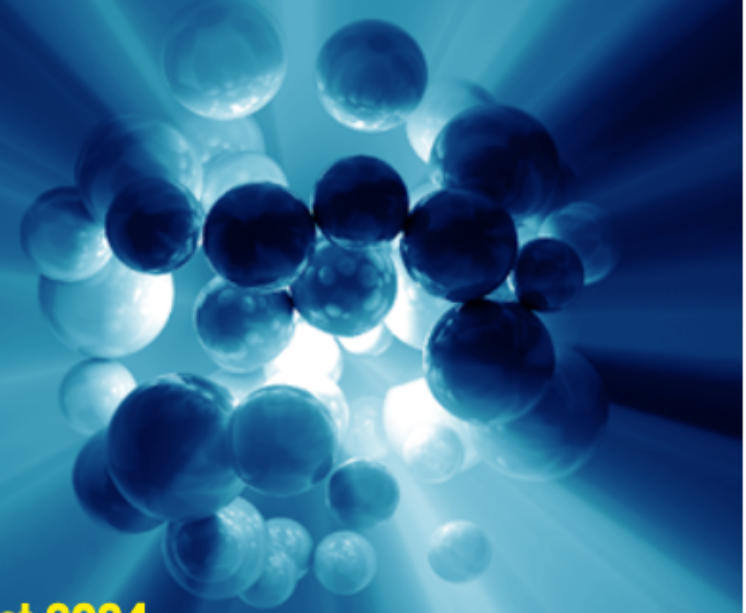
Complex Nanophotonics **Science Camp**

BRINGING TOGETHER EARLY CAREER SCIENTISTS TO BRIDGE NANOPHOTONICS, PLASMONICS, METAMATERIALS & BIOPHOTONICS OF COMPLEX MEDIA



KEYNOTE TALKS
Sophie Brasselet
Romain Quidant
Carsten Rockstuhl

INVITED TALKS
Yaron Bromberg
Emanuele Galiffi
Said Rodriguez
Sarah Bohndiek
Peter Wiecha
Humeyra Caglayan
Matthieu Bellec
Sílvia Pujals

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Sophie Brasselet

Aix-Marseille University, France

Nanoscale polarized imaging in 3D

Polarized fluorescence microscopy and optical fields' polarimetry follow well-known principles and methods in paraxial conditions, in which light polarization is manipulated in transverse planes. Its transposition to non-paraxial optics, i.e. for instance coming from high numerical apertures in microscopy, or at the near-field vicinity of complex nanostructures, is still a challenge. We will describe two contexts in which polarized microscopy brings a valuable approach for this problem: light scattering by nanoparticles excited by a random 3D polarization, and fluorescence emission from isolated molecular dipoles oriented in 3D. We will first describe recent methods in single molecule orientation and localization microscopy (SMOLM), which are capable of monitoring single dipole's orientation in addition to their localization, based on an optimal deformation of their point spread function (PSF) to encode orientation information. We will then address the extension of SMOLM to 3D nano-polarimetry, where any polarization state in 3D (including spin and depolarization) can be probed by PSFs from isolated scattering metal nanoparticles. Polarization properties are retrieved using a general 3D Stokes formalism that is shown to be computationally efficient in both fluorescence and polarimetry frameworks, in particular for the optimization of PSF engineering methods to retrieve polarization parameters with high-sensitivity.

Romain Quidant

ETH Zurich, Switzerland

Levitated optomechanics on a chip

The study and control of levitated nano- and micro-objects has gained considerable attention over the last decade owing to its potential to advance both fundamental science and technology. While early levitation experiments made use of optical potentials and weakly absorbing dielectric polarizable particles, the toolbox expanded in recent years to include techniques borrowed from the atom trapping community. The development of electrostatic and magnetic levitation made it possible to overcome excessive photoheating of the trapped specimen and extended levitation to a broader range of particles, including particles with internal degrees of freedom. Furthermore, on-chip integration has been identified as key to interface levitodynamics with other existing technologies, to increase platform robustness and compatibility with cryogenic conditions, and to devise autonomous and portable sensors. In this presentation we discuss our most recent advances in the development of integrated hybrid levitation platforms combining planar electrodes with integrated photonics and metaoptics. We introduce different architectures offering further control over the dynamics of levitated nanoparticles, with applications to both ultra-sensitive force sensing and the study of quantum mechanics with large objects. Finally, we discuss how our technology can be extended to the levitation of resonant silicon meta-atoms, opening new opportunities in the field.

Carsten Rockstuhl

Karlsruhe Institute of Technology, Germany

Light scattering in nanophotonic systems

Gustav Mie outlined more than 100 years ago a quasi-analytical solution for light scattering at a sphere. It constitutes an algebraic solution to Maxwell's equations, where the incident and scattered fields are expanded into a suitable basis set. A matrix then expresses the relation between the amplitude coefficients of the incident and scattered fields. The matrix is diagonal for a sphere. Still, this transition, or T-matrix, can be obtained numerically for more complicated objects. Even though mature at first glimpse, the topic continues to be vibrant, and many extensions have been made to explore light-matter interactions out of intellectual curiosity and to develop applications. This presentation outlines these recent developments. It looks into four-dimensional metamaterials (made from periodically arranged objects made from a time-varying material) or photonic devices made from molecules, where the molecular properties are described with a T-matrix calculated using time-dependent density functional theory. We also describe how machine learning methods can be leveraged to design scatterers on demand. Finally, we present efforts from a larger number of community members to define a standard for storing and distributing T-matrices. This would be one contribution from our community to lower our research's carbon footprint and enable data-driven research.

Peter Wiecha

LAAS-CNRS, France

Differentiable nano-optics: AI frameworks beyond deep learning

Deep learning (DL) has emerged as a versatile numerical method in various fields of research. For instance, DL is a promising method to solve ill posed problems, such as inverse design tasks [1]. It is fundamentally based on a technique called automatic differentiation, which makes deep learning libraries essentially differentiation toolkits [2]. After a brief introduction to DL and its underlying concepts, I will discuss potentials and opportunities that arise as a side-effect from the huge global development efforts and monetary invest of Big Tech players in today's DL frameworks like tensorflow, pytorch or jax. These highly optimized, GPU-ready automatic-differentiation tools enable various numerical applications for differentiable physics beyond the training of artifical neural networks. I will demonstrate possible applications through examples around nano-photonics design problems.

[1] Khaireh-Walieh, A. et al. "A newcomer's guide to deep learning for inverse design in nano-photonics." Nanophotonics 12, 4387–4414 (2023).
[2] Wiecha, P. R. "Deep learning for nano-photonic materials – The solution to everything!?" Current Opinion in Solid State and Materials Science 28, 101129 (2024).

Said Rodriguez

AMOLF, the Netherlands

There's plenty of energy in noise

In 1959 Richard Feynman gave an inspiring talk titled "There's plenty of room at the bottom", which led us into a new era of nanotechnology. By now, that room has been exhausted. I argue that the 21st century challenge is not just in shrinking technology, but mainly in making it energy efficient, fast, and precise. Understanding and harnessing the energy in noise is the way to achieve that. Even entirely new functionalities can be created with noise. In this spirit, I will present some results from my group on the physics of noise in optical systems. I will show how noise can be harnessed to amplify optical signals, improve optical sensing, and create novel functionalities based on spontaneously broken symmetries. I will also briefly discuss our recent discovery of arcsine laws of light, which apply to a wide class of noisy systems used in photonics. The laws further imply a weak ergodicity breaking, which can be harnessed to improve sensing precision without expanding the energy budget and measurement time.

Yaron Bromberg

The Hebrew University of Jerusalem, Israel

Wavefront Shaping of Entangled Photons for Quantum Communication and Quantum Key Distribution

Over the past decade, powerful tools for controlling the wavefront of classical light have been developed, providing unprecedented opportunities for aberration correction and compensation of scattering. These advancements have paved the way for new applications, such as spatial division multiplexing for optical fiber communication and endoscopic imaging through multimode fibers. Recently, these tools have been extended to control single and entangled photons. In my talk, I will review recent developments in this field, focusing on our work exploring the utility of wavefront control of spatially entangled photons for quantum communication and quantum computation. I will demonstrate that by reflecting entangled photon pairs ten times on a spatial light modulator, in a configuration known as multi-plane light conversion, we can rotate the state of the photons in a 25-dimensional space. This allowed us to demonstrate a 25-dimensional quantum key distribution and generate cluster states carrying information of more than nine qubits.

