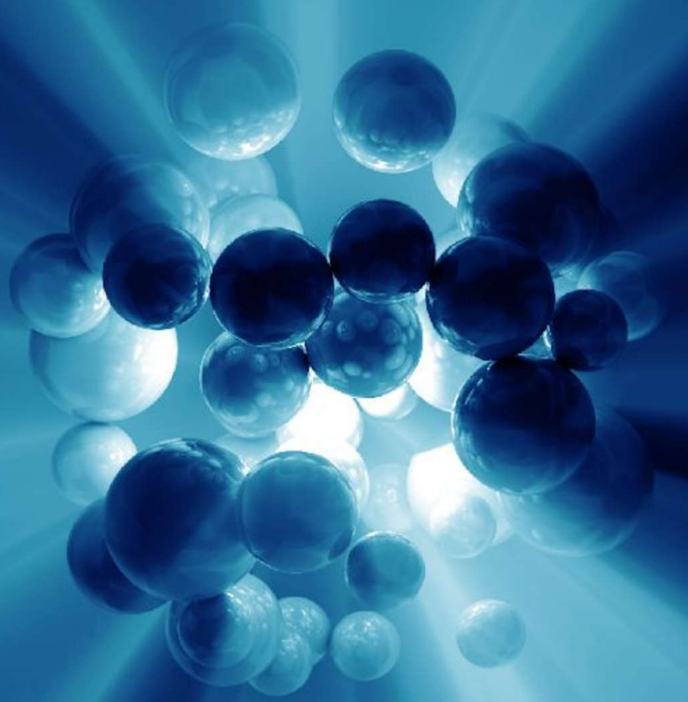
Complex Nanophotonics **Science Camp**

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

KEYNOTE TALKS
Roberto Di Leonardo
Frank Scheffold
Päivi Törmä

INVITED TALKS
Sol Carretero Palacios
Angela Demetriadou
Arthur Goetschy
Simon Horsley
Sasha Rakovich
Sabrina Simoncelli
Peter Wiecha

EVENING DEBATES
Jacopo Bertolotti
Ying Lia Li
Timmo van der Beek
Jess Wade



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UK META MATERIALS NETWORK

List of contributions

Keynote talks

Invited talks

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Posters

Roberto di Leonardo

Sapienza Università di Roma, Italy

Engineering bacteria to harness photons for mechanical power

A single photon of visible light has the energy of one hundred k_BT. Harnessing this energy in mechanical microsystems has numerous advantages related to the high resolution with which light can be distributed in space and time. After examining some strategies for energy transduction from optical to mechanical on a microscopic scale, I will show how bacteria can be genetically modified to perform this task in a very efficient and controllable manner. Using spatial light modulators we can use light as a remote control that can independently power thousands of cells and orchestrate their movements. These bacteria can be used a "living" paint controlled by light or as light driven propellers within biohybrid micromachines. Beyond applications, these cells can be seen as the light-driven 'atoms' of new materials whose non-equilibrium behaviour opens up many perspectives for fundamental research on the statistical mechanics of active matter.

Frank Scheffold

University of Fribourg, Switzerland

Light transport in amorphous photonic materials with localization and bandgap-regimes

I will discuss the properties, the fabrication, and the characterization of three-dimensional disordered hyperuniform silicon networks, a new type of metamaterials displaying photonic features for electromagnetic vector waves [1]. I will first present our results on fabricating polymer templates of the network structures using direct laser writing (DLW) lithography [2]. Next, with infiltration and double inversion, we converted the mesoscopic polymer networks into silicon structures with a refractive index near n=3.6. The resulting metamaterials display a pronounced photonic gap in the optical transmittance at λ=2.5μm [3]. By shrinking hyperuniform structures via heat treatment, we recently pushed the opening near λ=1.5μm, close to telecommunication wavelengths [4].

To understand the physical parameters dictating the properties of amorphous photonic materials, we have performed extensive numerical simulations of the density of states and optical transport properties [5]. To this end, we study the bandgap formation and Anderson localization in hyperuniform structures in two and three dimensions. We identify the evanescent decay of the transmitted power in the gap and diffusive transport far from the gap. Near the gap, we find that transport sets off diffusive but, with increasing slab thickness, crosses over gradually to a faster decay, signaling localization. We show that we can describe the transition to localization at the mobility edge using the self-consistent theory of localization based on the concept of a position-dependent diffusion coefficient [6,7].

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Päivi Törmä

Aalto University, Finland

Bose-Einstein condensation, lasing and topological photonics with plasmonic lattices

Bose-Einstein condensation has been realized for various particles or quasi-particles, such as atoms, molecules, photons, magnons and semiconductor exciton polaritons. We have experimentally realized a new type of condensate: a BEC of hybrids of surface plasmons and light in a nanoparticle array [1]. The condensate forms at room temperature and shows ultrafast dynamics, and the system provides easy tunability of the lattice and unit cell geometry and symmetries. Recently, we have observed formation of polarization textures and domain walls, and obtained the BEC phase for the first time using a phase retrieval algorithm [2]. Our measurements of spatial and temporal coherence show a change from exponential decay to powerlaw or streched-exponential when crossing to the BEC phase [3]. In the lasing regime, we have observed a bound state in continuum (BIC) mode of topological charge one [4], as well as higher charges [5]. We have also observed that when the nanoparticles are made of magnetic material, chiral modes and magnetic switching of lasing become possible [6]. This paves the way for future studies of topological effects in these systems.

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Sol Carretero Palacios

Universidad Autónoma de Madrid, Spain

Quantum trapping of photonic structures

The Casimir-Lifshitz force originates from the quantum vacuum fluctuations of the electromagnetic field. This force is especially intense between interacting objects at nanoscale distances, and it can be attractive or repulsive depending on the optical properties of the materials (amongst other parameters). This fundamental phenomenon is at the heart of the malfunctioning of nano- and micro-electromechanical devices (NEMS and MEMS) that integrate many of the gadgets we use in our daily lives. Absolute control over these forces would make it possible to suppress adhesion and friction in these NEMs and MEMs.

During this talk, I will show the possibility of controlling the Casimir-Lifshitz force by tuning the optical properties of the interacting objects. Specifically, I will present diverse examples of quantum trapping based on the Casimir-Lifshitz force, which include optical resonators, multilayer structures, or films with spatial inhomogeneities.

Angela Demetriadou

University of Birmingham, UK

Excitation and radiative properties of geometrically complex plasmonic nanocavities

Plasmonic nanocavities are usually formed by two tightly-coupled nano-metallic structures. They have the ability to confine and enhance light significantly, and efficiently radiate to the far-field. Due to these properties, plasmonic nanoantennas have been established as an ideal photonic environment to study and observe light-matter interactions at room temperature even with single molecules, such as surface enhanced Raman spectroscopy (SERS) and strong coupling.

Two of the most common designs are the dimer antenna and the nanoparticle assembled on a mirror (NPoM) configurations. These two designs are fairly similar, and often theoretical descriptions developed for the dimer antenna are adapted or qualitatively applied to the more complex design of NPoM. However, in this talk, we show that these two plasmonic nanoantennas have significant differences on how energy is coupled into the nanoantenna (i.e. excitation) and how the energy couples out (i.e. radiative behavior). The dimer antenna exhibits almost identical excitation and radiative decay rates, indicating that the energy couples-in and -out of the structure via the same mechanism. However, the NPoM configuration has a radiative decay rate that is significantly larger than its excitation rate.

Furthermore, I will show that plasmonic nanocavities support a complex set of modes, each with a different field profile and radiative properties, creating a complex system of photonic modes that all interact with a QE or a molecule placed in the nanocavity. Changes to the geometry of the nanocavity, even just few nanometers, dramatically change the fields of the modes in the nanocavity, their resonant frequencies and their radiative properties. Using nanocavity geometries formed by nanoparticle shapes commonly occurring during nanofabrication, I will show the set of modes emerging and their properties, aiming to understand how quantum emitters and molecules interact with such complex set of plasmon modes.

Arthur Goetschy

Institut Langevin, ESPCI Paris-PSL, France

Optimizing light deposition in scattering media

In recent years, new operators have been introduced to optimize various physical quantities in complex open systems, such as flux, dwell-time, information, or image formation. Once these operators are measured, wavefront-shaping techniques are used to generate one of the eigenstates that will maximize the quantity of interest. In this context, great attention has been paid to the range covered by the eigenvalues of these operators, with particular interest in the largest ones.

In this talk, we will discuss the spectral properties of three operators, which characterize the dwell-time, the energy deposition and the optical remission, respectively. For each case, we report the possibility of achieving, by shaping the wavefront, more than one order of magnitude enhancement over the typical value found under random illumination. These results will be explained within a unified framework that highlights the crucial and beneficial role of non-Gaussian and long-range correlations in strongly scattering media.

Simon Horsley

University of Exeter, UK

Exploring the space of electromagnetic materials

with J. C. Capers

There are many things we'd like to be able to do with light. Propagate it around an object without reflection, focus it into a sub-wavelength region of space, or simply emit more of it from a source. And there are many materials we could consider using to achieve these effects. There are, for example, 72 degrees of freedom describing just linear homogeneous materials!

The question is how we should go about finding the right materials; those necessary to control the electromagnetic field in a predetermined way. Here I shall discuss several theoretical techniques we have found for exploring this space of electromagnetic materials.

Firstly I shall discuss the use of analogies: the success of transformation optics, and how the close relationship between Maxwell's equations and the Dirac equation allow us to find materials where light can be robustly trapped at interfaces, forced to circulate in one sense, or made to propagate in an effective gauge field.

Following from this I shall explore the problem of multi-functional devices, where the challenge is to find a single distribution of materials that perform two or more functions depending on the illumination conditions. After deriving some general constraints that any multifunctional device should obey, I shall give some examples where we have designed multifunctional arrays of scattering particles and graded index devices.

