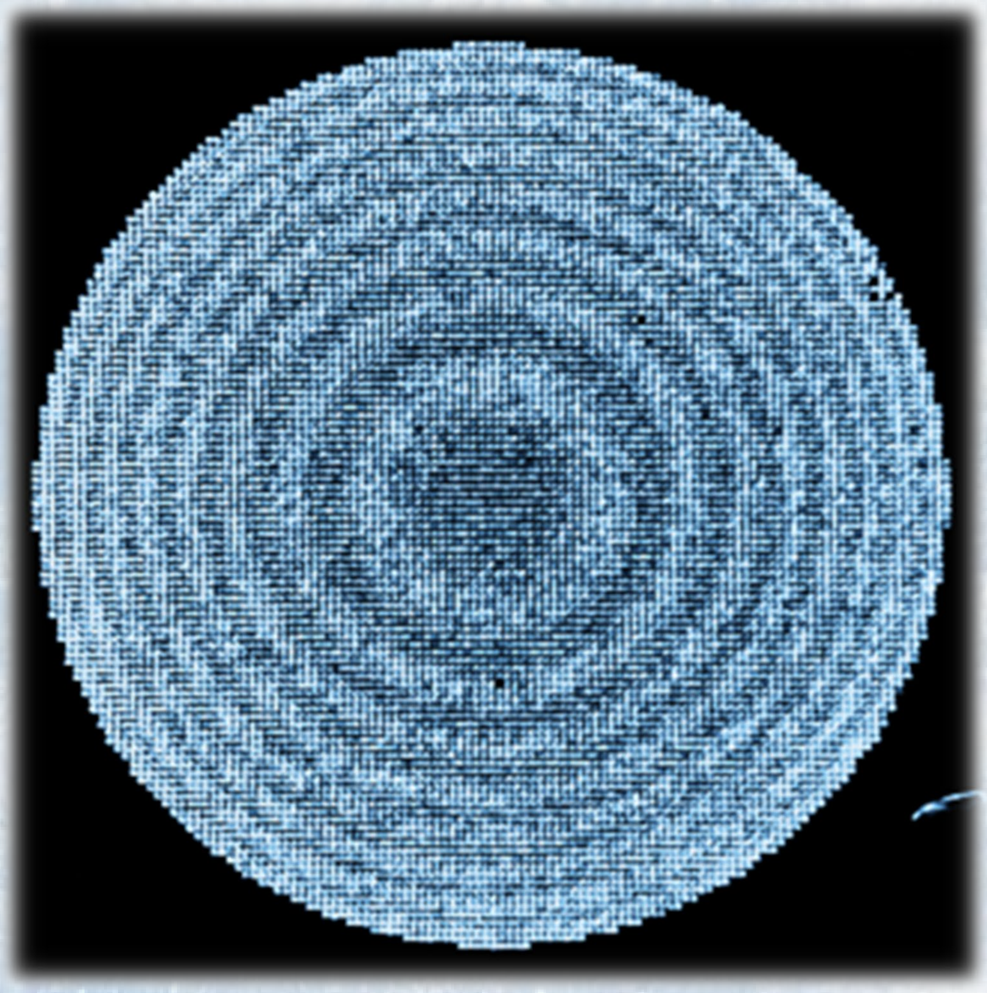

3rd Colloquium on the Physics and Applications of Metasurfaces

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Abstracts

Asymmetric angular transmittance in a metagrating

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Controlling all the degrees of freedom of light is essential for many applications in electromagnetics. Over the last two decades, metasurfaces have paved the way for controlling the polarization and the frequency response of light. Nevertheless, manipulating the angular response of light is still very challenging. Here, we explore the potential of diffractive media for breaking the symmetry of the angular response. In such media, multiple ports for routing the electromagnetic energy are available. Consequently, the angular symmetry of the reflectance could be broken without having to break the time reversal symmetry of the system (reciprocity). In other words, strong angular asymmetry in the transmittance could be achieved in a lossless system. This is in contrast to what is typically done in the literature where the symmetry in the angular reflectance is preserved, and the system is forced to be asymmetrically lossy to obtain angular asymmetry in the transmittance.
In this work, a metagrating is proposed, which can filter the positive (or negative) spatial frequencies of the incident transverse-magnetic (TM) polarized light while passing the negative (or positive) ones. In other words, the metagrating transmits the incident plane waves with negative angles with respect to the grating normal, and it retro-reflects the ones with positive angles. The origin of this angular asymmetry stems from the engineered scattering response of a thin metallic layer deposited on only one side of a triangular-shaped dielectric grating. Based on the generalized sheet transition conditions (GSTCs), a model is also developed to predict the response of the tilted metallic layer in the non-diffractive regime by applying a rotation to the susceptibility tensor of a non-tilted metallic layer.
This triangular-shaped pattern could be fabricated by KOH etching of a silicon wafer with a nitride mask. The thin metallic (gold) layer could then be deposited on this pattern by tilted evaporation. Such a metagrating could find many applications in analog signal processing and imaging. For instance, Schlieren imaging, which is based on filtering half of the momentum space, could be achieved without the need for a large free-space bulky system built from multiple mirrors or lenses.

Nonlocal Angular Invariant Multipolar Metasurfaces

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Typical low-loss optical metasurfaces are nowadays mostly made of dielectric resonators. Due to the low refractive index contrast between these resonators and the background medium, their physical size must be in the order of the wavelength for effectively affecting the light they interact with. This implies that such metasurfaces generally exhibit non-negligible multipolar and associated nonlocal responses, which typically increases their sensitivity to the angle of wave propagation. While this may be advantageous in some situations, e.g., for designing optical spatial filters with specific angular transmission functions, it is usually detrimental to their operation.
In this work, we demonstrate that, counterintuitively, nonlocal interactions may be leveraged to achieve angular invariant scattering. This concept is fundamentally similar to that of the Kerker effect, where equal electric and magnetic dipolar responses lead to full transmission and complete cancelation of backward scattering. In our case, we similarly show that by properly tuning certain

multipolar contributions, and setting others to zero, it is possible to achieve angular invariant transmission or reflection from a metasurface.
Our findings have been obtained using a metasurface model, which was derived based on generalized sheet transition conditions, and that was recently extended to include nonlocal and multipolar contributions. This approach allows us to analytically express the metasurface scattering parameters in terms of corresponding effective material parameters. Based on this modeling approach, we were able to identify relationships between some of these responses that lead to invariant angular scattering. Upon further inspections of these relationships, it may a priori appear that some of them are impossible to physically implement, such as, for instance, the case of purely bianisotropic responses with effective permittivity and permeability both being zero. However, we will numerically demonstrate that it is in fact possible to achieve near perfect angular invariance by properly tuning the resonances of low-loss resonators.

Towards a compact Sr optical clock system with integrated metasurfaces

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Development of compact, robust and scalable experimental systems that produce cold atomic ensembles would enable real-world, deployable applications in quantum sensing and precision measurement. In particular the development of a liter-scale, fully monolithic, alignment-free apparatus to produce 87Sr magneto optical trap (MOT), would enable transportable optical clocks based on their ultra-narrow optical transition. However, straightforward miniaturization of traditional optical infrastructure necessary to implement multi-step laser cooling has proven prohibitively complex. Multifunctional metasurface (MS) optics, planar photonic elements consisting of periodic arrays of dielectric nanopillars, are capable of exquisite control of the optical phase, amplitude and polarization, and offer the potential to perform the function of multiple traditional optics simultaneously using just a single semiconductor wafer-thickness optic, greatly reducing the footprint of the physics package. Here, we demonstrate the use of dielectric metasurfaces to simultaneously generate all the laser beams required for trapping and cooling of Sr in a fully monolithic, alignment free platform; and use it to experimentally realize a two-stage cooled magneto optical trap (MOT) for 87Sr. Our Sr MOT platform consists of a custom geometry of twelve optical beams for the two wavelengths involved with cooling and trapping Sr (six each at 461 nm and 689 nm); we integrate and control these with twelve MS optics nanofabricated on two fused-silica wafers. We engineer the MS optics and their placement on the wafers precisely to tailor the optical modes emitted from commercial optical fiber into the beams for laser cooling and trapping in a unique expanding beam MOT geometry. Each metasurface optic acts equivalent to several bulk optics in positioning the beam, expanding or collimating the beam, deflecting the beam to the center of the trap, and rotating the beam’s polarization to the circular polarization needed for atom trapping. The alignment of the counter propagating MOT beams at 461 nm for broad-line cooling and 689 nm for narrow-line cooling and their polarization is fixed upon assembly. We demonstrate the capability of our platform to cool and trap all four naturally occurring isotopes of strontium, including 87Sr, the isotope of preference for most optical lattice clocks. We determine the temperature of the atoms in the 88Sr MOT to be <2 mK with time-of-flight measurements of MOT expansion. These results demonstrate a CMOS foundry compatible, MS optics-based approach for laser cooling and trapping of strontium as a scalable, monolithic platform towards realization of a compact, fully integrated strontium optical lattice clock.

Metasurfaces for Biomedicine

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Nanophotonics excels at confining light into sub-wavelength volumes and generating dramatically enhanced near-fields. These unique nano-scale effects have been unveiling a plethora of fundamentally new optical phenomena as well as development of novel devices that can find numerous applications such as in energy harvesting, information technology, optical/quantum computing and health. Our research is focused on the later aspect with aims to introduce advanced bioanalytical devices that can have impact on areas including in basic research for life sciences, disease diagnostics, safety and point-of-care testing [1-5]. We engineer novel biosensing, biospectroscopy and bioimaging systems that are very sensitive, provide label-free, real-time, multiplexed and low-cost operation, and have compact footprint. We exploit plasmonic and dielectric metasurfaces to increase the interaction of light with nanometric sized biomolecules and depending on the detection principle we design their resonances within a broad spectrum ranging from visible [6-9] to mid-infrared [10-13]. We develop low-cost and wafer-scale nanofabrication methods for the manufacturing of nanophotonic metasurfaces [6, 11]. We integrate metasurfaces with microfluidic systems for efficient analyte handing [6, 8-9, 12-13]. We also use data science tools to achieve high sensor performance. In this talk I will present some of our most recent work [7-8, 12-13]. One example will describe an AI-aided and immunoassay coupled optofluidic mid-infrared sensor capable of differentiating different misfolded forms of proteins linked to neurodegenerative diseases using their unique IR absorption signatures [12]. The other example will describe optical and nanophotonic single-cell microarrays that can spatially and temporally map extracellular secretion profiles while simultaneously capture individual cell morphology at high-resolution and throughput [9, 14].

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Quantum control of ultrafast plasmon resonances in the pulse-driven extraordinary optical transmission

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Understanding the ultrafast processes at their natural-time scale is crucial for controlling and manipulating nanoscale optoelectronic devices under light-matter interaction [1]. In this study, we demonstrate that ultrafast plasmon resonances, attributed to the phenomenon of Extraordinary Optical Transmission (EOT), can be significantly modified by exploiting the spectral and temporal properties of the ultrashort light pulse [2]. In this scheme, electro-optical active tuning governs spatial, spectral, and temporal enhancement of plasmon oscillations in the EOT system without device customization. We analyze the spectral and temporal evolution of the system through two approaches. First, we develop a theoretical framework based on the coupled harmonic oscillator model, which analytically describes the dynamics of plasmon modes in the coupled and uncoupled state [3]. Later, we compare the evolution of the system under continuous wave and pulsed illumination. Further, we discuss time-resolved spatial and temporal dynamics of plasmon modes through 3D-FDTD simulation method and wavelet transform. Our results show that electro-optical tuning of oscillation time, intensity, and spectral properties of propagating and localized plasmon modes yields a 3-fold enhancement in the EOT signal. The active tuning of the EOT sensor through ultrashort light pulses pave the way for the development of on-chip photonic devices employing high-resolution imaging and sensing of abundant atomic and molecular systems. Also, our proposed electro-optical tunable plasmon-based EOT device enables real-time re-configurable and on-demand enhancement of optical signals. This is an essential requirement for optimizing integrated photonic circuits with tailored functionalities and unprecedented performance.