Humeyra Caglayan

Tampere University, Finland

All-optical switching in Si-compatible epsilon-near-zero hyperbolic metamaterials

All-optical switches enable ON/OFF conversion function by following the concept of light-controlled-by-light and are highly significant due to their potential to overcome speed limitations set by electrical switches. In this talk, we will present the ultra-fast responses of metamaterials at the effective epsilon-near-zero (ENZ) wavelengths and/or resonant wavelengths, unveiling response times down to a few hundred femtoseconds (fs). Our research holds the potential to significantly advance the field, especially with the introduction of a novel Si-compatible hyperbolic metamaterial based on Titanium nitrides (TiN) and indium-tin-oxide (ITO) multilayers that possess two different ENZ wavelengths. This material's unique switching time, measured in pump and probe, at both ENZ ranges could pave the way for a new era of ultra-fast optical switches.

Sarah Bohndiek

University of Cambridge, UK

From monitoring the body to monitoring planet Earth - a journey from health science to climate science

We are now entering a new era of optics and photonics, enabling exquisite control of light and its interactions with matter. Imaging and sensing with light offers numerous benefits, from direct observation of the chemical composition of an object through spectroscopy, to high-resolution imaging of Earth using satellites. In my research team, the VISIONLab at the University of Cambridge, we exploit spectroscopy to enable earlier cancer detection and I will give a summary of some of the key research questions that motivate us. I am currently on secondment as a Programme Director at the Advanced Research and Invention Agency (ARIA), an UK R&D funding agency built to unlock scientific and technological breakthroughs that could benefit everyone. I'll outline how ARIA is operating and introduce some of the big societal challenges that we are tackling as an agency, which has taken me on my journey from monitoring the human body to monitoring the planet!

Emanuele Galiffi

City University of New York, USA

Wave scattering in time-varying media

Complex photonic structures can tailor light propagation in surprising ways. So far, much attention has been devoted to spatial structures, which must obey fundamental limitations in terms of energy conservation, reciprocity and bandwidth of operation. Very recently, a rising interest was devoted to extending the advanced wave manipulation capabilities of photonic structures by relying on structuring matter in the temporal domain, delineating a pathway towards four-dimensional photonics. Temporal photonic structures can produce a variety of surprising wave phenomena, from fundamental building blocks of temporal scattering, such as temporal reflection, refraction and diffraction, to applications for broadband frequency-conversion, synthetic collisions between waves, various forms of amplification, ultra-broadband absorption and Floquet engineering of topological phases. In this talk I will provide a tutorial introduction to the field of time-varying media, starting from the basic ideas behind wave scattering in time-dependent photonic structures, setting the stage for more advanced discussions of the opportunities that are currently being investigated, and envisioning future directions in this field.

Silvia Pujals

Institute of Bioengineering of Catalonia, Spain

Single molecule localization microscopy methods for nanomedicine

Nanomedicine arose with the promise of selectively delivering therapeutic drugs to target sites, thus increasing its their effectivity while minimizing undesired side effects. However, tumour complexity and heterogeneity pose a great challenge to the design of effective therapeutic nanomaterials, and new approaches, from material design to new characterization techniques, are necessary. To study the behaviour of such complex nanomaterials in action a variety of optical microscopy techniques, in particular super resolution microscopy (SRM) are being used [1,2]. SRM can achieve a resolution down to 5 nm and represents an ideal tool to visualize nanosized objects in the biological environment. In particular, SMLM (Single Molecule Localization Microscopy) can be used to image a wide range of nanomaterials beyond the diffraction limit: nanoparticles, BTA fibers, peptidic nanostructures, etc. Remarkably, SMLM allows this observation in the biological environment, being able to follow the journey of nanomaterials inside the body: from protein corona formation to extravasation, targeting and tracking nanomaterials inside the cell. A super-resCLEM (super resolution correlative light and electron microscopy) method will be also introduced, specifically by combining one type of SMLM (DNA-PAINT) with TEM [3].

[1] Nat. Rev. Chem. 2019 3, 68–84.
[2] ACS Nano. 2019 13(9):9707-9712.
[3] Nano Lett. 2021 21(12):5360-5368.

Matthieu Bellec

University Cote d'Azur, France

Photonics in laser-structured complex media

Structured media allow to manipulate the flow of light with unusual features. Direct-laser-writing technique is a tool of choice to design such complex media. During this talk I will present few examples ranging from fluids of light in complex environments to topologically protected transport and laser filamentation in photonic lattices. I will also discuss new femtosecond laser-assisted fabrication processes of complex structures in optical fibers.

Alfonso Nardi

ETH Zurich, Switzerland

Mesoscopic transport of the second-harmonic light generated by a nonlinear complex medium

with Andrea Morandi, Romain Pierrat, Arthur Goetschy, Frank Scheffold and Rachel Grange

Nonlinear disordered photonic media are strongly scattering materials whose nanodomains are characterized by a second-order susceptibility tensor. Each nanodomain generates second-harmonic (SH) waves with random amplitude and phase when excited by a fundamental beam. The interference of the generated waves results in efficient generation of nonlinear light without stringent conditions on the polarization and wavelength of the fundamental light, which is not possible with bulk crystal. Moreover, thanks to the vast number of modes supported by the random structure, this class of disordered media enables large-scale nonlinear optical operators for encryption, all-optical logic gates, and photonic machine learning. Despite the widespread interest, the statistical properties governing the generated SH light remain scarcely explored. In this work, we study the statistics of the SH speckle patterns generated by a nonlinear disordered medium. Analysis of the SH intensity fluctuations reveals significant deviations from the predictions of diffusion theory. Assuming mesoscopic transport, that accounts for interference between different transmission channels, we conclude that the number of open transmission modes for SH light is one order of magnitude lower than for fundamental light. This implies that, when the fundamental beam is strongly focused at the input facet of the medium, the probability of having high intensity speckles for the SH light is orders of magnitude higher than for the fundamental light. Our result demonstrates the possibility of generating higher SH intensity condensed into few speckles. Furthermore, the deviations from diffusion theory indicate that, in the case where the fundamental light is strongly focused to achieve a higher SH signal, the propagation of waves through the complex nonlinear medium cannot be described by a fully random nonlinear input-output response. It is therefore essential to take this effect into account for applications that exploit the randomness to achieve large-scale nonlinear operations.

Filippo Pisano

University of Padua, Italy

Peering into the brain through sub-wavelength optical windows

with Di Zheng, Liam Collard, Muhammad Fayyaz Kashif, Maria Samuela Andriani, Antonio Balena, Marco Pisanello, Barbara Spagnolo, Francesco Tantussi, Liset M de la Prida, Manuel Valiente, Francesco De Angelis, Cristian Ciracì, Massimo De Vittorio, Ferruccio Pisanello

The interplay of photonics and neuroscience has been at the cornerstone of some of the most exciting research of the past two decades. Neuroscientists now enjoy unprecedented possibilities to disentangle brain functions using advanced optical methods to control and monitor neural activity through light-sensitive molecular probes. On the optics side, the main challenge of delivering and retrieving optical stimuli from deep brain areas with high spatial-temporal precision has been tackled with a broad class of approaches to circumvent the effects of tissue scattering, including wavefront engineering and implantable optical probes. While most of these strategies are based on micro-scale optical elements, with optical apertures larger than the wavelength of the light, an intriguing stream of research is exploring the boundaries of light-brain interactions for enhancing the extraction of information. In this direction, we studied the integration of sub-wavelength plasmonic nanostructures on multimode optical fibers acting as neural implants, finding that the complex interplay between guided modes and the nanostructures' response offers interesting opportunities. For instance, we observed that fiber fluorimetry performed through plasmonic nano-gratings allows encoding the direction of incoming light in spectral components guided in the fiber, with applications to fluorescence and Raman spectroscopy [1]. We also found that the interaction between guided modes and monolayers of metallic nanostructures can be used for wide-surface [2] or spatially resolved SERS [3]. In this contribution, we will describe the promises and limitations of our approaches, with particular focus on the interdisciplinary challenges that underlie the development of a novel generation of approaches for optical neural interfaces.

[1] Pisano, et al. (2022). Adv. Opt. Mater. 10, 2101649
[2] Zheng, et al. (2023). Adv Mat., 35 (11), 2370078
[3] Collard, Pisano et al. (2022). Small, 18 (23), 2270122

Rakesh Arul

University of Cambridge, UK

Bridging the visible and mid-IR with nano-optics to watch ultrafast vibrational energy cascades

with Fiona M. Bell, Zhongzheng Yu, Akshay Rao, and Jeremy J. Baumberg

Active particles, defined as units that autonomously extract energy from the environment to move or The spectrum of molecules in the infrared (IR) contains rich information about their chemical structure, enabling disease diagnosis, greenhouse gas monitoring, and the stunning images of exoplanets. Despite such promise, IR detection remains far from democratized due to the costs and limited practical utility of existing technologies. To circumvent this, we take advantage of efficient silicon sensors in the visible to help detect IR. However, using such sensors requires the conversion of IR light to detectable visible light. While theoretically proposed by Bloembergen in 1959, realising this conversion has proven challenging due to the fundamental mismatch between the wavelengths involved of visible (500 nm), IR light (10,000 nm) and molecular sizes (1 nm). We found that disordered layers of gold nanoparticles, assembled with very precise spacing using a dye molecule, possess dual infrared and visible resonances. These layers allow us to confine both infrared and visible light on a very small scale, and convert infrared light into visible light that we can detect. We've demonstrated the ability to detect incredibly faint signals from individual molecules absorbing infrared light, which opens a new area of studying fluctuations in the mid-infrared spectrum. Additionally, by placing lanthanide nanocrystals between these layers of gold nanoparticles, we can convert mid-infrared light directly into visible light, making it useful for practical detector applications. Using time-resolved picosecond IR-visible pulsed laser spectroscopy, we measure vibrational coherence and population decay when pumped with IR light. A new vibrational cascade mechanism is made possible due to the tight confinement of light within plasmonic nanogaps. Such energy transfer processes play a role in the formation of new collective super-radiance not observed with single emitters. Measurements of spatio-temporally resolved g(1) correlations via Michelson interferometry reveal the growth of long-range correlations. These findings suggest the existence of a new type of room-temperature exciton condensate, unique to structures that plasmonic nanocavities, which adds to our efforts to develop better ways of detecting light and understanding fundamental light-matter interactions.

