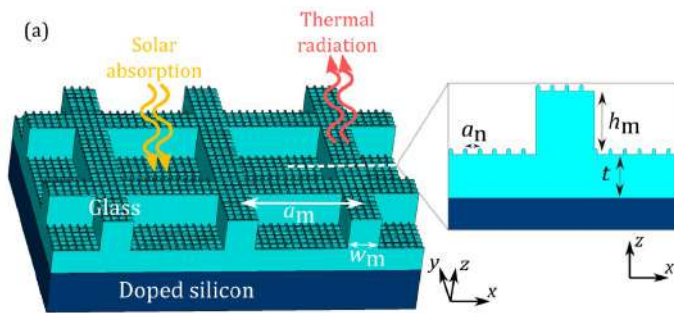


Fig. 1: Schematic of a nano-micro-structured glass grating coating/cooler atop of a doped Si layer in a Si solar cell. Inset shows a vertical cross-section of the structure. The cooler led to a close to 6° C temperature reduction and a 3.1% solar cell efficiency enhancement.

Employing our model, we evaluated different photonic coolers proposed in the bibliography, and we were able to design novel coolers that promise enhanced cooling and PV efficiency. Such a cooler is a double-periodic micro-nano-structured glass film, as shown in Fig. 1, which provided close to 6° C temperature reduction and more than 3% efficiency enhancement compared to common anti-reflection layers in silicon solar cells. The investigation of the structure of Fig. 1 and related structures demonstrated, among others, the potential of

multi-scale designs in radiative cooling systems, paving the way for scalable, single-material and effective solutions for photovoltaic applications.

Photonic coolers are even more significant in the case of next generation organic and perovskite solar cells. This is due to the sensitivity and easy degradation of organic and perovskite materials under high temperatures and impinging UV radiation. Designing and employing ultrathin (sub-micron) organic-inorganic cooling films in such solar cells, we were able to demonstrate more than 7° C temperature reduction, maintaining the high efficiency of the thin film cells.

In summary, our work finds that proper integration of different photonic approaches promises to considerably advance photovoltaics design, enabling more efficient and durable solar energy harvesting systems that can operate reliably under varying environmental conditions. The results and insights presented aim also to inspire further advancements in photonic cooling strategies and their practical implementation in real-world solar energy applications.

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Plasmonic titanium nitride nanomaterials for solar-thermal conversion

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Abstract: This contribution discusses the potentiality of two different strategies involving plasmonic titanium nitride (TiN) to design solar absorbers for solar-thermal conversion: on the one hand, separated nanotubes featuring nanoporous walls; on the other hand, planar ultrathin TiN/TiO₂/Ti as metal/insulator/metal multilayers.

Solar-thermal conversion aims at transforming light energy from the Sun into heat that could be used either directly, such as for domestic heating, or to generate electricity in so-called concentrating solar power (CSP) plants. To do so, the receiver unit of the device includes a solar absorber material that must capture solar light from the ultraviolet to the near-infrared range, i.e., 250–2500 nm. Therefore, a main goal is to achieve nearly-unitary absorption within this range to maximize heat generation under irradiation.¹

Titanium nitride (TiN) has recently emerged as a suitable plasmonic material to design solar absorbers thanks to its refractory nature, optical tunability by changing its morphology or stoichiometry, and compatibility with the semiconductor industry fabrication processes.^{2,3} Various absorber architectures featuring TiN nanostructured materials or planar thin films have been so far explored. For example, a metal-insulator-metal (MIM) metasurface made of TiN square arrays on SiO₂/TiN exhibited nearly unitary absorption in the 400–800 nm range and high thermal stability in vacuum up to 800 °C.⁴ Self-assembled TiN nanotube arrays showed a light absorption confinement within the height of the nanotubes (~ 250 nm) and reached ~ 600 °C under moderate light concentration (19 Suns).⁵ On the other hand, a planar MIM absorber consisting of ultrathin TiN (15 nm)/Al_{0.72}Sc_{0.28}N/TiN structure exhibited a tunable absorption maximum in the 500–1200 nm range by changing the spacer thickness.⁶

In this contribution, we discuss two different approaches toward solar absorbers based on plasmonic TiN. The first approach consists of electrochemical anodization of Ti to prepare spaced titanium dioxide (TiO₂) nanotubes and nitridation in ammonia (NH₃) to convert TiO₂ into titanium oxynitride (TiO_xN_y). The resulting spaced nanotubes exhibited ~ 99% optical absorption up to the near-infrared wavelength range. This behavior was explained by the formation of localized electric field enhancements around nanovoids in the tube walls and numerically reproduced by a “nanoporous permittivity model”. As a consequence, spaced TiO_xN_y nanotubes exhibited optimal photothermal properties, as confirmed by temperature experiments under irradiation and solar steam generation experiments.⁷ Furthermore, the same materials upon coating with Pt and Ru catalysts are being investigated in photothermal gas-phase carbon dioxide (CO₂) reduction experiments.

The second approach consists of realizing planar ultrathin MIM absorbers starting from Ti substrate and exploiting atomic layer deposition (ALD) as a synthetic technique to conformally coat large areas. First, TiN films were grown by a standard plasma-enhanced ALD method using TiCl_4 and NH_3 plasma at 450 °C on Si and glass substrates. A complete optical investigation by transmission/reflection spectroscopy, spectroscopic ellipsometry and Fourier-transform infrared (FTIR) spectroscopy allowed extracting the complex permittivity of the films and assessing its variation with respect to the film thickness in the 10–40 nm range. Afterwards, a preliminary unpatterned ultrathin planar absorber consisting of TiN (10 nm)/ TiO_2 (40 nm)/Ti substrate was realized by ALD and achieved an absorption maximum of ~ 98% at 576 nm, which well matched the solar spectrum peak (~ 510 nm).

In conclusion, two different approaches based either on nanoporous structures or on planar metal-insulator-metal multilayers showed the performance of plasmonic TiN-based materials as solar absorbers for solar-thermal applications with scalability potential. A further control on the optical tunability of these structures may open further applications, such as in solar cells, in terahertz (THz) detectors and plasmonic gas sensors.

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Holographic metasurfaces for biophotonics applications in the visible and near-infrared range

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Abstract: We discuss critically the advantages and limitations of plasmonic and ceramic material platforms for imaging, sensing, and all optical manipulation applications in microfluidic environments.

Holographic Metasurfaces (HMSs) are highly effective for controlling light-matter interactions at micro- and nano-scales, making them particularly valuable for biophotonic applications. These structures allow precise manipulation of optical fields near biological specimens, overcoming the limitations of conventional microscopy techniques. The choice of materials and meta-atom configurations plays a crucial role in determining their performance and feasibility for biophotonic research.

In this work, we will critically examine and present several platforms we have developed for applications in sensing, imaging, and optical manipulation.

The first platform utilizes reflective meta-atoms, following a widely adopted metal-insulator-metal design incorporating Pancharatnam-Berry phase elements [1]. Unlike conventional implementations, our meta-atoms also exhibit photonic resonances that vary with the refractive index of the surrounding medium. These HMSs have been successfully employed for both sensing [2] and optical trapping in the near-infrared range. Notably, we demonstrated that these metasurfaces can achieve trapping stiffness comparable to that of expensive, high numerical aperture microscope objectives, despite being much more compact [3].

A second approach involves ceramic-based metasurfaces designed for transmission applications. Recently, we have shown that ZrO₂ meta-atoms enable a shift in operating wavelength toward the blue spectral region, which is particularly beneficial for biophotonic experiments. Using this technology, we performed the first integrated trapping experiment at wavelengths below 500 nm [4]. Additionally, this platform provides unique advantages, including enhanced durability, making it well-suited for use in extreme conditions.

Finally, we will demonstrate how simple polymeric metasurfaces can generate high-quality holograms [5]. Photonic metasurfaces, with dimensions of just a few tens of micrometers, can be manipulated as precise tools inside microfluidic environments to drive whispering gallery mode lasers [6]. These metasurfaces also exhibit exceptional mechanical stability, making them ideal for investigating the optomechanical properties of single molecules and living cells.

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Advanced Nanophotonic Sensing with Bound States in the Continuum: Integrated Metasurfaces for Biomedical Applications

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Abstract: Photonic bound states in the continuum (BICs) enable ultrahigh-quality factor resonances for advanced sensing applications. Leveraging all-dielectric metasurfaces, we integrate biomolecular recognition elements to detect biomolecules at femtomolar levels. Our approach enhances sensitivity for biosensing, environmental monitoring, and bioanalytics, offering rapid, high-precision detection of key biomolecular interactions for healthcare and diagnostics advancements.

Photonic bound states in the continuum (BICs) represent an intriguing phenomenon in optics and photonics, opening new avenues for topological nanophotonics. Their non-radiative nature enables ultrahigh radiative quality factors (Q_r up to 10^6) [1, 2, 3]. BICs are special electromagnetic modes that exist within the continuum of radiation modes but do not couple with them. Unlike typical resonant modes, which radiate energy into the surrounding medium, BICs remain decoupled from external radiation. This strong confinement enhances interactions with surrounding materials, making them exceptionally sensitive to small refractive index variations. Such properties are particularly valuable for biosensing, environmental monitoring, and other sensing applications.

Addressing the evolving demands in healthcare—spanning global health initiatives, personalized treatments, and point-of-care solutions—requires transformative innovations in diagnostics and bioanalytical tools. To this end, we focus on designing innovative nanostructured sensing platforms based on BICs. These cutting-edge platforms are engineered to deliver exceptional accuracy, rapid response times, microfluidic integration, and high throughput while minimizing both device complexity and size. Our research group has demonstrated numerous applications of BICs, including biological and chemical sensing and imaging with the ability to detect molecules of ultralow weight [4, 5, 6, 7], as well as surface-enhanced fluorescence emission and Raman scattering [8] and directive giant upconversion via supercritical coupling [9].

Here, we present our recent advancements in an integrated optical biosensor that leverages BICs for biological applications. We employ large-area, transparent all-dielectric metasurfaces integrated with biomolecular recognition elements such as aptamers and molecularly imprinted polymers (MIPs), enabling the detection of TGF- β at femtomolar concentrations [10] - a multifunctional cytokine that regulates cell growth, differentiation, immune responses, and extracellular matrix production, playing a crucial role in processes such as tissue repair, fibrosis, and cancer progression. Additionally, we characterize the high-affinity interaction between Secreted Protein Acidic and Rich in Cysteine (SPARC), a key regulator of cell-matrix interactions and tissue remodeling,

and Human Serum Albumin (HSA). By leveraging the ultrahigh Q-factor of BICs, the system exhibits sufficient sensitivity to refractive index changes induced by molecular binding events, enabling the resolution of fast-kinetics processes. This approach ensures precise determination of the dissociation constant (K_D), providing crucial insights into SPARC-HSA interaction dynamics. Finally, novel metasurface designs are explored and compared, paving the way for substantial advancements in sensing technology.

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Scanning Near-Field Optical Microscopy on Hyperuniform Disordered photonic materials

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Abstract: A special class of disordered photonic heterostructures, hyperuniform disordered (HuD) photonic structures, allows to deterministically tailor Anderson localization and diffusive transport. Here, we detect for the first time the presence of level repulsion between delocalized states in a HuD photonic platform, by means of the Scanning Near-field Optical Microscopy technique.

Disordered photonic nanostructures have attracted tremendous interest in the past three decades, not only due to the fascinating and complex physics of light transport in random media, but also for peculiar functionalities in a wealth of interesting applications. Recently, the interest in dielectric disordered systems has received new inputs by exploiting the role of short and long-range spatial correlations within scatterer configurations. Hyperuniform disordered (HuD) photonic materials [1], that share features of photonic crystals and random systems, are an example of engineered disorder to control, through short range-order, both spectral and momentum responses of light.

Recently, an experimental study has revealed the transition from light localization to diffusive transport in an optically active platform with a HuD design [2], showing that this type of correlated disorder system hosts Anderson-like modes very promising for fundamental studies but also for technological applications in the field of light-matter interactions. The presence of deterministically tailored localized and diffusive transport within the same photonic platform has raised novel and exciting questions.

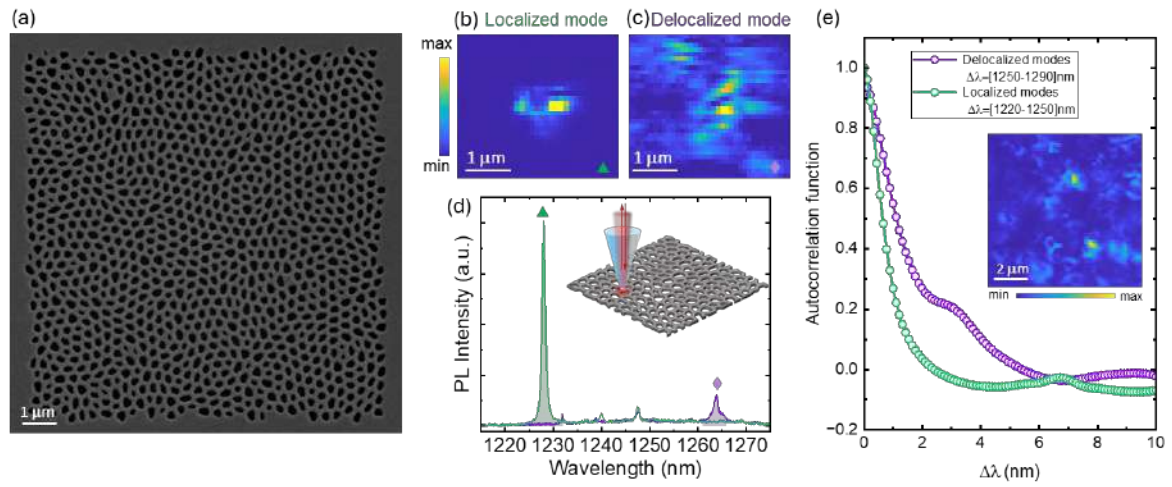
Quantum mechanical level repulsion in complex and disordered quantum systems has first been modeled by Wigner and Dyson's random matrix theory [3], and thanks to the many experimental verifications in various branches of physics, became a most valuable criterion for the study of the Anderson transition [4,5].

Here, taking advantage of the Scanning Near-field Optical Microscopy (SNOM) technique, we present the first experimental evidence of level repulsion in HuD systems in a tailored diffusive regime.

The studied samples consist in 200nm thick GaAs slabs patterned with a HuD design (Fig.1a); embedded in the middle of the slab are InAs quantum dots that act as optically active medium. The room temperature SNOM, capable of subwavelength spatial resolution in the near-IR range, is employed in illumination/collection configuration, meaning that the sample is excited with light from a diode laser (785 nm) coupled into a chemically etched optical fiber. Photoluminescence (PL) spectra from the sample are collected at each tip position through the same probe. Fig.1b-d report the results of a SNOM measurement performed on the sample; the PL SNOM maps of a typical Anderson localized mode (b) and of a delocalized one (c), along with their relative spectra acquired in the positions of maximum intensity (d).

The method employed to detect the level repulsion phenomenon is based on the evaluation of the autocorrelation function [4,6], which allows for a statistical description of the systems in terms of energy level distribution of the optical modes sustained by the system. Within a single SNOM scan performed on

the entire sample (as shown in the inset of Fig.1e) we have access to all the modes within a large spectral range. We selectively evaluate the autocorrelation function in the two spectral ranges corresponding to localized and delocalized modes, and the results are plotted in Fig.1e. The presence of a pronounced shoulder at short spectral distances in the purple curve is a clear indication of level repulsion between delocalized modes, differently, from what is observed in the autocorrelation function of localized modes. Moreover, through the evaluation of the spectral width of the autocorrelation peak, our spatially resolved spectroscopy technique gives direct insights on the typical hallmark of light localization regimes, like for example the smaller (larger) spectral width of localized (delocalized) modes.



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Pseudospectral Scaling in Lattices with Exponential Sensitivity

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Abstract: We investigate the sensitivity of non-Hermitian photonic lattices with asymmetric couplings, using the pseudospectra theory. We demonstrate that the extreme lattice nonnormality results in exponentially sensitive eigenvalue spectra and power growth dynamics. Our study may open new directions for creating ultrasensitive systems without relying on exceptional points.

One of the important features of non-Hermitian Hamiltonians $\mathbf{H}$ [1] is the existence of a unique type of singularities, the so-called exceptional points (EPs), where both the eigenvalues and eigenvectors of $\mathbf{H}$ coalesce [2]. When a system operates near an EP, it significantly amplifies imposed disturbances [3], a property that has led to the development of microresonators [4] and gyroscopes [5], among other applications. Another way to achieve ultrasensitive behavior, in lattices, lies in the presence of asymmetric couplings, where the non-Hermitian skin effect [6] commonly occurs. It has been demonstrated that the spectra of asymmetric lattices display exponential dependence on the lattice size N when the boundary conditions are varied, and this sensitivity has been linked to the lattice's topological properties [7]. In this work, we apply the pseudospectra theory [8] and show that not only the spectra, but also the growth of an initial state exhibit exponential variations with N , and that this effect is due to the extreme lattice nonnormality.

We will examine the sensitivity of the Hatano-Nelson (HN) lattice, schematically illustrated in Fig. (a1). The dynamics of the amplitude ψ_n at each lattice site $n = 1, \dots, N$ is governed by $\dot{\psi} = \mathbf{H}\psi$, where dot denotes differentiation with respect to time t (distance z) for light propagation in cavities (in waveguides) and $\psi = [\psi_1, \dots, \psi_N]^T$. The Hamiltonian $\mathbf{H}$ of the HN model is given by $H = \sum_{j=1}^{N-1} (t_L|j\rangle\langle j+1| + t_R|j+1\rangle\langle j|)$, where $|j\rangle$ is the state localized at lattice site j , t_R is the hopping amplitude for transitions from site $j+1$ to j , and t_L the hopping amplitude in the reverse

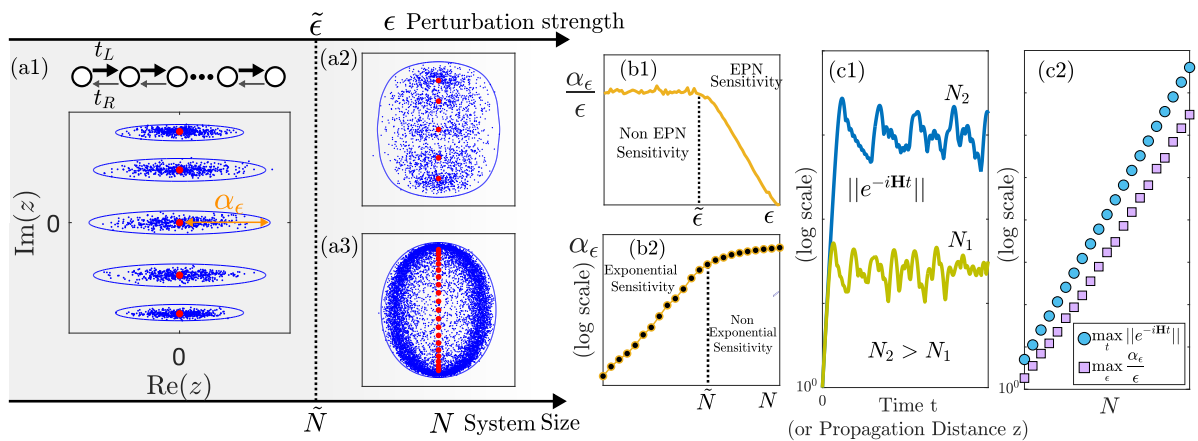


Figure 1: Spectrum (red dots) and pseudospectrum (blue dots) of $A = -iH$, for (a1) small N and ϵ , (a2) large ϵ and moderate N , and (a3) large N and moderate ϵ . (b1), (b2) Variation of the abscissa α_ϵ with (b1) ϵ and (b2) N . (c1) Time (or spatial) growth dynamics for light propagation through cavities (or waveguides) and for two lattice sizes $N_2 > N_1$. (c2) Power growth and Kreiss constant scaling with N .

direction. Let us note here that $\mathbf{H}$ is a nonnormal matrix, i.e. $[\mathbf{H}, \mathbf{H}^\dagger] \neq 0$, and due to this fact, nontrivial amplifying effects appear as we will discuss next.

In Fig. 1(a1) we show with red dots the spectrum $\sigma(\mathbf{A})$ (eigenvalues) of the matrix $\mathbf{A} = -i\mathbf{H}$ and with blue dots its ϵ -pseudospectrum $\sigma_\epsilon(\mathbf{A})$ [8], with the latter being defined as the set with the eigenvalues of perturbed matrices $\mathbf{A} + \mathbf{E}$, with $\mathbf{E}$ being a complex random matrix with 2-norm less than ϵ . Notice that for small N and ϵ , the pseudospectrum consists of N disks centered at the N eigenvalues of $\mathbf{A}$ [panel (a1)]. As the perturbation strength ϵ [panel (a2)] or lattice size N [panel (a3)] increases, the pseudospectrum extends in the complex plane; its size can be measured by the abscissa $\alpha_\epsilon = \max \Re[\sigma_\epsilon(\mathbf{A})]$, which scales as a power law (exponentially) beyond a (up to a) critical perturbation strength $\tilde{\epsilon}$ (critical lattice size $\tilde{N}$), as illustrated in panel (b1) [panel (b2)]. The latter results show the ultrasensitive sensitivity of the spectrum when the Hamiltonian is perturbed.

We will now demonstrate the sensitivity of the HN model in the context of power growth dynamics. We note first that the evolution of an initial state ψ_0 is given by $\psi(t) = e^{-i\mathbf{H}t}\psi_0$, where the matrix $e^{-i\mathbf{H}t}$ is referred as the propagator or evolution matrix [8]. A measure quantifying the power dynamics is the maximum growth at any given time t , given by $\max_{\psi_0} \frac{\|\psi(t)\|}{\|\psi_0\|}$, which is equal with the 2-norm of the propagator matrix $\|e^{-i\mathbf{H}t}\|$. Shown in panel (c1) is the time-evolution of the propagator norm for 2 lattice sizes $N_{1,2}$. Notice that amplification occurs ($\|e^{-i\mathbf{H}t}\| > 1$); this is due to the nonnormality of $\mathbf{H}$. Notice also that the maximum amplification $\max_t \|e^{-i\mathbf{H}t}\|$ increases with increasing N . In fact the $\max_t \|e^{-i\mathbf{H}t}\|$ scales exponentially with N as illustrated in panel (c2), revealing the exponential sensitivity of the growth. Moreover, the pseudospectrum provides an estimate of this growth, through the Kreiss matrix theorem which states that $\max_t \|e^{-i\mathbf{H}t}\| \geq \max_{\epsilon>0} \frac{\alpha_\epsilon}{\epsilon}$. The quantity on the right side of the latter inequality is known as the Kreiss constant and in panel (c2) it is shown that it increases exponentially with N as well.

In summary, we have presented a scaling analysis of pseudospectra in exponential sensitive lattices. Given that recent experiments in non-Hermitian photonics have realized such asymmetric optical lattices [6], our findings could enable the efficient design of ultrasensitive devices without relying on higher-order exceptional points.

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Plasmonic Nanostructures for Enhanced Electrocatalytic CO₂ Reduction and Sensing Applications

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Abstract: Localized surface plasmon resonance (LSPR) has become a highly attractive approach to enhance catalytic and electrocatalytic processes. Here, we propose different geometries and size of plasmonic nanostructures that may enable the improvement of electrocatalytic reactions and can be used for the electrochemical reduction of CO₂ and other catalytic reactions.

It is well established that catalytic and electrocatalytic processes can be enhanced by plasmons through localized surface plasmon resonance (LSPR) excitation. Recently, T. N. Saada et al. demonstrated the plasmon-enhanced electrochemical reduction of oxygen to water in alkaline media [1]. Additionally, surface plasmons have been employed to promote hydrogen evolution in acidic solutions and methanol oxidation on gold nanohole electrodes [2,3]. Despite the advantages of plasmons in improving selectivity during purely plasmonic (bias-free) photocatalytic CO₂ reduction, their effect on the Coulombic efficiency and product selectivity of CO₂ electrochemical reduction has not been extensively studied. In this work, we propose different plasmonic nanostructures that show promising performance for electrocatalytic reactions. Among these, we present a hexagonal array of copper nanoholes (Cu NHs), filled with water and deposited on a glass substrate (Fig. 1(a)).

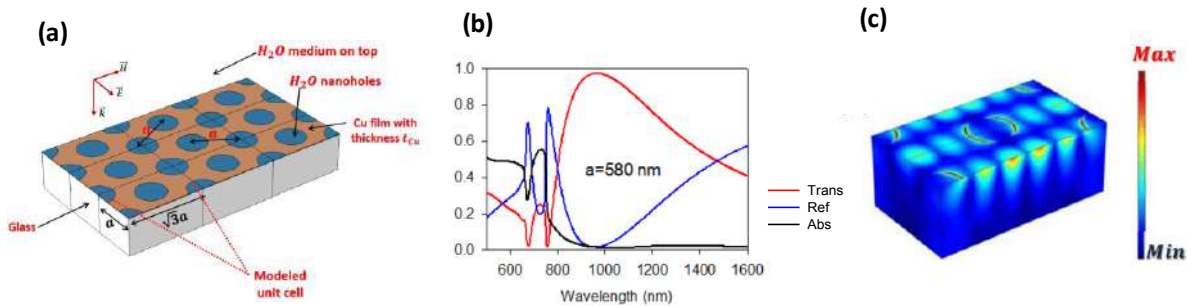


Figure 1: Sketch of Cu NHs 2D triangular grating, supported by a Glass substrate. The holes are filled with water. (b) Transmission (red curve), reflection (blue curve) and absorption (black curve) coefficients as a function of wavelength for the parameters: 420 nm for the holes' diameter, $a = 580 \text{ nm}$ for the grating constant and 60 nm as for the Cu-film thickness. (c) E field norm map depicted within the system at $\lambda = 760 \text{ nm}$,

The scattering properties of Cu nanohole (NHs) structures, including transmission, reflection, and absorption spectra are investigated, along with the eigenfrequencies of both isolated and coupled NHs. We also examine the localized and propagating behaviors of plasmonic modes according to various geometrical parameters, in order

to identify the best designs for fabrication. A comprehensive study of all geometrical parameters will be conducted, including lattice period, hole diameter, and sub-layer thicknesses.

Obviously, an enhanced plasmon mode should lead to significantly improved photo-electrochemical activity, as it is directly linked to scattering extinction (transmission, reflection, and absorption). An example of these results is shown in Fig. 1(b), presenting the transmission, reflection, and absorption spectra for a period of $a=580$ nm. As observed, there are two plasmon modes corresponding to the reflection maxima. An illustration of the electric field norm is given in Fig. 1(c), highlighting an example of an excited propagating surface plasmon-polariton (SPP) at the Cu/glass interface at a wavelength of $\lambda = 760$ nm, resulting from the diffraction of incident light by the NHs array. Additionally, these systems may also be used for sensing applications, by adjusting the water height and filling level. Other examples of nanostructures will be also highlighted in this work.

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Cavity-assisted generation of intense, super chiral fields for enantiomers separation

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Abstract: Helmholtz resonator in combination with a metallic disc is shown to form a cavity that can convert impinging laser pulse into collimated near fields with strongly enhanced intensity and chirality density. The fields are demonstrated to form almost lossless and to be useful for enantiomers separation.

In this contribution results are presented that show how spin-to-orbital angular-momentum (SAM to OAM) conversion allows the generation of focused, intense, super chiral fields. These fields in the visible range are demonstrated to be useful for tweezing and separating chiral objects via full numerical simulations [1]. The setup, as shown in Fig.1 consists of a micron-size Helmholtz hemisphere resonator with the opening at the pole. We consider a circularly polarized Gaussian laser field in the visible range impinging at the pole, entering the cavity and multipole scattered. The fields formed at the equator plane are shown to possess an intrinsic orbital angular momentum component with respect to the axis of the Helmholtz resonator. When brought in proximity to a metal plate, diffraction of the fields embodying OAM results in the formation of intense, subwavelength focused chirality density. The chiral fields form as a result of an interplay between resonator cavity modes and diffraction. No plasmonic losses are involved, and the fields can be generated at tunable frequencies by varying the radius of the resonator. We show that the fields produced so can move and separate radially chiral objects such as molecules on surfaces. The in-situ motion of the chiral molecules is illustrated by full numerical simulations. The generated fields are tunable by the parameters of the input fields (such as frequency and polarization) as well as by the radius of the hemisphere. Our results demonstrate an effective tool for chiral tweezing and enantiomer separation on the nanoscale under a realistic setting and with moderate input laser intensity.



Fig.1: Half Helmholtz resonator on top of metal (Ag) surface that convert and Gaussian laser pulse entering its neck into localized, intense (super) chiral near field. Left: Poynting vectors on the surface of the Ag-disk at the Helmholtz cavity resonator wavelength of 400 nm. The amplification of the power flow inside the Helmholtz resonator is

about 300 Right: Normalized chirality density in the Helmholtz resonator at the resonance wavelength of 400 nm. The chirality value equal +1 is that of incoming circularly polarized light.

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Enhancing the chiral coupling between light and molecules by 2-3 orders of magnitude via coherent multiphoton excitation

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Abstract: We consider enantioselective energy transfer from chiral light to a chiral isotropic molecular sample in the multiphoton regime. We identify the chiral light-matter couplings relevant for multiphoton transitions and show that they can be 2-3 orders of magnitude stronger than their one-photon counterpart, leading to high enantioselectivity.

Molecular chirality plays a huge role in the chemical industry and is rapidly emerging as a valuable resource for nanotechnology [1, 2]. However, the manipulation of chiral molecules remains difficult. A fundamental challenge is to transfer energy from an electromagnetic field into a chiral sample with enantiomer (left vs. right) selectivity [3]. Here we propose how to address this challenge using multiphoton transitions.

Enantioselective molecular excitation is challenging because of two reasons. First, opposite enantiomers of a chiral molecule share the same energy spectrum, which rules out using the photon energy for enantioselectivity. Second, the chiral coupling between light and molecules is typically very weak [3]. Indeed, in isotropic media, the excited molecular population is proportional to $|\vec{d}|^2|\vec{E}|^2 + g^{(1)}h^{(1)}$, where $\vec{d}$ is the transition electric dipole and $\vec{E}$ is the electric field [4]. The second term provides the chiral coupling because $g^{(1)} \equiv \vec{d} \cdot \Im\{\vec{m}\}$ has opposite signs for opposite enantiomers, while $h^{(1)} \equiv \Im\{\vec{E}^* \cdot \vec{B}\}$ has opposite signs for left and right circularly polarized light. Here $\vec{m}$ is the transition magnetic dipole and $\vec{B}$ is the magnetic field. The ratio of the chiral to the achiral couplings is proportional to $|\vec{m}||\vec{B}|/|\vec{d}||\vec{E}|$ and thus usually very small (< 0.01) [5], leading to vanishingly small enantioselectivity. Exceptions may occur in highly localized regions of space around electric field nodes $\vec{E} \approx 0$ [6] or for quasi-forbidden electric-dipole transitions $\vec{d} \approx 0$ [3], which is interesting but still too small for practical purposes.

The chiral coupling $g^{(1)}h^{(1)}$ results from interference between electric- and magnetic-dipole transitions [4] and is weak because the two interfering pathways are not well balanced. Multiphoton excitation provides a way to create balanced interference pathways and thus strong chiral couplings [7]. For example, in a three-level system, a field with frequencies ω_a , ω_b , and $\omega_c = \omega_a + \omega_b$ can excite the same transition via two different pathways: $|0\rangle \xrightarrow{\omega_a} |2\rangle$ or $|0\rangle \xrightarrow{\omega_b} |1\rangle \xrightarrow{\omega_c} |2\rangle$. The interference of these pathways is proportional to $g^{(3)}h^{(3)}$, where $g^{(3)} \equiv [d_{20} \cdot (d_{21} \times d_{10})]$ encodes the molecular chirality, and $h^{(3)} \equiv [\vec{E}_{\omega_c}^* \cdot (\vec{E}_{\omega_b} \times \vec{E}_{\omega_a})]$ encodes the *local chirality* of the field relevant for this process [8]. This chiral coupling can be of the same order as the achiral coupling, leading to highly enantioselective energy transfer.

The expression for $h^{(3)}$ reveals that multiphoton chiral couplings require non-coplanar polarizations and stable relative phases between the different frequencies. These ideas can be generalized to other multiphoton pathways [8], providing considerable flexibility for tailoring the

chiral couplings in time and space. Our ab-initio simulations in small chiral organic molecules reveal that enantioselectivity (chiral/achiral ratio) can be as high as 45% and that it can be either kept constant in space or made to oscillate on a subwavelength scale.

Our results have immediate consequences for chiral photochemistry and enantioselective synthesis. Moreover, the ability to modulate chiral light-matter couplings with a high dynamical range and high resolution in time and space opens enticing opportunities with regards to nonlinear and time-modulated metamaterials.

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Non-Lorentzian model for strong exciton-plasmon coupling

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Abstract: We study non-Lorentzian effects in the scattering spectrum of quantum emitters strongly coupled to surface plasmons in metal nanoparticles. We develop a semiclassical approach incorporating optical dispersion and losses in the metal to show that non-Lorentzian effects cause a shift of the spectral weight towards the lower energy polaritonic band.

The shape of scattering spectra of quantum emitters (QE) resonantly coupled to localized surface plasmons (LSP) in metal nanoparticles (NP) as the system transitions to the strong coupling regime has been an actively debated issue as the relative spectral weight of polaritonic bands is determined by several competing processes. In general, the scattering spectrum of a hybrid system characterized by a broad spectral band is enhanced on the higher frequency side due to a faster radiation rate of upper-energy states, implying that, in the strong coupling regime, the spectral band associated with the upper-energy polaritonic state should be relatively enhanced. Such a spectral profile is consistent with the classical model of two coupled oscillators (CO), in which one of the oscillators (LSP) couples much stronger to the electromagnetic (EM) field due to a much smaller QE optical dipole moment [1]. However, recent experiments for excitons resonantly coupled to LSP in metal-dielectric structures [2,3] reveal the opposite asymmetry pattern characterized by enhanced lower polaritonic band. In this paper, we demonstrate that non-Lorentzian effects originating from the material optical dispersion and losses strongly affect the optical spectra of hybrid QE-LSP systems and, in the strong coupling regime, results in a shift of the spectral weight towards the lower-energy polaritonic band, consistent with the experiment. Using the non-Lorentzian LSP Green function for NP of arbitrary shape [4], we set up non-Lorentzian Maxwell-Bloch equations which include complex dielectric function of the metal rather than Lorentzian approximation for the LSP resonance. We show that the non-Lorentzian effects show up prominently in the optical spectra of plasmonic systems due to an interplay between the real and imaginary part of the metal dielectric function which define, respectively, the plasmon coupling to the EM field and the broad plasmon optical band. Specifically, the temporal dispersion of its real part, which originates from free-electron absorption in metals, leads to a spectral weight shift towards the lower frequency side of the spectra. In the strong coupling regime characterized by well-separated polaritonic bands, such non-Lorentzian effects result in an inversion of spectral asymmetry as compared to the CO model predictions.

In Fig. 1 we show the scattering spectra for a QE near an Au NP calculated using non-Lorentzian model for three different LSP frequencies. As the QE-LSP coupling increases, the system undergoes transition to strong coupling regime signaled by the emergence of Rabi splitting between polaritonic bands. In the higher-energy region, the spectrum exhibits enhancement of the lower-energy polaritonic band, consistent with the experiment [2,3], while for lower energies, the spectral weight shifts towards the upper energy band. In contrast, for scattering spectra calculated in the Lorentzian approximation shown in Fig. 2, the upper energy polaritonic band is enhanced in the entire energy range, as predicted by the CO model. This difference can be traced to the effect of metal temporal dispersion on the LSP optical dipole moment which results in a suppression of the LSP radiation efficiency for higher energies.

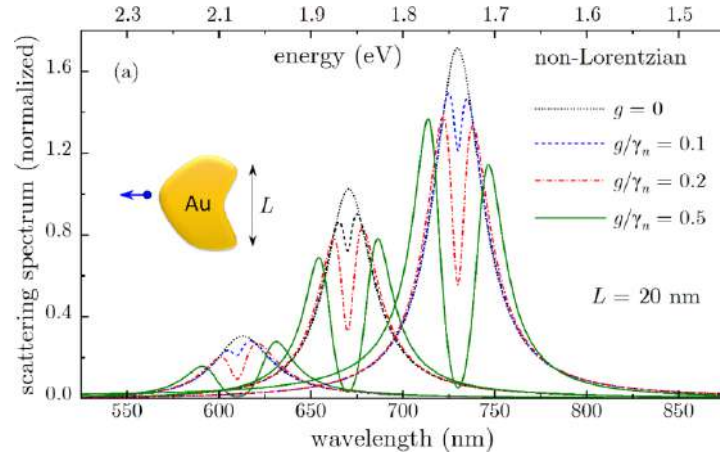


Figure 1. Scattering spectra for an Au NP coupled to a QE calculated using non-Lorentzian model.

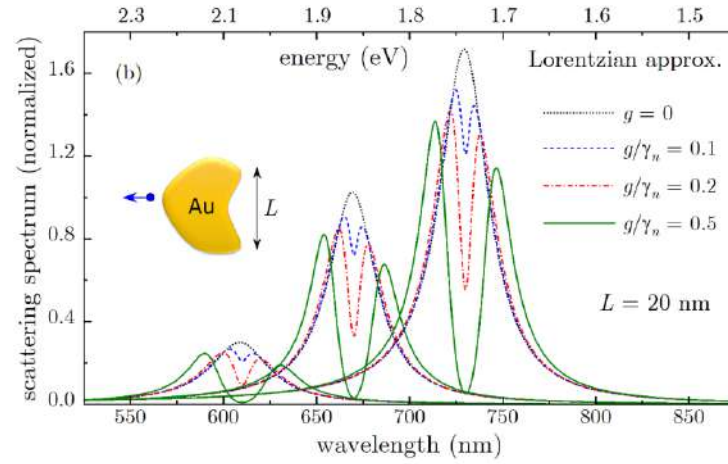


Figure 2. Scattering spectra for an Au NP coupled to a QE calculated using Lorentzian approximation.

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Dielectric metasurfaces for Laser Cooling and Trapping of Neutral Atoms

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Abstract: This study reports a novel scheme of using flat optics composed of geometric phase metasurfaces to prepare arrays of individual cold atoms trapped in the optical tweezers. Our method exploits the capabilities of metastructures in controlling the phase, amplitude and polarization states of light at the sub-wavelength resolution to generate specific wavefronts necessary for magneto-optical trapping (MOT) and dipole optical trapping (ODT) of alkali-metal atoms. This work highlights the potential of metasurfaces in integrating laser cooling and trapping within a compact apparatus, and the engineering of large scale many-body systems for quantum information processing, quantum simulations, and precision measurements.

Arrays of individual cold neutral atoms have recently emerged as promising platforms for a variety of applications including quantum metrology, quantum computing, and quantum networking. Notably, their long coherence times, scalable, and reconfigurable architecture have facilitated the essential primitives required for high-fidelity quantum information processing. In addition to fundamental studies on the physics of quantum systems involving cold atoms, significant efforts are underway to develop robust techniques to prepare array of atoms within a compact system. This is particularly crucial for effectively transferring cutting-edge quantum sciences into practical applications. However, the major challenge lies in the bulky optical elements employed in conventional magneto optical trapping (MOT) and dipole optical trapping (ODT) apparatus, which not only restrict the miniaturization but also hinder the scalability and fidelity of trapping individual atoms.

In this study, we propose and validate a novel scheme of using metasurfaces to ultimately manipulate the wavefront of light for cooling the alkali-metal atoms via MOT and assembling them into a periodic array via ODT. Metasurfaces are composed of nanofin structures of high-index dielectric materials which act as half waveplates. The spatial rotation of each nanofin by an angle α allows us to imprint the geometric phase at sub-wavelength resolution, as depicted in Fig. 1(a). This type of metastructure, known as geometric phase or Pancharatnam-Berry (PB) phase metastructure, facilitates the precise manipulation of optical amplitude, phase, and polarization, enabling the generation of arbitrary wavefronts.

In the magneto-optical trapping for cooling alkali-metal atoms, we propose a MOT configuration that leverages the capability of PB phase metastructure in manipulating the circular polarization states and the phase of light. In this setup, a single laser beam is incident on a metasurface, which is designed to diffract it into four beams with polarization states opposite to that of the incident light, while also transmitting one beam that retains its original polarization, as described in Fig. 1(b). The transmitted beam is reflected using a mirror and a quarter-wave plate, allowing it to intersect with the four diffracted beams at the center of a quadrupole magnetic field. By carefully tuning the diffraction angle and efficiency, the wave vectors of these beams sum to zero, generating the necessary restoring forces for atomic cooling and trapping. This configuration ensures the balance of restoring forces along the axial direction (z -direction) by forming two properly polarized axial laser beams, while the diffracted beams contribute to restoring forces in the lateral direction. Compared to previous MOT configuration

that relies on the reflective grating structures (e.g. grating-MOT or GMOT), which produces only a single properly polarized axial beam, as illustrated in Fig. 1(c)—our approach effectively eliminates the axial force imbalance inherent in GMOT.¹ Using this metasurface-based setup, we have successfully trapped and cooled cesium (Cs) atoms, which was previously challenging with the existing GMOT configuration.² The metasurface, composed of silicon nanofin structures in the donut-shape with the outer and inner diameter of 16 mm and 8 mm, respectively, was fabricated using electron beam lithography, followed by the etching of silicon using inductively coupled plasma reactive ion. Fig. 1(d) shows the scanning electron microscopic (SEM) image of the sample. The metasurface was then mounted onto an ultrahigh vacuum glass cell filled with Cs gas and irradiated with a collimated laser beam of 18 mm in diameter. The transmitted laser beam was subsequently reflected by a mirror and a quarter-wave plate positioned at the bottom of the glass cell, forming the MOT configuration depicted in Fig. 1(b). The diffraction angle and efficiency of each diffracted beam were 45° and 23%, respectively. When a quadrupole magnetic field was applied, the formation of the trapped and cooled Cs atom cloud near the field center was confirmed when the center of the quadrupole magnetic field was within the intersection of the four diffracted and two axial beams. Fig. 1(e) shows the fluorescence image of the cooled Cs cloud captured by a CCD camera, which verified the proposed MOT.

Atom ensembles, cooled by MOT, are then arranged into the desired array by employing the dipole optical trapping (ODT) based on the optical tweezer principle. It is essential to generate optical tweezers array with sufficiently high trapping potentials, while ensuring the geometric configurations, and intensity uniformity in each ODT traps. In this study, we also present a metasurface hologram which is capable of simultaneously generating and focusing light into holographic spots array with high trapping potentials.

In summary, we have demonstrated and verified the performance of metasurfaces in magneto-optical trapping and dipole optical trapping of alkali-metal atoms. The cooling and trapping of atoms with metasurfaces, without the need for extra optical components, demonstrates high optical efficiency, and scalability potential. These characteristics highlights the potential of metasurfaces in realization of compact and lower-power quantum systems, with diverse applications in quantum metrology, quantum information processing, and atomic physics.

Acknowledgements:

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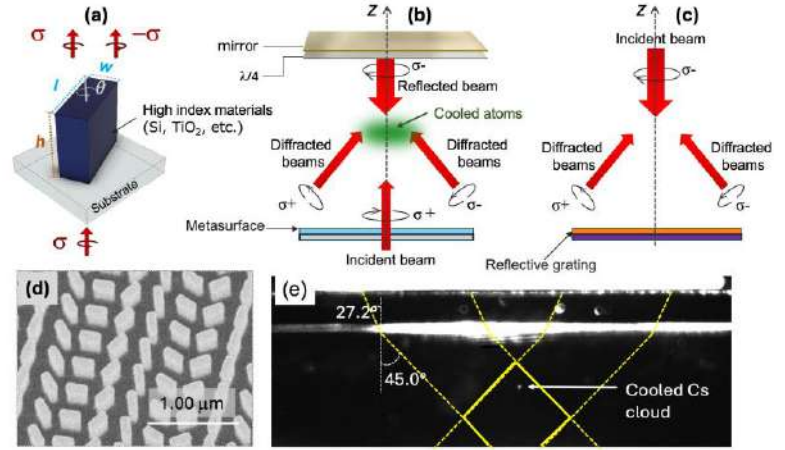


Fig. 1. (a) Unit structure of Pancharatnam-Berry (PB) phase metasurface, MOT configuration using (b) metasurface and (c) reflective grating (GMOT), (d) SEM image of the fabricated metasurface, and (e) fluorescence image of the cooled Cs cloud

Generalized Lorentz Model for Photons and Electrons interacting at the Deep Nanoscale

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Abstract: We present a generalized Lorentz model for quantum plasmonics in nanoplasmonics in deep nanoscale metals and semiconductors. We discuss the features and prospects of the scenario where the photons and electrons co-localized and interacting at the deep nanoscale.

In the past decade, the dramatic advents of material science and nanofabrication techniques have been pushing the optical confinement from micro/nano scale down to deep nanoscale or even to the atomic scale. These developments led to the situations to have simultaneous extreme confinement of the optical field and the electrons, where the complex optical responses cannot be described by classical local electromagnetic theory. In this talk, we will discuss the fundamentals and new opportunities associated with this emerging direction. In particular, we report a generalized Lorentz Model for correct and efficient description of the nonlocal and quantum effects associated with the ultrafine features of nanostructured materials. Based on the theory, we will show how one could grasp the optical response from the microscopic features of a macroscopic system. Moreover, we outline some unique opportunities of having photons and electrons co-localized and interacting at the deep nanoscale, or even down to the atomic scale.

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Tailoring the design space of structurally colored stretchable materials

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Abstract

Large scale-structural colored stretchable material was recently developed. We aim to parametrize its design space using two surface roughness parameters: the autocorrelation length and the Root Mean Square. By tuning roughness, we control diffuse and specular scattering, enhancing light diffusion and minimizing iridescence for improved sensing applications.

Large-scale, structural colored stretchable material was recently developed. We aim to parametrize its design space using two surface roughness parameters: the autocorrelation length and the Root Mean Square. By tuning roughness, we control diffuse and specular scattering, enhancing light diffusion and minimizing iridescence for improved sensing applications.

Structurally colored stretchable material was recently fabricated using Lippmann photography and photosensitive elastomers [1]. This process generates refractive index variations in the material, making it act as a distributed Bragg reflector. We aim to expand these materials' design space and improve their scattering properties by mainly controlling their surface roughness. Specifically, we want to modify the light scattering behavior—from specular to more diffuse—and minimize iridescence by tuning the roughness of the photonic material itself and adding a rough, transparent, thick top layer. Thus, this approach will provide new possible applications of these materials in optical sensors.

The idea behind using a rough top coat is to introduce initial diffusion before the light interacts with the Bragg reflector; this broadens the scattered light cone and enhances total diffusion. Selecting a thick top coat of the photonic material simplifies our analytical model. Since the thickness exceeds the coherence length of light, we can treat the system from a far-field perspective, allowing intensities to add up more straightforwardly. Additionally, assuming that the top coat is homogeneous and transparent, no scattering occurs within it, ensuring that light propagates through it without more diffusion.

To model the scattering behavior, we consider a system composed of three sequential scattering events: (1) transmission from air into the rough top coat, (2) reflection at the interface between the top coat and the photonic material, and (3) transmission back into the air from the top surface. By tuning the roughness of both the photonic material and the top coat, we can control the balance between specular and diffuse scattering.

For a fixed incident angle $(\theta_{\text{in}}, \varphi_{\text{in}})$ and a fixed observation angle $(\theta_{\text{out}}, \varphi_{\text{out}})$, the total intensity results from contributions spanning all possible intermediate angles (θ_1, φ_1) and (θ_2, φ_2) , accounting for the cumulative scattering effects. Here, θ represents the polar angle, and φ is the azimuthal angle. The resulting sequence of interactions is described as:

$$I(\theta_{\text{in}}, \varphi_{\text{in}}, \theta_{\text{out}}, \varphi_{\text{out}}) = \int_{\theta_1} \int_{\varphi_1} \int_{\theta_2} \int_{\varphi_2} T_1(\theta_{\text{in}}, \varphi_{\text{in}}, \theta_1, \varphi_1) \cdot R(\theta_1, \varphi_1, \theta_2, \varphi_2) \cdot T_2(\theta_2, \varphi_2, \theta_{\text{out}}, \varphi_{\text{out}}) \quad (1)$$

$$\cdot \sin(\theta_1) \cdot \sin(\theta_2) d\theta_1 d\varphi_1 d\theta_2 d\varphi_2 \quad (2)$$

To quantify intensities in both transmission cases T_1 , T_2 , and in reflection R , we adapt the Generalized Harvey-Shack (GHS) Method, a semi-analytical model used to describe the scattering signature of light on moderately rough surfaces. In the literature, only a numerical model using GHS was provided for the reflection scenario [2, 3]. Therefore, we aim to extend it to include the transmission case. This extension will enable us to provide a precise prediction of angular light behavior and will allow us to link the total angular spread intensity of the system to two main roughness parameters: the autocorrelation length (lateral distance) and the root mean square (height distribution).

To better understand the core concept of the Generalized Harvey-Shack Method [2, 3], this theory aims to provide a linear system that characterizes the scattering signature of a material depending on its surface parameters. As empirical experiments show a shift-invariance behavior of the scattered light when looked at from different incident angles, this suggests the existence of a Surface Transfer Function that universally describes the scattering behavior. This function is an analogy to the linear system formulation in image formation, particularly the Optical Transfer Function OTF, which characterizes the system's ability to transfer contrast and detail from an image object to its image. The Surface Transfer Function is given by the normalized autocorrelation function of the Pupil function of the scattering process (describing amplitude and phase variation due to roughness). The Fourier transform of the Surface Transfer Function represents the angular intensity variation of the propagation vectors in the far field, which is our primary interest to measure.

