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BOOK OF ABSTRACTS

4th Smart Nanomaterials: Advances, Innovations and Applications
Online-Onsite Conference
7-10 December 2021

This book includes only the abstracts presented at the online-onsite SNAIA 2021 Conference

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PLENARY

7-10 December 2021
Chimie ParisTech, Paris

The rise of Mie-tronics and metaphotonics

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Recent progress is nanoscale photonics is driven by the physics of Mie-resonances of high-index dielectric nanoparticles that provides a novel platform for localization of light in subwavelength photonic structures and opens new horizons for metamaterial-enabled photonics, or metaphotonics. In this talk, I will review the recent advances in Mie-resonant metaphotonics (also called "Mie-tronics") for isolated high-index dielectric nanoparticles and nanoparticle structures such as dielectric metasurfaces, and its applications to nonlinear, active, and topological photonics [1,2].

Also, I will introduce a novel physical mechanism for achieving giant quality-factors (Q factors) in finite-length periodic arrays of subwavelength optical resonators. The underlying physics is based on resonant coupling between the band-edge mode and another standing mode in the array and the formation of localized states with dramatically suppressed radiative losses.

Also, I will discuss the physics of photonic bound states in the continuum (BICs) and their applications to metadevices, including enhancement of nonlinear response, light-matter interaction, and development of active nanophotonic devices. I will discuss how BIC-empowered dielectric metastructures can be used to generate efficiently high-order optical harmonics from bulk and to boost the intrinsic nonlinearity of transition metal dichalcogenide flakes. Finally, I will demonstrate how tunability of BICs in the momentum space can be employed to realize a novel type of efficient nanolasers based on a finite-size cavity with a small footprint.

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Photonic Crystals as Non-Local Meta-surfaces and Topological Crystals

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Classical optical devices and conventional meta-surfaces modulate and route electromagnetic beams by modulating field amplitudes and phases locally at different positions in real space, and the beams are consequently refracted. Here we propose that beam modulations can be done in the momentum space in a non-local way. Instead of refracting the beams, normally incident beams can be shifted by applying the geometric phase gradient induced by momentum-space polarization field of a photonic crystal slab. We will also briefly review how simple dielectric photonic crystals can be used to manifest topological physics.

Liquid Light Computing: from logic to analogue simulation

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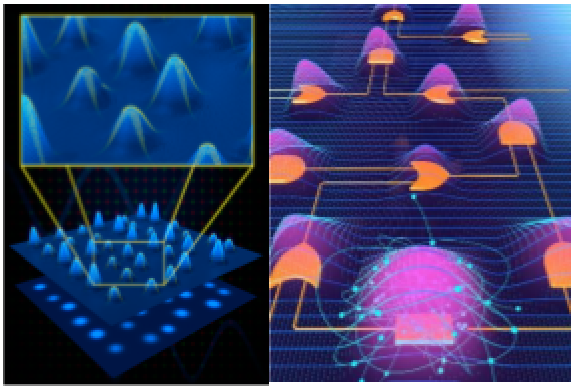
Modern digital computers have changed our lives in a variety of ways, but the technology on which they are built is rapidly reaching a hard limit due to inherent quantum effects. Two of the main pillars of our modern digital computers are the electronic transistor and the von-Neumann computer architecture. While the von-Neumann architecture established the physical separation of computing tasks like storage and processing, transistors are the fundamental building blocks in digital computers. The drive for faster and more powerful computers can be realised by increasing the number of transistors in a processor and the clock frequency. However, Moore's law will soon come to an end, whilst the breakdown of Dennard's scaling law means that clock frequencies have remain unchanged since 2006. This leads to the pressing quest to develop new kinds of transistors and alternative computing architectures that could one day lead to more efficient computers.

In our labs, we combine state-of-the-art photonic structures and light emitting semiconductor materials in which light and matter fuse to form new types of particles called polaritons. In a sense, polaritons bridge the fields of electronics and photonics by controlling the amount of light vs matter in these hybrid particles. At high densities, polaritons undergo 'condensation' forming micron scale droplets of liquid-light, with all particles within the droplet being coherent and indistinguishable from one another. In this seminar, I will describe the fundamental properties of such liquid-light droplets, aka polariton condensates, and their applications both in analogue (simulators) [1,2] and digital computing (logic) [3,4].



Schematics of (a) a liquid light analogue simulators, (b) liquid light circuit for digital computing

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Computing Fabrics

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Fabrics cover a truly valuable real estate - the surface of our bodies. Exposed to troves of data, important health insights would be revealed if only fabrics could compute: sense, store, analyze, infer, alert, and act while retaining their aesthetics, comfort and resilience. A fiber centric blueprint for appreciating the value of fabrics will be presented leading to the anticipated transformation of fabrics from a goods-based to a services and experiences industry.

"Carbon Nano Onion - a nanoscale material with bio at heart"

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There are many issues associated with free drug delivery including: adverse side-effects, multi-drug resistance, premature drug degradation, lack of tissue penetration, and non-specific toxicity. Targeted delivery, which utilises nanocarriers as payload delivery vesicles, has the potential to address and alleviate these prominent issues. Specifically, it involves nanomaterials functionalised with targeting agents, allowing for the selective uptake of these nanocarriers by cells overexpressing specific receptors. This approach explicitly increases the drug concentration in the target cell of interest whilst minimising the exposure of healthy cells to the therapeutic agent.

In this presentation, carbon nano-onions (CNOs) will be discussed as a potential vesicle for nanocarrier-type drug delivery systems.[1] CNOs, or multi-layer fullerenes, consist of multiple concentric layers of sp^2 hybridised carbon and are emerging as platforms for biomedical applications because of their ability to be internalized by cells and low toxicity. [2]

In my research group we have developed a synthetic methodology for the synthesis of pure, monodispersed CNOs and various chemical functionalization strategies for the introduction of different functionalities (receptor targeting unit and imaging unit) onto the surface of the CNOs. The modified CNOs display high brightness and photostability in aqueous solutions and are selectively taken up by different cancer cell lines without significant cytotoxicity. [3]

We have also developed supramolecular functionalization with biocompatible polymers as an effective strategy to develop engineered drug carriers for targeted delivery applications. We reported the use of a hyaluronic acid-phospholipid (HA-DMPE) conjugate to target CD44 overexpressing cancer cells, while enhancing solubility of the nanoconstruct. Non-covalently functionalized CNOs with HA-DMPE show excellent *in vitro* cell viability in human breast carcinoma cells overexpressing CD44 and are uptaken to a greater extent compared to human ovarian carcinoma cells with an undetectable amount of CD44. In addition, they possess high *in vivo* biocompatibility in zebrafish during the different stages of development suggesting a high degree of biosafety of this class of nanomaterials. [4]

To probe the possible applications of CNOs as a platform for therapeutic and diagnostic interventions on CNS diseases, we injected fluorescent CNOs *in vivo* in mice hippocampus. We analyzed *ex vivo* their diffusion within brain tissues and their cellular localization by confocal and electron microscopy. The subsequent fluorescent staining of hippocampal cells populations indicates they efficiently internalize the nanoparticles. Furthermore, the inflammatory potential of the CNOs injection was found comparable to sterile vehicle infusion, and it did not result in manifest neurophysiological and behavioral alterations of hippocampal-mediated functions [5].

We recently synthesised Boron/nitrogen co-doped carbon nano-onions (BN-CNOs) and examined their interactions with biological systems. Our study on the toxicological profiles of BN-CNOs and oxidized BN-CNOs in vitro in both healthy and cancer cell lines, as well as in vivo on the embryonic stages of zebrafish (*Danio rerio*) demonstrate that these new class of carbon nanoparticles have high cyto-biocompatibility and a high biosafety [6].

Our results encourage further development as targeted diagnostics or therapeutics nanocarriers.

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KEYNOTE TALK ON MICROSCOPY

7-10 December 2021
Chimie ParisTech, Paris

Nucleosome complexes with proteins and drugs through the prism of spFRET microscopy

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DNA is tightly packed in the nucleus, and special proteins check genome integrity, repair damages and provide controlled access to genomic information intelligently unpacking and packing back DNA. Many of these processes occur at a nucleosome level. Some of the proteins of genome machinery, in particular, histone chaperone FACT (FAcilitates Chromatin Transcription) and poly(ADP-ribose)polymerase 1 (PARP1) are recognized pharmacological targets for anticancer agents, which affect their functioning in the complexes with nucleosomes. Here we discuss how nanophotonics approach based on single particle Förster resonance energy transfer (spFRET) microscopy is used to study nucleosome interactions with proteins and drugs. We designed a set of fluorescently labeled nucleosome nanoparticles of different structure, assembling them from core histones and DNA of variable length containing a strong nucleosome-positioning sequence. A donor-acceptor pair of fluorophores introduced into neighboring gyres of nucleosomal DNA or into linker DNA enables probing of a nucleosome structure. Analysis of FRET at the level of single nucleosomes offers a unique opportunity to reveal various types of complexes with proteins and/or drugs, which are simultaneously formed in solution. We report on structural changes in a nucleosome structure induced by PARP1 and FACT [1, 2]. We also present the results of our studies of (i) curaxin, which disturbs nucleosome structure and promotes FACT-induced nucleosome unwrapping, as well as (ii) PARP1 inhibitors, which trap PARP1-nucleosome complexes [3-6].

The studies were supported by Russian Science Foundation (grant 19-74-30003).

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ALL-DIELECTRIC NANOPHOTONICS

7-10 December 2021
Chimie ParisTech, Paris

Nonclonal metasurfaces

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In this talk, we discuss our recent theoretical and experimental progress in the area of metasurfaces, in particular on the role of engineered nonlocality to enable a new degree of control over spectral and coherent features, in addition to wavefront manipulation.

We demonstrate frequency-selective and wavefront-selective responses based on these principles, of interest for augmented reality and secure communication applications.

We also discuss the impact of these concepts to manipulate thermal emission and photoluminescence and to realize efficient, compact and highly flexible optical sources.

Dielectric Metasurfaces for Enhanced Sensing of Chiral Molecules

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Determining the handedness of chiral molecules plays an important role in chemistry and pharmacy. Optical circular dichroism (CD) spectroscopy is a well-established means for determining the molecule's handedness. Unfortunately, acquiring optical CD spectra can be quite time consuming. This fact asks for means to enhance the CD signal and thereby reduce the measurement times.

Here, we review our recent theoretical work towards using silicon-disk arrays [1] or cavities containing one or two [2,3] such arrays for resonantly enhancing the CD signal in the infrared fingerprint spectral region. Resonant CD enhancement factors exceeding 100 have been obtained. Using the same arrangements, similar enhancements can be obtained for detecting the linear optical polarization rotation [4] instead of the CD signal. Experiments are in progress.

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Light driven microvehicles powered and steered by optical momentum transfer induced by embedded dielectric metasurfaces

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Nanostructured dielectric metasurfaces offer unprecedented opportunities to manipulate light by imprinting an arbitrary phase gradient on an impinging wavefront. This has resulted in the realization of a range of flat analogues to classical optical components, such as lenses, waveplates and axicons. However, the change in linear and angular optical momentum associated with phase manipulation also results in previously unexploited forces and torques that act on the metasurface itself. Here we show that these optomechanical effects can be utilized to construct optical metavehicles—microscopic particles that can travel long distances under low-intensity plane-wave illumination while being steered by the polarization of the incident light [1]. We demonstrate movement in complex patterns, self-correcting motion and an application as transport vehicles for microscopic cargoes, which include unicellular organisms. The abundance of possible optical metasurfaces attests to the prospect of developing a wide variety of metavehicles with specialized functional behaviors.

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Sound Trapping in an Open Resonator

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The ability of extreme sound energy confinement with high-quality factor (Q-factor) resonance is of vital importance for acoustic devices requiring high intensity and hypersensitivity in biological ultrasonics, enhanced collimated sound emission (i.e. sound laser) and high-resolution sensing [1]. However, structures reported so far demonstrated a limited quality factor (Q-factor) of acoustic resonances, up to several tens in an open resonator. The emergence of bound states in the continuum (BIC) makes it possible to realize high-Q factor acoustic modes. Here, we report the theoretical design and experimental demonstration of acoustic BICs supported by a single open resonator [2]. We predicted that such an open acoustic resonator could simultaneously support three types of BICs, including symmetry protected BIC, Friedrich-Wintgen BIC induced by mode interference, as well as a new kind of BIC: mirror-symmetry induced BIC. We also experimentally demonstrated the existence of all three types of BIC with Q-factor up to one order of magnitude greater than the highest Q-factor reported in an open resonator.