Amna Ammar

Bilkent University, Turkey

Limits of Phase-Only Wavefront Shaping in Multimode Fibers

with Sarp Feykun Şener, Mert Ercan, Hasan Yılmaz

Wavefront shaping allows the focusing of light through complex media, such as biological samples or multimode fibers, enhancing imaging capabilities for microscopy and fiber endoscopy. With perfect control over the input light field, all transmitted power can be efficiently collected at desired locations, resulting in an enhancement factor equivalent to the input number of degrees of freedom N. Here, we present a comprehensive work that consists of experiments and numerical and analytic calculations to find the upper limit on the enhancement factor for focusing light through a multimode fiber. We first theoretically find the upper limit on the enhancement factor using the mode decomposition method. We predict the input participation ratio (PR), quantifying the percentage of the contributing degrees of freedoms for phase-only modulation at the input field. Our theoretical calculations show that PR strongly depends on the basis that the phase-only modulation is performed in. In our experiments, we first measure the field transmission matrix using a common-path phase-shift interferometry. We use the stepwise sequential algorithm [1] (SSA) on the canonical (SLM pixel) basis and the dual reference algorithm [2] on the Hadamard basis to obtain the transmission matrix. We conduct experiments to explore factors that affect the enhancement factor, such as experimental noise and transmission matrix decorrelation. Using the Hadamard basis in contrast to the canonical basis improves the enhancement factor due to its signal-to-noise advantage and enables enhancement factor values close to the upper limits for the input number of degrees of freedom N > 2,000. In conclusion, we theoretically predict and experimentally approach the upper limit for the enhancement factor for focusing light through a multimode fiber using phase-only modulation of the incident wavefront. Our work introduces the upper limit of the enhancement factor, which is important for applications where phase-only input modulation is essential, such as in nonlinearity suppression and clean output beam realization through broad-area fiber amplifiers [3].

[1] I. M. Vellekoop and A. P. Mosk, Opt. Lett. 32, 2309-2311 (2007).
[2] B. Mastiani, and I. M. Vellekoop, Opt. Express, 29, 17534-17541 (2021).
[3] C.-W. Chen et al., Nat. Commun., 14, 7343 (2023).

Tianrui Zhao

King's College London, UK

Light focusing through dynamical scattering media with high-speed real-valued intensity transmission matrix

Wavefront shaping is increasingly attractive for its potential to facilitate various biomedical applications, such as deep-tissue imaging, by surpassing the optical diffusion limit. Despite recent technological advances, especially in leveraging non-invasive photoacoustic-guidance, demonstrating its effectiveness in vivo remains challenging, primarily due to the rapid decorrelation of tissue speckles. In this study, we developed a rapid photoacoustic-guided wavefront shaping approach to characterize a scattering medium using a real-valued intensity transmission matrix. This resulted in a system runtime of several tens of microseconds per input mode, a significant improvement over previously reported runtimes in the literature using photoacoustic-guided wavefront shaping, by three orders of magnitude. With this algorithm, we experimentally demonstrated light focusing through a dynamic diffuser with a decorrelation time of around 150 ms, marking a substantial advancement towards the practical application of wavefront shaping in vivo.

Suraj Goel

Heriot-Watt University, Scotland

Multiplexing Indistinguishable Quantum Emmitters using Structured Light

with Sheena Shaji, Julian Wiercinski, Moritz Cygorek, Antoine Borel, Natalia Herrera Valencia, Erik Gauger, Mehul Malik, and Brian D. Gerardot

Semiconductor quantum dots are bright and deterministic sources of narrow linewidth single photons, which play a vital role in quantum optical technologies. Applications that involve processing multiple photons at the same time often employ a single quantum emitter providing photons multiplexed in time. This is a bottleneck in quantum technologies including complex quantum networks and photonic quantum computing, causing challenges such as is inefficiency and poor scalability. The ability to collect and manipulate light from multiple independent emitters located randomly on a single sample remains an outstanding challenge. Here we demonstrate the control of multiple quantum dots on a single sample by harnessing the spatial structure of the emitted photons. This approach employs structured excitation with a spatial light modulator and collection with a multi-plane light converter (MPLC) to erase the spatial information of the emitted photons, rendering them indistinguishable. The use of an MPLC enables the programmability of optical circuits in the spatial degree-of-freedom of light, allowing us manipulate the emitted photons arbitrarily. Aside from practical applications, this also allows us to study another fundamental physical phenomenon encountered in single-photon emission, where indistinguishability induces cooperative emission from multiple quantum dots. Furthermore, we demonstrate programmable multi-photon interference of single photons emitted from independent quantum dots on the same sample. Our method serves as a powerful tool for interconnecting optical circuits with quantum dots paving a way towards scalable and efficient quantum information processing.

Alasdair Milne

Heriot-Watt University, Scotland

In-situ bend compensation for holographic micro-endoscopy through flexible photonic lantern fibres

with John Kilpatrick, Kerrianne Harrington, Jose Do Amaral Rocha, Helen Parker, Aurelien Benoit, James Stone, Tim Birks, David Phillips, Robert Thomson

Optical fibres enable in vivo optical imaging centimetres deep inside living tissue. Recently, there has been much interest in transmitting images through hair-thin multimode optical fibres (MMFs) using a technique known as holographic micro-endoscopy [1]. The transmission of light through such thin fibres scrambles the optical field as it propagates, meaning images are unrecognisably distorted. Holographic micro-endoscopy relies on first measuring how light will be scrambled during propagation, and then pre-compensating for this effect, yielding fine control over the optical field at the fibre output. This enables high resolution scanning imaging of cells located at the tip of a needle loaded with an optical fibre. However, if these fibres bend during use, their transmission properties change, rendering these holographic approaches very sensitive to changes in fibre conformation. As a result, most current methods require fibres to be rigidly held during imaging, and achieving diffraction-limited imaging through dynamically flexible optical fibres is an ongoing challenge. In this work we address this problem and introduce a new in-situ bend compensation strategy. This is made possible through the use of a novel type of fibre known as a photonic lantern, which losslessly couples light from an MMF to the independent cores of a multicore fibre [2]. We conduct proof-of-principle experiments demonstrating a suite of approaches to adaptively compensate for arbitrary fibre bends, requiring access only to the input end of the fibre. Our methods rely on either feedback from a fluorescent particle acting as a guide-star [3], or measurement of the photonic lantern reflection matrix. Our work holds promise to meet the long-standing challenge of biomedical imaging within mobile organisms through flexible optical fibres. More broadly, this concept has applications encompassing LiDAR, industrial inspection, and the remote delivery of spatially structured light fields.

[1] H. Cao, T. Čižmár, S. Turtaev, T. Tyc & S. Rotter (2023). "Controlling light propagation in multimode fibers for imaging, spectroscopy, and beyond". Advances in Optics and Photonics, 15(2), 524-612.
[2] D. Choudhury, D. McNicholl, A. Repetti, I. Gris-Sánchez, S. Li, D. Phillips, ... & Thomson, R. R. (2020). Computational optical imaging with a photonic lantern. Nature communications, 11(1), 5217.
[3] S. Li, S. Horsley, T. Tyc, T. Čižmár & D. Phillips (2021). "Memory effect assisted imaging through multimode optical fibres". Nature Communications, 12(1), 3751.