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Reconfigurable Metasurfaces for MRI

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Abstract: Optimized, reconfigurable metasurfaces for magnetic resonance imaging provide new degrees-of-freedom by the precise spatio-temporal control of the RF magnetic field, leading to new imaging paradigms. The decoding of spatial signal distributions and targeted improvements of imaging efficiency by enhanced local signal-to-noise-ratio or scanning speed are prime examples for possible applications.

The application of conformal and reconfigurable metasurfaces (MTS) in magnetic resonance imaging (MRI) allows for the enhancement of the imaging efficiency without a significant impact on patient comfort and without significant additional burdens on radiologists' workload.

In comparison to conventional coil arrays, MTS are only bound to the specific Larmor frequency of the scanner and not to any specific interface, which makes a MTS inherently vendor-independent, less bulky and potentially cheaper as less components are needed. Further integration into individual MRI systems can be achieved by, e.g., the vendor-independent sequence programming framework GammSTAR [GammaStar2019].

Tunable metasurfaces for MRI have been presented in a few publications, see e.g. [Wu2024]. In general, the control mechanisms rarely go beyond the global adjustment of the MTS's resonance frequency due to engineering challenges related to the control of individual cells [He2019]. Reconfigurable MTS for MRI were up to now sparsely shown in [Lippke2022, Stoja2023]. As highlighted in [Tian2024] reconfigurable, flexible MTS have gained traction in biomedical applications in recent years. Nevertheless, up to now, there is no flexible, reconfigurable MTS for MRI with a precise and reliable control framework in MRI.

For a real-world impact, the MTS must be reliable, easy to use and universally applicable for many imaging situations. We therefore present advances towards wirelessly reconfigurable MTS that allow for the precise spatio-temporal control of the RF magnetic field in the scanner (Tx and/or Rx field control). Moreover, a differentiable simulator is developed for the vectorized, time-efficient, gradient-based and non-gradient based optimization of all new degrees of freedom (DoF). A tailored control board for the reliable control of up to 64-DoF in MRI is designed and tested. Prototypes, as sketched in Fig. 2, allowing the TX-detuned spatio-temporal control in up to two dimensions along with the challenges encountered during design and testing will be presented.

The presented content will cover the entire design and test pipeline from simulation (Fig. 1), AI and conventional design-optimization up to lab-measurements and real-world application in MRI. Moreover, it is shown how applications related to the decoding of the spatial signal distribution and local signal-to-noise-ratio enhancements can be realized.

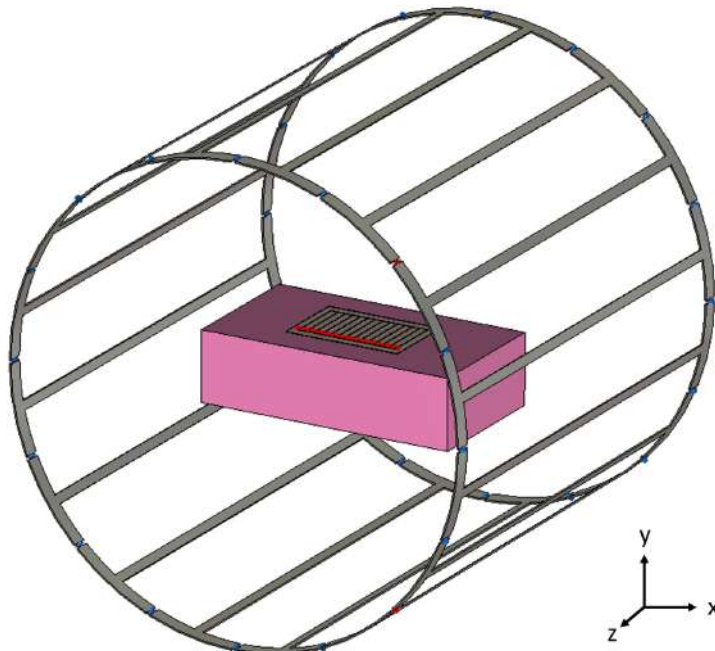


Fig. 1: A reconfigurable MTS with 14-DoF in a birdcage-coil simulation

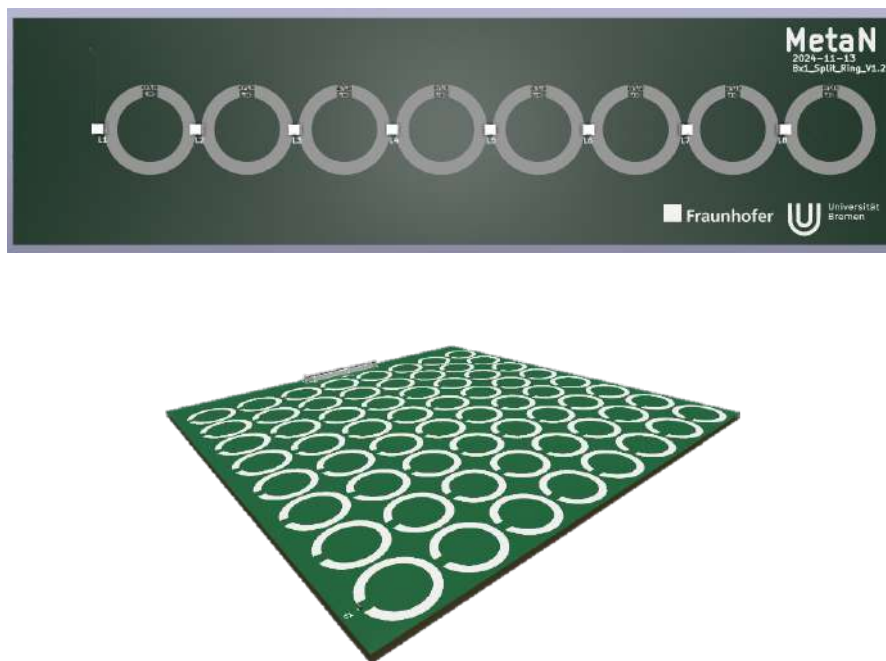


Fig. 2: A reconfigurable 8x1 and 8x8 MTS Split-Ring Design

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Hyperuniform Disordered Metasurfaces for Solar and Solar-Thermal Absorbers

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Abstract: Hyperuniform disordered structures exhibit significant potential for enhancing light absorption in solar cell and solar-thermal absorber architectures. Through unique light-trapping mechanisms, these structures can achieve absorption enhancements of up to 85% across the visible spectrum, contributing to record-breaking efficiencies in ultra-thin film solar cells.

In recent decades, advancements in nanoscience and nanotechnology have enabled precise manipulation of nanostructures, significantly improving solar energy capture, conversion, and storage. Cutting-edge fabrication techniques now provide unprecedented design flexibility, allowing for the creation of complex and aperiodic geometries, including hyperuniform, quasi-periodic, fractal, and seemingly random patterns. When optimally designed, these structures can surpass conventional approaches while exhibiting greater tolerance to fabrication imperfections. However, the lack of simple and systematic design methodologies has thus far limited their full potential.

In this work, we leverage novel hyperuniform and nearly hyperuniform disordered architectures [1]–[4] for selective absorbers to achieve precise control over solar spectrum absorption. By employing an inverse Fourier-space design approach, we identify optimal absorber configurations based on their Fourier components to accomplish two primary objectives: enhancing both the efficiency and angular acceptance of solar cell absorbers while optimizing the balance between undesirable out-of-plane scattering losses and advantageous in-plane light trapping. This methodology aims to drive absorption performance toward its fundamental theoretical limit.

The hyperuniform patterning is implemented as a textured layer atop a 1-micron-thick silicon slab, designed to enhance the coupling of incident solar radiation into the slab's supported optical modes [5]. Within the targeted spectral range of 400–1050 nm, silicon exhibits strong dispersion, resulting in significant curvature of the silicon light cone and substantial variations in absorption efficiency. At shorter wavelengths, absorption remains high even with suboptimal coupling to incident radiation. However, at longer wavelengths, effective coupling to the quasi-waveguided modes of the silicon slab becomes essential to compensate for silicon's inherently lower absorption. To address this, we focus on optimizing coupling to modes with wavevectors in the range of $[10, 20] \mu\text{m}^{-1}$, enabling efficient absorption in the spectral region where silicon absorption is weaker [6]. The absorption spectra of hyperuniform disordered structures exhibit several key characteristics. Most notably, the spinodal structure achieves the highest overall absorption efficiency, reaching 85%, representing a significant enhancement over an untextured silicon slab with an anti-reflective coating. Despite differences in morphology, the optimized structures share a common characteristic: filling fractions consistently within the 50–60% range. Additionally, the oscillations observed in the absorption spectrum of the unpatterned silicon slab are attributed to Fabry-Pérot resonances, which have previously been exploited to enhance absorption in thin-film solar cells.

To conclude, we have explored the application of hyperuniform disordered texturing to enhance solar radiation absorption. The efficiency of solar energy harvesting is governed by fundamental physical mechanisms,

including diffraction induced by surface patterning and coupling to the guided modes of the crystalline silicon (c-Si) slab. Our findings demonstrate that absorption enhancements of up to 85% of incident solar radiation can be achieved across the broadband range of 400–1050 nm in a 1 μm -thick silicon membrane. This approach can be extended to a range of solar energy harvesting applications, including solar-thermal absorbers for solar thermionic systems [6–8], where concentrated sunlight is harnessed to generate electricity with high efficiency and minimal cost. In this context, solar radiation absorption would occur within a specially designed metasurface, consisting of optimally engineered metal-dielectric-metal resonators arranged in a hyperuniform pattern to enhance coupling to the resonant modes.

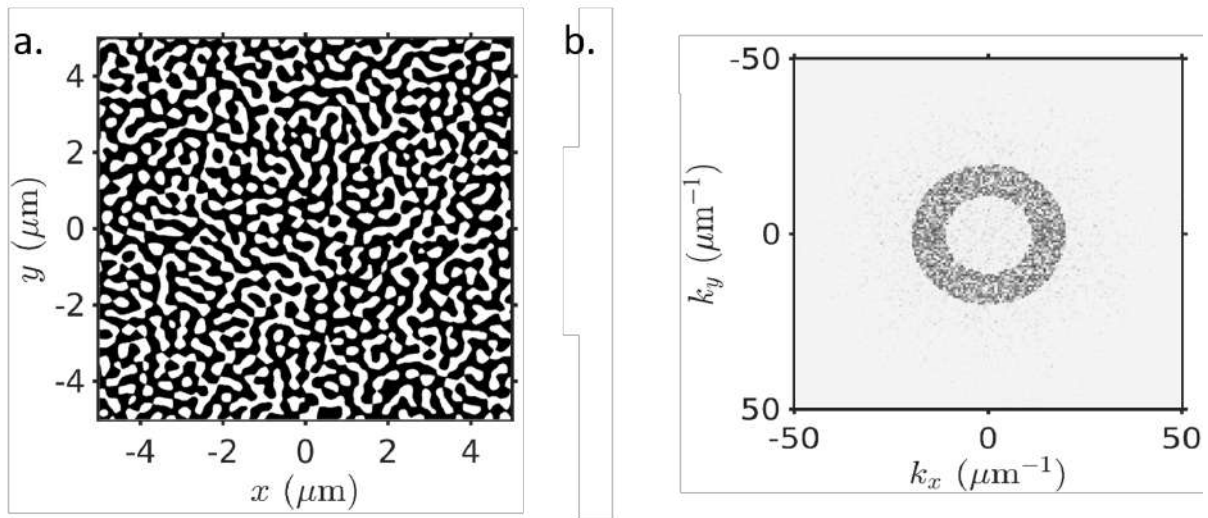


Figure 1 (a) A nearly hyperuniform distribution of dielectric material based on a density-wave expansion with constrained wave vectors. (b) Diffraction spectrum corresponding of the two-phases material depicted in Fig. 1(a), with majority of diffraction power concentrated within a circular shell of predefined boundaries.

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Application of metal nitrides based nanomaterials in SERS spectroscopy: challenges and perspective.

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Abstract: In this study, we report on the development of a highly-efficient SERS platform based on titanium nitride (TiN) nano and microstructures. SERS studies demonstrated excellent performance, comparable to that of gold. We found that the SERS activity can be further improved by the formation of dual-plasmonic Au-TiN nanomaterials.

Nowadays, SERS (Surface-Enhanced Raman Spectroscopy) is dominated by highly efficient platforms based on plasmonic metals such as silver and gold. The continuous development of noble metal-based SERS platforms has enabled the construction of extremely sensitive sensors for detecting many toxic reagents. However, the capabilities of noble metal plasmonic nanostructures are now practically exhausted. Therefore, the development of new types of non-metallic plasmonic nanostructures is ongoing.

Recent research has shown that metal nitrides (XN, where X is a metal) exhibit very interesting optical properties, making them promising materials for the construction of novel, noble metal-free SERS platforms. Titanium nitride (TiN), a typical ceramic material, demonstrates excellent temperature and chemical stability, as well as good biocompatibility¹.

In this work, for the first time, we present samples with the same morphology coated with both TiN and Au layers of the same thickness, which are characterized and applied as SERS platforms². Gold and TiN layers were deposited on chemically etched silicon micropylamids using the magnetron sputtering technique. The morphology of the samples was examined by scanning electron microscopy (SEM). The deposited Au and TiN layers were continuous and did not alter the morphology of the Si pyramids. Optical properties were studied using ellipsometry.

Tartazine dye was used as the Raman reporter molecule. It was found that SERS efficiency increased with the thickness of the deposited films, reaching a maximum at 160 nm film thickness. The detection limit for both gold and TiN SERS platforms was the same. Both materials allow for reusability, as dye molecules can be easily removed from the surface by water rinsing and drying. Our further studies showed that the SERS properties can be enhanced by surface modification of the TiN thin film with gold nanoparticles³. As a result, the Si-TiN-Au microstructures enable the detection of vitamin B12 molecules at concentrations as low as 10⁻⁹ M.

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Semiconductor Valley Photonic Crystal Waveguides with a Large Mode Area

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Abstract: Valley photonic crystal (VPhC) heterostructures, comprising two topologically distinct VPhCs placed on either side of photonic graphene, enable the realization of a single-mode optical waveguide with a large mode area. Here, we present our recent theoretical and experimental studies on semiconductor VPhC heterostructure waveguides, including their application to slow-light waveguides.

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Optical and Electrical Properties of Titanium Nitride (TiN) Thin Films at the Nanoscale

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Abstract: Understanding the properties of titanium nitride (TiN) at nanoscale is vital for plasmonic applications. TiN is a promising alternative to gold and silver. This study compares the optical and electrical properties of TiN and gold nanodisks and nanowires, highlighting TiN's superior morphological stability but similar optical and electrical degradation at elevated temperatures.

Understanding the properties of titanium nitride (TiN) thin films at the nanoscale is crucial for advancing various high-temperature plasmonic applications. TiN stands out due to its high melting point (2930 °C) and excellent thermal stability, making it a promising alternative to traditional plasmonic materials like gold and silver, which suffer from poor thermal stability [1]

At the nanoscale, the behavior of TiN thin films can significantly differ from their bulk properties. This is particularly important for applications such as heat-assisted magnetic recording (HAMR), thermophotovoltaics, and nanotherapeutics, where materials are subjected to high operational temperatures [2]. For instance, TiN thin films have been reported to retain their metallic behavior up to 1200 °C in vacuum [3], but they experience substantial deterioration in optical response when annealed in air at temperatures above 500 °C due to oxidation[4,5]. This degradation mechanism is critical to understand as it affects the performance and longevity of nanoscale devices. Moreover, the miniaturization of plasmonic devices necessitates a thorough understanding of TiN's behavior when patterned at the nanoscale. The morphology and optical constants of TiN nanostructures can be modified at high temperatures, impacting their plasmonic properties. Advanced characterization techniques, such as cathodoluminescence (CL) spectroscopy, allow researchers to investigate these changes with high precision, providing insights into the stability and performance of individual nanostructures.

This paper presents the results of a comparative study of the optical and electrical properties of single nanoscale gold discs and nanowires patterned on titanium nitride thin films on silicon substrates. Samples are annealed in air for 30 min each at temperatures ranging from 150 °C to 325 °C. Following each annealing stage, resistance, CL spectra and SEM images are collected to assess variations in the electrical, optical responses, and the morphology of the nano features. Experimental spectral data for the CL response of plasmonic discs are supplemented by simulations, identifying the excited plasmonic modes and confirming the oxidation-related mechanism of the change in the optical response of TiN nanodiscs with the annealing temperature.

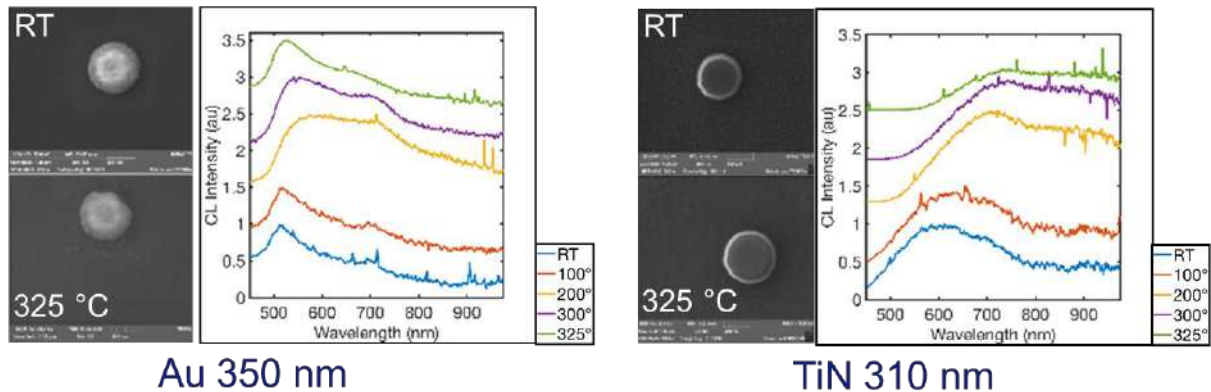


Figure SEM images and CL response from TiN and Au nanodisks. Visible degradation in Au nanodisks at 300°C while TiN nanodisks retain shape up to 600°C. Spectral changes for both Au and TiN nanodisks from 200°C.

It was found that although TiN displays superior thermal stability in comparison with Au when considering morphological changes and disc deformation, deterioration in the optical properties of both materials occurs at comparable temperatures. Also, the degradation of individual discs occurs at significantly lower temperatures than previously reported for plasmonic thin films. Thus, oxidation of TMNs remains a limitation to the integration of TiN components within plasmonic devices to be used at elevated temperatures.

Acknowledgements

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Probing Quantum Effects and Ultrafast Dynamics in Nanoplasmonics

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Abstract: We present approaches to quantitatively map the quantum mechanical response of nanoplasmonic systems using both optical and electron probes. In addition, we discuss ultrafast thermoelectric effects in nanostructures that can be leveraged to generate ultrafast fields and infer the complex nanoscale thermoelectric response of plasmonic nanosystems.

The ability to probe quantum nonlocal effects imprinted on the optical response of metallic nanostructures is pivotal to understand and manipulate plasmon-enabled light-matter interactions at the nanoscale [1]. In particular, we discuss how electron energy-loss spectroscopy (EELS) and cathodoluminescence (CL) can be used to infer quantum surface response functions (namely, the Feibelman d -parameters) that encapsulate those quantum effects [2]. Our proposed scheme provides a promising route for measuring the quantum surface response of metals using state-of-the-art electron-beam spectroscopies.

In the second part, we present a conceptually new approach whereby plasmon resonances in plasmonic nanostructures can be leveraged to create ultrafast nanoscale electric fields, arising from transient thermoelectric effects due to the presence of substantial temperature gradients across the nanostructures [3]. We consider both metallic nanoparticles and nanostructured graphene as suitable platforms to engineer such ultrafast thermoelectric phenomena, and provide designing rules to generate and probe the associated ultrafast electric fields. Our work opens enticing new directions for understanding the interplay between light, electrons, and phonons in nanomaterials.

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Ultrafast Electron and Phonon Dynamics in Metasurface-Driven Photocatalysis

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Abstract: We discuss recent advances in ultrafast electron and phonon dynamics modeling in nanophotonic systems. In particular, we describe the spatio-temporal evolution of plasmon-induced hot-carrier dynamics, demonstrate efficient energy funneling with dielectric metasurfaces, and uncover fundamental phenomena such as electron-phonon temperature inversion under pulsed illumination.

Predictive modeling of ultrafast dynamics in plasmonic nanostructures is critical for enhancing photocatalytic efficiency. We recently developed the Generalized Extended Two-Temperature Model (GE2TM), a comprehensive framework capable of describing energy transfer from plasmonically excited hot carriers to molecular adsorbates at short timescales. The GE2TM provides quantitative insights into how electron excitation dynamics and thermal effects interplay, enabling systematic optimization of reaction rates under pulsed illumination conditions [1].

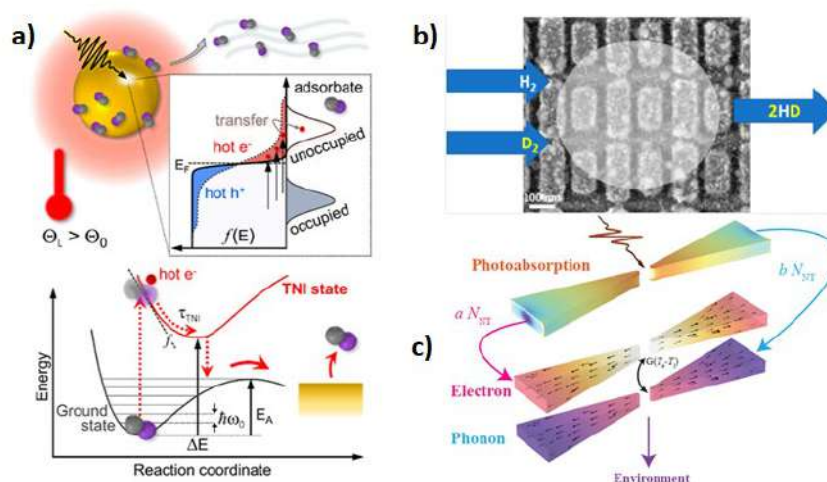


Fig. 1. **a)** Modeling approach for the ultrafast dynamics of plasmonic HCs in the presence of an adsorbate [1]. Adapted with permission from ACS Nano 2024, 18, 29, 18933–18947. Copyright 2024 American Chemical Society **b)** Hybrid metallo-dielectric metasurface for photocatalysis [2]. Adapted from Nano Letters, 24, 1, 172–179. Copyright 2024 American Chemical Society **c)** Electron-phonon coupling mechanisms in extended nanostructures [3].

However, beyond modeling electronic processes, optimizing overall photocatalytic efficiency critically depends on the effectiveness of funneling photons into active sites. In our recent work, we employed quasi-Bound States in the Continuum (quasi-BIC) dielectric metasurfaces to overcome these challenges, creating highly efficient antenna-reactor systems. These metasurfaces, composed of lossless Si₃N₄ structures decorated with Ni nanoparticles, concentrate electromagnetic fields and thus enhance photocatalytic reactions significantly. By

precisely engineering photon capture and concentration, these metasurface-based systems complement our hot-carrier injection model by maximizing photon utilization and catalytic efficiency [2].

Finally, by utilizing our modeling scheme, we show intriguing phenomena in ultrafast photothermal dynamics. Our recent predictive simulations reveal the unexpected possibility of sizable electron-phonon temperature inversion—where phonon temperatures transiently exceed electron temperatures—in spatially extended nanostructures under pulsed excitation. This counterintuitive mechanism emerges from complex interactions between electron-phonon coupling and spatial thermal diffusion. Such phenomena, so far explored in thin films, open new pathways to engineer nanostructured systems for controlled energy transfer mechanisms, leveraging this inverted thermal gradient to potentially enhance catalytic processes [3].

This integrated research approach—spanning predictive hot-carrier modeling, photon funneling optimization, and fundamental energy-transfer phenomena—offers new opportunities to advance the efficiency and selectivity of ultrafast nanophotonic devices.

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Revealing nanostructures' absorption and chirality with unconventional photothermal technique: widely tunable photo-acoustic spectroscopy

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Abstract: Photo-acoustic spectroscopy (PAS) is a scattering-free, stable, sensitive, and low-cost technique able to reveal material absorption in a non-destructive manner. We present a PAS set-up with many new degrees of freedom: tunable laser wavelength, polarization, direction, beam diameter, and the additional possibility of spatial and frequency mapping. We show its potential in characterizing commercial nanostructures. Finally, we enrich it with a microscope, thus opening a way to characterize absorption in precisely patterned small area nanostructured samples.

Direct experimental characterization of absorption is important in many research fields regarding nanostructures; e.g. nanomaterials can be designed to enhance otherwise weak chiro-optical light-matter interaction. Chirality can be revealed by circular dichroism (CD), measured as differential absorption of circular polarizations of opposite handedness. Apart from nanostructures mimicking chiral shapes¹, chirality can be induced in asymmetric nanostructures at oblique incidence, following the rules of so called “extrinsic chirality”.²⁻⁴ We previously explained spectral features and resonances of extrinsic chirality in metamaterials by conventional extinction spectroscopy, and then modelled their absorption behavior with commercial electromagnetic solver. Here, we show that photo-acoustic technique can be used as an unconventional tool to investigate nanostructures absorption and chirality with high precision. PAS relies on a periodically modulated light absorption, which creates pressure changes in the vicinity of the sample closed in the photo-acoustic cell: these changes correspond to an acoustic signal, caught by a close and sensitive microphone. PAS is intrinsically scattering-free, low-cost, non-destructive and sensitive. We previously applied it to measure absorption in asymmetric plasmonic-dielectric metasurfaces³ and GaAs nanowires asymmetrically covered by gold⁴. However, to precisely measure extrinsic chirality, the photo-acoustic response was obtained at single laser wavelengths.

Our new PAS set-up uses a widely tunable laser, overcoming limitations of single wavelength, low power and poor polarization and beam diameter control. The set-up is shown in Fig. 1(a): the laser wavelengths cover the near-infrared (680-1080 nm) and visible (340-540 nm) ranges, and its output is modulated by a tunable chopper. The polarization is defined by a linear polarizer and a quarter-wave plate, and the light can be focused before impinging on the sample in a closed PAS cell. The cell is attached to rotation and translation stages, which allows for incidence angle control, and surface scanning. In Fig. 1(b), we show spectral properties in commercial nanostructures covered by Au, conventionally used in Surface Enhanced Raman Spectroscopy (SERS) and purchased from Silmeco. The spectra are normalized to the reference Carbon glass sample. The increase of the chopper frequency leads to higher contribution of the nanostructured part to the overall absorption, showing potential of depth profiling. Fig. 1(c) maps absorption when an Ag-covered nanostructured sample is excited with left and right circular polarizations (LCP and RCP, respectively) at normal incidence; the laser wavelength was set to 800 nm and the beam was focused to 70 μm beam diameter. The maps present planar scans with 100 μm step in both directions. In the upper part of the absorption maps, the local absorption

increases due to the vicinity of the sample border. Finally, the overall CD of the zone goes to zero, as the sample is intrinsically achiral.

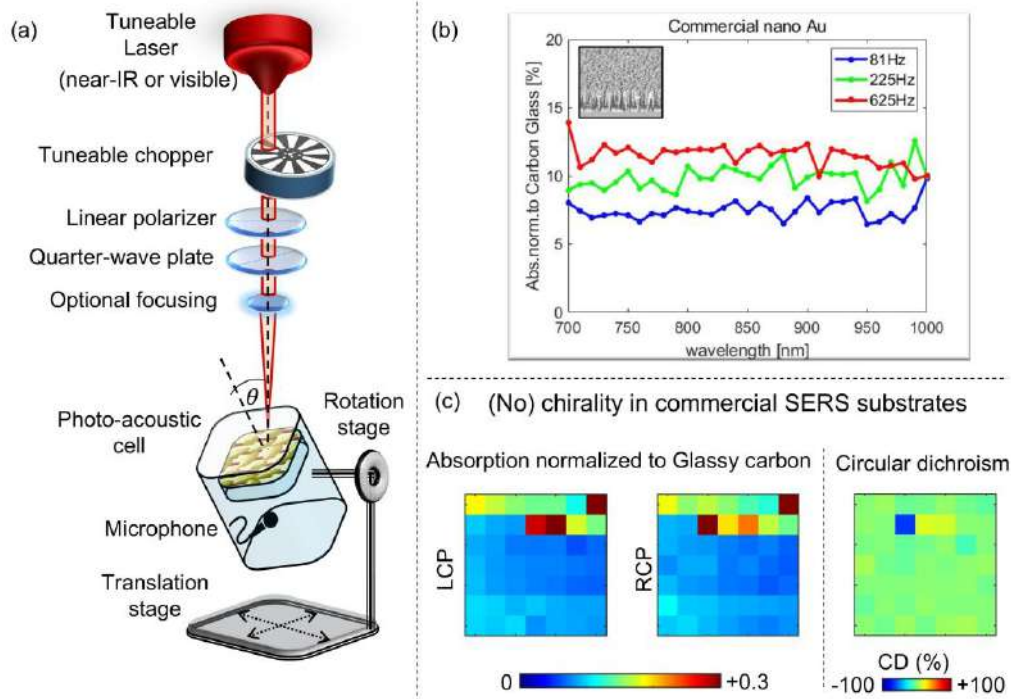


Figure 1 (a) Photo-acoustic set-up positioned on rotational and translation stages allows for multiple tunable parameters: laser wavelength, chopper frequency, polarization, beam-waist, angle of incidence. (b) Spectral properties of commercial nanostructures (Silmeco Au SERS substrates) at different chopper frequencies. (c) Spatial mapping of Silmeco Ag SERS substrates under left and right circular polarization excitation (LCP and RCP, respectively), at the wavelength of 800 nm, focused to 70 μm beam-diameter; chopper frequency was set to 81 Hz. Top zones of the absorption maps show the local absorption increase due to the vicinity to the sample's border. As expected, the overall CD is negligible.

More recently, we combined this set-up with a microscope, which will allow for finer absorption mapping in both intrinsically chiral and achiral samples patterned on small areas. We believe this research shows great potential for spectral absorption, uniformity and chirality mapping of nanostructured media.

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Efficient optical nonlinearities in metasurfaces enabled by bound states in the continuum

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Abstract: We introduce an innovative method for creating high-quality bound states in the continuum (BIC) within dielectric metasurfaces, leveraging magnetic dipole resonances paired with a mirror. This design achieves strong nonlinear light–matter interaction without requiring asymmetric geometries or polarization constraints, simplifying fabrication and expanding practical applications.

Hybridized collective plasmon modes in ordered 2D-metal nanoparticle arrays and its resulting dichroic SERS enhancement

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Abstract: Ordered metal-nanoparticle arrays with nano-metric inter-particle gaps (S) exhibit strong enhancement of electromagnetic (EM) near field and are suitable for large area SERS sensing, as well as studying surface selection rules and nonlinear Raman scattering phenomena. In this work, Raman scattering enhancements due to super and sub-radiant plasmon modes were studied.

Summary:

Non-percolated ultrathin Au films were deposited on corrugated transparent sapphire dielectrics. Nucleation of 2D-Au metal nanoparticle array (MNP) systems with in-plane anisotropic ordering were achieved under ultra-high vacuum at optimal deposition conditions [1] (see Figure 1a. and b.). Optical characterization of the sample revealed hybridization of the excited collective plasmon mode [2,3]. This hybridization caused an anisotropic plasmonic response dependent on the excitation polarization angle (σ) and S (see Figure 1c.).

Further, Polarized and wavelength scanned SERS measurements performed for a simple thio-phenol organic molecules revealed, at Raman excitation (λ_{exc}) = 633nm near the frequency of a sub-radiant SPP mode, the SERS enhancement of probed analyte was influenced primarily by S, where the effect of disorder in the arrays was negligible in these samples with $S \ll r$, where r is the radius of the Au grain. In contrary, ordering of the Au-MNPs as arrays enhanced the scattering of the super-radiant (antenna) mode at $\lambda_{exc} = 785$ nm. This resulted in highly anisotropic SERS enhancements dependent on σ (see Figure 1b.). These obtained results revealed that the anisotropy-induced SERS dichroism depends on the type of excited plasmon mode λ_P , λ_{exc} and σ [4]. As a result, the SERS dichroism of lower-frequency Stokes-shifted peak with a $\cos^2(\sigma)$ dependency differed from the higher-frequency Stokes-shifted peaks which exhibited a $\sin^2(\sigma)$ dependency. These experimental results validate and verify the EM near field mechanism of SERS enhancements. Finally the fabricated samples were suitable for enhanced SERS with a distributed hotspot and wider Stokes shifted spectral region.

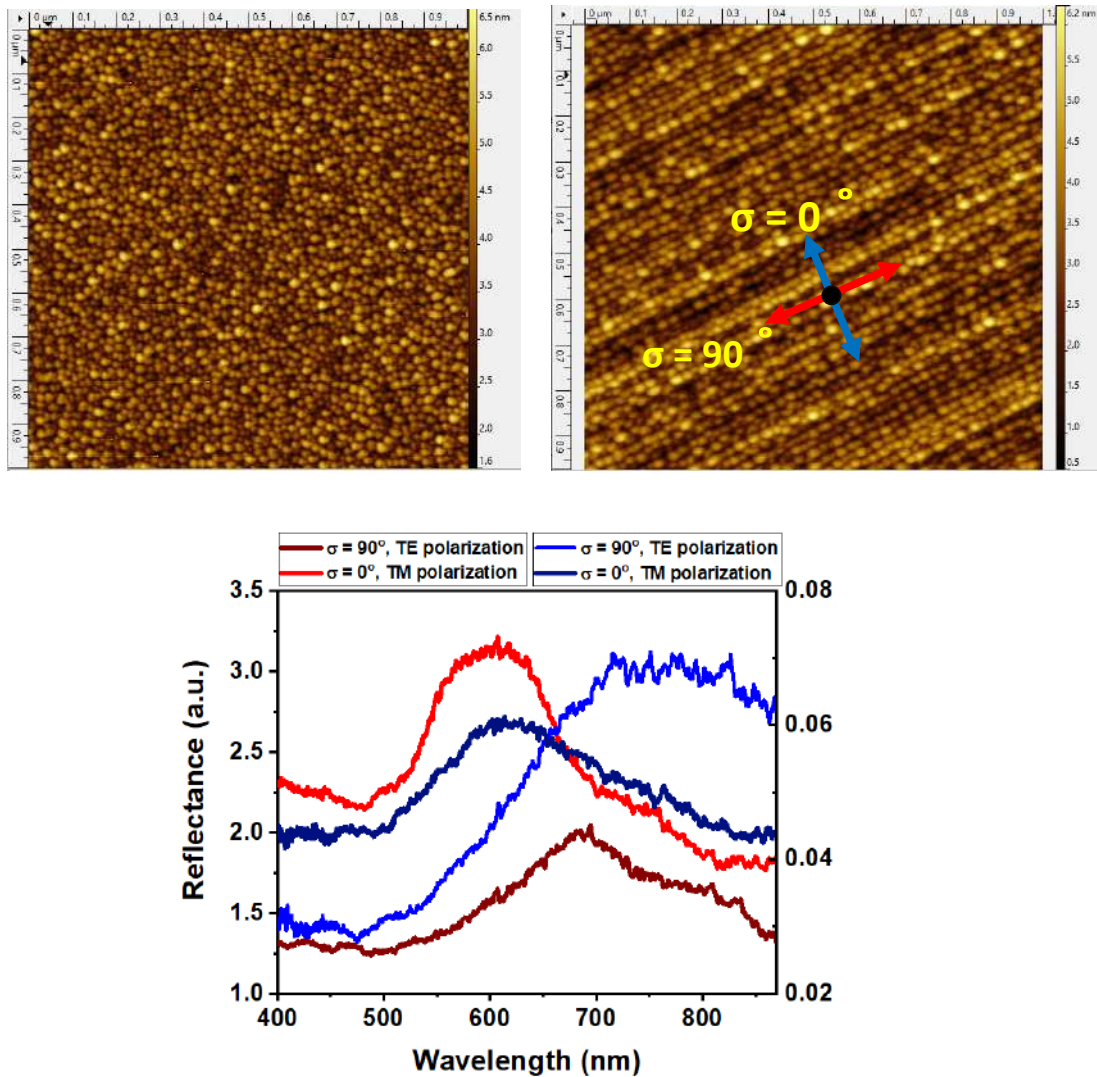


Figure 1. (a) Non-percolated Au film of thickness 7nm coated on flat sapphire substrate exhibiting randomly ordered Au grains, (b) Non-percolated Au film of thickness 7nm coated on corrugated sapphire substrate exhibiting ordered Au grains along the corrugated long axis, (c) Polarized Reflectance analysis of sample with ordered Au grains at excitation polarization angles $\sigma = 0^\circ$ and 90° (red shaded spectra's – s polarized excitation and blue shaded spectra's – p polarized excitation)

Acknowledgments:

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2020/02/Y/ST5/00086, and the Saxon State Ministry for Science, Culture and Tourism (Germany), grant No. 100577922, as well as from the tax funds on the basis of the budget passed by the Saxon state parliament. E.T.M. acknowledges support from the IDUB Mini grant (Internationalization of scientific research at the Doctoral School of the Adam Mickiewicz University, grant No. 054/13/SNŚ/0043).

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Ultrametricity and complex energy landscape in spin glass lasers

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Abstract: We report the ultrametric structure of the replica space in random lasers, as predicted in the Parisi Ansatz within the spin glass theory. Moreover, from the hierarchical topology of the states we obtain a direct observation of the complex energy landscape with evident breaking of ergodicity in the laser regime.

The architecture of complex systems is hierarchical and ultrametric geometry describes heterogeneous ensembles, hierarchic relations and dynamic contexts..

Applications spread across all fields: telecom technologies, clusterwise regression, information retrieval, analysis and synthesis of narratives and emotions

In physics, ultrametricity made its entry in the mean-field theory of spin glasses (SGs), which is the fundamental theory of order-to-disorder transitions [1]. In spin glasses the coexistence of disorder and frustration is responsible of a complex energy landscape, with many metastable minima that are pure states of the out-of-equilibrium system. These states have been identified as replicas, meaning identical copies of the same disordered system [2]. In the low-temperature SG phase, the existence of infinitely many pure thermodynamic states coincides with the breaking of the replica symmetry and hierarchy appears.

However, so far, the experimental demonstration is lacking. Recently, several concepts related to SG theory have been successfully applied in the field of random photonics [3], specifically for random lasers (RLs) [4–6]

Here we demonstrate the ultrametric structure of the RL overlap matrix that emerges above the laser threshold when the system enters in the glassy regime. We report the progressive clustering through the order-disorder transition reproducing experimentally the Parisi Ansatz formulated for spin glasses. The related dendrogram evidences the hierarchical topology of the observed replicas proving the predicted universal behaviour in the SG theory.

In addition, from the complex ultrametric structure of the overlap matrix we achieve the first experimental observation of the energy landscape with evident breaking of ergodicity in the RL glassy phase.

The hierarchical clustering of the states can be visualized by building the matrix of the overlap q . In the figure we show the formation of clusters with $q_{\alpha\beta}$ close to 1 and -1 values in the glassy high energy regime. This is an intrinsic characteristic of the system.

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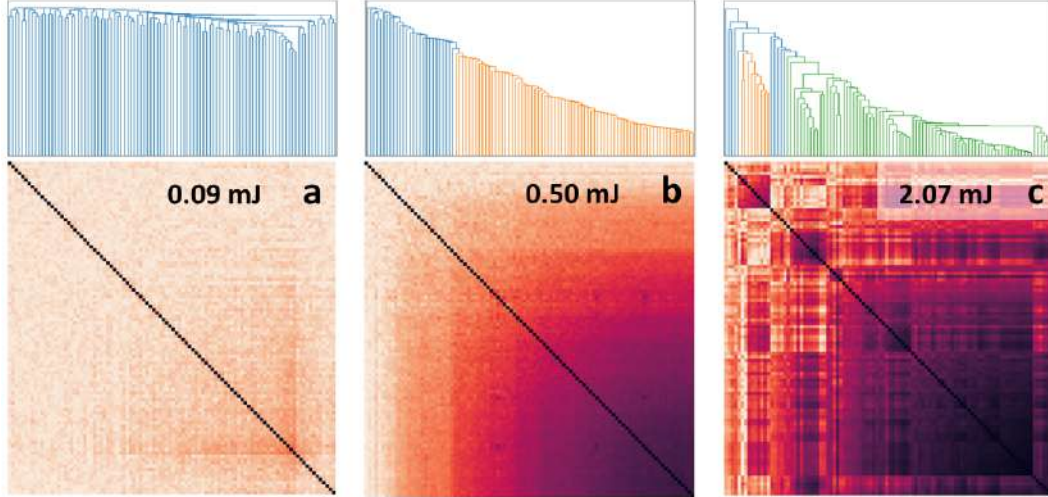


Figure 1: **Hierarchical clustering in spin glass RL reproducing Parisi overlap Ansatz.** Overlap matrix $q_{\alpha\beta}$: at low input energy 0.09 mJ photonic analogous of paramagnetic phase (a); at high energy 2.07 mJ spin glass RL phase (c); at the threshold the first clusters appear (b). In the matrices black pixels correspond to the self-overlap $q_{\alpha\alpha} = 0$ ($\alpha = \beta$), and the color changes from dark purple to white as q decreases. The order of the states in the experiments is given by applying the average linkage agglomerative clustering algorithm. In the upper panels the relative dendrograms are depicted.

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Data-Driven Control of High-Power States in Mode-Locked Lasers with Reinforcement Learning

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Abstract: We present our latest results on the application of Reinforcement Learning (RL) for automatic exploration and optimization of the dynamical landscape of Mode-Locked Fiber-Lasers (MLFL). By leveraging numerical and experimental results, we will discuss how different reward shaping techniques can unlock access to high-energy states in the system.

Mode-locked Fiber Lasers (MLFL) are indispensable tools for generating ultrashort pulses across diverse fields including frequency combs, precision manufacturing, and biological imaging. These systems are inherently complex, relying on the interplay of nonlinear, dispersive, and dissipative effects, which traditionally require complex setups and accurate tuning. As a result, numerous optimization frameworks have been proposed to automate the optimization of mode-locked systems [1-3]. However, heuristic optimization methods are hindered by intrinsic properties of the MLFL system, including sensitivity to environmental conditions and difficulties in capturing the multistability underlying the system dynamics. In this context, Reinforcement Learning (RL) is a promising data-driven approach based on a reward-driven decision-making process [4]. In control applications, RL can learn optimal control strategies, rather than simply maximizing a fitness function, and can adapt to changing environmental conditions, provided that the right reward strategy is implemented.

In this work, we present our recent results on the application of Reinforcement Learning (RL) for the automatic optimization of an experimental MLFL based on nonlinear polarization rotation. In our approach, inspired by recent works [5,6], the RL algorithm (Soft Actor-Critic) learns to identify the best parameter trajectory required to steer the system towards high-power states. Our RL agent is guided by a reward function that promotes stable, high-energy mode-locked states and can automatically learn optimal control strategies within a real-world laser environment, using experimentally measurable parameters such as the spectral shape and pulse energy in the system. We will discuss different reward strategies and their impact on achieving alignment trajectories that circumvent bistabilities, opening to the exploration and stabilization of high-energy states.

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Large-area α -MoO₃ films for novel tunable photonic devices

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Abstract: Our work focuses on the design and fabrication of tunable and dynamically controllable systems based on α -MoO₃, a strongly anisotropic polar material that exhibits hyperbolic behavior in the infrared (IR) range. To this end, we explored the combined use of MoO₃ and the thermochromic material VO₂. The results demonstrate that the proposed structure enables dynamic control of IR radiation and can serve as a building block for the development of platforms with advanced IR functionalities including IR sensors and sources.

Molybdenum trioxide (α -MoO₃) is an intriguing van der Waals material, as its α -phase exhibits three distinct Reststrahlen bands along its main crystalline axes. Thanks to its weak interlayer van der Waals bonds, α -MoO₃ can be easily exfoliated into crystalline flakes, thus its strong optical anisotropy attracts great interest for photonics applications across both the visible [1] and infrared [2] spectral ranges. However, working with exfoliated flakes often involves transfer-related challenges and compromises on layer thickness, which may not be optimal for device performance.

In this work, we first optimized the growth of large-area α -MoO₃ films using pulsed laser deposition (PLD), and performed a comprehensive structural, morphological, and infrared optical characterization. As a result, we successfully fabricated polycrystalline α -MoO₃ films exceeding 1 cm² in area, which retain the strong phonon-driven dispersion typical of exfoliated flakes [3].

Furthermore, we explored the integration of α -MoO₃ with vanadium dioxide (VO₂), a thermochromic material that undergoes an insulator-to-metal phase transition at ~68 °C [4]. This transition enables dynamic modulation of the optical properties of adjacent layers. By engineering a multilayer structure composed of α -MoO₃ and VO₂, we demonstrate the tunability of the optical phonon modes of MoO₃ via temperature control.

This approach lays the groundwork for a new class of reconfigurable photonic systems, offering dynamic control of infrared light-matter interactions over a wide area. Such systems hold promises for applications in actively tunable infrared devices, including modulators, thermal imaging components, and smart sensing platforms.

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Lorentz metamaterials: a new paradigm in Photonics?

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A variety of modern electromagnetic and photonic devices are based on materials or metamaterials that exhibit certain symmetry properties. For example, photonic crystals rely on discrete spatial translational and rotational symmetries. Depending on the specific properties of each crystal, the behavior of these systems can range from exhibiting forbidden energy bandgaps [1] to acting as topological insulators [2]. Another example is time-varying media, which are conceptually grounded in the breaking of continuous time-translational symmetry. These media have been used, for instance, to construct Floquet metamaterials [3]. Moreover, metamaterials that simultaneously change in space and time have also been reported in the literature, leading to applications related to moving dielectrics [4], among others.

Symmetries of electromagnetic fields are not only crucial for the design of metamaterials but are also essential for understanding fundamental optical phenomena. A prominent example is duality symmetry, which was long overlooked as a property of the electromagnetic field but has recently found applications across diverse fields, ranging from quantum field theory [5] to the optimization of photovoltaic cells [6]. Another recent advancement related to duality symmetry has been the identification of the origin of the Kerker effect in terms of the Euclidean symmetry group, i.e., the group that includes both continuous spatial translations and rotational symmetries. It has been proven that Kerker phenomena emerge in scenarios where such symmetries are broken in specific ways, leading to the conservation of Casimir invariants [7].

The wide range of applications and optical phenomena mentioned above suggests that incorporating materials and metamaterials with different sets of symmetries could lead to a new paradigm in the field. In this talk, I will discuss the possibility of incorporating Lorentz symmetries into the design of novel metamaterials [8].

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Electrically-driven, electrically-tunable coherent terahertz radiation from a superconducting source with an engineered cavity

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Abstract: We demonstrate our latest progress on developing an electrically-driven, electrically-tunable coherent terahertz (THz) radiation source based on a single superconducting emitter device with an engineered cavity. We achieve tunable frequency and controllable coherent THz radiation by tailoring the cavity geometry and applying bias control. This compact on-chip platform offers opportunities for cryo-compatible, power-efficient, stable THz emitters for quantum and communication technologies.

A polymeric platform for ultrathin conformable metasurfaces

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Abstract:

A novel platform to develop freestanding and highly conformable metasurfaces is presented. The combination of polymeric nanofilms with two-photon polymerization printing is shown to enable the fabrication of all-dielectric or hybrid dielectric-plasmonic ultrathin meta-devices with advanced applications for terahertz technology, and, in general, for flexible and integrated photonics.

Innovations in Electromagnetic Theory and Applications

Abstract: This paper explores recent advancements in electromagnetic theory and their practical applications, focusing on the integration of quantum electrodynamics with classical field theory.

Keywords: Electromagnetic theory, Quantum electrodynamics, Classical field theory, Innovations, Applications.

1. Introduction: The study of electromagnetic phenomena has long been a cornerstone of physics, with classical electrodynamics providing a robust framework for understanding the behavior of electric and magnetic fields.

2. Theoretical Foundations: This section reviews the fundamental principles of electromagnetism, including Maxwell's equations and the concept of gauge invariance, which are essential for understanding the underlying physics of the phenomena.

3. Quantum Electrodynamics (QED): The integration of quantum mechanics with classical electrodynamics has led to the development of QED, which provides a more comprehensive understanding of the interactions between light and matter at the subatomic level.

4. Applications: The theoretical advancements in QED have found numerous practical applications, including the development of quantum optics, quantum communication, and the design of novel materials with tailored electromagnetic properties.

5. Conclusion: The ongoing research in electromagnetic theory and its applications continues to push the boundaries of our understanding of the physical world, paving the way for future technological breakthroughs.

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Appendix A: Mathematical Derivations of Key Equations. This appendix provides detailed derivations of the equations used in the main text, including the derivation of the Dirac equation and the calculation of the QED Feynman diagrams.

Appendix B: Experimental Data and Comparison with Theory. This section presents experimental data on the anomalous magnetic moment of the electron and compares it with the theoretical predictions from QED, showing excellent agreement.

Appendix C: Future Perspectives and Open Questions. This appendix discusses the current challenges in the field of electromagnetic theory and outlines potential directions for future research, such as the exploration of non-Abelian gauge theories.

Appendix D: Glossary of Terms. This appendix provides a comprehensive list of terms and symbols used throughout the paper, ensuring clarity and consistency for the reader.

Appendix E: Acknowledgments. The author wishes to thank the funding agencies and colleagues for their support and contributions to this work.

Appendix F: Author Biographies. This appendix provides brief biographies of the authors, highlighting their research interests and previous work in the field of electromagnetism.

Appendix G: Index. This appendix provides an alphabetical index of the terms and concepts discussed in the paper, facilitating easy navigation and reference.

Broadbanding antennas and electromagnetic structures with non-Foster elements

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Abstract: Advantages, implementation issues and applications of non-Foster elements with the specified frequency dependence of reactance, which offer new possibilities for extension of the matching bandwidth of electrically-small antennas and design of broadband electromagnetic structures such as metasurfaces, are demonstrated and discussed.