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All-dielectric metasurface with correlated disorder as an anti-reflection coating for Silicon heterojunction solar cells

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While witnessing ever-decreasing wafer thicknesses of heterojunction Silicon-based solar cells nowadays, it became necessary to perceive alternative schemes to achieve an anti-reflection structure [1]. Traditional approaches such as individual layers offer a relatively poor performance but texturing the wafer with micro-pyramids becomes increasingly challenging. Here, we summarize our theoretical, numerical, and experimental efforts to solve this issue using all-dielectric metasurfaces designed while guided by helicity preservation principles [2]. Such a principle requires the metasurface to consist of strongly scattering discs with a balanced electric and magnetic response. Large-scale fabrication on centimeter-scaled wafers is demonstrated with a self-assembly approach [3,4]. The fabrication process leads to metasurfaces with well-controlled correlated disorder. That helps to effectively restore a sufficiently high rotational symmetry that is key to achieving suppressed back-reflection when combined with the helicity preserving property [5]. The disorder also renders the effect spectrally rather broad. That is essential to our experimental improvement of short-circuit currents in industrial standard solar cells by up to 5.1 % with optimized metasurfaces compared to reference cells with a flat anti-reflective layer [6].

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Quantum state generation in dielectric metasurfaces

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We report on experimental and theoretical investigations of nonlinear metasurfaces from silicon, gallium arsenide, lithium niobate, and metasurfaces hybridized with transition metal dichalcogenide monolayers. We show that the second-order nonlinear interactions in metasurfaces enable tailorable harmonic frequency generation as well as entangled photon pair sources by spontaneous parametric down-conversion.

In our work, we have experimentally investigated isolated nanoresonators and nonlinear metasurfaces from different dielectric/semiconducting materials featuring electric dipole and magnetic dipole Mie-type resonances at wavelengths in the near infrared. As an intermediate step towards quantum experiments, we characterized second-harmonic generation from the metasurfaces, when exciting with the long wavelength fundamental wave. With these results, we show that resonant interactions in nanoresonators are a suitable platform for second-harmonic generation. As a next step we demonstrate experimentally the generation of photon pairs by spontaneous parametric down-conversion, when exciting with the short wavelength pump wave.

Based on the principle of quantum-classical correspondence, both processes, second-harmonic generation and spontaneous parametric down-conversion, are tied together by the governing system parameters. We have also exploited this correspondence to develop predictive theoretical models for the design of nonlinear metasurfaces for quantum applications.

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Topological structures in and for light

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This lecture revolves around topological photonics. With experiments we investigate topological features in light fields, such as phase- and polarization singularities. We do this both in unstructured two-dimensional arena's and in nanophotonic structures that are intrinsically topologically non-trivial. In experiments on edge states between topologically non-trivial photonic crystals we investigate the relation between propagation direction and the pseudo-spin of the optical eigenstates and determine their bandstructure. With near-field microscopy we obtain subwavelength information about the wavefunctions of the states, find that the optical spin has a highly heterogeneous distribution in space, and quantify how robust robust is.

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Size Dependence of Rabi Splitting Using Gold Nano-Bipyramids on Monolayer MoS_2

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Rabi splitting in plasmonic systems occurs when the light-matter interaction is sufficiently strong such that the rate of exchange of energy between an exciton and optical resonator is faster than their intrinsic dissipation rates. Under the condition of strong coupling the resonance splits into two new eigenstates, above and below the original optical mode and exciton energy. These new states are known as polariton states. Working in the strong coupling regime can be used for many applications, including but not limited to, low threshold lasers, optical switching and sensing. Until recent times, accessing the strong coupling regime required working at cryogenic temperatures. Developments in nanoscience allow for the observation of room temperature strong coupling in open cavity plasmonic systems, using a single plasmonic nanoresonator.[1]

In this work strong coupling is demonstrated using a single gold nano-bipyramid on monolayer MoS_2. Bipyramid lengths of 60 to115 nm were investigated. The polaritons were detected by dark field scattering and correlated with scanning electron microscopy images which showed the size of the bipyramids. Rabi splitting of ~80 meV was observed with 100 nm long bipyramids. It is also reported that the coupling strength between the plasmon and A exciton is stronger for larger bipyramids. This arises due to two factors. Firstly, the larger bipyramids produce a larger field due to the increased number of electrons creating a stronger plasmon. Secondly, to maintain the plasmon resonance energy coincident with the exciton energy, the aspect ratio (length to width) of the larger bipyramids must be reduced. This results in an increased angle between the plasmon direction and the MoS_2 layer, and consequently, produces greater overlap of the electric field and MoS_2 dipole moment, without an increase in the mode volume.[2] The nano-bipyramid system allows for the Rabi splitting to be increased with increasing nanoantenna size without increasing the number of excitons in the system.

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Deep Inverse Design of All-Dielectric NanoPhotonics

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Inverse problems appear in many branches of science and engineering, and methods used for their solution remain an active area of study. Inverse problems may be classified as either well-posed or ill-posed, and many problems in photonic design fall under the later characterization. Ill-posed inverse problems (IIP) were defined by Hadamard through their failure to meet any one of three criteria: (H_1) existence, (H_2) uniqueness, and (H_3) stability. [1,2] Although the condition of being ill-posed means it is meaningless to look for exact solutions, it is none-the-less possible to explore the set of approximate solutions to find one, or several, that are good enough to be significant. Recently, deep learning has been applied to solve inverse problems and has demonstrated excellent results.

We present an inverse method termed *neural adjoint* (NA) based on deep learning. [3] The NA method is thus a data driven inverse approach, where the first step is to train a neural network to approximate a forward model connecting the photonic geometry (g) and its corresponding spectra (s). The pairs that are used for training form a dataset $D=\{g,s\}$, which are obtained from numerical simulation. Once an accurate forward function f has been obtained, i.e. $s=f(g)$, we freeze the weights and biases of the neural network and specify a particular scattering that we are interested in finding the geometry for – the inverse problem. A number of randomly selected geometries are chosen, and we use df/dg to descend towards locally optimal geometries g. It is important to detail that our accurate forward model f, provides a closed-form differentiable expression, from which it is trivial to obtain df/dg. Notably, modern deep learning packages allow us to efficiently estimate gradients given a defined loss function.

In order to quantify and compare the performance of the NA inverse method against other approaches, we propose and investigate three benchmark photonics problems: an all-dielectric metasurface, a plasmonic multilayer particle, and a color rgb filter. A total of eight inverse methods are used to solve for approximate solutions, and may be classified as either stochastic iterative, deterministic, or probabilistic. We find that stochastic iterative inverse methods, such as the neural adjoint, find the best solutions, as determined by the lowest error metric (MSE).

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Minimalistic efficient quantum devices build of dipole coupled nano arrays of quantum emitters

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An array of closely spaced, dipole coupled quantum emitters exhibits collective energy shifts as well as super- and sub-radiance with characteristic tailorable spatial radiation patterns. In particular optical absorption and emission properties of ring shaped sub-wavelength nanoscopic quantum emitter structures are unique. As striking example we identify a sub-wavelength sized ring of exactly 9 identical dipoles with an extra identical emitter with a extra loss channel at the center as the most efficient configuration to deposit incoming photon energy to center without reemission.

The enhancement is most pronounced a given resonance frequency but still stays visible for broadband light absorption. For very tiny structures below a tenth of a wavelength a full quantum description exhibits an even larger enhancement than predicted from a classical dipole approximation.

The origin of the effect can be tied to a specific geometric property of nonagons allowing for the appearance of a special collective dark state with dominant center occupation. By special design of the center absorber one can harness the same efficiency enhancement also at different wavelengths and for other geometric structures.

On the one hand this could be the basis of a new generation of highly efficient and selective nano antennas for single photon detectors for microwaves, infrared and optical frequencies as used e.g. in quantum information processing or single molecule spectroscopy, while on the other hand it could be an important piece towards understanding the surprising efficiency of natural light harvesting molecules.

Adding gain to such systems allows to design minimalistic classical as well as non-classical light sources.

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Quantum photon-pair generation and measurement with metasurfaces

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Quantum nanophotonics is an active research field with emerging applications that range from quantum computing to imaging and telecommunications. This has motivated the development of sources of entangled photons that can be integrated into nano-scale photonic circuits, which provide the ultimate in miniaturization. Dielectric nanoresonators [1] and nanostructured metasurfaces [2] offer a promising route to enhance and tailor the generation of photons pairs through spontaneous parametric down-conversion (SPDC). To date, however, metasurfaces have used relatively low quality factor Mie resonances with an accordingly broad emission spectrum.

We present an original theory [3] and experimental demonstration [4] of strongly enhanced photon-pair generation in metasurfaces supporting extended bound states in the continuum resonances. The extended resonances can facilitate the preparation of strongly entangled quantum states with a much higher spectral brightness compared to localized resonances. We performed fabrication of resonant structures on top of x-cut lithium niobate films with sub-wavelength thickness. We measure two-photon coincidence-to-accidental ratios larger than the classical bound, confirming the generation of non-classical photon pairs. These results pave the way towards the generation of spatially and polarization entangled photon states in nonlinear metasurfaces with the properties tailored to various applications.

We also show that a dielectric metasurface can perform a complimentary task of single-shot characterization of the distinguishability between two photons in all degrees of freedom including time, spectrum, and polarization [5]. By utilizing a topology optimization algorithm, we designed free-form silicon metasurfaces that can achieve high transmission efficiency and facilitate low sensitivity of the scheme to measurement noise across a target spectral region in the telecommunication band. The metasurface can be tailored for multi-photon states and spatial modalities, providing versatile and ultra-compact quantum optical elements.

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Determining poles, anapoles and optimal materials with approximate Mie coefficients

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Subwavelength sized Mie-scatterers exhibit anomalous scattering due to the excitation of a set of eigen-frequencies [1]. The spectral response of Mie resonances features anomalies such as resonances and anapoles.

We propose to derive approximate expressions of first order Mie scattering coefficients from which can be derived the complex eigen-frequencies of the spherical scatterer and minimal and maximal scattering bounds [2]. By solving the equations satisfying the physical bounds with the approximate Mie coefficents, the conditions leading to anapoles and scattering maxima can be analytically solved. Besides zeros for anapoles, unitary limit for the maximum of electromagnetic scattering [3], one can also consider ideal absorption in lossy materials [2,4]. In all cases, the conditions can be solved *via* the parameter size or the composition of the material. In the latter case, we provide simple but accurate expressions of the dielectric permittivity of the scatterer that satisfy the scattering and absorption bounds.

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Hybridizing Photonic Metasurfaces with Two-Dimensional Materials

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Photonic metasurfaces, namely two-dimensional arrangements of designed nanoresonators, offer unique opportunities for controlling light fields and for tailoring the interaction of light with nanoscale matter. Due to their flat nature, their integration with two-dimensional materials consisting of only a single molecular layer is particularly promising [1].

This talk reviews our recent and ongoing activities in hybridizing optical metasurfaces composed of resonant metallic or dielectric building blocks with different types of two-dimensional materials, including monolayer transition metal dichalcogenides (2D-TMDs) and carbon nanomembranes (CNMs). On the one hand, we will show that CNMs can serve as mechanically stable substrates for free-standing metasurface architectures of nanoscale thickness [2]. On the other hand, we will demonstrate that the ability of the nanoresonators to concentrate light into nanoscale volumes can be utilized to carefully control the properties, such as pattern and polarization, of light emitted by 2D-TMDs via photoluminescence or nonlinear processes [3,4].

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Low-index platforms for non-conventional phase matching in third-harmonic generation

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All-dielectric platforms have recently gained attention in nanophotonics due to the possibility of extreme light confinement without compromising the level of losses. In this work, we report on our advances in investigating the third harmonic generation conversion efficiency by a material with effective near-zero mode index. Our activity is closely related to the remarkable properties of epsilon-near-zero media, which are typically associated with metals, transparent conducting oxides and polaritonic materials, the latter exemplified by SiC [1]. For instance, such materials exhibit high transmission through distorted waveguides, low crosstalk in extremely dense waveguides crossings and high effective nonlinearities [1-3]. However, conductive materials inevitably possess intrinsic losses in the optical domain weakening or even completely annihilating the effect of near-zero permittivity.

We study third-order optical nonlinear processes both in the epsilon-near-zero material regime of conductive oxides, such as ITO and in the special modal regime of photonic crystals associated with near-zero-index propagation modes [4, 5]. In both cases, a tight field confinement and facilitated phase-matching conditions contribute for pronounced enhancement of nonlinear interactions. We perform FDTD simulations using the commercial software Lumerical with two real materials having rather close third-order susceptibilities, ITO and AlGaAs. We show that the epsilon-near-zero regime of ITO around 1680 nm increases the conversion efficiency of the third harmonic generation when compared to the conventional semiconductor. Moreover, we clearly demonstrate that phase-matching conditions are automatically satisfied leading to the high harmonic wave generation in all possible directions.