Sébastien Bidault

PSL University, France

Nanoscale Control over Magnetic Light-Matter Interactions

with Benoît Reynier, Eric Charron, Obren Markovic, Xingyu Yang, Bruno Gallas, Alban Ferrier, Mathieu Mivelle

Light-matter interactions are generally considered to be mediated solely by the electric field of light, overlooking its magnetic counterpart. However, the magnetic field plays a pivotal role in various optical processes such as chiral phenomena (circular dichroism, circular photoluminescence...). We demonstrate here how magnetic light-matter interactions can be controlled and imaged at scales both larger (Optica 10, 841, 2023) and smaller (arXiv:2402.17426, 2024) than the wavelength of light. In particular, by creating a standing wave below an aluminum-covered scanning-probe tip, we manipulate the spatial distributions of electric and magnetic fields and their associated local densities of states, allowing a selective control over the excitation and emission of electric and magnetic dipolar transitions in europium-doped nanoparticles. By tuning the distance between the emitters and the mirror, we can image, in 3D, the electric and magnetic nodes and anti-nodes of the fields' interference patterns with nanoscale precision. Furthermore, by exciting specific plasmonic cavity modes within the aluminum-covered tip, we can extend, down to subwavelength scales, this control over both magnetic and electric light-matter interactions. This allows us to map the electric and magnetic fields, as well as the electric and magnetic local densities of states, with nanoscale precision. This work opens exciting perspectives on controlling the full electromagnetic range of light-matter interactions, in order to maximize chiral processes or to design nanostructures behaving solely as magnetic sources of light.

Roos de Boer

AMOLF, the Netherlands

Continuous-Wave Nonlinearity and Polarization Rotation in a Perovskite Cavity

with G. Keijsers, B. Verdonschot, K. J. H. Peters, Z. Geng, Kiana Malmir, Jason Smith, and S. R. K. Rodriguez

Optical nonlinearities and birefringent media have enabled the exploration of fascinating many-body states of light and spin-orbit coupling phenomena in optics, respectively. However, to date, the combination of a strong continuous-wave nonlinearity and birefringence in condensates of light has remained elusive. Here we present experiments demonstrating strong continuous-wave nonlinearity and birefrigence in a CsPbBr3 perovskite cavity. Our perovskite cavity exhibits bistability when probing a single mode, and signatures of tristability when probing nonlinearly coupled orthogonally-polarized modes. Our experiments reveal intriguing physics emerging from the interplay of polarization and nonlinearity in this system. We furthermore explore the temperature dependent optical hysteresis of our cavity, and we discover a surprising boost of the nonlinearity at a specific temperature. We suspect that the perovskite semiconductor we study undergoes a phase transition at that temperature, thereby opening up fascinating perspectives for exploring strongly correlated states of light in this system.

Romain Rescanieres

PSL University, France

Open channels and dwell-time eigenstates in resonant disordered media

with Romain Pierrat and Arthur Goetschy

Recent advances in wavefront shaping techniques have made it possible to measure the scattering matrix of highly complex media, such as disordered materials made up of dielectric particles or chaotic cavities. These works have revealed the existence of open channels, reflectionless states, and optimized dwell-time eigenstates, even in the diffusive regime where light-matter interaction is strong. Until now, these discoveries have been made using complex non-resonant media. However, resonant systems are widely used in nanophotonics and atomic optics. The aim of this work is to evaluate the influence of material resonance on the statistical properties of the scattering matrix and the energy storage (or dwell-time) operator. We study a set of resonant light scatterers, which can be considered as individual atoms or high-Q dielectric particles, randomly dispersed in a two-dimensional waveguide. By solving the wave equation, we compute the transmission matrix and the dwell-time operator, and evaluate the statistical properties of their spectra by simulating a large number of disorder configurations. This procedure is repeated for different incident field frequencies, in order to characterize the impact of the material's resonance. Our results reveal that when we approach the scatterer resonance by simply changing the frequency, the transmission eigenvalue distribution changes from a single-peak distribution, where light is mainly transmitted through the system, to a bimodal distribution in the diffusive regime, and then to a long-tailed distribution in the Anderson localization regime. Furthermore, by investigating the distribution of dwell-times, we gain access to the energy that each eigenchannel can deposit within the medium. We show that these distributions are strongly affected by the transport regime of light in the sample. In particular, the maximal dwell-times in the medium can differ by several orders of magnitude in the ballistic and localized regimes. This study demonstrates the potential of resonators to modulate the transparency of complex media and to store large amounts of energy within them.

Marco Locarno

Delft University of Technology, the Netherlands

In Vivo Plasmonic Enhancement of the Photocycle Dynamics and Fluorescence of Genetically Encoded Voltage Indicators

with Qiangrui Dong, Xin Meng, Cristiano Glessi, Daan Brinks

Genetically Encoded Voltage Indicators (GEVIs) are invaluable tools for investigating electrical signal propagation in neurons. However, their utility is limited by factors such as brightness, response speed, and sensitivity. Traditional biochemical approaches to enhance GEVIs have faced challenges due to the vast number of potential proteins and mutations. Here, we present a physical approach using plasmonic coupling to nanoparticles to manipulate and enhance the photodynamics and fluorescence of the GEVI QuasAr6a. Through Finite-Difference Time-Domain (FDTD) computational modeling, we designed optimal nanostar shapes for plasmonic coupling. Synthesized nanostars exhibited tunability to optimal wavelengths and robustness against noise sources. Colloidal nanostars were successfully synthesized and characterized, demonstrating compatibility with live biological samples. Preliminary experiments with Cyanine-5 (Cy5) as a model molecule showed promising results, with up to 42% fluorescence enhancement. Further experiments with HEK293T cells expressing QuasAr6a showed a significant increase in fluorescence, with enhancements of 28% and 69% in simple addition and fibronectin-embedded nanostars, respectively. Additionally, voltage clamp experiments revealed altered voltage sensitivity and response speed in QuasAr6a under plasmonic enhancement, indicating potential manipulation of the protein's photocycle. These findings suggest the feasibility of plasmonically enhanced voltage imaging, paving the way for improved neuroscientific techniques with enhanced spatial and temporal resolution.

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David Globosits

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A Photonic Floquet Scattering Matrix for Wavefront-Shaping in Time-Periodic Media

with Jakob Hüpfl, Stefan Rotter

The physics of waves in time-varying media provides numerous opportunities for wave control that are unattainable with static media. In particular, Floquet systems with a periodic time modulation are currently of considerable interest. In my talk I will demonstrate how the scattering properties of a finite Floquet medium can be correctly described by a static Floquet scattering matrix, which satisfies a pseudo-unitary relation. This algebraic property is a consequence of the conservation of wave action for which one can formulate a continuity equation. Using this Floquet scattering matrix, I will further demonstrate how it can be used to generalize also the seminal Wigner-Smith operator from static to Floquet systems. The eigenstates of the corresponding Floquet Wigner-Smith matrix are shown to be light pulses that are optimally shaped both in their spatial and temporal degrees of freedom for the optical micromanipulation of time-varying media.

Jaime Echave-Sustaeta

Universidad Autónoma de Madrid, Spain

Photon pair creation in photonic time crystals

with Francisco J. García-Vidal, P.A. Huidobro

Time-varying media open the door to new forms of control over the propagation of electromagnetic waves. When a material's optical response (given by the permittivity and the permeability) is modulated in time, energy becomes no longer conserved, and a myriad of new physical phenomena, some with no counterpart in spatially structured systems, is unravelled. Some examples are the following: time refraction and reflection, temporal diffraction, photon pair creation, frequency conversion, non-reciprocal physics, synthetic motion or the possibility of studying black holes analogues. All these processes stem from the time-reversal symmetry breaking that takes place in time-varying media, which is responsible for energy no longer being a conserved quantity. In this work, we study photon pair creation and squeezing in a photonic time crystal (PTC), the temporal counterpart of a conventional photonic crystal. We assume periodic and instantaneous changes in the refractive index between two values and follow a transfer matrix approach to describe quantum mechanically the electromagnetic field in the PTC. We discuss how the transfer matrix is equivalent to a Bogoliubov transformation and how this results in the generation of photon pairs, through dynamic Casimir type processes. We show that the photon pair creation probability, which is a quantum phenomenon, is controlled by the reflectivity of the PTC, a classical quantity. Lastly, we study the time delayed second order coherence function for a variety of quantum states, as well as the time evolution of the photon number fluctuations. We demonstrate how the second order coherence remains qualitatively similar, whilst photon number fluctuations increase with increasing classical reflectivity, and can in some cases be phase sensitive in a manner akin to the degenerate parametric amplifier.