Active circuits that violate Foster’s reactance theorem and exhibit negative slope of the frequency dependence of the input reactance and susceptance mimic behavior of hypothetical negative inductors and capacitors referred to as the non-Foster elements (NFEs). Linvill’s negative impedance converter (NIC) [1], which transforms the load impedance into a negative input one by flipping the sign of the load voltage, is widely used to realize NFEs. Thanks to the unique frequency characteristics, NFEs are used to compensate reactance of the ordinary networks over a wide frequency band that allows broadband matching of electrically-small antennas (ESAs) and extending the operational bandwidth of various microwave devices.

The NFEs are commonly designed to achieve a frequency response being in a given frequency band as close as possible to that of an ideal negative capacitor or inductor, whose target value of capacitance or inductance is assumed to be constant, i.e., frequency independent within the operational bandwidth. Accordingly, a variation of the negative capacitance or inductance is considered to be a conversion error that should be minimized. To design NFEs with tight tolerances, the step-by-step design procedure was developed [2].

A different approach to design NFEs assumes that the negative capacitance or inductance is not constant but depends on frequency according to a specified dispersion law [3]. It can be achieved by using either a frequency-dependent NIC conversion ratio or a frequency-dependent NIC load impedance or the both simultaneously. In particular, the close to constant reactances, which are advantageous to design broadband immittance inverters and bandpass filters based thereof [3], [4], can be realized by using this approach [3]. In this paper, we discuss implementation issues and applications of NFEs with a more complex frequency dependence of reactance, which offer possibilities for further extension of the ESA matching bandwidth and design of broadband electromagnetic structures such as metasurfaces.

Since ESAs operate at frequencies much lower than the resonant one, they have small physical size compared to the wavelength of operation and consequently find applications in portable electronics with the purpose of miniaturization. Because of a large reactance and a low radiation resistance ESAs are characterized by a high Q -factor that complicates antenna matching in a wide frequency band. When using an ordinary inductor or capacitor to compensate the ESA reactance, a very narrow matching bandwidth is achieved as the antenna reactance is fully compensated at a single frequency only and the net reactance varies rapidly with frequency. In turn, using an NFE allows for compensation of the antenna reactance at any frequency, resulting in the theoretically infinite matching bandwidth [5]. However, the simple RC - or RL -model approximates the ESA input impedance with some degree of accuracy. As a result, the practical matching bandwidth of ESA is finite if the NFE is designed to have a constant negative capacitance or inductance. Although the matching bandwidth is much wider compared to that obtained from the ordinary matching circuit, there is still plenty of room for further

bandwidth extension by using an NFE with the specified frequency-dependence of reactance. The necessary reactance can be implemented, e.g., by loading the NIC with an *RLC*-circuit, whose components are converted into the negative ones at the NIC input. The obtained negative resistance can compensate parasitic input resistance of the NIC [2]. Moreover, using the *RLC*-load allows for stability improvement of the NIC with connected ESA [6]. Some examples of stably operated broadband ESAs, which are matched with NFEs having the specified frequency dependence of reactance, are demonstrated.

Realization and application of NFEs with the even more complex frequency dependence of reactance were presented in [7] for the purpose of mushroom-like metasurface bandwidth enhancement. The necessary frequency dependence of reactance was realized by means of a NIC with a multicomponent *RLC*-load. By loading the metasurface unit cells with such NFEs, the metasurface reactance can be efficiently compensated and the operational bandwidth is therefore extended remarkably. The compensation efficiency depends on the number of components in the *RLC*-load. It is worth mentioning that the NFE-loaded metasurface can operate stably.

Another interesting example under consideration is the self-oscillating antennas and metasurfaces [8]-[10] with the reactance compensated by its negative counterpart, which is produced by a NIC loaded with another such structure. The self-oscillating antennas and metasurfaces operate in the unstable regime and are extremely broadband [8]. They are considered to be the extreme case of the electromagnetic structures employing NFEs with the specified frequency-dependence of reactance for broadbanding.

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Luminescence-based Optomechanical Coupling in a Suspended Nanomembrane

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Abstract: We propose a luminescence-driven optomechanical system with a suspended nanomembrane, demonstrating the coupling between incoherent luminescence and mechanical vibrations. This enables mechanical resonance detection via photoluminescence and theoretically establishes optomechanical coupling through luminescence-induced optical force (LIOF). Our findings open new avenues for quantum information transmission and the control of emitters.

"Optical force," generated by the momentum exchange between light and matter, has been widely used to manipulate microscopic materials, such as in optical tweezers [1]. Our study focuses on luminescence-induced optical force (LIOF) to advance optomechanics technology. Conventional optomechanics [2] relies on optical forces from externally applied laser light, where optical cavity resonance couples with mechanical oscillations. However, whether incoherent luminescence from quantum emitters can generate optical forces and couple to macroscopic coherent vibrations remains open question. In this study, we propose a model in which a luminescent nanofilm is suspended over a metallic substrate, forming an optomechanical resonator, as illustrated in Fig. 1(a). We demonstrate the coupling between incoherent luminescence and coherent mechanical vibrations within this system.

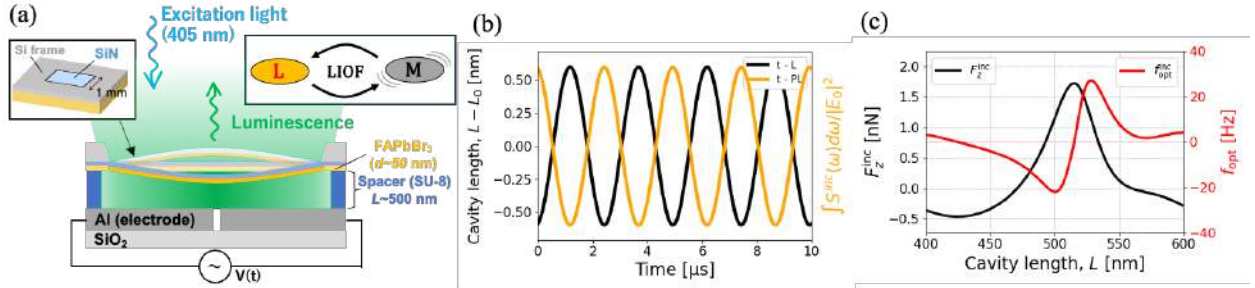


Fig.1 (a) Schematic diagram of the optomechanical resonator. A 50 nm-thick luminescent film FAPbBr₃ [3] (emission wavelength: $\lambda_{PL} \sim 553$ nm) was fabricated on a square-shaped SiN membrane (1 mm $\times$ 1 mm $\times$ 50 nm) and suspended over a metallic (Al) substrate. The suspended membrane acts as a mechanical oscillator with the following parameters: mechanical frequency $f_m = 400$ kHz and quality factor $Q_m = 4 \times 10^4$. The membrane can be actuated by applying a voltage to the Al substrate. Excitation light: 405 nm laser with intensity $I = 50$ W/cm². (b) Mechanical oscillation (black) and corresponding integrated PL intensity dynamics (yellow) at an initial cavity length $L_0 = 500$ nm under actuation with a force amplitude $f_a = 40$ pN. (c) Dependence of LIOF (black) and optical spring effect (red) on cavity length L .

Fig. 1(b) presents the calculated results of integrated photoluminescence (PL) intensity modulation and mechanical vibrations of an externally driven membrane under continuous laser excitation (50 W/cm², 405 nm). The results indicate that PL intensity varies in response to mechanical vibrations due to optical interference within

the optical cavity, confirming the feasibility of detecting mechanical resonance via PL probing. Based on our theoretical predictions, our experimental validation further confirms that the measured mechanical resonance aligns with laser-probed results. These findings demonstrate that incoherent luminescence enables readout of mechanical modes of oscillators, confirming its coupling to mechanical oscillations.

As confirmed above, luminescence undergoes optical interference in this system, resulting in strong optical confinement at half the emission wavelength period, $n\lambda_{\text{PL}}/2$. We theoretically evaluated this enhanced luminescence-induced optical force (LIOF), F_z^{inc} , acting on the oscillator, as shown by the black line in Fig. 1(c), referencing the PL theory of excitons in solids [4] and the optical force theory based on Maxwell's stress tensor [5]. Our findings reveal that LIOF can spontaneously induce and modulate mechanical vibrations. Notably, we quantitatively demonstrate that the enhanced LIOF shifts the mechanical resonance frequency f_m of the oscillator, a phenomenon known as optical spring effect [6], $f_{\text{opt}} (= f_{\text{eff}} - f_m)$. The optomechanical modulated frequency f_{eff} is evaluated in Fig. 3(c) by the following equation:

$$f_{\text{eff}} = f_m \sqrt{1 - \frac{\nabla F_z^{\text{inc}}}{K_m}}, \quad (1)$$

where K_m is mechanical spring constant of the oscillator. In experimental observations of the optical spring effect in LIOF, photothermal frequency shifts occur simultaneously with emitter excitation. Therefore, it is crucial to distinguish photothermal effects from the optical spring effect. To address this, we exploited the fact that the photothermal effect has a significantly longer response time compared to optical forces [7]. This approach enabled precise frequency shift measurements with Hz-level accuracy while eliminating thermal interference. This technique enabled us to confirm the feasibility of observing the theoretically predicted optical spring effect, which leads to demonstrate the optomechanical coupling via LIOF.

Our study establishes a novel optomechanical system that directly couples incoherent luminescence modes of quantum emitters with mechanical modes, despite their significantly different resonance frequencies. Furthermore, this system can operate without an external light source by alternative excitation methods, such as carrier injection into the luminescent material. This mechanism paves the way for advanced optical force applications in the transmission and control of quantum mechanical information specific to luminescent materials.

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Nonlinear plasmonics in nanostructured 2D materials

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Abstract: We employ ab initio modeling to explore plasmon-driven nonlinear optical phenomena in phosphorene and graphene nanoribbons. Our simulations reveal intriguing possibilities to achieve strong nonlinear light-matter interactions by resonantly exciting plasmons sustained by charge carrier doping or absorbed photothermal energy.

Nonlinear optical phenomena enable the control of light by light both temporally and spectrally, and therefore represent a crucial resource for emerging integrated photonic and quantum optical technologies [1,2]. Extreme light-matter interactions, driven by intense optical fields, lead to nonlinear electron dynamics that allow photons to interact strongly. A striking example is high-harmonic generation (HHG), where light is emitted at integer multiples of the driving frequency, with a sharp cutoff at a characteristic energy.

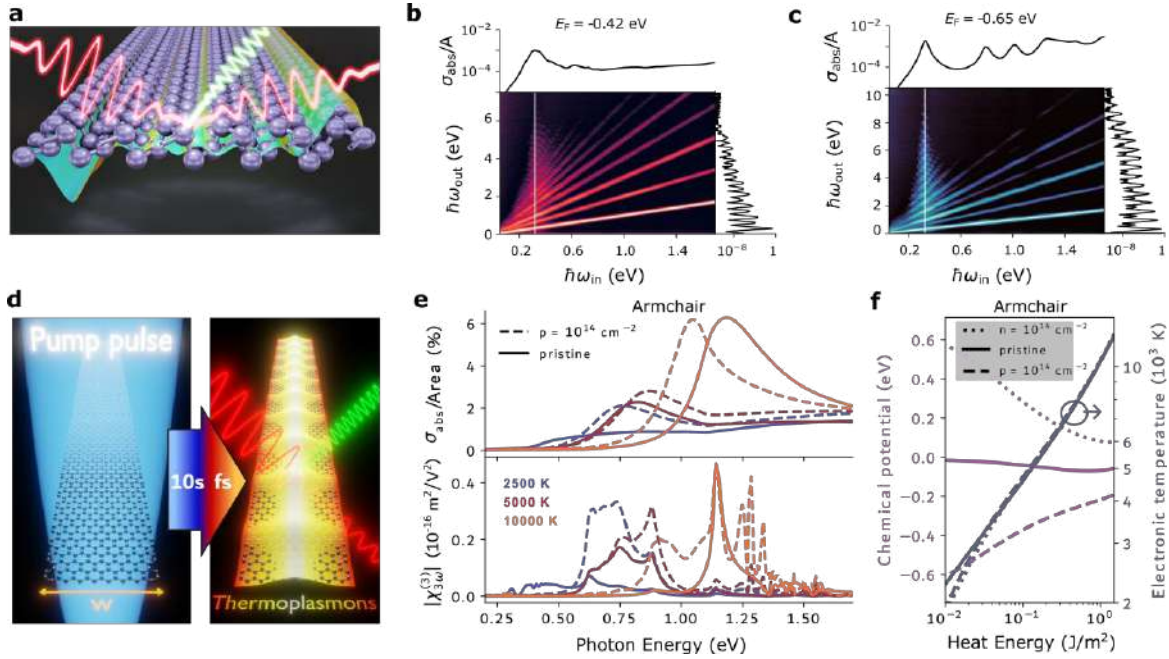


Fig. 1 High-harmonic generation in phosphorene nanoribbons (PNRs) and transient thermoplasmons in graphene nanoribbons (GNRs). **a** Schematic illustration of a PNR illuminated by light polarized in the confinement direction. The dipole acceleration produced in $W \approx 5 \text{ nm}$, hole-doped armchair (AC) **(b)** and zigzag (ZZ) edge-terminated **(c)** PNRs by an ultrashort optical pulse is presented as a function of the input pulse carrier energy $\hbar\omega_{\text{in}}$ and the generated output photon energy $\hbar\omega_{\text{out}}$. The upper panels in each figure show the linear absorption spectra at the indicated doping level as a function of $\hbar\omega_{\text{in}}$, while the right-side panels show the output dipole acceleration spectrum at the input pulse energy indicated by the vertical white lines overlaying the contours. **d** Schematic illustration of a GNR of width W

that is photoexcited (left panel) by an intense ultrashort pulse. After a few tens of femtoseconds, its electrons occupy a thermalized state that can be probed in ultrafast nonlinear spectroscopy (right panel). **e** Linear absorption cross-section (upper panel) and third-harmonic susceptibility (lower panel) of an AC-terminated GNR with $W \approx 5$ nm. The electronic occupations are determined by Fermi–Dirac statistics at the indicated electron temperatures and corresponding chemical potentials, satisfying particle and energy conservation laws for an undoped GNR (solid curves) and a hole-doped GNR with hole density $p = 10^{14}$ cm⁻² (dashed curves). **f** Electronic temperature and chemical potential as functions of the added thermal energy Q per unit area for the same $W \approx 5$ nm AC GNR at high electron (dotted curve) and hole (dashed curve) doping levels, contrasted with the undoped GNR (solid curve).

Using ab initio modeling and self-consistent perturbation theory, we introduce a framework based on Maximally Localized Wannier Functions (MLWFs) that captures quantum-mechanical effects in both the linear, perturbative nonlinear, and extreme nonlinear optical response of nanostructured 2D materials [3,4]. Applying this framework, we characterize the localized plasmonic resonances and associated nonlinear optical effects in phosphorene nanoribbons (PNRs), revealing their potential for optoelectronics and attosecond nanophotonics. Our results reveal highly tunable plasmonic resonances, influenced by edge termination, doping, and ribbon width, and leading to an excellent nonlinear optical response and HHG, see Figure 1 (a-c).

Additionally, we have explored the thermal activation of mid- and near-IR plasmons in narrow (≤ 10 nm) graphene nanoribbons, revealing their ability to drive strong nonlinear optical responses [5]. Due to graphene’s low electronic heat capacity, energy absorbed from intense ultrashort pulses rapidly converts to electronic heat within ~ 10 femtoseconds, raising the electron gas temperature to several thousand Kelvin. We show that moderate heat energy densities (~ 1 J/m²), comparable to those in ultrafast optical experiments, induce pronounced thermoplasmonic features in both linear and nonlinear optical responses, see Figure 1 (d-f). This approach therefore represents an experimentally feasible, robust, and non-invasive method to realize transient nonlinear plasmonic effects at near-IR frequencies without excessive charge carrier doping.

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Broadband Thin Film Absorbers for Millimeter Waves

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Abstract: High-performance thin film absorbers for the millimeter band are created using a genetic algorithm. The absorber is a graphite-dispersed siloxane composite multilayer on a metallic substrate. The designed absorber with a thickness of 0.5 mm exhibits a broadband absorptance of more than 20 dB over W-band (75-110 GHz).

We designed a highly absorptive, thin, and practically manufacturable multilayer absorber of graphite-dispersed polydimethylsiloxane (PDMS) for automotive radar applications [1]. First, we created a 10-layer multilayer film with different graphite contents on a metal substrate using a genetic algorithm. As a result, we created a thin film with a thickness of 0.5 mm and an absorption rate of over 20 dB across the entire W band (75-110 GHz). This film contains graphite on the outermost layer on the air side and the innermost layer on the substrate side, and the layers in between have a thick PDMS layer with little graphite.

Based on these results, we simplified them into a three-layer absorber. In the design, we fixed the thickness at 0.5 mm and comprehensively swept the graphite content ratio and film thickness to search for a structure with an absorption rate of over 20 dB across the entire W band. As a result, we found structures with the desired performance, although the absorption rate is slightly lower than that of a 10-layer multilayer film. We proposed a thin, lightweight, high-performance millimeter wave absorber structure.

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Generation of Longitudinally Varying Vector Vortex Beams Using Dielectric Metasurfaces

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Abstract: We numerically demonstrate the generation of vector vortex beams using dielectric metasurfaces, where the beams' topological features evolve longitudinally during propagation. This distinctive characteristic, along with the ability to control it, could enable new applications in remote sensing for topological light.

Vector vortex beams are light beams that possess topological features in their phase and polarization distributions in space. These unique properties have attracted significant research interest, not only for their fundamental physics but also for their potential applications in communications and remote sensing. Meanwhile, metasurfaces enable precise control over light propagation, facilitating functionalities such as narrow-band wavelength filtering, focusing, beam deflection, beam expansion, and the generation of vector vortex beams [1-4]. Due to their compact form factor and compatibility with established semiconductor nanofabrication techniques, silicon-based dielectric metasurfaces are particularly well suited for generating such topologically structured light beams.

In this talk, we present our recent work on generating vector vortex beams whose topological features evolve longitudinally during propagation. We argue that this type of evolution is often overlooked in topological light research, particularly for monochromatic light in the paraxial regime. Using numerical simulations, we demonstrate the generation of such beams using silicon metasurfaces. We also demonstrate the analytical methods for controlling their topological features along the propagation direction. Our findings could contribute to the development of topological light-based remote sensing techniques.

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Exploring Thermal Photonics for Next-Generation Energy Conversion

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Abstract: We present three studies integrating thermal photonics and nanomaterials for efficient energy conversion. Strategies include near-field thermal transport, far-field waste heat harvesting, and CNT-based solar absorption.

Thermal photonics has emerged as a transformative approach to enhance energy conversion by controlling thermal radiation at the nanoscale [1-3]. This work synthesizes three studies that demonstrate the potential of thermal photonics and nanomaterials in developing next-generation sustainable energy technologies. The first study investigates enhanced radiative heat transport in the near-field regime using engineered nanostructures, achieving heat transfer beyond the blackbody limit. The second study explores a thermophotonic system for recovering low-grade waste heat, leveraging spectrally selective emitters and filters to exceed far-field radiative transfer limits [4]. The third study focuses on carbon nanotube (CNT) films exhibiting wavelength-selective solar absorption and thermal emission, offering superior spectral control and thermal stability for solar thermal applications. Together, these studies underscore how nanoscale photonic engineering can drive high-efficiency, adaptable energy systems beyond conventional thermodynamic constraints.

Acknowledgement

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Ensuring Signal Integrity in High-Speed Aerospace Data Links: Techniques and Trends

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Abstract: The design of PCBs for high-speed lines such as 10Gbps, 25Gbps, and beyond involves significant complexity and challenges. These high frequencies necessitate rigorous optimization across several aspects to ensure reliability and performance. This paper outlines the primary challenges and presents potential solutions.

1. INTRODUCTION

The growing demand for faster electronic devices has driven the need for PCBs handling extremely high data rates. To meet these needs, addressing challenges such as signal integrity, electromagnetic interference (EMI), and cost efficiency are crucial. This article delves into these issues, with a focus on optimizing via's structure, fanout, AC coupling, copper roughness, and design precision, while balancing associated costs.

2. PCB TECHNOLOGY

As data rates continue to increase, PCB complexity keeps growing, it's essential to consider the real structure of conductive and insulating layers. In particular, we must consider the impact of surface roughness and the influence of materials such as fiberglass on signal integrity. Innovative materials and advanced simulation tools play a pivotal role in enhancing performance. Furthermore, integrating cutting-edge manufacturing techniques ensures the reliability of high-speed PCBs.

A. Copper Roughness

Conductive losses in PCBs are influenced by factors such as surface roughness, etching, skin effect, and metal losses. These losses become more pronounced in high-density interconnect (HDI) designs, especially with long and narrow traces. While roughness has a negligible impact up to 10 GHz, it becomes more significant at higher frequencies, affecting circuit's performances. Copper roughness increases the spacing between conductors, raising capacitance and the dielectric constant (Dk), further influencing signal integrity [1, 2].

B. Dielectrics

Choosing the right dielectric material is crucial for ensuring PCB reliability, especially in demanding environments like aerospace. The inhomogeneity in dielectric materials can lead to "glass weave skew," causing propagation velocity discrepancies within differential pairs. This results in impedance mismatches, skew, mode conversions, and losses that can cause bit errors, reduced signal quality, and increased jitter [3]. Balancing performance needs with cost is a critical trade-off in competitive markets.

In summary, as signal speeds increase, careful consideration of copper roughness and dielectric properties is key to optimizing PCB performance and maintaining signal integrity in high-speed designs.

3. OPTIMIZATION

The discontinuities like vias, connectors, DC blocking capacitors, and BGA fanouts can severely degrade signal integrity by introducing impedance mismatches, leading to signal reflections, energy losses, and EMI (Fig.2) susceptibilities. Optimizing and analyzing 3D transitions is crucial in high-speed links design to minimize these

effects. Each transition must be meticulously assessed to minimize its impact on performance.

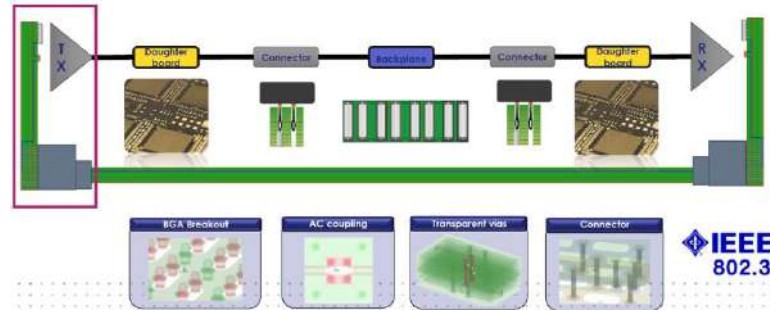


Figure 1. Optimization of discontinuities for high-speed links under 3D electromagnetic solver

Routing high-speed links in electronic systems requires strict design principles, such as using stripline structures between ground layers to reduce EMI and leveraging microvias for efficient high-frequency signal handling in BGA devices. Breakout structures like dog-bone or via-in-pad are used to ensure optimal routing for BGAs. Precision cutouts in reference planes under components like capacitors and BGAs are essential for minimizing signal reflections, while carefully designed antipads for vias and connectors maintain signal integrity by avoiding unintended electrical contacts [4].

AI-based algorithms are increasingly used to streamline this complex design process [5], enabling faster decision-making and routing optimization, while balancing manufacturing constraints, costs, and PCB's density. Design validation is based on comparing simulations with real-world parameters like dielectric constant (Dk), dissipation factor (Df), and surface roughness, ensuring the design meets performance criteria for specific protocols and data rates. By integrating AI and adhering to these design best practices, high-performance, reliable, and cost-effective electronic systems can be achieved, meeting stringent industry standards.

4. CONCLUSION

To ensure the reliability and performance of electronic components in avionics, particularly under extreme conditions, a robust methodology combining design, testing, and ongoing R&D is necessary. This approach is increasingly vital as electronic systems advance in complexity and frequency. Current developments for aerospace projects involve high-speed links up to 25 Gbps and high-density boards designed to withstand environmental challenges such as EMC, thermal stress, and vibration. A test board, set to arrive shortly, will be used for evaluation purposes, benchmarking EDA tools, comparing various models, and validating measurements while maintaining a balance between cost and performance.

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Bidirectional interaction between metamaterials and artificial intelligence

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Abstract: Metamaterials interacted with computer science have recently attracted immense interest to motivate scientists to revisit respective communities. These two seemingly-unrelated fields are benefiting from each other in a complementary, detailed but less noticeable manner. Especially in the past five years, we have witnessed a proliferation of fruitful works on a scale not seen. In this talk, I stand from a unified perspective to connect these nascent fields. We term the forward interaction (AI for metamaterials) as intelligent metamaterials, and the backward interaction (metamaterials for AI) as metamaterials intelligence.

Wavefront shaping in nonlinear and time-periodic media: Focusing and Micromanipulation

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Abstract: Wavefront shaping enables focusing and optical micromanipulation of targets in disordered media, but typically requires additional system information such as a guide star. We present two approaches that circumvent this requirement: one exploits the nonlinear responses for noninvasive focusing; the other applies Floquet theory to time-periodic wavefront control.

Neuromorphic photonics for next-generation computing: opportunities in devices and systems

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Abstract: Optical computing has seen a resurgence of interest due to the accumulated maturity of photonic integrated circuits and the pressing need for faster, energy-efficient processors. This talk will discuss the development of active and brain-inspired opto-electronic devices which leverage the bandwidth and speed of photonics for parallel information processing and storage.

Wavelength-multiplexed full-color metasurface holography based on of silicon nitride nanopillars

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Abstract: We demonstrate a $4\text{ mm} \times 4\text{ mm}$ full-color metasurface hologram visible to the naked eye. Using 20,000 silicon nitride nanopillars meta-atoms, the metasurface achieves broad phase control, enabling polarization-insensitive holography across all RGB wavelengths.

Holography records and reconstructs object light and is promising for 3D displays with reduced eye strain. Metasurface holograms offer wide viewing angles due to their subwavelength-scale structures (meta-atoms), making them suitable for 3D displays, cryptography, memory devices, and AR/VR glasses [1-2]. A major challenge has been projecting full-color 3D images, as it's difficult to independently control phase for RGB wavelengths. Previous approaches used polarization multiplexing.

In this study, we realized full-color holograms with independent RGB phase distributions using 20,000 high-aspect-ratio silicon nitride nanopillar shapes covering the visible spectrum. Fig. 1 shows the designed (a) and observed (b) 3D holographic images of a 1.5-mm cube with color-tiled faces. Fig. 2(a) depicts the meta-atoms: 20,000 silicon nitride nanopillars with a pitch of 340 nm and height of 1750 nm, achieving over 70% average transmittance. Fig. 2(b) presents their RGB phase distributions.

Using Wavefield Tools, we computed light propagation from a cube 10 mm behind the metasurface to derive the RGB phase profiles. These were matched with phase vectors of the 20,000 meta-atoms using least-square error optimization. The $4\text{ mm} \times 4\text{ mm}$ metahologram was fabricated via electron beam lithography, Cr evaporation and lift-off, and reactive ion etching. A 45° -tilted SEM image is shown in Fig. 3.

As seen in Fig. 1(a), full-color 3D projection with motion parallax was achieved using RGB LED light. The holograms were visible to the naked eye and captured by a standard smartphone camera. Future work includes improving image clarity and gradation using coherent light sources.

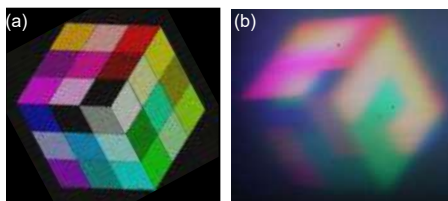


Fig. 1 Designed (a) and observed (b) images of the 3D metaholography.

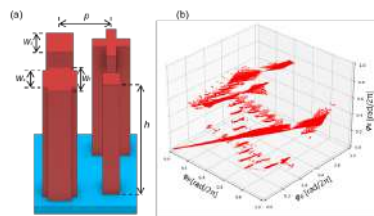


Fig. 2 the schematic drawing (a) and phase coverage (b) of meta-atom.

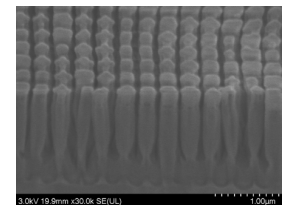


Fig. 3 An inclined SEM image of the metahologram

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A Theory for Unidirectional Magnetoresistance in Nanoscale Bilayers

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Nanoscale magnetic/non-magnetic bilayers exhibit universal unidirectional magnetoresistance (UMR) under high current density. Current understanding often involves various mechanisms related to the interconversion of charge current and spin current, giant magnetoresistance, thermal magnonic effects, thermoelectric effects, and diverse spin dependent scattering processes. This raises a fundamental question: do the universal behaviors observed in a wide range of systems stem from underlying general principles? We demonstrate here that both UMR and unusual anisotropic magnetoresistance (UAMR) [1], another universal phenomenon in magnetic bilayers, arise from electron transport influenced by the magnetization vector present in the magnetic material and the interfacial potential inherent in heterostructures. Specifically, UAMR represents current-independent resistance (resistivity) of bilayers. UMR is the resistance proportional to the current although electron transports of the bilayers are the linear response to high current densities and their induced thermal gradients. Our theory introduces a novel approach that considers the interplay between the magnetization vector, thermal gradients, and the effective internal electric field at the interface. This framework provides a unified explanation for both UMR and UAMR, effectively capturing key experimental features such as dependence on current direction, magnetization orientation, film thickness, and magnetic field strength. Furthermore, it offers a universal perspective that bridges UMR and UAMR effects, enhancing our understanding of spin-dependent transport phenomena in bilayers.

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Antenna theory and design

A Magnetic Monopole Antenna

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Abstract: We propose a photonic nanoantenna that mimics a magnetic monopole. A half-nanoslit in gold creates a nanoscale, enhanced magnetic field that radiates efficiently, offering a new model for studying magnetic monopoles and optical magnetic light-matter coupling across visible to GHz frequencies.

Magnetic monopoles are hypothetical particles which, similarly to the electric monopoles that generate electric fields, are at the origin of magnetic fields. Despite many efforts, to date, these theoretical particles have yet to be observed. Nevertheless, many systems or physical phenomena mimic the behavior of magnetic monopoles. Here, we propose a new type of photonic nanoantenna behaving as a radiating magnetic monopole¹. We demonstrate that a half-nanoslit in a semi-infinite gold layer generates a single pole of an enhanced magnetic field at the nanoscale and that this single pole radiates efficiently in the far field (Figure 1). We also introduce an effective magnetic charge using Gauss's law of magnetism, in analogy to the electric charge, which further highlights the monopolar behavior of this new antenna. Finally, we show that different plasmonic and metallic materials can provide magnetic monopole antennas covering the visible to near infrared range, and even down to GHz frequencies. This original antenna concept opens the way to a new model system to study magnetic monopoles and a new optical magnetic field source to study the “magnetic light-matter coupling”. Furthermore, it opens potential applications at lower frequencies, such as in magnetic resonance imaging.

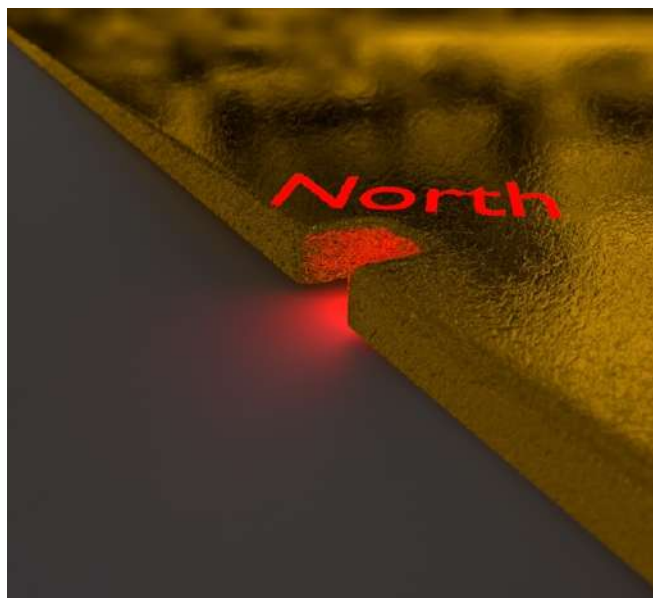


Figure 1. Illustration of a magnetic monopole nanoantenna made in a semi-infinite gold layer.

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Iterative regularization methods in non-Euclidean settings for microwave inverse scattering medical imaging

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Abstract: *Microwave inverse scattering imaging is very useful in biomedical applications where the dielectric properties of human tissues have to be restored by means of minimally-invasive techniques. In this talk we discuss iterative regularization algorithms developed in non-standard functional spaces, with application to continuous monitoring of hemorrhagic brain strokes.*

In imaging by electromagnetic inverse scattering, the characterization of the dielectric properties of an unknown scattering object inside an investigation domain is based on retrieving the equivalent source from the scattered field outside the source region, due to the illumination by a known electromagnetic incident field. Inverse scattering imaging is very useful in biomedical applications where the dielectric properties of human tissues have to be restored by means of minimally-invasive techniques. Microwave imaging techniques are one of the newly explored methodologies due to their potentiality as diagnostic tools based on nonionizing radiation and cheap instrumentation, essentially similar to the one used in mobile communications.

When a quantitative reconstruction is required, it is well known that the full-wave problem should be addressed, which results in nonlinear relationships between the target properties and the field it scatters. Hence, the mathematical model of this inverse problem leads to the solution of an ill-posed, nonlinear and implicit equation, based on the Lipmann-Schwinger integral operator [1], [2]. The integral equation can be written as functional equation $F(x)=y$, characterized by an ill-posed operator $F:X\rightarrow Y$ between two functional spaces, namely X is the functional space of scalar real-valued dielectric permittivities, and Y is the functional space of the complex-valued scattered electric fields.

In this talk, non-Euclidean, that is non-standard, normed spaces X and Y are considered. Most inversion procedures have been formulated in the standard framework of Euclidean spaces, due to the presence of well-established mathematical tools. Essentially, a change in the functional space, as in our approach, provides a different way to evaluate the misfit between modelled and measured scattered fields. Of course, this change will significantly affect reconstruction results. More specifically, we deal with iterative minimizations of a functional based on the residual, or cost function, $\|F(x)-y\|$, without any direct inversion since no (closed form of the) inverse of F exists in this setting. In particular, we study generalizations of one-step gradient methods, which act as implicit regularization algorithms when combined with an early-stopping criterion to prevent over-fitting of the noise on the scattered data y . The effectiveness of the proposed method is assessed by analyzing numerical results with multifrequency transverse magnetic illumination conditions in a tomographic configuration for detection of hemorrhagic brain strokes.

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Reconfigurable High-Frequency RF devices using Microfluidics

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Abstract: We present lightweight and flexible RF metamaterials for next-generation 5G, 6G, and satellite communications. Using continuous-flow lithography, we fabricate scalable, high-conductivity components with tunable resonances ranging from 10 to 600 GHz. This technology enables adaptive high-frequency performance across a broad range of next-generation communication applications.

Electromagnetic resonators play a critical role in sensing, signal processing, and telecommunications. Microfluidic techniques offer a promising approach, enabling the self-assembly of structures with tunable resonance frequencies [1]. In this work, we employ elastocapillarity to create C-shaped electromagnetic resonators at the microscale. A conductive polymer fiber of thickness r can spontaneously wrap around a droplet when its size exceeds a critical value determined by the elastocapillary length [2]. When a fiber is partially immersed in a droplet, a capillary imbalance at the three-phase contact line drives the fiber into the droplet. Viscous dissipation limits retraction, and confinement within the droplet significantly influences energy loss [3].

A conductive polymer fiber of thickness r can spontaneously wrap around a droplet when its size exceeds a critical value given by the elastocapillary length $L_{BC} = \sqrt{Er^3/\gamma}$, where E and γ denote the Young's modulus and surface tension, respectively [2]. The fiber bends into a C-shape around the droplet, forming an electromagnetic resonator equivalent to an LCR circuit.

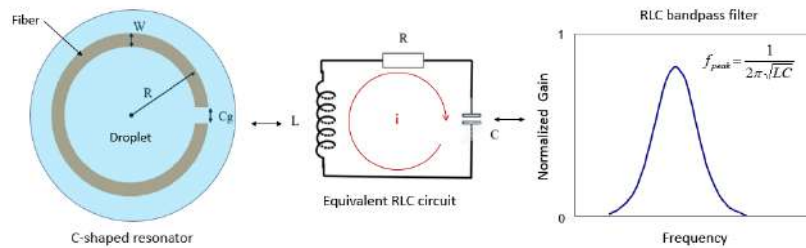


Figure 1: Electromagnetic resonator encapsulated in a droplet. A conductive fiber is used to create a split ring resonator (SRR). The equivalent LCR circuit is shown in the middle and the corresponding resonance frequency on the right.

A microfluidic device was fabricated, consisting of two droplet generators and a fiber extrusion channel. The creation of individual resonators involves three steps: (i) a single conductive droplet is released and then extruded into a fiber through UV polymerization; (ii) a non-conductive droplet is introduced near the extruded fiber; and (iii) a spontaneous coiling

event occurs upon contact between the fiber and the droplet.

Reconfigurable metamaterials consist of arrays of split-ring resonators with tunable positions. When the average separation between resonators is comparable to their size, the material functions as an electromagnetic wave filter [4]. Maximum attenuation of the reflected wave field occurs at the resonant frequency of the individual resonators. The bandwidth can be tuned by varying the separation between resonators and their size distribution [5].

The reconfigurable metamaterial can filter multiple bandwidths by embedding resonators of varying sizes at precise locations within a polymer substrate. Multi-layer absorption is also achievable by applying different functional materials to each layer, enhancing the overall electromagnetic response. This technology enables adaptive, high-frequency performance across a broad spectrum of communication applications.

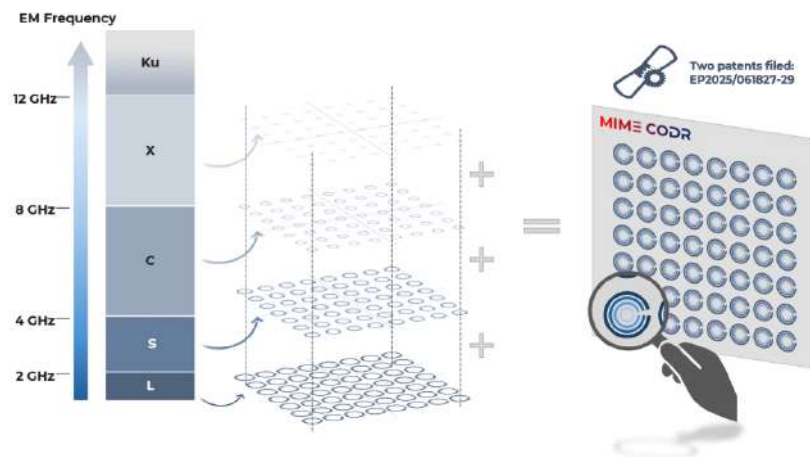


Figure 2: Configurable metasurface based on coiled droplets. Multiple resonant frequencies can be addressed by placing different droplet sizes on a single surface. Each resonator targets a specific frequency.

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Dielectric characterization of a Debye half-space medium

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Abstract: The problem of the dielectric characterization of an half-space medium from GPR multi-monostatic measurements is addressed. The Fresnel coefficient (as function of the incident angle) is retrieved from the inversion of a linear integral equation for multiple frequencies. It is then used to retrieve the Debye model’s coefficients that identify the material with the Variable Projection algorithm, which leverages the separability of the problem.

The estimation of the dielectric characteristic of half-space materials is a relevant problem in the literature and in many applicative contexts, such as moisture level control, soil contamination and soil monitoring in general [1]. Moreover, in GPR (Ground Penetrating Radar), the knowledge of the host medium is necessary for subsurface imaging to obtain properly focused images [2].

The procedure we introduce involves three steps: retrieving the Fresnel coefficient from the scattered field, then retrieving the permittivity, finally retrieving the Debye coefficients of the material under test.

Regarding the first step, a class of investigation techniques is based on the measurement of the reflection/transmission coefficients in free space conditions, mainly under plane wave incidence assumption. On the contrary, in this work, free-space measurements are no longer required by taking into account the spatial spectrum of the incident field and by exploiting a multi-static scheme to collect data.

The considered bi-dimensional geometry, shown in fig. 1, consists of two homogeneous half-spaces separated by a planar interface (the air/medium interface located at $z = 0$). The upper layer is the free-space; the lower half-space has a generic permittivity $\varepsilon(\omega)$.

The field radiated by the transmitting antenna can be expressed in terms of its plane-wave spectrum and reads

$$E_i(\underline{r}, \underline{r}_S, k_0) = \int_{-k_0}^{k_0} A(k_0, k_x) e^{-jk_z|z-z_S|} e^{-jk_x(x-x_S)} dk_x \quad (1)$$

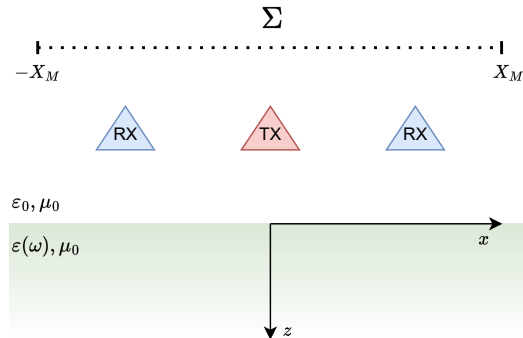


Figure 1: Geometry of the problem

where $\underline{r} = (x, z)$ is the generic point on the air/medium interface, $\underline{r}_S = (x_S, z_S)$ is the transmitting antenna position, $A(k_0, k_x)$ is the source plane-wave spectrum, k_0 is the free-space wave-number, and $k_z = \sqrt{k_0^2 - k_x^2}$.

The Fresnel coefficient as function of the angle of incidence is retrieved from the inversion of a linear integral equation for each frequency. Indeed, the field reflected back by the interface is

$$E_r(\eta, k_0) = \int_{-k_0}^{k_0} A(k_0, k_x) e^{-2jk_z d} e^{-jk_x \eta} \Gamma(k_0, k_x) dk_x$$

where $\eta = x_O - x_S$ is the difference between the positions of the receiving antenna and the transmitting antenna.

The involved operator is inverted by means of the Truncated Singular Value Decomposition (TSVD). View diversity (in conjunction with multi-frequency data) can be used for medium estimation.

The second step can be done by a simple algebraic relation for a homogeneous half-space.

This procedure has been already introduced in [2], [3], and here is extended and enhanced by adding the third step: the determination of the coefficients of the single-pole Debye model describing the soil permittivity.

This step would entail the solution of a non-linear optimization problem with 3 non-linear unknowns. However, it is possible to exploit the separability of the dispersion relation to be optimized, i.e., the fact that the model parameters can be separated into two sets of parameters, one that enters linearly into the model and one that enters non linearly. Thanks to the Variable Projection Algorithm [4], which leverages the mentioned separability, the non-linear least square problem can be recast as a non-linear separable problem with only one non-linear parameter, easing its resolution and improving the convergence of the procedure.

Acknowledgement

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Array antennas, active, adaptive and reconfigurable antennas

Implementation of a machine learning architecture for multi-user frequency selective beam steering with reconfigurable intelligent surfaces

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Abstract

Reconfigurable Intelligent Surfaces (RIS) are used in 5G and 6G communication for beam steering applications, e.g. to ensure signal coverage for otherwise obstructed areas. We propose a customized neural network-based machine learning architecture to efficiently find RIS switching patterns that allow multi-user beam steering using multiple working frequencies.

Due to the use of radiation in higher frequency bands in 5G and 6G wireless communication compared to earlier generations, the obstruction of beams by obstacles, such as buildings, becomes a severe problem [1]. Reconfigurable Intelligent Surfaces (RIS) offer a way to redirect radiation transmitted by a base station towards obstructed areas as depicted in Fig. 1 [2]. A RIS mainly consists of an array of unit cells whose phase shift on reflected radiation can be individually tuned. In our case, varactor diodes are used to control the phase shift via the applied bias voltage. The RIS is characterized by measuring the S-Parameters of the unit cells depending on the bias voltage and working frequency, so that a voltage map is obtained (see [3] for more details).

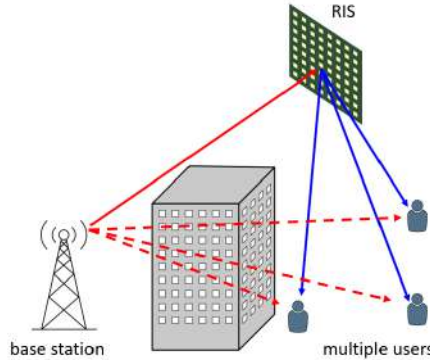


Figure 1: Schematic of a RIS used to redirect radiation from a transmitter to multiple receivers in an area obstructed by a building.

To target different user areas in a given time sequence, the voltage patterns can either be calculated analytically or by classical optimization methods. If, however, a large scale RIS is used to deflect and focus radiation to several moving target positions simultaneously, a more sophisticated and scalable machine learning approach is required. Therefore, we implemented a customized neural network that optimizes the bias voltage pattern of a RIS. In a first approach, the carrier frequencies $\nu_1 = 27$ GHz and $\nu_2 = 31$ GHz were chosen to steer two beams to two different target positions P_I and P_{II} simultaneously. The optimization algorithm used to solve this problem is schematically shown in Fig. 2. Using the Kirchhoff diffraction formula, the phase

pattern for focusing the beams to the target positions is calculated and subsequently used as the input for the neural network. The network itself is fully-connected and consists of three hidden layers with 148 neurons each. The output of the network is a matrix containing the bias voltages that have to be applied to the RIS for the desired radiation pattern.

To train the neural network, random deflection angle pairs that correspond to two points P_I and P_{II} in the evaluation plane are generated and their phase pattern is used as input data. The electric field distributions $\hat{\mathbf{y}}$ are calculated from the obtained voltage matrices using the voltage map and the Kirchhoff diffraction formula. The vectors $\hat{\mathbf{y}}$ are then compared to the labels $\mathbf{y}$ of the training data which are sparse vectors with only non-zero entries at the target positions P_I and P_{II} . The comparison is done by calculating the categorical cross-entropy loss function that provides a gradient for the training of the neural network.

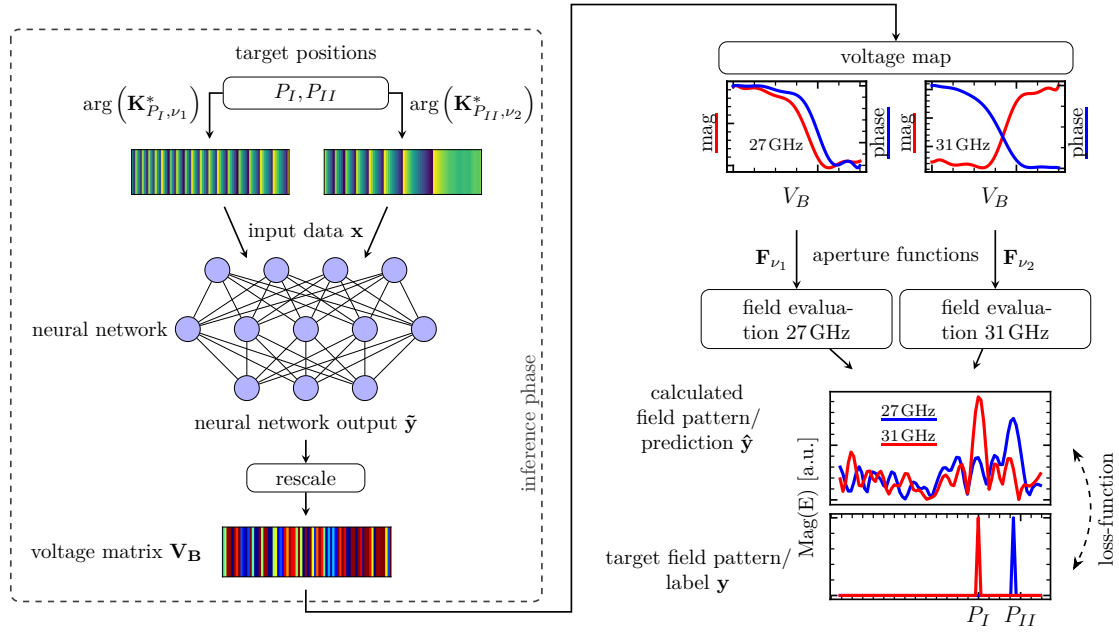


Figure 2: Machine learning architecture. To compute the bias voltage vector for the RIS the phase patterns at the target positions P_I and P_{II} are used as input to a neural network. To train the network, the electric field distribution is calculated using the voltage map and the field evaluation layer. The loss function compares the calculated electric field distribution $\hat{\mathbf{y}}$ to the target field pattern $\mathbf{y}$ by categorical cross-entropy. This provides a gradient for the training process of the neural network.

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Miniaturized, Broadband, Polarization Reconfigurable Metasurface Antenna for Outdoor Mobile Communication

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Abstract: A miniaturized, broadband, CP-reconfigurable MTA using full multiplexing concept is proposed in this paper. This full-multiplexing configuration drastically enhances spatial efficiency. And, additional inter-unit gaps lead to supplementary edge capacitances, allowing for a more compact radiation aperture of the FMMTS antenna.

Fig. 1 shows the geometry of the proposed miniaturized broadband MTA with CP-reconfigurable characteristics. The proposed MTA unit employs a pair of Rogers RO4003C copper-cladded substrate layers (relative dielectric constant $\epsilon_r = 3.55$, loss tangent $\tan \delta = 0.0027$, and copper cladding thickness 0.035 mm). These layers share the same transverse dimension, 20.2 mm $\times$ 17.8 mm. Layer_1 has a thickness of 1.524 mm and Layer_2 has that of 0.406 mm. In Figs. 1(a) and (b), the radiation patch consists of the modified FMMTS and is located on the upper surface of Layer_1, where each diamond structure has a length of L_2 and a spacing of G_1 .