Sasha Rakovich

King's College London, UK

Plasmon-assisted rectification of Brownian motion of nanoparticles for lab-on-a-chip applications

The last few decades saw the emergence of many techniques for deterministic control of nanoparticle localization on substrates; however, less attention has been paid to the attainment of such control in liquid environments. Yet, developments in this area could not only facilitate single- to few-particle investigations but could also be directly translated to the control of motion of biomaterials such as viral particles and other biomarkers for biosensing applications. In this talk, I will describe one of the emerging methods by which control of nanoparticle motion can be achieved in solution – plasmonic ratchetting. This method relies on generation of a periodic and asymmetric potential for the suspended colloidal nanoparticles via a substrate patterned with a plasmonic nanoantenna array. The nature of this potential results in a preferential diffusion of the nanoparticles in a predetermined direction, irrespective of nanoparticles' composition and size.

Sabrina Simoncelli

University College London, UK

Nanophotonic approaches for nanoscale imaging & single-molecule detection

Recent years have seen tremendous progress on the design of plasmonic antennas that can amplify and confine optical fields at the nanoscale, offering encouraging perspectives for imaging and sensing. These optical antennas, fabricated with metallic nanostructures, convert free-space light into localized fields by coupling electronic-optical oscillations at the metal interface. The magnitude and spatial distribution of these high-field regions are very sensitive to the size, geometry and material of the nanostructure. Indeed, these characteristics make them powerful tools to control external radiation down to the sub-wavelength regime and to deeply modify the optical properties of nearby emitters, essential to enhance current optical microscopy detection limits in unprecedented fashions. During this talk, we will explore how plasmonic devices can be exploited to enhance the photo-stability of fluorophores, trigger and spatially control chemical reactions, and even efficiently and controllably heat at the nanoscale. We will also discuss the possibility of coupling these devices to study biological phenomena at the nanoscale.

Peter Wiecha

LAAS, University of Toulouse, France

Deep learning for modeling and design in nano-photonics

with Otto Muskens

Artificial intelligence and in particular deep learning (DL) has proven in recent years to provide powerful numerical methods, with rapidly increasing applications in various fields of scientific research [1]. DL is for instance often used to obtain fast approximations for optical properties of nano-structures or nano-photonic devices. Most DL models are trained on very specific problems, but there are ways for generalizing neural network predictor models in nano-optics [2-3]. In addition to modeling, DL is highly promising for inverse design tasks [4]. I will give a brief overview and critically discuss recent developments.

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[4] https://doi.org/10.1021/acsphotonics.0c01481

Christian Anker Rosiek

Technical University of Denmark

Disorder and robustness in silicon photonic topological insulators

with Guillermo Arregui Bravo, Anastasiia Vladimirova, Marcus Albrechtsen, Babak Vosoughi Lahijani, Henri Jansen, Rasmus Ellebæk Christiansen & Søren Stobbe

Photonic crystals (PhCs) formed in dielectric materials give rise to a wealth of physical phenomena, allowing for optical cavities with sub-wavelength confinement and waveguides supporting slow light, thus enhancing light-matter interaction and nonlinear dynamics. Even with state-of-the-art nanofabrication, however, experimental realizations of such structures will necessarily exhibit nanoscale roughness due to random fabrication imperfections. While the inevitable structural disorder in the PhC leads to intriguing phenomena such as the random formation of cavities with high Q-factors and strong confinement [1], it also induces backscattering at high group indices, posing a significant obstacle to the technological application of PhC waveguides [2].

Photonic topological insulators (PTIs) have received considerable attention as a possible way to nullify the adverse effects of disorder in PhCs. Designed using the principles of topology, PTIs are inspired by analogous solid-state systems that offer robust propagation topologically protected from backscattering. Unidirectional edge modes can be realized by breaking time-reversal symmetry but this implies absorption losses at optical frequencies. We focus on dielectric PTIs, which are absorption-free but feature only bi-directional edge modes. While this protection allows for transport through sharp bends [3], it is no guarantee that PTIs are free of backscattering and Anderson localization in the presence of realistic fabrication disorder. We will report on onging experiments in our laboratory, aiming to compare the loss length of conventional and PTI waveguides.

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Rakesh Arul

University of Cambridge, UK

Disordered plasmonic nanoparticle metafilms enable resonant confinement of infrared light and efficient lasing of molecular emitters

with Rohit Chikkaraddy, Niclas S Mueller, David Benjamin-Grys, Junyang Huang, Lukas Jacob, Ermanno Miele, Angelos Xomalis & Jeremy Baumberg

Nanomaterials capable of confining light across the visible to infrared (IR) spectrum are desirable for SERS and SEIRA spectroscopies, enhancement of nonlinear upconversion, and control of chemical reactions. We demonstrate how short-range-ordered Au nanoparticle multilayers (NPnML with n layers), self-assembled by a precise sub-nm molecular spacer, support collective plasmon-polariton resonances in the IR region. These resonances are continuously tunable beyond 11 µm by simply varying the nanoparticle size, number of layers, and by placing the NPnML on a mirror. The collective plasmon-polariton mode is highly robust to nanoparticle vacancy disorder and is sustained by the consistent gap size defined by the cucurbit-5-uril molecular spacer. The simplicity of self-assembly enables the creation of robust amorphous metasurfaces. Rather than being a burden, disorder is here a strength as it aids diffusion of molecules into the gaps for flow sensing.

The resulting molecule-plasmon system approaches the vibrational strong coupling regime, and displays giant Fano resonances with SEIRA enhancement factors ~10^6, exceeding the enhancement of most state-of-the-art lithographically fabricated plasmonic antennae. Molecules within NPnML structures experience molecule-plasmon coupling strengths of g ~100 cm^-1 and compression of IR light into mode volumes ~10^-8. The small mode volume is a result of localization of the plasmon propagation due to disorder.

The extraordinarily strong light-matter interaction within these structures also supports collective light emission in the visible regime. By placing emitter molecules (e.g. Rhodamine B and methylene blue) within barrel-shaped cucurbit-7-uril molecules inside nanogaps, we show a lasing threshold in the emission intensity, and a threshold in the spatial emission area which expands up to 6x the pump irradiated area. We investigate the spatial and temporal coherence of this process using interferometry and g(2) correlation.

Jeremy Boger-Lombard

Hebrew University of Jerusalem, Israel

Passive non line of sight localization with light and sound

with Ori Katz

Non line-of-sight (NLOS) imaging through diffusive, visually-opaque barriers and around corners is an important challenge in many fields, ranging from defense to biomedical applications. Optical NLOS imaging is challenging since in such scenarios one can only measure scattered light that has lost all directional information. Recently, imaging and tracking of objects hidden from view was demonstrated using active LiDAR-based techniques that combine time-of-flight (ToF) measurements with computational reconstruction, using short pulsed laser sources and ultrafast detectors to retrieve 3D information. Inspired by techniques used for passive RADAR and geophysical mapping, we have shown that it is possible to retrieve femtosecond-scale temporal information from cross-correlations of ambient broadband light, without any active source or ultrafast detectors, and to use this information for 3D scene reconstruction.

Given the successful results of our optical method we decided to realize a similar passive technique for acoustic localization around the corner. Sound waves in audible frequencies, show specular reflection from white painted walls, i.e. white walls behave as near perfect mirrors allowing more direct imaging around the corner. Recent works in the field measure ToF information by active sonar approach - emitting a sound pulse and measuring the time from transmission to reception of reflections. Using solely an array of microphones we retrieved ToF information from temporal cross-correlations of acoustic white noise, which was used for localizing and tracking a human being around the corner.

David Bronte Ciriza

CNR-IPCF Messina, Italy

Elongated active particles in speckle fields

with Carlijn Van Baalen, Lucio Isa, Onofrio M. Maragò, Giorgio Volpe & Philip H. Jones

Active particles, defined as units that autonomously extract energy from the environment to move or perform work, are ubiquitous in nature. Even though some interesting properties of these systems can be understood by approximating the particles as spheres, the shape of these particles has recently been highlighted as a key property to engineer their active motion. The motion of these non-spherical active particles has been well characterized in homogeneous energy landscapes; however, real life active systems often find themselves in much more complex environments. Light speckle patterns can generate random energy landscapes introducing part of the complexity of real-life situations.

The role that the shape plays in the dynamics of active particles in complex environments remains to be explored. In this work, we study the dynamics of 3D printed elongated active particles in a speckle light field. The particles are coated with platinum on one end, creating an asymmetry that is exploited for activating the particles when illuminated with laser light. In this way, light plays a double role. It does not only generate a potential energy landscape, but also induces activation by thermophoresis when heating the platinum. We find that the properties of the particles' dynamics are strongly affected by parameters like their aspect ratio, the speckle grain size, and the intensity of the light. Furthermore, the particles' trajectories tend to generate a network where particles starting from different positions can end up following very similar paths.

Clara Bujalance

University of Sevilla, CSIC, Spain

Ultra-Strong coupling phenomena in broadband light-harvesting molecules

with Victoria Esteso, Laura Caliò, Giulia Lavarda, Tomás Torres, Johannes Feist, Francisco J. García-Vidal, Giovanni Bottari & Hernán Míguez

The strongest light-matter interactions observed in polaritonic systems are those that couple electronic transitions with large dipolar moments from organic molecules [1]. These type of materials have the same spectral features as those used in solar devices which has motivated the integration of polaritonic systems in solar cells [2]. In view of this, it is interesting to make a systematic analysis of the absorption properties of the strongly coupled multilayer structure in order to optimise the spectral and angular response of the device [3].