To make sure that near-zero index nonlinear phenomena can be extended to a dielectric platform, we analyze nonlinear processes in a photonic crystal, designed to exhibit constant-phase modes in order to allow phase matching in non-conventional directions. A square patch of such crystal made of Si pillars emits the triple-frequency photons in all possible directions of the lattice. Thus, near-zero-index materials or structures with effective low indices enable higher conversion efficiencies, compactness and flexibility in the design of nonlinear devices on-chip.

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Anapole response of a trimer-based dielectric metasurface

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The phenomenon of anapole has attracted considerable attention in the field of metamaterials as a possible realization of radiationless objects. We comprehensively study this phenomenon in the cluster-based systems of dielectric particles by considering conditions of anapole manifestation in both single trimers of disk-shaped particles and metamaterial composed on such trimers. Our analytical approach is based on the multipole decomposition method and the secondary multipole decomposition technique. They allow us to associate the anapole with the multipole moments of the trimer and the separate multipole moments of its constitutive particles. The manifestation of anapole in a two-dimensional metamaterial (metasurface) is confirmed by checking the resonant states in the reflected field as well as from the electromagnetic near-field patterns obtained from the full-wave numerical simulation. It is demonstrated that the anapole excitation in trimers results in the polarization-independent suppression of reflection with the resonant enhancement of local electromagnetic fields in the metasurface. Finally, experimental verification of the theoretical results is presented [1].

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Low-threshold topological nanolasers

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Topological photonics has been attracting attention as a fundamental framework for robust manipulation of light. In this talk, I will present two novel topological nanolasers – topological corner-state laser and bound states in the continuum (BIC) laser.

First, I will talk about lasing action of topological corner states in a rationally designed photonic cavity [1]. We measured four corner-state lasing modes, which originate from the coupling between the corner states in a square-lattice topological cavity characterized by distinct quantized Zak phases in the nontrivial and trivial domains. Second, I will present the super-BIC laser. Super-BIC mode appears by combination of the symmetry-protected and accidental BICs in a finite periodic photonic structure [2]. We measured the far-field laser image with strong angular confinement, the reduced threshold to ~1.47 kW/cm^2, and the increased Q factor up to ~7300 in the super-BIC regime. We believe that our approach based on topological resonant modes will be particularly useful for the development of an ultralow-threshold light source for advanced photonic integrated circuits.

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Tunable dielectric nanoantennas and metasurfaces

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Recent explosive developments in the field of nanoantennas and metasurfaces pave the way to novel flat optical technologies, which can substitute conventional optics in a wide range of applications, from optoelectronic devices to imaging and microscopy. In particular, nanoantennas made of high refractive index nanostructures supporting Mie resonances [1] provide possibilities to achieve low-loss high-performance optical components with various functions in the visible and near-IR spectral range. Of particular application interest are those components, which can present a tunable functionality and which can be dynamically controlled by external stimuli. In this presentation, I will review our recent progress in the field of tunable dielectric nanoantennas and metasurfaces [2] and demonstrate novel spatial light modulations based on dielectric nanoantenna concept having individually controlled pixels with size down to 1 micron.

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Artificial intelligence enabled high-performance ultra-flat optics for vectorial light management: from components to integrated systems

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In this invited talk, I will review our recent theoretical, and experimental results in the field of artificial intelligence (AI) assisted inverse design of a new class of flexible ultra-flat optics (thickness < 100nm) for high efficiency (close to unitary) vectorial control of light. These devices are supported by a layer of "physical" neural network units in suitably engineered optical nanoresonators. These systems act as universal approximators of arbitrary defined input-output responses, processing information at the speed of light. I will discuss basic optical components and new integrated systems for processing high-dimensional visual information in real-time.

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Broadband and Achromatic Metasurfaces at Microwave Frequencies

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Metasurfaces are receiving increasing attention as low-profile alternatives to conventional bulky lenses, at frequencies ranging from microwave to visible. However, this compact size comes at the expense of operating bandwidth, since the phase profile on the metasurface is often controlled only at the center frequency. Achromatic metasurfaces have emerged to resolve this problem, where both the phase and its first derivative (group delay) are controlled separately for each element. In the visible and near-infrared frequency ranges, this approach has been successfully implemented with all-dielectric structures, often with thickness comparable to the operating wavelength.

At microwave and millimeter-wave frequencies, achromatic metasurfaces are also required, for broadband applications such as 5G communications, security imaging and short-range radar. However, in these frequency ranges, all-dielectric designs are inconveniently large, and incompatible with well-established fabrication techniques. Instead, the preferred architectures are based on printed circuit technology, most commonly containing 3 patterned metallic layers, or a single patterned layer above a ground plane. We show how synthesis procedures for such structures can be adapted to create achromatic structures. Furthermore, we analyze the bandwidth limits of the resulting structures, showing that achievable bandwidth scales inversely with aperture size, but increases with substrate thickness [1-3].

Our analysis shows that for practically achievable metasurface dimensions, the operating bandwidth of achromatic metasurfaces may be too narrow for many applications. Therefore we also consider broadband dispersive structures – those which maintain high efficiency scattering into a chosen diffraction order over their bandwidth. This leads to a shift in the focal length with frequency, but overcomes the limitations on aperture size, allowing practically sized structures to be experimentally demonstrated. We also consider the angular response of broadband lens structures, where experimental results show stronger off-axis aberrations than predicted by ray-optical models [4]. By analyzing the angular response individual meta-atoms, we show that these aberrations are due to the excitation of higher order modes, which must be controlled for optimal angular response.

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The total helicity of electromagnetic fields and matter

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The electromagnetic helicity of the free electromagnetic field and the static magnetic helicity are shown in [1] to be two different embodiments of the same physical quantity, the total helicity. The total helicity is the sum of two terms: The optical (electromagnetic) helicity, which measures the difference between the number of left-handed and right-handed photons of the free field, and another term that measures the screwiness of the static magnetization density in matter, proportional to the static magnetic helicity. Each term is the manifestation of the total helicity in different frequency regimes: $\omega > 0$ and $\omega = 0$, respectively. This new link between optics and magnetism establishes the theoretical basis for studying the conversion between the two embodiments of total helicity upon light-matter interaction. In my talk, I will explain this result in detail and focus on a particular area of potential application: Interaction of light with solid-state magnetic systems.

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Designing photonic topological states via staggered bianisotropy

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Photonic topological structures supporting spin- momentum locked topological states underpin a plethora of prospects and applications for disorder-robust routing and resilient localization of light. One of the cornerstone ideas to realize such states is to exploit uniform bianisotropic response in periodic structures with appropriate lattice symmetries, which together enable the topological bandgap. Here, it is demonstrated that staggered bianisotropic response gives rise to the topological states even in a simple lattice geometry whose counterpart with uniform bianisotropy is topologically trivial. The reason behind this intriguing behavior is in the difference in the effective coupling between the resonant elements with the same and with the opposite signs of bianisotropy. Based on this insight, we design one- [1] and two- [2] dimensional topological structures composed of resonant bianisotropic scatterers with alternating signs of bianisotropic response. Our results pave a way toward flexible engineering of topologically robust light localization and propagation by encoding spatially varying bianisotropy patterns in photonic structures.

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Reconfigurable devices with phase change materials: GaS, Ga_2S_3 and MoO_x

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Nanophotonics has rapidly grown from plasmonics with conventional metals, like gold and silver, to the most recent advances with phase-change materials (PCM). These attractive materials show different optical properties when an external stimulus (thermal, electrical or optical) is applied.

In this contribution, we will present our recent research with PCM like Ga_2S_3, GaS and MoO_x ($2<x<3$). These show as promising candidates for plasmonic applications for building reconfigurable devices with fast and low-loss response, for instance, pixels for reflective display applications and new broadband devices for switching and photodetection purposes [1, 2].

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Acknowledgements

This project has received funding from the European Union's Horizon 2020 Research and Innovation Program under Grant Agreement No. 899598—PHEMTRONICS

Novel Hybrid anapole state and non-Huygens transparent metasurfaces

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Dielectric photonics has been developing rapidly in the recent years, in particular, due to the fact that it finds applications in many fields of science and technology [1–4]. By controlling the electrical and magnetic components of light on a subwavelength scale with negligible losses, it became possible to produce thin optical devices that are already used in flat optics. Dielectric metasurfaces have allowed the manufacturing of flat lenses [5,6], hologram displays [7,8], light-managing devices [9–12], and dispersion control applications [13]. Most modern developments on dielectric metasurfaces are based on Huygens metasurfaces, which allow changing the phase of radiation passing through them with almost complete transparency [14,15]. However, their efficiency is fundamentally limited by the near field coupling between the constituents of the metalattice [16], which has motivated the search for alternative means to achieve the desired 2π phase variation [17].

The recently observed hybrid anapole states [18] are nonradiating sources that, unlike conventional anapoles, simultaneously suppress electric and magnetic contributions to radiation (fig. 1). Unlike Huygens sources, this feature can be used to suppress the connection between metasurface elements both in the far and near fields. In this work, we develop a completely transparent metasurface consisting of meta-atoms in a hybrid anapole state, which is able to control the phase of the transmitted radiation [19]. Such metasurfaces can act as an alternative to the Huygens effect.

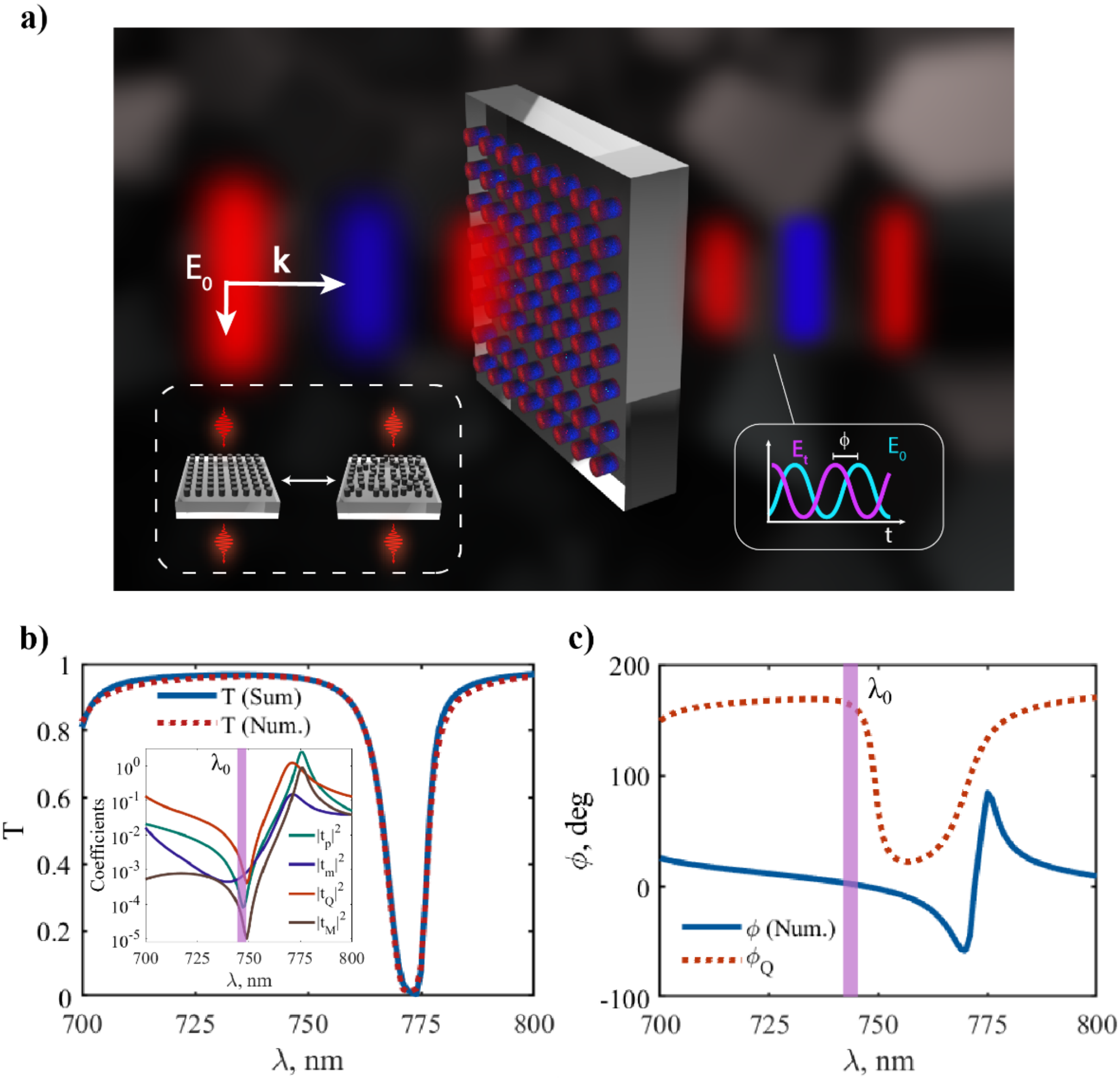

Figure 1. Artistic representation of the considered silicon metasurface composed of nanocylinders, illustrating its new functionalities: full transmission, almost complete independence of properties from the position of meta-atoms and the ability to control the phase (a), dependence of the transmission of radiation with fixed distance between cylinders s = 300 nm (inset: absolute values of the dominant multipolar contributions) (b), total transmitted phase ϕ obtained numerically, and phase variation experienced by the electric quadrupole ϕ_Q (c).