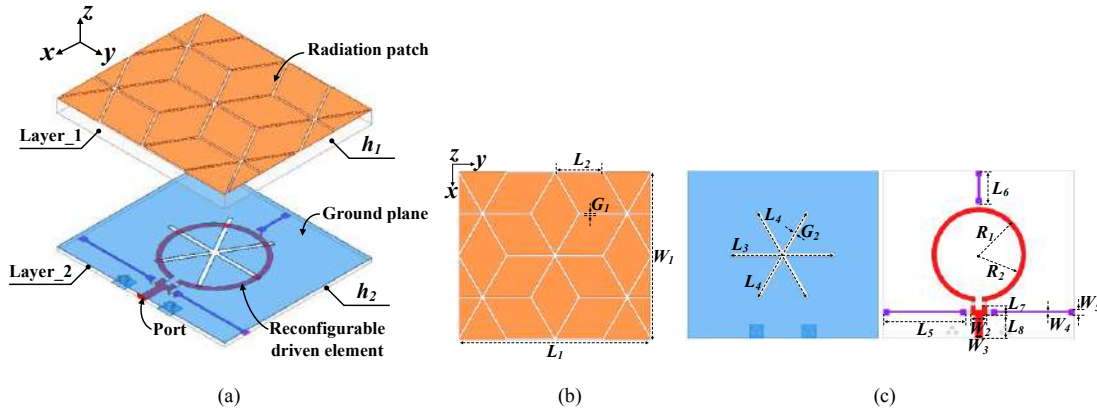


Fig. 1. Configuration of the miniaturized broadband CP-reconfigurable MTA using hexagonal-shaped FMMTS. (a) 3-D isometric view. (b) Upper surface of Layer_1. (c) Upper and lower surface of Layer_2. $h_1 = 1.524$, $h_2 = 0.406$, $L_1 = 20.2$, $L_2 = 4.88$, $L_3 = 11.0$, $L_4 = 10.5$, $L_5 = 8.75$, $L_6 = 3.5$, $L_7 = 0.97$, $L_8 = 2.5$, $W_1 = 17.8$, $W_2 = 1.7$, $W_3 = 0.8$, $W_4 = 0.2$, $W_5 = 0.6$, $G_1 = 0.2$, $G_2 = 0.4$, $R_1 = 5.0$, $R_2 = 4.5$ (all units: mm).

The measured and simulated performance characteristics of the prototype CP-reconfigurable MTA are presented in Fig. 2. The measurement shows good agreement with the simulation results. In Fig. 2(a), the measured impedance bandwidth (BW) is 28.4% (5.92-7.88 GHz and 5.91-7.87 GHz) for both the LHCP and RHCP states. The measured axial ratios (AR) are plotted in Fig. 2(b), where it is evident that the prototype exhibits a 3-dB ARBW of 21.1% (6.23-7.7 GHz) for the LHCP state and 21.2% (6.22-7.7 GHz) for the RHCP state. It is observed that the entire 3-dB AR bandwidth is encompassed within the impedance bandwidth. Consequently, both the available bandwidths, defined as the overlapped bandwidths of the 3-dB AR and -10-dB return loss, are 21.1% (6.23-7.7 GHz).

The peak realized gains (RG) of proposed CP-reconfigurable MTA are also depicted in Fig. 2(b). The

antenna maintains stable gains throughout the entire available band for both the LHCP and RHCP states. Due to the electrical size of the proposed antenna at the lower operating frequency $f_{low, meas} = 6.23$ GHz is $0.41\lambda_{low} \times 0.37\lambda_{low} \times 0.04\lambda_{low}$, the measured RGs range from 4.21 to 5.63 dBic and 4.21 to 5.38 dBic within its operational frequency band for the LHCP and RHCP state, respectively.

In addition, the measured and simulated radiation patterns for the LHCP and RHCP states in xz - and yz -planes are plotted in Fig.3, the unidirectional property of the radiated fields is clearly seen. Their maximum radiation is directed along the $+z$ -axis, which are basically consistent. For the LHCP state, the measured peak RG and radiation efficiency (RE) values are ~ 4.57 dBic (5.24 dBic), and $\sim 88\%$ (85%) at 6.52 GHz (7.48 GHz), respectively. For the RHCP state, the measured peak RG and RE values are ~ 4.52 dBic (5.15 dBic), and $\sim 87\%$ (85%) at 6.52 GHz (7.48 GHz), respectively. The amplitude difference between the LHCP and RHCP radiation is at least 23 dB at the elevation angle of 0° , indicating a good purity of the CP radiation.

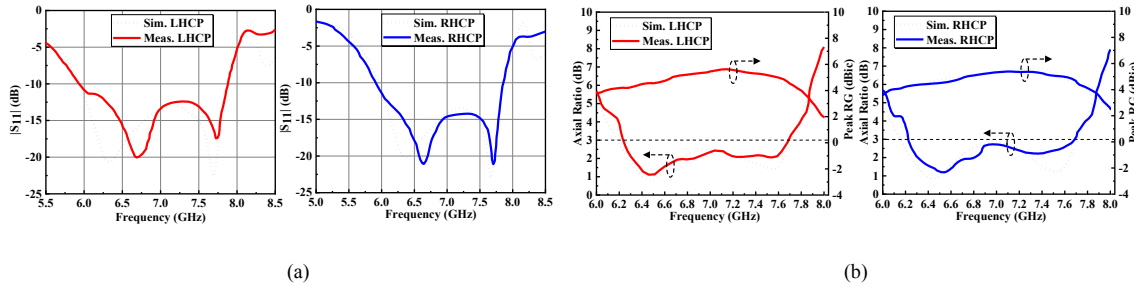


Fig. 2. Measured and simulated results of the miniaturized broadband CP-reconfigurable MTA. (a) $|S_{11}|$ values in the LHCP and RHCP states. (b) AR and peak RG values in the LHCP and RHCP states.

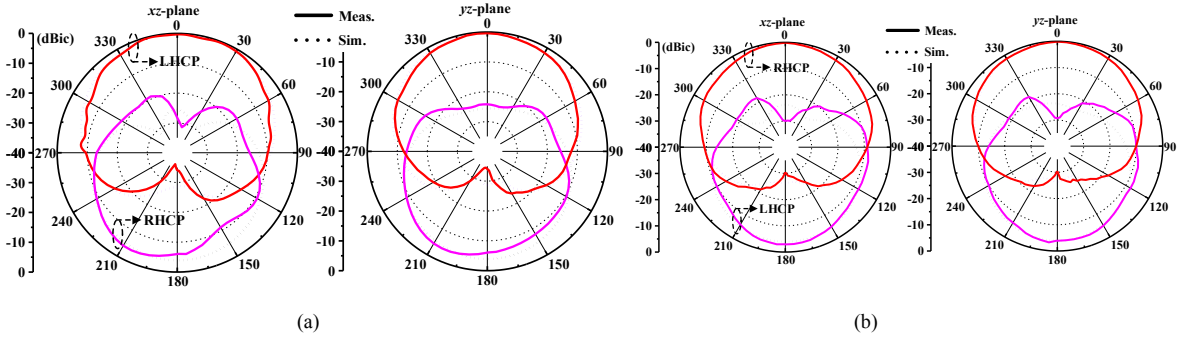


Fig. 3. Measured and simulated RG patterns of the miniaturized broadband CP-reconfigurable MTA. (a) LHCP at 6.52 GHz. (b) RHCP at 6.52 GHz.

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Antenna Design Toward the New Generation of Wireless Systems

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Abstract: Modern antenna design techniques toward the new generation of wireless systems are presented. Antenna array design under linear and non-linear constraints, using orthogonal methods in conjunction with Lagrange and perturbation techniques is given. Also, machine learning-based beamforming techniques for massive MIMO systems are presented.

Modern antenna design techniques toward the new generation of wireless systems are presented. It is well known that the performance of wireless communications depends on a variety of factors and procedures from physical up to the application layer. In the physical layer the role of antennas for the performance and evolution of wireless systems is fundamental. That is because the antenna is the physical means through which eventually the signal is transmitted or received. In modern antenna design systems, beamforming under constraints is a topic that one must cope with searching for the most efficient and feasible procedure. In the array design techniques, the proper excitation and/or position of the elements depend on the platform where they are positioned.

Beamforming presupposes the configuration of an antenna array with strong signal correlation between the antenna elements. The array design, see Fig.1, under linear and non-linear constraints, using modern procedures, (matrix formulation, Genetic and Stochastic Global Optimization Algorithms, GS and SVD Orthogonal Methods, Lagrange technique etc.), [1], will be presented.

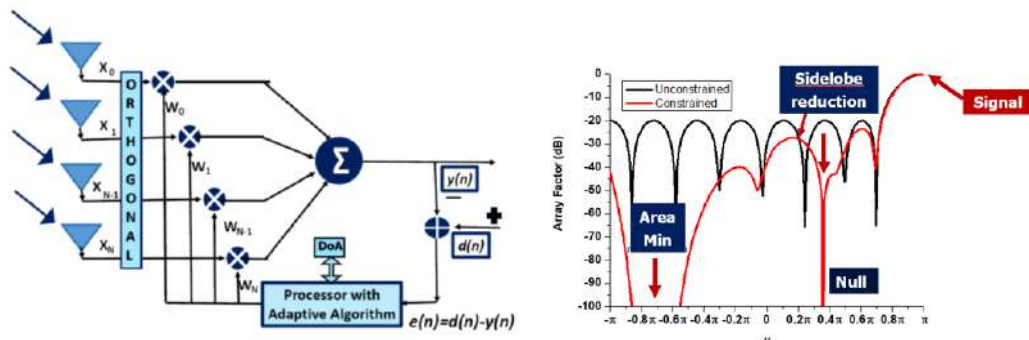


Figure 1. The array and the desired pattern under constraints on nulls, SLL, and performance indices.

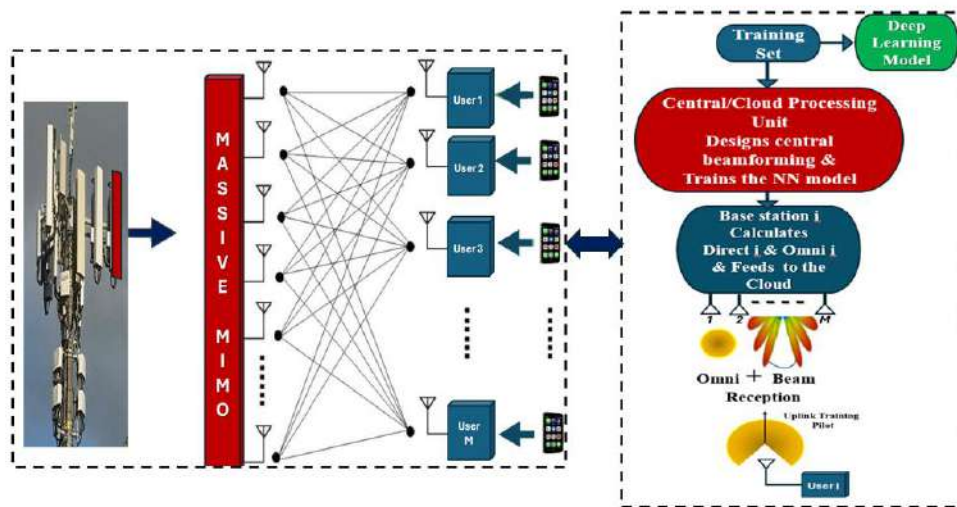


Figure 2. Beamforming of massive MIMO systems.

A big issue in modern wireless communications is the increase of data transmission rate. For a given antenna geometry and configuration, this can be achieved using spatial multiplexing structures which are commonly known as MIMO (Multiple Input-Multiple Output) systems, [2], [3], see Fig. 2. Our presentation will include massive MIMO antenna design and will explain the giga MIMO approach for 6G.

Concluding, antennas in current and future wireless communication systems will be discussed.

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Electromagnetic theory: analytical, computational, and numerical methods

Enhancing Electromagnetic Field Resolution Using Trilinear and Nonlinear Interpolation for Real-Time 3D Near-Field Measurement Systems

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Abstract: This work presents an approach for enhancing the resolution of electromagnetic field measurements using trilinear and nonlinear interpolation techniques. The proposed methods improve spatial accuracy and data fidelity, facilitating better electromagnetic field analysis. Results demonstrate the effectiveness of both approaches in refining field measurements.

Introduction

Accurate measurement and analysis of electromagnetic (EM) fields are crucial for applications like wireless communications, biomedical imaging, and electromagnetic compatibility testing. Despite advances in sensor technology, spatial resolution limitations persist. This research addresses these limitations by using interpolation techniques to reconstruct higher-resolution field representations from sparse measurements. Various interpolation methods have been explored [1], but gaps remain. Our study enhances EM field measurement resolution using trilinear and nonlinear interpolation techniques.

Objectives: (1) develop and implement these techniques for EM field measurements, (2) evaluate their performance using simulated data, and (3) refine the nonlinear method for better accuracy.

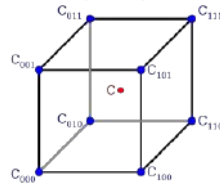
The paper is organized as follows: Section 2 describes the trilinear interpolation method, Section 3 outlines the nonlinear approach, Section 4 presents results and discussion, and concludes with future work suggestions.

Methodology

Trilinear interpolation

Trilinear interpolation estimates a value inside a cube using the eight neighboring points in a three-dimensional space. It combines these corner values based on their relative distances through successive interpolations along the x-, y-, and z-axes. The magnetic field components at the cube's corners are extracted, and the point of interest is positioned using normalized parameters u, v, and w. This method refines grid resolution by interpolating new values, ensuring a more accurate approximation of the magnetic field without data loss. When a resolution increase is required, this technique is used to populate the grid with interpolated values, preserving accuracy. If the grid is increased by a factor of N, each original interval between two points now contains N-1 intermediate points. For an initial M×M×M grid, the total number of points after increasing the resolution follows the relation:

$$M'=(M-1)N+1$$



Nonlinear interpolation

The processing of experimental data begins with extracting voltage measurements from a file, followed by identifying the maximum values for each direction to calculate the magnetic field components. These components are obtained by dividing the measured values by the product of the measurement loop surface S and the angular frequency ω , defined as $\omega=2\pi F$, where F is the signal frequency:

$$B_x = \frac{A_x}{S \times \omega}, \quad B_y = \frac{A_y}{S \times \omega}, \quad B_z = \frac{A_z}{S \times \omega}$$

Next, the components of the auxiliary field are calculated by dividing these values by the permeability of free space μ_0 :

$$H_x = \frac{B_x}{\mu_0}, \quad H_y = \frac{B_y}{\mu_0}, \quad H_z = \frac{B_z}{\mu_0}$$

Nonlinear interpolation follows several steps. First, the six closest points to the target location are selected based on their radial distance:

$$r = \sqrt{x^2 + y^2 + (z + h_{Robot})^2}$$

A conversion to spherical coordinates is then performed to transform the Cartesian field components using the following relations:

$$\begin{aligned} H_r &= H_x \sin \theta \cos \phi + H_y \sin \theta \sin \phi + H_z \cos \theta & H_\theta &= H_x \cos \theta \cos \phi + H_y \cos \theta \sin \phi - H_z \sin \theta \\ H_\phi &= -H_x \sin \phi + H_y \cos \phi \end{aligned}$$

where the spherical angles are defined as:

$$\theta = \arccos\left(\frac{z}{r}\right), \quad \phi = \arctan\left(\frac{y}{x}\right)$$

Interpolation relies on corrective parameters that account for distance and angular frequency, integrating field attenuation. The interpolation coefficients are given by:

$$I_r = \frac{2\pi H_r}{S k^3 \cos \theta F(\theta, r)}, \quad I_\theta = \frac{4\pi H_\theta}{S k^3 \sin \theta G(\theta, r)}$$

where $k=\omega/c$ is the wave number, and $F(\theta, r)$ and $G(\theta, r)$ are corrective functions that depend on field attenuation with distance.

Finally, an inverse transformation reconstructs the interpolated field values in Cartesian coordinates:

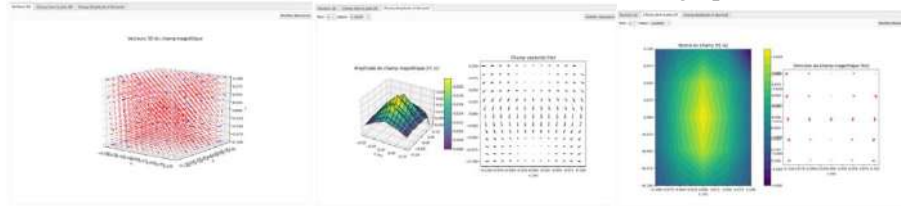
$$\begin{aligned} H'_x &= H'_r \sin \theta \cos \phi + H'_\theta \cos \theta \cos \phi - H'_\phi \sin \phi & H'_y &= H'_r \sin \theta \sin \phi + H'_\theta \cos \theta \sin \phi + H'_\phi \cos \phi \\ H'_z &= H'_r \cos \theta - H'_\theta \sin \theta \end{aligned}$$

This approach ensures a more precise estimation of the magnetic field components by incorporating nonlinear relationships and accounting for electromagnetic wave propagation and attenuation phenomena.

Results and discussion

To evaluate the performance of both interpolation techniques, we applied them to a set of simulated electromagnetic field data. The trilinear interpolation method performed exceptionally well, providing an efficient and accurate estimation of the field. However, the nonlinear interpolation method still requires adjustments, as the current algorithm is not yet fully optimized and does not yield perfect results when applied to a simulated field. Further refinements are needed to improve its accuracy. Future work will include testing the nonlinear method on real measured field data to assess its performance under practical conditions.

Here is an example of the visualization of the field we can have in our graphical interface.



Acknowledgements

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Design of a 3D Electromagnetic Field Instrument for Real-Time Direct Visualization and Near-Field EM Measurement

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Abstract: This paper presents the design and fabrication of an electromagnetic probe for NFC applications. The probe, developed at ISEN Yncrea Méditerranée, optimizes field measurement accuracy through and multi-axis sensing. Simulations and fabrication processes ensure high precision, enhancing NFC technology for improved data acquisition and signal processing.

1. Introduction

The goal of our project is to design an electromagnetic probe and develop algorithms to improve the accuracy of electromagnetic field measurements during NFC contact. By optimizing component size and implementing advanced calculations, we aim to enhance precision while reducing measurement time. The project consists of two primary components: the probe itself and the algorithm that processes the collected data. The probe, mounted on a robotic arm, moves around a credit card, capturing electromagnetic field data, which is then transmitted to an oscilloscope and a PC for further processing and visualization. This method will collect three-dimensional data but will also reduce the time needed for measurement process.

2. Antenna Design

Antenna design is based on defining key parameters such as length (number of turns in the coil), width, and thickness. These characteristics influence the antenna's ability to capture the electromagnetic (EM) field and generate a voltage, thereby enabling the assessment of the received signal power.

$$E = -NS \frac{dB}{dt} \quad (1)$$

To study the impact of these parameters, we designed antennas with surface areas of 10, 20, and 30 mm², featuring 1, 2, and 3 turns. We used an antenna width of 1.50 mm, a spacing between turns of 1.50 mm, and an antenna thickness of 0.035 mm. Given our requirement for a 3D probe, we designed three orthogonal rectangular antennas to measure electromagnetic fields along the X, Y, and Z axes. The final antenna design was chosen based on NFC application requirements and STMicroelectronics guidelines.

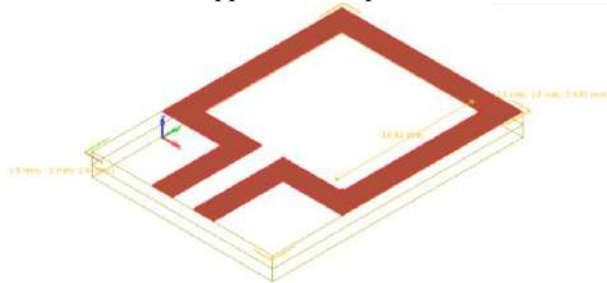


Figure 1: 3D representation of the 10mm² antenna with single turn

3. Antenna Layout and fabrication

The layout and fabrication of the antennas must be precise and adhere to specific criteria. The manufacturing process is carried out according to the technologies available in our facilities.

Thus, we used an FR4 substrate with vias of 0.6 mm in diameter. These specifications allow us to design antennas with multiple turns.

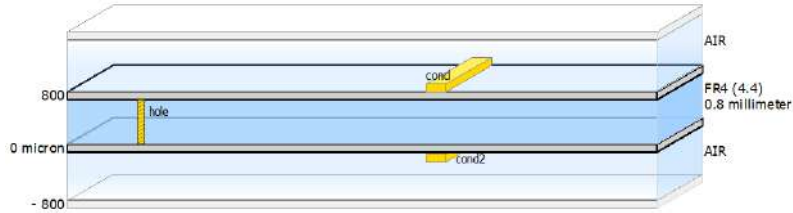


Figure 2: 3D representation of the substrate for a multiple turn antenna

4. Electromagnetic simulations

By simulating various types of antennas, we were able to analyse and compare their reliability and accuracy. The results show that at the NFC operating frequency of 13.56 MHz, gave a correct impedance. This shows how the antenna used as a voltage tool measurement could capture the EM field that flows by. By adding 3 antennas on each axis, we would then be able to measure the 3D EM field that is generated when NFC contact occurs. Then we elaborate the following structure to fix antennas on the robot arm.

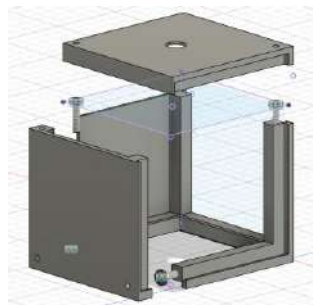


Figure 3: 3D representation of antennas support

5. Conclusion

Through a structured approach involving 3D antenna design, layout and electromagnetic simulations, we successfully developed a functional electromagnetic probe tailored for NFC applications. The manufacturing process, supported by advanced simulation tools, ensures high accuracy and efficiency in field measurement. The 3D EM field could then be measured at different points and on a certain surface, the voltage on each point could then be imported into a software algorithm to calculate the field, visualize it and extend the number of points measured.

Acknowledgements:

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A Method for Credibility Assessment of Target Electromagnetic Statistical Characteristics

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Abstract: In response to the statistical data of target electromagnetic characteristics obtained using full-wave or approximate methods, a feature selective validation (FSV) method is proposed in this paper. The credibility of the data acquired by the proposed method is assessed from multiple dimensions, including amplitude, trend, and error.

1. Introduction

In previous studies, various computational methods have been proposed to address the issue of shape uncertainty in metallic targets. However, the evaluation of computational results has been limited to factors such as root mean square error (RMSE) [1], with insufficient comprehensive data processing and analysis. This paper introduces a novel data evaluation method for assessing the similarity, or credibility, between two sets of data. By quantifying the credibility of simulation results, the proposed method can reduce the variability of subjective evaluations and provide a direction for the optimization of numerical algorithms. Additionally, this quantitative evaluation approach enhances the reliability of results, ensures the scientific validity and accuracy of simulation analysis, and thereby provides a more solid basis for decision-making in engineering and scientific research.

The feature selective validation (FSV) method [2] was initially proposed by A. J. M. Martin in 1999 and first applied to the validity assessment of power system dynamic simulations. It has since undergone continuous development. Currently, this technique is recognized as a critical component of the electromagnetic simulation validity evaluation system specified in the IEEE Standard 1597.1. It enables the simulation of expert data evaluation processes through numerical algorithms based on data features.

2. Method

The core principle of the FSV method is based on performing a Fourier transform on two datasets to convert them into the frequency domain, followed by further processing to extract different frequency components. First, the two datasets are ensured to have the same number of sampling points, and a Fourier transform is applied to obtain their frequency-domain representations. Second, the first four points of the spectrum are subjected to an inverse Fourier transform to derive the direct current (DC) component. Then, starting from the fifth point, the remaining data are filtered using the FSV-specific low-pass and high-pass filters, followed by an inverse Fourier transform to obtain the low-frequency and high-frequency components, respectively. The DC, low-frequency, and high-frequency components are then calculated to construct amplitude difference measures (ADM), feature difference measures (FDM), and global difference measures (GDM). Finally, the evaluation level is determined by referencing the FSV assessment scale.

ADM quantifies the amplitude differences in the data, primarily derived from the combination of the DC and low-frequency components, thus reflecting the DC differences and overall consistency. FDM captures the trend differences in the data, mainly obtained through the combination of derivatives of the low-frequency and high-frequency components, thereby reflecting the trend variations. GDM is a comprehensive measure derived from both ADM and FDM, representing the combined differences in amplitude and trend. These three metrics

were obtained through point-to-point data discrepancy calculations. Furthermore, the FSV assessment scale is utilized to provide qualitative and quantitative evaluations of these metrics.

Table 1. FSV Assessment Rating Scale.

Grade number	Valuation range	Degree
1	$X \leq 0.1$	Excellent
2	$0.1 \leq X \leq 0.2$	Very Good
3	$0.2 \leq X \leq 0.4$	Good
4	$0.4 \leq X \leq 0.8$	Fair
5	$0.8 \leq X \leq 1.6$	Poor
6	$X > 1.6$	Very Poor

3. Result

A numerical example is presented to apply feature selection validation techniques for the credibility assessment of electromagnetic statistical characteristics of targets with uncertain shapes. The study subject is a simplified satellite model. The incident wave frequency is 400MHz, with an incident angle of $\theta_i = 0^\circ$ and $\varphi_i = 0^\circ$, while the observation angles are $\theta_s = 0^\circ - 180^\circ$ and $\varphi_s = 0^\circ$. The research data consists of bistatic radar cross section (RCS). The mean value of RCS calculated by Monte Carlo (MC) method is used as reference data. The electromagnetic statistical characteristics of the satellite model are computed using the method proposed in [1], and the obtained mean value of RCS serves as the data to be evaluated. Initially, the DC, low-frequency, and high-frequency components of the data are extracted. Subsequently, indicators such as ADM, FDM, and GDM are calculated. Results of the FSV assessment analysis of the satellite model is shown in Fig. 1. Fig. 1(d) illustrates that the results obtained using the methodology proposed in [1] are rated as ‘Excellent’.

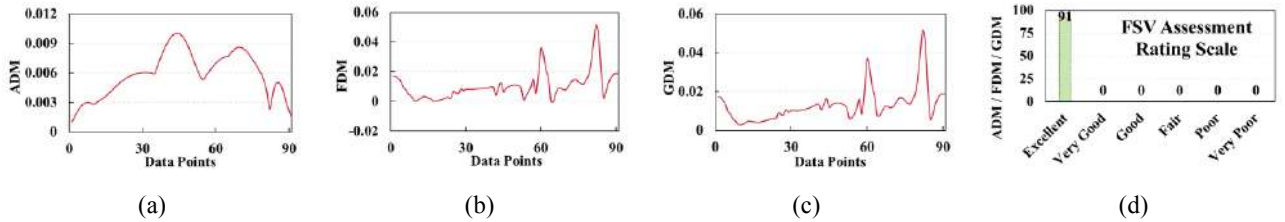


Fig. 1. Results of the FSV assessment analysis of the satellite model (a) ADM (b) FDM (c) GDM (d) FSV assessment.

4. Conclusion

In order to comprehensively reflect the specific characteristics of the data for its confidence evaluation, this chapter adopts the FSV assessment method to assess the confidence of the target RCS data in the context of shape uncertainty from multiple perspectives, such as magnitude, trend, error, etc., and the assessment results have certain reference value.

Acknowledgements

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Data Fusion Method Based on the Bistatic Model

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Abstract: When obtaining data, frequency and angle information may be missing. This study proposes a bistatic model-based two-dimensional fusion method, using sparse dictionary representation and the POMP algorithm to address low-resolution issues in radar data. Experimental results show an RMSE below 3dB between fused and original RCS.

1. Introduction

The bistatic RCS demonstrates a high degree of sensitivity to variations in the receiving angle. Modest alterations can substantially impact the precision of target description and the extraction of scattering center (SC) parameters. The perturbation orthogonal matching pursuit (POMP) algorithm [1], based on the bistatic scattering center (BSC) model, enhances the accuracy of SC parameter extraction.

This paper introduces a two-dimensional data fusion method based on the BSC model, addressing missing frequency and angle data. By fusing radar echo signals from multiple frequencies and angles, the method reconstructs radar signals with larger bandwidths and angles, thus filling in missing information. Existing fusion methods often overlook the continuity of target components and are limited by fusion angles. The proposed method ensures accurate SCs extraction while modeling radar echoes from large bistatic angles, overcoming these limitations.

The fusion method combines multi-frequency and multi-angle data with the POMP sparse reconstruction algorithm, transforming the problem into a sparse signal recovery task. Experimental results show that the root mean square error (RMSE) between fused and original RCS signals is below 3dB, validating the method's accuracy and reliability.

2. Method

According to SC theory, the radar target echo can be represented as the sum of the responses from multiple independent SCs. In this paper, a bistatic SC model is adopted, as described in [2].

In radar-related research, the sparsity theory of SC is often used to construct corresponding models. Specifically, a full-band, full-angular domain model can be established. On a dictionary grid, only a few coefficients typically exhibit non-zero values. This unique distribution allows the model represented by sparse expressions to effectively capture the sparse nature of the signal [3].

Let the working frequency sampling of Radar 1 be $f_1 \in \{f_0, \dots, f_0 + (M_1 - 1) \cdot \Delta f\}$, with M_1 sampling points. The pitch angle sampling of Radar 1 is $\theta_1 \in \{\theta_0, \dots, \theta_0 + (N_1 - 1) \cdot \Delta \theta\}$, with N_1 sampling points. Similarly, the working frequency sampling of Radar 2 is $f_2 \in \{f_0 + (M - M_2 + 1) \cdot \Delta f, \dots, f_0 + (M - 1) \cdot \Delta f\}$, with M_2 sampling points, and the pitch angle sampling of Radar 2 is $\theta_2 \in \{\theta_0 + (N - N_2 + 1) \cdot \Delta \theta, \dots, \theta_0 + (N - 1) \cdot \Delta \theta\}$, with N_2 sampling points. For the full-band, full-angle radar signal, the working frequency sampling is $f \in \{f_0, \dots, f_0 + (M - 1) \cdot \Delta f\}$, with M frequency sampling points, and the full-band, full-angle pitch angle sampling is $\theta \in \{\theta_0, \dots, \theta_0 + (N - 1) \cdot \Delta \theta\}$, with N sampling points. The principle of the multi-frequency, multi-view data fusion method is shown in Fig. 1.

The radar echoes for each frequency at different angles of Radar 1 and Radar 2 are arranged in column vectors. Using the discretization formula, the column vectors of echoes for each angle are summed to obtain the target echo. The disturbance dictionary matrix Φ is constructed using the known echo data from Radar 1 and Radar 2. Then, the sparse coefficient vector ζ is solved using the POMP algorithm. By multiplying the sparse coefficient vector ζ with the complete disturbance dictionary matrix, the reconstructed full-band, full-angle bistatic radar echo data is obtained.

3. Result

The proposed method is validated using the hemispherical cone model, with dimensions of $0.18\text{m} \times 0.49\text{m}$. The radar parameters are shown in Table 1. The incident radar pitch and azimuth angles are both set at 0° and 0° , respectively. The receiving azimuth is measured at 0° . The full-band, full-angle radar echo signal is generated from the echo signals of Radar 1 and Radar 2 using the proposed method. The results are shown in Fig. 1. The root mean square error (RMSE) of RCS is 0.55dB.

Table 1. Radar parameter settings

Parameters	f_c	Bandwidth	M	Receiving Angle	N	Polarization
Radar 1	8.5GHz	1GHz	21	Theta= 150° - 153°	11	VV
Radar 2	10.5GHz	1GHz	21	Theta= 156° - 159°	11	VV
Full frequency angle	9.5GHz	3GHz	61	Theta= 150° - 159°	31	VV

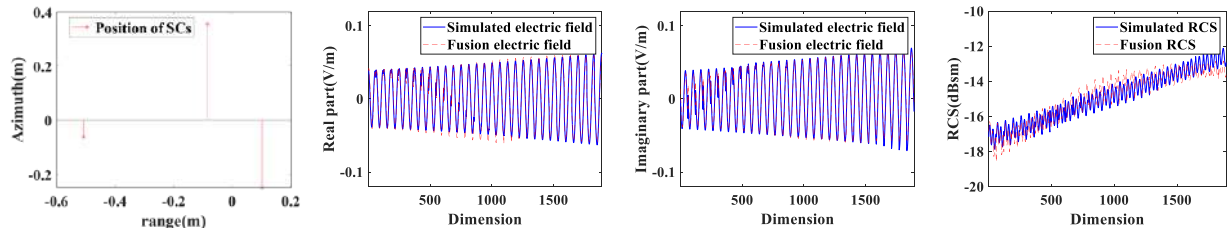


Fig. 1 Fusion calculation of full frequency radar RCS results using ball cone model. (a) Extraction results of SC's position; (b) Real part of electric field after fusion; (c) Imag part of electric field after fusion; (d) RCS of electric field after fusion.

4. Conclusion

This paper proposes a data fusion method based on the BSC model, transforming the complex data fusion problem into a sparse signal reconstruction problem. By using the bistatic attribute SC model and the POMP algorithm, the method enables the reconstruction of echo data at larger bandwidths and angles. The fusion method is validated using the hemispherical cone model, showing that the RMSE between the fused RCS signal and the original model RCS signal is less than 3dB.

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Strong Enhancement of Nonreciprocity in Gyrotropic Multilayer

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Abstract: Electromagnetic nonreciprocity is essential for unidirectional wave propagation, crucial in optical isolation and waves control. Traditional gyrotropic materials require strong magnetic fields but exhibit weak nonreciprocal responses. This study proposes gyrotropic heterostructures with alternating gyrotropic and plasmonic layers to enhance nonreciprocity by suppressing diagonal permittivity elements. Our model demonstrates significant enhancement in nonreciprocal behavior. These findings pave the way for compact, high-performance photonic devices for photonic applications.

Electromagnetic nonreciprocity, a key feature in photonic materials, enables asymmetric wave propagation, crucial for applications such as optical isolation and wave control [1,2]. Conventional methods of achieving nonreciprocity often rely on gyrotropic materials subjected to strong magnetic fields, but their inherent nonreciprocal response is weak, as a result leading to bulky structures. In this work, we propose several approaches to significantly enhance nonreciprocity by employing gyrotropic heterostructures composed of alternating gyrotropic and plasmonic layers [1]. The fundamental mechanism behind this enhancement is the suppression of diagonal permittivity elements in the effective medium approximation, allowing the off-diagonal elements responsible for nonreciprocity to dominate.

By approaching epsilon-near-zero (ENZ) regime [1], we demonstrate that gyrotropic/plasmonic multilayers can achieve orders of magnitude enhancement in nonreciprocal response compared to bulk gyrotropic media. Our theoretical model is validated through numerical simulations, revealing strong unidirectional transmission and near-perfect optical isolation. The impact of realistic material losses and frequency dispersion is also investigated, showing that the enhanced nonreciprocity remains robust even under realistic material configurations. To demonstrate this idea, we illustrate in Fig. (1), the transmission amplitude τ_+ and τ_- as a function of (D/λ) . Here, we assume that the gyrolayer is characterized by $\epsilon_t = 0$ and $\epsilon_g = \pm 0.012$. As seen in Fig. (1), around $D/\lambda = 4.55$ (first-order Fabry-Perot resonance) and $D/\lambda = 9.1$ (second-order Fabry-Perot resonance) there is a perfect discrimination ($\Delta\tau = 1$) between the two polarization states.

The study highlights the potential of gyrotropic heterostructures for next-generation photonic devices. Specifically, the effective medium formed by structured multilayers exhibits tunable nonreciprocal properties that can be optimized for different operational frequencies. The work presents a comprehensive analysis of the design parameters, including the thickness of individual layers, the number of unit cells, and the influence of different material choices. Our findings suggest that by fine-tuning these parameters, one can maximize nonreciprocal effects while minimizing material losses, thereby paving the way for compact, high-performance nonreciprocal photonic components.

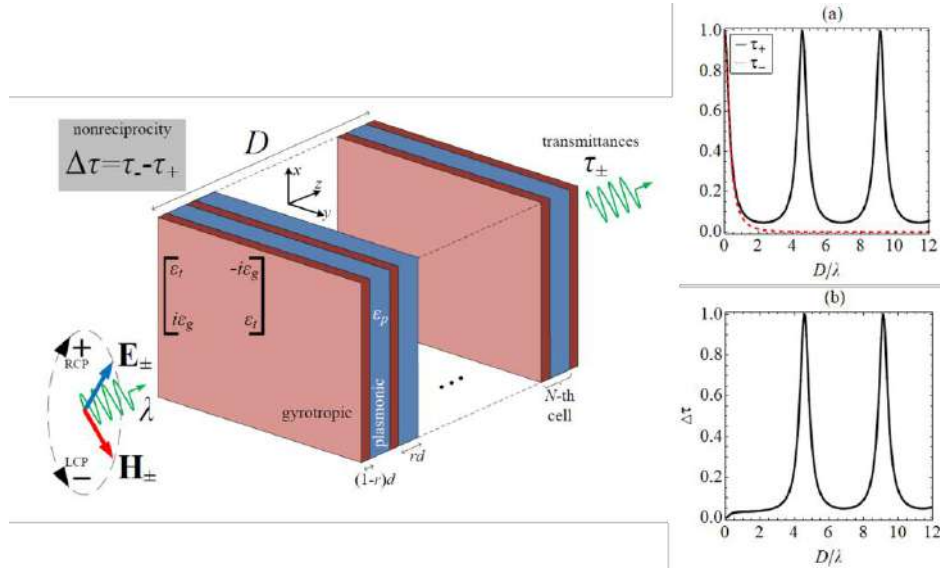


Figure 1: A multilayered structure of thickness D and N cells, each of which comprises a gyrotropic slab with relative permittivity tensor $[\epsilon]$ and a plasmonic slab with relative permittivity ϵ_p . The structure is excited by a normally incident circularly polarized wave. Each cell has thickness d and the plasmonic layers have a filling factor $0 < r < 1$ into the whole configuration. For each of the directions of rotation of the incident electromagnetic fields the structure produces transmissivities $\tau_{\pm}$. The difference $\Delta\tau \equiv \tau_- - \tau_+$ is a metric of how nonreciprocal is the structure. (a) The transmissivities $\tau_{\pm}$ as functions of the thickness of the gyrolayer D normalized by the operational wavelength λ . (b) The difference in the transmissivities ($\Delta\tau$) as function of D/λ . Plot parameters: $\epsilon_t = 0.0$, $\epsilon_g = 0.012$.

Our results indicate that gyrotropic multilayers can be designed to achieve significant nonreciprocal transmission even with relatively weak gyrotropic responses in the constituent materials. This approach mitigates the need for extremely strong external magnetic fields, reducing power consumption and simplifying device integration. The findings of this research provide a viable pathway for developing advanced nonreciprocal photonic technologies, with applications in telecommunications, optical computing, and sensor systems. By utilizing structured gyrotropic-plasmonic interfaces, we introduce an efficient method for enhancing nonreciprocity without requiring extreme material properties.

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MU-METAL THICKNESS PARAMETRIC EVALUATION STUDY FOR SENSOR DESIGN

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Abstract—Mu-metals are used for magnetic shielding. Sensor design is a field where mu-metals are often used so that sensors are protected from different external magnetic fields. In this study, different designs for mu-metal covers are examined parametrically in which thickness serves as the main parameter. Thickness, which is the key parameter of this study, is very important for magnetic shielding and weight considerations.

Keywords—mu-metal, mu-metal thickness, magnetic permeability, effective shielding, magnetic shielding, parametric study, magneto static analysis

I. INTRODUCTION

Mu-metal is frequently used in sensor designs to protect the sensor from the Earth's magnetic field and external electromagnetic fields. Magnetic fields cause a bias error in sensor measurements. Mu-metal acts as a shield against externally applied magnetic fields and bends the field through the material, thereby protecting it. Mu-metal materials are mostly effective against low-frequency AC (<20 Hz) and DC fields.

The thickness of the mu-metal shall be determined according to the expected performance of the sensor. Mu-metal shall have the minimum possible thickness as much as possible. The reason for the minimum thickness is “weight” foremost, as there is more than one sensor which is protected by a set of mu-metal cover(s) meaning more and more weight. The importance is more emphasized, especially if the sensors are used on air platforms and each gram becomes more problematic which makes redesign phase start. One other restriction to be considered when determining the thickness for mu-metal is manufacturing methods. Such materials can be shaped by sheet processing (water jet, deep drawing, etc.) and welding (laser, etc.) methods, though the latter one has some drawbacks. A very low thickness or very thick material is hard to manufacture and the thickness limits the manufacturing method.

Although there are many different designs for mu-metals, the most preferred ones are designs that overlap or are glued on top of each other. In this article, parametric studies conducted to examine the effect of the parameters in design (mu-metal thickness, overlap amount, gap in between and overlap values, slot/hole effects, magnetic field direction, etc.) are explained.

II. MAGNETIC SHIELDING WORKING PRINCIPLE

A. Mu-metal working principle

According to Maxwell's laws, magnetic flux shall necessarily complete a magnetic circuit. Therefore, it is necessary to ensure that the magnetic flux flows around the volume that needs to be shielded. For this purpose, the volume to be shielded must be wrapped with a shield material in a closed loop that allows the magnetic flux to flow around it. In order for the magnetic flux to be able to flow around the volume without leaking into it, a shield made of materials with very high magnetic permeability, such as mu-metal, is needed. In practice, since the volume to be shielded is often vacuum or air, the geometry of the shield and the magnetic permeability of the material used shall be the main determinants of the final shielding effect [1].

B. Effect of Magnetic Permeability on Shielding

As the magnetic permeability of the shielding material used in shielding increases, a larger portion of the magnetic flux shall flow over the shield instead of flowing from the volume to be shielded. (This is similar to electrical current preferring to flow over the smaller of two parallel resistors.) Therefore, an ideal shielding material should have a very high magnetic permeability.

In practice, relatively permeable metal alloys such as mu-metal can be produced, but these materials begin to lose their shielding effects after reaching a certain magnetic flux, and magnetic saturation is observed. This saturation effect causes the mu-metal alloys commonly used for magnetic shielding to lose their shielding effects in high magnetic fields. Therefore, in magnetic shield design, the highest magnetic fields to be exposed should be taken into consideration, and whether the material shall reach saturation or not in these fields should be analyzed. The material that keeps the field away and saturates as little as possible is the right choice for this kind of application and often the materials, which reach saturation easier, have lower magnetic permeability. Once the material for shielding is chosen, which is mu-metal for this study, , increasing the shield thickness or the number of shield layers are common solutions [2,3] which means a trade-off here.

C. Effect of Shield Geometry on Magnetic Permeability and Shielding

For effective shielding, the magnetic flux entering the shield must completely flow around the volume and then exit the shield. Any discontinuity (such as a hole) on the shield creates a weak point where the magnetic flux can penetrate. Therefore, the ideal shield geometry is a shell that completely surrounds the volume to be shielded, without any cuts or holes. However, the production and integration of this ideal shield geometry pose significant challenges. Since access to the interior of the shield is necessary, a shield geometry consisting of multiple parts, such as a box-lid pair or layers glued on top of each other, with junction points intersecting as much as possible, is preferred over a single-piece shield with perfect continuity.

In addition to the magnetic permeability mentioned in the section B, the thickness of the shield also facilitates the flow of magnetic flux through the shield. At the same time, the magnetic saturation effect mentioned in the same section is also dependent on the thickness of the shield. Thin shields reach magnetic saturation in a lower field. Therefore, the thicker the shield, the better the shielding effect and saturation performance will be, but it is important not to use excess mu-metal material, which is both costly and relatively heavier.

Therefore, the highest magnetic field that the sensor can tolerate in the context of its use should be determined, the shielding factor that the shield needs to provide should be determined, and the minimum shield thickness which provides this factor should be selected. Besides thickness, the effective length of the shield, which is the average length of the path that the flux travels through the shield, also affect the magnetic permeability of the shield. As the path length increases, permeability decreases. Therefore, in order to keep the effective path length as short as possible, the shield should be wrapped as closely as possible around the volume to be shielded. In some cases, increasing the thickness of the shield to reduce the saturation effect can improve the saturation performance by causing a slight increase in the effective magnetic flux path length, but it can also reduce the shielding factor by reducing the magnetic permeability. Therefore, there may be a trade-off between saturation performance and magnetic permeability when calculating shield thickness.

III. ANALYSIS SETUP DETAILS

In “Comsol” program [4], magneto static analyses are conducted for the external magnetic field affecting a coil protected by mu-metal covers. The coil, which has the rectangular cross section, is the point of interest for this sensor; the mu metal covers are the parts, which overlap onto each other and within a distance in-between, protect the coil from the external magnetic field. (Fig. 1) Analyses are run for DC frequency, and there is no study based on AC (variable) frequency. The aim is to see the cases in which the thickness can be minimized, so the design shall be optimized [3].

To shorten solution times, mainly “coarse mesh” option is used. It is certain that more accurate results can be obtained with finer mesh option, but significant differences are not observed in the analyses conducted with both coarse and fine

meshes at the beginning of the study. Due to the lack of significant differences in the results, analyses continued with the coarse mesh to complete the numerous analyses here.

Analyses can be performed in 2D or 3D. 2D analyses (axisymmetric) shorten the solution time. However, in this study, 3D modeling (derived from a 2D sketch) is utilized to see the change in magnetic flux density across all sections. It is important to provide constraints within the sketch because structure can be distorted due to changes in parameters during analysis.

A larger spherical volume covering all parts is determined for the analysis, and all empty regions are assumed to be filled with air. For analyses conducted at room temperature, temperature changes and therefore dimensional changes in the parts or changes in material properties due to temperature are neglected.

The input value for magnetic flux density is determined as 10 mT (0.01 T). This value is accepted to be due to external influences and is much larger than another effect, which is the Earth's magnetic field. It is generally expected that the input magnetic flux value shall decrease to the order of 1/100-1/1000 on the coil in these analyses. DC magnetic permeability value is accepted to be 140,000 as a characteristic of mu-metal.

Although this value is higher in various sources (up to 400,000-500,000), a lower value has been taken from the literature for the desire to remain on the safe side due to the change in the permeability property of mu-metal over time. In addition, this value has been obtained by conducting various tests on the shield at hand.

In nested mu-metal cover designs, there is a clearance gap due to the tolerance of the productions. (The inner part diameter is larger than the outer part diameter, and an interference fit is generally preferred.) To fill this clearance gap, Kapton tape is often wound around the inner cover external side. Another function of the tape is to hold the covers together against external factors (vibration, etc.). In addition, these covers are screwed onto the bodies to which the coil is connected.

The thickness of the inner and outer covers is assumed to be the same along the section. Having the same thickness along the section also facilitates manufacturing in bringing the parts to their final dimensions.

In the analyses, parameters are increased by the same amount of increment, and the start and end values are based on experience. Thickness analyses, which started at 0.6 mm, are parametrized by increasing 0.1 mm in all parts and ending at 1.5 mm. Thickness is increased for all parameters at the same time; for example, a thickness of 0.6 mm is kept constant as a parameter, and any other thickness is not modeled as 0.8 mm; all thicknesses are increased gradually the same way. The reason for this is that having numerous analyses in this way and the processes taking too long. Additionally, such designs are not very practical in practice. In addition, the amount of overlap is simultaneously changed with the shield thickness. (i.e. as the thickness of the covers is increased 0.1 mm in each step, the overlap is increased 1 mm at the same time and this is achieved by parametric sketch design in the simulation environment)

In real situations, there are radii on the inner and outer corners of sheet metal parts due to bending. These radii vary depending on the thickness of the material during mold production. During (parametrically defined) analyses, radius information for the inner or outer cover has not been specified. Although the absence of radii results in increased flux density at sharp corners, this situation has not been considered as it does not reflect reality.(Fig. 3)

The volumetric average magnetic flux of mu-metal covers is being considered as the important result, while the local flux density should be neglected.

There is no total weight limit specified for the covers, and as mentioned, preferred one is to go with the lightest possible design.

The characteristics of the coil that the shield needs to cover, as well as the distances to the inner and outer mu-metal covers, are determined based on a specific design in the initial analysis, and as the parameters change, the distances also change. (The distances between the coil and mu-metal cover are not constant, meaning a volume limit has not been set.)

IV. ANALYSIS CASES

In this section, the analysis cases are named and described. (see Fig. 2)

Case 1 (V1): In the first case, parameters such as the amount of overlap, outer mu-metal side thickness, outer mu-metal top thickness, inner mu-metal side thickness, and inner mu-metal top thickness are determined as the main parameters. Parametric analysis has been run to see how the magnetic field density changes for varying thicknesses. It should be noted again that the parameters are increased/decreased simultaneously.

Case 2 (V2): In the second case, the first case is conducted again this time to see the effect of parameters individually by increasing each single parameter step by step while keeping the others constant. In the analyses of the first and second cases, since the covers are brought into contact with each other, the gap is negligible.

Case 3 (V3): In the third case, a different study is done to see the effect of the gap between covers, the gap begins from 0 and ends at 1 mm. The gap can be imagined as the interference between covers.

Case 4 (V4): In the fourth case, effects are observed by changing the flux direction. (direction x and 45° vectored combination of x and z directions(inclined)). The combined magnitude is the same for all subcases.

Case 5 (V5): In the fifth case, a slot is added to one of the covers, and the effect of the slot was observed for direction x, direction z and again 45° vectored combination of x and z directions(inclined) magnetic flux.

Case 6 (V6): In the sixth case, 3 screw holes were added to the cover without a slot, and analyses were run for the worst-case scenario, which is an inclined magnetic flux.