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Metasurface-Enhanced Computational Microscopy for Extended Depth of Field Imaging

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Studying biological samples often involves the examination of three-dimensional structures with varying depths. Traditional microscopy techniques struggle to maintain precise focus across the entire depth range of these samples, resulting in potentially blurry or incomplete images. Typically, depth scanning methods are employed to mitigate this issue, but they suffer from light scattering effects.
To address this problem, our study introduces a comprehensive optimization framework for developing a computational Extended Depth of Field (EDOF) microscope. This approach combines a 4-f microscopy optical setup, featuring learned optics at the Fourier plane, with a post-processing

deblurring neural network. Our approach presents an end-to-end differentiable model, enabling a systematic design methodology for computational EDOF microscopy tailored to the specific imaging requirements of the sample under examination. Additionally, we demonstrate the advantages of incorporating metasurface optics, particularly in extreme EDOF imaging scenarios, which outperform the current state-of-the-art techniques.

Compound anapole approach to meta-particles and metamaterials

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Invisibility and transparency effects such as cloaking, transformation optics, electromagnetically induced transparency, and anapole states have limitations following Devaney-Wolf theorems. Accordingly, the weak and strong solutions obey the condition for the suppressed radiating harmonics in the far-field zone. In real systems, this condition is fulfilled only for certain harmonics that can be considered invisible. From the multipole decomposition approach, all effects allow one to suppress certain main multipoles, while the higher-order non-resonant multipoles will be presented in the system. Nevertheless, in this talk, we discuss the compound multipole approach demonstrates the lack of radiated multipoles for two particles system. In accordance to multipole approach, the radiating multipoles of each particle compensate to each other in the compound system independent on angles and polarizations of the incident wave. We study single particles and metamaterials theoretically and experimentally and show superinvisibility and transparent metasurface in THz and microwave regimes.

Optical resonant nanostructures for enhancement of electro-optic coupling

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Optical resonators are essential for many photonic devices. The important parameters that describe a resonance feature are its visibility and spectral linewidth. From the perspective of electro-optic modulation, resonances with high visibility and narrow linewidth are desirable. Higher resonance visibility provides a higher modulation depth, and a narrower linewidth allows modulation at smaller voltages. In this work, we study the reflection and transmission properties of electro-optic nano-resonators that modulate the light through Guided-Mode Resonances (GMRs)[1] and Quasi-Bound States in the Continuum (QBIC)[2]. The nonlinear organic electro-optic (OEO) molecules JRD1 [3] in polymethylmethacrylate with a large Pockels coefficient is deposited on top of the nano-resonators and an array of metallic gold strips are patterned to apply tuning voltages to the nonlinear OEO material. We study the electric and optical field overlap inside the OEO material to maximize the interaction of light with the nonlinear material and eventually increase the modulation efficiency. Furthermore, we explore different tensorial components of nonlinearity in different scenarios, in which the electric field components of the incident light are perpendicular and parallel to the metallic strips. We further investigate the influence of the concentrations of JRD1: PMMA on the resonant properties of the guided modes in each scenario.

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Recovering the S-matrix of optical components with the singularity expansion method

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Controlling the interaction of electromagnetic fields with optical components to obtain specific behaviours is a challenging topic of high importance. There exist many tools to design different types of components with an ever-increasing accuracy, yet the options to theoretically model and study them seem to be limited. One of the most common and efficient such method, and also among the oldest ones, is the S-matrix method, which links scattered fields to incident fields in the harmonic domain, after an expansion over different modes or ports. While the S-matrix can be used to describe a wide range of components, retrieving its coefficients remains a difficult task and often suffers from too much generality, as in the case of the resonant state expansion where the resonant states and their associated frequencies are determined for the full diagonalized S-matrix, or, paradoxically, from too much specificity, in which case many hypotheses or complex models are needed.

Here, we show how the singularity expansion method accurately describes optical components in terms of their singularities, i.e. the complex frequencies which naturally describe the response of a system to an excitation. We show that the singularities and their associated parameters in the complex frequency plane can be retrieved from experimental or simulated data at real frequencies. We expand the coefficients of the S-matrix individually using the same formalism, while utilizing their connection to constrain the set of singularities which offers the most accurate description.

Active metasurfaces based on low loss phase change material Sb2S3

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Active metasurfaces are a promising solution to overcome the inherent passive functionalities of standard metasurfaces, potentially enabling a wide range of applications. Several tuning mechanisms are explored for external control of metasurfaces, such as liquid crystals, mechanical actuators, chemical tuning, 2D materials, or Phase Change Materials (PCMs). In particular, standard PCMs, such as GeSbTe and GeTe, widely used in mature non-volatile memories technologies, possess remarkable optical and electrical properties that can be modulated by reversibly changing the crystallinity of the material. Metasurfaces based on PCMs can be a good candidate to overcome the limitations encountered in some applications. Indeed, they are solid-state devices allowing easy integration in

complex architecture with CMOS compatibilty. In addition, PCMs offer high optical index modulation with relatively short switching time and the extensive PCMs library makes them suitable for a wide range of applications. Exploring compositions and stoichiometry of PCMs enabled the emergence of a new class of PCMs: Sb2S3, Sb2Se3 and GeSbSeTe which exhibit low optical loss in visible and near infrared, in contrast to the standard high-loss PCMs (GeSbTe and GeTe). In particular, Antimony trisulfide (Sb2S3) is a low-loss PCM that has attracted a lot of attention in the field of active metasurfaces for the visible to the near-infrared regime. Unfortunately, this material presents many challenges, which explain the lack of experimental demonstrations, in particular, the first challenge is the high resolution nanostructuring of Sb2S3 due to its high chemical reactivity with many resist developers such as TMAH, the second challenge being the difficulty to thermally crystallize the nanostructures due to the lack of nucleation germs in the meta-atoms where crystallization can be initiated.
This work explores the potential use of Sb2S3 as a PCM for active metasurfaces in the visible and near infrared spectrum. To address the chemical reactivity and nanostructures crystallizations challenges, the study focuses on using Sb2S3 as a meta-atom for an active metasurface and optimizing parameters to provide optical active functionalities for spatial and spectral light control. The work also addresses the nanofabrication and characterization challenges faced in experimentally demonstrating the concept, and provides a recipe for nanostructuring Sb2S3 using electron beam lithography and nanoimprinting methods. The study proposes a design approach and nanoimprint development approach to overcome the difficulties in crystallizing nanostructures. Finally, the study highlights the inherent anisotropy of the material and proposes new approaches to address it, presenting a new research opportunity.

3D Artificial Spin Ice: Challenges in imaging and opportunities for 3D metasurfaces

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Artificial spin ices (ASIs) are arrangements of dipolar-coupled nanomagnets with magnetic moments that behave like Ising spins because of their shape anisotropy. Originally envisaged to display frustration analogue to that observed in bulk, rare-earth pyrochlores, they have proven an excellent playground in which to realise aspects of phase transitions, non- equilibrium phenomena, and collective dynamics such as monopole motion. Up until now, most examples of these artificial spin ices have been restricted to planar systems, or ones that were trivially three-dimensional.
To mimic the full three-dimensional nature of rare-earth pyrochlores, we fabricate a polymer scaffold based on two unit cells of the pyrochlore lattice using two-photon lithography. The nanomagnets are then created by thermally evaporating permalloy onto the sloped surfaces of the scaffold. The platforms are raised from the surface so that they are decoupled from the thin-film in the background. To ensure that the nanomagnets are single domain we subject the scaffold to pyrolysis before evaporating the magnetic material. This process shrinks the printed lattice down to one third of its original size.
The magnetic imaging of these samples is extremely challenging due to their pronounced three-dimensional nature. We achieved the best results using x-ray photoemission electron microscopy at MAX IV, where the x-ray direction is normal to the sample surface, which avoids shadowing. We

were able to switch and image the magnetization of all the nanomagnets by using an out of plane magnetic field. However, in one of the two directions, the magnetic contrast is extremely weak. Therefore, we are currently exploring other techniques that can provide a more reliable magnetic imaging.

Combining two-photon lithography with pyrolysis provides a tool to fabricate arbitrary 3D shapes with high aspect ratios and minimum feature sizes down to 100nm. This capability might be interesting beyond the magnetism community for producing metasurfaces.

Bianisotropic metasurface enables a nonlinear pseudo-diode: asymmetric second-harmonic generation

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Bianisotropic metasurfaces empower planarized optical components with subwavelength thicknesses that are not amenable to conventional optics. In particular, bianisotropy gives control over the spatial dispersion and allows engineering of both spectral and directional responses simultaneously, yielding devices with unprecedented functionalities.

In this work, we demonstrate a nonlinear bianisotropic metasurface that features asymmetric second-harmonic generation (SHG). The concept of the device is as follows: SHG from the metasurface occurs only upon excitation in the forward direction, whereas backward excitation does not result in efficient SHG, effectively making the metasurface perform as a nonlinear pseudo-diode. Such functionality is achieved by employing two common plasmonic materials – aluminium (Al) and silver (Ag) as constitutive materials of the meta-atos. Apart from exploiting the stronger second-order nonlinear response of Al, we show that tailored mixing of these two metals provides an elegant and simple approach to engineer the spatial dispersion, which is required to achieve such an asymmetric response. In turn, the geometrical parameters of the metasurface are optimized to exhibit SHG maximum upon excitation at 800 nm wavelength (resulting in SHG peak at 400 nm).

We demonstrate the experimental implementation of the metasurface and discuss the fabrication method that is based on a bottom-up approach. To further substantiate our findings, we perform a homogenization analysis, which allows for extracting the effective susceptibility tensors and unambiguously reveals the bianisotropic response of our metasurface. Finally, we discuss the implications of our results from the more fundamental perspectives of reciprocity and time-reversal asymmetry.