Figure 1 shows the dependence of the transmission (b) and phase shift of the tranmitted radiation (c) of the metasurface depending on the wavelenght with fixed distance between the surfaces of the meta-atoms. It is seen from the figure that even highly compact metasurfaces display almost unit transmission. In addition, contrarily to other recently proposed effects inducing zero transmission, the hybrid anapole is preserved when deposited over substrates having almost zero refractive index contrast. This reduces the requirements for the technical production process, allowing more design flexibility in terms of the material of the underlying substrate.

Thus, in this work, a metasurface model was developed, which, in terms of its optical properties, can become a worthy alternative to Huygens' metasurfaces. The developed non-Huygens' metsurface model based on nanocylinders in a hybrid anapole state has a number of indisputable advantages, such as full transmission of incident radiation, zero phase shift when radiation passes through it, and the possibility of deposition on various types of substrates without significant changes in the optical properties of the metasurface. All of the above properties make it possible to largely unlock the potential for creating various devices based on metasurfaces, for example, various lenses, sensors, holographic devices, and so on.

The authors gratefully acknowledge the support of the RFBR Grant 20-52-00031 for the multipolar decompositions. The transient calculations for the disordered metasurfaces have been partially supported by the RSF Grant 21-12-00151. This research is partially funded by the Latvian Council of Science, project "DNSSN", project No. lzp-2021/1-0048.

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Propagation and interaction of intense optical pulses in planar systems with strong light-matter coupling

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In this talk I consider propagation of the pulses in dielectric planar waveguides with build-in quantum wells. The regime of strong interaction between the excitons and the photons can be achieved in the systems provided that the waveguide can support electromagnetic waves with the frequency close to the frequency of the exciton resonance. In this case hybrid half-light half-matter excitations having rich dispersive and nonlinear properties appear in the system. The dispersion of these hybrid excitations originates mostly from the strong coupling and is much higher compared to the dispersion of pure guided photons. Another virtue of the hybrid waves is their large nonlinearity appearing because of the exciton component. These two factors allow to observe nonlinear modification of the optical pulses at the propagation distances of order of tens microns which makes the systems promising from the point of view of nonlinear optics.

The problem of propagation of intense pulses is considered for different parameters of the waveguide. In particular it is shown that the formation of solitons is possible in the system. The effect of the nonlinear losses on the pulse dynamics is addressed too. The second part of the talk is devoted to the resonant interaction between the solitons and the dispersive waves propagating in the system. Different regimes of the collision of the solitons and the linear pulses are discussed in detail.

Resonance Width Control in Nanoparticle Lattice with High Index and High Losses

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The research of suitable material platforms for photonic nanostructures and their functionalities is one of the rapidly growing directions in the fields of nano-optics, nanophotonics, and material research in general [1,2]. Metaphotonics is an emerging multidisciplinary research direction that deals with controlling electromagnetic fields in nanoengineered strucutre, materials, and surfaces using both electric and magnetic components of the field, their interactions, and coupling. Taking advantage of high refractive index, high losses, and strong anisotropic response in semiconductors and layered van der Waals materials, we develop photonic nanostructures with tunable resonance width. We study periodic arrays of nanoantennas made of a high-index and lossy materials placed on a low-index oxide substrate or in a uniform environment. We show that the nanostructure resonances and coupling between nanoscatteres and environment can be controlled by the variation in the array size, dimensions, and surrounding index.

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Radial bound states in the continuum for polarization-invariant nanophotonics

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All-dielectric nanophotonics driven by the physics of bound states in the continuum [1] (BICs) have enabled breakthrough applications in nanoscale light manipulation, frequency conversion and optical sensing [2-4]. Leading BIC implementations range from isolated nanoantennas with localized electromagnetic fields [5] to metasurfaces with broken in-plane inversion symmetry and controllable resonance quality (Q) factors [6]. However, such approaches often require either structured light illumination with complex beam-shaping optics or large, fabrication-intense arrays of polarization-sensitive unit cells, limiting their effective use for tailored nanophotonic applications and on-chip integration. In this presentation, we will introduce radial quasi bound states in the continuum (rBICs) as a new class of radially distributed electromagnetic modes controlled by the structural asymmetry in a ring of dielectric rod pair resonators. Our rBIC platform provides polarization-invariant and tunable high-Q resonances with strongly enhanced near-fields in an ultracompact footprint as low as 2 μm^2, which makes them ideal for boosting light-matter interactions. We will present experimental rBIC realizations in the visible wavelength range for sensitive biomolecular detection and enhanced second-harmonic generation from monolayers of transition metal dichalcogenides. Our results demonstrate that rBICs can open new perspectives towards compact, spectrally selective, and polarization-invariant metadevices for multi-functional light-matter coupling, multiplexed sensing, and high-density on-chip photonics.

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Reversible optical switching of GeSbTe spherical nanoparticles

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During the last decade, phase-changing materials based on Ge-Sb-Te compounds have garnered much attention for their convincing evidence in the vast literature as promising material of advanced metaphotonics [1,2]. Ge-Sb-Te have two beneficent properties that are the high refractive index and the non-reversible phase transition between crystalline and metastable amorphous phases. The transition is accompanied by almost two times modulation of the refractive index of the material. While both crystallization and amorphization of GeSbTe occur with thermal heating the former is much simpler in practical realization than the latter. The amorphization process requires thermally assisted disordering of the atoms with rapid quenching freezing the chaotic displacement of the elements. The literature reports on several approaches to switching of the phase and the electric or optical pulses are the most application-oriented treatments.

Here I present the results of reversible optical switching of GeSbTe spherical nanoparticles fabricated by ablation technique [3]. At the first step a donor GST film was prepared by thermal evaporation in vacuum with deposition of the material onto a substrate. The nanoparticles were fabricated by placing the donor film in close contact with a receiver glass substrate. Application of intensive infrared optical pulses from a femtosecond laser results in an ablation process with multiple nanoparticles produced at each pulse. The nanoparticles were examined by means of dark-field microscopy, Raman spectroscopy and second-harmonic generation experimental techniques. All techniques reveal strong modification of the measured data during the phase transition. With dark-field experiments we achieved the reversible switching by application of a train of low-intensity pulses for the amorphous-to-crystalline transition of GST and a single femtosecond pulse regime delivering energy of high intensity causing the reverse transition to the initial amorphous phase.

I acknowledge the support from the Russian Scientific Foundation (Grant No. 21-19-00677).

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Correlative electron-photon spectroscopy

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Electron energy-loss spectroscopy and cathodoluminescence (CL) spectroscopy are common techniques for characterizing the optical responses of nanostructures with unprecedented spatial resolution and spectral bandwidth [1]. Recent activities to resolve the dynamics of materials excitations by merging laser pumps and electron probes have opened a new era, namely, photon-induced near-field electron microscopy (PINEM) [2]. Electron-light interactions provide plethora of possibilities for fundamental investigations of quantum phenomena as well, such as quantum-path interferometry [3] and strong-coupling effects [4, 5].

Here, I propose a technique for correlative electron-photon experiments without a laser [6]. We introduce an electron-driven photon source (EDPHS) that is able to emit photons of tailored properties upon electron irradiation [7, 8] and use it within an electron microscope to excite exciton polaritons in a transition metal dichalcogenide flake (Fig. 1a). It will be shown for the first time that the far-field radiation pattern of the combined EDPHS and sample demonstrates a rich set of interference phenomena that depend on the delay between the arrival time of the electron beams and EDPHS radiation (Fig. 1b). Our observations demonstrate the ability of using correlative CL angle-resolved mapping as a novel technique for resolving the dynamics of materials excitations.

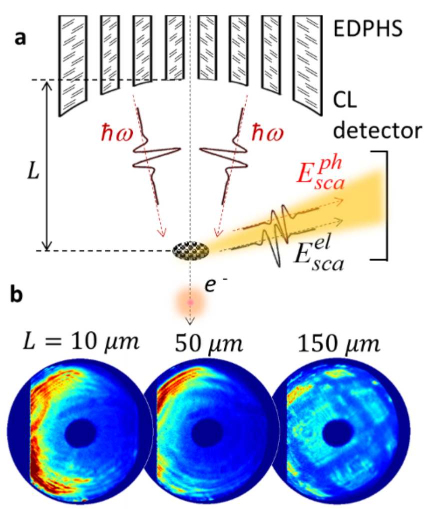

Fig. 1. (b) An electron beam interacting with EDPHS generates photons that are synchronized with the electron beam itself. Both EDPHS radiation and electron beam excites the sample, where the delay between them is controlled by the distance L between the sample and EDPHS. (b) Measured angle-resolved patterns in the far-field that demonstrate the ability of EDPHS radiation to control the far-field radiation pattern of the combined system.

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Parametric frequency conversion in lithium niobate metasurfaces

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Lithium niobate (LN) is an attractive material for nonlinear photonics due to its wide transparency range and high second-order nonlinearity. However, most applications of LN to date were using bulk LN crystals or waveguides. Mie-type nanoresonators in LN as well as metasurfaces have only been studied recently, showing promise also for applications of this material system in nanophotonics.

In my talk, I will show experimental results from nonlinear metasurfaces consisting of LN nanocubes realized in a LN thin film on a SiO2 substrate. For classical second-harmonic generation, we could demonstrate that the electric-dipole (ED) and magnetic-dipole (MD) resonances in these metasurfaces enhance the conversion efficiency for second-harmonic generation, that the generated second harmonic is predominantly emitted in the forward direction, and that the specific structure of the nonlinear tensor of LN leads to significantly different dependences of the generated light on the polarization of the excitation for the ED and MD resonances [1].

The majority of my talk will be devoted to the generation of photon pairs in these metasurfaces. To this end, we used spontaneous parametric down conversion (SPDC). Our experiments successfully demonstrated the generation of photon pairs in the LN metasurface with high signal-to-noise ratio [2]. We could also show, that photon pair generation is controlled predominantly by the ED resonance and that the spectrum of the emitted photon pairs can be tuned by changing the wavelength of the pump laser with respect to the ED resonance.

With these results, we show that resonant metasurfaces based on lithium niobate are a suitable platform for parametric three-wave mixing to generate classical and non-classical light. Our results are an important step towards the use of metasurfaces for the tailored generation of photon pairs.

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Chalcogenide and tellurite photonic resonators with whispering gallery modes

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Resonators with whispering gallery modes (WGMs) based on dielectric materials provide unique capabilities for controlling fundamental properties of coherent light. Such resonators have huge *Q*-factors and large nonlinearity, which make it possible to attaine nonlinear and laser effects at low pump powers [1]. Microresonators are used for various applications dealing with classical and non-classical states of light. Sensing and biosensing, optical filtering, linewidth narrowing, coherent communication, dual-comb spectroscopy, generation of non-classical states of light, e.g. correlated photon pairs and squeezed light are just a few of them [1]. The use of new materials with outstanding optical properties allows expanding the capabilities of photonic resonators.

Chalcogenide glasses (consisting of one or more chalcogens (Se, S or/and Te) in conjunction with As, Ga, Ge, P, Sb, and some other electropositive elements) are very promising materials for use in various photonic devices including WGM microresonators. One of the reasons is giant values of optical $\chi^{(3)}$ Kerr and Raman nonlinearities of chalcogenide glasses, 2-3 orders of magnitude higher compared to silica glass [2]. Chalcogenide glassy materials are transparent in the near-IR and mid-IR and demanded for these spectral ranges [2]. Spherical microresonators with *Q*-factors of order 10^6-10^8 can be made of commercially available As_2S_3 and As_2Se_3 fibers, which makes their production a fairly accessible technology [3]. Tellurite glasses (based on tellurium dioxide TeO_2) are another promising materials. Their nonlinear refractive index is 20-30 times higher compared to silica glass and they are transparent up to ~5-6 μm [2]. They can be easily doped with rare-earth ions for obtaining laser generation in the 1-3 μm range.