Case 7 (V7): In the final part, in the 7th case, the effect of mu-metal plates adhered to a closed mu-metal volume is examined step by step, first plate put above the cover and then to both above and below of the cover.

The “_” sign shows the subcase of the main case. The coordinate system is shown on the results. The direction is also implied in Fig. 2.

V. CONCLUSION

The following points are important as they shall be considered during design period. The results are also given here in this chapter. (examine the figures in RESULTS page)

The magnetic flux input and direction should be known and/or measured accurately.

Even if the weight/volume requirement (or maximum limit) is not given to the designer, it should be expected as the most important parameter in such designs.

The permeability of mu-metal should be checked not only through the raw material datasheet but also through measurement. The permeability of mu-metal changes over time and is related to aging and can also be affected by handling during transportation. Additionally, mechanical production processes to obtain the final part can cause changes in permeability. (It is known that there is a change in permeability with heat input.) Therefore, measuring the permeability on the final part manufactured is beneficial.

There is no gap between the sheets except the V3 case. Difference in results can be observed by adding an air gap to the cover parts at the same time with the parameters changed. This study is a future work as the previous subject discussed.

The results indicate that the direction of the magnetic field affects the flux generated in the parts.

The slot is both important as a single parameter and considering the direction of the external field also has a major role for the results.

All cases show that the corners and areas close to corners on the coil are, not always but, often show high magnetic flux density compared to the other areas. This is due to numerical errors of coarse meshing and to the fact that these areas are close to both ends of the overlap.

Even the thinnest design decreases the magnetic flux density on the coil to 1/100th of the original flux. This is valid for completely enclosed volume simulations such as V1 and V2.

The first case (V1) implies that as the thickness increases, the flux density decreases. Though this being a very anticipated result, the overlapping is highly effective to function as a barrier and to decrease the overall average flux values on the coil.

The second case (V2) shows that the external cover's side thickness's change alone has more impact on the decrease in the flux density on the coil compared to other parameters. It should be kept in mind that if the requirements are tight and the designer is allowed to do little change on the parameters, this thickness shall be the one to be considered first.

In the third case (V3), the gap between the covers seems to be remarkably effective on the flux density inside the closed volume. As the gap increases, it is sure that the flux is allowed inside directly onto the coil. Though this is not a real case, the designer should be aware of this situation and close the gap with proper material while using necessary tolerances for the fit between covers.

The fourth case (V4) shows that though the volume is again enclosed one, the direction of the external magnetic field has a major effect on the results.

Both the flux density distribution and magnitude on the coil are very dependent on the input, i.e. the direction and magnitude of the field applied, as shown in the figures. These are again important parameters to consider in the early stages of design.

Though the total flux density is close in terms of magnitude for both cases (i.e., V4_1 and V4_2), the results are more emphasized on yz plane rather than on xz plane when the field is in direction x.

Another conclusion is that increasing the thickness (side thicknesses of the covers) in V4_1 is more effective on decreasing the flux density.

In the fifth case (V5), the slot seems to drive the results for all subcases. Though the scenario is not a real one, in the sense that the holes are closed with some proper material in design, the designer again should be careful about this point. Parametric analyses should be run for the hole with the smallest possible dimensions.

If a hole like a slot is available on the cover, then increasing the thickness does not seem to lower the flux density as much as it does in other cases if the field is not perpendicular to the slot. As in case V5_3, increasing the thickness of the material is effective when the field is perpendicular to the slot.

If the magnetic field direction is exactly known, then the slot should not be imposed to the field directly, better be on the other side of the cross section if possible. This not only decreases the flux density results, but also lets the designer be effective in increasing or decreasing the right thickness of the covers accordingly.

The sixth case (V6) shows similar results with case 5. The screws are close to the coil, so the distribution is very much affected from the design particularly.

In the seventh case (V7), though different cases are considered, the results show that even a slight increase in the new plate cover thickness (glued on top the old cover), there is an improvement to decrease the density. The direction is not effective for cases V7_1 and V7_2, which are the initial trials for this case.

It is worthy to note that, compared to all other cases, V7_3 shows that even for the least thickness (0.5 mm), the results are greatly improved considering the magnitude of the density on

the coil. (the results are $1/200^{\text{th}}$ of 10 mT at most) However, the results seem to change not so effectively as the thickness is increased for the case V7_2, as the results are already improved as a sheet of mu metal is put to the other side.

Cross checking all parameters at the same time is recommended as an additional part for this work. To clarify, for instance simulations are run while all thicknesses are 0.9 mm, except that one of the cover's top thickness ranges from 0.5 to 1.5 mm. If all these thickness trials are done, this means a very big set of data and seem to be very time consuming. The simulations in this study are simplified, but this kind of intricate study is the best way to achieve the minimum material usage. Manufacturing constraints are important for all cases even this study is further done (let us say irrespective of which parameter it is, all thicknesses are 0.6 mm, while one of them is 1.5 mm, it would be better to think whether it is feasible to manufacture or not).

It would be better to say that this study shall be referred to as a guide for the designers working on this kind of application rather than say that the best case is determined as a result of this study. Given all constraints, the designer shall go with the lightest possible design, as mentioned throughout the study, which means that these parametric analyses shall be conducted.

Besides all, it should be kept in mind that these results are all simulation based and the real cases for a determined thickness is planned ahead of this study, which will give the test and analysis comparison.

ACKNOWLEDGMENT

Thanks to colleagues Ahmet Rahmetullah Çağıl, Ece Alaçakır Demir and Eray Humalı for their contribution.

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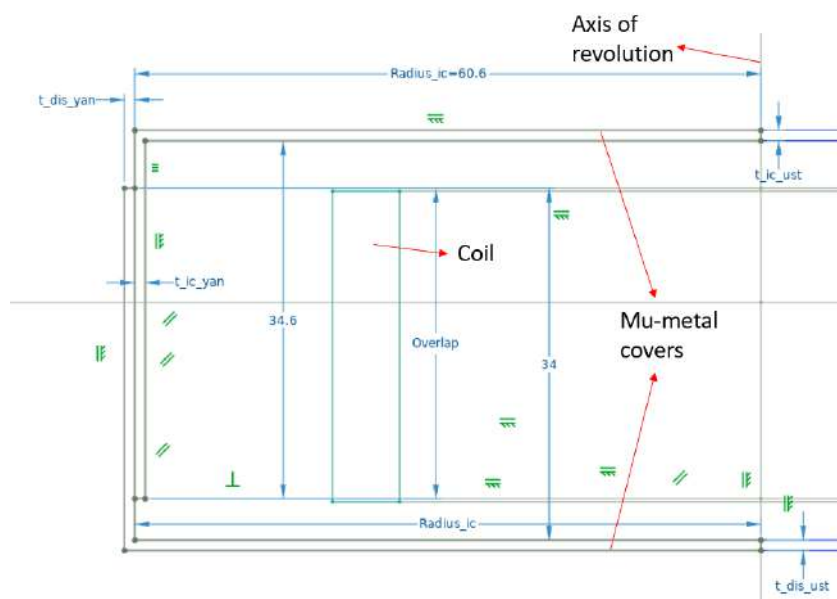


Fig. 1. 2D sketch in Comsol (cross section is revolved around the axis denoted)

Configuration	Parameter name	Range as specified in Comsol (mm)*	Magnitude (Tesla)	Direction
V1	Overlap	range(23,1,32)	0.01	+z
	t_dis_ust	range(0,6,0.1,1.5)		
	t_dis_yan	range(0,6,0.1,1.5)		
	t_ic_ust	range(0,6,0.1,1.5)		
	t_ic_yan	range(0,6,0.1,1.5)		
V2_1	Overlap	range(22,1,32)	0.01	+z
V2_2	t_dis_ust	range(0,6,0.1,1.6)	0.01	+z
V2_3	t_dis_yan	range(0,6,0.1,1.6)	0.01	+z
V2_4	t_ic_ust	range(0,6,0.1,1.6)	0.01	+z
V2_5	t_ic_yan	range(0,6,0.1,1.6)	0.01	+z
V3	gap	range(0,0.1,1)	0.01	+z
V4_1	Overlap	range(23,1,32)	0.01	+x
	t_dis_ust	range(0,6,0.1,1.5)		
	t_dis_yan	range(0,6,0.1,1.5)		
	t_ic_ust	range(0,6,0.1,1.5)		
	t_ic_yan	range(0,6,0.1,1.5)		
V4_2	Overlap	range(23,1,32)	0.007	+x
	t_dis_ust	range(0,6,0.1,1.5)	0.007	+z
	t_dis_yan	range(0,6,0.1,1.5)		
	t_ic_ust	range(0,6,0.1,1.5)		
	t_ic_yan	range(0,6,0.1,1.5)		
V5_1	Overlap	range(23,1,32)	0.007	+x
	t_dis_ust	range(0,6,0.1,1.5)	0.007	+z
	t_dis_yan	range(0,6,0.1,1.5)		
	t_ic_ust	range(0,6,0.1,1.5)		
	t_ic_yan	range(0,6,0.1,1.5)		
V5_2	Overlap	range(23,1,32)	0.01	+x
	t_dis_ust	range(0,6,0.1,1.5)		
	t_dis_yan	range(0,6,0.1,1.5)		
	t_ic_ust	range(0,6,0.1,1.5)		
	t_ic_yan	range(0,6,0.1,1.5)		
V5_3	Overlap	range(23,1,32)	0.01	+z
	t_dis_ust	range(0,6,0.1,1.5)		
	t_dis_yan	range(0,6,0.1,1.5)		
	t_ic_ust	range(0,6,0.1,1.5)		
	t_ic_yan	range(0,6,0.1,1.5)		
V6	Overlap	range(23,1,32)	0.007	+x
	t_dis_ust	range(0,6,0.1,1.5)	0.007	+z
	t_dis_yan	range(0,6,0.1,1.5)		
	t_ic_ust	range(0,6,0.1,1.5)		
	t_ic_yan	range(0,6,0.1,1.5)		
V7_1_1	t_icust	range(1,0.1,1.1)	0.01	+z
	t_icalt	range(1,0.1,1.1)		
	t_ustparca	range(1,0.1,1.1)		
V7_1_2	t_icust	range(1,0.1,1.1)	0.01	-z
	t_icalt	range(1,0.1,1.1)		
	t_ustparca	range(1,0.1,1.1)		
V7_1_3	t_icust	range(0.5,0.1,1.6)	0.01	-z
	t_icalt	range(0.5,0.1,1.6)		
	t_ustparca	range(0.5,0.1,1.6)		
V7_2	t_icust	range(1,0.1,1.6)	0.01	+z
	t_icalt	range(1,0.1,1.6)		
	t_ustparca	range(1,0.1,1.6)		
	t_altparca	range(1,0.1,1.6)		

Fig. 2. Parameters table for the cases mentioned
(*the middle value denotes the increment)

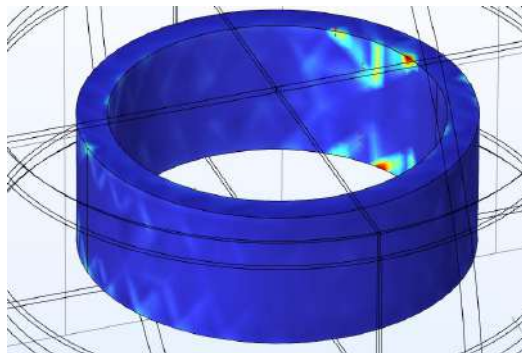
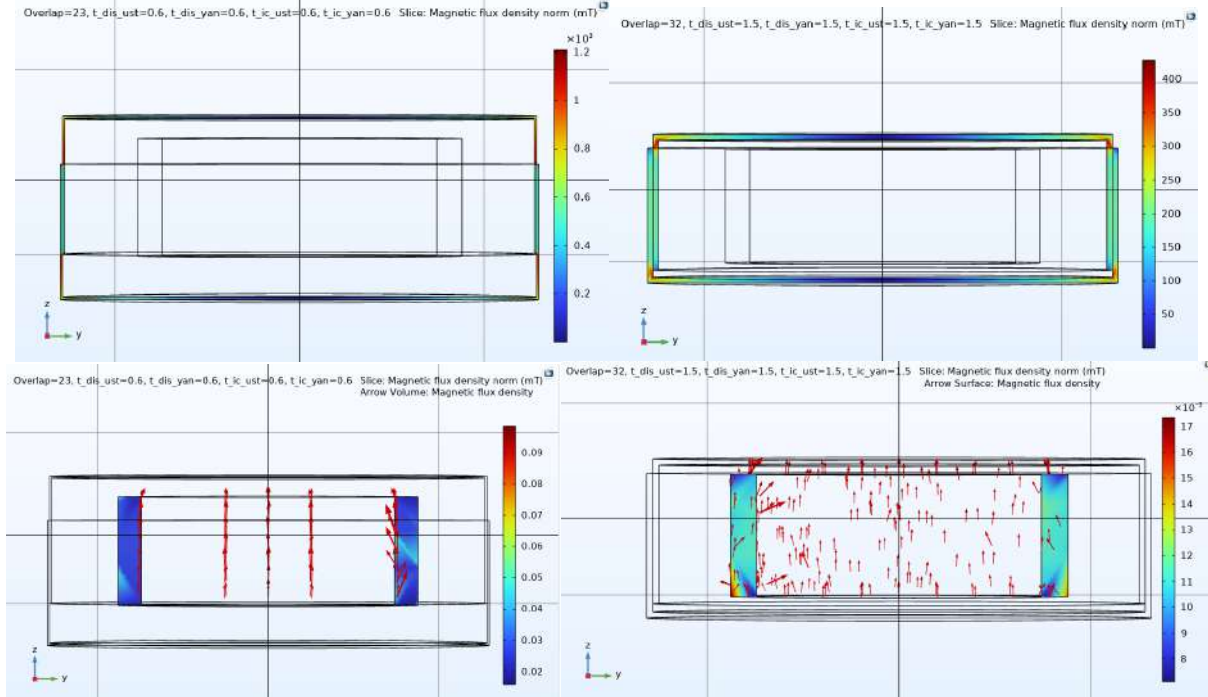


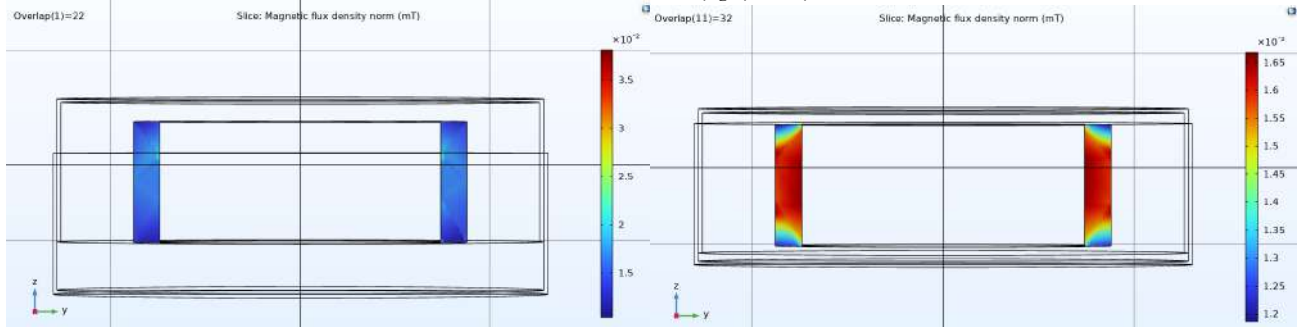
Fig. 3. Corner flux density details

RESULTS

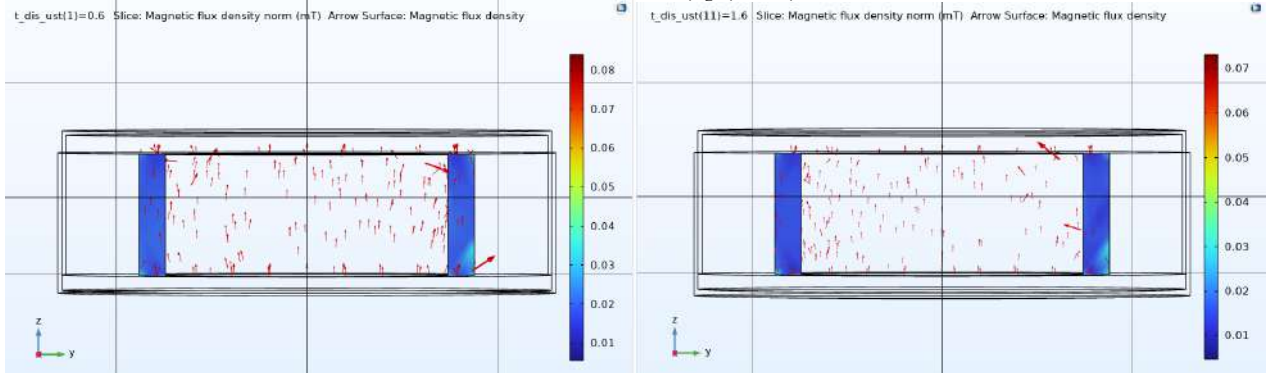
V1 (min. (left) and max. (right) values)



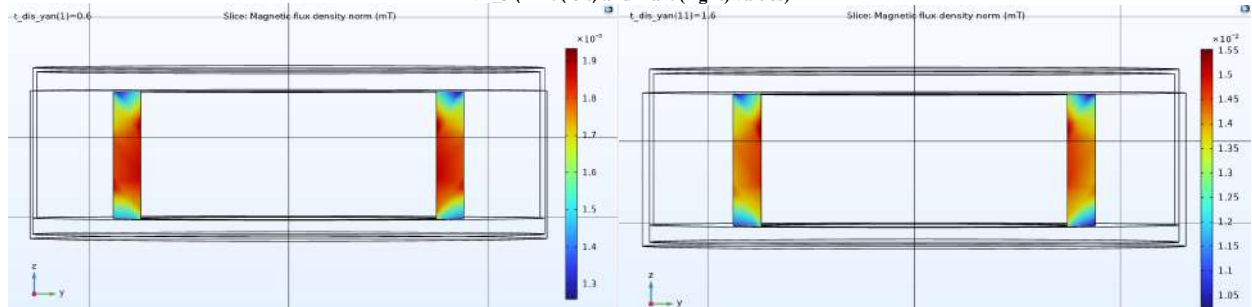
V2 1(min. (left) and max. (right) values)



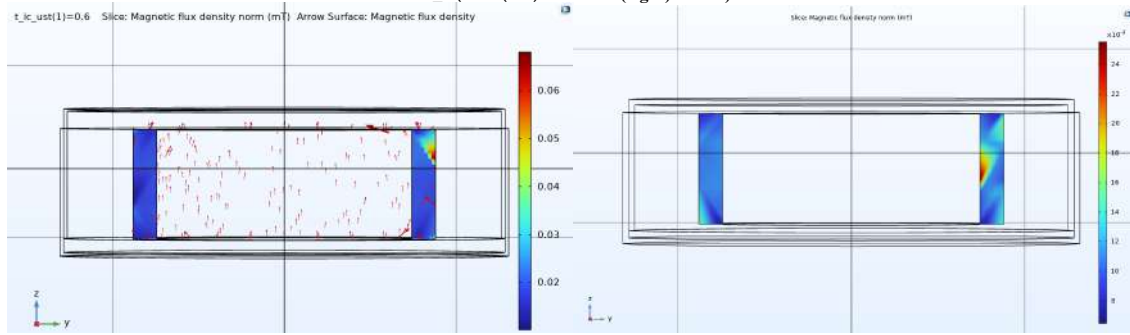
V2 2 (min. (left) and max. (right) values)



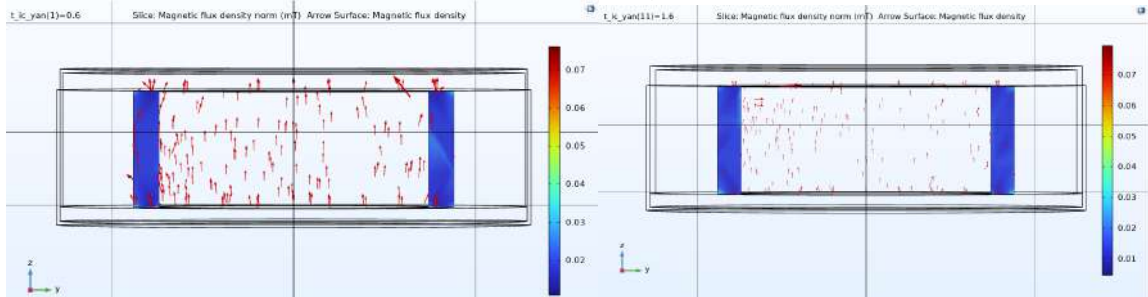
V2 3 (min. (left) and max. (right) values)



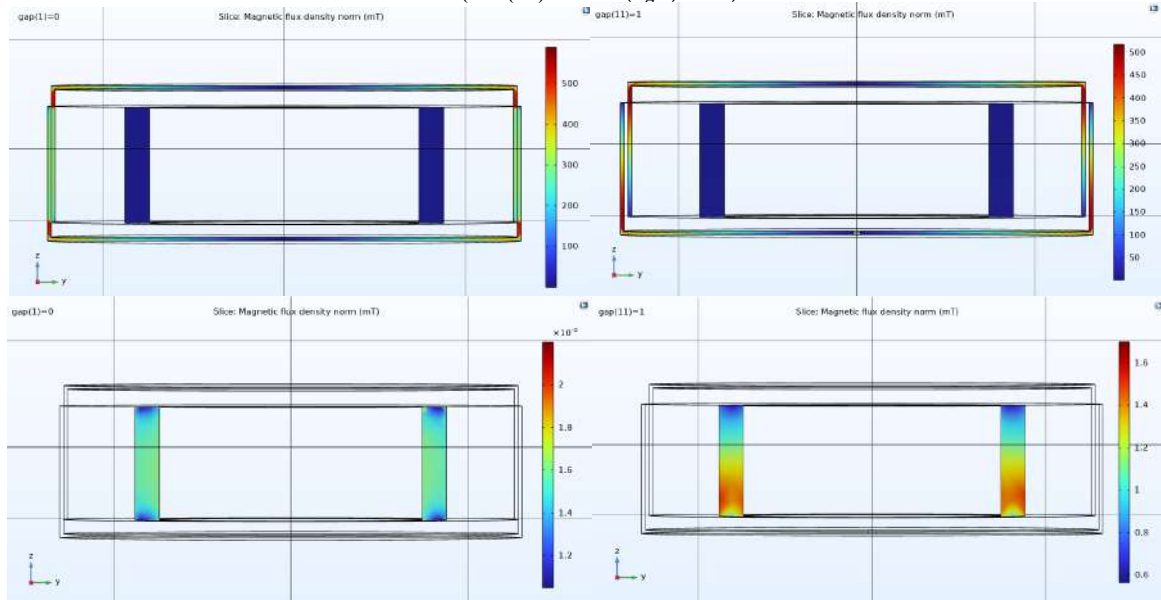
V2 4 (min. (left) and max. (right) values)



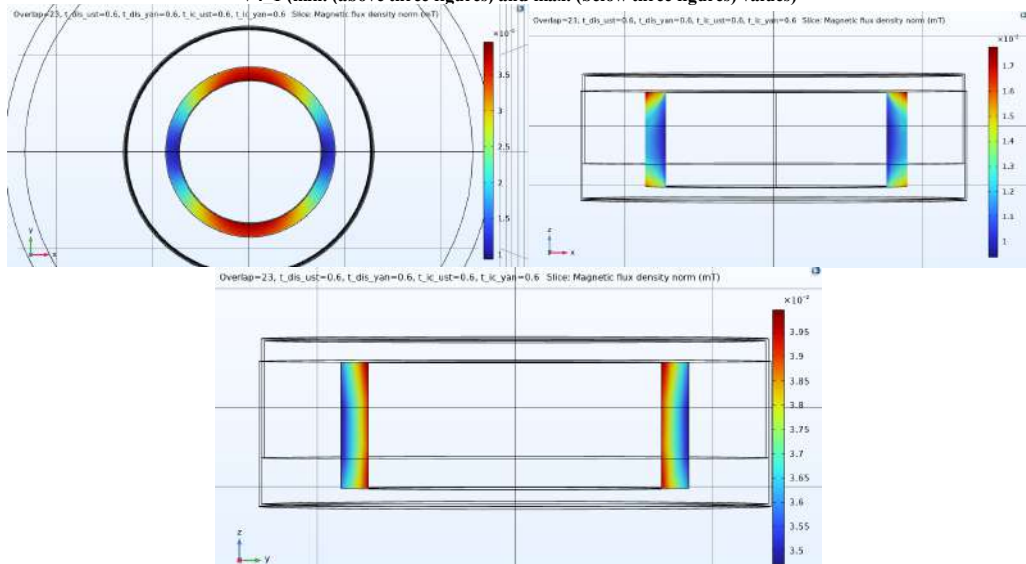
V2_5 (min. (left) and max. (right) values)

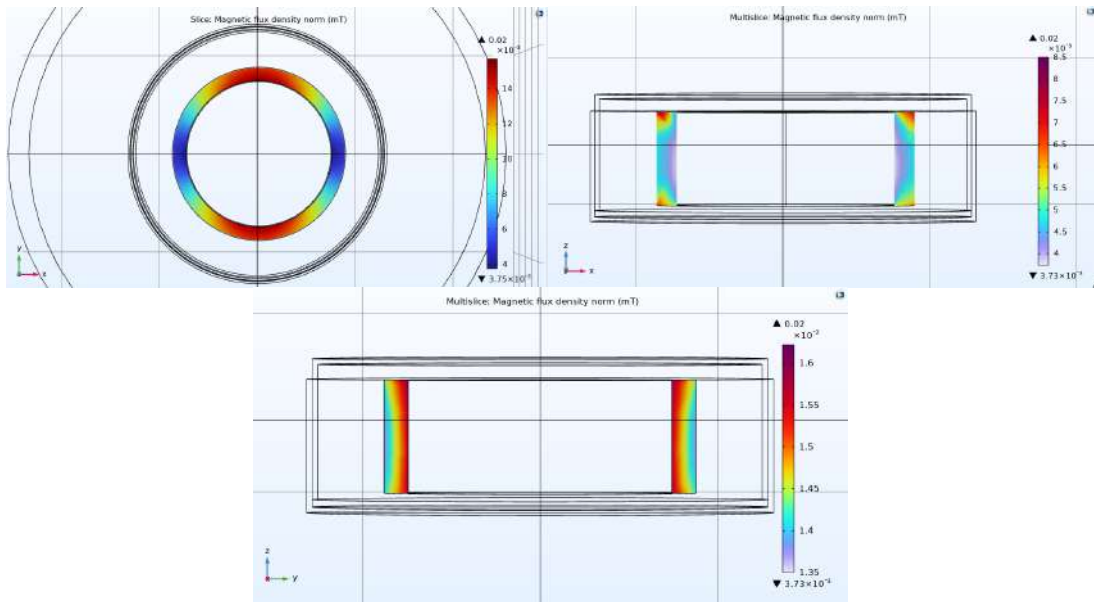


V3 (min. (left) and max. (right) values)

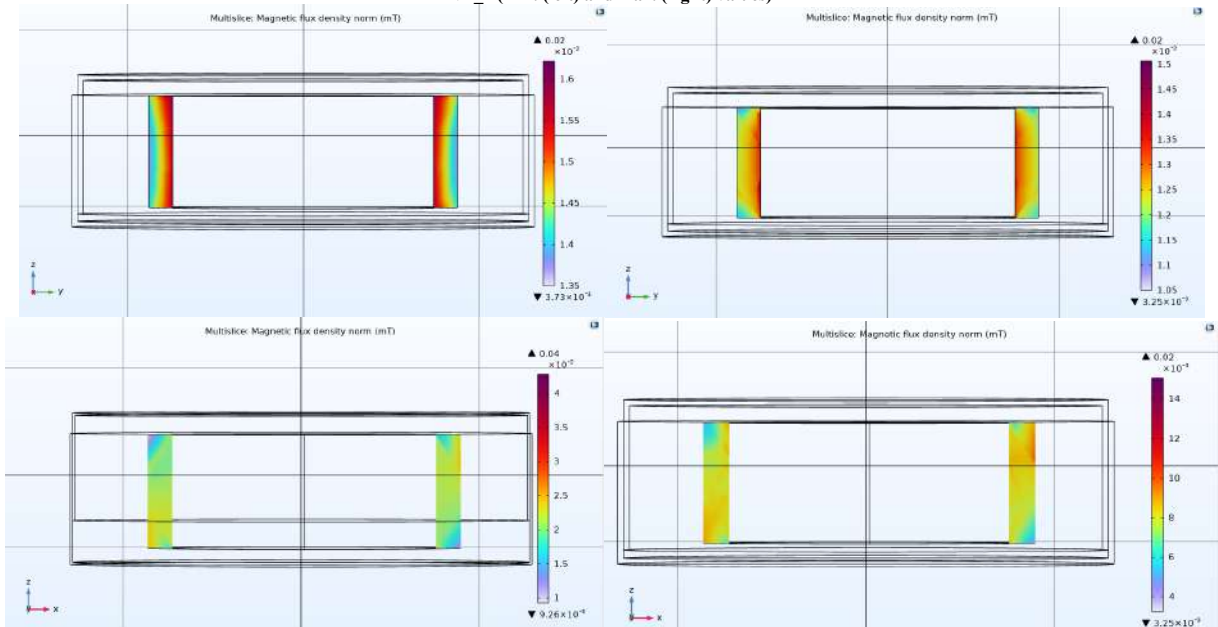


V4 1 (min. (above three figures) and max. (below three figures) values)

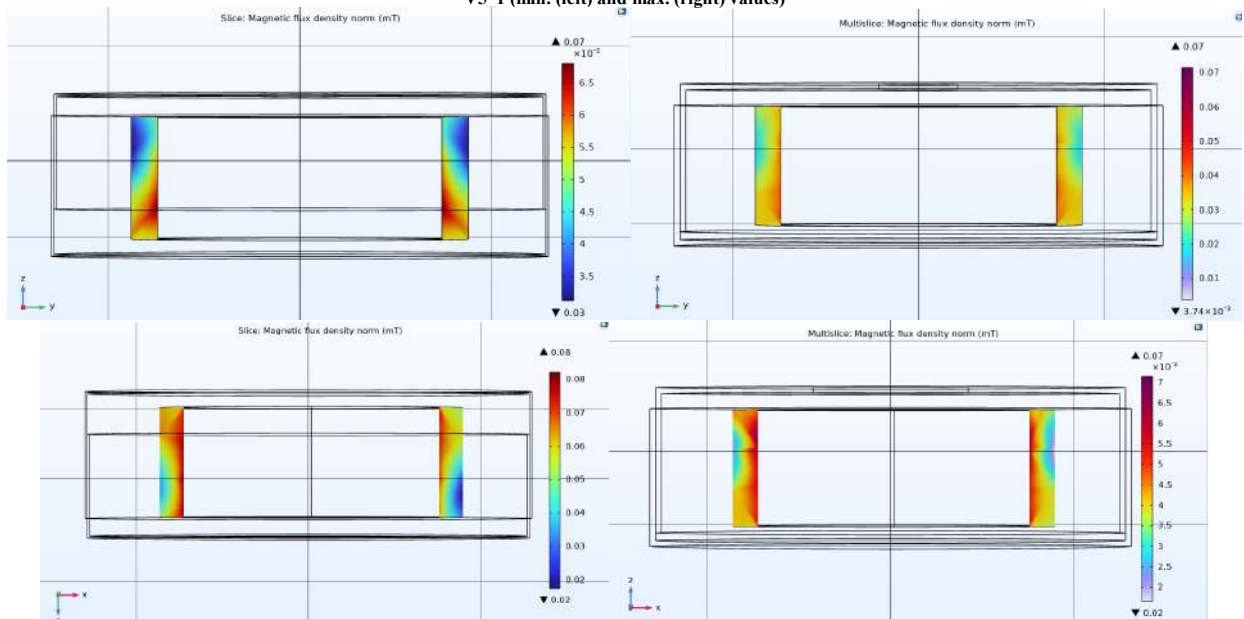




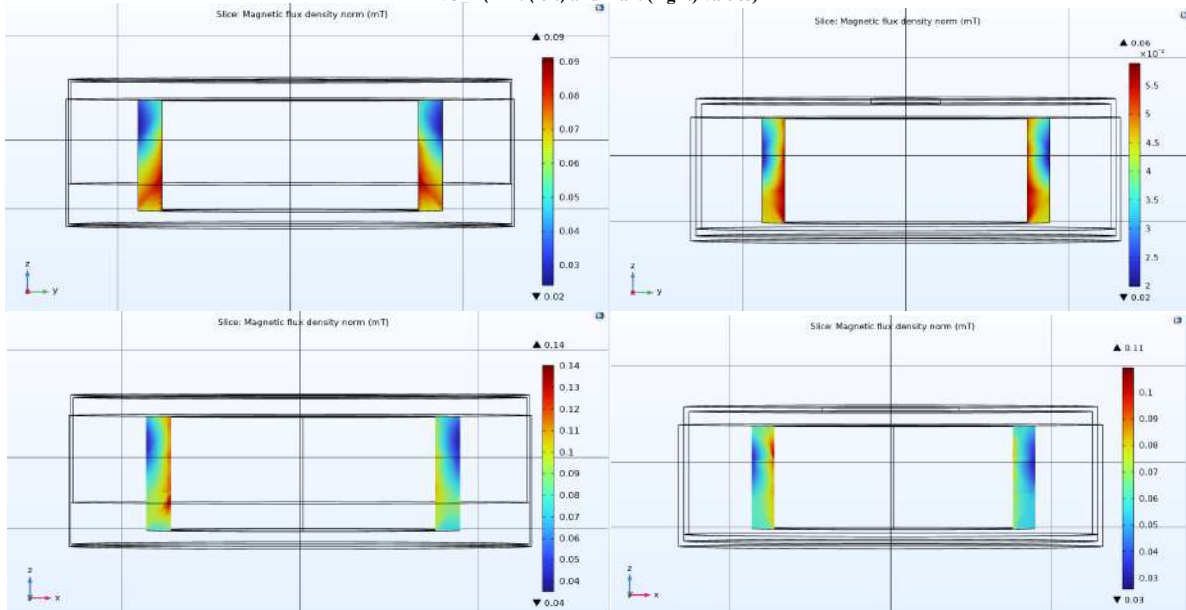
V4_2 (min. (left) and max. (right) values)



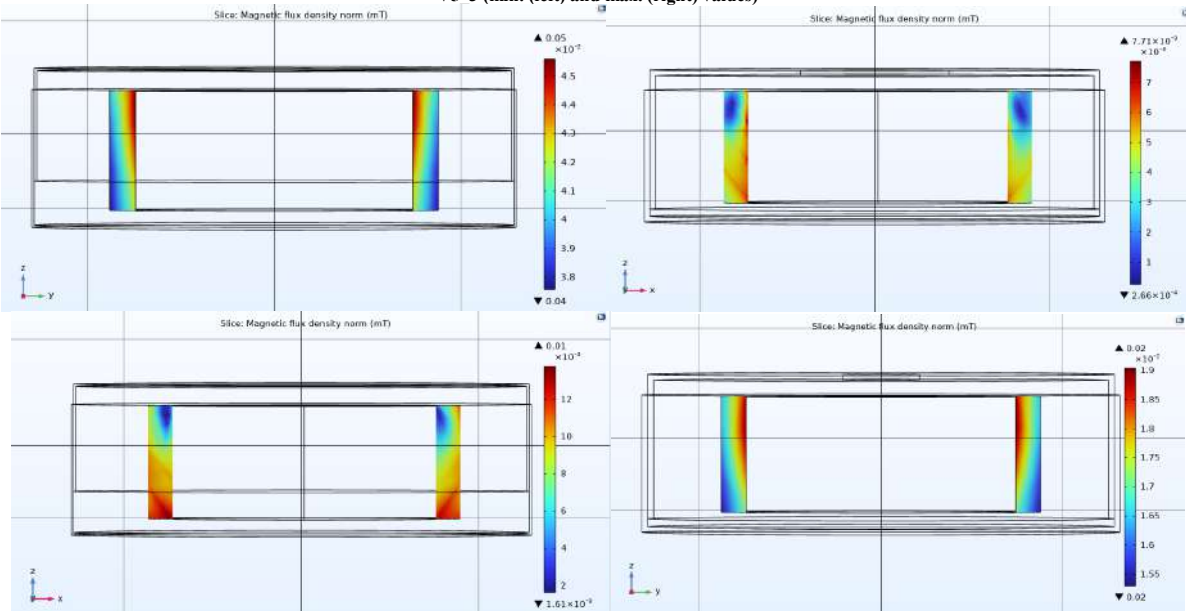
V5_1 (min. (left) and max. (right) values)



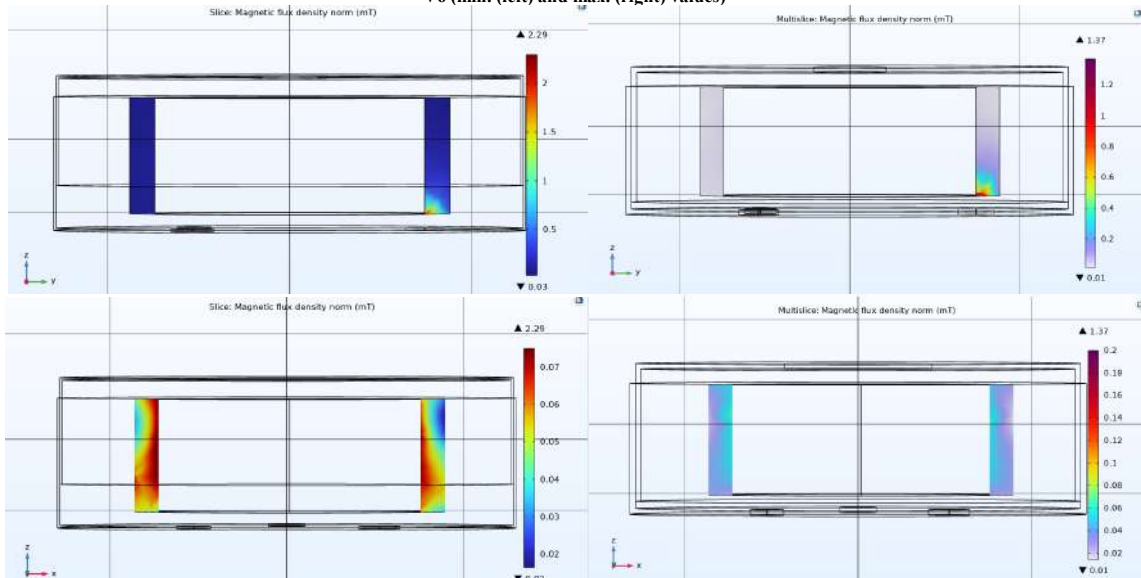
V5 2 (min. (left) and max. (right) values)



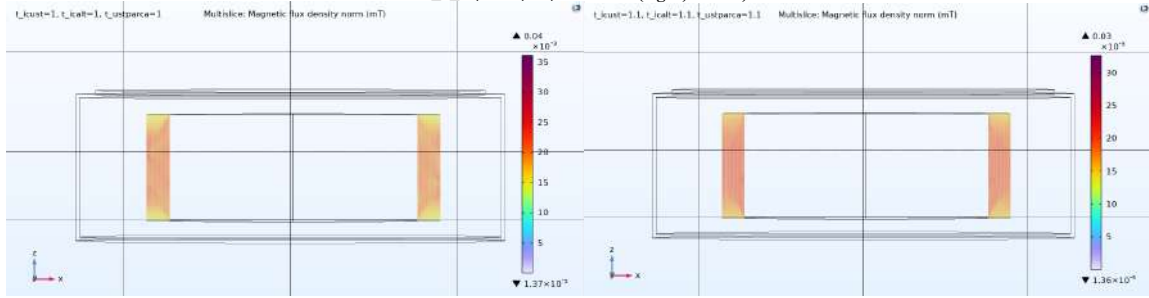
V5 3 (min. (left) and max. (right) values)



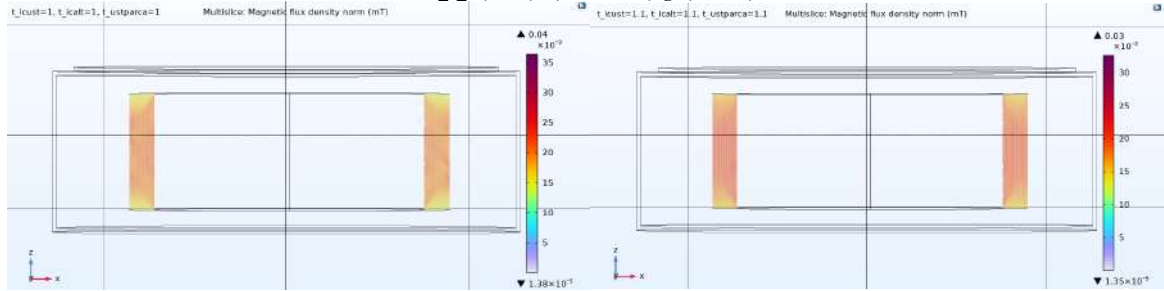
V6 (min. (left) and max. (right) values)



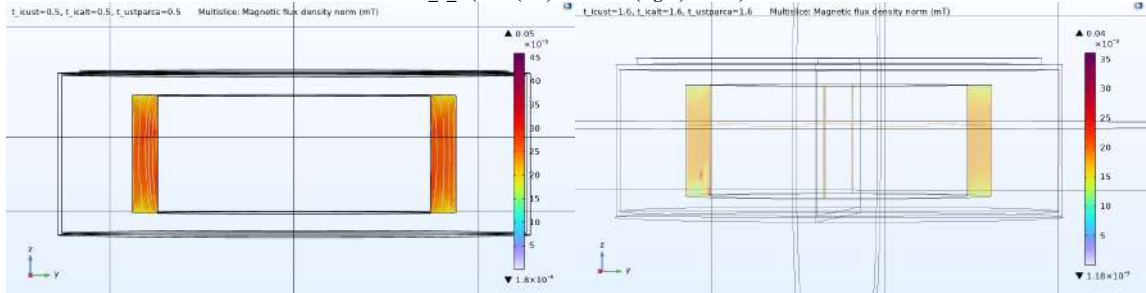
V7_1_1 (min. (left) and max. (right) values)



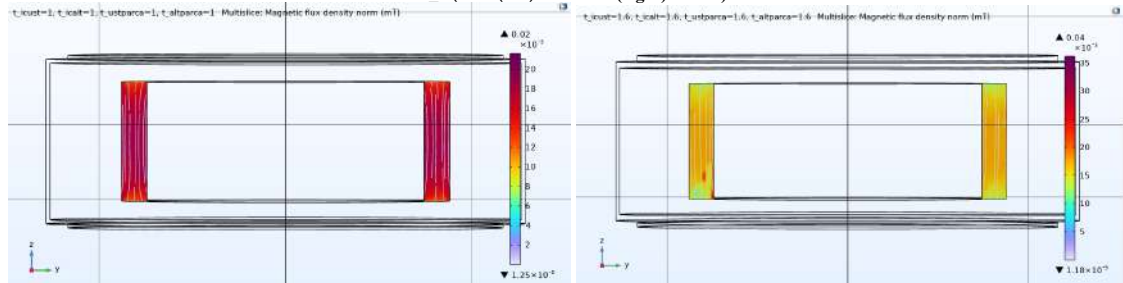
V7_1_2 (min. (left) and max. (right) values)



V7_1_3 (min. (left) and max. (right) values)



V7_2 (min. (left) and max. (right) values)



Novel materials, metamaterials, metasurfaces, FSS and EBG

Novel Sensing Technique for Non-destructive Composites Monitoring

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Abstract: We experimentally measured the transmission parameter and hysteresis loops of the composites containing magnetic microwire inclusions during the composites matrix polymerization. A remarkable change of the transmission in the range of 4-7 GHz upon the matrix polymerization is observed. Obtained results are useful for non-destructive and contactless composites monitoring.

Amorphous magnetic wires can present an unusual combination of excellent magnetic properties (e.g. high magnetic permeability, giant magnetoimpedance, GMI, effect, magnetic bistability, Matteucci and Widemann effects,) and superior mechanical properties (plasticity, flexibility) making them suitable for numerous industrial applications [1,2]. Furthermore the preparation method involving rapid melt quenching is quite fast and cheap and above mentioned magnetic softness can be realized without any complex post-processing treatments [1,3]. The development of novel applications of amorphous materials requires new functionalities, i.e. reduced dimensions, enhanced corrosion resistance or biocompatibility [1]. Therefore, great attention has been paid to development of low dimensional amorphous materials prepared using melt quenching [1,2]. Glass-coated microwires prepared using the Taylor-Ulitovsky method fit to most of aforementioned expectation: such magnetic microwires have micro-nanometric diameters (typically 0.5-100 μm) covered by thin, insulating, biocompatible and flexible glass-coating and can present excellent magnetic properties [3].

One of the promising applications of such microwires is a novel sensing technique involving free space microwave spectroscopy utilizing ferromagnetic microwire inclusions quite sensitive to external stimuli [4].

In this work, we provide our recent results on study of the stresses and heating arising during the polymerization of the matrix in FRCs on permittivity of the FRC with embedded amorphous Co-rich microwire inclusions. The amorphous structure is maintained up to the crystallization temperatures, T_{cr} , of about 554 °C.

Hysteresis loops of employed microwires have been measured using fluxmetric method previously described elsewhere [3]. Such hysteresis loops were measured under effect of tensile applied stresses and during the resin polymerization. During the polymerization process of the resin, volume shrinkage of about 8.2 % occurs and solid cured resin is obtained. However, apart of the matrix shrinkage considerable heating up to 80 °C takes place.

In order to evaluate the effect of the matrix shrinkage, we measured the influence of applied tensile stress on the hysteresis loops of studied samples and the hysteresis loops during the resin polymerization (see Figure 1). The hysteresis loops maintain their linear shape under applied tensile stress. On the other hand, the change of the hysteresis loops of the microwires embedded in the resin during its polymerization exhibits a different behavior: For a short polymerization time, t , the hysteresis loops maintain the inclined character (similar to the behavior of the individual wires under tensile stress) (see Figure1b).

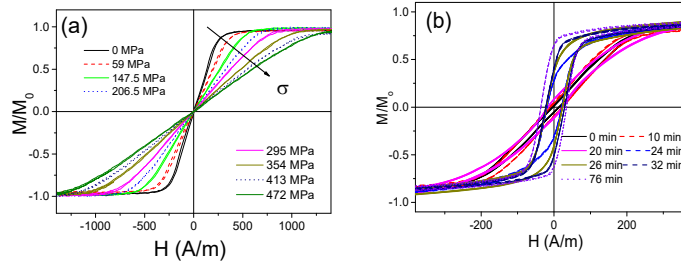


Figure 1. Effect of applied stress on hysteresis loops of studied microwires (a), and evolution of the hysteresis loops of the microwires embedded in the thermoset resin during its polymerization (b)

However, as t increase, the hysteresis loops become almost rectangular. This behavior is the opposite to the effect of tensile stress shown in Fig.1a. Therefore, we must assume the matrix shrinkage effect that create the compressive stresses and effect of heating affecting the hysteresis loops.

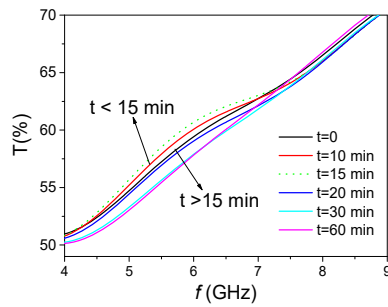


Figure 2. The Transmission, T , parameter measured using free-space system during the

As described above, we performed in-situ experiments of composites placed inside the un-echoic chamber with the glass-coated microwires embedded in a polymerized composite. We measured the transmission, T , parameter of the composite containing Co-rich microwires ($\text{Fe}_{3.8}\text{Co}_{65.4}\text{Ni}_1\text{B}_{13.8}\text{Si}_{13}\text{Mo}_{1.35}\text{C}_{1.65}$) using the free space system. As can be appreciated from Figure 2, considerable variation of the T -parameter is observed in the range frequency, f , of 4-7 GHz upon thermoset matrix polymerization. A non-monotonic variation of T -parameter upon polymerization is observed (Figure 2).

Observed changes of electromagnetic properties can be related to two main phenomena arising during the composite matrix polymerization: heating and mechanical stresses.

Eventually the same technique can be used for the remote monitoring of stress or temperature not only during the polymerization, but also for real time non-destructive monitoring of local stresses and temperature during the exploitation of the composites.

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Angle-Stable Dual-Polarized Binary Reconfigurable Intelligent Surface for Ultra-Wideband Applications

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Abstract

This work proposes a novel binary RIS using Jerusalem cross metasurfaces to achieve an ultra-broadband operation with an 82% fractional bandwidth, ensuring angular stability and dual-polarization compatibility for 5G/6G applications.

1 Introduction

Reconfigurable Intelligent Surfaces (RISs) have emerged as a promising solution, capable of dynamically controlling reflected electromagnetic waves to optimize signal direction and mitigate path loss. However, most RIS models overlook critical factors such as frequency dispersion and angular dependence of reflection phases. This paper presents a novel binary RIS designed for ultra-wideband applications, achieving an unprecedented 82% fractional bandwidth. The proposed RIS employs a self-resonant grid of metal Jerusalem crosses placed on a metal-backed dielectric substrate, with tunability enabled through binary-controlled pin-diodes. This design ensures angular stability and dual-polarization functionality, making it highly suitable for next-generation wireless networks.