Herein we show the polaritonic properties of a metallic cavity resonant mode interacting with a broadband absorption of a dye film in ultra-strong coupling regime. The analysis is focused on the resonant conditions of the multi-transition absorption band and the photonic resonance, showing that standard one-transition models are able to predict the polaritonic energy levels. Furthermore, we make a decomposition of the absorption in the different layers from electric field intensity calculations inside the cavity, which allows discriminating between the dye (productive) and the metallic absorption (parasitic). Finally we make an angular study of the solar spectrum weighted absorption, observing an independence on the incident direction of the light, as it is desirable for light-harvesting applications [4].

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James Capers

University of Exeter, UK

Inverse design of disordered metamaterials

with Stephen J Boyes, Alastair P Hibbins & Simon A R Horsley

Designer manipulation of light at the nanoscale is key to several next–generation technologies, from sensing and biological imaging to optical computing. One way to manipulate light is to design a material structured at the sub–wavelength scale, a metamaterial, to have some desired scattering effect. Metamaterials typically have a very large number of geometric parameters that can be tuned, making the design process difficult. Existing design paradigms either neglect degrees of freedom or rely on numerically expensive full–wave simulations. To address this, we have developed a simple semi–analytic inverse design method for designing metamaterials built from sub–wavelength elements that exhibit electric and magnetic dipole resonances. These approximations apply well to nanophotonic systems where Mie or plasmonic resonances are accessible. Our approach [Capers et. al., Commun. Phys. 4, 209 (2021)] can be used to solve a wide range of design problems, including manipulating the radiation from a source, focusing plane waves and tuning the coupling between nearby emitters. Importantly, our approach allows for the design of relatively large strongly interacting scattering systems that are intractable to full-wave solvers. More recently, we have extended this to the design of multi-functional metamaterials: fixed materials that have different functionalities when polarisation or incidence angle is changed. These structures can be used to beam—steer, or sort waves by polarisation or incidence angle. In the future, we hope to address other inverse design problems such as spectral tuning and creating designer resonances.

Daniel Dahl

University of Queensland, Australia

High-dimensional Stokes-space spatial beam analyzer

with Martin Plöschner, Mickael Mounaix, Nicolas K. Fontaine & Joel Carpenter

We demonstrate a device that performs a single-shot measurement of amplitude, phase, and coherence of an unknown beam by generalising the principles of Stokes polarimetry to the arbitrary N-dimensional spatial case. The device can distinguish multiple mutually incoherent wavefronts within a single beam, without an external reference in a near lossless fashion and in real-time.

Current methods such as homodyne, heterodyne and self-reference techniques could be used to perform a similar measurement to our device, however each have their own drawbacks. For homodyne and heterodyne, a well-defined reference is needed, but is not always available. Self-reference techniques on the other hand, do not require an external reference and work by interfering the beam's spatial components with itself, either in a sequential or single-shot fashion. However sequential methods may not be appropriate for real-time applications and both sequential and single-shot methods incur beamsplitter-like losses that scale with the number of modes.

Our device uses multi-plane light conversion (MPLC), which transforms a beam through a cascade of phase manipulations. The MPLC allows every spatial state in the higher-dimensional Stokes-space that describes the beam, to be interfered with every other spatial state. The device consists of order N phase planes, where N is the number of spatial modes the device must support. The device approximates a unitary transformation between an input beam composed of N=6 Laguerre-Gaussian spatial components, and an output array of 2N^2-N=66 Gaussian spots. From the intensity of those spots the complete spatial state of the beam is acquired. Akin to measuring the polarisation state of a beam (N=2) by measuring the intensity in 3 different polarisation bases.

The device could be used for a variety of applications such as: spatial state tomography in quantum optics, mode division multiplexing, or to characterise the spatial state of an arbitrary light source.

Chiara Devescovi

Donostia International Physics Center, Spain

Cubic 3D Chern photonic insulators with orientable large Chern vectors

with Mikel García-Díez, Iñigo Robredo, María Blanco de Paz, Barry Bradlyn, Juan L. Mañes, Maia G. Vergniory & Aitzol García-Etxarri

A 3D Chern insulator is a Time Reversal Symmetry (TRS) broken topological phase characterized by a vector of three first Chern invariants [1-3], associated with the planes supporting topologically protected surface states. In this work [4], we devise a general strategy to design 3D Chern Insulating (3D CI) cubic Photonic Crystals (PhCs) with orientable and arbitrarily large Chern vectors, in a reduced TRS broken environment. The strategy proceeds in two steps: formation of photonic Weyl points in a magnetic PhC, and their annihilation via geometric modulation on multifold supercells. The resulting crystals present the following novel characteristics: First, large Chern vectors can be obtained by design, making the PhC ideal for multi-modal operation. Second, full orientability of Chern vectors is achieved in the 3D space, opening up larger 3D CI/3D CI interfacing possibilities as compared to 2D Chern PhCs. Finally, non-zero Chern vectors can be achieved at reduced magnetization conditions, interestingly for photonic applications in the frequency regime where the magnetic response is weak.

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Anna Fischer

Imperial College London, UK

Tuning coupled InP microdisk lasers around exceptional points through selective excitation

with Jakub Dranczewski, Wai Kit Ng, Philipp Staudinger, Heinz Schmid, Dhruv Saxena, T. V. Raziman, Kirsten Moselund & Riccardo Sapienza

We experimentally study mode interactions between coupled semiconductor nanolasers around exceptional points. Epitaxially-grown on-chip InP microdisks with diameters in the range of 1-3 microns are fabricated to support resonant whispering gallery modes. When two microdisks are in close proximity, their modes start to couple through near-field interactions, leading to mode hybridisation. When excited non-uniformly, via a digital micromirror device (DMD), the symmetry of the system is broken, and the coupled laser's modes evolve around the exceptional point. We will show that selective excitation is a tool to tune the mode interaction, and in turn design the mode frequency and threshold. Specifically, we will report on mode switching and reversing pump dependence. Moreover, when many disks are coupled, complexity arises, and the role of exceptional points becomes less clear. We will touch on the role of complexity in these non-hermitian systems. Coupled nanolasers are important as on-chip laser sources and have potential as building blocks of physical neural networks, helping to reduce energy consumption in machine learning and AI processes.

Natalia Herrera Valencia

Heriot-Watt University, Edinburgh, UK

Unscrambling Pixel Entanglement through a Complex Medium

with Suraj Goel, Vatshal Srivastav, Saroch Leedumrongwatthanakun, Hugo Defienne, Matej Pivoluska, Marcus Huber, Nicolai Friis, Will McCutcheon & Mehul Malik

The spatial and temporal structure of photons offers the possibility of enhanced capacity and noise-robustness in the encoding of quantum information. While qubit-entanglement has been distributed over large distances through free-space and fibre, the transport of high-dimensional entangled states of light is hindered by the complexity of the channel, which encompasses effects such as free-space turbulence or mode-mixing in multi-mode waveguides.

In this work, we address these challenges using the discretised position-momentum or "pixel" basis. First, we demonstrate the generation of high-dimensional two-photon pixel entanglement with record quality, speed, and dimensionality. Using tailored spatial mode bases, precise spatial-mode measurements, and an efficient entanglement witness, we reach state fidelities of up to 98% and entanglement dimensionalities up to 55 [1]. We then use the pixel basis to demonstrate the unprecedented transport of high-dimensional entanglement through a complex medium: a 2m long commercial multi-mode fibre. Our technique uses the entangled state itself to measure the transmission matrix of the medium and reverse the detrimental effects of scattering by only manipulating the photon that doesn't enter the fibre [2].

Our work demonstrates the feasibility of harnessing the full potential of high-dimensional encoding for developing entanglement-based quantum technologies and opens a new pathway toward the control of complex scattering processes in the quantum regime.

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Customized anti-reflection structure for perfect transmission through complex media

with M. Kühmayer, C. Ferise, S. Rotter & M. Davy

Wave scattering in complex media leads to intricate and seemingly unpredictable interference patterns, resulting in numerous complications like a reduced Wi-Fi connectivity or a limited line of sight in a foggy environment. To cope with such effects, high hopes have been placed on wavefront shaping techniques to excite open transmission channels in disordered media. Even though a high level of control is required to couple to these channels, experiments have meanwhile been reported that achieve this in both the optical and in the acoustical regime [1,2]. Since, however, these open transmission channels are always accompanied by channels with very low transmission, only a small subset of possible input channels are fully transmitting. The fundamental question we address here is, whether an operational procedure can be found in which not only a single, specially designed light field, but actually all field patterns impinging on a disordered medium get perfectly transmitted. To solve this problem, we show here that a structureless medium composed of randomly assembled scattering elements can be made fully transmitting to all incoming wavefronts by putting a customized complementary medium in front of it [3]. This special situation is achieved when the reflection matrices of the two media surfaces facing each other satisfy a matrix generalization of the condition for critical coupling. For given random media composed of several dozen scattering elements we then use inverse design to find such complementary media. Implementing these designs both numerically and experimentally in an electromagnetic waveguide, we confirm that they are fully translucent. These media also have the promising property of being able to store incident radiation in their interior for remarkably long times.

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Cooling levitated mesoscopic particles through wave-front shaping in the far-field

with N. Bachelard, M. Kaczvinszki, M. Horodynski, M. Kühmayer & S. Rotter

Particles on the nano- to micrometer scale can be levitated and cooled down towards their motional ground state using optical forces [1]. A major challenge in the field of levitation consists in extending the methods to many particles. This would allow for the entanglement of mesoscopic objects or could provide a platform to test many-body quantum effects at the mesoscale. Indeed, a significant roadblock so far has been the requirement to monitor the particles' many degrees of freedom simultaneously and to engineer complex light fields to respond to their motion in real time.

Here[2,3], we solve both of these problems by introducing and computationally verifying a novel multi-particle cooling approach using a generalization of the Wigner-Smith time-delay operator [4-6]. For macroscopic electromagnetic fields we connect the eigenvalues of this operator with the energy shift the corresponding fields induce in the particles. Through this, we can identify spatially modulated wave-fronts that can optimally counteract the motion of multiple particles in parallel. Remarkably, our approach only uses far-field information and decouples the degrees of freedom of the light field from those of the particles, naturally leading to good scaling properties.