Enhanced nonlinear THz generation in lithium niobate thin films driven by phonon-polaritons

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We investigated nonlinear terahertz (THz) generation in lithium niobate films and crystals of varying thicknesses when subjected to near-infrared femtosecond pulses through optical rectification. Our research entailed polarization-resolved measurements and rigorous numerical calculations which were found to be in excellent agreement. Our results reveal a two-orders-of-magnitude enhancement in the nonlinear response compared to optical frequencies, shedding light on the potential for a novel avenue in integrated broadband THz emitters and detectors. Although THz generation by optical rectification in lithium niobate has reached significant progress thanks to the tilted pulse front method, this approach is limited in the bandwidth of the generated radiation due to self-absorption of the THz signal and it is still based on thick crystals that hinder integration. On the other hand, our results in thin lithium niobate films hold the promise of a transformative impact on the field of integrated THz photonics.
The sizeable enhancement of the nonlinear response that we observed arises from the intricate interplay between optical phonon modes at 4.5 THz and 7.45 THz and the distinctive properties inherent to lithium niobate. Notably, the most striking augmentation in THz generation occurs in films thinner than 2 µm, effectively circumventing the limiting factor of THz self-absorption. Furthermore, our research underscores the potential for precise control and manipulation of the THz generation process within the realm of nanophotonic structures. This includes sub-wavelength resonators and metasurfaces, illustrating the vast potential within the thin film platform. To illustrate the convenience of our findings, we conducted a rigorous numerical investigation of optical-to-THz conversion driven by localized surface phonon-polariton resonances in sub-wavelength lithium niobate rods. This numerical analysis highlights the adaptability and versatility of our findings, offering tantalizing prospects for tailoring THz generation to specific technological requirements.
In summary, our study unveils a remarkable two-orders-of-magnitude enhancement in nonlinear THz generation in lithium niobate thin films due to phonon-polaritons. These groundbreaking results hold the potential to redefine the landscape of integrated THz photonics, opening new avenues for advanced THz emitters and detectors based on sub-wavelength resonators and metasurfaces, while simultaneously illuminating the path toward transformative innovations in nanophotonics and terahertz science.

All-optical free-space routing of upconverted light by metasurfaces via nonlinear interferometry

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Optical interferometry is a key-enabling phenomenon exploited in a wide range of applications, such as homodyne detection, radar interferometry, LiDAR technology, gravitational waves detection, and molecular photometry. Light upconversion is a nonlinear process that consists in the interaction of either energy-degenerate photons, such as in second-harmonic and third-harmonic generation (THG), or photons with different energies, such as in sum- frequency generation (SFG). We recently investigated frequency upconversion both in plasmonic and dielectric nanoantennas [1,2]. Thanks to the adopted dual-beam pump scheme, whereby an ultrashort pulse (frequency ω) at telecom wavelength (λ = 1551 nm) impinges on the sample along with its frequency-doubled replica (2ω), THG (ω+ω+ω) and SFG (ω+2ω) are degenerate infrequency at 3ω. Degeneracy, along with coherence, makes the interference between the two processes possible. Yet, the opposite parity of THG and SFG fields hinders such interference in systems featuring axial symmetry [1]. Therefore, symmetry breaking becomes crucial to enable it. By applying the above dual-beam pump scheme to a periodic nonlinear metasurfaces of AlGaAs, we break the detection symmetry attaining all-optical switching of the upconverted telecom photons in specific k-space directions corresponding to the diffraction orders of the metasurface. Using the relative phase between the pump pulses as a tuning knob, we could steer the upconverted radiation among different diffraction orders with a contrast up to 90%. We also demonstrate that varying the polarization state of both pump and emission reconfigures the switching between different sets of diffraction orders [3]. Notably, we reach an overall conversion efficiency $\beta=P(3\omega)/(P(2\omega)\times P(\omega)) > 10E\text{-}5\ W^{-1}$ at relatively low pump peak intensities (10 MW/cm²). Our approach adds a twist to optical interferometry. In fact, the sensitivity of the upconverted light to the impinging photon phase along with its nonlinear character is appealing for sensing applications.

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Enhanced harmonic generation in the UV and visible ranges in metal and semiconductor nanostructures

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Currently, nanostructures are routinely integrated in different photonic devices for a variety of applications. At this scale light-matter interaction displays interesting new phenomena. Traditionally, harmonic generation has been studied in nonlinear transparent materials, under phase-matching conditions, ensuring large conversion efficiencies. However, when the material size is reduced to the nanoscale, the scenario is totally different: the electric dipole contribution no longer predominates and other terms, usually neglected, become important. Understanding and quantifying these new nonlinear sources at the nanoscale is pivotal to engineer and implement any nanodevice.
We present here a collection of experimental results of second and third harmonic generation in nanostructures made of semiconductors and metals in the visible and UV spectral range, where these materials show absorption at the harmonic frequencies. We show that light emission is possible even when this spectral range falls into the opaque region of these materials. Moreover, we design quite simple nanostructures that are able to localize and enhance the electromagnetic field and consequently enhance the nonlinear interaction efficiency.
From one side we report measurements of harmonic generation from undoped silicon membranes. Using experimental results and simulations we identify the effective mass of valence electrons, which determines second harmonic generation efficiency, and oscillator parameters that control third order processes. We can then accurately predict the nonlinear optical properties of complex structures, without artificially separating the effective $\chi(2)$ into surface and volume contributions, and by simultaneously including effects of linear and nonlinear dispersions. Our results suggest that judicious exploitation of the nonlinear dispersion of ordinary semiconductors can provide reasonable nonlinear efficiencies well into the UV range.
We also study the harmonic generation from a gold nanograting exhibiting a plasmonic resonance in the near infrared. The enhancement of nonlinear optical processes produced by the field localization in the nanograting when compared with a flat gold layer manifests itself dramatically from the UV to visible range: second harmonic conversion efficiencies increase by more than three orders of magnitude, while we report a third harmonic generation conversion efficiency enhancement factor of 3200, both in excellent agreement with our theoretical predictions. Minor geometrical modifications are shown to lead to the enhancement of THG efficiencies by nearly five orders of magnitude. The clear inferences one may draw from our results are that our model describes the dynamics with unprecedented accuracy and that much remains to be revealed in the development of nonlinear optics of metals at the nanoscale.

Mini CO2 Refineries : Microfluidic Platform Assisted Photocatalysis

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Conversion of carbon dioxide into renewable fuels via sunlight is an appealing concept with the ongoing climate crisis, yet a challenging task to achieve. The inert nature of CO_2 and its low solubility in the most common electrolytes are among limiting factors before achieving any significant efficiencies. In this proof-of-concept study, we use a microfluidic platform that allows illumination of particles with no shading and allows us to design a fully controlled gas-liquid-solid environment for photocatalytic CO_2 reduction. The microfluidic device is enhanced with metasurfaces to allow maximal absorption of light by photocatalytic nanoparticles.

Design of Metalenses for Improving Photocatalytic and Photoelectrochemical Systems

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Conversion of carbon dioxide into renewable fuels via sunlight is an appealing concept in frame of the ongoing climate crisis, yet a challenging task to achieve. Concentration and efficient absorption of light can be beneficial for energy devices such as photocatalytic and photoelectrochemical systems. Herein, we are investigating the design of metalenses that can be integrated in a microfluidic flow reactor towards enhanced solar to fuel conversion efficiency. The metalenses allow concentration of light to a confined volume where CO_2 reduction and oxygen evolution reactions take place at the catalytic surfaces.

Physical-model-based wave control in metasurface-programmable complex media

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Light-matter interactions are traditionally controlled by shaping the impinging wavefront or engineering a metamaterial. Currently, a new trend is emerging across scales and wave phenomena: tuning a complex medium in situ using a programmable metasurface embedding inside the complex medium. To efficiently optimize the metasurface configuration for a desired functionality, an accurate setting-specific model mapping configuration to transfer function is necessary. Here, we experimentally demonstrate that a compact model derived from first physical principles can precisely predict how scattering coefficients in complex scattering environments depend on the programmable-metasurface configuration. The model is calibrated using a very small random subset of all possible metasurface configurations and without knowing the setup's geometry. Our approach achieves two orders of magnitude higher precision than a deep learning-based digital-twin benchmark while involving hundred times fewer parameters. Strikingly, when only phaseless calibration data is available, our model can nonetheless retrieve the precise phase relations of the scattering matrix as well as their dependencies on the metasurface configuration. Thereby, we achieve coherent wave control (focusing or enhancing absorption) and phase-shift-keying backscatter communications without ever having measured phase information. Finally, our model is also capable of retrieving the essential properties of scattering coefficients for which no calibration data was ever provided. These unique generalization capabilities of our pure-physics model significantly alleviate the measurement complexity. Our experiments are presented in the microwave regime in the context of smart radio environments but our approach is also directly relevant to emerging in situ reconfigurable nanophotonic, optical and room-acoustical systems.

All-optical control of the nonlinear emission through symmetry breaking at the nanoscale

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The past decade witnessed a significant push toward downsizing of photonic platforms, driven by the potential functionalities it could unlock in nanostructured devices. Important future capabilities are frequency conversion and mixing through nonlinear parametric optical processes. To this aim, great care in the nanostructure design is needed, due to the strong dependence of nonlinear processes on the nanostructures constituent material and geometry. In first place, the perturbative nature of nonlinear optics requires a proper engineering of nanostructures resonant modes, to achieve the field enhancement necessary to boost their efficiency. We investigated two device concepts: (i) single AlGaAs nanocylinders, where a significant nonlinear enhancement is obtained by exciting at a magnetic-dipole resonance [1] or at the anapole condition [2], and (ii) single asymmetric gold nanoantennas featuring a double resonant behavior [3]. Moreover, the exploitation of the nanostructure geometry as an additional degree of freedom in comparison to bulk systems, enables the control of other parameters conversion efficiency, like polarization and far-field. An instructive example comes from our recent investigations of the abovementioned nanostructures [2,4] in a double, semi-degenerate pumping scheme (ω+2ω). The result is the excitation of two upconversion processes: third-harmonic generation (THG, ω+ω+ω) and sum-frequency generation (SFG, ω+2ω). The coherent nature of parametric nonlinear processes allows for interference effects between THG and SFG. However, the coherent superposition of processes involving different number of photons determines a non-trivial dependence on the nanostructure symmetry, which can be exploited to tailor the interference between THG and SFG. Specifically, in presence of axial symmetry, the excited upconversion pathways have opposite parity with respect to the coordinate inversion, due to the even/odd number of participating photons, resulting in interference suppression [2]. This suggests the possibility of using symmetry breaking as a design tool to enable coherent interaction between THG and SFG [4]. This finding has been the starting point of the implementation of a nonlinear metasurface able to exploit interference to perform a phase-controlled all-optical routing of the nonlinear emission [5], paving the way for devices suitable for nonlinear sensing or ultrafast control of upconverted light. In conclusion, we stress the importance of engineering nanostructures in terms of material and geometry to implement the desired functionality in nonlinear metasurfaces.

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Wafer Scale Metasurfaces

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The availability of high-resolution and high-throughput lithographic fabrication technologies, such as electron-beam lithography, based on variable shaped beam writing and character projection opens the way to flexibly fabricate metasurfaces for the most demanding applications. We show that such applications are enabled by the technqiues combination of high speed, high resolution and flexible use of substrates, with lateral precision on the nanometer scale for substrates up to 300 mm in size.

We discuss the technical features, advantages, and limitations of these pattering approaches and show how they can favorably be combined to realize optical nano-structures for a set of applications and substrate materials. Among the applications are highly efficient laser pulse compression gratings for ultra-short laser pulses, broadband, non-polarizing, high-resolution spectrometers, computer generated holograms for asphere testing and wavefront sensing, metasurface-holograms for applications in quantum communication, UV-polarizers and integrated photonic architectures for quantum computing.

The material base ranges from state-of-the-art silicon and SiO2 to more advanced substrates such as Germanium or Diamond but also to optical coatings and customized thin films.