2 Design and Methodology

A key challenge in designing broadband RISs is maintaining a stable reflection phase across various incident angles and frequencies. Traditional approaches use continuous phase gradients, which are complex and error prone. Instead, we implement a binary metasurface with two distinct capacitance states, ensuring robust phase contrast and reflection locality. Our analytical model establishes the relationship between reflection phase variation and surface impedance characteristics. The theoretical limit of the fractional bandwidth is governed by:

$$\left(\frac{\Delta\omega}{\omega_0}\right)_{\max} = \frac{\pi^2}{16n} \quad (1)$$

Where n is the effective refractive index of the substrate. This equation suggests that maximizing the operational bandwidth requires minimizing the refractive index while ensuring the substrate thickness remains within the practical quarter of the wavelength limit.

Simulation results demonstrate that the proposed RIS achieves angular stability for incident angles up to 40°. The optimized metasurface maintains phase contrast within the target range of 140°–220°, ensuring reliable performance for practical wireless communication scenarios [1]. Geometrical structure of the MS based on Jerusalem crosses are shown in Fig.1(a). The reflection phase for both binary states ('0' and '1') was simulated over the 10-40 GHz band (See Fig.1(b)). Though in a practical RIS, the required phase shift associated with these binary states should be achieved by switching the pin-diodes, in the present study we did not aim to tune the

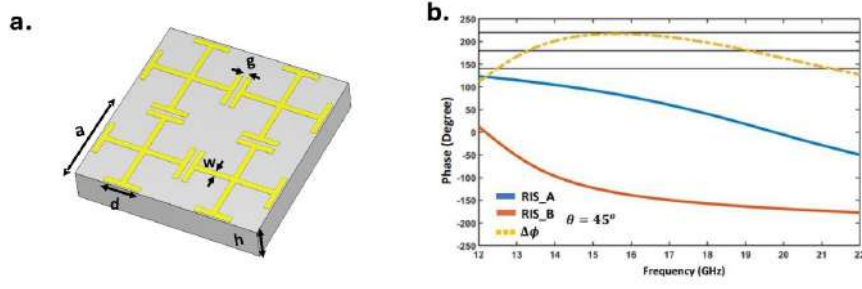


Figure 1: (a) Geometrical structure of the MS based on Jerusalem crosses. (b) Reflection phases and their difference for a MS of Jerusalem crosses studied in work [2].

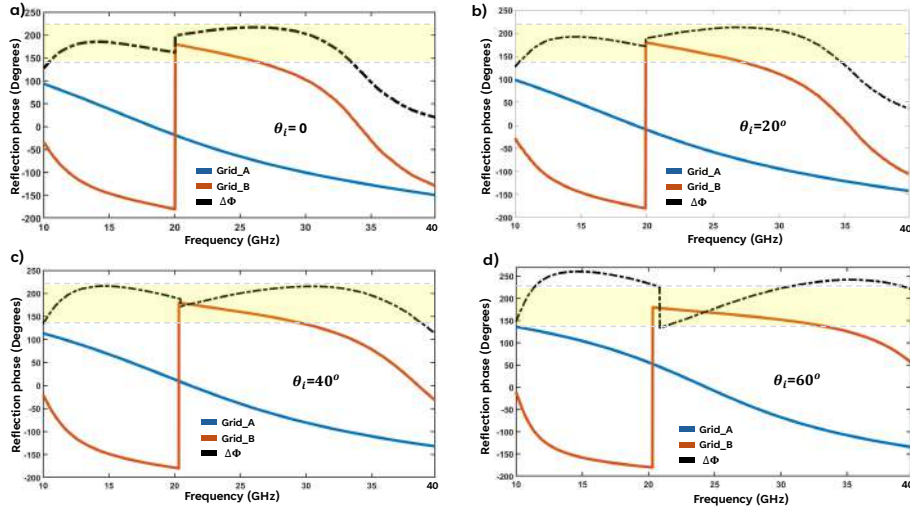


Figure 2: Reflection phases Φ_0 and Φ_1 of the suggested binary MS and their difference $\Delta\Phi_R$ in the TE case for (a) $\theta = 0^\circ$, (b) $\theta = 20^\circ$, (c) $\theta = 40^\circ$, and (d) $\theta = 60^\circ$.

anomalous reflection, and two binary states in our MS were mimicked by two different grids of Jerusalem crosses – Grid A and Grid B alternating on top of the same substrate. Geometrical parameters of the grids were optimized so as to ensure that the reflection phase of both half-periods of the binary MS (half-period A and half-period B) remains maximally stable for varying incident angles and the slope of the reflection phase would be sufficiently stable over the maximal frequency band. The geometric parameters of the grid A are as follows: $a=2.5$ mm, $d=0.06$ mm, $w=0.1$ mm, and $g=0.2$ mm. For grid B we have the same a, w but $g=0.05$ mm and $d=1$ mm. Fig. 2(a)-(d) shows the reflection phase for different incident angles from the normal incidence up to 60° for the TE polarization of the incident wave.

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Unfoldable / foldable antenna solutions using textile features

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Abstract: Scienteama Company is developing new textile antenna solutions. One of the possible application is newspace and nano satellite. Antenna deployment is a very interesting point for these very small satellite with antenna bigger than the mechanical structure.

In the context of newspace, antenna deployment is a solution for solving the problematic of larger size of antenna versus smaller size of spacecraft structure.

Combining very low mass and high flexibility, textile antenna solutions answer well to the requirement (close to 4 time less than a classic antenna and wrinkled to be installed in a small area).

Scienteama has developed several kind of antenna structure with a proprietary textile approach using textile properties and memory form wires combined directly in the textile structure.

Thank to this technology that is patented by Scienteama, several kind of antenna made with textile implementation could be equipped with deployment features:

- Parabolic antenna that could be unfolded with bio inspired method coming from flower opening.
- Dipole and monopole structure permitting long structure deployment for low frequency.
- Patch antenna.

These antennas provide a new interesting vision of trading of the size, mass and performances.

Combining origami textile method and thermic based deployment of memory form structures.

Antenna structure with this technic is composed of textile assembled following a Scienteama process in order to get the best mass / size ration including the memory form property optimized in the positioning in order to get the best energy / deployment ratio using thermal increase with propagation of a current.

Power necessary for unfold the antenna is depending of the size and mass of the structure.

In earth atmosphere the air is acting as a cooling system and reduces the thermal elevation and a solution is to manage thermal gradient in the textile architecture.

In space, without convective heat transfer, the vacuum configuration is helping the mechanism.

Scienteama will present a status in the development in textile antenna for newspace :

- The development of textile antenna structure with good antenna performances has been achieved and validated.
- Deployment in not extreme conditions has been developed and tested.
- Folding has also been developed and tested.
- Double feature unfoldable and foldable is now developed by Scienteama and first trial on monopole will be present.

Double feature for textile antenna is facing to the technical roadblock of :

- Size of antenna vs maximum input power that the antenna withstands for deployment energy.
- For long structure, managing the deployment process is a challenge facing to energy and mechanical equilibrium.
- Cohabitation between the two-antagonist process of foldable and unfoldable at a key point.

In this context Scienceteama will present a first double feature unfoldable and foldable antenna.

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Comparative Analysis of Machine Learning Algorithms for Antenna Alignments

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Abstract: This study predicts the impact of antenna angle alignment on frequency transmission using S-parameters. Various MIMO and MISO algorithms, including Levenberg-Marquardt and Gaussian Process Regression, are evaluated. The proposed method minimizes errors and achieves up to 99% accuracy in predicting identical antenna alignments through advanced error reduction techniques.

One of the most important measuring quantities in electromagnetic wave metrology is antenna characteristics, which are governed by factors such as power gain, energy or radiation pattern, and polarization properties [1], [2]. Accordingly, S-Parameters must be immediately identified, discovered, and categorized in order for high-range frequency transmission operations to perform properly. The S-parameters have been used in literature for a number of analysis tasks, including frequency identification, radiation pattern analysis, power transmission characteristic analysis, and MIMO (multiple input, multiple output) antenna array analysis [3], [4]. This study suggests in usage of the S parameters which is using them for antenna alignment. Generally, the S-parameters are calculated and predicted as follows: S-parameters mainly deal with relationships between inputs and outputs of the ports in spectrum energy system. In this proposed method, S12 refers to the energy transferred from Port 2 to Port 1 and the two ports referred to as Port 1 and Port 2. As shown by S21, energy was transported from Port 1 to Port 2. In a general multi-port network, SNM commonly referred the energy that was transmitted from Port M to Port N, and S is typically represented as the scattering parameters [1], [5]. In this proposed method, S1 antenna has been fixed as static and S2 antenna works as dynamic, and the dynamic antenna S2 has been rotated every 30 degrees from 0 to 360 degrees. All the S-parameter values, i.e., S11 and S22 self-reflection and transmission power, S12 and S21, have also been calculated for different distances of the antenna and, in particular, S21 has been considered to compare the values of S11 and S22 since the S-parameter energy values calculated from static antenna port S1 to dynamic rotation port S2 and the experimental setup is shown in figure1. The calculated S-parameter values are generated by different angles such as 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, and 360 for different distances such as 2mm, 13mm, and 150mm. Finally, all the recorded parameter statistical values have been compared by using artificial neural networks to identify and classify the performance of antenna gain and radiation or reflection pattern. The basic working function of artificial neural networks (ANN) is discussed as follows. Recently, there has been rapid development in the field of Artificial Intelligence (AI), machine learning as derived from the concept of artificial neural network. The challenge of evaluating and comparing with competing and traditional methods has emerged as a result of the many unique ideas and techniques that have been developed to address classification and regression challenges. This research mainly focused on statistical procedures to analyze and review methodology for better comparison and exploration with the help of machine learning regression-based algorithms. It has been elevated to understand by non-statisticians with the help of advanced parametric or non-parametric tests, and the performance of algorithms is significant in order to select the appropriate regression model analysis must consider the finding of suitable regression algorithms [6].

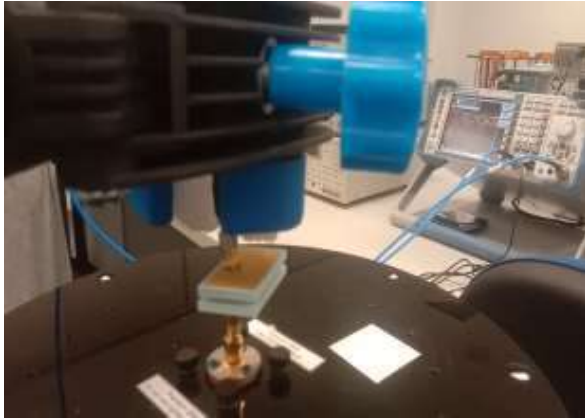


Fig. 1 The experimental setup

Simply put, the output must ensure correct evaluations of the algorithms' effectiveness on certain data sets. Such a technique also ensures the measurements are taken objectively. The second goal was to investigate and test for normality the regression method's results across multiple data sets. This is a crucial issue because researchers frequently struggle with the decision of whether to apply a parametric test or if it would be preferable to use a nonparametric test depending on whether the results of their studies have a Gaussian distribution [7]. The normality tests may help in determining the best

decision. If enough measurements were made, one might also ponder if it was safe to assume that the findings were from a normal distribution. From the above statements, it is clear the importance of statistical analysis with machine learning techniques.

The S-parameter values as reflection energy (S11 and S22) were successfully matched or aligned with transmission energy (S21) by using simple machine learning based regression methods using both the MIMO and MISO strategies. In particular, and representing the MIMO strategy, ANN optimized using LM and BR was tested over various ranges of angles and separation distances. Alignment accuracies up to 99% were achieved using this method with BR performing slightly better than LM. On the other hand, GPR and BET algorithms, which both represent the MISO strategy, have been tested and reached as well alignment accuracies up to 99%.

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Characterization of Plasma Tubes for Reconfigurable Metasurfaces and Adaptive Electromagnetic Systems

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Abstract: Reconfigurable metasurfaces demand innovative solutions for their dynamic electromagnetic control. This study characterizes plasma tubes through waveguide measurements, evaluating their reconfigurability and adaptive potential. The findings confirm plasma tubes suitability as a tunable electromagnetic element, paving the way for advanced applications in reconfigurable metasurfaces and adaptive electromagnetic systems.

Reconfigurable metasurfaces have emerged as a powerful tool for dynamically controlling electromagnetic waves [1]-[2]. A key area of interest is their integration with radiating structures to enhance or modify antenna performance. In particular, cylindrical metasurfaces surrounding dipole or monopole antennas have been explored in the literature as a means to shape radiation patterns, improve directivity, and enable frequency agility [3]-[4]. These approaches typically rely on lumped circuit elements, such as varactors or PIN diodes, to achieve reconfigurability. While effective, such components introduce complexity, losses, and limitations in tuning speed and power handling capabilities.

Plasma, with its unique ability to dynamically modify its electromagnetic properties through external stimuli, offers an alternative path to achieving reconfigurability in metasurfaces without the need for discrete circuit elements [5]-[7]. By varying the electron density and, thus, the plasma frequency, plasma can emulate the tunable characteristics of traditional electronic components while potentially increasing tuning speed and enhancing power handling.

This study investigates the electromagnetic behavior of plasma tubes through waveguide measurements, assessing their suitability for adaptive applications in the X-band (8-12 GHz). In particular, the measurement setup, schematically represented in Fig. 1 (a), was used to determine the scattering parameters of a plasma tube inserted into a rectangular waveguide under different excitation conditions (i.e., varying current levels in the plasma tube). By comparing these results (Fig. 1 (b) and Fig. 1 (c)) with an equivalent simulation model, key plasma parameters such as electron density n_e and plasma frequency f_p were extracted and cross-verified using approximate theoretical models based on electrical diagnostics [8]-[9]. The values, reported in Fig. 1 (d), confirm the possibility of finely tuning the plasma tube's response by gradually varying the induced current value.

Building on these insights, adaptive electromagnetic systems can be designed, utilizing plasma tubes as fundamental elements of a reconfigurable metasurface. Further details on the design and experimental validation will be presented at the conference.

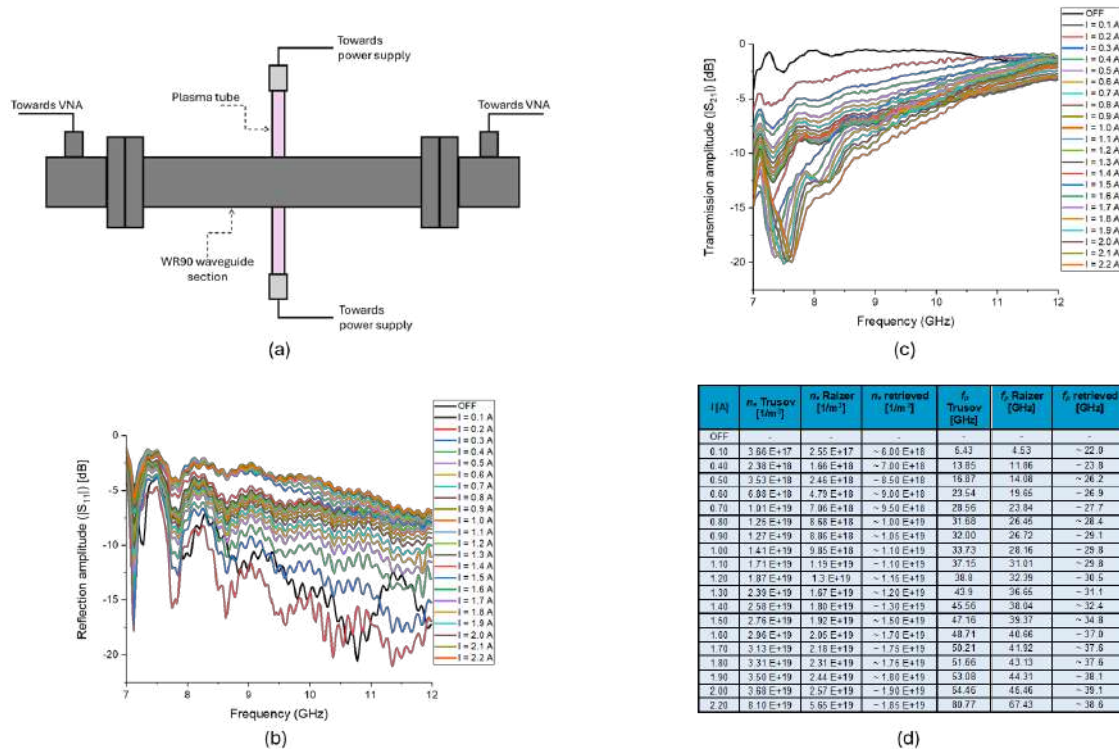


Figure 1: (a) Schematic representation of the measurement setup for the experimental characterization of the plasma tube; (b) reflection and (c) transmission amplitude of the measurement setup for different current values induced in the plasma tube; (d) retrieved parameters for the plasma tubes compared with those predicted by approximate theoretical models.

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Semiclassical analysis of Klein tunneling in graphene placed in a non-uniform magnetic field

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Abstract: The effect of an external non-uniform magnetic field on the tunneling of charge carriers through a smooth electrostatic barrier in graphene was studied. The wave function of charge carrier was found as a semiclassical solution of the Dirac equation. The dependence of transmission on the angle of incidence was investigated.

The study of the possibilities to control the transport of the charge carriers in graphene by external electrostatic and magnetic fields is important for construction of electronic devices.

At low energies, the wave function of a charge carrier (Dirac fermion) in a graphene monolayer satisfies the Dirac equation. Unlike nonrelativistic electrons, Dirac fermions completely penetrate an electrostatic barrier at normal incidence, even if the barrier height is greater than their energy. This is the Klein paradox [1]. Reflection occurs if the angle of incidence is different from normal. Among the many studies on Klein tunneling through barriers describing $n-p-n$ or $p-n-p$ junctions without an external magnetic field, we mention papers [5]–[7], in which a semiclassical approach was developed. The effect of a constant magnetic field on Klein tunneling was studied primarily for model potentials [2]–[4]; the case of a linear potential is considered in [2], the case of a parabolic potential in [3]. We cannot provide a complete list of references.

We present here a semiclassical approach to solving the Dirac equation in the presence of external static inhomogeneous electric and magnetic fields that smoothly vary only in one spatial variable x . The wave function of charge carrier is taken in the form

$$\Upsilon(\mathbf{r}, t) = e^{i(p_y y - \mathcal{E}t)/\hbar} \Psi(x), \quad \mathbf{r} = (x, y), \quad (1)$$

where $\mathcal{E}$ is the carrier energy. Let the carrier momentum have components $(\beta(x), p_y)$. If there are no external fields at $x = 0$, then $\beta(0) = v_F^{-1} \mathcal{E} \cos \theta$, $p_y = v_F^{-1} \mathcal{E} \sin \theta$, where v_F is the Fermi velocity, θ is the incidence angle of the carrier. The function Ψ in (1) satisfies the system

$$-i\hbar\hat{\sigma}_1 \frac{d\Psi(x)}{dx} = \hat{\mathcal{K}}(x)\Psi(x), \quad \hat{\mathcal{K}}(x) = \begin{pmatrix} v_F^{-1}(\mathcal{E} - U(x)) & i(p_y + eA_y(x)) \\ -i(p_y + eA_y(x)) & v_F^{-1}(\mathcal{E} - U(x)) \end{pmatrix}, \quad (2)$$

$$\hat{\sigma}_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad A_y(x) = \int_0^x B(\tilde{x}) d\tilde{x},$$

where e is the electron charge, $U(x)$ and $A_y(x)$ are the electrostatic potential and the y -component of the vector potential, respectively; $B(x)$ is the magnetic field. If $\hbar \ll 1$, then two solutions of (2) can be found in the adiabatic approximation

$$\Psi_{\pm}(x) \approx \exp\left(\pm \frac{i}{\hbar} \int^x \beta(s) ds\right) \left(\Phi_{\pm}^{(0)}(x) + \dots\right). \quad (3)$$

If $\beta(x)$ is real (complex), then x belongs to the classically allowed (forbidden) zone. We introduce such $x_{\mathcal{E}}$ that $\mathcal{E} = Q(x_{\mathcal{E}})$. Let the angle of incidence θ be restricted by the estimate

$$p_y + A_y(x_{\mathcal{E}}) = \sqrt{\hbar}\gamma(x_{\mathcal{E}}), \quad \gamma \sim 1. \quad (4)$$

Then the matrix $\hat{\mathcal{K}}$ admits the representation

$$\hat{\mathcal{K}}(x) = \mathcal{K}(x) + \sqrt{\hbar}\mathcal{B}, \quad \mathcal{B} = -\gamma(x_{\mathcal{E}})\sigma_2, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad (5)$$

near $x_{\mathcal{E}}$. The point $x = x_{\mathcal{E}}$ is the intersection point of the curves $\pm\beta(x)$ if $\gamma(x_{\mathcal{E}}) = 0$. It is near this point that the classically forbidden zone appears if $\gamma(x_{\mathcal{E}}) \neq 0$, and the approximation (3) fails near it. To calculate the coefficient of transition through this zone, we use the general results from [10] obtained for the equation (2) with the operator $\hat{\mathcal{K}}$ in the form (5) without specifying the type of the self-adjoint operators $\mathcal{K}$, $\mathcal{B}$ and $\hat{\mathcal{K}}$. The article [10] presents an analogue of the Landau-Zener formula obtained in [8], [9] for nonadiabatic transitions in a diatomic molecule.

As a result, we found formulas for the reflection and transmission coefficients in the case of $n - p$ and $p - n$ junctions, as well as in the case of a barrier describing the $n - p - n$ junction, and numerically studied the dependence of the transmission coefficient on the angle of incidence. The calculation results show Fabry-Perot resonances caused by multiple reflections inside the barrier.

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Structural health monitoring in austenitic steels based on the detection of martensitic phase inside the austenitic phase

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Abstract

In this paper, our first attempt to demonstrate the ability of determining the initiation of austenitic steel failure is presented, based on the early detection of the martensitic phase using magnetic techniques, since it appears at the end of the austenitic steel life time.

1. Introduction

Austenite steels are important for several demanding sectors in industry, energy, transportation and large research infrastructures. Demanding heat exchangers and critical shaft structures are made of austenitic steel for industrial, energy and transportation applications. Apart from that, critical vessels under pressure are also made of the same steel grade(s). Finally, accelerating rings in large research infrastructures employ austenitic steels. Therefore, the structural health monitoring of this type of steel is of critical importance.

Our technology to monitor residual stress in magnetic steels could be used for this steel grade, based on the magnetic stress calibration (MASC) curves, as well as the Universality Law declared some ten years ago [1]. The problem of using our magnetic technology for structural characterization of austenite steel is difficult since it doesn't present magnetic properties. However, before the failure of the austenite steel, it is transformed into martensitic steel, that has magnetic properties. Therefore, determination of magnetic mass inside the austenite phase declares the beginning of its transformation into martensitic phase, indicating the beginning of its failure. Hence, we have the motivation and initiated work towards the determination of magnetic mass (martensitic phase) into the austenite steel. The present paper is the first presentation of this type of measurements.

2. Experimental

This way, the first attempt has been the study of the martensitic phase from 0% up to 45%, that is more or less the threshold after which the austenitic steel will fail. We have ordered austenitic steel grades in the form of 1 mm thin sheets, namely 304, 316, 316L and 316LN steel grades with 1%, 3%, 10%, 20%, 30%, 40% and 45% of martensitic phase and we determined their magnetic response by using our own single sheet tester. Figure 1 illustrates the dependence of magnetic response in our Magnetic Barkhausen Noise (MBN) set-up in austenitic steels with different percentage of martensitic phase. The magnetic response was defined as the envelop of the MBN response of the under test steel. The observed dependence of the magnetic response on the amount of austenitic steels has been linear for excitation frequencies from 0.1 Hz up to 1 Hz, indicating the ability of the magnetic response to determine the percentage of the martensitic phase in the austenitic steel.

Apart from these experiments we have determined the response of 3D AMR sensors with respect to the size and the depth of martensitic spheres and needles inside a non-magnetic foam, thus simulating the austenitic steel. The preliminary results of such a dependence have been proven to be monotonic and are presented in this work. In fact, the field response was very much dependent on the shape of the magnetic substance, as it was expected: the response of the magnetic spheres was much less profound in comparison to the magnetic ribbons.

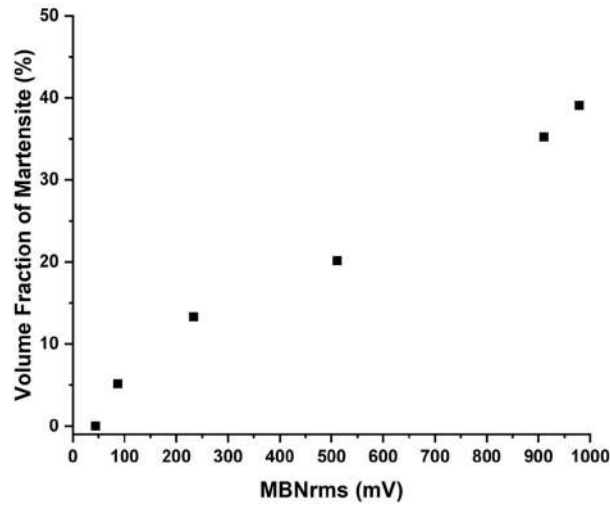


Figure 1. Dependence of the MBN response on the percentage of martensitic phase in austenitic steel samples.

Figure 2 illustrates the response of the AMR sensor with respect to its distance from a Fe-Co magnetic sphere and needle of the same mass, i.e. 17 mg. The response of the magnetic sphere is obviously smaller. This is due to the shape induced anisotropy of the needle that allows for a large magnetic field distribution around the magnetic needle. In the contrary, the magnetic sphere has a relatively smaller field distribution around its surface, not allowing large field measurements.

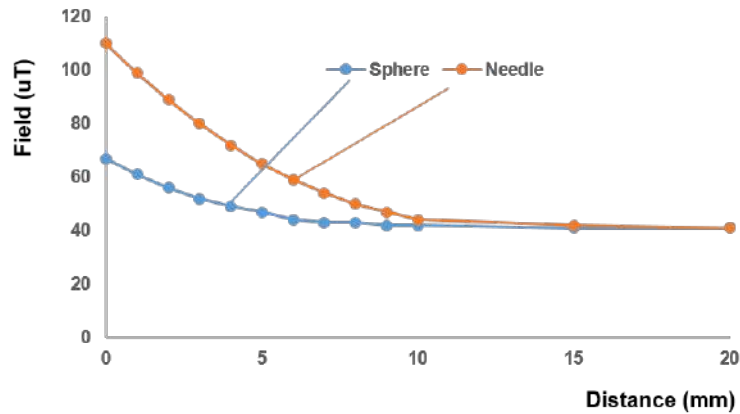


Figure 2. 3D AMR field comparison of magnetic sphere and needle of the same stoichiometry and mass (17 mg)

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Nanophotonics, plasmonics and quantum optics

Plasmonic Nanoparticles Synthesis and characterization: Harnessing Enhanced Visible Absorption for Dye Molecule Applications

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Abstract

In recent decades, gold nanoparticles (NPs) have captivated significant attention owing to their distinctive qualities, such as localized surface plasmon resonance (LSPR), biocompatibility, and facile surface functionalization. These attributes render them appealing for diverse applications, spanning optoelectronics, sensing, biomedical applications, catalysis, and surface-enhanced spectroscopies. Surface enhanced absorption, a plasmonic phenomenon associated with surface enhanced fluorescence, Raman scattering, and the infrared region, has been asserted to extend into the visible spectrum of light. Azo dyes, known for their robust light absorption in the visible region, can benefit from the unique capabilities of gold nanoparticles, which serve as light sources confined to LSP modes, emitting light in all directions. The amalgamation of these two materials results in surface enhanced absorption within the visible spectrum. This study focuses on the successful synthesis of spherical gold nanoparticles (AuNPs) in an aqueous solution, followed by their transfer to an organic solvent. Varied concentrations of AuNPs were introduced to the azo dye Disperse Red 1 (DR1), and the subsequent impact on maximum absorption was investigated using UV-Visible spectroscopy. Our findings underscore that the incorporation of plasmonic nanoparticles effectively enhances the absorption of azo dyes within the visible region, showcasing the potential of surface enhanced spectroscopy.

Keywords: Nanoparticles, Surface enhanced absorption, Azo dyes

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Nanofabrication of Periodic Arrays of Single-Crystal Atomically Flat Gold Nanoplates

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Abstract: In this presentation, we introduce a novel method for fabricating periodic arrays of metallic nanostructures, including nanoplates, nanotriangles, and helical spirals. Our approach integrates vapor-phase epitaxy with chemical reduction processes to achieve precise and controlled fabrication of these structures.

Enantiomeric discrimination of chiral drugs via plasmon-enhanced circular dichroism

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Abstract: We investigate surface-enhanced chiroptical sensing of dilute chiral solutions. Circular dichroism is amplified by the surface plasmon resonances, enabling sensitive analysis of solvated reparixin and advancing the development of chiroptical sensors.

Chiral sensing is crucial in the pharmaceuticals, as the enantiomeric form of a drug influences its efficacy and toxicity [1]. This study investigates surface plasmon polaritons at noble metal interfaces for enhancing chiroptical sensing of nanoliter-scale chiral drug solutions. These techniques enable real-time analysis, integrate with lab-on-a-chip systems, and expand applications in nanomedicine. Here, we focus on isotropic assemblies of reparixin, a CXCR2 inhibitor that mitigates inflammatory responses and is used to treat hospitalized patients with COVID-19 pneumonia) solvated in water with dilute number molecular density $n_{\text{mol}} = n_{\text{mol}}^{(R)} + n_{\text{mol}}^{(S)} \approx 10^{-2} \text{ nm}^{-3}$, where the number densities of R and S enantiomers are represented by $n_{\text{mol}}^{(R,S)}$. Our results comes from quantum chemical calculations adopting a hybrid computational approach that integrates Molecular Dynamics, time-dependent Density Functional Theory, and the Perturbed Matrix Method. [2]. The interactions between radiation and matter are studied from first principles using the density matrix formalism. Macroscopic optical parameters, including dielectric permittivity, magnetic permeability, and chiral coefficients of the dilute drug solution, are obtained by perturbatively solving the density matrix equations within the dipole approximation. We evaluated the plasmon-enhanced circular dichroism differential absorption (CDDA) [3] in both the Otto and Kretschmann configurations. We attain a CDDA enhancement by a factor of ≈ 20 for silver metal substrate in the Otto configuration. In turn, by measuring the CDDA we can retrieve the enantiomeric imbalance in the drug solution. Our findings are relevant for the development of innovative chiroptical sensors capable of measuring the enantiomeric imbalance of nl volume chiral drug solutions.

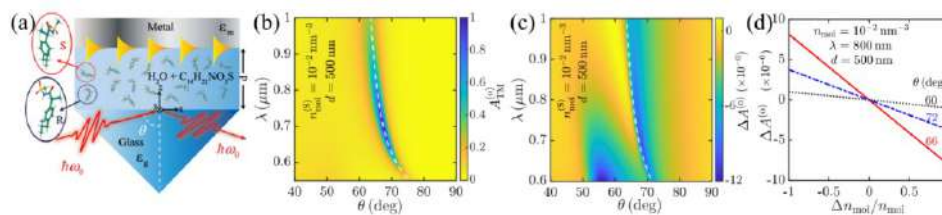


Fig. 1 (a) Schematic representation of plasmon-enhanced CD in the Otto configuration. The considered chiral sample is a solution of S and R reparixin enantiomers dissolved in water with molecular density n_{mol} . [(b) and (c)] Dependence of (b) TM absorbance $A_{\text{TM}}^{(o)}(\theta, \lambda)$ (for TM linear polarization excitation) and (c) CDDA $\Delta A^{(o)}(\theta, \lambda) = A_R(\theta, \lambda) - A_L(\theta, \lambda)$ (for circular polarization excitations) over the vacuum wavelength λ and the angle of incidence θ of the impinging radiation. The plots refer to a pure S reparixin enantiomer dissolved in water. (d) Dependence of CDDA over the enantiomeric number density imbalance $\Delta n_{\text{mol}} = n_{\text{mol}}^{(S)} - n_{\text{mol}}^{(R)}$ for several distinct incidence angles θ and fixed excitation vacuum wavelength $\lambda = 800$ nm. The dashed white curves in [(b) and (c)] indicate the SPP dispersion relation.

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High-harmonic generation driven by out-of-equilibrium electron dynamics in epsilon-near-zero media

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Abstract: We theoretically model third-harmonic generation produced by collision-driven nonlinear electron dynamics in near-zero index heterogeneous nanostructures. We model the harmonic generation process of three different setups composed of sodium and aluminum to explore their potential for the development of compact extreme ultraviolet radiation sources and for integrated spectroscopy schemes.

Nonlinear (NL) radiation-matter interactions give rise to many physical phenomena particularly relevant to quantum mechanical processes and offer a promising platform to devise compact ultraviolet (UV) radiation sources. To enhance NL effect one may utilize photonic materials with low dielectric permittivity, known as epsilon near zero (ENZ) media, that thanks to their natural ability to bypass phase-matching requirements play a crucial role in several NL phenomena, e.g., high harmonic generation (HHG) processes. Typically, ENZ media are adopted to enhance coherent NL radiation-matter interactions in the near-infrared spectral region, where doped semiconductors, oxides, and nitrides display this behavior. To obtain plasmonic effects in the UV range we can adopt the poor materials, like aluminum (Al), titanium (Ti), tungsten (W) and sodium (Na), that show marked ENZ feature in this spectral region. Indeed, these materials are promising for guidance [1] and for resonant third-harmonic generation (THG) in thin films [2], and for manipulation and guidance of extreme-UV (XUV) radiation.

Here, to model THG and HHG driven by out-of-equilibrium (OOE) electron dynamics in ENZ heterogeneous nanostructures, we consider the Fokker-Planck-Landau (FPL) theoretical framework, obtaining a set of hydrodynamical equations (HDEs) by solving analytically the Landau collisional integral in the weak coupling limit [3]. Moreover, thanks to a perturbative approach, we derive an analytical expression for the collision-driven NL-susceptibility, obtaining an analytical expression of the forward (FW) and backward (BW) THG intensity by both transverse electric (TE) and transverse magnetic (TM) pump polarisation for three different setups: the first one involves a Na – based thin films [2], the second one a Na/Al-based nanospheres [4], and the third one a Na-Al bilayer [5], all with nanometer-size thicknesses. Now, we focus our discussion mainly on the latter configuration. Indeed, in Fig. 1a, where we depict the dependence of the FW intensity of the THG signal over the pump wavelength λ and incidence angle θ , one can see that the THG process exhibits a double resonance for TM pump excitation $\lambda_{\text{THG}} = \lambda/3$ in the ENZ regime due to the coupling of the pump field enhancement and the radiation of the microscopic dipoles. Conversely, for TE pump excitation, see Fig. 1e, we observe THG enhancement due to the excitation of Fabry-Perot resonances. Finally, note that in the ENZ regime of Na it's possible to excite surface plasmon polaritons (SPPs) at Na-Al interface, because in this regime this setup is analogous to an Otto's configuration, obtaining a THG enhancement factor of 7 orders to magnitude, suggesting the potential of NZI heterogeneous nanostructure devices in the development of integrated XUV source.

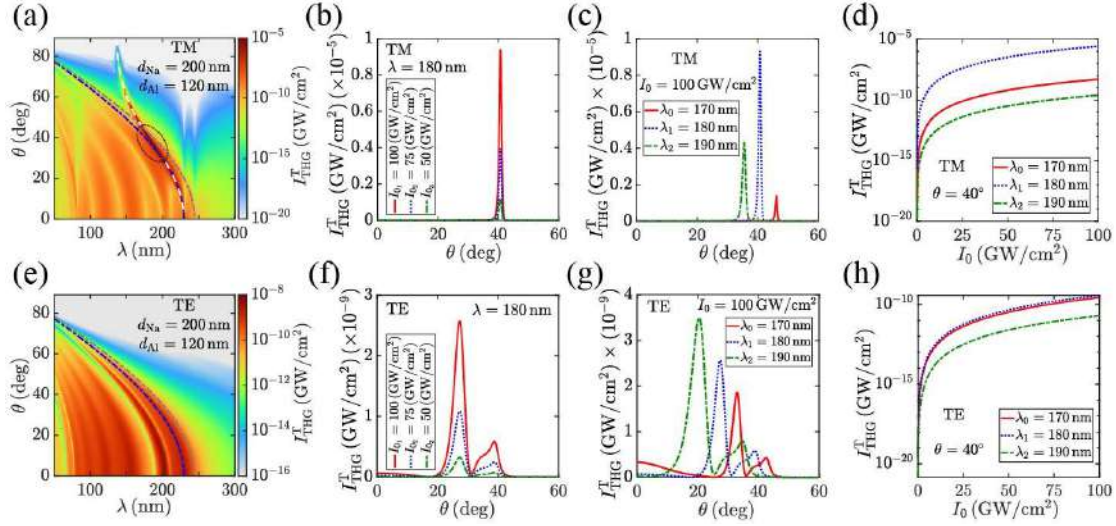


Fig. 1. **(a,e)** Dependence of the FW intensity of the THG signal I_{THG}^T over the pump wavelength λ and incidence angle θ for fixed pump intensity $I_0 = 100 \text{ GW/cm}^2$. The dashed white curve in **(a)** indicates the SPP dispersion curve, while the dot-dashed grey and blue curves indicate the Al and Na NZI dispersion curves, respectively for λ_{THG} and λ . **(b,c,f,g)** Dependence of I_{THG}^T over the pump incidence angle for **(b,f)** fixed pump wavelength $\lambda = 180 \text{ nm}$ and several intensities $I_0 = 50, 75, 100 \text{ GW/cm}^2$, and **(c,g)** fixed pump intensities $I_0 = 100 \text{ GW/cm}^2$ and several wavelengths $\lambda = 170, 180, 190 \text{ nm}$ [highlighted by the black circled area in **(a)**]. **(d,h)** Dependence of I_{THG}^T over the pump intensity I_0 for fixed incidence angle and several wavelengths $\lambda = 170, 180, 190 \text{ nm}$. All plots are obtained for $d_{\text{Na}} = 200 \text{ nm}$ and $d_{\text{Al}} = 120 \text{ nm}$ and refer to either **(a-d)** TM or **(e-h)** TE polarisation of the impinging pump field.

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Radiative-Coupling-Induced Spontaneous Resonance between Plasmon and Electron-hole pairs

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Abstract: This study investigates the coherent coupling between plasmon and electron-hole pairs, proposing a “spontaneous resonance” mechanism for hot carrier generation (HCG) in metallic systems. By extending the Bohm-Pines theory, we demonstrate the significant radiative coupling in Ag film, which could account for the recently observed nontrivial internal quantum efficiency.

In metallic systems, elementary excitations can be classified into two types: plasmon excitations and electron-hole pair (e-h pair) excitations. It is well known that when plasmons are optically excited at a metal surface, they can generate high-energy e-h pair excitations known as hot carriers beyond thermal equilibrium [1]. The injection of these hot carriers into semiconductors or molecules enables photoelectric conversion in the visible to near-infrared range. This capability is promising for applications for compact photodetectors and photocatalysts [2]. However, further investigation is required to improve conversion efficiency. To achieve efficient photoelectric conversion, the rapid conversion of plasmon energy into hot carriers is essential. Conventional theories have phenomenologically treated the hot carrier generation as relaxation through Landau damping [3], leaving critical details unresolved. Recent experimental studies have demonstrated that the internal quantum efficiency (IQE) spectrum, which represents the photoelectric conversion efficiency normalized by photon absorption, exhibits a peak near the plasmon resonance energy [4]. This behavior cannot be explained merely as a relaxation process, necessitating a more detailed examination based on a microscopic theoretical framework.

In this study, to solve this mystery and further to explore efficient photoelectric conversion mechanisms, we developed a novel metal optical response theory by applying the Bohm-Pines theory [5], which quantum mechanically treats electron-hole exchange interactions, to metallic thin films that interact with light. Considering the Jellium model, the Hamiltonian of the metallic film shown in Fig. 1(a) is expressed as follows:

$$\hat{H}_{\text{mat}} = \sum_{i=1}^N \frac{\hat{p}_i^2}{2m^*} + V(z) + \frac{e^2}{4\epsilon_0 V} \sum_{i \neq j}^N \sum_{\mathbf{k}_{\parallel} \neq \mathbf{0}, m} \frac{1 - (-1)^m e^{-|\mathbf{k}_{\parallel}|d}}{k_{\parallel}^2 + k_{z,m}^2} e^{i\mathbf{k}_{\parallel} \cdot (\hat{\mathbf{p}}_i - \hat{\mathbf{p}}_j)} e^{ik_{z,m}(\hat{z}_i - \hat{z}_j)} \quad (1)$$

where m^* is the effective mass of electrons, N is the number of electrons in the metal film. $V(z)$ is the infinite quantum well potential. $\hat{\mathbf{p}}_i, \hat{z}_i$ are the in-plane and z position operators of i -th electron and $\mathbf{k}_{\parallel}, k_{z,m} (= m\pi/d)$ are the in-plane and z direction wavenumbers. Following the formulation of Bohm and Pines [5], this Hamiltonian can be expressed as follows:

$$\begin{aligned} \hat{H}_{\text{mat}} = & \sum_{\mathbf{k}_{\parallel}, \mathbf{K}_{\parallel}'} \sum_{n, n'} \hbar \omega_{e-h}(\mathbf{k}_{\parallel}, \mathbf{K}_{\parallel}', n, n') \hat{A}_{\mathbf{k}_{\parallel}, \mathbf{K}_{\parallel}, n, n'}^{\dagger} \hat{A}_{\mathbf{k}_{\parallel}, \mathbf{K}_{\parallel}, n, n'} \\ & + \sum_{\mathbf{k}_{\parallel}, m} \hbar \omega_p(\mathbf{k}_{\parallel}, m) \hat{B}_{\mathbf{k}_{\parallel}, m}^{\dagger} \hat{B}_{\mathbf{k}_{\parallel}, m} + \hat{V}_C + \hat{V}_{e,p} \end{aligned} \quad (2)$$

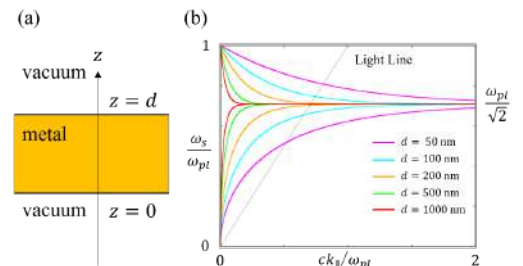


Fig.1: (a) Schematic view of metal film. (b) Dispersion relation of electrostatic plasmon in metallic thin film. This is consistent with Ferrell's dispersion [6].

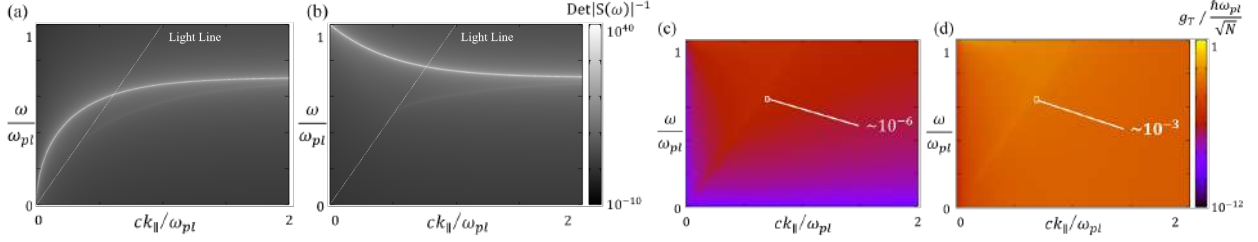


Fig.2: (a,b) Dispersion relation for coupled plasmon-radiation field system in Ag film with thickness of 50nm. SR-SPP and LR-SPP appear as a surface mode of even plasmon (a) and odd plasmon (b), respectively. (c,d) Radiative coupling strength between plasmon ($m=0$) and e-h pair ($n=105, n'=220$ (c) and $n=110, n'=220$ (d)) in the same Ag film.

where $\hat{A}_{\mathbf{k}_{\parallel}, \mathbf{K}_{\parallel}, n, n'}^{\dagger} (\hat{A}_{\mathbf{k}_{\parallel}, \mathbf{K}_{\parallel}, n, n'})$ is creation (annihilation) operator of electron-hole pair and $B_{\mathbf{k}_{\parallel}, m}^{\dagger} (\hat{B}_{\mathbf{k}_{\parallel}, m})$ is creation (annihilation) operator of plasmon. $\hat{V}_C, \hat{V}_{e,p}$ denote the screened Coulomb interaction between electrons and the residual interaction between plasmon and e-h pairs, respectively. $\hbar\omega_{e-h} (\hbar\omega_p)$ are the energy quanta of e-h pair (plasmon) and expressed as follows:

$$\hbar\omega_{e-h}(\mathbf{k}_{\parallel}, \mathbf{K}_{\parallel}, n, n') = \frac{\hbar^2}{2m^*} [\mathbf{k}_{\parallel}^2 + 2\mathbf{k}_{\parallel} \cdot \mathbf{K}_{\parallel} + k_{z,n'}^2 - k_{z,n}^2] \quad (3)$$

$$\hbar\omega_p(\mathbf{k}_{\parallel}, m) = \frac{\hbar\omega_{pl}}{\sqrt{2}} [1 - (-1)^m e^{-|k_{\parallel}|d}], \quad (4)$$

where ω_{pl} means plasma angular frequency and the plot of Eq. (4) is shown in Fig. 1(b), which is degenerate for even and odd numbers of m . The dispersion relation for plasmon derived from our theory is consistent with Ferrell's [6] and validity of this theory was confirmed. Given the interaction of light and matter in this system, we can evaluate the radiative corrections to plasmon's eigenenergy and radiative coupling strength between the plasmon and e-h pairs by perturbation theory. As a result, in Ag film with thickness of 50nm, we can show the dispersion of well-known Short (Long) Range -Surface Plasmon Polariton (S(L)R-SPP) (see Fig.2 (a) (b)) and elucidate that the radiative coupling between plasmon and e-h pairs is 10^3 times larger when z polarization parities of the plasmon (m) and e-h pairs ($n' - n$) are matched (Fig.2 (d)) than when they are not matched (Fig.2 (c)). Furthermore, achieving substantial coupling strength was found to be significant to induce Fano type resonance, so this physics of 'spontaneous resonance' caused by the radiative coupling has the potential to solve the mystery of IQE spectra [4] and to suggest the novel efficient photoelectric conversion mechanism. In the future, we will analyze the population dynamics and discuss in detail the HCG process caused by 'spontaneous resonance'.

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Microscopic and self-consistent theory of tip-enhanced linear and non-linear resonant Raman scattering for electronic forbidden transition

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Abstract: We developed a self-consistent, nonlocal theory for resonant tip-enhanced Raman scattering. Our calculations describe the Raman signal through specific electronically forbidden transitions (EFTs). Additionally, we found that the nonlinear response significantly enhances the visibility of scattering via EFTs.

Recently, tip-enhanced Raman scattering (TERS) has attracted significant attention for single-molecule observation. The plasmonic picocavity enables strong field confinement, allowing TERS to achieve ultra-high spatial resolution beyond the diffraction limit. As a result, single-molecule structures can be resolved based on their molecular vibrations¹. Under electronic resonance conditions, Raman scattering occurs via specific electronic transitions. Notably, the strong near-field gradient effect around the metal surface facilitates scattering through not only electronically allowed transitions but also electronically forbidden transitions (EFTs). Scattering via EFTs has also been observed in surface-enhanced Raman scattering (SERS) of single-walled carbon nanotubes². Therefore, TERS has the potential to provide real-space observation of Raman scattering via EFTs. A deeper understanding of TERS for EFTs is crucial for a more detailed investigation of the nature of EFTs.

The long-wavelength approximation (LWA) becomes invalid when evaluating TERS images. Consequently, a sample molecule must be treated microscopically, whereas the metal structure is too large to be handled in the same manner. Due to their differing size scales, distinct theoretical treatments are required for the sample and the metal. Several theoretical approaches have been proposed to address this multi-scale problem. One method employs quantum chemical calculations, modeling the metal nanoparticle as a collection of charges and dipoles³. Another approach defines Raman polarizability without relying on the long-wavelength approximation, treating the near-field as a given input⁴.

Under the resonant condition, the sample molecule is strongly excited due to electronic resonance, which subsequently influences the near-field. Therefore, a self-consistent treatment of both the molecular response and the electric field is essential for resonant TERS. In our study, we developed self-consistent microscopic theory for TERS and demonstrated its ability to evaluate TERS maps reflecting molecular quadrupole. Furthermore, we examined the spatial resolution of tip-enhanced coherent anti-Stokes Raman scattering (TECARS), which is believed to provide higher spatial resolution than TERS due to its nonlinear nature⁵. Given this property, we propose that TECARS may be particularly useful for observing quadrupole structures.

In this system, the electric field and the molecular response cannot be treated separately. To accurately describe Raman scattering in this system, it is essential to derive it from a Hamiltonian that incorporates both the molecular response and photon interactions, as follows:

$$\hat{H} = \hat{H}_{\text{mol}} + \sum_{\eta} \hbar \omega_{\eta} \hat{a}_{\eta}^{\dagger} \hat{a}_{\eta} - \int d\mathbf{r} \hat{\mathbf{P}}(\mathbf{r}) \cdot \hat{\mathbf{E}}(\mathbf{r}), \quad (1)$$

where the first term represents the molecular Hamiltonian, the second describes the photon modes in the entire space, including the plasmonic structures (indexed by η), and the third term accounts for the interaction between the molecular polarization $\hat{\mathbf{P}}(\mathbf{r})$ and the electric field $\hat{\mathbf{E}}(\mathbf{r})$. This interaction, expressed as a spatial integral, varies with the tip's position, enabling the evaluation of TERS images for a single molecule. Additionally, this theory captures the interaction between the localized field and molecular quadrupole. Using perturbation theory

and the Hamiltonian in Eq. (1), we obtained the molecular linear polarization, third-order polarization, and the inelastic scattered photon number. Maxwell's equations, incorporating these polarizations, were solved self-consistently to determine the electric field distribution. The inelastic scattered photon number also includes incoherently scattered photons. Since each photon mode has a different eigenfunction $\mathbf{f}_\eta(\mathbf{r})$, direct calculation of all modes computationally demanding. However, these modes can be renormalized into the Green's function of Maxwell's equation for the plasmonic structure, similar to recent optomechanical approaches for SERS⁶:

$$\mathbf{G}(\mathbf{r}, \mathbf{r}', \omega) = 2\pi \sum_\eta \frac{i\omega_\eta \mathbf{f}_\eta(\mathbf{r}) \mathbf{f}_\eta^*(\mathbf{r}')}{2\varepsilon_0} \{ \delta(\omega_\eta - \omega) + \delta(\omega_\eta + \omega) \}. \quad (2)$$

Since the Green's function can be efficiently computed, explicit evaluation of each $\mathbf{f}_\eta(\mathbf{r})$ unnecessary. Furthermore, the Green's function ensures self-consistency at the Raman scattering frequency.