We can thus propose an experimental implementation, where wave-fronts are constructed in real time to cool an ensemble of levitated objects.

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Photoacoustic tomography through a multimode fibre using wavefront shaping

with Edward Z Zhang, Paul C Beard & James A 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 cancers in the GI tract. 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 a number of 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 feasibility by making ultrasonic measurements, and perform a detailed system characterization. We then use the system to do PAT of tissue phantoms and human tissue. By demonstrating the basic 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. Moreover, reading out these sensors via wavefront shaping represents a new application of this complex photonics technique, with some interesting challenges and properties to discuss.

Zihao Lu

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Chiroptical composite material made of disordered ensembles of plasmonic nanoparticles embedded in helicoidal chitin-nanocrystal films

with Thomas G. Parton, James A. Dolan, Aurimas Narkevicius, Heather Greer, Kevin Vynck & Silvia Vignolini

Understanding chiral light-matter interaction is of great importance in many disciplines of natural science. In recent years, extensive interest has been attracted to engineering plasmonic nanostructures for strong artificial chiroptical properties, due to promising applications such as polarization control, negative-index materials and chiral sensing. However, the current design and realization of artificial optical activity rely intensively on the precise control over the geometry of nanoscale materials, which fundamentally limits their preparation at greater scales and in solid-state. Here, we demonstrate that disordered ensembles of achiral plasmonic nanoparticles can be optically active, and thereby impart well-defined circular dichroism (CD) to centimetre-scale composite films. Furthermore, our preparation methods, inspired by silver mirror reaction, utilizes the chiral nematic liquid crystalline behaviour of chitin nanocrystals, and features a simple wet-chemistry pathway that facilitates large-area fabrication of such materials.

Ulysse Najar

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Non-invasive and Passive Measurement of an Optical Transmission Matrix Deep Inside a Scattering Medium

with Victor Barolle, Paul Balondrade, Laura A. Cobus, Kristina Irsch, A. Claude Boccara, Mathias Fink & Alexandre Aubry

As light travels through a disordered medium, it undergoes scattering events, due to spatial variations of the refractive index. Large-scale variations of the refractive index induce distortions of the propagating wavefront, known as aberrations. Small-scale variations of the refractive index cause multiple scattering of light. These effects strongly hinder optical microscopy, as they cause a degradation of contrast, resolution and brightness in the image. However, the information contained in the distorted wave field is not lost; only scrambled. Unscrambling it opens up the possibility of refocusing light inside the medium, at any given depth. Inspired by previous works in acoustics, we present a matrix approach of reflective 3D optical microscopy, to get an access to this hidden information. We perform passive measurements of the impulse responses between the focal points in a field of view deep inside a scattering sample, using an experimental set-up based on full-field optical tomography (a low-coherence interferometry technique which allows for transverse cross-sectional imaging). From these measurements, we extract the distorted components of the back-scattered wavefronts, associated with every point in the focal plane. Their analysis leads to an estimation of the local aberration phase laws, associated with each elementary cell in the field of view. These local laws are stored in a 'transmission matrix'. This matrix is then used to locally compensate for the aberrations, thus enhancing the image's resolution and contrast, beyond the usual isoplanatic limit of adaptive optics. Applying this method to the 3D imaging of a 350-µm thick opaque cornea, we dramatically enhance the penetration length inside the sample by a factor 4, as if the whole cornea had been made transparent.

Alfonso Nardi

ETH Zurich, Switzerland

Controlling spatial coherence with an optical complex medium

with Massimiliano Rossi, Felix Tebbenjohanns, Shawn Divitt, Andreas Norrman, Sylvain Gigan, Martin Frimmer & Lukas Novotny

Spatial coherence deals with the correlations between optical fields at different points in space. Several methods have been proposed to control the spatial coherence, all of which are limited to slow modulation speed or to a single pair of optical fields. While some of the existing approaches rely on complex media and others on wavefront shaping devices, until now there was no method that combines the two technologies to overcome the aforementioned limitations.

Only recently, we reported a new method of controlling the spatial coherence based on an optical linear port, realized using a combination of a spatial light modulator (SLM) and a complex medium. With this approach, it is possible to control in a single-shot fashion the mutual correlations between an arbitrary number of optical beams.

We have experimentally demonstrated the control of the mutual correlations (or mutual degrees of coherence) in the case of three spatially separated beams. We have shown that any combination of degrees of coherence can be achieved, within an average relative error of 1%.

Our work adds an important tool to the techniques available in optical engineering. In particular, the obtained control allows using the degree of coherence as a physical carrier for logic bits. This results in a novel coding scheme for optical communications, that would lead to an advantageous quadratic scaling of the number of encoded data symbols with the number of transmitted fields.

Guillaume Noetinger

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Rotating dynamic structured illumination

with Sébastien Popoff, Mathias Fink & Fabrice Lemoult

Diffraction limits the observation of objects small compared to the wavelength. In this work we combine the use of wavefront shaping and time as a new degree of freedom into a new approach of structured illumination [1] namely dynamic structured illumination.

Compared to a standard confocal microscope we add a DMD (Digital Micromirror Device) on the illumination path in the Fourier plane of the sample as a wavefront shaper to spatiotemporally modulate the illumination. The additional degrees of freedom provided allow to enhance the space-bandwidth product of the confocal microscope similarly to ptychographic imaging [2]. The illumination is chosen to be a pattern rotating with respect to the optical axis so that a periodic modulated signal is measured by the photodiode for each point of the sample instead of a single scalar. On a Fourier point of view such a periodic temporal modulation consists in a frequency comb, each frequency corresponds to its own Point Spread Function (PSF). As a result multiple images of the same object with different PSFs are obtained at the same time. A powerful feature is that we can extract different spatial frequencies of the observed sample including higher frequencies than the diffraction limit, the maximum frequency being two times higher similarly to tomographic imaging [3].

We provide an experimental proof of concept of this approach. Preliminary results demonstrate its ability to enhance the signal-to-noise ratio of confocal imaging and to recover images with a better resolution than a confocal microscope.

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Spectral Control of Random Lasers

with Wai Kit Ng, Alexis Arnaudon, Dhruv Saxena, Andrea Camposeo, Dario Pisignano, Mauricio Barahona & Riccardo Sapienza

We show both theoretically and experimentally that random lasing spectra of network lasers can be finely controlled by non-uniform pumping, and driven by machine learning.

Unlike conventional lasers with a gain medium in a cavity, random lasers employ multiple scattering in an active medium to amplify light. Random lasers can emit at multiple wavelengths due to multimode scattering. Although random lasers are more robust and easier to fabricate, controlling the lasing mode frequencies is difficult, preventing their adoption in technologies requiring fine spectral control. Network lasers are a novel random lasing platform permitting more control over the geometry of multiple scattering [1]. Light is amplified as it passes through random paths in active waveguides connected in the form of a network. Although with network theory and scattering matrix models describe the passive modes of network lasers, they fail at describing crucial nonlinear effects involved in lasing.

We develop a theoretical formalism combining steady-state ab-initio laser theory (SALT) with network theory to model mode competition and nonlinear phenomena in network lasers [2]. We show that the complexity of the network can be harnessed to achieve precise spectral control over emission, making it possible to select dozens of lasing modes for exclusive lasing. We demonstrate this effect experimentally by achieving selective lasing in polymer networks by tailored non-uniform pumping. Further, we utilise machine learning on experimentally measured lasing spectra from random lasers to identify pump profiles for exciting specific lasing modes. We show that after training, arbitrary combinations of lasing modes can be generated efficiently, providing fine spectral control. Machine learning-based pump selection in random lasers can pave the way for light sources with fast multiwavelength spectral switching.

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Rabisankar Samanta

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Intensity-dependent speckle decorrelation in fundamental and second-harmonic light scattered from nonlinear disorder

with Romain Pierrat, Rémi Carminati & Sushil Mujumdar

When coherent light propagates through a scattering medium, a speckle pattern emerges due to the interference effect. Although a speckle pattern is composed of random dark and bright spots, it carries a lot of information. Disordered medium with second-order nonlinearity simultaneously generates speckle patterns of both the fundamental and second-harmonic light. Here, we explore speckle decorrelation in the fundamental and second-harmonic transmitted light while changing the power of the fundamental beam. We experimentally observe that speckle shows strong spatial correlations at low input power. As the input power increases, speckle correlations for both harmonics start to decrease and become nearly zero beyond a certain power value. Interestingly, fundamental speckles are found more correlated than the second-harmonic speckles irrespective of the input power. Next, we build a theoretical model that accurately depicts the harmony between second-order nonlinearity and light diffusion. The model differentiates the contribution of two components in the decorrelation. One of them arises from the generation of second-harmonic light while the other one is from the propagation. Our study sheds light on the exquisite mechanism of fundamental and second-harmonic light in a nonlinear disordered medium.

Christina Sharp

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Navigating light through moving scattering media

with Chaitanya Mididoddi, Simon AR Horsley & David B Phillips

The scattering of light was once thought to fundamentally limit imaging through opaque samples, as transmitted light becomes spatially scrambled. However, scattering effects can be captured by measurement of the Transmission Matrix (TM) - a linear matrix operator mathematically encapsulating how incident fields will interact with the scatterer and be transformed into new fields on the other side of the medium. Knowledge a scattering sample's TM enables scrambling to be reversed, and imaging through or inside opaque media becomes possible. Despite these successes, this approach generally requires that the scattering medium remains completely static while the TM is measured and applied. Spatial control of light propagating through dynamic scattering systems remains a very challenging open problem.