Here we present our recent experimental and theoretical results concerning nonlinear and laser effects in chalcogenide and tellurite WGM microresonators including Raman lasing, optical frequency comb generation, and laser generation [3,4]. In particular, cascade Raman lasing up to 4th order is experimentally attained in the near-IR (initially the 1st-order Raman radiation is generated which serves as the pump for the 2nd-order Raman radiation, and so on). The possibilities of Raman lasing as well as generation of dissipative Kerr solitons in the mid-IR are studied numerically. Laser generation in Er-doped and Tm-doped tellurite resonators in different regimes is predicted theoretically and confirmed experimentally. The opportunities of further progress in such photonic devices are discussed.

This work is supported in part by the RSF, Grant No. 20-72-10188 (study of tellurite resonators) and in part by the Mega-grant of the Ministry of Science and Higher Education of the Russian Federation, Contract No.14. 075-15-2021-633 (study of chalcogenide resonators).

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Fast syntheses of phase-only metasurfaces for full-state and high-efficiency control of electromagnetic fields

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Metasurface holography is a powerful tool of imaging and advanced field control. To enrich the functionality of metasurface holography for broader applications, independent and simultaneous controls of the field amplitudes and phases in the region of interest (ROI) are highly desired. Traditionally, it has been believed that such functionality can be achieved only by metasurface holograms with both phase and amplitude modulations in the local transmissive or reflective coefficients, and recent efforts have devoted to such phase-and-amplitude (PA) metasurface holograms. However, it should be stressed that the power efficiencies of the PA metasurface holograms are usually less than 10%, which is unfavorable for many applications.

In this presentation, we synthesize the field amplitudes and phases in ROI simultaneously and independently with high efficiencies by using the phase-only (PO) metasurface. All points in ROI may have independent values of field amplitudes and phases, and the requirements for X and Y components may be different in achieving spatially varied polarization states. To this end, we present an efficient design method based on equivalent electromagnetic model and gradient-based nonlinear optimization. Full-wave simulations and experimental results demonstrate the feasibility of the design method in synthesizing almost arbitrary amplitude and phase values at every points in ROI and their polarization states using the PO metasurface, which has 10 times higher power efficiency than the PA metasurface. This work opens a way to realize more complicated and high-efficiency metasurface holography, and extends the application scope of electromagnetic engineering with metasurfaces. In general, this work creates a paradigm of engineering complicated fields with high efficiencies. This topic is of interest and relevance to scientists across a broad range of directions, including optical trapping, structured illumination microscopy, cloaking and illusion, data storage and encryption, 3D display and interference lithography.

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Efficient characterization of resonant dielectric particles

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In order to efficiently control the electromagnetic fields on small scales, materials with a strong contrast of refractive index are generally desired. At optical frequencies, metals generally exhibit such contrast, at the expense of moderate to high losses. As a low-loss alternative to metal, resonant dielectric particles are often used. Near the resonant frequency, the response of such particles to incident light is strong, paving the way for compact and efficient designs to manipulate light. However, since the response of such particles is associated with a resonance, their behavior is intrinsically dispersive.

A popular way to describe such particles is to model them as polarizable electric or magnetic dipoles or multipoles with associated complex resonant frequencies. These models can be improved using full-wave electromagnetic solvers. Using the latter, the exact distribution of the fields associated to each resonant mode can be obtained.

Several fast methods have been proposed in the literature to rapidly and accurately determine the resonant modes and associated resonant frequencies, each of them with their associated advantages and drawbacks [1]. Most of the existing techniques are based on volumetric solvers. Indeed, using contrast sources, the determination of the resonant frequencies of a scatterer can be formulated as a linear problem for non-dispersive materials.

Recently, a fast method based on Surface Integral Equation (SIE) has been proposed, which is based on the Geometrical Method of Moments (gMoM) [2]. Using SIE, only the surface of the structure needs to be discretized, resulting in a reduced number of unknowns w.r.t. their volumetric counterparts. However, using SIE, the eigenmode search cannot be formulated as a linear problem. Because of this, the determination of the resonant frequencies of a structure requires computing the impedance matrix of the structure for several frequencies, slowing down the procedure. The computation of the impedance matrices is the time limiting step of the method and thus limit its applicability. Using the gMoM, the frequency dependence of the impedance matrix is reformulated as a rapidly converging series of purely geometrical terms, *i.e.* not depending on frequency nor material properties [3]. Thus, the impedance matrix can be rapidly evaluated for many frequencies.

During the presentation, we will present the method and apply it to several dielectric material configurations proposed in the literature.

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Superscattering and supermultipoles of interfering resonances

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The scattering of light by particles is a long-standing problem in electromagnetism. In particular, enhancing scattering from multipoles excited in subwavelength particles is of paramount importance for state-of-the-art applications in nano-optics, such as biosensing[1] or energy harvesting[2,3]. However, the scattering cross section of one multipole is thought to be bounded by a rigorous limit. The concept of "superscattering" was proposed a decade ago[4] to overcome this problem. By overlapping resonances from several multipolar channels, the scattering cross section can be made several times larger than the limit for one multipole. Here, we reveal a completely new strategy to achieve the superscattering regime, based on the Friedrich-Wintgen mechanism of interfering resonances[5]. Contrarily to common believe, we demonstrate that the scattering cross section of an isolated multipole can exceed the limit by itself, forming a "supermultipole". We formalize our results with a general non-Hermitian model to describe interfering resonances of open non-hermitian systems. We then design subwavelength dielectric nonspherical resonators exhibiting a super-dipole moment, almost two times stronger than the limit (see Figure 1). Our results reveal novel physics of non-Hermitian systems suggesting important applications for metadevices.

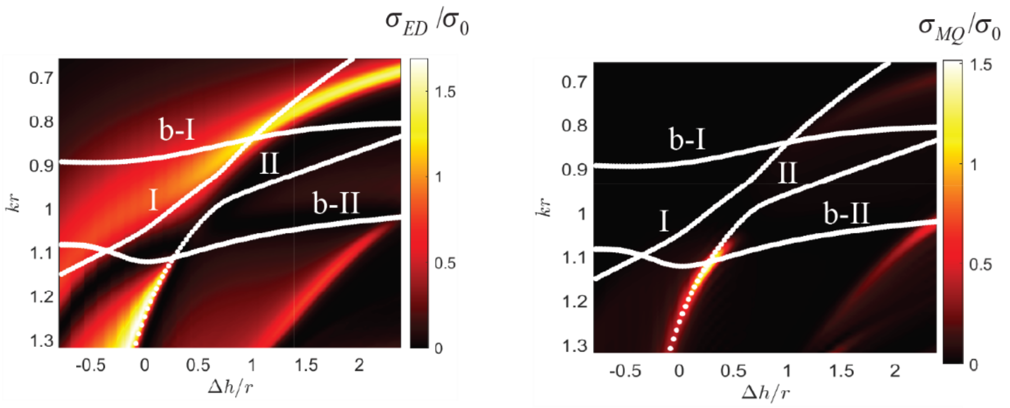

Figure 1. Colormaps: scattering cross sections of the electric dipole (left) and magnetic quadrupole (right) multipole moments, obtained from changing the height of a silicon nanorod by Δh. All the cross sections are normalized by the scattering limit of the electric dipole. At some points, the electric dipole is seen to exceed largely the conventional limit, i.e. a 'super

dipole' moment appears. The original nanorod has radius $r = 130$ nm and height $h = 180$ nm. The dotted white lines indicate the evolution of the resonant frequencies. An avoided crossing of modes I-II, characteristic from the Friedrich-Wintgen mechanism, can be clearly observed.

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Superscattering channels mediated by the Friedrich-Wintgen mechanism

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In our work [1], it is revealed for some specific examples that strong coupling of Mie-resonant multipolar modes provides an alternative pathway to the enhancement of light scattering in addition to the overlapping of uncoupled modes. Where the latter is the currently accepted method to enhance scattering to several folds higher than the uncoupled dipolar channels maxima, also known as supescatteing. The increment of power, in a two-level modal system for instance, results in diving the low order multipolar channels to exceed uncoupled channel limitation [2]- a phenomenon of superscattering within the channel itself that is forbidden in Mie resonators retaining spherical symmetry. The avoided resonance crossing, as described in the Friedrich-Wintgen mechanism of interfering modes, leads to energy exchange between the radiation channels allowing to control both Qfactors and multipolar contents of resonances while maintaining a high scattering cross-section. Scattering maxima also is shown to occurs at the crossing points of two uncoupled modes originating from two separate coupling mechanisms. Thus, superscattering in nonspherical resonators is shown to be realized in a practical setup at a broadband spectrum with significant enhancement at multifrequency points by only varying a one geometrical parameter. The proposed method employing the recently developed quasi normal modes QNMs of an open resonator effectively reveals the physical mechanisms behind superscattering phenomena and reduces the complications of real frequency calculations. It was then suggested and demonstrated a simple and intuitive strategy to further enhance the scattering amplitude and/or resonance quality by assembling cylinders in symmetric clusters while controlling the inter-particle distances.

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SMART NANOMATERIALS

7-10 December 2021
Chimie ParisTech, Paris

Momentum alignment of photoexcited carriers in low-dimensional Dirac materials

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Devices made from conventional semiconducting materials manipulate electron flow based on their charge or spin (spintronics), the later offers the promise to revolutionize the way we do computing. In graphene and graphene-like materials, there is an alternative electron property which can be harnessed for device applications: the so-called valley degree of freedom, which could be utilized in an analogous manner to spin in spintronics and has been suggested as a basis for carrying information in graphene-based devices. The ability to control the valley degree of freedom practically is still an outstanding problem. We propose a new method of control, using linearly polarized light, to open the door to optovalleytronics.

One of graphene's most widely known optical properties is its universal absorption, defined through the fine-structure constant, which holds true across a broad range of frequencies from the sub-infrared into the visible. A lesser-known feature is that linearly polarized light creates a strongly anisotropic distribution of photoexcited carriers with their momenta predominantly aligned normally to the polarization plane [1]. We show how this momentum alignment effect together with graphene's spectrum anisotropy (trigonal warping) at high energies can be utilized for the spatial separation of carriers belonging to different valleys in graphene and gapped graphene-like materials [2]. The optical control of valley polarization in gapped 2D Dirac materials such as phosphorene and single-layer transition metal dichalcogenides can also be achieved via a well-known effect of using circularly polarized light. In gapped materials, the optical selection rules associated with linearly polarized light of near-band-gap energies are valley-independent, in stark contrast to the valley-dependent optical selection rules associated with circularly polarized light. This valley dependence of the circularly-polarized transitions can be utilized to measure the degree of valley polarization induced by linearly polarized light of high (well above the band gap) energies, by analyzing the degree of circularly polarization of the band-edge luminescence at different sides of the light spot.

The momentum alignment phenomenon also explains the hitherto overlooked effect of the giant enhancement of the band gap edge interband optical transition rate in narrow gap carbon nanotubes and graphene nanoribbons [3] which occurs in the terahertz range, thus opening a route for creating novel terahertz radiation emitters.

This work was supported by the EU H2020 RISE project TERASSE (Grant No. 823878).

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Nano-antennas Based on Transition Metal Dichalcogenides for Photonics Applications

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Transition metal dichalcogenides (TMDs) have shown great potential as next generation photonics materials [1]. Their monolayers have direct bandgaps in a large portion of the visible spectrum with near-unity photoluminescence (PL) efficiencies. Their bulk materials (10s to 100s nm thick) have large refractive index while maintaining low absorption, therefore, bulk TMDs can be explored as an excellent candidate material for nano-photonic resonators. Here, we fabricate WS_2 nano-antennas with different shapes, enabled by balancing isotropic and anisotropic etching in the fabrication process. Using dark field spectroscopy, we reveal multiple Mie resonances, to which we couple PL from a monolayer WSe_2. In such monolayer-on-bulk TMD system, we demonstrate a PL enhancement of more than 240 folds. We also reveal that these WS_2 nano-antennas with ultra-small gaps can be employed for optical trapping with exceptional performance [2].