Ultimate performance of active wavefront shaping metasurfaces

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We propose a straightforward methodology for designing active metasurfaces operating in reflection mode with ultimate wavefront shaping performance. Our innovative design approach relies on designing asymmetric Gires–Tournois (G-T) resonators to achieve comprehensive phase modulation of light with near-unity efficiency.
Applying this condition, we demonstrate that light reflected from a G-T resonator can undergo a robust nonlinear phase modulation of 2π with nearly perfect reflection. This resonant phase can be actively tuned by varying parameters such as cavity thickness, operating frequency, or refractive index.
The active metasurface resonators filled with either silicon or hetero-structured materials. These choices allow for the utilization of thermo-optical or electro-optical effects, respectively. Remarkably, in both cases, complete phase modulation, combined with a 100% reflection amplitude, is observed, even when dealing with exceedingly low refractive index changes on the order of 0.01.
Yet, conventional phase gradient designs relying on standard look-up tables may not be as efficient for beam forming due to the strong resonant characteristics of excited optical modes. To address this, we employ a global statistical learning optimization strategy, resulting in a significant enhancement in beam-steering efficiency at various deflection angles.
We apply our methodology to two practical designs involving semiconductor G-T cavities. These designs leverage either thermo-optical effects in Si nano-cells or electro-optical effects in multiple quantum well structures. Through our approach, we demonstrate active deflection and beam steering, achieving exceptional performance exceeding 90%.

The realization of highly efficient active beam shaping at high frequencies holds the potential for significant applications in areas such as imaging microscopy and three-dimensional light detection and ranging (LiDAR).

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Singular Metaphotonics: applications for laser wavefront engineering and Light imaging and ranging technology

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Metasurfaces are artificial optical interfaces designed to control the phase, the amplitude and the polarization of an optical wavefront. These optical surfaces rely on the coherent scattering of light by a sizable distribution of nano-scatterers of various shapes and material compositions.
During this tutorial, I will introduce the different physical mechanisms that the community is using for designing optical metasurfaces. I will notably talk about the fundamental properties of light scattering by nanoparticles, placing a significant emphasis on the topological properties of the transmission, reflection and polarization conversion coefficients. Building upon the general theory of topological singularities, we have shown that by encircling a complex zero in the metasurface parameter space, novel topological phase ranging from 0 to 2π, different from the usual Pancharatnam-Berry phase, can be harvested for wavefront shaping1. Our new explanation will relate to existing conventional metasurface designs to provide the audience with an in-depth understanding of the physics underlying the well know Huygens Metasurfaces2-3.
It is also important to point out that beyond addressing exciting physical problems, Metasurfaces also hold great potential for on-chip integration of photonic components. They are even expected to promote significantly the future development of miniaturized optoelectronic systems. As such, our group made several attempts in demonstrating their potential in applications. To summarize some of our latest development on metasurface LiDAR technology for 3D imaging and integrated laser wavefront manipulation, I will conclude this talk by mentioning a few disruptive applications of metasurfaces for directional light collection and laser emission, and LiDARs5-7.

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Materials for Metasurfaces

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Metasurfaces are ultra-thin, man-made structures meticulously engineered to control and manipulate electromagnetic waves. Comprising subwavelength resonant features arranged in a planar array, they facilitate transformative advancements in optics and photonics, enabling the creation of compact, high-performance optical devices that transcend conventional optical technologies.

This tutorial delves into the essential role of materials, including noble metals, transition metals, III-V semiconductors, and 2D materials, in driving diverse metasurface designs. We will provide an in-depth exploration of two primary material classes: noble metals for plasmonic applications and III-V semiconductors for all-dielectric metasurfaces. By demonstrating how these materials are meticulously structured into metasurfaces through advanced nanolithography techniques, we illustrate the vast array of applications they encompass. These applications span from conventional linear optics to the intricate domains of nonlinear and quantum optics.

Optical Fourier Surfaces for Holography

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Optical Materials Engineering Laboratory, D-MAVT, ETH Zurich "Controlling light is crucial for modern technologies, such as solar cells, biosensors, and optical communication. A common approach involves the fabrication of nanostructured surfaces with sub-wavelength feature sizes to manipulate electromagnetic fields through diffraction. However, current lithographic methods are typically restricted to “binary” surface profiles with only two depth levels, limiting their optical performance. Here, we overcome this limitation by exploiting thermal scanning-probe lithography to fabricate grayscale diffractive surfaces, known as optical Fourier surfaces (OFSs) [1]. We explore the possibility to use these OFSs as reflective holograms in silver to control the amplitude and phase of the diffracted wavefront in the far field. Due to the non-trivial relation between the surface profile and diffraction output [2], an adapted Gerchberg–Saxton algorithm [3] is applied to inversely design the OFS holograms. Furthermore, we extend the concept of OFS holograms to diffract bound electromagnetic modes, such as surface-plasmon polaritons [4] and waveguided photons [5], to free space. This approach may provide expanded possibilities for holography, beam shaping, and optical display technology.

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Engineering of a THz time-reversal symmetry breaking chiral metamaterial

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A metamaterial of resonators capable of sustaining circularly polarized electromagnetic modes has been developed and it is reported to give rise to chiral light-matter hybrid states when coupled to the cyclotron resonance of a two-dimensional electron gas. The cavity design, which is crucial to ultra-strongly couple to the solid-state system, could potentially be implemented to manipulate topological properties of materials, or to affect their transport behavior, about which one can gain insights via a circuit model that we have developed.

Chiral Metasurfaces: Expanding Sensing Horizons for Highly Selective Biosensing Platforms

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Advancements in biosensing platforms demand heightened sensitivity and specificity for effective technological translation. This research expands on the exploration of light–matter interaction control at the nanoscale by investigating various chiral structures within plasmonic metasurfaces. Our focus extends beyond the 3D out-of-plane chiral plasmonic metasurface, delving into different metasurface designs with distinct chiral configurations. Through comprehensive numerical analyses, we elucidate the potential of these metasurfaces as integral components in sensing platforms. By leveraging the interplay of plasmonic and lattice modes, we demonstrate their capacity to detect changes in the refractive index of the surrounding medium. Our findings reveal that chiral metasurfaces exhibit a remarkable sensitivity. Importantly, the tunable properties of these metasurfaces enable the optimization of optical responses, offering a versatile platform for refractive index sensing applications. Furthermore, we extrapolate the implications of these studies to the broader context of engineering highly selective and specific chiral metasurface-based sensing platforms. We discuss the modulation of optical responses by tailoring metasurface properties, thereby enhancing sensitivity and specificity. Looking forward, we propose a promising avenue for future applications in the realm of biosensing. By functionalizing these metasurfaces with a bio-interface resistant to fouling, we anticipate their potential for enantiospecific recognition of chiral biomolecules in complex biological fluids. This innovative approach holds promise for advancing biosensing technologies, offering a pathway to address the challenges of sensitivity and specificity in the detection of intricate biomolecular structures. [1] Guglielmelli A., et al. "Numerical Modeling of 3D Chiral Metasurfaces for Sensing Applications." Crystals 12.12 (2022): 1804. [2] Lininger A., et al. "Chirality in light–matter interaction." Advanced Materials 35.34 (2023): 2107325. [3] Guglielmelli

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Tunable Diamond Metasurfaces via Nematic Liquid Crystals

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Tuning the response of optical metasurfaces is of current interest for applications in displays, virtual reality, and holography. However, obtaining such tunability in the visible regime is challenging due to the scarce availability of materials with high refractive index and low losses in this range of the electromagnetic spectrum. Diamond offers a promising solution in this regard due to its relatively large and constant refractive index of about 2.4 in the visible spectral range. Here we present a numerical study on the tunability of diamond metasurfaces via nematic liquid crystals (LCs). LCs are typically simulated as homogeneous or without considering anchoring conditions at the location where they touch the nanoparticles. In this study, the non-homogeneous LCs realignment in contact with the diamond nanoparticles is simulated with a $\boldsymbol{Q}$-tensor approach [1-2] in three dimensions (3D) as a function of voltage also including their alignment around the nanoparticles [3]. We will show the opportunities for optical tunability and achieving resonances with high Q-factors in the visible regime.

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Intracavity spatiotemporal metasurfaces

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Optical metasurfaces are endowed with unparallel flexibility to manipulate the light field with a subwavelength spatial resolution. Coupling metasurfaces to materials with strong optical nonlinearity may allow ultrafast spatiotemporal light field modulation. However, most metasurfaces demonstrated thus far are linear devices. Here, we experimentally demonstrate simultaneous

spatiotemporal laser mode control using a single-layer plasmonic metasurface strongly coupled to an epsilon-near-zero (ENZ) material within a fiber laser cavity. While the geometric phase of the metasurface is utilized to convert the laser's transverse mode from a Gaussian beam to a vortex beam carrying orbital angular momentum, the giant nonlinear saturable absorption of the ENZ material enables pulsed laser generation via the Q-switching process. The direct integration of a spatiotemporal metasurface in a laser cavity may pave the way for the development of miniaturized laser sources with tailored spatial and temporal profiles, which can be useful for numerous applications, such as superresolution imaging, high-density optical storage, and three-dimensional laser lithography.

Ultrastrong Light Matter Interaction with Single Meta Atoms

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Plasmonic metasurfaces are a common tool for confining light into highly subwavelength volumes for investigating (ultra-) strong light-matter interactions, and studying their effect on quantum matter. [1] In particular, at terahertz (THz) frequencies, metasurfaces have been used to couple THz light to electronic Landau level transitions in two-dimensional electron gases (2DEGs) in semiconductor quantum wells, leading to normalised coupling ratios as high as 1.4 [2,3].

In this case, the metamaterial unit cell consists of an LC-type split ring resonator (cSRR), with highly subwavelength confinement of THz radiation at arbitrary frequencies.

In standard spectroscopic measurements of such systems, large-area metasurfaces are measured to be able to detect the material's collective spectral response. The resonant modes are excited by inter-resonator coupling via in-plane wavevectors.

Alternatively, measuring an individual meta-atom allows for more accurate estimation of the effective cavity volume and number of electrons contributing to the coupling. However, due to the inherent field confinement and low radiation into the far-field, measuring single meta-atoms with standard spectroscopy techniques is highly challenging. Recently, we demonstrated that it is possible to measure the ultrastrong coupling of a single cSRR to a 2DEG by employing an asymmetric silicon lensing system [4]. The lenses provide the necessary k-vectors to excite the resonance, as well enabling outcoupling into the far-field.

Here, we investigate the limits of the single-element ultrastrongly coupled system by studying how the coupling and spectroscopic visibility in the far-field is affected by the meta-atom design. We numerically and experimentally compare a variety of different resonant structures with highly subwavelength field confinement. In addition, we investigate how the coupling interaction can be modified in-situ by applying a voltage bias, depleting the electrons in the 2DEG. By reducing the number of electrons contributing to coupling, this work approaches ultrastrong-coupling in the few electron limit, where novel spectral responses have been predicted [5]. Furthermore, we are hereby developing a platform in which the ultrastrong light matter interaction between the Landau electrons in high quality exfoliated graphene and a THz mode can be performed. This would open the possibility of studying the optical response of high mobility graphene flakes for the first time at THz frequencies.