James Guggenheim

University of Birmingham, UK

Photoacoustic memory imaging – a novel technique for non-invasive imaging deep behind scattering layers

with Arnon AB, Ben Keenlyside, Dylan Marques, Ivo Vellekoop

Optical imaging through scattering layers is desirable in medical imaging, nanotechnology and other areas. However, conventional optical techniques break down in the presence of significant scattering. One way to subvert this limitation is to exploit the so-called "angular memory effect" (AME). The AME describes how the seemingly random optical speckle patterns formed by beams transmitted through scattering layers can be "scanned" simply by changing the beam's incident angle. In conjunction with image reconstruction methods using prior knowledge of fundamental speckle properties, this has enabled non-invasively imaging fluorescent objects hidden behind opaque layers (Bertolotti et al. Nature. 2012). However, the approach has limitations, foremostly compatibility with only simple objects and an inability to define the object's location. Thus, while a hidden object's shape can be found, it is not possible to obtain its position or size, nor to faithfully image multiple or 3D objects. To address this limitation, we developed a technique called photoacoustic memory imaging (PAMI). PAMI exploits the photoacoustic effect, by which pulsed light generates ultrasound waves in absorbing materials. In PAMI, the AME is used to scan pulsed speckles behind a scattering layer, exciting ultrasound waves that are detected and used to reconstruct images. By employing photoacoustic measurements which contain time-domain and ultrasonically-defined localization information, PAMI allows addressing the limitations of conventional AME imaging. Foremostly, it yields depth and localization information, enabling the 3D imaging of complex objects (with accurate size). In addition, as the approach is based on light absorption rather than fluorescence, it is expected to work label-free for any pigmented object. We will present the first experiments demonstrating the feasibility of PAMI, discuss its features and our future directions, and hope to incite some interesting discussions.

Yijie Zheng

University of Nottingham, UK

Neural Networks for dynamic transmission matrices recovery in optical fibre imaging

with George S.D. Gordon

Next-generation medical endoscopes can utilize ultra-thin optical fibre (e.g. multimode fibre) to access deep sites of human body through a thin needle. This has great implications for enhancing early disease detections in organs such as the pancreas. However, light transmission through the fibre can distort images at the output site. To address this, it's crucial to understand the fibre transmission matrix (TM) since it can facilitate fibre bending tracking and encompass multi-wavelengths optical imaging systems. Previous methods primarily focused on measuring the static TMs of the fibre, which poses challenges if the fibre is moved or perturbed during the imaging process. First, the TMs are highly sensitive to the perturbations and temperature variations so measuring the static TMs is not suitable for real-time calibrations. Second, the bulky optical components at distal end makes these systems impractical for clinical in vivo use. Therefore, recent development has focussed on measuring and calibrating dynamic TMs without distal facet access (e.g. guide stars [1], tracked virtual beacons [2]) . Here, we proposed a neural network-based model to recover dynamic TMs through a reflection-mode optical fibre system [3] and demonstrated the recovery performance by successfully reconstructing wide-field images. This model is a physically-inspired model that incorporates the physical concept of compensating for the global phase. Typically, our approach requires ~1s prediction time, which shows great promises for near-real time image reconstruction applications. Also, this model learns the dynamic representations of the fibre TMs, which allows fibre perturbations in a real-world system. This model will pave the way for physical-inspired AI models capable of handling phase information, especially for scattering media, holographic imaging applications.

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How to characterize dynamic media in the multiple scattering regime with Photon Doppler Velocimetry ?

with J-R. Burie, O. Durand, R. Pierrat and R. Carminati

Since its introduction, Photon Doppler Velocimetry (PDV) has been widely used to characterise ejecta, clouds of fast particles produced in some shock physics experiments [1, 2]. Under the assumption of single scattering, the usual PDV result representation, the time-velocity spectrogram,provides the velocity distribution of the particles at a given time. Nevertheless, previous experimental and numerical works have demonstrated the presence of multiple scattering in such type of media - the thickness of the ejecta can be 40 times larger than the scattering mean free path [3–5]. Obviously, analyzing experiments in the deep multiple scattering regime with the picture described above is irrelevant. In a recent work [6], we have shown that the PDV spectrogram can directly be calculated from the solution of a transport equation (generalized radiative transfer equation) that takes into account multiple scattering as well as the dynamics (particle displacements) and inhomogeneities (density fluctuations) of the cloud. This theoretical work is supported by a Monte Carlo numerical scheme which allows to solve the RTE in ejecta. This has enabled us to recover through simulation spectrograms of well understood experiments. More interestingly, we have recently performed simulations of complex ejecta in gas. Coupled with standard hydrodynamic simulations of ejecta [7], we have been able to understand the physics of previously unintelligible experimental spectrograms.

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Ernesto Pini

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Resolving light transport in structurally anisotropic media

with Alexander Gatto, Henrik Schäfer, Diederik S. Wiersma, Lorenzo Pattelli

Structural anisotropy is an ubiquitous feature of many scattering media, ranging from fibrous media as wood, tendons and paper, to isotropic materials under mechanical deformation. Despite their relevance for several applications, however, anisotropic light transport properties in these materials are often overlooked or disregarded altogether. Moreover, even when they are taken into account, the non-trivial interdependence between the observed diffusion rate along a given direction and the microscopic scattering parameters prevents their accurate retrieval. Hence, anisotropic transport models need to be implemented and solved analytically or numerically, the properties of which are still largely under-explored. We present a comprehensive characterization of anisotropic light transport in diverse materials, including common materials like paper or teflon, and biological samples like human brain white matter. Experimental measurements are based on a time-domain imaging technique leveraging on an optical-gating scheme, which allows us to capture the spatial spread of diffuse light with sub-ps resolution upon ultrashort focused pulsed illumination. Experimental results show excellent agreement with a generalized anisotropic Monte Carlo model, which can be used to retrieve the diffusive rate and scattering coefficient tensors along all three directions. In addition to numerical modelling, we present analytical solutions for the diffusion tensor components in index-matched scattering media with uniaxial structural anisotropy, revealing the general relation linking anisotropic scattering coefficients to the resulting macroscopic diffusion tensor components along different directions. These results can be used to infer a quantitative estimation of the systematic error that is typically present in previous reports when disregarding or incorrectly accounting for the presence of structural anisotropy in scattering media.

Luis Alberto Razo Lopez

University Cote d'Azur, France

Experimental observation of 3D strong electromagnetic wave localization in Vogel spirals

with J. Aubry, F. Pinheiro, F. Mortessagne

Experimentally, strong localization of electromagnetic waves in three dimensions has never been achieved, despite extensive studies. Moving away from the paradigm of disordered systems, we perform microwave transport experiments in planar aperiodic Vogel spiral arrays of cylinders with high dielectric permittivity. By characterizing the electromagnetic modal structure in real space, we observe combinations of long-lived modes with Gaussian, exponential, and power law spatial decay. This distinctive modal structure, not present in conventional photonic materials with periodic or disordered structures, is the cause of significant electromagnetic wave localization that persists even in a three-dimensional environment.

Niklas Rocca Schwarz

University of Fribourg, Switzerland

Polymer-based non-iridescent photonic pigments

with Ullrich Steiner, Andrea Dodero

This project aims to manufacture non-iridescent, brilliant and long-lasting photonic pigments. Such structural pigments obtain their reflectance response through constructive interference of the incident light instead of selective absorption like conventional pigments. The main advantage of structural colour is that it does not suffer from bleaching out, hence prolonging its lightfastness. Nature is an inspiration source for structures producing photonic band gaps (i.e., spectral regions where light propagation is forbidden). For instance, many beetles and butterflies possess complex arrangements of chitin on their scales that cause non-iridescent structural colouration.[1] The self-assembly of linear diblock copolymers in emulsion droplets produces microspheres acting as photonic pigments. The copolymer chains arrange themselves in a concentric lamellar structure with alternating polymer phases. Unlike planar Distributed Bragg Reflectors (DBRs), the spherical arrangement of the polymer layers causes angle-independent reflection peaks (i.e., the displayed colour is independent of the viewing angle).[2] However, the pristine refractive index contrast between the polymer phases is low, thus causing a limited reflectance. Transparent high-index nanoparticles – such as titanium dioxide or zinc oxide – are selectively incorporated into one of the block copolymer domains to enhance the refractive index contrast and, thus, the reflectance.[3] Such a strategy is based on a simple co-assembly process in which specific surface ligands can control the nanoparticle spatial distribution via entropic and/or enthalpic contributions. This system offers a novel platform for developing efficient non-iridescent photonic pigments based on structural colour. The fabrication of such microspheres, their structural characterisation and their optical properties are explored. Photonic pigments contribute to the expanding field of photonic materials and are promising candidates for substituting conventional pigments on an industrial scale.

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Label-free imaging and 3D single particle tracking in complex media via interferometric scattering microscopy (iSCAT)

with Mahdi Mazaheri, David Albrecht, Jan Renger, Tobias Utikal, Cornelia Holler, and Vahid Sandoghdar

Interferometric scattering (iSCAT) microscopy circumvents limitations of traditional fluorescent labeling methods such as photobleaching and phototoxicity while achieving single-molecule sensitivity [1,2]. However, iSCAT microscopy on complex samples such as biological cells confronts challenges due to dynamic speckle patterns caused by coherent scattering from different sample constituents. To address this, we manipulate the spatial coherence of the illumination laser beam. This approach mitigates dynamic speckle, preserving sensitivity and enabling high-speed imaging over extended fields of view with diffraction-limited resolution. Experimentally, we demonstrate iSCAT imaging of biological nanostructures at high frame rates well beyond 1kHz. Additionally, we report on long-range 3D tracking of nanoparticles using iSCAT. Prior works were limited to a range of few hundred nanometers along the axial direction [3]. Our approach localizes nanoparticles in 3D over tens of micrometers, with high temporal resolution and nanometer axial localization precision [4]. We demonstrate the performance of our 3D tracking algorithm by simultaneous tracking of more than 1000 vesicles within a COS-7 cell. These advancements hold promise for diverse scientific applications of label-free iSCAT microscopy, particularly in cell biology and material science, enhancing understanding of nanoscale phenomena.