In this work we study light control through a new class of scattering media: partially moving scattering systems, which possess time-varying local regions embedded at unknown locations throughout a static matrix. This situation describes, for example, tissue in which small capillaries conducting blood flow represent faster moving regions surrounded by a matrix of static tissue. We explore several strategies to identify light fields that propagate through these types of samples while avoiding the moving regions. These methods rely only on external camera measurements recording scattered light and are independent of the rate at which dynamic regions move. We present both theoretical and experimental results demonstrating the navigation of light around moving parts of a scattering medium. Our work adds to the toolbox of techniques to control light in highly scattering environments.

Isam Ben Soltane

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Shaping the response of an optical system through its singularities and zeros: Study case of two interacting Fabry-Perot cavities

with Rémi Colom, Brian Stout & Nicolas Bonod

Light-matter interaction problems often aim at studying the response of an optical system to an excitation field to produce an output or scattered field. In the case of linear systems, that interaction can be fully described in the harmonic domain by the transfer function. A lot of effort has been put in the characterization of optical transfer functions via their singularities (associated with resonant states) as well as their zeros, both of which are complex frequencies. More specifically, singularity factorizations and expansions have been a topic of growing interest as they provide a clearer description of phase-shifting and amplitude-scaling properties from these complex frequencies. Various phenomena, such as perfect absorption, zero-scattering, or even exceptional points, can be explained by the study of the zeros and singularities. Several applications may thus arise from the control of their positions and trajectory in the complex plane. We consider the specific case of two interacting Fabry-Perot cavities. We derive accurate expressions of the temporal response of the system, showcasing the role of the singularities in the transient regime in particular. In the harmonic domain, we show that the coupling between the two cavities result in controllable zeros and singularities which are different from those of each cavity, and that the fields reflected and transmitted by the complete system can be fully described by these coupling frequencies. Finally, we introduce the case of multiple-order singularities which can be obtained with more complex materials.

María Blanco de Paz

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Exploring subradiant optical modes in quantum metasurfaces

with Alejandro González-Tudela & Paloma Arroyo Huidobro

Optical metasurfaces have made possible to realise unusual electromagnetic responses that are not available with natural materials. The possibility of merging the concept of metasurfaces with the use of quantum emitters gives rise to a new class of metasurfaces: quantum metasurfaces. These consist of ordered arrays of single photon emitters, whose properties enable new regimes of light-matter interactions.

We propose quantum metasurfaces based on periodic arrays of quantum emitters with more than one emitter per unit cell. We study the optical response of these arrays considering subwavelength periodicity, that is, with lattice constant smaller than the transition wavelength of the emitters. In this scenario, coherent dipole-dipole interactions between all the quantum emitters of the lattice result in collective cooperative effects that lead to drastic changes in the optical properties depending on the lattice parameters. An important instance of cooperative effects are sub-radiant optical states whose coupling to the photonic environment is greatly reduced compared with that of isolated emitters. Introducing more than one emitter per unit cell provides new ways to tune subradiant states. On one hand, we consider a square bipartite array with two quantum emitters per unit cell whose resonance frequencies are slightly detuned. The small detuning between the emitters allows the emergence of subradiant collective states under an incident plane wave excitation. These are modes of very high quality factor that are dark for standard, more symmetric lattices. On the other hand, we explore the effect of introducing uniaxial anisotropy in a subwavelenght honeycomb lattice. The symmetry breaking introduced by the lattice anisotropy enables the emergence of different generalised Dirac dispersions, such as semi-Dirac or tilted Dirac cones, which provide novel forms of light-matter interactions like long range photon- mediated coupling between probe emitters.

Tobias Bucher

Friedrich Schiller University Jena, Germany

On the nature of chiral dipole emission from monolayer molybdenum disulfide

with Mostafa Abasifard, Rajeshkumar Mupparapu, Emad Najafidehaghani, Heiko Knopf, Marijn Rikers, Antony George, Falk Eilenberger, Thomas Pertsch, Andrey Turchanin & Isabelle Staude

We experimentally investigate the nature of chiral dipole emission from monolayer molybdenum disulfide (1L-MoS2) by polarization resolved emission spectroscopy and imaging at 4 K. Chiral emitters are commonly modelled by a rotating electric dipole using full-wave simulations [1,2]. The model assumes two crossed electric dipoles with a $\pm\pi/2$ phase shift in analogy to a circularly polarized plane wave. However, the localized nature of the emitter results in an achiral symmetry with non-uniform farfield helicity with respect to the full solid emission angle. Alternatively, a truly chiral dipole emitter was proposed [3] as a collinear superposition of an electric and magnetic dipole with a $\pm\pi/2$ phase shift. The introduction of the magnetic dipole will majorly impact the multipolar coupling of the chiral dipole as compared to the spinning dipole when integrated with Mie-type resonant nanostructures.

In this work, we conducted the following experiment to probe the nature of chiral dipole emission from 1L-MoS2. We dispersed gold nanoparticles (NPs) on 1L-MoS2 where their size was chosen to match the electric dipolar resonance with the spectral emission band of 1L-MoS2. Upon circularly polarized pumping, we observed an emission helicity of up to 0.65 for bare 1L-MoS2 whereas for positions of individual NPs atop the 1L-MoS2 the helicity is consistently reduced to ~0.15. We address this polarization quenching to the selective multipolar coupling with the electric dipolar resonance of the NPs. This finding is fully consistent with the chiral dipole model whereas the rotating dipole model would predict a conservation of the farfield helicity. Our work will help to accurately model chiral emission from 2D materials using electromagnetic solvers - a crucial step in the design of future nanophotonic and valleytronic devices.

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Spatiotemporal Pump Probe Spectroscopy of Light Scattering in Complex Disordered Media

with Idris Ajia & Otto Muskens

Mesoscopic disordered media continue to be the focus of a variety of research areas, from fundamental physics through to photovoltaics and random lasing. Pump Probe spectroscopy is a powerful tool for investigating light scattering at a fundamental level in complex media. Using this technique in extreme scattering environments, where the transport mean free path is sufficiently short, it is possible to observe the diffusion characteristics of light inside the sample over many scattering events. The pump probe response can be resolved temporally to show light propagation through the sample, as well as providing a spatial mapping of light diffusion across the sample. Using this method, it is possible to determine valuable parameters experimentally, such as the diffusion constant D and the transport mean free path lt. We then combine these results with: Coherent Backscatter spectroscopy, total transmission and total reflection measurements; which show good agreement. Carrying this technique forward will enable us to directly probe the dynamics of light as we approach the sub-diffusive regime with more strongly scattering samples.

Unė Būtaitė

University of Exeter, UK

Enhancing optical trapping using wavefront shaping

with Michael Horodynski, Christina Sharp, Graham Gibson, Stefan Rotter, David Phillips & Jonathan Taylor

With their ability to manipulate micro-particles with just a touch of light, optical tweezers have fascinated the science world for nearly 40 years now – both as a research subject and as a tool employed in a range of fields from biology and materials science to statistical and quantum physics. The go-to optical trap is the humble Gaussian beam which, if tightly focused, is capable of confining micro-sized objects to remain close to the beam focus. However, optical momentum is most efficiently transferred to a particle when light is concentrated near its edges. This condition is far from being met in cases where the size of the particle exceeds the size of the Gaussian focus – meaning that we can improve upon the shape of the trapping beam. Specifically, in this work we tailor light fields with the intent of enhancing the 3-dimensional trapping stiffness - a measure of how tightly an optical trap holds a particle in place. We have developed a fast trap optimisation framework to compute optimum trap shapes in just a few seconds. We use interior point optimisation formulated using Generalised Lorenz-Mie Theory and the Generalised Wigner-Smith operator, which also accounts for multiple scattering within the particle itself. Our optimiser starts with a particle sitting at the focus of a Gaussian beam – for example a microsphere of known radius and refractive index. The beam profile is then iteratively altered while keeping track of the trapping stiffness, making sure that it increases from one iteration to the next. After a few iterations, our optimiser converges to a solution light field that fits the particle like a glove – enhancing the trapping stiffness by up to 60 times compared to a Gaussian beam of the same power. We have explored how the enhancement varies as a function of particle size and material, and we are currently working on testing the performance of our optimised traps in experiments.

Niall Byrnes

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Polarised Light Scattering in Disordered Media: A Random Matrix Model

with Matthew R. Foreman

The random scattering of light in complex media is detrimental to information transfer in a variety of scenarios, such as astronomy, remote sensing, and biomedical imaging. When coherent light passes through a disordered medium, the scattered field is typically depolarized and exhibits a spatially random speckle pattern. In recent years, techniques that harness multiply scattered light, such as exploiting the optical memory effect, have enabled imaging through random media beyond the ballistic regime. In addition, spatial light modulators, which allow for the determination of transmission and reflection matrices, have enabled focusing through ordinarily opaque media. These matrices are blocks of the scattering matrix, which encodes a medium's complex, yet deterministic response to arbitrary incident illumination. Random matrix theory, in which the scattering matrix is randomly sampled from a matrix ensemble, has proven to be fruitful at uncovering universal properties of disordered systems, such as the existence of highly transmitting 'open eigenchannels' in optically thick media. Many random matrix models, however, neglect the vectorial properties of light and are thus unable to account for polarization-specific phenomena, such as the polarization memory effect for circularly polarized light. We have addressed this problem by developing a numerical method for generating vector scattering matrices for random media with slab geometry of arbitrary thickness. We adopt a perturbative approach based on a cascade of transfer matrices. Our method employs a complex, multivariate Gaussian distribution whose statistics can be determined by the properties of the scatterers in the medium. We demonstrate some results for different types of scatterers, including isotropic and chiral spheres, and discuss possible extensions and applications.