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Reconfigurable Amorphous Silicon Metasurfaces: Design, Fabrication, and Dynamic Response to Continuous Wave and Pulsed Illumination

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In our study, we investigate the dynamic behaviour of amorphous silicon (a-Si) reconfigurable metasurfaces under both continuous wave (CW) illumination and pulsed laser conditions. Utilizing Comsol Multiphysics software, we finely tailored the optical properties of the a-Si metasurface with Mie type resonances and surface lattice resonances. Following this, we achieved nanoscale precision in the fabrication process by top-down method with electron beam lithography, ensuring that the metasurface retained its intended characteristics. To gain insights into the metasurface's dynamic response and collective heating, we employed Raman spectroscopy for local temperature measurements during CW illumination. Remarkably, under CW illumination, our a-Si metasurface exhibited an impressive optical transmission modulation capability, achieving more than 50% modulation in the visible spectrum and full reconfigurability. Additionally, we identified specific spectral regions where the metasurface displayed ultrafast modulation relaxation in first 10 ps and dynamic detuning by time and spectrally resolved pump and probe measurements in the visible spectrum. Our approach also involved mode engineering to precisely control these ultrafast regions and also the dynamics. To provide a comprehensive understanding of the metasurface's behaviour, we developed a detailed model describing its transient response under varying illumination conditions by computing the transient change in the dielectric function ($\Delta\epsilon$_(a-Si)) of a-Si. This research advances our understanding of reconfigurable metasurfaces, presenting exciting prospects for advanced photonics, optoelectronics applications, and time-varying metasurfaces where precise optical control and dynamic response are crucial.

Passive and tunable flat optics based on dielectric metasurfaces

Arseniy Kuznetsov, Institute Of Materials Research And Engineering, A*star, Switzerland

Metasurfaces have recently emerged as a novel platform for precise manipulation of light at the nanoscale. Dielectric nanoantennas in particular have been successfully used as low loss building blocks for metasurfaces, which can provide full phase coverage with high efficiencies, reaching industry standards. In this talk, I will demonstrate our progress on developing metasurface-based devices for two different application directions. First, I will show how dielectric nanoantenna-based metalenses can achieve 180-degree field of view imaging with just a single layer of nanostructures. Moreover, I will demonstrate that combining three of such metalenses together allows to cover the whole visible spectral range and achieve good-quality white-light imaging performance with just a single-layer metasurface device. In the second part of my talk, I will show how the combination of metasurfaces with CMOS electrode platform and liquid crystal technology allows to achieve single-pixel tunable metasurfaces, which can perform dynamic 2D and 3D holography and 2D beam steering with the largest field of view and the smallest form factor compared to convention spatial light modulator analogues. This emerging technology is particularly attractive for applications in Light Detection And Ranging (LiDAR) and future 3D holographic displays.

Flat lenses under polychromatic illumination: What can and what cannot be achieved?

Uriel Levy, HUJI, Israel

Flat lenses, a class which includes diffractive lenses and metalenses are attracting growing attention due to their potential to replace conventional refractive optical elements in imaging and illumination systems. Such lenses offer significant advantages in cost, size, and weight and are thus particularly attractive for mass market applications, in which miniaturization and cost reduction are prime considerations. However, the utilization of flat lenses comes with penalty in performance. Particularly, imaging systems based on flat lenses show sever chromatic aberration, making their utilization in applications based on polychromatic illumination extremely challenging. Hereby, we discuss the limitations of such systems and analyze their performance for different operating conditions. Following, we demonstrate an indoor imaging system based on flat lens. Finally, we show the strength of the hybrid approach, where flat lenses and proper algorithms can work together to provide superior image quality.

Electrically-controlled metasurfaces at visible frequencies

Laura Na Liu, University Of Stuttgart, Germany

Light projection displays play an increasingly important role in our modern life. Core projection systems including liquid crystal displays and digital micromirror devices can impose spatial light modulation and actively shape light waves. Recently, the advent of metasurfaces has revolutionized the design concepts in display technologies, enabling a new family of optical elements with exceptional degrees of freedom. In this talk, we will present examples of electrically-controlled metasurfaces for dynamic holographic displays. We will also outline the possibility to achieve programmability and addressability of optical metasurface devices at the single pixel level.

Bio-inspired metalens array for directional detection in 3D light imaging and ranging

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Over the last two decades, many optical components have been largely inspired by biological systems, and some of them are based on the operating principle of arthropod faceted eyes. Each facet of the eye is an optical subsystem, named ommatidium. The curvature of the eye has specifically evolved so that each subsystem forming this compound imaging system can capture light originating from a very specific direction only. In order to mimic arthropod vision, some works show examples of microlens arrays fabricated on a thin flat layer of polymer. This polymer is bent into curved geometries by applying a stress, with the objective of obtaining shapes that are as close as possible of that of the arthropod eyes. From our side, to imitate the eye of an arthropod, we

designed a flat component consisting of an array of metalenses and a detection surface made up of a set of photosensitive pixels. Each pixel is associated with an off-axis metalens featuring a unique phase profile. By adjusting the phase profile of all the lenses, we reproduce the curvature of the eye while retaining a planar component. As a result, all the metalenses focus light at the same distance, facilitating on-chip integration.
This component can be used in various imaging systems, such as the plenoptic cameras, based on a lens assembly. As a proof of concept, we experimentally demonstrated the imaging capability of our metasurface in a scanning LiDAR experiment. We prooved that by combining a laser source and this metasurface, we can perform angular time-of-flight detection of the objects making up a scene.
The aim of this presentation is to explain how this metasurface was conceived, how we characterized it and to present the results of the LiDAR experiment.

Modeling hybrid metasurfaces

Parmenion Mavrikakis, EPFL, Switzerland
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Hybrid metasurfaces are built from meta-atoms that include both dielectric and plasmonic materials. The former are known to support a strong magnetic dipolar response, while the latter have a strong electric response. By combining both together, one can achieve effects that are not possible with either dielectric or plasmonic metasurfaces. From a modeling point of view the combination of different materials, as well as the different types of electromagnetic effects supported by the structures pose some challenges. In this work, we resort to the surface integral equation (SIE), which is based on the integral form of Maxwell's equations. A finite elements approach is used to discretize the equations and we show that different basis functions provide specific advantages for modeling the electric or the magnetic response of the system. Based on this accurate numerical framework, we perform a detailed study of different hybrid metasurfaces built from silicon (a high index dielectric) combined with different plasmonic metals (gold, silver and aluminum). In order to obtain a strong optical response, it is indeed important that electric and magnetic resonances overlap spectrally, which requires adjusting the metal. Using multipoles expansions obtained from the full-field electromagnetic calculations, we evidence the interplay between different modes that lead to an extremely rich spectral response, which includes narrow spectral features associated with extremely strong near-field. We also observe that the anapole state – usually only seen in pure high refractive index dielectrics – can be excited in the metallic part of the system. The multipoles excited in the dielectric and in the metal interfere in a complex manner, leading to unexpected high-order vector spherical multipolar responses in the far-field. These effects are studied in detail both in the near-field and in the far-field. We also establish a clear link between the responses of individual hybrid meta-atoms and their hybridization into a metasurface as a function of its lattice parameters. In that context, using realistic meta-atom models derived from effectively fabricated nanostructures, we show that the design of metasurfaces can be quite forgiving to fabrication imperfections and inhomogeneous broadening can be kept under control.

Symmetry and Topology in Photonics Nanostructures

Abdoulaye Ndao, UCSD, USA

The quest for smaller, lighter, and more efficient optical components usually comes at the price of reduced functionalities. In this talk, I will provide an overview of how topological approaches to control light-matter interaction enable novel photonic devices with unique features and enhanced performance.

Design and simulation of metasurfaces for OAM beam generation

Arttu Nieminen, Tampere University, Finland
Humeyra Caglayan, Finland

The orthogonal modes of optical beams carrying orbital angular momentum (OAM) provide a robust way for transmitting multiplexed data over the free space. However, current approaches usually rely on bulky optical systems and external laser sources, making their use in integrated circuits/photonics limited. Metasurfaces provide a solution for compact on-chip generation of OAM beams, which is crucial for wide implementation of OAM technologies. OAM beam of any topological charge can be achieved by a suitable arrangement of meta-atoms creating the phase profile of the corresponding OAM mode. This work will present the design of a metasurface consisting of amorphous silicon nanopillars on a sapphire substrate, which is used to generate OAM beams for 1200-1300 nm wavelengths. The OAM beam and generation and propagation are simulated via combination of full FDTD simulations and diffraction integral calculations. Moreover, we present the creation of superposition of OAM beams from a single metasurface by superimposing the phase profile of desired modes on the metasurface design. The design of metasurfaces which can generate OAM beams with high mode purity with low energy cost is crucial for the on-chip implementation of OAM multiplexing for the use of free-space optical communications. Doctoral Researcher.

Leveraging hot-carriers for high performance thermophotovoltaics

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Global energy demands are increasing dramatically, necessitating renewable energy methods like photovoltaics (PV) to operate close to the Carnot limit. Theoretically, the efficiency of a PV cell to convert the radiation coming from the Sun into electrical energy can be as high as 93.3% (Landsberg limit), however, the spectral mismatch between the bandgap of the cell and the solar spectrum bounds its efficiency to 34%. The large discrepancy between these two estimates clearly suggests the possibility of increasing efficiency by implementing different concepts.

Thermophotovoltaics (TPV), in which a thermal emitter substitutes the Sun and provides extensive spectral control, stands out the most with an impressive conversion efficiency of 40%. In principle, a narrowband TPV emitting photons with energy equal to the bandgap of the PV cell can achieve a conversion efficiency close to the Carnot limit, but with zero power density. Broadening the emitter spectrum, on the other hand, boosts power density, but at the expense of efficiency due to the spectral mismatch between the emitter and the PV cell. This trade-off can be overcome by integrating the concept of the hot-carrier solar cell (HCSC) into TPV systems. The idea of a HCSC is to harvest the excess energy the photogenerated carriers gain upon absorbing high-energy photons before they thermalize. Recovering the power lost in thermalization as extra electrical work using energy-selective contacts can theoretically result in efficiencies up to 85%, in solar cells, with the collected energy per extracted electron-hole pair exceeding the bandgap energy. In this work, we consider the impact of suppressing thermalization and extracting hot-carriers in TPV devices. We demonstrate the potential benefits of considering hot carriers in TPV devices, resulting in enhanced power densities and approaching thermodynamic limits, particularly with the use of a broadband thermal emitter.

Solution-derived Lithium Niobate for Nonlinear Metasurfaces

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Lithium Niobate (LN) is a metal oxide characterized by a trigonal crystalline structure, resulting in broken inversion symmetry. Remarkable properties exhibited by this material include ferroelectricity, second order optical nonlinearity (second-order nonlinear coefficient of d33 = 27 pm/V), high-speed Pockels electro-optic effect (electro-optic coefficient r33 = 31 pm/V), a wide transparency range from 350 nm to 4500 nm, and chemical inertness [1].

To date, established nanofabrication techniques for LN metasurfaces primarily employ top-down methods such as focused ion beam milling or electron beam lithography (EBL). While these techniques ensure design reproducibility, they are infrastructure demanding and the spatial resolution for densely packed structures is limited by the side-wall angles. Conversely, bottom-up approaches are time and cost-efficient, yet self-assembly based approaches do not enable deterministic placement of nanoresonators [1].

In this work, we combine the advantages of EBL with the convenient availability of sol-gel derived LN through direct soft nano imprint lithography (SNIL), as explained in [2]. We optimize the sol-gel recipe to achieve the correct stoichiometry, overcoming volatility issues associated with Li+ ions and minimizing the presence of secondary compounds that interfere with the desired nonlinear optical properties. Furthermore, we improve the aspect ratios of the imprinted nanostructures by vacuum treatment of the nanoimprint molds, which generates additional capillary force during molding [3]. For improved optical properties of the imprinted devices, we also develop strategies to minimize residual films.