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Edge-state tunneling in topological insulators

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Tunneling between two 2D layers separated by a weakly transparent potential barrier is a prime example of resonant tunneling phenomena in semiconductor nanostructures. In such a structure the energy and in-plane momentum conservation put tight restrictions on the tunneling so that the conductance exhibits sharp maximum at zero bias, while at any finite voltage applied across the barrier the transitions between the layers are forbidden. Such a behaviour has been experimentally observed both for the semiconductor heterostructures containing two spatially separated quantum wells. The spin-orbit coupling in the layers leads to a complex interference picture in the I-V characteristuc carrying information about SOC parameters of the material [1]. In this work we consider theoretically quantum tunneling between edge states of two pieces of topological insulator (TI) separated by a normal isolator (NI) forming a topologically trivial tunnel barrier. Tunnel energy splitting and the eigenfunctions have been obtained analytically for the TI-NI-TI heterostructure described by Bernevig-Hughes-Zhang Hamiltonian with proper matching conditions at the interfaces. Using the obtained stationary solution we have calculated the non-stationary tunneling current between the two TI edge states. As shown by the calculations the differential tunnel conductance exhibits resonant pattern with most pronounced peaks at zero bias as well as at the bias corresponding to the Fermi energy. We come up with a suggestion of experimental proof of the predicted phenomenon.

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Novel 2D Glassy-Graphene Devices for Broadband Photodetection and Volatile Organic Compound Sensing

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Multifunctional devices are of great interest for integration and miniaturization on the same platform, but simple addition of functionalities would lead to excessively large devices. Here, the photodetection and chemical sensing device is developed based on novel 2D glassy-graphene[1,2] that meets similar property requirements for the two functionalities. An appropriate bandgap arising from the distorted lattice structure enables glassy-graphene to exhibit similar or even improved photodetection and chemical sensing capability, compared to pristine graphene. Due to strong interactions between glassy-graphene and the ambient atmosphere, the devices are less sensitive to photoinduced desorption than graphene. Consequently, the few-layer glassy-graphene device delivers positive photoresponse, with a responsivity of 0.22 A/W and specific detectivity reaching 10^{10} Jones under 405 nm illumination. Moreover, the intrinsic defects and strain in glassy-graphene can enhance the adsorption of analytes, leading to good chemical sensing performance. Specifically, the extracted signal-to-noise-ratio (SNR) of the glassy-graphene device for detecting acetone is 48, representing more than 50% improvement over the graphene counterpart. Additionally, bias voltage and thickness dependent VOC sensing features are identified, indicating the few-layer glassy-graphene is more sensitive. This study successfully demonstrates the potential of glassy-graphene for integrated photodetection and chemical sensing, providing a promising solution for multifunctional applications further beyond.

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Optically Induced Coherent Phonons in Bismuth Oxyiodide (BiOI) Nanoplatelets

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We have studied bismuth oxyiodide (BiOI) nanoplatelets, a material which combines intriguing optical and structural properties for photocatalysis. In particular, its crystal structure comprised of alternatingly charged 2D layers may give rise to a built-in dipolar electric field along the stacking direction affecting charge carrier dynamics in BiOI.

In a pump-probe experiment, we show that excitation by a femtosecond laser pulse creates coherent phonons which leads to an oscillating modulation of the differential optical density. We found that the two underlying frequencies originate from lattice vibrations along the [001] crystallographic axis, the stacking direction of the oppositely charged layers. This is consistent with a sub-picosecond charge separation in the built-in dipolar field, which screens the electric field partially and thus creates coherent phonons. Further, we determine the two major dephasing mechanisms that lead to the loss of vibronic coherence: (i) the anharmonic decay of an optical phonon into two acoustic phonons and (ii) phonon-carrier scattering. We apply that knowledge to optimize the hydrogen evolution rate in photocatalytic experiments by controlling the BiOI nanoplatelet thickness via surface ligands.

Our results provide the first direct demonstration of the presence of an electric field in BiOI along the [001] axis and show its role in efficient charge separation. [1] This separation is crucial for photocatalytic applications of BiOI which we confirm in photocatalytic experiments.

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SMART NANOMATERIALS

7-10 December 2021
Chimie ParisTech, Paris

4D Printing Green Nanomedicine: 20 Years of Learning from Nature to Fight COVID-19, Reverse Infection, and Grow Tissues

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3D printing has already revolutionized medicine through the development of more inexpensive and effective implants that can be printed at the site of surgery. However, recent developments have made 3D printing even better: the use of green or natural nano materials and 4D printing (where the 4^{th} dimension is time and the geometry of 3D printed materials can be controlled remotely and on-demand) [1]. This presentation will introduce and highlight recent advances in 4D printing of green nanomaterials for various applications including technologies to stop the spreading of COVID-19, developing surfaces to inhibit bacteria and virus attachment, as well as fabricating improved medical devices that enhance tissue growth (such as for orthopedic, neural, cartilage, and other applications). In such applications, green or natural materials have not only improved material efficacy at reducing bacteria and virus functions, but have also decreased toxicity. Nanomaterials, through their unique small features, have further promoted material efficacy. Lastly, 4D printing has enabled for the on-demand release of green materials to promote material function. This presentation will provide in vitro as well as in vivo data showing the promise of 4D printing green nanomedicine for numerous applications. This presentation will also cover what has been learned in over two decades of research in 4D printing green nanomedicine for the field to continue to mature.

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The composition of metal particle catalyzed ternary III-V nanowires

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The ability to grow ternary III-V semiconductor materials is of highest importance for design and fabrication of modern nanoscale devices. One promising approach relies on heterostructured nanowires with precisely tuned bandgap along the nanowire. This requires composition control and several research groups have focused their efforts on composition control in ternary nanowires, see ref. [1] for a recent review.

In this presentation I will explain how to use two-component classical nucleation theory to estimate the composition of ternary nanowires growing by the vapor-liquid-solid mechanism. The materials systems of interest are gold- and self-catalyzed ternary III-V nanowires, such as InGaAs and related materials. In our model we use realistic chemical potential differences between the quaternary liquid alloy catalyst particle and the nanowire material. The chemical potentials are calculated from assessed thermodynamic parameters for Au, In, Ga, As, Sb, InAs, GaAs, GaSb, and InSb in all relevant phases. Using this approach, we are able to link the composition of the catalyst particle to the composition of the nanowire under different conditions [2].

Below certain temperatures, some of these ternary materials have a miscibility gap. For example, below 543ºC, $In_xGa_{1-x}As$ has a miscibility gap, meaning that a range of compositions, *x*, are thermodynamically forbidden. Still, in most experiments where InGaAs nanowires are grown at temperatures below 543ºC, the miscibility gap is conspicuous with its absence. We propose two different explanations to this phenomenon. The first one relies on kinetic, instead of nucleation-controlled composition [3]. The second explanation relies on including the surface energy of the nucleus in the calculation [4].

Finally, I will show a verification of our models in a recent *in situ* experiment, where gold catalyzed InGaAs has been grown in a high-resolution transmission electron microscope where the compositions of the catalyst particle and of the nanowire were monitored during growth [5].

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Graphene-based materials for wastewater treatment

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One of the most important decontamination techniques is considered to be adsorption. It is fast, simple, low-cost with many opportunities to modify the initial materials after appropriate synthesis routes etc. Numerous adsorbent materials are prepared the last years having as ultimate scope to remove some pollutants especially from contaminated waters (effluents originated from industries). But the composition of each type of effluents is varying. Dyes, heavy metals, pharmaceutical compounds are some major components of industrial wastewaters. In the last years, graphene attracted many researchers employing with adsorption technique, because of its excellent properties and 2-D structure. Researchers proceeded with that and achieved even more effective graphene adsorbents making some additions to initial graphene structure, preparing many graphene composites. This work summarizes the important contribution of graphene composites to adsorption technique from the research team of Prof. George Z. Kyzas. Many preparation routes of graphene composites are given along with the respective characterization techniques, properties of the materials, and of course detailed adsorption evaluation of graphene composites. The latter is based on some adsorption parameters as maximum adsorption capacity, kinetic behavior, thermodynamics, and possible reuse ability. To highlight the superiority of graphene composites, comparison with other adsorbents is mandatory.

Acknowledgment: The financial support received for this study from the Greek Ministry of Development and Investments (General Secretariat for Research and Technology) through the research project “Intergovernmental International Scientific and Technological Innovation-Cooperation. Joint declaration of Science and Technology Cooperation between China and Greece” with the topic “Development of monitoring and removal strategies of emerging micro-pollutants in wastewaters” (Grant no: T7DKI-00220) and it is gratefully acknowledged.

Surfactant effect on graphene oxide/polymer nanocomposites films

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Graphene oxide/polymer nanocomposites continue to draw considerable research interest due to their versatility in terms of physicochemical, mechanical and electronic properties for a variety of applications. Despite extensive research, control over the intrinsic properties of the graphene oxide/polymer nanocomposites to achieve desirable properties remains a challenge. Surfactants are frequently employed in the fabrication of polymer/graphene-based nanocomposites via emulsion techniques. However, the impact of surfactants on electrical and mechanical properties of such nanocomposite films was not understood. We conducted systematic studies using commercial (water soluble) and in situ generated surfactants to understand their influence on the fundamental properties of the nanocomposites. In this talk, the importance of surfactant chemistry on the final properties of the nanocomposite will be discussed. We will provide strategies that can be adopted to manipulate the properties of nanocomposites by judicious selection of the concentration and/or type of surfactant.

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Porous silicon microparticles as a multimodal drug delivery system

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Visible photoluminescence, natural porosity and large surface-to-volume ratio, together with biodegradability, biocompatibility and absence of immunogenicity and toxicity are the properties that make porous silicon (pSi) particles an ideal traceable carrier for both therapy and diagnosis purposes. Fabrication and surface hydrosilylation methods of pSi are well known[1,2]. We successfully overcame the issue of pSi optical and structural degradation in aqueous media by both organic[3] and inorganic coating[4]. Moreover, results achieved with the loading and release of (Cobinamide) Cbi[3] together with an established method to decorate pSi microparticles with SPIONs[5], led the system to become a multimodal platform that can find application in theranostics.

Moving from these recent findings, we investigated pSi microparticles ability to load and deliver Pam3CSK4, a synthetic Toll-like receptor (TLR) 1 and 2 agonist, able to enhance immune responses mediated by dendritic cells (DCs). DCs are antigen-presenting cells that can recognize TLR agonists, thus inducing the production of cytokines and promoting T-cell activation and inflammatory responses. This suggested that DC-mediated immune response might be enhanced by loading a TLR agonist inside pSi microparticles to avoid its degradation. Pam3CSK4 was chosen because of its dimensions and multiple binding sites that make it suitable to be loaded within carboxyl-functionalized pSi microparticles. After performing preliminary *in vitro* tests, DCs were isolated from human donors and stimulated with different concentrations of Pam3CSK4 successfully loaded within pSi-COOH microparticles (as demonstrated by confocal microscopy). DCs activation was proved by optical microscopy and confirmed by the elongation of the dendrites. Encapsulation efficiency was investigated by fluorescence spectroscopy and estimated to be around 34%. Immune response, evaluated based on the release of some cytokines by ELISA-assay, showed a promising enhancement effect resulting from the association of Pam3CSK4 with pSi microparticles.

Moreover, since we wanted to achieve a higher immune response, we started to work with a pH responsive polymer, acetalated dextran, known to promote MHC I and II presentation, to eventually encapsulate pSi microparticles. We successfully synthetized it and we did some preliminary tests to encapsulate pSi microparticles by nanoprecipitation, further investigations will follow. These first results seem promising and might lead our delivery platform to interesting applications not only in the field of theranostics but also in cancer vaccination and immunotherapy.

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Enhanced Strong Coupling of WSe_2 monolayer by Bound State in the Continuum

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Transition-metal dichalcogenides (TMDCs) monolayers have been considered a perfect platform for realizing exciton-polariton at room temperature due to their direct bandgap and large binding energy of exciton. It is well established that strong coupling depends on the field enhancement induced by optical nanocavity with high quality factor (Q-factor). In this work, we demonstrate the enhanced strong coupling between the exciton of WSe_2 monolayer and the cavity resonance based on a symmetry protected magnetic dipole (MD) bound state in the continuum (BIC) and electric toroidal dipole (TD) BIC. It is found that Rabi-splitting strongly depends on the location of TMDC monolayer, Q-factor of the resonator, and the thickness of the structure. After optimizing the structure, Rabi-splitting of 38 meV was achieved.