Sing Teng Chua

University of Cambridge, UK

Light transmission within immobilized culture of microalgae

with Daniel Wangpraseurt & Silvia Vignolini

With growing commercial interest in the mass cultivation of microalgae, immobilised culture has emerged as a viable technique addressing some challenges posed by conventional suspension cultures. Research has focused on studying immobilisation photobioreactor from a bulk analysis approach, however, with little attention has been paid to natural formation of algal aggregates within the encapsulating matrices. Light transport efficiency is vital in a photobioreactor where self-shading of microalgae could deprive the cells underneath of sufficient light for photosynthetic activities. Here, we perform optical characterisation of individual algal cells and cell clusters. Using Monte Carlo simulations, we study the resultant light intensity profile in the encapsulated microalgal cultivations. In agreement with Mie scattering theory as well as experimental validation, the overall light attenuation within the culture volume is alleviated with larger cell clusters as the extinction efficiency is inversely related to the particle size. Overall, this study has important implications for the engineering of novel photobioreactors and designing microalgae-based photosynthetic living materials.

Ming Fu

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Directional surface enhanced Raman scattering coupled into plasmonic waveguide with near unity β factor

with Mónica P. dS. P. Mota, Xiaofei Xiao, Andrea Jacassi, Nicholas A. Güsken, Yi Li, Ahad Riaz, Stefan A. Maier & Rupert F. Oulton

To enhance the Raman scattering efficiency of photons by molecules, various techniques relying on either stimulated or surface enhanced Raman scattering (SERS) have been developed. But they are either limited by the poor control of scattered light, narrow bandwidth of resonance frequency, or restricted area of field enhancement. Here we present a unique waveguide approach to achieve broadband enhanced Raman scattering of molecules with precisely controlled propagation direction. We demonstrated 99% of the Raman photons can be coupled into the waveguide.

In this talk, we report directional broadband Raman scattering of light by molecules which are chemically coated onto plasmonic slot waveguide. The waveguides are decorated with optical antennas that allow light to couple in and out of the waveguide with 30% efficiency. We have been able to spatially resolve the coupling in of the excitation laser and coupling out of Raman scattering. This enables us to precisely investigate how the scattered Raman photons of molecules couple into the waveguide, propagate and couple out via the antennas. We have experimentally determined the fraction of spontaneous Raman scattering coupled into a plasmonic waveguide (β factor), for the first time. The near-unity Raman β factor is due to the largely enhanced spontaneous Raman scattering rate into the waveguide mode. The enhancement mechanism can be understood analogously to fluorescence emission enhanced by the Purcell effect, which is due to increased vacuum fluctuations and increased density of states. While Raman scattering in highly localised metallic hotspots offers high enhancement factors for a few molecules, here, a plasmonic waveguide offers predictable broadband enhancement for many molecules with a greatly improved interaction volume compared to other SERS approaches.The ability of waveguide-SERS to direct Raman scattering is relevant to Raman sensors based on integrated photonics with applications in gas and bio-sensing.

James Guggenheim

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Ultrasensitive photoacoustic wavefront shaping

with Maxim N Cherkashin, Thomas J Allen, Benjamin Keenlyside, Edward Z Zhang & Paul C Beard

Guidestar assisted wavefront shaping offers the prospect of focussing light in strongly scattering media like biological tissue. This could revolutionise biomedical optics by allowing high-resolution optical imaging and therapy at unprecedented depths. The fundamental idea is to optimally structure an incident light field so as to produce a high intensity focus at a target location in or through tissue. To realise this, the optimisation of the field is driven by evaluating the strength of a feedback signal, called a “guidestar”, which measures the light intensity at the target location. For focussing light in tissue, promising candidate guidestars include photoacoustic signals. Photoacoustic signals are ultrasound waves generated by the absorption of pulsed light in tissue, which can be detected at the tissue surface. Several compelling demonstrations of photoacoustic wavefront shaping have been made to date. However, photoacoustic wavefront shaping is challenging and most demonstrations provided relatively weak foci through relatively thin scattering media. Producing stronger foci at greater depths presents a number of challenges. One is detecting photoacoustic signals with higher sensitivity to allow detecting signals from greater depths and manipulating more optical modes. A second challenge is getting around the fact most photoacoustics compatible laser sources have short coherence lengths, limiting the maximum penetration depth of wavefront shaping. To address these challenges, we present a new photoacoustic wavefront shaping system featuring a long coherence length pulsed laser and an ultrasensitive optical ultrasound sensor. We discuss this system and investigate its capabilities in terms of the focussing power (enhancement), penetration depth and other characteristics. By pushing the limits of photoacoustic wavefront shaping, this work could pave the way to expanding the capabilities of various biomedical optics techniques using wavefront shaping.

Fei He

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Transfering ultra-thin metallic metasurfaces onto fibre endoscope probes for advanced imaging

with Rafael Fuentes-Dominguez, Richard Cousins, Christopher J. Mellor & George S. D. Gordon

Imaging through hair-thin optical fibers has opened up new paradigms for biomedical imaging. The state-of-art of this technology typically requires accurate fiber transmission matrix (TM) characterisations, which is inevitably sensitive to the live environment. Gordon et al. proposed a method to characterise nonunitary fiber TMs without access to the distal facet meanwhile maintaining the hair-thin property of the fiber, which is by introducing a multi-layer stack of partially reflecting metasurfaces onto the fiber facet. However, the conventional top-down fabrication of metasurfaces on millimeter-sized bulk substrates is not technologically compatible with fiber optics platform. Despite substantial investigations on possible metasurface-to-fiber transfers, these methods are not well-suited to flexibly transfer multi-layer stacks of custom-designed patterns onto fiber tips. Such designs are necessary to unlock the full range of possible fiber imaging devices.

In this summer camp, I present a method to fabricate and transfer ultra-thin polymer-encapsulated metallic metasurfaces onto the tips of optical fibers. This method can be easily scaled up to fabricate multi-layer metasurface stacks. The fabrication process involves conventional e-beam lithography process to define metasurfaces on a silicon substrate and encapsulation of the metasurfaces by a photo-resist layer. After align-patterning the resist layer to disk shapes, the encapsulated metasurfaces are peeled off from the substrate and glued onto the fiber tips. As proof-of principle demonstrations, I will further present the measurement results of Fresnel zone plates and wiregrid polarizers at the tips of single- and multi-mode fibers.

Saba Nashreen Khan

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High Sensitivity Speckle Metrology with Integrating Spheres

with Morgan Facchin, Kishan Dholakia & Graham D Bruce

Integrating spheres as a tool to generate highly sensitive optical probes has been overlooked in the past. The multiple reflections of light inside an integrating sphere produce highly sensitive speckle patterns with an intensity distribution close to a Gamma distribution with shape parameter 2. The growing developments in Nanophotonics demand highly sensitive, accurate, and robust measurement schemes that can be reasonably met by speckle metrology with an integrating sphere. Recently, we reported that the speckle produced from a typical integrating sphere is four orders of magnitude more sensitive to wavelength changes [J. Phys. Photonics 3, 035005, 2021] than equivalent multimode fiber-based speckle, with attometre-level precision already demonstrated [Nat. Commun. 8, 15610, 2017; Laser Photonics Rev. 14, 2000120, 2020]. Integrating spheres as probes offer an additional advantage of being more robust to mechanical perturbations, as they are monolithic with no moving parts, which can be difficult to ensure using fibres. Notably, the sensitivity of the generated speckle patterns depends only upon the reflectivity and radius of the integrating sphere. The broad distribution of optical path lengths in the sphere also allows sensitive probing of the refractive index of encapsulated gases at a level of one part in 10^9 [ACS Photonics 9, 830−836, 2022], an improvement of three orders of magnitude compared to other speckle-based methods. Finally, a concatenated geometry comprising two identical hemispheres can probe displacements of one hemisphere with an uncertainty of tens of picometres (i.e., λ/20000) [arXiv:2110.15939v1, 2021]. All the above measurements are based on an evaluation of the speckle similarity parameter that we relate to the measurand (wavelength/refractive index/displacement) following our developed analytical model.

John Kilpatrick

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Guide-star assisted imaging through multimode optical fibres

with Shuhui Li & David B. Phillips

Endoscopes are a tool used to look deep inside the body. Traditionally, they have a large inherent diameter (~ a few mm), making them an invasive option for imaging. Building an endoscopic system out of a multimode optical fibre (MMF) provides a way to minimise their footprint to a fraction of a mm across. Imaging through a MMF requires knowledge of its optical transmission matrix (TM) – an operator that characterises the way the fibre scrambles light fields that propagate through it. Measurement of the TM typically requires access to both ends of the fibre, and is highly sensitive to fibre configuration, limiting its practical applications to endoscopy.

It has recently been shown that if a ‘guide star’ is placed on the distal end of the fibre, then the TM can be estimated with only optical access to the other end [1]. A guide star relays the local intensity incident on it to the other end of the fibre, allowing for the measurement of the optimal input field to create a focus on the guide-star. By using priors about the fibre, we can then image across a region around the guide-star (determining the field-of-view) with an approximate transmission matrix (ATM). However, the field-of-view is limited by the our levels of prior knowledge in this approach - and would be enlarged if we were able to gather information from more than just a single point at the distal facet.

In this work, we explore computational techniques to expand the field-of view by considering how to best extract information from multiple guide-stars or directly from the scene itself. Our work takes a step towards real-time imaging through flexible MMFs.

[1] S. Li, S.A.R. Horsley, T. Tyc, T. Čižmár & D.B. Phillips (2021). Memory effect assisted imaging through multimode optical fibres. Nature Communications, 12(1), 1-13.