Our calculation model is illustrated in Fig. 1(a). We modeled the Ag probe tip as a 6 nm diameter sphere with a protrusion at its tip apex. A single pentacene molecule is placed between the tip and the Ag substrate as the sample. We considered 1383 cm^{-1} vibrational mode, which corresponds to a totally symmetric vibration of pentacene. The frequency of the incident light was set to match one of pentacene's forbidden transitions, specifically the transition between HOMO-1 and LUMO. The transition dipole moment associated with this transition exhibits a quadrupolar structure. We computed the TERS map, as shown in Fig. 1(b). The results indicate that Raman scattering is significantly enhanced when the tip is positioned at four specific regions. These positions correspond to configurations where the dipole on the tip, excited by the incident light, couples with the molecular polarization. This finding demonstrates that our theory accurately evaluates TERS maps for EFTs in a single molecule. Furthermore, we investigated TECARS for pentacene's EFT, and the results are shown in Fig. 1(c). The TECARS map reveals that scattering intensity is enhanced in the same four regions where TERS enhancement is observed. However, the enhanced regions in TECARS are smaller than those in TERS, indicating that TECARS offers higher spatial resolution than TERS. A more detailed discussion will be provided in our presentation.

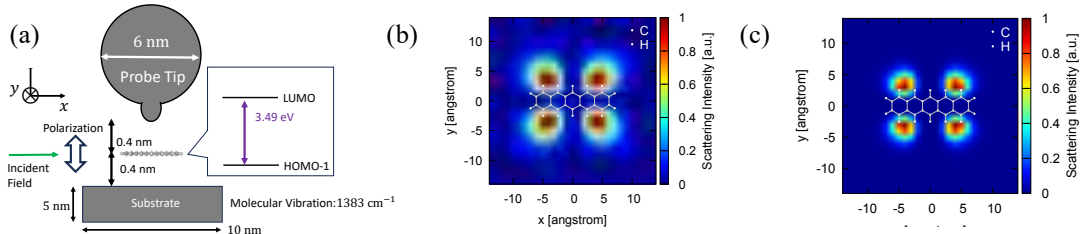


Fig. 1 (a) Schematic of our calculation model. (b), (c) Calculated TERS and TECARS maps for pentacene's EFTs.

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Control of Nanoparticle Rotation Direction Using Recoil Force Generated by Stimulated Emission

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Abstract: The mechanical recoil force exerted on a material due to stimulated emission occurs in the direction opposite to the propagation of light. In this study, we theoretically demonstrate that this recoil force can be observed by using an optical vortex and reversing the rotational direction of an NV-containing nanodiamond.

Since Ashkin's discovery in 1970, optical manipulation has been studied as a non-destructive method for controlling matter [1]. In particular, resonant optical manipulation, which utilizes resonant light, can significantly enhance optical forces on nanomaterials [2]. However, in the high-intensity regime, absorption saturation limits the efficiency of optical manipulation. To overcome this, we propose optical manipulation using stimulated emission, in which materials experience a recoil force opposite to the propagation of light, known as the stimulated recoil force (SRF) [3]. This recoil force was experimentally demonstrated [4][5], but photobleaching was a major challenge. To address this, this study focuses on fluorescent nanodiamonds, particularly NV-center-containing nanodiamonds, which do not undergo photobleaching. Additionally, the study introduces optical vortices, which carry orbital angular momentum, to explore new aspects of light-matter interactions. We theoretically demonstrate that when stimulated emission is induced using an optical vortex, the direction of material rotation is reversed compared to conventional cases, enabling precise control of rotational motion.

The optical force is evaluated using the time-averaged Lorentz force [6]:

$$\langle \mathbf{F} \rangle = \frac{1}{2} \Re \left[\sum_{\omega} \int d\mathbf{r} \{ \nabla \mathbf{E}^*(\mathbf{r}, \omega) \} \cdot \mathbf{P}(\mathbf{r}, \omega) \right], \quad (1)$$

where, $\mathbf{E}(\mathbf{r}, \omega)$ is the incident electric field, and $\mathbf{P}(\mathbf{r}, \omega)$ is the polarization. The electric field is modeled as a Laguerre-Gaussian (LG) beam, a paraxial eigenmode of the Helmholtz equation:

$$u_{lp}^{LG}(r, \phi, z) = \sqrt{\frac{2p!}{\pi(p + |l|!)}} \sqrt{\frac{\pi}{2}} \frac{\omega_0}{\omega(z)} \left[\frac{r\sqrt{2}}{\omega(z)} \right]^{|l|} L_p^{|l|} \left(\frac{2r^2}{\omega^2(z)} \right) \\ \times \exp \left[-\frac{r^2}{\omega^2(z)} \right] \exp \left[i \left\{ \frac{qr^2}{2R(z)} + l\phi - (2p + |l| + 1) \tan^{-1} \left(\frac{z}{z_r} \right) \right\} \right], \quad (2)$$

where, p and l represent the radial and azimuthal mode indices, respectively. In this study, $p = 0$ and $l = 1$ are used. Polarization can be decomposed into resonant and non-resonant components. The resonant component is determined through non-perturbative solutions of the density matrix equation of motion:

$$i\hbar \frac{\partial \hat{\rho}}{\partial t} = [\hat{H}, \hat{\rho}] - \hat{\Gamma} \hat{\rho}, \quad (3)$$

The non-resonant polarization is evaluated using the Clausius-Mossotti relation:

$$\vec{\mu}_{\text{nonres}} = \alpha_{\text{CMRR}} \mathbf{E}(\mathbf{r}, \omega), \quad (4)$$

In the computational model, the NV-ND is modeled as a four-level system, as shown in Figure 1(a). As illustrated in Figure 1(b), two excitation LG beams are applied from the same direction, along with an additional stimulated LG beam. The excitation LG beams are adjusted so that their rotational forces nearly cancel each other out, making the rotational force induced by the stimulated LG beam dominant. Finally, we assume room-temperature water as the solvent. The motion of the nanodiamond in the solvent can be evaluated using the following Langevin equation:

$$m \frac{dv}{dt} = F_{\text{light}} - 6\pi\eta r v, \quad (5)$$

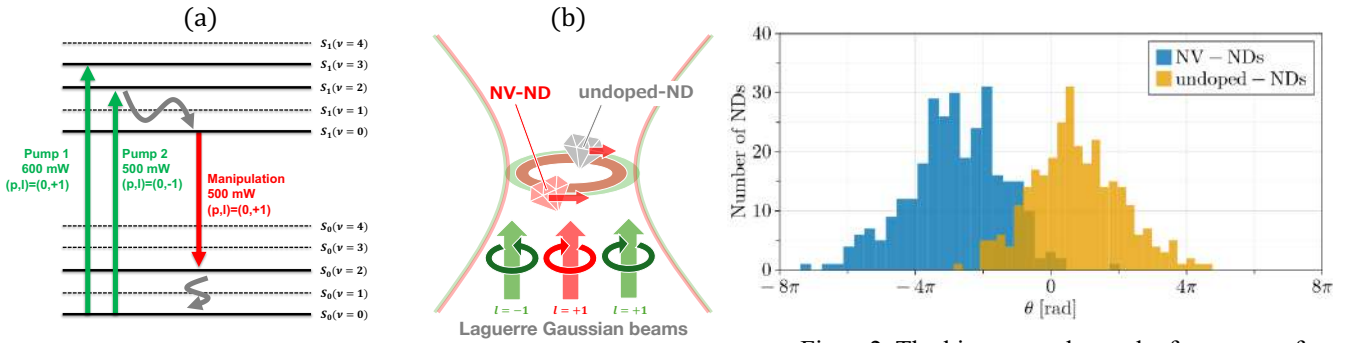


Figure1. (a) Energy level diagram of NV-ND.
(b) The system assumed in the simulation.

Figure2. The histogram shows the frequency of occurrences for the accumulated rotation angle, θ , at 0.1 seconds from the initial position. The horizontal axis represents θ , while the vertical axis indicates the number of occurrences per trial for each θ value. The blue bars correspond to undoped-ND, while the orange bars

Using the rigorously calculated radiation pressure and equation (5), we performed simulations. The histogram in Figure 2 shows the accumulated rotational angle from the initial position to evaluate the torque. The simulation time was set to 0.1 seconds. For reference, the trajectory of an undoped nanodiamond (undoped-ND), which does not contain defect centers, is also shown. From the results, it can be observed that the rotation direction is reversed between undoped-ND and NV-ND, and that even in room temperature water, the rotation overcomes thermal fluctuations. This theoretically demonstrates that controlling the rotation direction using SRF is experimentally feasible. The findings of this study provide new insights into the interaction between optical vortices and nanomaterials, opening new possibilities for optical manipulation.

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Plasmonic titanium nitride thin layer on anodic aluminum oxide substrate for rapid detection of neurotransmitters by SERS

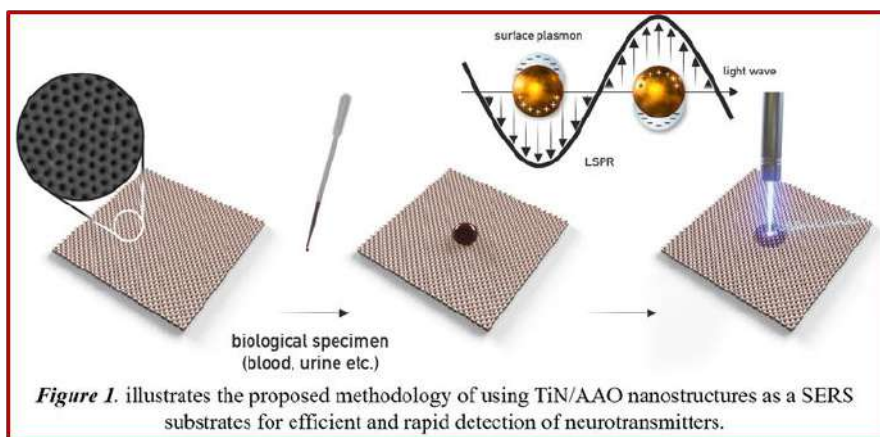
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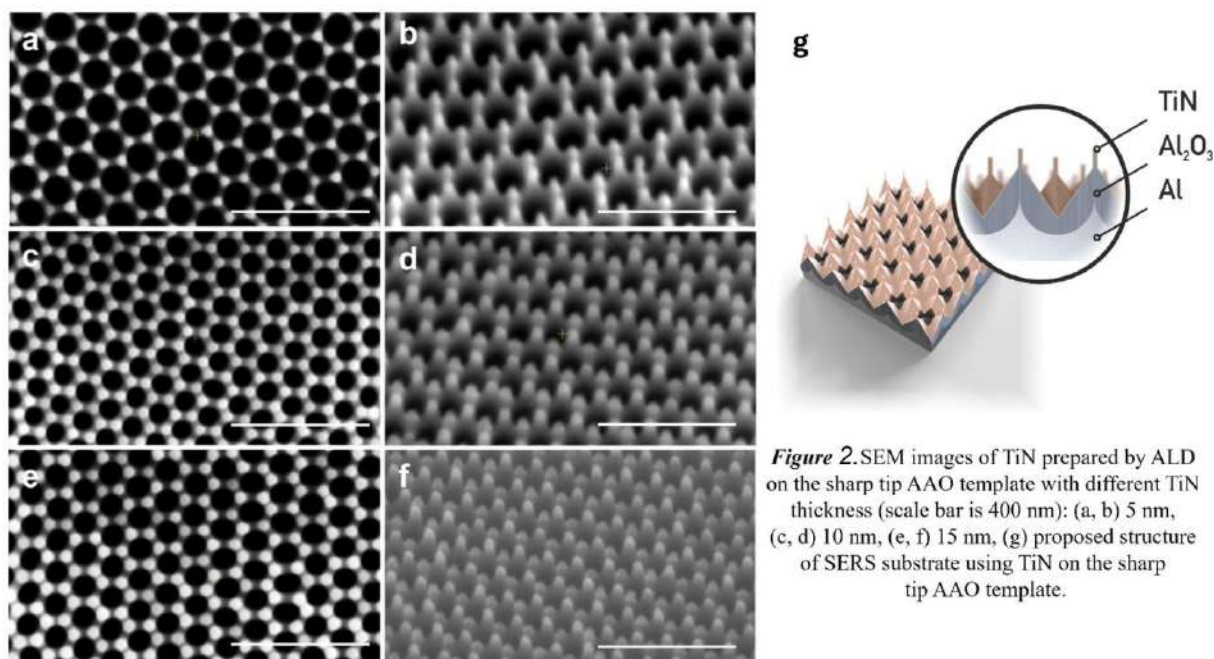
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Abstract: Surface-enhanced Raman spectroscopy (SERS) enables highly sensitive detection of biologically active substances. Titanium nitride (TiN) combined with anodic aluminum oxide (AAO) nanostructures enhances Raman signals while improving stability and biocompatibility. By optimizing TiN deposition and nanostructure morphology, we propose a TiN/AAO hybrid platform for advanced SERS applications in healthcare and environmental monitoring.



The search for precise and reliable detection methods of biologically active substances is paramount in various fields including healthcare, environmental monitoring, and food safety. The emergence of Surface-enhanced Raman spectroscopy (SERS) has revolutionized the field by offering remarkable sensitivity and specificity in detecting

target molecules. However, to fully harness the potential of SERS for practical applications, advancements in substrate materials are essential. Titanium nitride (TiN) combined with Anodic Aluminum Oxide (AAO) nanostructures present a promising solution, offering enhanced Raman signals due to their unique properties (Figure 1). By using these nanostructures, the detection of biologically active substances can be significantly improved, opening doors for more precise and rapid detection methods with implications in healthcare, environmental monitoring, and beyond. The plasmonic characteristics responsible for local field enhancement are significantly influenced by the morphology of the nanostructure and the selection of metallic materials. Noble metals, such as silver and gold, are widely recognized as exemplary plasmonic materials for SERS substrates.^{1,2} Nevertheless, they possess drawbacks including high cost, low stability, and limited biocompatibility. In recent times, titanium nitride has garnered attention due to its optical properties capable of exhibiting resonant plasmonic behavior. Previous research has demonstrated that TiN can produce localized electromagnetic field enhancements similar to those observed with noble metals.³ Moreover, TiN, characterized by good chemical stability, a high melting point, and exceptional hardness, emerges as a promising alternative plasmonic material.⁴ The plasmonic attributes of TiN can be fine-tuned by adjusting the metal-to-nitrogen ratio, thereby enhancing its appeal for SERS substrate development. While TiN nanoparticles and semiconducting thin



films have been fabricated as SERS substrates; their SERS intensities require enlargement for practical applications. We can synthesize the different Anodic Aluminum Oxide substrates as SERS materials via anodic deposition technique further using a plasmonic TiN arrays (Figure 2). The TiN/AAO array is proposed to improve both stability and sensitivity for SERS applications. Notably, TiN nanostructures offer a larger surface area compared to nanoparticles, thereby facilitating enhanced molecular adhesion. Control over the titanium-to-nitrogen ratio enables the establishment of optimal deposition conditions for TiN nanostructures, yielding highly sensitive SERS signals. We have successfully developed nanostructures of AAO. The nanopores of the substrates are highly ordered in a large scale, emphasizing the reproducibility of SERS signal after deposition of plasmonic TiN. Figure 2a-f show plasmonic TiN on the sharp tip of AAO template prepared by ALD with different thickness: 5 nm (Figure 2a, b), 10 nm (Figure 2c, d) and 15 nm (Figure 2e, f).

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Chiroptical sensing via vibrational circular dichroism in plasmonic nanostructures embedding chiral drugs

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Abstract

We examine the mid-infrared chiroptical response of Aluminum-doped zinc oxide (AZO)-based plasmonic nanostructures embedding chiral pharmaceutical drug solutions. Our study explores the potential of localized surface plasmon resonances (LSPRs) to enhance vibrational circular dichroism (VCD) of the chiral drug solution, focusing on developing innovative chiroptical sensing methods.

Chiroptical sensing is crucial in various scientific disciplines, such as pharmaceutics, pharmacology, and biotechnology, as the specific enantiomers of chiral molecules exhibit different functional properties and toxicity [1]. The current state-of-the-art chiral sensing techniques are capable of detecting enantiomeric imbalance precisely; however, they are not suitable for real-time analysis and wider nanomedicine applications. Here, we examine the potential applications of LSPRs in plasmonic nanostructures based on AZO and a layer of realistic chiral drug solutions, in particular an isotropic mixture of aqueous Ladarixin (a dual allosteric inhibitor of CXCL8 (IL-8) receptors, CXCR1 and CXCR2 employed to treat diabetes patients) for plasmon-enhanced VCD. The bi-anisotropic optical constants of the considered chiral sample with dilute molecular number density $n_{\text{mol}} = 10^{-2} \text{ nm}^{-3}$ are calculated through a robust computational method [2]. LSPRs of the nanostructures, see Fig. 1, are evaluated through an electrostatic approach enabling the calculation of the VCD differential absorption cross-section (VCDDA) $\Delta\sigma = \sigma_{\text{R}} - \sigma_{\text{L}}$, where σ_{R} and σ_{L} indicate the absorption cross-section upon right and left circular polarization, respectively. The enantiomeric imbalance expressed as $\Delta n_{\text{mol}} = n_{\text{mol}}^{\text{S}} - n_{\text{mol}}^{\text{R}}$, can be detected by measuring the VCDDA since $\Delta\sigma$ is proportional to Δn_{mol} . We observe that the plasmon-induced VCDDA can be enhanced by a factor ranging from $\simeq 3$ to $\simeq 20$, thanks to enhanced near-field intensity offered by LSPRs. Our results are compatible with designing promising platforms to probe molecular chirality at the nanoscale level.

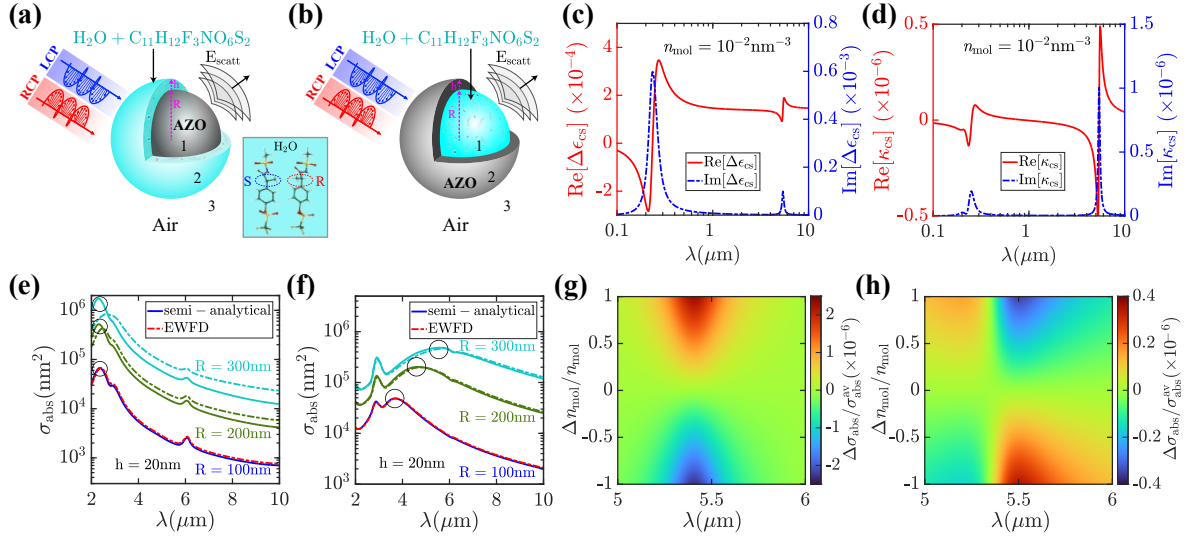


Figure 1: Fig. 1 Schematic illustration of considered nanostructures configurations—(a) Type-1 geometry, which contains an Al-doped ZnO (AZO) nanosphere of radius R covered by a layer of aqueous Ladarixin with thickness h immersed in air, (b) Type-2 geometry which consists of AZO-based nanoshell with respective inner and outer radii R and $R+h$, embedding chiral sample at its core and immersed in air. Vacuum wavelength λ dependence of (c) relative dielectric permittivity $\epsilon_r(\lambda)$ and (d) chiral parameter $\kappa(\lambda)$ calculated at a fixed molecular density n_{mol} of R and S Ladarixin dissolved in water. Vacuum wavelength λ dependence of the absorption cross-section $\sigma_{\text{abs}}(\lambda)$ of (e) Type-1 and (f) Type-2 configurations upon right circular polarization excitation for several R and fixed $h = 20$ nm. Dependence of the relative vibrational circular dichroism differential absorption over λ and enantiomeric imbalance calculated for (g) Type-1 and (h) Type-2 configurations with $R = 100$ nm thickness $h = 20$ nm.

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Tailoring XUV Radiation-Matter Interaction via ENZ Titanium-Aluminum-Titanium multilayer

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Abstract: Radiation-matter interaction in the extreme ultraviolet (XUV) spectral range is limited by high absorption, which hinders ultrafast spectroscopy and nonlinear optics. Here we investigate the potential of epsilon-near-zero (ENZ) heterostructures for guiding and confining XUV radiation at the nanometric scale, leading to a giant enhancement of third-order Kerr nonlinearity

We investigate XUV radiation localization at the nanometer scale by the exploitation of near-zero-index (NZI) heterostructures [1], with a particular focus on Titanium-Aluminum-Titanium multilayers. By solving fully vectorial Maxwell's equations semi-analytically, we obtain the transcendental dispersion relations of several transverse-electric (TE) and transverse-magnetic (TM) plasmon polariton modes. The dispersion relations of these modes are numerically evaluated using a Newton-Raphson algorithm.

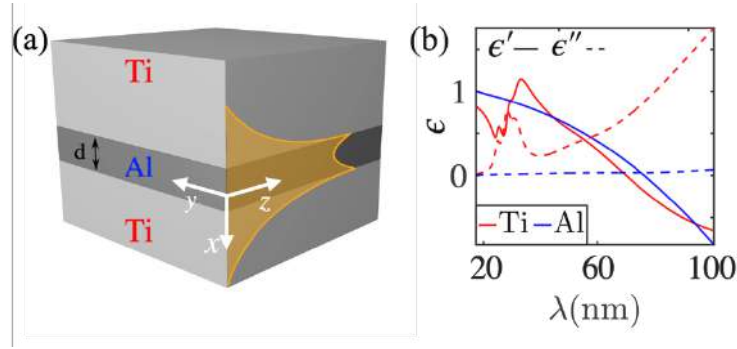


Fig. 1 **(a)** Schematization of the Ti-Al-Ti heterostructure, with Al thickness d , supporting plasmon polaritons mode propagating over the z -direction. **(b)** Wavelength dependence of the real (solid line) and imaginary (dotted line) part of the complex dielectric permittivity for both Titanium (red curves) and Aluminum (blue curves).

We systematically analyze the confinement properties and attenuation lengths of these modes, demonstrating that radiation confinement can be efficiently tuned by adjusting the Al thickness. In fact, we observe that 20 nm wavelength radiation can propagate through this heterostructure for distances exceeding 10 times its wavelength (approximately 500 nm) while remaining highly confined (less than 10 nm) at the interface between Titanium and Aluminum. We emphasize that XUV radiation guidance is achieved thanks to the ENZ properties of both Al and Ti in the considered spectral range. In this regime, the complex interplay between plasmon polariton modes and spatially structured absorption (see Fig. 2b) leads to guided modes.

Moreover, we find that TM modes provide the best effective mode length for nonlinear XUV applications under the ENZ condition of Al (around 80 nm). Consequently, the slow-light propagation characteristic at the ENZ wavelength results in an enhanced radiation-matter interaction, producing a significant boost in the nonlinear Kerr effect. In conclusion, ENZ heterostructures represent a promising platform for achieving nanometric confinement of XUV radiation. Our results pave the way for the design of novel XUV spectroscopic devices that exploit extreme radiation confinement to enhance radiation-matter interaction.[2]

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Efficient Method for Computing Super-Bound States in the Continuum in Periodic Structures

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Abstract: In periodic structures, a super-bound state in the continuum (super-BIC) is a special BIC near which the resonant modes have ultrahigh Q factor for a wide range of wavevectors. Super-BICs are particularly useful in applications. An efficient method for computing super-BICs is developed in this paper.

In a 2D structure that is invariant in x , periodic in y , bounded in z , and surrounded by air, a bound state in the continuum (BIC), in the E or H polarization, is a guided Bloch mode with an x component of the field given as $u(y, z) = \phi(y, z)e^{i\beta_*y}$, where β_* is the Bloch wavenumber, ϕ is periodic in y , $\phi \rightarrow 0$ as $z \rightarrow \pm\infty$, ω_* is the angular frequency, c is the speed of light in vacuum, and $\omega_* > c|\beta_*|$. Near a BIC, there are resonant modes with Bloch wavenumber β , and their Q factor satisfies $Q \sim 1/|\beta - \beta_*|^m$. For a normal BIC, $m = 2$. A super-BIC has $m \geq 4$ and is particularly useful, since the nearby resonant modes have an ultrahigh Q factor for a wide range of wavenumbers [1].

Most super-BICs are obtained by the merging process, that is, one or more structural parameters are tuned, so that a number of regular BICs in a single dispersion surface (of the resonant modes) merge together [2]. The process is manageable if only one parameter must be tuned. In case m is large or the structure has less symmetry, a super-BIC can only be found by tuning more than one structural parameters, then the merging process is extremely inefficient. Moreover, for structural parameters near those of a super-BIC, the dispersion surface may not contain multiple regular BICs.

Our method is to solve ω_* and β_* of the super-BIC and the structural parameters $\xi_1, \dots, \xi_n$, from a nonlinear system

$$\mathbf{G}(\omega, \beta, \xi_1, \dots, \xi_n) = \mathbf{0}. \quad (1)$$

The vector $\mathbf{G}$ depends on m , may be simplified if it is known that the super-BIC has $\beta_* = 0$, and/or if the structure and the super-BIC has some useful symmetry. If after possible simplifications, $\mathbf{G}$ contains l real independent conditions, then $n = l - 2$ if β_* is an unknown, or $n = l - 1$ if $\beta_* = 0$. The vector G comes from a perturbation analysis for resonant modes near a BIC [3], and can be defined even when $(\omega, \beta) \neq (\omega_*, \beta_*)$. To evaluate $\mathbf{G}$, we need to solve a couple of homogeneous and inhomogeneous Helmholtz equations.

As a numerical result, we use the above method to find a super-BIC with $m = 10$ in a simple periodic slab of period L and thickness h . Each period of the slab contains two segments of different homogeneous media. The first segment has a width w and refractive index $n_1 = 1.45$, and the second segment has width $L - w$ and refractive index $n_2 = 2.55$. This super-BIC is found as an isolated point in the w - h plane and marked as D in Fig. 1(a) and (b). It is an

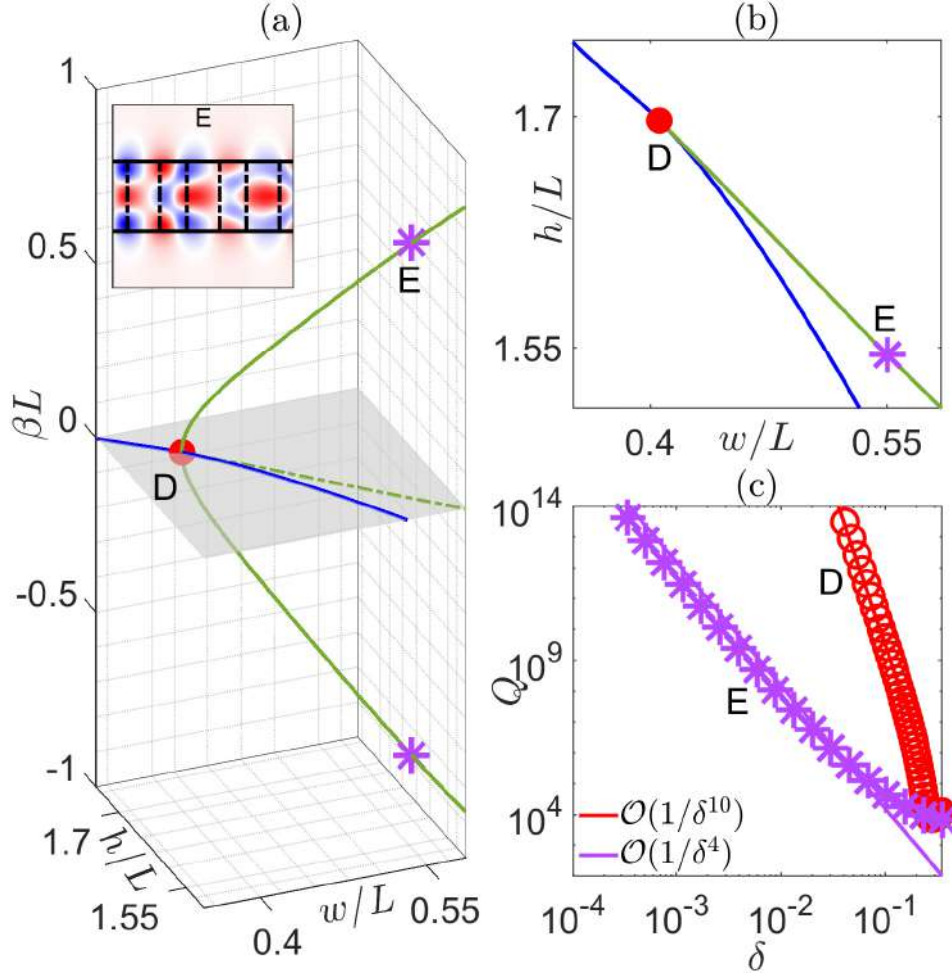


Figure 1: Two families of super-BICs in a periodic slab. (a) Dependence of Bloch wavenumber β on structural parameters w and h . (b) Parameters at which super-BICs exist. D is a super-BIC with $m = 10$, E is a super-BIC with a nonzero β and $m = 4$. (c) Validation of m for super-BICs D and E.

anti-symmetric standing wave with $\beta_* = 0$, and it corresponds to the case $(l, n) = (3, 2)$.

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Molecularly Detailed View of Strong Coupling in Supramolecular Plexcitonic Nanohybrids

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Abstract: A quantum approach is proposed to model hybrid states (plexcitons) of systems of interacting molecules and plasmonic nano-antennas. Our model accounts for the multilevel structure of chromophores and spatially varying interactions with a given plasmon mode, providing valuable insights into the character and local structure of the resulting plexcitons.

Plexcitons are a peculiar kind of hybrid state, originating from the mixing of molecular and plasmonic characters in strongly interacting composite systems.[1,2]

Our theoretical investigation[3] was originally prompted by the observation of distinct plexcitonic signatures in the supramolecular assemblies of a functionalized porphyrin on ligand-capped spherical Au nanoparticles (NPs).[4,5] In particular, a characteristic Rabi splitting in the absorption spectrum was identified in an energy window that corresponds to the excitation of the Q-type transitions of the chromophore in its monomeric form. The formation of plexcitons involving the Q bands is particularly puzzling due to the modest transition dipole moments of the molecular excitations and relatively poor spectral overlap with the plasmon, which suggests that collective coupling effects were operating to some extent.

To our knowledge, at that time, the state-of-the-art description of plexcitonic systems mainly relied on very simplified quantum optics models (for instance, the multichromophoric Tavis-Cummings model),[6] often considering the molecular component as a simple two-level system coupled with the localized surface plasmon (LSP), also treated as such.

In this work, we proposed and applied a full quantum model for the theoretical investigation of the reference plexcitonic system to enable more detailed insights into the hybrid states underlying the spectroscopic observations.[3] Our approach aims to provide a description of realistic plexcitonic nanohybrids that explicitly maintain single-molecule resolution, while potentially allowing for an arbitrary complexity of the molecular and plasmonic components.

We therefore accounted for all molecules individually and introduced an original methodology for calculating the interaction between molecular and plasmonic excitations, which automatically takes into account spatial inhomogeneities in molecular transitions.[3] In addition, all relevant excitations were included for each dye (i.e., both Q and B transitions for porphyrins), along with the corresponding couplings with a set of quantized plasmon modes of different nanostructures (employing a quantum-PCM model of LSP recently developed in our group),[7] as well as purely intermolecular (excitonic) ones.

All these efforts extended the reference quantum optics models and provided what is, to date, one of the most detailed models of the optical properties of a plexcitonic system. Important features of the plexcitonic wavefunctions, which have relevant implications for both our fundamental understanding and practical applications but remain hidden in coarser approaches,

are captured, starting from their highly inhomogeneous distribution over the molecular assembly (notwithstanding the need for the collective coupling of all considered molecules to reproduce experimental Rabi splitting).[3] This marked inhomogeneity, which reflects differences in the individual molecule-plasmon couplings, suggests that harvested energy is likely funneled toward specific molecular sites within a plexcitonic assembly.[8]

Moreover, we demonstrated the role of direct intermolecular interactions in making the plexciton formation more tolerant to some residual molecule-plasmon detuning, as well as in the promotion of an assorted band of quasi-dark states, which are likely involved in the relaxation pathways following the photoexcitation of a plexcitonic state. Finally, the inclusion of multiple excitations for each dye revealed the possibility of mixing molecular excitons of different kinds through the plasmons.[3] These latter aspects nicely supported the results of further ultrafast pump-probe experiments on the target system of porphyrins and Au NPs.[9]

Although originally devised for a specific experimental reference, we believe that the presented strategy is flexible and can find broader applicability. For instance, it can be directly transferred to the modeling of other plexcitonic nanohybrids, where either the organic dye or the plasmonic NPs or both are changed. Moreover, it can be straightforwardly extended to include the vibrational structure of electronic excitations. Finally, it can provide an effective and reliable starting point for the study of more complex spectroscopic experiments or photochemical processes.

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Femtosecond imaging of space-time plasmon polaritons

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Abstract: We visualize space-time surface plasmon polariton wave packets (ST-SPPs) with diffraction-free propagation and controllable group velocity using femtosecond time-resolved two-photon fluorescence microscopy. The observed lattice-like patterns confirm phase inversion and structural stability, demonstrating ST-SPPs' potential for broadband plasmonic signal routing and structured light applications.

Recent research on structured light has advanced the understanding of spatiotemporal behavior of spatially inhomogeneous optical fields, while also giving rise to methods for generating various optical beams with novel propagation characteristics, such as diffraction-free beams, optical vortices, propagation-invariant wave packets, and skyrmion beams [1,2]. The evanescent waves and surface waves such as surface plasmon polaritons (SPPs) are also included in the concept of the structured light [3]. By controlling the wavefront of SPPs, surface-wave analogs of free-space structured light have been demonstrated, such as diffraction-free SPP beams, SPP vortices carrying orbital angular momentum, and topological plasmonic spin-skyrmions with discrete topological charges [4,5]. In particular, diffraction-free SPP beams, offer potential applications in signal routing without the need for waveguides in plasmonic devices. However, there are challenges in realizing SPPs with both localized and linear trajectories, and in accommodating broadband input light, *e.g.*, femtosecond pulsed light.

In this study, we realize structured SPP wave packets with a regulated field distribution, stable shape, and diffraction-free propagation along a straight path by exciting space-time SPP wave packets (ST-SPPs) with time durations in the 10-fs range on a metal surface [6-9]. It also enables external manipulation of the properties of the wave packets, *e.g.*, the group velocity.

ST-SPPs are the surface wave correspondence of space-time wave packets (STWPs), which have realized free-space diffraction-free light sheets that travel along a straight line using pulsed beams [10,11]. We explore the spatiotemporal evolution of ST-SPP by using a pump-probe femtosecond time-resolved two-photon fluorescence microscopy (TR-2PFM) [12]. A 10-fs, 800-nm light pulse is synthesized into an STWP and focused on a silver (Ag) film with a straight nano-ridge milled as a coupler. The durations of the ST-SPPs are approximately 16 fs,

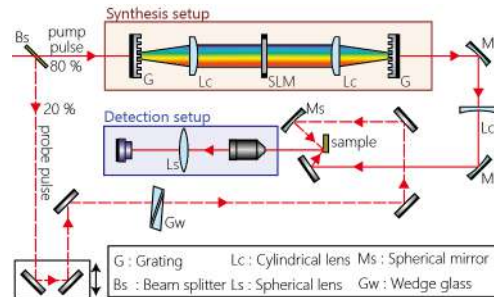


Figure 1. Schematic of the TR-2PFM equipped with the STWP synthesizer.

providing sufficient temporal resolution to explore the wave packet dynamics. The beat pattern of the surface field, formed over a few tens of micrometers along the axial direction where the ST-SPP and the probe light pulse overlap spatiotemporally after controlled delay time (τ), is visualized through the observation of 2PF emission from the sample surface (Fig.1).

Time-resolved movies of the surface fields reveal the diffraction-free characteristics of the ST-SPPs, as well as allow for determination of the group velocities. Figure 2 shows a typical time-resolved frame of a striped ST-SPP WP. The TR-2PFM image displays a characteristic lattice-like pattern that matches well with the simulation. This provides experimental evidence of phase inversion by π -rad between adjacent rows of SPP stripes arranged on the surface, which preserves the diffraction-free nature of the WP during propagation. Furthermore, the TR images confirmed the group velocity of this WP matches that of a conventional SPP.

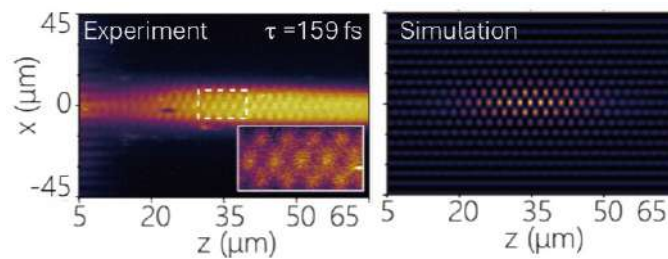


Figure 2. A typical TR-2PFM image of a time-resolved movie of striped ST-SPP.

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Periodic Plasmonic Nanoantenna Arrays for Photothermal and Photocatalytic Applications

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Abstract: In this contribution, we present two approaches for fabricating periodic plasmonic nanoantennas: electrodeposited nickel nanopillar arrays coated with gold and alumina oxide nanospikes overlaid with titanium nitride. These nanostructures were utilized for hydrogen production through photoelectrochemical water splitting and ammonia decomposition, respectively.

The integration of periodic plasmonic nanostructures with semiconductors holds immense potential for efficient solar energy conversion and storage. While gold-based nanoantenna arrays have been extensively studied, their high cost and limited scalability hinder broader applications. In this contribution, we present two distinct approaches for fabricating periodic plasmonic nanoantenna arrays using scalable and cost-effective methods, each based on a different structural scaffold: (i) electrodeposited nickel nanopillar arrays and (ii) electrochemically anodized anodic alumina oxide (AAO) nanospikes. These plasmonic platforms were designed for photoelectrochemical water splitting and ammonia decomposition for hydrogen production, respectively, leveraging tailored plasmonic resonances to enhance reaction efficiency.

We demonstrate that nickel nanopillar arrays can sustain complex electromagnetic resonances that significantly enhance the photoelectrochemical response of CdS thin films. By precisely tuning the pitch size and nanopillar diameter, we achieved broadband light absorption spanning from ultraviolet (UV) to near-infrared (NIR) wavelengths, leading to substantial photocurrent enhancements. The observed enhancement arises from the interplay of photonic modes in the UV range and hybrid cavity-plasmonic modes in the visible and NIR regions, facilitating efficient energy transfer and hot carrier injection between the metal nanostructures, the semiconductor, and the electrolyte. Compared to planar Ni/CdS samples, the Ni nanopillar arrays exhibit a substantial improvement in photocurrent, matching the performance of previously reported Au nanostructures, while utilizing Earth-abundant materials. These results highlight the potential of Ni-based plasmonic scaffolds as a viable alternative for scalable, low-cost photoelectrochemical solar energy conversion.¹

Efficient and sustainable hydrogen production is key to advancing clean energy technologies, with ammonia (NH₃) emerging as a promising hydrogen carrier due to its high energy density and ease of storage. However, conventional ammonia decomposition requires high temperatures, making the process energy-intensive. We will present a plasmon-assisted catalytic system for low-temperature NH₃ decomposition, leveraging a sharp-tip anodized alumina oxide (AAO) nanospike array coated with a plasmonic Au film (nanoantenna) and decorated with Cu nanoparticles (reactors). This system utilizes surface plasmon resonance (SPR) to generate hot carriers, significantly enhancing catalytic efficiency under visible light irradiation.

The optimized AAO@Au@Cu nanostructure exhibited an impressive hydrogen evolution rate of 227 $\mu\text{mol h}^{-1} \text{gCu}^{-1}$ under 1 sun illumination at only 35°C, with peak activity observed at 565 nm, corresponding to the SPR mode of the nanostructure. Mechanistic insights from XPS, TOF-SIMS, and spin-polarized density functional theory (SP-DFT) calculations suggest a stepwise NH_3 decomposition pathway involving NH_2NH_2 (hydrazine) and NH-NH intermediates. This plasmon-driven approach demonstrates a significant reduction in energy requirements for hydrogen production, underscoring the potential of plasmonic nanoarchitectures to revolutionize sustainable catalysis. We will also describe how to exchange Au for much cheaper but yet active plasmonic titanium nitride (TiN).^{2,3}

By employing electrodeposited Ni nanopillars and anodized AAO nanospikes, we establish two distinct yet complementary strategies for harnessing plasmonic nanoantennas in photocatalytic applications. These scalable, cost-effective platforms offer promising pathways for photoelectrochemical water splitting and low-temperature ammonia decomposition, paving the way for next-generation solar-to-fuel conversion technologies with enhanced efficiency and reduced energy consumption.

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Phase singularity effect on metasurface sensor working at the critical coupling

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Abstract: Approaching the critical coupling or perfect absorption is presented in this work with the help of phase change material or by tuning the geometrical dimension of the nanostructured metasurface. The thermal phase sensor properties are studied when the critical coupling is approached for a Tamm plasmon photonic crystal.

With resonant photonic sensors, it is recognized that the phase sensitivity increases dramatically as the critical coupling is approached. Consequently, it leads to better phase sensors. In order to better understand the behavior of the sensor with phase singularities, we propose here to fine-tune the critical coupling for Tamm plasmon metasurfaces by tuning the refractive index of the phase-change material for unstructured Tamm plasmons or by controlling the filling factor (FF) of the grating during fabrication for structured Tamm plasmons. Thanks to an original interferometer with spatial light modulator and holography [1], we are able to measure the complex reflectivity spectra of the metasurfaces for very low levels of reflected light. The ability to approach critical coupling and to precisely measure amplitude and phase at very low reflectivity values has opened the way to studying the behavior of Tamm plasmon nanostructures used as sensors.

The experimental complex reflectivity shows the behavior when passing through the critical coupling from the undercoupled to the overcoupled regime as the FF increases. A plot of the reflectivity in the complex plane provides a straightforward visualization of the resonance and the two regimes. The resonances can be resumed to two constant times due to internal absorption and radiative loss when the resonance is modelled by temporal coupled mode theory (TMC). The constant values are extracted from the experimental complex spectra and we can deduce from the two constant times evolution, the conditions of critical coupling.

Sensitivity measurements when the metasurfaces are heated show that the phase sensitivity increases drastically as the critical coupling is approached. The phase sensitivity values follow a law that we established in a previous work[2] for surface plasmon by modelling the resonance with TMC and that we generalize for the case of Tamm plasmon metasurfaces. In this paper we present for the first time experimentally what are the physical parameters that govern the value of the phase sensitivity. Finally, we experimentally qualify the noise of the sensor and it turns out that approaching the phase singularities has no effect on the limit of detection. This result goes against to what is generally accepted.

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Harnessing plasmonic phenomena in glass composites obtained by crystal growth techniques

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Abstract: Volumetric glass materials grown by micro-pulling-down technique will be presented, particularly from the perspective of their enhanced optical properties upon doping with plasmonic nanoparticles.

Plexcitonic systems integrate plasmonic properties with excitonic emission, leading to enhanced system performance characterized by rapid and intense luminescence. These features are particularly desirable for applications in optoelectronic devices, ultrafast optical switches, and quantum information science.

In this study, we present optically active volumetric materials fabricated using the micro-pulling-down method. By employing the NanoParticle Direct Doping (NPDD) technique, we create nanocomposites with tailored plasmonic properties, enabling the observation of enhanced optical responses. This innovative approach, developed in our laboratory, facilitates the direct introduction of plasmonic nanoparticles into glass matrices, allowing precise control over their electromagnetic characteristics. Consequently, we can fine-tune localized surface plasmon resonances (LSPR) to optimize targeted effects, such as the photoluminescence (PL) enhancement of quantum dots.

By integrating advanced material fabrication with comprehensive characterization, our research paves the way for cost-effective photonic devices with enhanced functionalities.

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Self-induced nonlinear optics in the XUV regime

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Abstract: Nonlinear optics represents a strong research field in the visible, and near infrared. The recent advent of high brilliance sources in the extreme ultraviolet (XUV) has enabled investigations in this regime. Here, an overview of self-induced nonlinear optics in the XUV regime is presented.

Self-driven third order nonlinear effects represent a key element for the realization of several optical spectroscopies and photonic devices. By the simple interaction between one pulse and matter, they can induce spectral modifications, such as supercontinuum generation, wavelength converters, and chirped pulse amplification. The lack of stable and high brilliance light sources prevents such observation in this fundamental regime dominated by core electron interactions. The recent advent of Free Electron Lasers (FEL) and high-harmonic generation (HHG) systems enables the extension of these effects in the wavelength regime of X-ray and XUV and the realization of new spectroscopic schemes taking advantage of the shorter wavelength involved. No evidence for intrapulse dynamics, however, has been reported at such short wavelengths, where the light-matter interactions are ruled by the sharp absorption edges of core electrons. We will show the first experimental evidence for self-phase modulation of femtosecond seeded FEL pulses [1], allowing peak intensity $> 200 \text{ TW/cm}^2$.

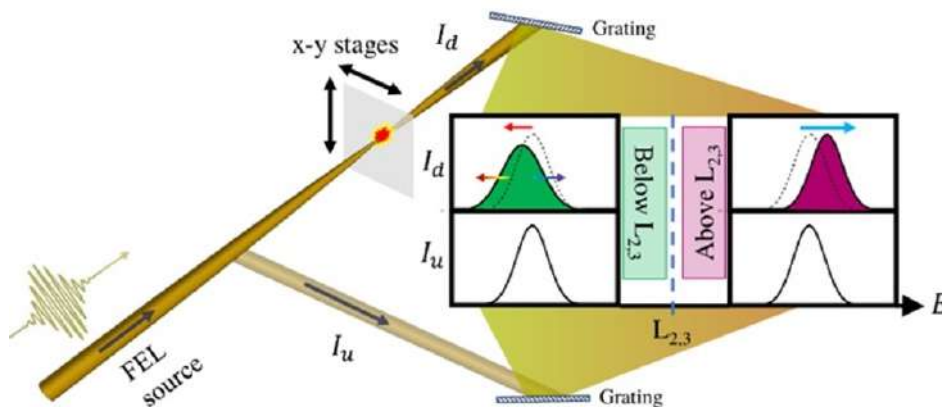


Fig. 1 Sketch of the experimental scheme for the detection of self-induced nonlinear effect in XUV. The simultaneous spectral detection enables the comparison of the spectral modification induced by nonlinear interaction.

Specifically, the single shot comparison of the spectra reveals a spectral modification from a non-linear blue-

shift to a red-shifted broadening, above and below the absorption edge L2,3, respectively (see Fig. 1) [1]. In this experiment the FEL wavelength are tuned around the absorption edge of materials to enhance the nonlinear response. These findings are rationalized accounting for ultrafast ionization of electrons [2], self-phase modulation and delayed thermal response of highly excited electrons [3].

This disruptive first observation has enabled the investigation of methods to gain enhancement of the nonlinear signal. Here, we report the enhancement of self-induced nonlinear effects by means of plasmonic interaction in a submicrometric foil of aluminum [4]. Specifically, the near-zero effective-index (NZI) condition leads to a dramatic field enhancement, amplifying nonlinear responses with remarkable efficiency.

The near-zero effective-index (NZI) condition, i.e. $\text{Re}\sqrt{\epsilon_{Al}(\lambda) - \sin^2 \theta_{NZI}(\lambda)} = 0$, can be reach by tuning opportunely the impinging angle θ of light at specific $\theta_{NZI}(\lambda)$. In this regime, broadband Ferrell-Berreman (FB) modes in the Al thin foils occurs, leading to an enhancement of self-induced nonlinear effects. Particularly, during the ultrafast interaction between the femtosecond FEL pulse, the electron in Al undergoes ultrafast heating, followed by a relaxation process via electron-phonon collisions. This complex dynamic is theoretically taken into account by modeling the temporal electronic temperature, which causes a modulation of the refractive index.

In conclusion, we report the recent evidence of self-induced nonlinear effects in XUV and the first observation of ENZ enhancement of these nonlinear effects. Moreover, in our extended theoretical model [5], we describe the enhancement of nonlinear effects that can occur at the epsilon-near-zero (ENZ) wavelength for a nanometric bilayer of poor metal, where plasmons play a crucial role in light-matter interaction.