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Effect of Structural Phase Transitions on Photonic Density of States

with Ullrich Steiner, Matthias Saba

Structural color arises from visible light interference in the presence of correlated photonic structures found in many animals and plants [1,2]. As the dielectric contrast increases, such structures can form complete photonic band gaps, where light cannot enter the structure from any angle [3]. These phenomena are well established for periodic systems, so-called photonic crystals [4]. However, the emergence of a reduced photonic density of states due to the interplay of order and disorder in amorphous structures is still not fully understood. Here, we investigate how structural correlations at different length scales affect the photonic density of states. To this end, we generate 4-connected 3D continuous random networks with tunable disorder using a Metropolis Monte Carlo algorithm [5-6]. Utilizing a Monte Carlo bond-switch move, this algorithm simulates structural phase transitions in a 3D 4-coordinated network model, the transitions from a crystalline to an amorphous diamond. The effect of these structural phase transitions on the photonic response is analyzed through a finite-difference time-domain spectral method and approximative analytical calculations.

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Bright White Scatterers Beyond Titania

with *Andrea Dodero, Viola Vogler-Neuling, Frank Scheffold, Ullrich Steiner*

Titanium dioxide (TiO2) is widely used in several industrial fields because of its unique properties and low cost. Among others, it scatters light very efficiently due to its high refractive index (n_o = 2.6, at 587nm) [1], thus being often used to impart a white colour, enhancing the brightness of other colours, and increasing the UV-filtering capabilities of food and drug colorants, coating products, cosmetic products, and sunscreen components [2]. However, despite its remarkable properties, titanium dioxide was banned as a food additive in all European Union countries in 2022 due to health concerns [3]. In this context, there is an urge for a biocompatible white pigment replacement, with guanine appearing to be a promising alternative. In nature, highly refractive guanine crystals are indeed responsible for a diverse array of optical phenomena in animal coloration [4]. These organisms exhibit a vibrant spectrum of colours from blue to white through the organization into stacked structures of these crystals, whose optical properties derive from a high in-plane refractive index (n = 1.83) that endows them with the capability to scatter light, similarly to titanium dioxide. Our objective is to develop a guanine crystal-based pigment that can approximate the optical properties of titanium dioxide, providing a biocompatible alternative. In this study, we successfully replicated the synthesis of homogeneous guanine crystals using an anti- solvent method and demonstrated the potential for shaping these crystals into spherical forms through confined crystallization. We employed two main techniques: the one-step recrystallization method, which yielded highly uniform crystals with an average size of 17 μm, and the inverse emulsion method, which produced spherical crystals ranging from 5 to 15 μm in diameter. With these findings, the synthesis of spherical guanine crystals with sizes between 400 and 800 nm is conceivable. Such advancements could lead to the development of a novel white pigment that effectively reflects wavelengths within the visible light spectrum.

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Exploring Strong Light Localization and Bandgap Formation in Amorphous Networks through numerical studies

with Frank Scheffold

Strong Anderson Localization manifests as an interference wave phenomenon within finite-sized mediums, potentially leading to localized states under infinite extension. We propose a framework for characterizing light transmission through three-dimensional high-refractive amorphous materials, showcasing both localization and photonic band gaps. Leveraging advanced numerical techniques and recent advancements in Finite-Difference Time-Domain (FDTD) simulations, we explore how light behaves in complex materials and how these effects interact near the bandgap.

Daria Panova

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Broadband optical properties of Ti3C2 MXene revisited

with Gleb Tselikov, Georgy Ermolaev, Andrey Vyshnevyy, Aleksey Arsenin, Valentyn Volkov

The discovery in 2011 of a new family of 2D layered materials, transition metal carbides, nitrides and carbonitrides, called MXenes, has revolutionised materials science. Their exceptional metallic behaviour makes them excellent candidates for energy storage applications [1]. However, their applications in photonics and optical engineering are much less explored. Obstacles include significant differences (up to 50%) in optical constants between results obtained for one of the most widely used MXenes, Ti3C2 [2–4]. Moreover, the mechanisms governing the absorption peak of Ti3C2 at 800 nm remain unclear. While some studies [4,5] claim it to be a plasmonic resonance, others [2,6] argue that it is an interband transition. We investigate the optical properties of Ti3C2 MXene by using spectroscopic ellipsometry to obtain broadband (300-3300 nm) optical constants, validated by transmission measurements and quantum mechanical calculations. In this talk, we report a strong optical response of Ti3C2 and identify two interband transitions at 300 and 800 nm and plasmonic behaviour beyond 1415 nm, contrary to the previous understanding. Motivated by recent success in fabricating transition metal dichalcogenide nanospheres that retain the crystalline structure and optical response of the bulk material [7], we suggest the use of Ti3C2 nanoparticles for cancer theranostic applications. Ti3C2 nanospheres can achieve dual resonant absorption in two biomedical spectral windows due to the different nature of the absorption peaks: Mie resonance with interband absorption in the first therapeutic window (700-980 nm) and localised surface plasmon resonance in the second (1100-1700 nm). Therefore, our study revisits the broadband optical constants of Ti3C2 and extends its photonic applications.

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Nonlinear effects in multi-resonant metamaterials

The goal of our metastructures is to produce a nonlinear signal by a simple reflection of the pump(s) on it. This device could be useful for creating a new type of optical sources and could be particularly useful for wavelength ranges that are poorly provided such as the terahertz one. Their principle is to exalt the electric field inside of a thin nonlinear crystal (typically 0,2 µm). The effects we are currently interested in are of second order: second harmonic generation (SHG) and difference frequency generation (DFG). Therefore, these effects are proportional to the square of the local field. This is why it is all the more crucial to be able to concentrate it. We use a GaAs crystal because of its high value of second order nonlinear susceptibility (150 pm/V). Our structures are composed of a thick layer of gold above which there is the crystal layer that is covered by a series of periodic gold bars. The crystal is therefore almost surrounded by gold and light can be trapped in this space. However, our structure must be designed to let the light go inside of the structure for the pump wavelength and outside of it for the signal wavelength. To do so, one can use some light modes of the structure that are coupled with free space. These resonances can be spotted by the presence of a reflectance fall for a narrow range of wavelengths. These resonances are for instance vertical or horizontal nano Fabry-Perot (since the effective optical index inside the crystal is not homogeneous due to the presence of plasmons on the gold bars). They can be modulated by modifying geometrical parameters such as the bar width, their period or the crystal thickness. However, it is not enough to get critical resonances (i.e. null reflectances) for both pump and signal wavelengths. To do so, one must add a degree of liberty by alternating gold bars of different widths. It allows us to create a coupled nano Fabry-Perot due to how light beneath each bar interfere with each other. These critical resonances allowed us to get a factor 10 for our efficacity of nonlinear conversion.

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Exploiting wavefront shaping for photoacoustic tomography through multimode fibre

with Dylan Marques, David Phillips, Edward Zhang, Paul Beard, and James Guggenheim

Photoacoustic tomography (PAT) is a rapidly advancing biomedical imaging technique in which pulsed light is used to generate ultrasound waves in biological tissues. This provides 3D images of blood vessels and other tissue structures. Accordingly, PAT can be used to study a range of biological processes such as vascular development, and diseases such as diabetes and cancers. While most PAT systems operate at the tissue surface, there is interest in extending PAT to an endoscopic regime. This could open new applications, including in surgical guidance and the early detection of GI tract cancers. However, developing endoscopic PAT systems is difficult. The main problem is it is challenging to miniaturise traditional ultrasound detectors sufficiently to fit in an endoscope. To address this challenge, we investigate developing a PAT system based on small, ultrasensitive, optical ultrasound sensors. The idea is these sensors, which are based on optical microresonators, could be read out through a multi-mode fibre (MMF) using optical wavefront shaping techniques. Compared to the current state of the art, this approach could provide several advantages, foremostly reducing the required endoscope aperture size by at least an order of magnitude. To test the concept, we present a prototype system for reading out the sensors through MMF using wavefront shaping. We demonstrate the feasibility of this approach by imaging a number of phantoms, and characterise the systems sensitivity and resolution. We then use this system to image a human fingertip in-vivo. By demonstrating the feasibility of doing PAT using optical ultrasound sensors and wavefront shaping, this work paves the way to developing a new range of PAT endoscopes offering advantages over the state of the art. We also find that this approach could be attractive beyond endoscopy, for handheld, flexible, MRI-compatible imaging devices. Moreover, reading out these sensors via wavefront shaping represents a new application of this complex photonics technique, revealing and clarifying several interesting challenges and properties for discussion.