Hlib Kupianskyi

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High-dimensional spatial mode sorting

with Unė G. Būtaitė, Simon A.R. Horsley & David B. Phillips

Monochromatic light fields can be decomposed into sets of orthogonal spatial modes, which constitutes a change of the basis in which the light field is represented. In this work we design and build prototype devices that can physically perform these basis transformation operations on incident light fields. Such optical mode sorters can passively redirect incident photons into separate output channels based on their spatial state. In general, mode sorters require a complicated three-dimensional structure to efficiently scatter photons in the desired manner. We achieve this by building on recent advances in multi-plane light converter (MPLC) technology that uses a series of 2-D diffractive planes separated by free-space. New optimisation techniques are developed to design a variety of optical mode sorters of increasing complexity, including those acting on the Bessel basis, Zernike basis, and - most generally - arbitrary randomly generated ‘speckle' mode bases. We experimentally demonstrate prototype MPLCs capable of sorting up to 55 spatial modes using up to 5 reflections on spatial light modulators. We also describe the design of a mode sorter capable of efficiently sorting up to 400 step-index fibre modes, and show how it enables single-shot wide-field incoherent imaging through multimode optical fibres. Our work offers promise in a variety of fields including seeing through scattering media, super-resolution imaging, high-capacity optical communications and quantum computing.

Marciano Palma do Carmo

King's College London, UK

Plasmon-Driven Ratchetting of Nanoparticles in Aqueous Solutions

with David Mack, Diane J. Roth, Steve Po, Miao Zhao, Stefan A. Maier, Paloma A. Huidobro & Aliaksandra Rakovich

Manipulation and trapping of submicron-sized particles has applications in multiple fields, including biology and soft-condensed matter physics. Despite being used for this purpose, optical twezers not only lack scalability as they also provide trapping sizes significantly limited by diffraction. Nanostructures made of plasmonic materials have the ability to concentrate energy to very small dimensions and therefore can act as traps for nanometer-size objects, providing large field enhancements and thus avoiding the need to use large input powers. Nonetheless, and while providing such advantages, these techniques lack the ability to control the motion of the trapped objects over long distances.

For this reason, in this work we present a Brownian ratchet capable of driving subwavelength particles over long distances. Using COMSOL Multiphysics we model the geometries of these plasmonic ratchets, calculate their respective electric fields and also the optical forces experienced by the nanoparticles, which were afterwards processed with MATLAB®. In addition, the rectification of the random thermal motion of different types of particles into one particular direction was experimentally demonstrated by periodically turning on and off a laser beam that illuminates the plasmonic array of nanostructures and exploiting the asymmetries in the system.

Dean Patient

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Controlling Reflection at grazing incidence

with Simon A. R. Horsley

Electromagnetic waves approaching an interface at grazing incidence will almost always reflect. Examples of this can be found in simple situations such as the Fresnel coefficients which describe the reflection between two infinite media. More complex examples can include graded index structures of finite thickness. This residual reflection can manifest as unwanted features in various circumstances. For radar absorbers, these shallow angled waves can induce a large, scattered field, which in turn increases the radar cross section. Artificially made structures also exhibit this reflection at grazing: Perfectly Matched Layers (PMLs) are a material used in numerical simulations to absorb any waves near the simulation boundary, to remove the effects of said boundary. These PMLs work as a form of co-ordinate transform and are designed such that the reflection of a plane wave through a PML next to a mirror will be zero. This is true for angles approaching grazing, however as the angle tends to the limit of grazing, non-zero reflection can occur. It is clear that being able to control reflection in this limit is important. In our work, we use the equivalence between quantum mechanics and optics (where the energy of a particle is proportional to the cosine squared of the angle of incidence of a wave) to design materials that do not reflect grazing incidence waves. In Quantum Mechanics, there exist so-called half-bound states, which are states of a quantum system that are bound to the confines of the potential, but decay to non-zero constants outside if the particle has zero energy. In optics, we can design structures that support analogues of these half-bound states for grazing incidence waves using quantum frameworks to factorise the Helmholtz equation. In this way, we design a class of dielectric profiles that will necessarily not reflect grazing incidence waves.

Jonathan Pinnell

University of Cambridge, UK

Manipulation of nanoparticles in hollow-core photonic crystal fibres using structured light

with Ralf Mouthaan, Natalie Wheeler, Marlous Kamp & Tijmen Euser

Hollow-core photonic crystal fibres (HC-PCFs) offer a unique environment for studying a variety of opto-fluidic phenomena. The tight confinement and low loss of light within their microscopic cores (where an analyte can be flowed) facilitates a greatly enhanced light-matter interaction compared to cuvette. Such an enhanced interaction has been exploited in the past to achieve novel particle manipulation along the length of the fibre. What is relatively unexplored, however, is the use of higher-order (structured) fibre modes which should improve the versatility of existing techniques. Here, we present preliminary findings that tailoring light within the core of HC-PCFs allows more complex optical nano-manipulation to be achieved, which, for example, may foster applications in gas sensing.

Luis Alberto Razo López

Institut de Physique de Nice, CNRS, France

Localization landscapes for tight-binding lattices

with G. J. Aubry, M. Filoche & F. Mortessagne

We theoretically and numerically investigate 1D and 2D tight-binding lattices with diagonal disorder through the prism of the Localization landscape theory. We extend the dual landscape concept, that gives high energy localized states, to all type of lattices, showing the crucial role played by the symmetry of the dispersion reaction with respect to E=0. Finally, we show that the extrema of the landscape and its dual are proportional to the eigenvalues of the original tight-binding Hamiltonians, the proportionally depends on the strength of the disorder.

Sudhir Kumar Saini

University of Twente, The Netherlands

Fabrication of dielectric mirror-symmetric scattering media using direct laser writing

with Kayleigh M.E. Start & Pepijn W.H. Pinkse

High precision fabrication of predetermined disordered scattering media opens up the potential for controlled light scattering applications. The latest advancement in direct laser writing fabrication technology enables the exact synthesis of designed three-dimensional (3D) disordered scattering structures with a minimum feature size and accuracy of better than ~200 nm. Hence, it is possible to create scattering media with features on the scale of the optical wavelength. Here we study the effect on light propagation of mirror-symmetric disorder in a multiple-scattering medium. A commercial direct laser writing technique based on two-photon polymerization is used to synthesize the mirror-symmetric disordered samples. Light transport experiments combined with quantitative 3D modeling are used to study the effect of mirror symmetry on the media's scattering properties. The samples are optically characterized using LED and laser light. The results establish the symmetry plane deviation from the bulk speckle-averaged intensity distribution. Further, to validate our experimental results, finite-difference time-domain and modified-Born-series methods are employed to numerically investigate the effect of mirror symmetry on the light scattering properties of a dielectric multiple scattering medium. Applications of such designed mirror-symmetric scattering media are envisioned in fundamental light propagation studies and anti-counterfeiting products.

Falko Schmidt

Friedrich Schiller University Jena, Germany

A monolithic nanophotonic system based on single-photon emitters

with Purujit Chauhan, Malte Plidschun, Markus Schmidt & Falk Eilenberger

The second wave of quantum technologies is in full swing and promises application-driven solutions in quantum communication, sensing, and microscopy. Compact nanophotonic systems are a key pillar of this technology where, in particular, 2D materials are ideally suited as single-photon sources. Despite the immense scientific progress in the last decade, transferring such systems into real-world applications is still hindered by the complexity and low adaptability of bulky instruments or the requirement of cryostat environments.

Here, we focus on the development of monolithic nanophotonic solutions that integrate hBN nanoflakes, a room-temperature single photon emitter, directly into a single-mode optical fibre. We show that large coupling efficiencies can be achieved thanks to a high-NA lens printed directly on the fibre's end by two-photon polymerization. In this configuration, hBN nanoflakes can be optically trapped inside the focal spot of the lens providing self-alignment of the system and thus an alternative, faster solution for integrated photonic systems. We carefully characterize our system for quantum purity and its specific emission spectrum.

Our proposed system provides, both, high portability and compatibility with a multitude of instruments such as employed for quantum communication networks, single-photon microscopy or ultra-sensitive detectors.

Joe Shields

University of Exeter, UK

Amplitude-only spatial light modulation using phase-change materials

with Carlota Ruiz de Galarreta, Harry Penketh, Jacopo Bertolotti & C. David Wright

Full control of the spatio-temporal nature of light would allow for dynamic wavefront shaping and would provide a crucial tool for a range of applications such as imaging through scattering media, optical computation or biomedical diagnostics. Currently, spatial phase control, using spatial light modulators is a relatively mature technology, however amplitude only control is more limited. Technologies used currently, like spatial light modulators and digital micromirror devices are relatively slow, bulky, and volatile. A missing element to enable efficient full wavefront control is that of an amplitude-only modulator that is reliable and fast, and which could be paired with a phase-only modulator enabling full wavefront control.

Here we present the design, fabrication and characterisation of a phase-change material (PCM) based spatial light modulator which, when the PCM is switched from amorphous to crystalline, gives a large amplitude modulation and a near-zero modulation in the phase of light reflected from the device. The PCM GeTe is used here due to its large electro-opitcal contrast at visible wavelengths.

In order to characterise the devices an off-axis digital holography interferometer was designed and built in order to measure the spatial phase variation across regions of the device with both crystalline and amorphous sections. It was found that the amplitude modulation between amorphous and crystalline sections was high $\Delta R(\%) = 220\%$ and the phase variation was minimal $\Delta\phi < \pi/50$ radians (operation wavelength of 632.8 nm).

The results presented here offer a potential route to ultra-fast, low power and compact solid-state amplitude-only spatial light modulation.

Marie-Caroline Solignac

Saint-Gobain Recherche & University of Bordeaux, France

Optical properties of a single layer of metallic nanoparticles in a thin-film stack

with Hervé Montigaud, Iryna Gozhyk, Matteo Balestrieri, Kevin Vynck & Philippe Lalanne

Metallic nanoparticles exhibit localized surface plasmon resonances (LSPR) that result in strong light absorption and near-field intensity enhancement near the resonance frequency. LSPRs strongly depend on the nanoparticle size, shape and composition, as well as on the nanoparticle environment (presence of other particles or interfaces, properties of the surrounding medium) [1]. Industrially, incorporation within the thin film stack of an absorbing layer made of plasmonic nanoparticles can be used to tailor the color of a coating. An example is Saint-Gobain's Natura® mirror, which generates a light reflection in warmer colors than an ordinary mirror.