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Measurement of the refractive index using a plasmonic Hong-Ou-Mandel sensor

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Abstract: We propose a Hong-Ou-Mandel sensor using a plasmonic beam splitter depending on refractive index in sensing layer. The proposed sensor achieves a higher precision compared to its classical benchmark. This work is not limited to plasmonic structure but has the potential to any beam splitter-type structures.

Recent years have witnessed the application of nanophotonic structures in quantum optics to enable novel functionalities, such as reduced loss, efficient pumping of quantum emitters, and enhanced precision in quantum sensors [1]. In this context, we propose a quantum plasmonic Hong-Ou-Mandel (HOM) sensor for refractive index measurement, exploiting the rapid response of plasmonic structures and the sensitivity of HOM interferometry. In a previous report, a HOM sensor for estimating optical path achieved precision at the attosecond level [2].

A plasmonic beam splitter for HOM interference is designed using two symmetric Kretschmann structures. The plasmonic beam splitter consists of five layers: two glass prisms ($n = 1.5$), two gold films, and one sample layer. The properties of the beam splitter, such as its transmittance and reflectance, vary depending on the refractive index of the sample. The coincidence probability between the output ports is also affected by the sample. The precision of this sensing scheme is bounded by the inverse of the Fisher information, known as the Cramer-Rao bound. The Fisher information $I(n_s)$ can be defined as

$$I(n_s) = \sum_i \left(\partial_{n_s} P_i(n_s) \right)^2 / P_i(n_s)$$

, where a set of probability $P_i(n_s)$ for detected photons i ($= 0, 1, 2$), given the refractive index n_s . The Fisher information of HOM is compared to that of the coherent state. For fair comparison, the average photon number is set to 1.

In summary, we propose a HOM sensor with a plasmonic beam splitter for refractive index measurement. The detection probability distribution of photons is determined by the beam splitter's properties, which depend on the transmittance $T(n_s)$ and reflectance $R(n_s)$. The HOM sensor demonstrates superior performance compared to its classical benchmark. Interestingly, this sensing scheme is not limited to plasmonic structures, but can also be applied to any beam splitter-type sensor, provided that the beam splitter's response is known, because the probability set P_i used in the Fisher information is independent of the plasmonic properties. This work has the potential to broaden its application to various beam splitter-type structures [3].

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Plasmonic light-matter interaction for enhanced molecular detection in MIR using metal and semiconductor-based optical sensors

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Abstract: Our research explores light-matter interaction applications, focusing on enhancing optical sensor transducers for low-concentration molecular detection using plasmonic effects in MIR. A comparison of the enhancement factor will be presented based on materials and antennas. In the end, we also target integrating these sensors into microfluidic systems.

Plasmonic light-matter interactions have emerged as powerful tools for enhancing optical sensor performance, especially for molecular detection at low concentrations. Conventional plasmonic sensors often rely on noble metals, yet their integration with semiconductor platforms and scalability remain limited. In this work, we focus on exploiting plasmonic effects in heavily doped semiconductors to develop efficient optical transducers operating in the mid-infrared (MIR). This approach opens avenues for scalable, integrable plasmonic sensors tailored for applications in health monitoring and environmental sensing.

In this presentation, we will introduce our systematic methodology for the design and simulation of plasmonic structures using FDTD and RCWA methods, optimizing material parameters and geometries. Then, the fabrication of the transducer structures, including heavily doped semiconductor layers and surface antennas with various shapes (1D ribbons, 2D bowtie, honeycomb). The optical characterization of plasmonic resonances is done by a microscope adapted to Fourier transform IR spectrometer. The spectroscopic fingerprint detection is done via surface enhanced IR absorption (SEIRA) with measurements of the transducer amplification factors.

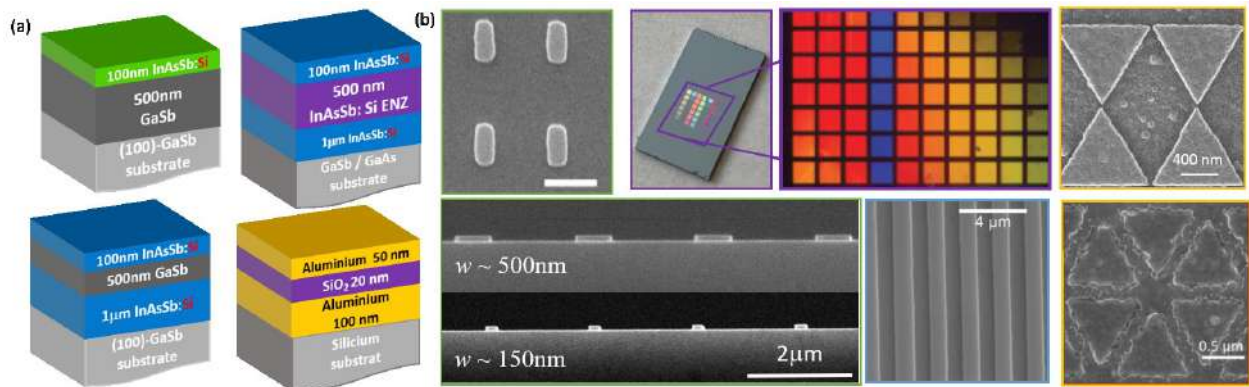


Figure 1: (a) Plasmonic structures based in a single layer and perfect absorbers (b) Antennas realizations.

We have developed and analyzed several generations of plasmonic sensor structures, as shown in figure 1. A single layer model simple design consisting of heavily doped semiconductor layers (GaSb, InAs) on substrates, supporting plasmonic resonances in MIR. Surface antennas in ribbon shapes enabled demonstration of molecular detection. Then, a perfect absorber model, a more complex structure, mimicking a metal-insulator-metal (MIM) configuration but replacing metals with doped semiconductors, undoped GaSb and InAs served as insulating

layers, enhancing absorption and resonance control. Finally, an ENZ model integrates an ENZ material based on InAs further improved field confinement and sensitivity. This model allowed selective and rapid detection of gas-phase molecules at concentrations down to ~ 500 ppm.

For all designs, we demonstrated plasmonic resonances in reflection and absorption modes across the MIR. The SEIRA technique confirmed detection of molecular fingerprints, while the perfect absorber model enabled SETES spectroscopy, utilizing the structure's thermal emission as a light source. Additionally, we explored an aluminum/SiO₂-based perfect absorber structure, aiming for silicon integration. Advanced antenna geometries, including bowtie and honeycomb patterns, yielded an amplification factor of $\sim 10^7$, surpassing initial ribbon-based designs by three orders of magnitude. This resulted in detection sensitivity down to $\sim 10^4$ molecules per antenna, approaching the state of the art.

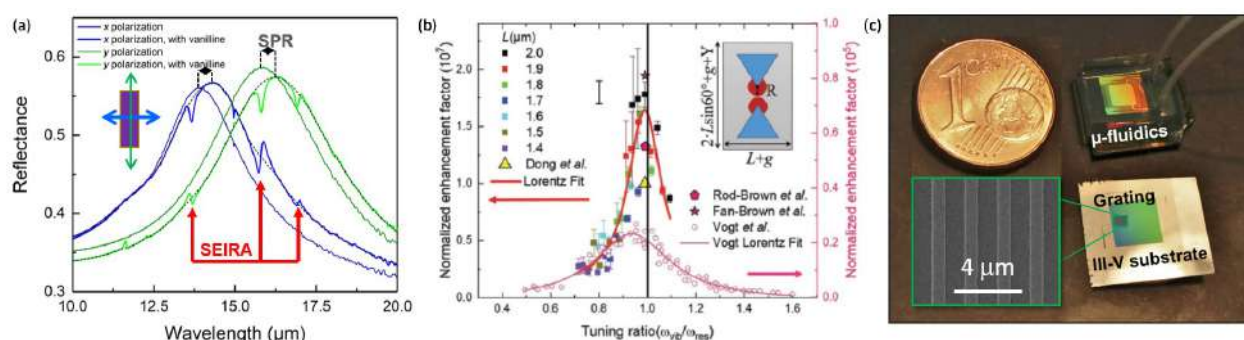


Figure 2: (a) SEIRA demonstration (b) Enhancement factor comparison, (c) Integration with microfluidics

To move towards real-world applications, we successfully combined the semiconductor-based plasmonic transducers with PDMS microfluidic systems, fabricated via soft lithography. This integration enabled SPR-based IR spectroscopy under flow conditions, enhancing detection speed and specificity. In summary, we have demonstrated the systematic improvement of semiconductor-based plasmonic transducers for molecular detection in the MIR. Our results highlight the potential of these structures for sensitive detection, integration with microfluidics, and compatibility with silicon platforms. Future efforts will focus on advancing on-chip integration, exploring broader application fields such as environmental monitoring, and extending detection capabilities through dynamic metasurface designs.

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Topological photonic integrated circuits for controlling internal degrees of freedom of light

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Abstract: Topological photonics brings mathematical topology into the field of optics, which allows us to handle information derived from internal degrees of freedom of light, such as optical spin and orbital angular momentum. In this talk, we present analytical methods, fabrication technology, and application of topological photonics to optical circuits.

Tracing the topology of electronic systems in topological insulators and Weyl semimetals into photon systems is called ‘topological photonics’ [1]. In the field of topological photonics, it is well known that the Z₂ topology is expressed by using photonic structures consisting of a honeycomb lattice of unit cells, where the dielectrics are arranged with C_{6v} symmetry [2, 3]. Above systems have a greater degree of freedom for interactions, making it possible to design photonic bands more flexibly.

One of the best-known phenomena in topological photonic systems is the topological edge state at the interface between two photonic structures with distinct topology, which allows the propagation of light with a specific spin (i.e. circular polarization) and orbital angular momentum (i.e. optical vortex). Circularly polarized light and optical vortices are considered key elements for increasing optical transmission capacity, and topological photonics system, which can propagate and maintain them in an optical circuit, has a wide range of applications.

Against this background, we have proposed to replace a part of Si photonic integrated circuits with a topological photonic system (TPICs; topological photonic integrated circuits). To realize TPICs, it is essential to include at least the following three basic passive elements: (1) *topological converters* that enable highly efficient coupling from normal silicon waveguides to topological systems [4], (2) *topological vertical couplers* for efficient coupling from free space to topological systems [5], (3) *topological splitters* that divide optical signals into arbitrary intensities while maintaining the internal degrees of freedom of light [6].

A series of passive elements for input/output and splitting/coupling are indispensable in conventional optical circuits, and this is also true for topological photonic systems. In this talk, each of these elements will be discussed in detail.

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Optics, photonics, optoelectronics, photonic
materials and devices

Transition metal dichalcogenide-based excitonic hybrid 2D materials: An ideal platform for fundamental and applied photonics and optoelectronics

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Abstract: Transition metal dichalcogenide monolayers (TMD-MLs) exhibit high exciton binding energy and mobility, making them a promising platform for a wide range of novel exciton-based photonic and optoelectronic devices. In our recent studies, we have shown that TMD-ML lateral heterojunctions can be used to filter, focus, collimate and trap neutral excitons.

Transition metal dichalcogenide monolayers (TMD-MLs) have been the focus of extensive research in recent years thanks to their strong light-matter coupling and intriguing optical and excitonic properties.¹⁻⁵ A particular emphasis has been placed on the manipulation of neutral excitons at room temperature (RT) in these materials, which is a direct consequence of their tight binding energies and notably high mobilities.⁶⁻⁸ Indeed, controlling the spatial motion of these quasiparticles has the potential to yield significant advancements in excitonic circuits, photonics, and optoelectronics. However, the neutral charge nature of the main excitons in TMD-MLs limits their interaction with external electric or magnetic fields, making their manipulation a challenging task. Several studies have focused on their spatial manipulation and the localization of their emission using local strain gradient engineering of TMD-MLs deposited on nanoantennas.⁹⁻¹⁰ Furthermore, combining two or more TMD-MLs with different optical properties for designing innovative vertical heterojunctions(VHs)¹²⁻¹⁵ and lateral heterojunctions (LHs)¹⁶⁻¹⁸ have recently been the center of a considerable attention thanks to their unique excitonic properties, such as Moiré interlayer excitons and charge transfer excitons.

Recently, we demonstrated efficient unidirectional transport of excitonic flux from a higher bandgap TMD-ML to a lower bandgap TMD-ML at RT in high-quality type-II band alignment CVD-grown LHs¹⁹. Near-field optical spectroscopies based on tip-enhanced Raman scattering and photoluminescence (PL), providing a spatial resolution of about 30 nm, were performed on high-quality WSe₂-MoSe₂ LH, exhibiting an excitonic diode-like effect. Indeed, neutral excitons generated inside WSe₂ (large bandgap) are able to pass through the junction before recombining inside MoSe₂ (narrow bandgap), while the reverse case is not allowed. This phenomenon gives rise to a Kapitza resistance-like effect,²⁰ which manifests as a strong discontinuity in the excitonic density at the interface between both materials. As a result, the higher bandgap material-related PL is quenched, while the lower bandgap material-related PL is enhanced near the junction. Furthermore, by using μ -PL imaging combined with numerical simulations based on statistical approach of randomly moving excitons

through specific geometries of sharp CVD-grown WSe₂-MoSe₂ LHs, we showed that various shapes formed by those interfaces enable advanced in-plane control of both excitonic distribution and fluxes over large distances²¹. Thus, a triangular shape LH allows both exciton focalization and flux collimation, resulting in the formation of parallel current lines extending a few micrometers away from the source. We also proved that sub-wavelength MoSe₂ triangles embedded in a WSe₂ matrix provide efficient systems for trapping and confining excitons in adjustable size spaces¹⁴. Our finding about sharp TMD-LHs opens new perspectives for the manipulation of neutral excitons in flat semiconducting 2D materials, hence for the design and production of new excitonic devices.

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Anisotropic Photonic Crystals for Highly Performing Chiral Mirrors

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Abstract: The capability of anisotropic media to exert an optical torque on electromagnetic fields constitutes a promising platform for polarization control. We investigate ultra-compact stacks of uniaxial anisotropic media to engineer chiral mirrors showing reflectance $>99\%$ for one circular polarization and $<1\%$ for the other.

We perform a comprehensive theoretical analysis of the proposed device, studying the optimal conditions that allow our system to show a very high reflectance for one circularly polarized (CP) component and very low reflectance for the other one, depending on the specific reciprocal orientations of the extraordinary axes of neighbouring slabs and on their thicknesses. The realization of chiral metamaterials and metasurfaces with similar properties faces several challenges requiring expensive and time-consuming procedures to create complex geometries at the nanoscale, materials compatibility, scalability and integration with existing devices [1]. Moreover, high absorption and ohmic losses limit the performance of plasmonic metasurfaces [1].

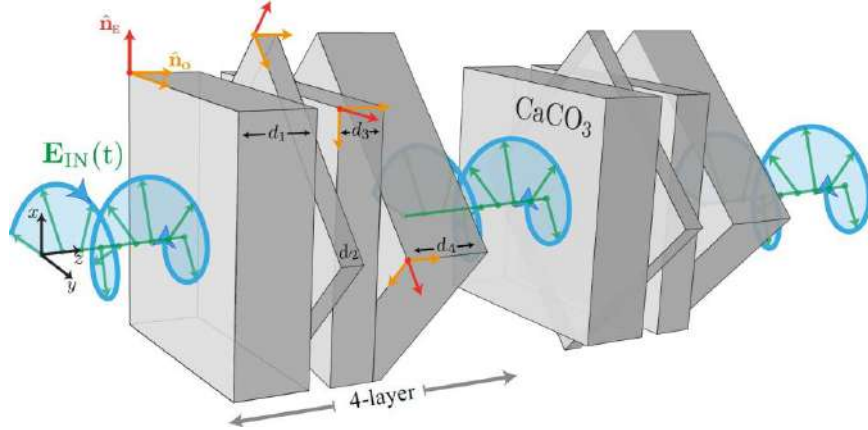


Figure 1. Schematic of the optical system with N 4-layers stacks of uniaxial anisotropic media of calcite. Each layer in each stack has a specific thickness and a certain extraordinary angle with respect to the x -axis, which is progressively increased. The mirror is illuminated by an electromagnetic field with arbitrary vacuum wavelength, incidence angle, and impinging polarization. For the sake of simplicity, we show a normally incident circularly polarized field.

We present a device based on a simple but powerful physical mechanism, that is, the optical torque (density) exerted by an anisotropic medium on the electromagnetic (EM) field [2],

$$\boldsymbol{\tau}_V^{\text{EM}} = -\mathbf{P} \times \mathbf{E} = -\mathbf{D} \times \mathbf{E}. \quad (1)$$

We consider an impinging monochromatic plane EM wave with an arbitrary angle of incidence and use the theory of electromagnetic propagation in birefringent layered media based on the transfer matrix approach [3]. As a measure of the local density of chirality of the EM field, we also refer to the optical chirality [4,5],

$$C = \frac{1}{2} [\mathbf{E} \cdot (\nabla \times \mathbf{D}) + \mathbf{H} \cdot (\nabla \times \mathbf{B})]. \quad (2)$$

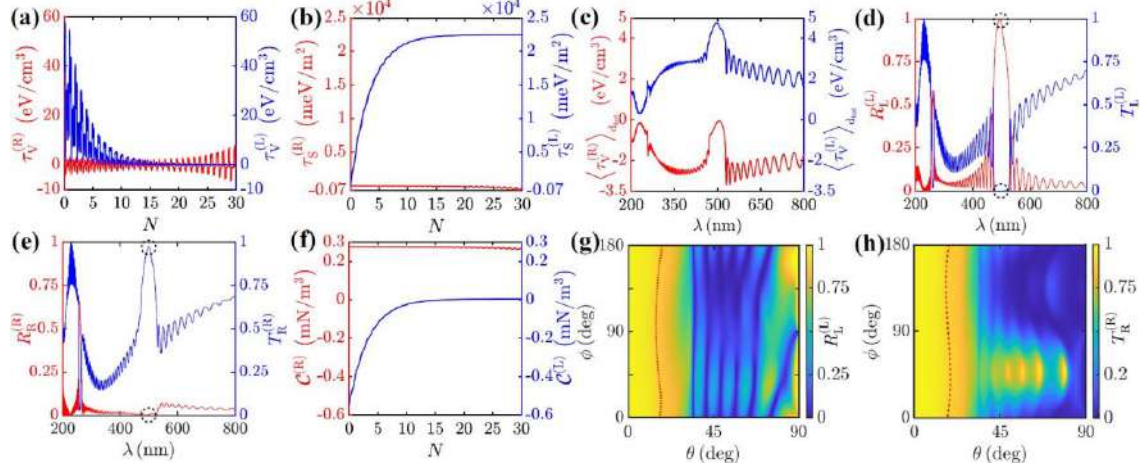


Figure 2. Normally incident EM field with $\lambda=500$ nm unless otherwise specified. **(a)** Optical torque volume density for both right CP (RCP) and left CP (LCP) light. In the former case, it oscillates around zero, so that the net effect is almost null, while in the other case it is significant at the beginning (the device tries to force the opposite polarization to LCP light) and then goes to zero. Due to the definition of the optical torque, this means that the electric field amplitude goes to zero during forward propagation, i.e., LCP light is (almost) completely reflected. **(b)** Integral of the optical torque volume density over the propagation coordinate z for both RCP and LCP light. It is close to zero in the former case, while in the latter it grows rapidly till saturation. **(c)** Wavelength dependence of the length average of the optical torque density for both normally incident RCP and LCP light. **(d)** Reflectance and transmittance of LCP light for incident LCP light. **(e)** Reflectance and transmittance of RCP light with incident RCP light. The dashed circles in **d,e** indicate the reflectance/transmittance at $\lambda=500$ nm. **(f)** Optical chirality for both normally incident RCP and LCP light. In the former case, it stays positive, while in the latter it initially has a negative value and then grows to zero. **(g)** Dependence of LCP light's reflectance with incident LCP light on the incidence angle. For θ from zero to the red dashed line its value is greater than 0.90. **(h)** Dependence of RCP light's transmittance with incident RCP light on the angle of incidence.

This device is a promising candidate for a new class of miniaturizable (the system characterized in Fig. 2 has a total thickness of $4.578 \mu\text{m}$), low-loss, easy to fabricate and cheap circular polarizers, and holds also great promise for applications in quantum technologies and polarization-sensitive optical detectors.

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Toward the Realization of High-Repetition-Rate Ultrafast Lasers in Microresonators: From Exceptional Points to Sol-Gel Doping

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Abstract: Ultrafast lasers employing whispering-gallery-mode (WGM) microresonators offer compact designs with high repetition rates. We revealed how exceptional points enhance the saturable-absorber-like behavior, while sol-gel Er doping realizes integrated gain in microtoroids. Together, these developments pave the way for robust on-chip ultrafast lasers with minimal external components and simplified design.

Ultrafast optics relies on generating ultrashort pulses at high repetition rates. Such pulses enable faster data acquisition in sensing, enhanced throughput in materials processing, and higher bandwidth in optical communications. Conventionally, mode-locked lasers with repetition rates beyond a few GHz were difficult to achieve because we had to make a cavity with significantly short resonator length. Whispering-gallery-mode (WGM) microresonators offer a promising path forward: their small diameters naturally support repetition rates of tens to hundreds of GHz, making them ideal candidates for on-chip, ultrafast laser sources.

A route to achieve passive mode-locking is to incorporate a saturable absorber (SA) material, such as carbon nanotubes, onto a gain-doped WGM resonator (Fig. 1(a)). A numerical study on Er-doped silica toroids [1] indicates three key requirements for stable single-pulse mode-locking: (1) a sufficiently high intrinsic Q to compensate for small per-round-trip gain, (2) near-zero or slightly anomalous dispersion to enable self-phase modulation, and (3) adequate SA modulation depth (Fig. 1(b)). Simulations show that a diameter of around 300 μm (with $Q \sim 10^7$) strikes a balance between stronger Er gain (larger mode volume) and manageable dispersion. Experimentally, thin CNT/PDMS layers transferred onto microtoroids have shown appropriate saturation power ($\sim 15 \text{ MW}/\text{cm}^2$) and minimal additional loss.

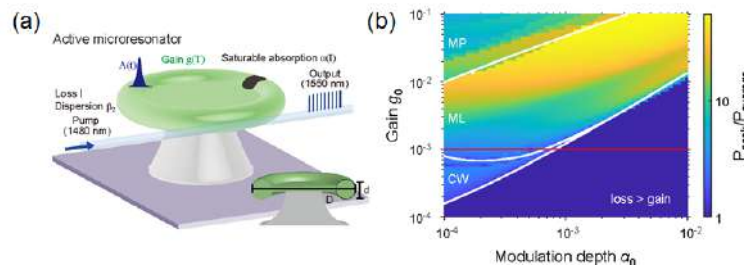


Fig. 1: (a) Illustration of SA-functionalized Er-doped microtoroid. (b) Calculation of the mode-locking (ML) condition for different Er gain (/roundtrip) and modulation depth of the SA for a cavity with $Q = 10^8$.

Though the results provide us with a sweet spot for achieving mode-locked laser in a single WGM microcavity (red line in Fig. 1(b)), it is still an experimental challenge because the integration of CNT directly to a gain cavity will induce additional loss, which usually makes the Q low. Our recent theoretical work [2] demonstrates that separating these two functions into two cavities, namely, coupling a gain microresonator to a lossy auxiliary resonator (Fig. 2(a))—tuned near an exceptional point (EP)—can replicate the effect of an SA without using dedicated absorbing materials. Near an EP, small Kerr-induced refractive index changes cause

significant variations in the system's hybrid modes (Fig. 2(b)), momentarily decoupling the main resonator from the lossy cavity at the pulse peak. This mechanism lowers loss for high-intensity regions of the circulating light and increases it for the low-intensity background (Fig. 2(c)). Simulations predict sub-30-fs pulses after tens of thousands of round trips (Fig. 2(d)), highlighting the power of non-Hermitian physics in mode-locking lasers and eliminating the usual need for specialized absorber materials.

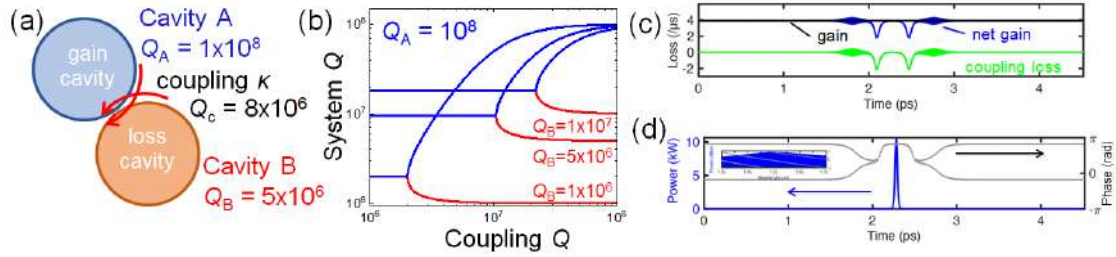


Fig. 2: (a) Coupled cavity with gain and loss. (b) System Q in function to the coupling. (c) Instantaneous gain and loss in a roundtrip (d) Calculated waveform (inset: spectrum).

One needs a robust, uniform doping process to realize a gain in a high- Q silica WGM resonator experimentally. Traditional ion implantation risks damaging the host lattice, reducing Q . As an alternative, we use a sol-gel coating to deposit erbium ions into silica films or directly onto microresonator structures [3] (Fig. 3). Careful tuning of parameters (water-to-precursor ratio, spin speed, and annealing temperature) mitigates common defects like cracking, peeling, or de-wetting. Large-diameter ($450 \mu\text{m}$) Er-doped sol-gel microtoroids with Q s above 10^6 have been demonstrated, lasing at $1.55 \mu\text{m}$ with thresholds under 1 mW. Critically, doping does not significantly alter the device's anomalous dispersion, preserving conditions for ultrafast pulse generation.

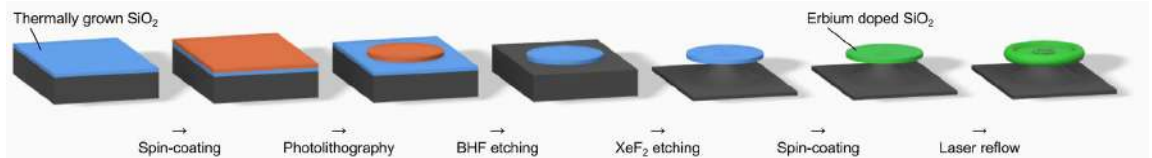


Fig. 3: Fabrication step of an Er sol-gel coated toroid.

Taken together, these three investigations showcase complementary strategies for achieving microresonator-based ultrafast lasers. The EP-driven approach eliminates the need for a conventional SA, relying instead on non-Hermitian coupling near an exceptional point. Meanwhile, the sol-gel doping protocol enables flexible integration of erbium gain, and an SA method (e.g., CNT-based) offers a more traditional but well-understood route to pulse formation. Both methods leverage high- Q silica microcavities to sustain net gain and exploit carefully designed dispersion to stabilize ultrashort pulses. By merging these techniques, one can envision compact, gigahertz-to-terahertz repetition rate lasers suitable for advanced ultrafast optics applications—paving the way for faster, smaller, and more power-efficient photonic systems.

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Intrinsic photovoltaic effect in engineered van der Waals materials

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Abstract: Intrinsic photovoltaic effects, in which zero-bias photocurrent response occurs even in the absence of conventional semiconductor junctions, have been observed in engineered van der Waals materials, providing novel design principles for functional nanodevices based on inversion symmetry breaking.

Intrinsic photovoltaic effect indicates the emergence of the zero-bias photocurrent reflecting the symmetry breaking and can appear even without conventional semiconductor junction (Fig. 1). It has been reported in a variety of quantum materials and is now attracting much attention due to its potential application in the solar cell as well as its quantum mechanical origins. In particular, enhanced intrinsic photovoltaic effect has been observed in engineered van der Waals materials [1-5], in which symmetry can be controlled by utilizing the characteristics of van der Waals crystals, such as easy deformation and the ability to freely make interfaces.

In this presentation, I will talk about several examples of intrinsic photovoltaic effect realized in engineered van der Waals materials. Characteristic properties of the intrinsic photovoltaic effect including the directional dependence, laser position dependence, laser power dependence, photon energy dependence, light polarization dependence etc. will be introduced. Possible microscopic mechanism will be also discussed.

The results provide new design principles for functional nanodevices based on inversion symmetry breaking and also reveal that van der Waals materials are promising material systems for large intrinsic photovoltaic effects.

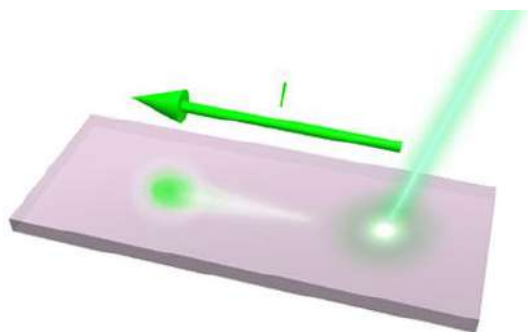


Fig 1. A schematic of the intrinsic photovoltaic effect. Zero-bias photocurrent response occurs even in the absence of conventional semiconductor junctions

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Harnessing Deep Learning for Inverse Design of Topological Photonic Properties

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Abstract: Deep learning enhances photonic structure design by solving inverse problems. This study predicts Zak phases in 1D photonic crystals using data-driven models that map geometric parameters to optical performance. This approach advances deep learning applications in topological photonics, enabling efficient design and unlocking new possibilities in photonic devices.

Photonic topological states are crucial in photonic structures, enabling the design of robust devices [1]. In one-dimensional systems, the Zak phase [2] predicts topological interface states, which are robust to certain perturbations and disorders [3]. Most studies on topological photonics use a forward-design approach, where geometric parameters are defined to obtain wave responses like dispersion [4]. A more challenging yet intriguing approach is the inverse design, where the desired photonic performance directly informs the structure, requiring exploration of a larger design space. Recent advances in deep learning (DL) have proven efficient in solving the inverse design problem [5], such as predicting the Zak phase in 1D photonic [6,7] and phononic [8,9] systems. In this work, we propose using DL models for the inverse design of topological photonic systems with targeted Zak phase properties, providing insights into DL's application in complex photonic systems.

The model consists of two networks: a forward network and an inverse network. The forward network is trained using stochastic gradient descent (SGD) with a learning rate (LR) of 0.1. The forward network has 6 hidden layers, each with 256 neurons, and converges in under 1000 epochs. The inverse network shares the same optimizer settings but has 4 hidden layers with 256 neurons each, converging similarly within 1000 epochs.

The forward model achieves 97.545% accuracy on the test dataset, which represents 20% of the 2 million data samples, indicating it has learned meaningful patterns and is reliability for the task. To test the model, we input an initial phase to the inverse network, which generates a predicted geometry. This geometry is passed to the forward model to produce a predicted phase. Finally, we compare the predicted phase to the real initial phase (see Fig. 1 for the stubbed photonic structure composed of stubs of lengths d_2 separated by segments of length d_1) to assess the model's accuracy in capturing the relationship between the phase and its geometry both theoretically and experimentally.

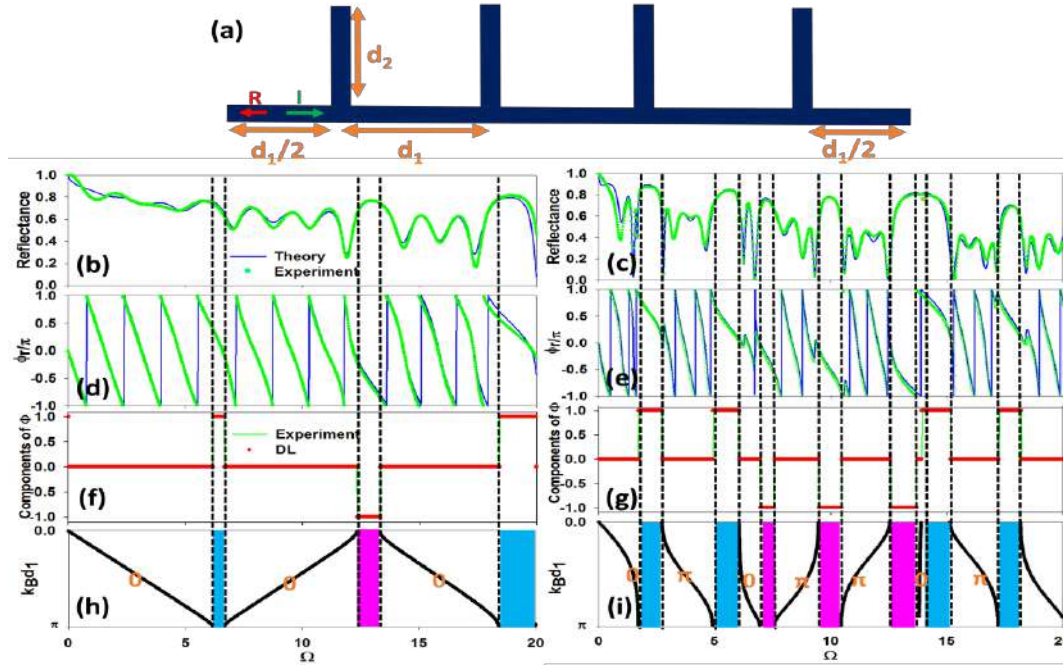


Figure 1 Reflectance through the finite stubbed system is shown numerically (blue) and experimentally (green circles) for two geometry cases, with reflection phase and DL model predictions compared in (f)-(g). Dispersion curves are presented in (h)-(i), highlighting the sign of the reflection phase in the gaps and the corresponding Zak phases in the bands.

In conclusion, we successfully applied Deep Learning to design optical structures with targeted topological properties, using the Zak phase as a key invariant. Our method offers valuable insights into designing topological materials and can be extended to 2D photonics and other fields like topological phononics.

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Supertoroidal Electrodynamics

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Abstract: This talk will present recent developments in toroidal electrodynamics, focusing on new types of pulses exhibiting non-diffracting propagation and spatiotemporal superoscillations, and on non-reciprocal light-matter interactions involving charge-current configurations of toroidal topology.

Toroidal electrodynamics is a newly emerging field of electromagnetism studying excitations of toroidal topology, both in free-space (as toroidal pulses) and in matter (as toroidal charge-current configurations). Recent advancements in this area have introduced a new class of pulses known as supertoroidal pulses, which possess topological features akin to skyrmions found in condensed matter and exotic propagation dynamics, such as non-diffracting propagation over arbitrary distances, energy transfer patterns reminiscent of "vortex streets" in fluid dynamics, and space-time superoscillations. Additionally, their localized counterparts in the form of supertoroidal charge-current configurations are shown to lead to new non-radiating configurations and to non-reciprocal electromagnetic interactions.

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Nanophotonics for ultra-stable laser resonators

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Abstract: We present pathways for interfacing integrated photonics with ultra-stable laser resonators to realize multi-functional cavity mirrors. As initial step we discuss strategies to combine grating couplers with cm-scale resonators.

Ultra-stable lasers (USLs) are essential for advancing the quantum revolution, providing the stable frequencies required for precise interrogation of narrow atomic transitions. They are also crucial for precision measurements in areas like gravitational wave detection [1] and fundamental physics tests [2,3]. Current USLs reach a relative instability of 4×10^{-17} , limited by resonator noise. Their bulky design, requiring heavy thermal shielding, leads to large optical systems [4]. While micro-ring resonator-based integrated lasers offer compactness, they lack the necessary mid- and long-term stability [5]. A new resonator concept using multifunctional mirrors is proposed to meet the quantum revolution's stringent demands regarding size, weight, and power.

This work presents initial developments toward low-noise multifunctional resonator mirrors that integrate photonics with meta-materials in free-space USL resonators. Here, we present design strategies and methods to achieve macroscopic output beam diameters with near-normal light emission, to achieve mode matching with cm scale resonators. Once combined with ultra-low noise meta-mirrors [6], this will pave the way to multifunctional low-noise resonators.

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Light Engineering at the Nano-Scale: Insights from Plasmonics and Metamaterials

Polarization controllable laser with chiral metamaterials

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Abstract: We present a compact chiral metamaterial for circularly polarized (CP) lasing. The design features twisted-cross meta-atoms in a gain medium, where tuning the twist angle, but also changing the polarization of the linearly polarized pump wave, controls the emission's polarization, from nearly pure left- to right-circular. This highly adaptable metamaterial offers a robust and practical approach to tailored CP lasers.

Polarization-controllable lasers, especially those generating circular polarization (CP), are becoming increasingly important in light-matter interactions. These lasers hold significant promise for applications such as spectroscopy, sensing, and display technology. Additionally, CP lasers are essential tools for studying chiral-light-matter interactions, with broad implications across fields like chemistry, biophysics, and quantum optics [1-4]. To generate CP lasers, both a gain medium and a chiral response are needed. While natural chiral materials, like liquid crystals, tend to have a weak chiral response, research has shifted towards artificial chiral nanostructures which include 3D chiral metamaterials and 2D planar designs [5-8], which enhance the interaction between CP light and matter, unlocking new possibilities for various applications. In particular, there is a rising demand for compact chiral light sources capable of producing a high degree of circular polarization, suitable for a wide range of uses. In this study, we present a novel chiral metamaterial design that employs twisted isotropic crosses [9]. Through numerical simulations, we validate the ability of this design to control circularly polarized (CP) laser emission. By modifying the angle between the crosses and by changing the polarization of a linearly polarized pump wave, we can finely tune the chiral response, enabling precise interactions with the optical gain band to produce a range of laser emission characteristics. This active chiral metamaterial system introduces an innovative approach to designing circularly polarized emission lasers, offering a more efficient solution that bypasses the need for costly and labor-intensive fabrication processes.

The unit cell of the proposed chiral metamaterial structure consists of a pair of twisted crosses embedded in a dielectric host. The structure features a square periodicity of $a = 300$ nm, with each cross having a length of $l = 100$ nm, and the dielectric host has a refractive index of $n = 1.41$. The gain material is created by doping the dielectric host with dyes, with the atomic response described by a four-level system [8]. To understand the underlying lasing process, we first excite the gain molecules using a short, intense Gaussian pump pulse, centered at 335 THz, with a duration of 2 ps. In Figures 2 (a)-(b), we observe the electric field components for right-handed circular polarization (RCP, blue line) and left-handed circular polarization (LCP, red line) as a function of time. To detect lasing and assess the strength of the emitted radiation around the lasing frequency of 207 THz, we apply a Fourier transform to the time-dependent transmitted electric fields. The results, presented in Figures 2 (c)-(d), show that the dominant lasing mode is primarily right-handed circular polarization (RCP/-), with left-handed circular polarization (LCP/+) emission being negligible. By adjusting the relative twist between the two crosses, we can further control the polarization of the lasing emission. Notably, when the twist angle ϕ is set to -22.5° (counterclockwise relative to the bottom cross), the lasing mode is predominantly left-handed

circular polarization (LCP/+), and the emission of right-handed circular polarization (RCP/-) is reduced to the noise level. This analysis demonstrates our ability to produce a highly pure circularly polarized emission laser, with an ellipticity of the emitted wave as high as 0.95. To our knowledge, this represents one of the most efficient methods for achieving and controlling pure CP lasing in such a compact form.

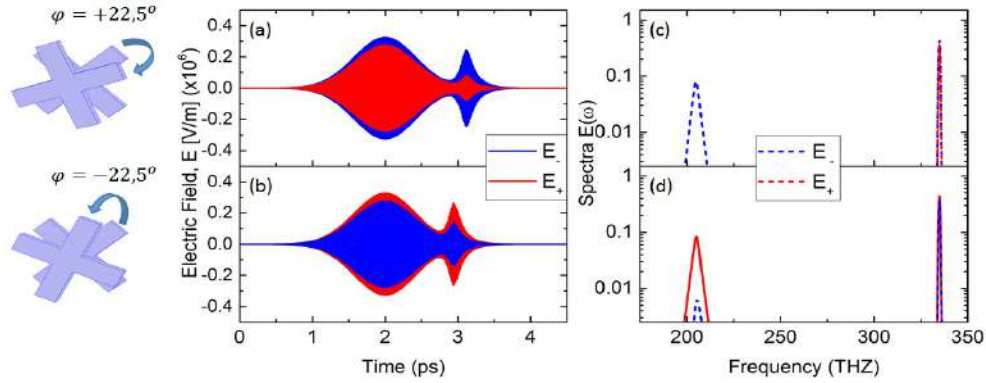


Figure 1: Panels (a) and (b): transmitted E_+ (red line) and E_- (blue line) vs time for the silver based twisted-crosses chiral metamaterials structure depicted (the unit cell) on the left side of the figure. Panels (c) and (d) are the corresponding spectra of the transmitted waves.

In conclusion, we demonstrate controllable circular polarization lasing using a chiral metamaterial with twisted crosses. Adjusting the cross rotation angle and changing the polarization of a linearly polarized pump wave allows selective amplification of left- or right-handed polarization, offering new possibilities for photonics applications.

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Controlling chirality using bound states in the continuum in metasurfaces

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Abstract: A plasmonic metasurface with symmetry-broken nanoholes supports Bound States in the Continuum (BICs), with maximally chiral optical response. Interaction with an active medium gives rise to a strong coupling regime, yielding chiral polariton BICs. Similarities and differences between dielectric and plasmonic metasurfaces will also be discussed.

Maximizing the chiral response in photonic and plasmonic systems is a key goal in current nanophotonics research. Bound states in a continuum (BIC) in dielectric metasurfaces yield ultra-narrow resonances, with low radiative losses and enhanced radiation-matter interaction [1]. They give rise to topological singularities that split into circularly polarized states (CPS) with maximum chirality upon symmetry breaking [2,3].

In this work, we demonstrate that BICs can also appear in plasmonic metasurfaces and can be exploited to yield a strong chiral response [4]. We consider a metasurface consisting of a gold layer on glass, which is etched with a square lattice of nanoholes (Fig. 1a), whose shape is deformed from circular to oval (Fig. 1b). Upon symmetry breaking, a quasi-BIC appears in absorption spectra at the low-energy side of the surface-plasmon polariton peak. At a finite angle of incidence along the x orientation, the BIC has a strongly chiral optical response with nearly maximum circular dichroism (CD), see Fig. 1c. The maximum CD is nearly independent of the deformation, thus the chiroptical response is robust with respect to structure parameters. Analysis of the symmetry properties and of the local field profiles confirms that the resonance is indeed a symmetry-protected BIC, with strong enhancement of the local electric field. Maximum CD is also found in calculated emission spectra.

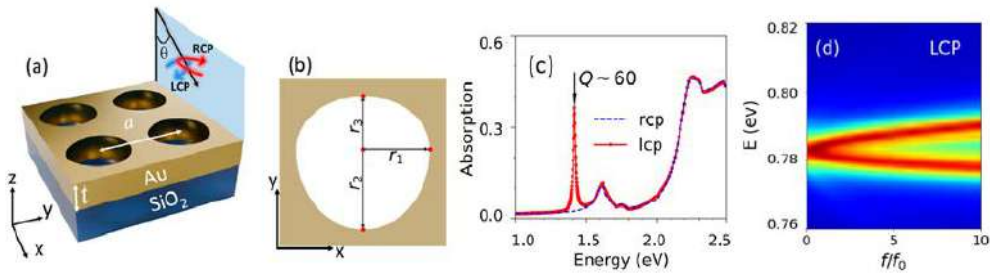


Fig. 1 (a), (b): Sketch of the metasurface with broken-symmetry holes studied in this work, $t=100$ nm. (c) Absorption spectra for a metasurface with lattice constant $a=500$ nm, $r_1=200$ nm, $r_2=240$ nm, $r_3=160$ nm at $\theta=4^\circ$ for right and left circular polarizations (rcp, lcp), showing a BIC resonance with chiral response. (d) Absorption for a metasurface with $a=1$ μm , $r_1=400$ nm, $r_2=480$ nm, $r_3=420$ nm, at $\theta=3^\circ$ for lcp. The metasurface contains a resonant medium at the bottom of the nanoholes, in a ring of 50 nm width and 10 nm height. The absorption map is shown as a function of the oscillator strength of the active medium, in units of $f_0=10^{24}$ m⁻³.

Next, we include an active medium at the bottom of the nanoholes (which can consist, e.g., in colloidal quantum dots) and consider the interaction of the BIC with a Lorentz-like resonance of the active medium. On increasing the oscillator strength of the resonance, the interaction between the BIC and the active medium gives rise to two absorption peaks that show a vacuum Rabi splitting, typical of the strong coupling regime. For oval holes at finite incidence angle, as shown in Fig. 1d, the strongly coupled quasiparticles are chiral with nearly maximum CD. Absorption maps as a function of the angle of incidence show the typical anticrossing behaviour of the strong coupling regime. Thus, the present metasurface with active medium supports the formation of chiral hybrid polariton BICs, which are the analog of polaritons in microcavities [5] or in photonic crystal slabs.

Bound states in a continuum are states with an infinite radiative Q-factor, but they may still have a finite Q-factor due to dissipative losses. This effect is especially important in plasmonic systems. We study the balance of radiative and nonradiative losses by increasing the lattice constant, which has the effect of moving the resonances towards the infrared – where metallic losses are reduced. The results consistently show a relation between the increase of Q-factor, the increase of maximum CD, and the increase of local-field confinement.

The results of the present work may prove useful in order to maximize the chiral response of plasmonic metasurfaces by means of a simple design concept, which is based on BICs with symmetry breaking. The results can also be used in order to demonstrate strong light-matter coupling with hybrid chiral polariton BICs in plasmonic metasurfaces, possibly leading to quantum and nonlinear phenomena related to polariton interactions.

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Large area nanostructuring of van der Waals materials for photon harvesting in the flat optics regime

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Abstract: 2D-Transition Metal Dichalcogenides (2D-TMDs) are two-dimensional semiconductors featuring high optical absorption coefficient combined with good transport and mechanical properties. Although mechanically exfoliated TMDs flakes ensure the best optoelectronic properties, homogeneous large-area growth techniques are mandatory for real-world applications [1,2]. At the same time, in view of light conversion applications in the extreme thickness regime of 2D-TMDs, it is essential to develop effective photon harvesting flat optics strategies derived from nanophotonics.

Here we demonstrate that periodic modulation of few MoS₂ and WS₂ on large area nanostructured samples fabricated by laser interference lithography (either MoS₂ nanostripes arrays or conformal MoS₂ layers grown on top of nanogrooved silica templates). These nanopatterned layers can effectively steer light propagation via Rayleigh Anomalies in the flat optics regime, promoting strong in-plane electromagnetic confinement and broadband omnidirectional photon absorption enhancement, with strong impact in photoconversion. [3,4].

As a case study aiming at photoconversion applications, we demonstrate that flat-optics light harvesting in periodically corrugated TMD layers (MoS₂) employed as photocatalysts, can boost photodissociation of Methylene Blue (MB), a polluting dye molecule commonly used in the textile industry. When illumination occurs at the optimized angles which couple light to the photonic anomalies a two-fold faster photodissociation rate is observed with respect to planar MoS₂ films [5].

In another example, we highlight the possibility of exploiting of periodic TMD nanostripes instead, as directional scatterers.

Another hot topic is the urgent request to scale-up the lateral size of the 2D van der Waals (vdW) heterostructure devices, typically limited to micrometric flakes, and to engineer their shape at the nanoscale. Here the nanoscale reshaping of 2D vdW heterostructures based on TMDs layers is shown over large-area (cm² scale) [1-4]. We show a flat-optics scheme based on large-area few-layers vertically stacked WS₂-MoS₂ heterostructures, endowed with type-II band alignment, and forming periodic nanogratings [6]. These large-area van der Waals heterostructures provide novel platforms with a strong potential towards real-world use of 2D TMDs layers in scalable nanophotonics, photoconversion [7] and energy storage applications.

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Optical characterization of the extrinsic chiral response in self-assembled plasmonic nano-antennas

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Abstract: Self-assembled asymmetric metasurfaces enable cost-effective, large-area control of circularly polarized light. These structures exhibit effective chiral optical responses in both near and far fields. We present their linear and nonlinear optical chiral characterization, demonstrating their potential and versatility for advanced photonic applications.

Symmetry breaking in plasmonic nanostructures enables strong manipulation of circular polarization at the nanoscale. Among various fabrication techniques, self-assembly offers a scalable, cost-effective approach for producing large-area chiral metasurfaces. In this talk, we explore the interplay between chirality and symmetry breaking, including pseudo-chirality and extrinsic chirality, and their impact on chiro-optical responses in self-assembled plasmonic nanostructures.

We present experimental results using multiple characterization techniques, including standard reflection/transmission, second harmonic generation (SHG) and we will put particular emphasis on photoacoustic absorption (PA), showing the potentiality of such technique.

Our study covers different metasurface architectures studied over the years.

Tilted Gold Nanowires (NWs): A self-ordered forest of 300 nm-long Au NWs, fabricated via Glancing Angle Deposition (GLAD) at ~300 K, exhibits extrinsic chirality in reflection, PA, and SHG due to asymmetric orientation with respect to the incident light.

Au-Coated GaAs Nanowires: Self-catalyzed GaAs NWs (5 μm long) partially covered with Au show a pronounced enhancement in circular dichroism compared to uncoated counterparts, verified through reflection, PA, and SHG measurements. These samples show how PA technique leads to retrieve information on the depth of the absorption centers, an information that standard spectroscopy cannot address.

Polystyrene nanospheres covered by asymmetric metallic shells (PSNs), and also samples where the spheres were removed, yield elliptical nano-hole-arrays (NHAs) with broadband chiral properties in the near-infrared. We demonstrate their tunable chiral response via incident angle-dependent coupling to Rayleigh anomalies and surface plasmon polaritons, supported by chiral transmission, and PA measurements.

These results highlight the potential of self-assembled plasmonic metasurfaces for tailoring chiro-optical responses, paving the way for advanced applications in nanophotonics and chiral sensing.

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