Samaneh Moeini

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On noise in optomechanical resonators

with Clivia M. Sotomayor Torres

Optomechanical resonators, where light and mechanical vibrations interact, are susceptible to various sources of noise that can affect their efficiency and sensitivity. Understanding and mitigating these sources is essential to achieve optimal device functionality. Common sources of noise in optomechanical resonators include device imperfections, nonlinear effects, thermal noise, environmental conditions and mechanical mode shift. Different strategies can be employed to mitigate each of these effects. This study focuses primarily on two sources of noise: thermal noise and mechanical mode shift. Variations in critical dimensions such as size, shape or material properties can cause changes in the mechanical resonant frequencies of the resonators. These changes can arise from manufacturing imperfections or environmental influences. Shifts in resonant frequency can disrupt the coupling between the mechanical and optical resonators, potentially altering device performance. Conversely, thermal energy in the system can cause fluctuations in the critical dimensions of the mechanical resonators, leading to the mechanical mode shift mentioned above. In addition, thermal dissipation can affect the overall stability and effectiveness of the optomechanical system. Thermal fluctuations can induce random motion in the mechanical resonator, introducing noise into the system and potentially limiting its sensitivity and precision. In this study, we propose a simplified model consisting of two coupled optomechanical resonators, both of which experience fluctuations in their resonant frequencies. While not precluding the study of more complex models, we focus on investigating the effect of noise using this two-resonator model.

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Coherent Perfect Absorption of Arbitrary Wavefronts at an Exceptional Point

with Lena Wild, Yevgeny Slobodkin, Gil Weinberg, Ori Katz, and Stefan Rotter

The phenomenon of coherent perfect absorption (CPA) has been one of the key discoveries in the emerging field of non-Hermitian photonics, with the original prediction [PRL 105, 053901 (2010)] together with the first experimental realization [Science 331, 889 (2011)] now being cited well over a thousand times. Particularly appealing about this concept is not only its technological relevance, but also the insight that a coherent perfect absorber is an "anti-laser", i.e., it is the time-reversed counterpart of a laser, where absorption and interference act together [Nature 467, 37 (2010)]. Unfortunately, while conceptually elegant and eye-opening, leveraging the concept for applicative use was, and still is, extremely restricted fundamentally, due to the coherent absorption occurring usually for a single spatial mode and for a single frequency only. Many efforts are currently focused at overcoming these hurdles. For example, recent work succeeded in taking advantage of the so-called 'exceptional point' (EP) for CPA [Science 373, 6560 (2021), Nature Communications 13, 599 (2022)] to overcome the narrow bandwidth challenge. However, also the concept of an EP-CPA is fundamentally limited to the absorption of only two spatial modes, which merge at an EP. On the other hand, our own recent work [Science, 377, 6609 (2022)] demonstrated coherent perfect absorption of more than a thousand spatial modes with a massively degenerate (MAD) CPA. This approach, in turn, is limited to narrow-band absorption only, such that no CPA concept has been presented to date that overcomes both the spectral and the spatial restrictions simultaneously. In our latest work, we present a new CPA design, which, for the first time, yields both spectral and spatial degeneracy. This new type of CPA is capable of perfectly depositing a light beam in a weak absorber over a wider spectral range as compared to a conventional CPA and also regardless of the light beam's spatial wavefront. The fundamental insight that led to our novel concept is that it is possible to merge the two ideas of an EP-CPA, and a MAD-CPA, respectively, by critically coupling two spatially degenerate cavities with each other. We also demonstrate that this concept is not limited to a single implementation, but can be realized experimentally in different ways. Being very excited about this new concept, we strongly believe that our work is of interest to several communities, such as those working on lasing, wavefront shaping, light harvesting, and non-Hermitian physics.

Jiewen Nie

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Computational spectral imaging based on liquid crystal metasurface

with Weijie Wu,Shan Jiang, Haining Yang, Daping Chu

In the evolving field of computational spectral imaging, this study introduces an innovative approach by employing liquid crystal metasurfaces, characterized by their high integration level, low sampling costs, and mature fabrication processes suitable for mass production. Our investigation is divided into two core components: single-pixel spectral imaging and snapshot spectral imaging, both facilitated by the advanced capabilities of liquid crystal metasurfaces. The first component explores a single-pixel imaging system that integrates a spectral encoding filter based on liquid crystal metasurfaces with compressed sensing. This combination not only achieves high-resolution spectral imaging with a single detector element but also significantly reduces the system's complexity and cost. The liquid crystal metasurface's ultrathin profile eliminates the need for additional spectral separation devices, thereby enhancing the system's integration. Furthermore, the application of hardware-end subsampling based on compressed sensing, paired with high-performance computational reconstruction via generative models, drastically lowers the sampling costs. In the second part, we develop a snapshot spectral imaging technique using polarization-independent liquid crystal metasurface devices. Utilizing the polarization-twisting properties of TN liquid crystals, these devices permit instantaneous spectral encoding without the polarization limitations of conventional systems. The technique's rapid imaging capability is particularly advantageous for real-time applications, such as in biomedical imaging or remote sensing. Notably, the proposed solution benefits from a high tolerance to variances in the metasurface, allowing for large-scale manufacturing through nanoimprint lithography. This advantage, combined with the highly mature, stable, and cost-effective liquid crystal technology, positions our approach as a scalable and economically viable option for spectral imaging. The integration of liquid crystal metasurfaces in computational spectral imaging heralds a new era of compact, efficient, and high-performance imaging systems, unlocking potential across various scientific and industrial applications.

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A mixed perturbative-nonperturbative treatment for strong light-matter interactions

with Johannes Feist, Francisco J. García-Vidal

The full information about the interaction between a quantum emitter and an arbitrary electromagnetic environment is encoded in the so-called spectral density. We present an approach for describing such interaction in any coupling regime, providing a Lindblad-like master equation for the emitter dynamics when coupled to a general nanophotonic structure. Our framework is based on the splitting of the spectral density into two terms, leveraging the underlying physics of the light-matter interaction. On the one hand, a spectral density responsible for the non-Markovian and strong-coupling-based dynamics of the quantum emitter. On the other hand, a residual spectral density including the remaining weak-coupling terms. The former is treated nonperturbatively with a collection of lossy interacting discrete modes whose parameters are determined by a fit to the original spectral density in a frequency region encompassing the quantum emitter transition frequencies. The latter is treated perturbatively under a Markovian approximation, such that its effect is reduced to an energy shift on the emitter energy levels, which does not induce any additional numerical cost. We illustrate the power and validity of our approach through numerical calculations of the excited state population of a two-level emitter in the problem of spontaneous emission. We test three different setups supporting strong light-matter interactions: the first one is a simple model consisting of a sum of Lorentzian resonances, the second one is a realistic hybrid metallodielectric nanostructure, and the third one is a single-mode setup corresponding to a two-level emitter under ultrastrong coupling to a single physical mode.

Morgan Facchin

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Unveiling the role of multiple scattering in speckle metrology

with Saba Khan, Kishan Dholakia, Graham Bruce

Speckle patterns are well known random interference patterns. Sometimes seen as a nuisance, they can also be used to measure various physical quantities, allowing remarkably simple setups with high sensitivity: this is the field of Speckle Metrology. A wide variety of speckle metrology techniques exists, in the way to produce and analyse speckles. Recent work showed that the performance of these techniques can be improved by several orders of magnitude by using speckle patterns resulting from the multiple scattering of light, as opposed to simple scattering. I will present our work in modelling speckle patterns which explains this empirical observation. Intriguingly, our work also shows that multiple scattering offers no improvement for certain measurands. The improvement is either considerable or null. We formulate a general criterion which allows one to determine whether multiple scattering is beneficial for a given metrology task. This provides a valuable guide for the design of optimised experimental set-ups.

José Carlos do Amaral Rocha

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All-optically untangling light propagation through multimode fibers

with Hlib Kupianskyi, Unė G. Būtaitė, Tomáš Čižmár, Simon Horsley, Joel Carpenter, David B. Phillips

When light propagates through a complex medium, such as a multimode optical fiber (MMF), the spatial information it carries is scrambled. In this work we experimentally demonstrate an all-optical strategy to unscramble this light again [1]. We first create a digital model capturing the way light has been scattered, and then use this model to inverse-design and build a complementary optical system–which we call an optical inverter–that reverses this scattering process. Our implementation of this concept is based on a technology known as multi-plane light conversion [2], and can also be understood as a physical matrix pre-conditioner, or a linear diffractive optical neural network. We present three design strategies allowing different aspects of device performance to be prioritized [3]. We experimentally demonstrate a prototype optical inverter capable of simultaneously unscrambling up to 30 spatial modes that have propagated through a 1m long MMF, and show how this promises near instantaneous incoherent imaging, without the need for any beam scanning or computational processing. We also demonstrate the reconfigurable nature of this prototype, allowing it to adapt and deliver a new optical transformation if the MMF it is matched to changes configuration. Finally, we show how MMF inverters could be scaled up in the future to process hundreds of modes simultaneously for micro-endoscopy applications [4]. Our work represents a first step towards a new way to see through scattering media. Beyond imaging, this concept may also have applications to the fields of optical communications, optical computing and quantum photonics.