This work relies on experimental and theoretical approaches in order to improve the understanding of the optical properties of disordered assemblies of metallic nanoparticles embedded in a thin film stack. We fabricate monolayers of randomly distributed silver nanoparticles by magnetron sputtering deposition: we take advantage of the Ag 3D-growth on dielectric to directly obtain nano-islands on the substrate. We investigate (i) the island growth with in situ surface differential reflectivity spectroscopy [2], (ii) the optical properties of the stack (transmission, reflection) with angle and polarization resolved instrumentation and (iii) the embedded islands morphology with an adapted protocol for imaging buried tiny particles (1-10 nm size) with a transmission electron microscope. In order to interpret the experimental results and to understand the role of the electromagnetic interactions at play in this complex nanostructure, we calculate the specular transmission and reflection of the studied system with the numeric GPM method [3]. We compare these results to existing analytical model, which are usually not adapted for dense and disordered nanostructures.

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[2] Grachev S. et al., J. Phys. D: Appl. Phys., 46 (2013)
[3] Bertrand M. et al., J. Opt. Soc. Am. A, 37, 70 (2020)

Adriana Stohn

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Using pseudophase to locate optical vortices in intensity speckle for memory effect imaging

with Michael E. Gehm

The optical Angular Memory Effect enables imaging through thin, complex scattering media, such as biological tissue. The Angular Memory Effect uses correlative properties to expose non-obvious structure in the measured scattered intensity, or optical speckle. An algorithmic reconstruction process can then obtain an approximate image of the object before scattering. Intuitively, we expect that the incorporation of optical phase information into the reconstruction step could enhance the quality of this imaging process. Speckle intensity fields naturally contain topological phase structures such as vortices, and in this presentation I will discuss our work toward identifying phase vortex locations based on speckle intensity measurements via a pseudophase method. I will report on our progress and implications for eventual use in tissue imaging.

Ulle-Linda Talts

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Bottom-up fabrication of nonlinear barium titanate photonic crystals with down to 60 nm critical dimensions

with Viola V. Vogler-Neuling, David Pohl, Helena C. Weigand, Joel Winiger, Juerg Leuthold & Rachel Grange

Non-centrosymmetric metal-oxides such as barium titanate (BTO) are well-known for their advantageous physical properties of high stability, broad transparency window as well as large optical nonlinear coefficient.[1] While the two latter characteristics provide motivation for producing high-speed communication modulators as well as various quantum devices, the chemical inertness results in inherent difficulty of efficient top-down fabrication of BTO-based photonic devices. Solution-processed nanoparticles have been previously combined with cost-effective self-assembling colloidal solutions or imprint lithography to produce photonic crystals [2]. However, the tetragonal crystal phase, responsible for the nonlinear properties in barium titanate, is known to be present in crystals with domain sizes above 30 nm which limits the critical dimensions of densely filled structures from nanoparticles to several hundred nanometers range. Here, we demonstrate a method that enables fabrication of high quality BTO photonic crystals with up to 60 nm critical dimensions with aspect ratios of 10 and refractive index of 2.0 at 600 nm using combination of solution processed BTO sol-gel [3] with soft-nanoimprint lithography (SNIL).

Standard SNIL protocol was followed to imprint nanostructures into a thin film of spin-coated BTO sol-gel. As an example of a challenging structure to fabricate using conventional top-down processing, BTO 2D photonic crystal structures with a L3 cavity were fabricated using SNIL with optimized design based on FDTD simulations. The devices were characterized to showcase the potential of this technique for scalable production of variety of BTO metastructures for improved refractive index modulation efficiencies as well as active nonlinear photonic crystal devices.

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[2] Vogler-Neuling, V. V. et. al Phys. Status Solidi B 2070024 (2020)
[3] Edmondson, B. I. et al, J. Am. Ceram. Soc. 103:1209–1218 (2019)

Laurynas Valantinas

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Artificial neural networks and light wave scattering in disordered media

with Tom Vettenburg

Accurate optical scattering calculations do not always keep pace with experiments. Light propagation in disordered media such as biological tissue has long been considered intractable for all but the smallest problems. Calculations on the scale of biological cells (≈15µm) can take days or even weeks to finish. Yet, numerical analysis, free of experimental noise and losses, is often the only means to explore the chasm between simplified analytical models and experimental evidence. Scattering calculations can provide insights for the study of open and closed channels, inverse optical design, as well as for study of novel light control methods in disordered media. This requires novel numerical approaches.

We show how Maxwell's equations of electrodynamics can be faithfully mapped onto the structure of an artificial neural network. This enabled us to leverage all the machinery of the bourgeoning deep-learning community to accurately solve Maxwell's equations. The calculations fully account for multiple scattering and, unlike most machine learning applications, are provably deterministic. Using Google Colab, a publicly available cloud computing platform, we demonstrate a 100-fold reduction in calculation time. This leap in efficiency enabled us to analyse large loss-less random scattering matrices and propagate waves through arbitrary – millimetre-size – structures in a matter of minutes.

Xiyue (Sissi) Wang

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Scattering matrix model for integrated lithium niobate photonic networks

with Romolo Savo, Andreas Maeder, Fabian Kaufmann, Stefan Rotter, Riccardo Sapienza & Rachel Grange

We develop a scattering matrix-based computational model for integrated photonic devices, specifically for the lithium niobate on insulator platform (following the model for random lasers developed in [1]). This allows us to both study the transport properties between external ports of a device, as well as to visualise the internal field distribution on internal waveguide connections. First, the validity of the model is verified with small resonator devices, where for ring and interferometric resonators the model achieved quantitative and qualitative agreement with physical measurements. It is then applied to scaled up complex random photonic networks, to study the effect of multiple scattering and interference in this discretised 2D setting. Such networks display complex spectra features and strong spectral decorrelation. Furthermore, the electro-optic property of LNOI is exploited to tune the effective geometry of networks, resulting in altered field distribution and transmission spectra. The generalised Wigner-Smith operator [2] method is used to select the tuning edges with the most pronounced effect.

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[2] Focusing inside Disordered Media with the Generalized Wigner-Smith Operator. Philipp Ambichl, Andre Brandstötter, Julian Böhm, Matthias Kühmayer, Ulrich Kuhl, and Stefan Rotter. Phys. Rev. Lett. 119, 033903

Maximilian Weissflog

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A Quasinormal Mode Formalism for SPDC in Nanoresonators

with Sina Saravi, Romain Dezert, Vincent Vinel, Carlo Gigli, Giuseppe Marino, Adrien Borne, Giuseppe Leo, Thomas Pertsch & Frank Setzpfandt

Photon-pairs generated by spontaneous parametric down-conversion (SPDC) are the backbone for various quantum optical technologies. Recently, dielectric nanoresonators with sub-wavelength dimensions have been demonstrated as a new platform for SPDC. The high degree of control over scattered light already demonstrated using nanoresonators in the classical regime, also promise a large potential for generating quantum biphoton states with engineered, spectral, spatial and polarization properties. The highly multimodal and non-Hermitian nature of these nanocavities, however, makes a rigorous description of pair-generation challenging.

Here, we show how to overcome this issue and demonstrate an approach that models pair-generation in nanoresonators by considering just a small number of their natural resonances, the quasinormal modes (QNMs). We employ a Green's function (GF) formalism that can handle SPDC in open and lossy systems and use a QNM expansion of the GF to obtain expressions for the pair-generation rate. Our method gives full access to the emission directionality, spectral properties and density matrix of the polarization state of the generated photon pairs for various SPDC detection schemes. We exemplify the capabilities of our method by taking cylindrical AlGaAs nanoresonators as a model system. While these resonators in principle support many modes, we show that in practice only a small set of eigenmodes efficiently couples to the SPDC excitation field. Therefore, by revealing the underlying modal interactions, our QNM-formalism can effectively reduce the complexity of the nonclassical frequency conversion problem and allows an intuitive understanding of the down-conversion paths. Based on this, we demonstrate how the SPDC detection scheme, nonlinear tensor orientation and pump beam properties can be leveraged to shape the biphoton emission directionality and spectrum as well as the generation of polarization entangled states from AlGaAs nanocylinders.

Ilia Zykov

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Optical Near-Field Electron Microscopy

with Hanieh Jafarian, Peter Kunnas, Raphaël Marchand, Amin Moradi, Guido Stam, Nestor Fabian Lopez Mora, Jaganandha Pandaa, Jan van der Molen, Ruud Tromp, Radek Šachl, Martin Hof, Martin Kalbach, Mariana Manuela Amaro & Thomas Juffmann

The imaging of the dynamical processes on surfaces with nanometric spatial and millisecond temporal precision over extended periods is required for applications in various fields such as biology, plasmonics, or electrochemistry. The microscopy techniques used for that often have limitations since the sample of interest has to be labeled, or it suffers much from the damage caused by the measurement. A new imaging technique called Optical Near-field Electron Microscopy (ONEM) is being developed to overcome these limitations. The brief idea of this technique is that it combines light optics to nondestructively interact with a sample and electron optics to read the result of this interaction with a sub-nanometers resolution at a high frame rate. The light from a laser passes through the optical system to scatter on the sample. The result of this scattering is a field that preserves features of the sample with a nanometer resolution in the near-field. The thin layer of low work function photocathode material is placed within the distance from the sample where the near-field is still present. This layer transforms photons into electrons. Photoelectrons are then read through low-energy electron microscope (LEEM). There are applications that ONEM will be applied in. One of them is the characterisation of plasmonic devices for particle trapping and characterisation. ONEM would make it possible to perform such experiments in a liquid chamber mapping the near-field in high spatial and temporal resolutions. ONEM could also be applied in electrochemistry, studying, the nucleation and growth of nanoscale copper clusters in a liquid environment. ONEM could also be used to image membrane proteins interaction in a native environment.