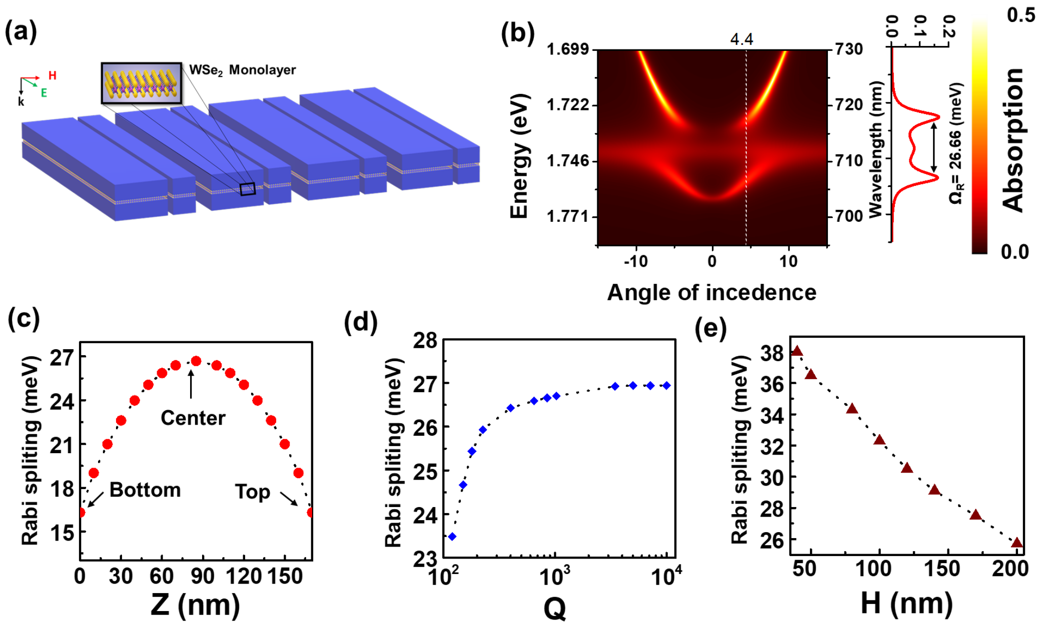

Figure 1. (a) Schematic drawing of WSe_2 inside SIN NW array with small slit. (b) Absorption spectrum mapping versus incident angle theta while other parameters are fixed (c, d ,and e) present the rabi-splitting as a function of the position of the WSe2 monolayer, the Q-factor, and the height of the nanowires, respectively.

Green Chemistry – Manufacturing Novel Nanomaterials in Water

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Significant effort has been made to generate reliable synthetic methods to produce metal nanoparticles, and the development of greener syntheses is particularly desirable in order to enable the use of these type of nanomaterials in a wider range of applications. This talk will cover different aspects of this research area, and more specifically be based on a green one-pot synthesis of novel functionalised metal nanoparticles in water for their potential use in biomedical applications, and its comparison with the corresponding traditional method and process mass intensity (PMI) calculations. In our system, organophosphorus ligands play key roles as coating and reducing agent at the same time [1]. The green synthesis of functionalised metal nanoparticles was carried out in water and at different temperatures, ranging from 60 and 100°C. UV-Visible, XPS spectroscopic and TEM studies have shown that the organophosphorus ligands bind to the surface of metal nanoparticles, which are typically around 5 nm in diameter [2]. These highly stable nanomaterials can offer a great opportunity in the design of novel biorecognition and drug delivery systems.

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Synergistic antibacterial effect of silver nanoparticles combined with antibiotics: Mechanism study using fluorescence microscopy

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Silver nanoparticles (NPs) strongly enhance antibacterial activity against broad spectrum of bacterial strains when combined with antibiotics [1]. However, the mechanism of their synergistic effect is not yet fully understood and may vary for different bacterial strains and antibiotics [2]. In this work we present a mechanism of the combined antibacterial effect of silver NPs and vancomycin against *E. faecium* strain sensitive and resistant to vancomycin. For the first time the synergistic mechanism was described based on the localization of fluorescent labeled silver NPs and vancomycin-BODIPY FL fluorescent conjugate using high resolution fluorescence microscopy. It can be concluded that the synergistic effects of silver NPs and vancomycin mainly consists in the mutual disruption of the permeability and strength of the cell wall, which becomes unstable and loses its strength and it is subsequently disrupted and detached. In addition, silver NPs significantly deform bacterial DNA, which also significantly contributes to the inhibition of bacterial growth. This work can help to better understand the mechanisms of synergistic effects of silver NPs with antibiotics against resistant bacteria which represent an important finding for potential approach to an effective fight against the unresolved problem of an increasing resistance of pathogenic bacteria against traditional antibiotics.

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Enhanced Photocatalytic Activity of ZnO Nanorods/(Graphene Oxide, Reduced Graphene Oxide) for Degradation of Methyl Orange Dye

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Advanced oxidation processes (AOPs) are technologies for the removal of organic contaminants in water. One of the leading effective AOP technologies to degrade toxic contaminants, such as dyes and other organic pollutants, into harmless by-products such as carbon dioxide is the photocatalytic process. ZnO has been well-known as a significant photocatalyst material. One-dimensional ZnO nanorods (ZnO-NRs) have been of utmost interest due to their high surface area, efficient charge transport, and superior photosensitivity. These features make ZnO based nanorods exciting candidates for applications in photocatalysis. Even though photocatalysis using bare ZnO NRs is useful in pollutant remediation, two main drawbacks scale down their performance as photocatalysts. First, ZnO NRs absorb mainly the UV light, which compromises a small portion of the solar spectrum, and second, the high recombination rate in the ZnO NRs prevents the path of electron-hole outward and then reduces the photocatalysis efficiency. In this research work, ZnO-NRs, ZnO-NRs/Graphene Oxide (GO), and ZnO-NRs/Reduced Graphene Oxide (RGO) arrays composites were vertically grown on conductive glass substrates of SnO_2: F (FTO). The films were synthesized by a three steps method: first, ZnO seed layers were deposited by spray pyrolysis technique on FTO substrates at 350°C from a precursor solution of zinc acetate. The second step was the growth of nanorods in a supersaturated solution of zinc nitrate and hexamethylenetetramine (HMT) at 92°C from the deposited seeds. Finally, nanosheets of GO and RGO were anchored onto the surface of the as-prepared ZnO-NRs by using the spray technique. The obtained films were characterized structurally by using X-Ray Diffraction (XRD), morphologically by scanning electron microscopy (SEM), the elemental composition was determined by X-ray spectroscopy by Energy Dispersive (EDS), and their optical properties were studied by UV-Visible Spectroscopy and photoluminescence. The SEM images confirm the presence of nanosheets of GO of RGO onto the obtained films of ZnO NRs of between 50-200 nm of diameter. The diffractograms indicate that the nanorods have a wurtzite hexagonal structure, with preferential growth direction along the axis "c". Finally, The photocatalytic activity of these materials was studied by analyzing the degradation of methylene orange (MO) in an aqueous solution under ultraviolet light, and we found that the decoration of ZnO-NRs with nanosheets of GO and RGO resulted in a significant enhancement of the photocatalytic degradation efficiency being ZnO-NRs/RGO more efficient than ZnO-NRs/GO and this last better than pure ZnO-NRs.

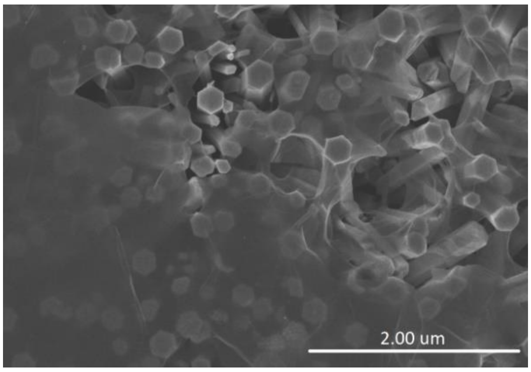

Figure 1 . SEM image of ZnO-NRs/RGO

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Hybrid materials based on diatomite modified by gold nanoparticles: fabrication and photoacoustic characterization

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The production of modern functional and structural hybrid materials using natural objects such as unicellular diatoms microalgae as templates has become one of the fastest-growing research areas. Here, we employed for the first time the combination of two approaches—layer-by-layer assembly and freezing-induced loading—to fabricate hybrid materials based on diatomite, composed of the remains of fossilized diatoms, and gold nanoparticles with an average size of 19 nm. To characterize the fabricated gold-coated diatomite structures, we applied the dynamic light scattering method, absorbance spectroscopy, scanning (SEM), scanning transmission (STEM), and transmission electron microscopy (TEM), Energy Dispersive X-Ray Analysis (EDX), and raster scanning optoacoustic mesoscopy (RSOM) technique. The fabrication methods allowed us to obtain different coverage of diatomite by gold nanoparticles, depending on the number of applied layers. The photoacoustic signal excited at a wavelength of 532 nm increased with increasing loading cycles up to three polyelectrolyte-gold nanoparticle bilayers, after which a decrease in the signal intensity was observed. The hybrid materials based on diatomite modified by gold nanoparticles can be used as surface-enhanced Raman scattering (SERS) substrates.

FUNCTIONAL MATERIALS BASED ON 1D AND QUASI-1D STRUCTURES

7-10 December 2021
Chimie ParisTech, Paris

InGaN nanostructures grown by MBE

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Keywords: III-N nanostructures, MBE, Si based substrate

III-N nanostructures are among the most promising candidates for ultraviolet and visible solid-state lighting and renewable energy sources. GaN nanowires (NWs) are well known, most of the growth parameters are well studied. An issue of the unintentional doping due to high growth temperature is still under the examination. In the first part of the talk we will focus on the substrate influence (Si or SiC/Si) on the Si ascending doping of the NWs. Another part of the talk will be dedicated on less studied system, namely InGaN nanowires and nanoflowers grown on Si and SiC/Si substrates. We will show that the elastic strain relaxation on the nanowire sidewalls can help to overcome the InGaN miscibility gap and achieve better band-gap tunability than in a bulk alloy. It appears that InGaN/Si NWs system is quite delicate and a change in the growth temperature of just ~20 degrees Celsius leads to a significant change in structural properties of nanowires and shifts the photoluminescence emission from orange to blue. We will also demonstrate that InGaN NWs under appropriate growth conditions would form a core/shell structure where In content in the core is an order of magnitude higher than that in the core one. A novel approach to the growth of InGaN NWs at a small temperature gradient of over the substrate surface has demonstrated the potential for the implementation of multi-colour light emitters monolithically grown on a Si substrate. In addition, we will show that InGaN nanowires on SiC/Si have a lower indium content (about 10%) compared to the nanowires grown on Si under similar growth conditions except of the substrate itself.

GaP nanowires: versatile platform for nanophotonics

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Low-dimensional nanostructures have proven themselves as very efficient light emitters due to both photonic and electronic spatial restriction. An iamportant example of the nanostructures used in fabrication of the nanophotonic elements are semiconductor nanowires (NWs). An important property of the NWs is the ability to vary their crystallinity and chemical composition both in vertical (axial heterostructures) and lateral (core-shell heterostructures) directions providing growth protocols unavailable with the other structure geometries. One of the most intriguing possibilities for nanophotonics and optoelectronics relates to synthesis of vertically stacked nanosized insertions in NW. This allows control over the coupling of the emission and increase of the quantum efficiency due to resonant properties of the NW acting as an optical cavity.

Gallium phosphide (GaP) is a peculiar semiconductor material. In terms of the optical properties GaP is lossless pretty much over the entire visible and IR ranges and optically dense making it priceless for fabrication of waveguides and cavities. Despite being indirect bandgap material, GaP can be diluted with other isovalent elements such as As, N, Al, In etc. making it direct bandgap. This chemical variation provides opportunities for fabrication of active photonic elements based on GaP NWs.

Here we report on the study of the micro- photoluminescence response generated in multiple nano-sized GaPAs insertions in GaP NW and discuss its anisotropic nature and spectral peculiarities occurring due to the structure geometry.

Author thanks Russian Science Foundation (grant 20–72–10192).

Characterization of optical and nonlinear properties of individual GaP nanowires using optical tweezers

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Continuous demand for miniaturization of photonic devices attracts research interests towards individual nanostructures as elements of photonic circuits. Semiconductor nanowires being self-assembled structures following bottom-up approach, offer certain advantages compared to more conventional top-down techniques (like lithographic processing), such as high throughput of growth of multiple individual wires in a single process. So far nanowires were demonstrated as a platform for single-photon emitters[1], detectors and converters[2], nonlinear gates[3] and many others.

III-V nanowires, such as GaP are commonly grown using epitaxial techniques and offer distinctive advantages, such as flexible band-gap engineering[4] and tailor-made electrical properties[5]. Optical properties of individual nanowires can be obtained by cleaving and depositing them in an optically transparent substrate, allowing to probe micro-PL, Raman, and, to an extent, darkfield scattering. However such planar arrangement complicates excitation along the wire axis, which allows it to probe linear and nonlinear processes, such as waveguiding modes or second harmonic generation in a single nanowire. On the contrary, optical trapping allows to immobilize individual nanowires and to study their linear and nonlinear properties.[6]

Here we report on spectroscopic studies of individual GaP nanowires immobilized in optical traps. We explore correlations between nanowire's geometry and its second harmonic response both experimentally and theoretically. An impact of the nanowire geometry on phase-matching and efficiency of second harmonic response will be discussed.