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Long-range molecular energy transfer mediated by strong coupling to plasmonic topological edge states

with Jose A. Sánchez-Gil, Vincenzo Giannini, William L. Barnes, Marie S. Rider

Using coupled electric dipole formalism, we study weak and strong coupling between molecules and topological edge states of arrays of metallic nanoparticles to enhance highly-directional long-range energy transfer between molecules.

Changyan Zhu

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Broadband on-chip spectrometer enabled by machine learning methods

with Nussupbekov, Ayan and Zhu, Bofeng and Sun, Fangyuan and Qiang, Bo and Zhang, Baile and Wang, Qijie and Chong, Yidong

In this work, we present a novel machine learning-based approach for high-accuracy broadband spectrum reconstruction in on-chip random spectrometers. Furthermore, we generalize the concept of random spectrometers using random matrix theory and introduce a new spectrometer design that offers a smaller footprint while maintaining equivalent performance.

Johannes Bentzien

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Optical PT-symmetry in the absence of gain or loss

with Julien Pinske, Lukas J. Maczewsky, Steffen Weimann, Matthias Heinrich, Stefan Scheel, and Alexander Szameit

Our conventional understanding of physics is based on the fundamental concept of energy conservation that manifests itself in the real-valued energy spectra of Hermitian Hamiltonians. However, so-called open systems can exchange energy with their environment, and, as subsystems of a larger whole, may exhibit non-Hermitian dynamics. Along these lines, non-Hermiticity established by local attenuation and coherent amplification has been firmly established on a variety of platforms. More recently, the concept of parity-time symmetry has been associated with the wave-mechanical interplay of gain and loss in complex-valued potentials. Here, by contrast, we present a projective approach to synthesize genuinely non-Hermitian dynamics without any injection or removal of intensity from the system. To demonstrate the capabilities of our technique, we observe nonorthogonal modes in femtosecond laser-written waveguide arrays and leverage the fluorescent properties of the waveguide cores to selectively probe the on-site intensities. Projective parity-time symmetry makes features of non-Hermiticity accessible in scenarios where actual amplification and/or attenuation may be unavailable or would disrupt the desired physics, e.g. in quantum optics or nonlinear systems.

Dylan Danese

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Programmable Generalised Measurements for Photonic Time-Bins using Complex Media

with Vatshal Srivastav, Saroch Leedumrongwatthanakun, Will McCutcheon, Mehul Malik

High-dimensional time-bin states of light are promising for high-capacity and noise-robust quantum communication systems. However, manipulating and measuring time-bin qudits poses persistent challenges, primarily due to the lack of scalable, versatile, and high-fidelity measurement schemes. Here, we propose a novel technique that tackles these challenges by harnessing space-time coupling in the form of spatial mode dispersion in a long multi-mode fibre (MMF). By characterising the multi-spectral transmission matrix of a step-index MMF and then shaping the spatial mode of an input photon, we are able to program generalised projective measurements for photonic time-bin states, including states from the discrete Fourier transform and Hadamard bases in dimension four. Our method offers significantly lower complexity than unbalanced Franson-type interferometers with clear potential for extensive scalability, opening exciting avenues for high-dimensional time-bin-based quantum information protocols.

Federico Maestri

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Nonlinear Physical Unclonable Functions (PUFs) for cryptography

with Sara Nocentini, Diederik Wiersma, Francesco Riboli

Optical PUFs are 3-D diffusive material. Thus, if illuminated with coherent light they produce an interference pattern called "speckle" composed of bright and dark spots. In its spatial distribution is contained the information on how that specific material is illuminated. Then, for a given spatially modulated beam as input, the PUF returns the corresponding speckle as output. Eventually the output result gets filtered and hashed to retrieve a binary key that can be used for cryptography tasks. PUFs are characterized by a disorderd structure that provides a high dimensional Input-Output space and that is unfeasible to clone. These two features ensure a good reliability of the PUFs as cryptographic primitive. We are interested in enhancing PUFs security by employing structural nonlinearity. A kind of nonlinearity that emerges when we vary the scattering potential of the medium and that is proportional to the scattering strength of the PUF. We perform this variation by the use of liquid crystals that can be reoriented if stimulated, resulting in different speckle patterns under the same input. We are able to do that in a controllable and reversible manner, hence preserving the determinism essential for cryptography.

Xiaomeng Sui

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Polarimetric Calibration of Dual-SLM Holography with Uneven Liquid Crystal

with Allard Mosk

Liquid crystal on silicon (LCoS) is a widely used spatial light modulator (SLM) in computer-generated holography (CGH). However, the phase-modulating profile of LCoS is often not ideally uniform in application, bringing about undesired intensity fringes. In this study, we overcome this problem by proposing a highly robust dual-SLM complex-amplitude CGH technique, which incorporates a polarimetric mode and a diffractive mode. The polarimetric mode linearizes the general phase modulations of the two SLMs separately, while the diffractive mode uses camera-in-the-loop optimization to achieve improved holographic display. Experimental results show the effectiveness of our proposal in improving reconstructing accuracy by 21.12% in peak signal-to-noise ratio (PSNR) and 50.74% in structure similarity index measure (SSIM), using LCoS SLMs with originally non-uniform phase-modulating profiles.

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Topological invariants in space-time photonic systems with travelling wave modulation

with P.A. Huidobro

Topology studies whether objects can be transformed continuously into each other. In condensed matter physics, two Hamiltonians are said to be topologically equivalent if one can be deformed into the other without ever closing their energy gaps. This property can be extended to the band structure of photonic systems, which result from solving Maxwell`s equations, by transforming the permittivity and permeability of the material instead of the Hamiltonian's parameters. More interestingly, through the bulk-boundary correspondence, if two topologically distinct materials are put in contact, then the band gap must close somewhere in the interface region, thus supporting localized edge-states. These boundary states are robust against any perturbations on the interface because their existence is conditioned only on the topological properties of each bulk, making them a potential mechanism to obtain robust and efficient energy transport. In this work, we study the topological properties of photonic time-varying media, putting a special focus on traveling-wave modulations. With time as a new degree of freedom, we can explore new avenues for wave control not previously found in conventional nanophotonic systems, such as magnet-free nonreciprocity or synthetic motion. Furthermore, new topological phenomena like edge-states appearing in time, or the excitation of said states with frequencies below the band gap are also found, making the characterization of such systems highly desirable. More precisely, we will focus on how the Zak phase, which characterizes the topological properties of one-dimensional systems, is defined in media with broken time reversal symmetry and reciprocity, as is the case with travelling wave modulations. In addition, we will present a study on the bulk-boundary correspondence in such systems by calculating the edge-modes between two topologically distinct materials through transfer-matrix-like calculations.

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Synthesis of CsPbBr3 perovskite nanocrystals stable in polar solvents

with Leo Rosado Godon, Jaime Bueno Benito, Sol Carretero Palacios, Miguel Anaya Martín, Marta Quintanilla Morales

Perovskite nanocrystals have emerged as highly promising candidates in the domain of optoelectronic applications, notably in the development of light-emitting diodes (LEDs). Their appeal lies in a set of remarkable attributes, encompassing a high quantum yield, the ability to fine-tune emission wavelength through composition and size adjustments during synthesis, and a narrow emission bandwidth [1]. While these qualities position perovskite nanocrystals as frontrunners in technological advancements, their susceptibility to instability in the presence of polar solvents presents a significant obstacle to their widespread application. This instability is rooted in their highly ionic bonding and low formation energy [2]. Furthermore, existing procedures demand an extended preparation period, involve numerous encapsulation stages using various materials [3]. In this study, we introduce a novel approach to tackle the instability issue by encapsulating CsPbBr3 nanocrystals within micelles. This pioneering technique allows for the synthesis of perovskite nanocrystals using the preferred synthesis method, followed by a streamlined straightforward process wherein a protective micelle forms on the nanocrystal surface. The significance of our approach lies in its ability to enhance the stability of perovskite nanocrystals specifically in polar solvents, such as ethanol and 2-propanol, without the need for intricate synthesis procedures. By addressing the inherent instability challenges of perovskite nanocrystals, our method not only contributes to the fundamental understanding of their behavior in polar environments but also paves the way for their integration with other structures, such as plasmonic nanoparticles.

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