We demonstrate the potential of this novel fabrication technique by making polycrystalline LN metalenses. The direct SNIL enables to achieve aspect ratios of 2 with critical dimensions below 200 nm without the characteristic side-wall angles of etched LN. The imprinting is reproducing the intended design and yields in a strong second harmonic generation contrast between the fins and the residual layer within the metasurface. The linear and nonlinear beam shaping properties are investigated for various unit cell designs. Leveraging the exceptional nonlinear optical properties and nanometer-sized control over sample morphology, sol-gel derived LN emerges as an optimal candidate for nonlinear meta-optics.

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Intuitive nanostructuring for highly efficient achromatic metasurface design.

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Metasurface elements, based on fixed nanostructures, are inherently limited in terms of dispersion for the design of achromatic components. Looking at the design of a simple metadeflector, achromaticity implies that the wavefront should remain deflected at the same angle for the whole bandwidth, i.e. that the phase shifts are distributed along the interface differently for each of the wavelength of interest (or said differently, the dispersion is spatially distributedchanging). This generally prevents us of reusing the same structure twice, and therefore the use of simple designs such as nanodiscs. This is why various approaches, based on complex designs with high tunability or multilayer metasurfaces, are generally studied to fabricate achromatic components. Based on these ideas, we present a design method that achieves high achromatic performance in the visible (400-700nm) for polarization-insensitive metasurfaces.

First, based on simple simulations of GaN nanopillars on a sapphire substrate, we select a fixed periodicity pitch of the metaatoms forming the metasurface so as to achieve the highest relative efficiency for all desired wavelengths. From there, we explain the design of a ""super-meta-atom"", defined as a group of 4 nanopillars (2 by 2) linked together by structural bonds. The first advantage of this design is that it is high flexible due to the large number of links available, promising achromatic performance. The second advantage is that we keep having the structures placed according to the periodicity previously selected, which gave the best relative efficiencies for the visible domain.

We therefore generated a dense look-up table of over 5000 different structures using FDTD simulations (open-source python module Meep), with periodic and infinite boundary conditions surrounding the structures. Then, to check whether the infinite-periodic approximation - used for the design of monochromatic metasurfaces - is verified, the simulation of an achromatic cylindrical metalens with a length of 100µm, in the 400-700nm range, was carried out and confirmed the agreement. Finally, we designed, fabricated and optical characterized the achromatic response of our metalens over the 400-700nm spectral region.

Terahertz time domain spectroscopy of a single meta atom coupled to an amino acid crystal

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THz spectroscopy is expected to be valuable for analyzing biological samples. However, far-field spectroscopy techniques such as THz Time Domain Spectroscopy (THz-TDS) are subject to the diffraction limit, which is two orders of magnitude larger than biological objects such as bacteria, cells, proteins, or viruses. Therefore, samples are often in the form of pressed powder pellets or diluted in liquid. However, this approach is limited in cases where the samples are not in sufficient quantity to form a pellet or when the signature depends on the crystalline structure that is absent in the liquid form.

Our approach to surpass the diffraction limit is to place the sample inside a structure to confine the energy from a propagating THz beam. Resonant structures such as Split Ring Resonators (SRRs) can confine an electric field in a deeply subwavelength volume. However, such experiments are typically done with a large array of SRRs on which the particles are randomly distributed. This means that each SRR is coupled to the particle in a different way, and has a different response. Therefore, measuring the array altogether only gives access to an average of many different responses, which is not suitable for quantitative measurement of the particle properties. Extracting the particle properties from a measurement on SRRs requires either to have each SRR identically coupled to the particles, or to perform the experiment on a single SRR.

In this abstract, we demonstrate THz-TDS performed on a single SRR coupled with a glutamic acid (GA) crystal. We show how the correction of a systematic error coming from TDS systems allows us to extract the SRR signal from the large background signal and how stuffing the SRR with GA allows us to get information from the sample.

Thanks to this approach, we successfully demonstrated that commercial THz-TDS systems are sensitive enough to detect the weak signal from a single subwavelength SRR, even on a transparent sample with a large background signal. This enabled the extraction of the resonance parameters of GA from less than a microgram of material. The possibility to accurately detect the signal from a single SRR opens the way to new experiments such as probing the vibration mode of single proteins, ultra-strong coupling with single biomolecules, and testing the spatial range of delocalized vibration in crystals.

Optical metasurfaces saving energy in optical computing and photovoltaics

Albert Polman, NWO-Institute AMOLF, Netherlands

"I will present our recent collaborative work on the design, fabrication and operation of silicon-based optical metasurfaces that perform mathematical operations in an analog way, using light fields as input and output signals. We show how the interplay between scattering components in silicon metasurfaces creates a mathematical derivative on an input image. We then design and fabricate a silicon metasurface that solves an integral equation by using visible light in which we use grating orders as input and output ports on a periodic metasurface with a specially tailored unit cell. The new analog optical computing concepts operate with very low energy consumption, at the speed of light, and can form the basis of more complex geometries solving multiple equations and can be applied in optical neural networks, control systems, and more.

In the second part of the talk I will introduce an integrated near field/far-field multiple scattering formalism to control the absorption of light in solar cells. We design and fabricate a metallodielectric metasurface back contact for an ultra-high efficiency InGaAs/InGaAsP/Si multi-junction solar cell and enhance the light trapping inside the silicon bottom cell by multiple scattering, creating a record photovoltaic energy conversion efficiency for silicon-based multifunction solar cells of 36.1%.

Understanding the influence of symmetry and connectivity on the plasmonic environment in complex plasmonic antennas based on undirected graphs

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Natural transportation networks, such as some species of lichens, fungi or corals, show a variety of outstanding properties, notably their adaptability in a dynamic environment and resistance to perturbations due to inherent redundancy.
Here, we study the plasmonic environment of various plasmonic antennas, based on undirected networks, namely small-world networks, Cayley trees, Voronoi diagrams and giant components in random binominal graphs. Such model complex antenna structures appear promising as building blocks for plasmonic metasurfaces, whose optical response could be engineered by tuning a plethora of knobs, such as local connectivity or broken symmetries, which are not accessible for simple meta-atoms.
The localized surface plasmon resonances sustained by these complex antennas were studied by electron energy loss spectroscopy (EELS), which allows to probe the photonic local density of states with sub-nanometer resolution. EELS spectra and maps of the model nanostructures were simulated using a boundary element method.
EELS analysis revealed plasmon resonances in the IR and visible regions of the electromagnetic spectrum, in good accordance with simulations of comparable size and geometry. Voronoi networks exhibited excitation of modes at the same energy in different-sized edges and junctions, suggesting the occurrence of a collective plasmonic network response.
A clear redshift in the resonance energy was noted when increasing the size of Cayley tree nanostructures. Higher order modes appeared with the addition of edges to a tree. The evolution of the plasmonic response of such structures when modifying their local connectivity was investigated.
In random binomial graphs, collective surface plasmon modes were observed for graphs with high connectivity, while in the lower connectivity ones the dipolar modes of individual disconnected edges seemed to dominate.
This work demonstrates the value of simple 2D model nanostructures to deepen our understanding of the relation between topology and surface plasmon resonances in complex network nanostructures. EELS proved to be a profitable tool to this aim, allowing to map plasmon resonances of aluminum nanostructures down to extremely low electron energy losses and with high spatial resolution.

Reverse engineering of the structured color and iridescence of metasurfaces

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Sustainable And Bio-inspired Materials, Max Planck Institute of Colloids and Interfaces "Recent advances in the field of metasurfaces have opened up new avenues for the manipulation of light at the nanoscale, offering unprecedented control over optical properties. Conventionally, researchers have predominantly focused on simulating and characterizing metasurface responses under specific illumination and viewing conditions. Alternatively, numerical optimizations are utilized for designing a desired functionality. Exploring the recent advances in analytical description of metasurface response under arbitrary illumination, a novel approach emerges – the analytical reverse engineering of metasurface response. In this approach, the intricate relationship between the basic block of the metasurface (the nanoparticles) and its arrangement is analytically linked to the optical response of the metasurface, enabling the reverse engineering of metasurface recipes for desired optical effects.

The study exploits the recently developed analytical tools (cf. https://onlinelibrary.wiley.com/doi/full/10.1002/adom.202102059) to predicatively design metasurfaces that yield specific colors and iridescence profiles. The research bridges the gap between simulation and design by introducing a novel framework that translates desired color and iridescence outcomes into metasurface parameters.

The primary focus of this investigation lies in periodic metasurfaces, where the existing analytical equations enables a systematically reverse engineer metasurface design for specific color and iridescence profile. Exploiting the analytical equations, the given target optical profile is analytically broken down to the design of a single nanoparticle. Instead of starting from a known design parameter (nanoparticle size, material, lattice constant, illumination/viewing angle) and simulating it, we start from the desired optical response. This process cuts the computational burden from the simulation of an infinite number of design parameters (nanoparticle shape, size and material, embedding material, lattice constant) to the reverse design of a single particle. The single particle, represented by a polarizability tensor, is designed using shape optimization methods. For nano particles with spherical symmetries (e.g. homogenous and core-shell particles), a Mie angle method can be utilized (https://doi.org/10.1364/OE.390331).

This research not only deepens our understanding of light-matter interactions but also empowers researchers and engineers to tailor light with unprecedented flexibility.

Metasurfaces to shape free-electron--light interactions

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Metasurfaces have become over the past decade a paramount technology, enabling, among other things, the design of novel light sources, detectors, and devices controlling the polarization, spectral, and angular distribution of light. Metasurfaces can tailor the interaction of light with matter, either by shaping light propagation at the nanoscale, or by controlling emission from atoms and molecules. In this talk, I will show how metasurfaces can be designed to enhance and tailor radiation from a completely different type of emitter: free electrons flying in their vicinity. I will present a framework to model, tailor, enhance, and even optimize radiation from free electrons (and other high-energy particles) interacting with nanophotonic structures like metasurfaces. I will then describe the building of a featured experimental setup to record spectrally-resolved light emission from free electrons interacting with nanophotonic structures. I will utilize these methods to demonstrate metasurfaces (1) that can control the spectral and angular distribution of free-electron radiation, realizing free-electron “metalenses”; (2) enhance the emission from free electrons by several orders of magnitude by utilizing flatbands.

Optical metasurfaces for levitodynamics

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Optical metasurfaces are a hot topic of current research due to their ability to manipulate light at sub-wavelength scale [1]. By assembling a periodic or quasi-periodic array of carefully chosen light scatterers [2], one can engineer phase, amplitude, and polarization of incoming light, thus creating arbitrary complex phase profiles [3]. Furthermore, it offers the possibility to control the near-, intermediate, and far-field [4].

These metasurfaces are used to redesign classical optical components, such as high NA lenses with negligible aberration [5], polarization-sensitive metasurfaces with a tunable intensity profile based on the incoming light polarization [4], or achromatic and dispersion engineered metasurfaces for polychromatic laser driving [6] beyond many other applications.

In the context of levitation optomechanics, metalenses promise robust trapping performance and effective detection of the particle motion, while providing a small volumetric footprint and might have the potential of better performance in comparison to standard optics in the future. Furthermore, metalenses might be particularly suitable to study classical nonlinear or time dependent dynamics with levitated nanoparticles.

Here, we present the design, simulation, and characterization of a highly transmissive silicon-on-insulator metalens with a focal length f = 100 µm and a numerical aperture NA = 0.9 for operation in the near-IR. This metalens traps optically a silica nanoparticle at ambient pressure and at high vacuum; we determine the trapping frequencies and the signal-to-noise ratio of the particle motion. Furthermore, the metalens allows the integration with RF-electrodes on the same chip for enhanced nanoparticle control in dark potentials.

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Digitized Metamaterials Enabled Ultra-Miniaturized Waveguide Crossings in One-Dimensional Grating Waveguides

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The pursuit of compact, low-energy silicon photonic waveguide crossings is becoming more challenging due to silicon's limitations, notably its lack of a direct band gap and weak second-order nonlinearity, in response to the growing need for on-chip optical routing and cross-connectivity. Currently, while a number of crossings have been devised for multimode and photonic crystal waveguides by applying principles from single-mode waveguide crossings, the design of such crossings in one-dimensional grating waveguides, frequently utilized in optical true time delay line systems, has yet to be achieved. This challenge is rooted in the significant asymmetry exhibited by Bloch mode profiles in these waveguides, which is a consequence of their steeper dispersion relationship and higher group velocity, causing these guided modes to be compressed toward the outer sidewall. Therefore, we propose and demonstrate, for the first time to the authors' best knowledge, ultra-miniaturized, ultra-low loss waveguide crossings based on digitized metamaterials for an extensively corrugated one-dimensional grating waveguide on silicon-on-insulator (SOI) platform with a footprint of only 2.1 × 2.1 μm^2. The proposed silicon waveguide crossing comprises a digitized metamaterial situated within its central intersection zone, along with the inclusion of four one-dimensional grating waveguide structures that are interconnected at the four respective ports. The crossing structure exhibits a cumulative insertion loss of -0.46 decibels and possesses the capability to sustain an exceptionally broad bandwidth, spanning from 1500 to 1600 nanometers, as demonstrated in numerical simulations. In the characterization of the fabricated device, it is observed to have an insertion loss of -1.32 decibels within the wavelength range of 1530 to 1580 nanometers (limited by the experimental setup). To validate the reciprocity of the designed meta-structure, identical inputs are applied to four distinct channels, and subsequent measurements affirm its reciprocal performance with a minimal error margin of 0.02 percent. Furthermore, the efficacy of the engineered metamaterial structure has been enhanced through the utilization of the aluminum hard mask technique for shaping the cladding layer, in contrast to the traditional unetched cladding-based photonic manufacturing process.

THz metasurfaces for ultrastrong light-matter coupling

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Sub-wavelength electromagnetic field localization is a central theme in photonic research, as it allows sensing capabilities as well as increasing the light-matter coupling strength [1]. Recently, the strong and ultrastrong light-matter coupling regime in the THz range with split-ring resonators coupled to magnetoplasmons has been widely investigated, achieving successive world-records for the largest light-matter coupling ever achieved. In this talk, I will review the work we conducted in coupling the near-fields of strongly subwavelength THz metallic resonators to electronic transitions. Particularly, I will discuss ultrastrong light-matter coupling using the Landau polaritons platform [2]: different implementation with direct and complementary metasurfaces will be presented, as well as superconducting metasurfaces based on Type-II and high Tc superconductors. Ever-shrinking resonators have allowed to approach the regime of few electrons strong coupling, in which single-dipole properties can be modified by the vacuum field [3]: few electrons [4,5] ultrastrong coupling experiments in metallic cavities will be presented. Finally, I will discuss experiments reporting spectroscopy of a single, ultrastrongly coupled, highly subwavelength complementary resonator (cSRR) operating at 300 GHz [6]. By using a combination of immersion lenses we unravel the linewidth dependence of planar metamaterials as a function of the meta-atom number indicating quenching of the superradiance. On these grounds, we investigate ultrastrongly coupled Landau polaritons at the single resonator level , as well as discussing spectroscopy of exfoliated 2D materials

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Resonant absorption and harmonic generation in aluminum nanolayers and nanostructures

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Unlike most noble metals, which display Lorentz-like behavior (interband transitions) in the UV range, aluminum is characterized by an absorption resonance near 810nm, which uncharacteristically splits the plasmonic range, and sets its linear and nonlinear optical properties apart. Indeed, while studies of aluminum nanostructures having complex three-dimensional topologies abound, in view of reported inconsistencies in the spectral response, the basic nonlinear optical properties have yet to be explored and compared in detail with the properties of other better-known materials. Thus, the possibility of realizing new UV sources, which for example may be useful for underwater communication, disinfection, fluorescent microscopy, anti-forgery, and precise optical measurements, to name a few. Here we report experimental observations of second and third harmonic generation from aluminum nanolayers, accompanied by a theoretical treatment using a hydrodynamic-Maxwell approach that accounts for linear and nonlinear material dispersions, and all relevant surface and bulk nonlinearities. Our results point to unusual consequences of resonant absorption, namely an unexpected yet critical role that bound electrons play especially for nonlinear interactions across the optical spectrum, leading us to the following conclusions: (1) aluminum may not behave like an ordinary free electron system, with repercussions on both linear and nonlinear light-matter interactions; (2) the influence of bound electrons should not be either excluded or discounted even at wavelengths where pure plasmonic behavior is expected; (3) an open channel of energy flow in the bound electron dynamics can either act like a controlling catalyst or completely dominate the interaction.

All-Optical Tunability of Metalenses Permeated with Liquid Crystals

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Metasurfaces have been extensively engineered to produce a wide range of optical phenomena, allowing exceptional control over the propagation of light. However, they are generally designed as single-purpose devices without a modifiable postfabrication optical response, which can be a limitation to real-world applications. In this work, we report a nanostructured planar-fused silica metalens permeated with a nematic liquid crystal (NLC) and gold nanoparticle solution. The physical properties of embedded NLCs can be manipulated with the application of external stimuli, enabling reconfigurable optical metasurfaces. We report the all-optical, dynamic control of the metalens optical response resulting from thermoplasmonic-induced changes of the NLC solution associated with the nematic−isotropic phase transition. A continuous and reversible tuning of the metalens focal length is experimentally demonstrated, with a variation of 80 μm (0.16% of the 5 cm nominal focal length) along the optical axis. This is achieved without direct mechanical or electrical manipulation of the device. The reconfigurable properties are compared with corroborating numerical simulations of the focal length shift and exhibit close correspondence.

Solution-derived Barium Titanate as a Platform for Nonlinear Photonic Devices

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Solution-derived Barium Titanate as a Platform for Nonlinear Photonic Devices
Barium titanate is a metal-oxide that has outstanding optical properties with reported electro-optic modulation coefficient ranging from r42=1300 pmV-1 in bulk crystal to 37 pmV-1 in nanoparticle films, a second order nonlinear coefficient of d15=15.7 pmV-1, transparency down to 360 nm and a refractive index above 2 in the visible wavelength range [1]. Similar to other ceramics, it is also known for its large laser damage threshold, high mechanical stability and chemical inertness. These material properties and the limited availability of crystalline thin films make conventional top-down nanofabrication of barium titanate devices inherently challenging.
To circumvent these issues, we propose a fabrication platform that combines solution derived barium titanate with soft nanoimprint lithography. The scalable method enables to fabricate micro- to nanoscale structures using advanced e-beam or deep-ultraviolet lithography tools in standard silicon substrates, and subsequently transferring the same design to the desired metal-oxide. Here, we investigate the optical properties of sol-gel barium titanate by characterizing the crystallinity, refractive index, second harmonic generation and electro-optic modulation efficiency.
The barium titanate precursor solution solidifies within the nanostructured mold, enabling high conformity to the design and smooth sidewalls [2]. We demonstrate highly tunable metasurface arrays with minimal critical dimensions of 60 nm and aspect ratios of 7. Barium titanate pillars and nanoholes in a slab can be achieved, which are the first building blocks for more complex metamaterial designs [3]. We have shown how resonant nanohole arrays increase the second harmonic generation efficiency by an order of magnitude. Resonant pillar arrays enable to enhance electro-optic modulation efficiency providing a scalable fabrication platform for active metadevices. Additionally, the imprint lithography is highly compatible with layer-by-layer fabrication providing a fabrication route for 3D nonlinear photonic crystals. From a theoretical point-of-view, the technique provides a platform for complex polycrystalline nonlinear photonic devices for investigation of higher order light propagation in disordered media [4]. We introduce details of nanoimprint lithography by nanostructure design governed sol-gel recipes and strategies to enhance the crystalline properties through annealing and substrate optimization.

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Terahertz metamaterials with ultra-subwavelength confinement for quantum devices

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Metamaterials, consisting in the periodic repetition of artificially designed meta-atoms with dimensions much smaller than the wavelength of interest are often described as high frequency inductor-capacitor (LC) resonators sustaining a resonance. The peculiar ability of metamaterials to efficiently confine the electromagnetic field on a subwavelength scale is at the heart of their macroscopic behavior, and opens new prospects for optoelectronic devices. The LC circuit concentrates the electric field in an extremely small effective volume linked to its capacitive parts. Light-matter interaction occurring in the coupling between an absorber/emitter and the electric field of the capacitors circuit scales as the inverse of the square root of the capacitor volumes and can thus be strongly enhanced.
I will describe the development of a three-dimensional TeraHertz metamaterial LC resonator strongly subwavelength capacitors. This type of structures has been specifically designed for quantum heterostructures that sustain optical activity in the Terahertz frequency range. This metamaterial architecture allows for many degrees of freedom, and in particular its radiation loss can be tailored in a very controllable way. Such metamaterials have recently been used for THz quantum well detectors with reduced dark current. In such structures, we have also experimentally observed the ultra-strong light-matter coupling regime: a peculiar regime of interaction where the vacuum Rabi splitting of the coupled system is comparable to the frequencies of the uncoupled oscillators. I will also discuss the possibility to observe the quantum fluctuations of the light-matter coupled states in such metamaterials.

Templated Dewetting as a Scalable Fabrication Platform for All-Dielectric Metasurfaces

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All-dielectric and optical metasurfaces have emerged as a promising alternative approach to traditional bulky photonic devices. Such metasurfaces consist of precisely arranged nanoparticles that act as tuneable resonant light scatters, thus providing a complete control on light emerging from those surfaces at a reduced scale. However, high-resolution manufacturing methods are required, which typically comes along with limitations in terms of cost and throughput. Recently, we introduced an innovative fabrication method for high-index dielectric nanostructures, leveraging controlled fluid rearrangement via pattern-directed dewetting of thin amorphous optical glass films (Das Gupta et. al., Nature Nanotechnology 2019). By optimizing process-flow parameters, this fabrication method can yield state-of-the-art photonics metasurfaces, matching the performance of traditionally made counterparts created via lithographic processes.
As an initial step of the proposed process flow, a nano-imprinted substrate featuring a periodic array of nanostructures is replicated from a master, offering a platform for process scalability. Next, a thin layer of optical glass is evaporated and thermally annealed above its glass transition temperature. This process results in a fluid-dynamic rearrangement of the glass film, yielding low-roughness, curved nanostructures with different predictable shapes (L. Martin-Monier et. al., Phys. Rev. Applied 2021). A variety of optical nanostructures can be realized with this approach, which relies on high-resolution yet cost-effective and scalable fabrication methods.

This novel fabrication approach paves the way towards various photonics applications. We first present the successful creation of a nano-antenna array comprised of rounded selenium nanoparticles formed via pattern-driven dewetting, located atop a 350nm periodic array of inverted pyramids. This configuration achieved complete backscattering, with experimental specular reflection reaching 98% at 660nm in the visible spectrum. Engineering the substrate itself, second harmonic generation was also achieved from similar structures (Das Gupta et. al., Nanophotonics 2021). We also engineered near-infrared resonances in a 1µm periodic array of As_2Se_3 glass nanoparticles, exploiting them to monitor the change of refractive index in an analyte solution flowing upon the metasurface. As the analyte solution's refractive index increased, we observed a significant shift in the transmission spectrum, achieving a high BRIS value of more than 800nm/RIU. Lastly, we propose to use this technology to realize efficient, large-scale metalenses to magnify light for applications in the visible.

Nonlinearities in Metasurfaces

Maria Antonietta Vincenti, University of Brescia, Italy

Metasurfaces are two-dimensional arrays of subwavelength optical resonators, designed to achieve specific functionalities by exploiting the properties and the interaction of their meta-atoms. While they were originally investigated as planar realization of metamaterials mostly to understand the properties of their bulk counterparts, they have soon emerged for their unique frequency and polarization responses. Moreover, thanks to their unprecedented control over light-matter interaction at the nanoscale, they have also been pinpointed as promising candidates to boost nonlinear optical interactions. This is mainly due to their ability to enhance field localization in extremely small volumes and their flexibility in terms of combining different materials within the same nanostructure. All these features allow to overcome the inherently weak nonlinear response of natural materials and to go beyond the need for bulky optical components and complex phase-matching techniques.
In this tutorial presentation we will overview the key concepts, applications, and challenges associated with nonlinear processes in metasurfaces. More specifically, we will first review the type of nonlinear interactions that have been investigated so far in those nanostructures, including harmonic generation, frequency mixing and nonlinear wavefront shaping. We will then try to understand how those nonlinear processes relate to specific applications, such as ultrahigh-resolution imaging, nonlinear microscopy, and quantum photon sources, to name a few. Finally, we will go through the main challenges that remain in the development of practical nonlinear metasurfaces: we will focus on the role of optical losses and how they limit the efficiency of metasurface-based devices and on the limitations imposed by current fabrication technologies.

Transformation and measurement of multidimensional quantum states of light with metasurfaces

Kai Wang, McGill University, Canada

Photons promise important roles in quantum technologies owing to their versatile degrees of freedom that can encode information in multidimensional quantum states. Traditional methods to control and measure such photonics states based on bulk optical elements are cumbersome, error-prone, and inefficient. Recent progress in nanostructure metasurfaces promise unparalleled precision and flexibility in controlling light in all degrees of freedom, offering advantages in efficiency, miniaturization, and scalability. While most of the effort in developing metasurfaces focused on classical light, designing metasurfaces for quantum photonics is playing an enabling role in changing the way we control and measure quantum states of light.

In this talk, I will present some of our results that leverage optical metasurfaces to mediate the interference, tomographic measurement, and nontrivial transformations of quantum states of light encoded in the polarization, photon number, and spatial degrees of freedom. These results point to a pathway toward using meta-optics to advance the generation, control, and measurement of quantum states of light across many platforms.

Electro-optic Modulation of Sol-gel Barium Titanate Nanostructures

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The shift to high-speed and efficient data transmission has been enabled by the ability to efficiently transfer signals between electronic and optical devices. The prevailing technology platform to reach modulation speeds of several GHz is exploiting the electro-optic Pockels effect present in non-centrosymmetric crystals. The rather small modulation strength by this effect can be compensated by increasing the interaction length or by engineering resonant structures like metasurfaces to enhance the light-matter-interaction. Well-known electro-optic materials include lithium niobate or barium titanate (BTO). However, those metal oxides are inherently chemically inert and mechanically stable, which makes top-down nanofabrication challenging.
Here, we present electro-optic modulation by a BTO metasurface made via soft nanoimprint lithography. Our previous work has shown how this method enables to produce resonant nanohole arrays which enhance the second harmonic generation efficiency compared to an unstructured slab [1]. To demonstrate the flexibility and scalability of the bottom-up fabrication technique, we fabricate arrays of individual 50x50 µm2 large BTO metasurfaces consisting of pillar-shaped unit cells with highly tunable resonances in the visible and near-IR wavelength range, by sweeping periodicity (400-800 nm) and pillar diameter (70-200 nm). While soft-nano-imprint lithography is compatible with arbitrary substrates, we choose crystalline magnesium oxide for lattice matching reasons.
We demonstrate electro-optic modulation of a metasurface (p=600 nm, d=240 nm) with a resonance in the transmission spectrum at 1050 nm (quality factor of 56). An electric field along the device plane is applied across the metasurface and the modulation is measured by monitoring the transmission of a 1064 nm laser diode upon application of an AC electric field. The modulation is monitored with a lock-in detection scheme while applying a large DC bias of 60 V (1V/µm) to align the polycrystalline BTO domains. The modulation strength is comparable to the modulation of a top-down fabricated LNO metasurface reported in literature [2]. A weaker modulation is observed by off-resonant metasurfaces or by a thin film suggesting that the modulation is enhanced by the resonant nanostructures. This electro-optic metasurface therefore successfully combines large-scale nanofabrication and active modulation, with numerous applications like beam-steering or display applications yet to be explored.

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3R-MoS2: A New Platform for Nanoscale Entangled Photon-Pair Generation

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Transition metal dichalcogenides (TMDs) like molybdenum disulfide (MoS_2) have evolved into an efficient platform for classical nonlinear processes, owing to their excitonic resonances and high nonlinear susceptibility. Further enhancement and control of nonlinear frequency generation is achieved by combining monolayer TMDs with resonant photonic metasurfaces [1] or directly fabricating metasurfaces from thicker TMD crystals [2]. A very interesting application of these TMD-based nonlinear systems would be the generation of entangled photon-pairs, which are at the core of many applications in quantum optics. However, up to now photon-pair generation e.g. based on spontaneous parametric down-conversion (SPDC) in TMDs could not be experimentally demonstrated, mainly due to the limited overall signal yield from ultra-thin mono- and few-layer TMDs with second order nonlinearity. In this work, we use MoS_2 in its 3R-phase, a layer-stacking configuration that maintains the second-order nonlinear response also in more efficient, moderately thicker crystals [3], and experimentally demonstrate the generation of several, maximally polarization-entangled quantum states via SPDC.

We use a mechanically exfoliated, unstructured 3R-MoS_2 crystal with a mean thickness of 280 nm and excite SPDC via a cw-laser with wavelength 788 nm. The measured coincidence-to-accidental ratio (CAR) of CAR~9 is a clear signature of a nonclassical down-conversion process. Using fiber spectroscopy, we measure that the generated photon pairs span a broad bandwidth from 1350 nm-1900 nm.

The basis for the intrinsic generation of polarization entanglement in 3R-MoS_2 are the in-plane nonlinear tensor components of the crystal. We show theoretically and experimentally that its C3v point-group tensor enables with equal efficiency the generation of different, maximally entangled Bell states, which can be tuned using the pump polarization. The state fidelity F measured in our quantum state tomography experiment reaches up to F=0.96.

In sum, we demonstrate for the first time the generation of polarization entangled photon-pairs from a thin TMD crystal. The intrinsic generation of polarization entanglement, without further optical components needed, combined with its high refractive index and nonlinear susceptibility, renders

3R-MoS_2 a very promising material platform for fabricating nonlinear quantum metasurfaces [4] which can potentially generate complex, hyperentangled quantum states.

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Configurable structural colors in a dielectric nanocup metasurface with order-disorder transition

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Color identification is a critical part in visual perception. We intuitively associate “STOP” with a red traffic light or “inedible” with a green tomato. The generation of color and the associated light-matter interactions keeps inspiring research and development in nanophotonics. Especially, the design of photonic systems that enables access to the full color gamut remains on ongoing challenge.

Here, we develop a platform to generate the entire range of colors based on the material couple silicon - aluminium brass. We start with an asymmetrical optical nanocavity based on an ultra-thin amourphous silicon layer (>25 nm) on top of an aluminium brass backreflector, allowing for large scale angle independent optical coatings. For local color control, we transform the silcon layer into a metasurface, i. e. array of nanocups, where control over the perceived color of the arrays is readily achieved by altering the nanocup dimensions. Furthermore, we show, that the color gamut can be extended, by coupling the optical mode of the metasurface to a broadband cavity (network metamaterial), which is engineered by chemical dealloying.

The complex metasurface introduced here, can serve as a testbed to study the light matter-interaction and mode coupling of ordered and disordered components in photonic systems.

Metasurface for multidimensional light field sensing

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Conventional camera systems can only detect light intensity while losing important information about the target scene, including depth, polarization, and spectrum. In order to further obtain the multi-dimensional light-field information of the target object, it is often required to use bulky and expensive instruments. Metasurface is composed of an array of optical antennas that can manipulate the amplitude, phase, polarization, and spectrum of light at the subwavelength scale. By replacing conventional diffractive of refractive elements with metasurfaces in imaging systems, one may be able to build optical sensors for high-performance multidimensional light sensing with low size, weight, power, and cost. Here, I will present our group’s recent effort to replace conventional camera lenses with metalenses. By leveraging the unique capability of metasurface to tailor the vectorial field of light, in combination with an advanced image retrieval algorithm, we aim to build compact camera systems that can capture multi-dimensional light field information of a target scene in a single shot under ambient illumination conditions. Specifically, I will show how we use a polarization-multiplexed metalens for imaging through turbid water (Laser & Photonics Reviews 15, 2100097 (2021)). Recently, we further extended such a concept to build a monocular camera that can capture a 4D image, including 2D all-in-focus intensity, depth, and polarization of a target scene in a single shot (Nature Communications 14, 1035 (2023)). I would also like to present our effort to commercialize flat-optics-based passive monocular 3D cameras, which drastically differ from existing 3D imaging hardware, including LiDAR and binocular cameras. The miniaturized 3D camera module may be seamlessly integrated with smartphones, AR/VR headsets, and robots for a variety of applications, including face and gesture recognition, spatial localization and mapping, and collision avoidance.

Planar tunable polarization-dependent 16-band filters based on DBR-metasurface-DBR structures for integrated image sensors

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We design and experimentally demonstrate a planar polarization-dependent 16-band wavelength selective filter with a DBR-metasurface-DBR structure. DBR comprises 3.5 pair Si/SiO_2 multilayers, the metasurface comprises Si grating structures with different width, which are then flattened by SiO_2. Wavelength selectivity and tunability are achieved by top and down symmetric DBR and different Si grating widths. A 16-band planar filter is fabricated with one single e-beam lithography step confirming the expected wavelength selectivity and tunability. We discuss several key parameters for DBR-metasurface-DBR filter design. The structure with thinner cavity layer results in higher tunability. We also discuss polarization dependency by comparing the spectral response and the electric field density inside the structure under TE-and TM-polarization. The DBR-metasurface-DBR structure shows a similar FP resonance under TE-polarization and Talbot effect under TM-polarization. We measure the transmittance response under arbitrary polarization angle and we reconstruct the polarization angle through the measured spectrum. By simulating electric field propagation inside the structure, we compare the design structure with FP resonance and observe the Talbot effect in the bottom DBR under TM-polarization. This structure opens the doors to lab-on-chip applications, polarization dependent imaging and other novel imaging applications related to planar optics.