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Dopants impact on planar GaAs nanowires growth

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Semiconductor nanowires (NWs) are widely considered as promising building blocks for novel opto- and nanoelectronic devices. Formation of p-n junction in nanowires and assembling the NWs array are key steps for the device fabrication. Usually, these processes are considered separately.

Here we would like to discuss about the influence of dopants on growth of planar NWs via Vapor-Liquid-Solid mechanism (VLS). In the present study we investigate the dopants impact on the shape and growth direction of planar NWs. We focused on the following aspects of planar nanowire growth: in-plane rotation of NW marked R in Figure 1 and NW detachment marked D in Figure 1.

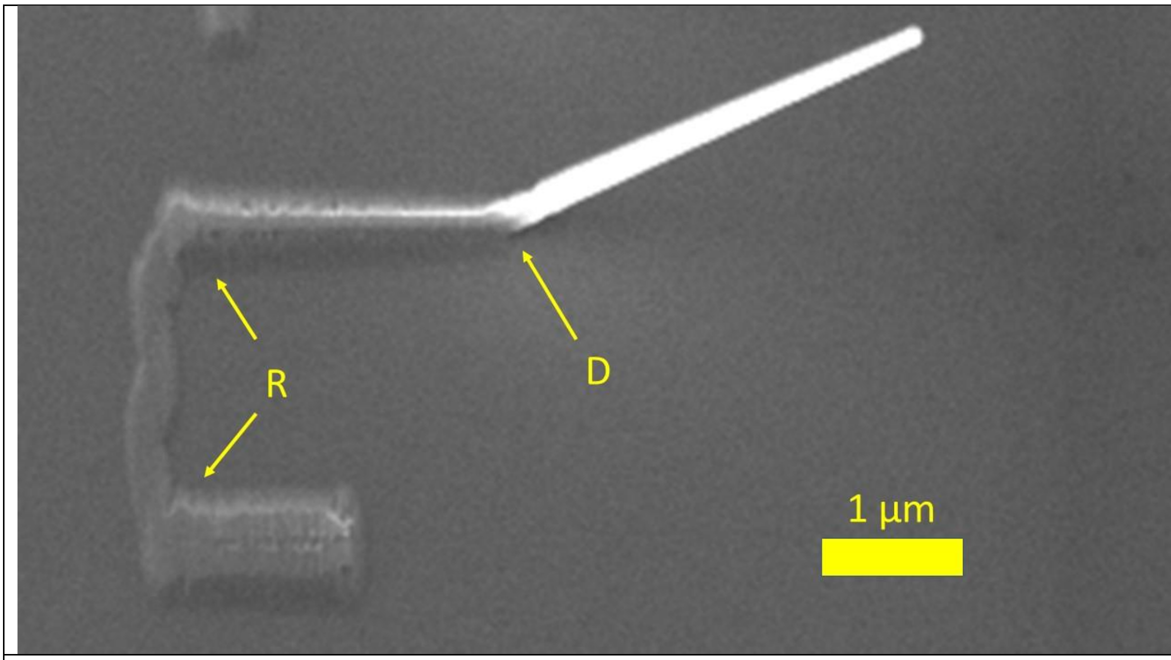

Fig. 1. Change of nanowire growth direction caused by the change of doping level: in-plane rotation is marked with R and nanowire detachment is marked with D.

We propose a theoretical model based on the nucleation limited mode of NW growth. Our main results can be formulated in the following way: NW rotation and detachment are caused by the change of the catalyst droplet surface energy and volume. An unwanted change of NW dopant level growth direction should be compensated by variation of NW growth rate and V/III ratio.

Optical sensing of organic solvents vapor with lead halide perovskite nanowire lasers on one-dimensional polymer nanograting

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The rapid development of the chemical industry in recent decades has induced an increase of the chemical safety standards. Substances that are harmful in low concentrations or have a cumulative effect on human health, such as volatile organic solvents - acetone, toluene, chloroform, and others - require special attention. The need for their usage in the wide range of chemical processes necessitates the creation of cost-effective and ultra-high sensitive gas sensors. Ideal candidates in this sense are lead-halide perovskite nanostructures known for their unique optical properties, including high-Q lasing at low thresholds [1]. Perovskite nanolasers demonstrate a sensitive optical response to small changes in the effective refractive index (n_{eff}) of the surrounding medium when integrated with nanostructured substrates. A further improvement in sensitivity is associated with the ability of the nanostructured substrate to change its geometric parameters and, consequently, n_{eff} by absorbing analyte molecules [2].

In this work, we report on a theoretical study of the mechanism for sensing of organic solvents vapor in the air with $CsPbBr_3$ nanowire (NW) lasers on a polystyrene nanograiting (PS NG). In our model, the absorption of analyte molecules causes an increase in the width of the PS NG ridges and, consequently, an increase in the effective refractive index under the NW laser. A small change of n_{eff} affects the spectral position and Q-factor of the laser mode (Fig.1). It has been shown that for a NW laser on a nanograting with a period of 280 nm, a ridge width of 180 nm, and a depth of 110 nm, even a small enlargement of the ridge width by 5 nm leads to a shift of the high-order laser mode (TE_{22}) by 0.3 nm to the long-wavelength region of the spectrum. These results can be useful for further progress in the field of optical gas sensing based on perovskite nanostructures.

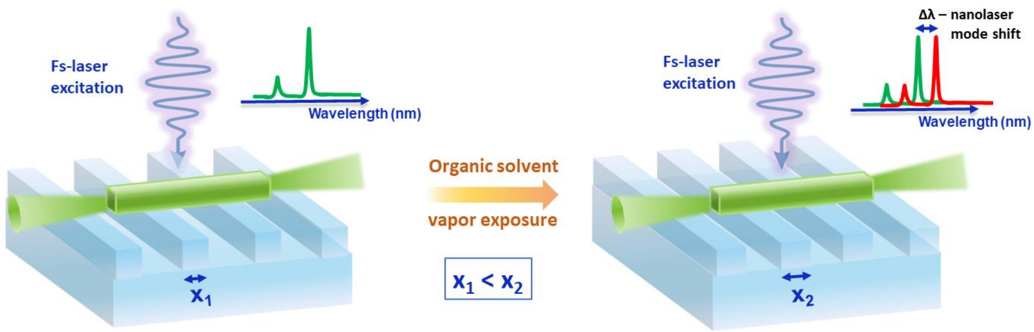

Figure.1. Schematic illustration of vaporized solvent detection with $CsPbBr_3$ NW laser placed on PS NG.

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Acknowledgement
This work was supported by RFBR (project no. 20-33-90212).

Gallium phosphide nanowires for biological ammonia concentrations detection

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Ammonia is found both in nature and in the human body, and its detection is very important in biology and medicine as well as in environmental monitoring systems. Concentration of the order of 1 ppm of ammonia produced with human breath is the biological marker of pathological changes in the body, while ammonia in concentrations of the order of 100 ppm is toxic and hazardous. Among modern methods for liquid probes analysis, voltammetry methods are mostly often used. Classical sensor devices based on metal oxides, which have proven themselves in gas sensing, are widely presented [1–4]. To improve the sensitivity features of the semiconductor based adsorption sensors, structures with developed area should be used. Despite the high ratio of the surface area to volume of epitaxial nanostructures and the pronounced conductivity features of quasi–1D structures compared to bulk materials, the adsorption properties of III–V NWs and their correlation with electrical characteristics are still poorly studied [5–6].

This work is aimed at fabrication and study of precise, technological and relatively cheap ammonia sensors compatible with a liquid medium. We use GaP epitaxial nanowires (NWs) as adsorption elements for ammonia sensors fabricated via a simple protocol. The device properties with addition of ammonia to the reference medium (water) are studied in terms of change in sensor impedance spectrum. The potential of electrical impedance spectroscopy for characterization of interaction between low–dimensional nanostructures and environment is shown. Ammonia sensors based on III–V NWs have been developed, and a physical interpretation of their impedance spectra in the presence of water and ammonia is given. GaP–based devices exhibit sufficient response to the ammonia presence with the detection limit lower than 2,5ppm.

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Influence of plasmon effects on the electromagnetic waves localization in GaP nanowires

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The main object of this study is gallium phosphide (GaP) NWs grown by molecular beam epitaxy (MBE) on Si (111). The choice of this material is justified by the low value of the absorption coefficient in almost the entire visible range [1]. Thus, it becomes possible to design passive optical elements with great freedom in the choice of size and geometry. The development of a waveguide nanostructure of small size requires high localization of the electromagnetic wave. One of the promising methods for controlling light at nanoscale is the plasmon effects.

Numerical simulation showed [2] that the localization of the incident wave field in GaP NWs is enhanced in the presence of a gallium droplet. To confirm the simulation results experimentally, the method of Raman scattering spectroscopy with local excitation was used. To carry out measurements, GaP NWs with a length and diameter of about 4 μm and 120 nm respectively possessing a gallium growth catalyst droplet were transferred from the growth substrate and planarized on a glass substrate. To determine the location of each NW, gold marks with an indium-tin oxide sublayer, visible through an optical microscope, were preliminarily deposited on the glass. Further, SEM images were obtained to determine the geometry of the studied NWs.

After the SEM procedure, the substrate with the NWs was placed in a Raman spectroscopy setup, where the scattering response was mapped over the entire surface of several nanostructures, including those with different polarization orientations of the laser beam. Scanning was performed through a hundredfold objective (N.A. = 0.9) with a step of 40 nm. The laser spot size (532 nm) was about 1 μm. According to the mapping results, an increase in the integral signal from 450 to 3000 counts was registered as we approach the gallium droplet interface. Maps obtained with different polarizations showed that with polarization parallel to the NW axis, the signal intensity is much higher. In addition to the enhancement of Raman scattering due to plasmon effects, the influence of polarization on the photoluminescence intensity of single GaP NWs with direct-gap GaPAs inserts was investigated. In this case, the spectra were measured under excitation of one of the end faces with a subsequent change in the direction of polarization. The experiment also showed a significant increase in intensity with parallel polarization.

Authors thanks the Ministry of Science and Higher Education of the Russian Federation (grant № FSRM–2020–00011) for support of nanostructures optical characterization and Russian Science Foundation (grant 20–72–10192) for support of theoretical models design.

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Computational Design of Spin-mediated Sensors Based on V3S4 Monolayer

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Search for new two-dimensional material suitable for electronic and especially sensing applications is a challenging issue for materials scientist. Here we computationally discover new ultrathin two-dimensional ferromagnets V_3S_4 displaying unique stability and electronic properties making this material prospective for widespread applications in spintronics and gas sensing devices.

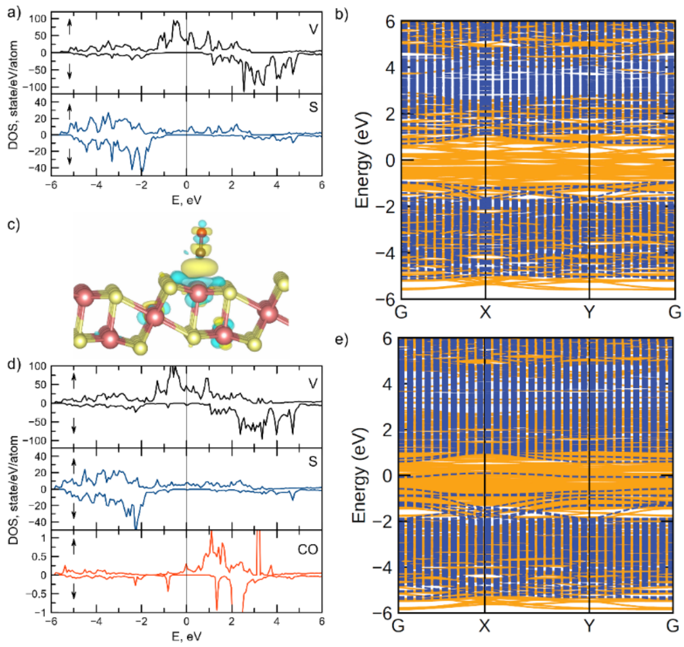

Figure 1. Spin- and atom-projected density of states and band structure of V_3S_4 nanosheet before (a, b) and after adsorption of CO (d,e). Solid orange and dashed blue lines in band structure correspond to different spin polarization of electrons. Charge density difference in V_3S_4 nanosheet with adsorbed CO molecule is shown in the inset (isosurface level: 0.0003 eV/Å^3). Color legend: V, light red; S, yellow; yellow and turquoise surface densities represent electrons gain and loss, respectively.

Electronic structure calculations within DFT+*U* approach show that V_3S_4 is a half-metal with band gap > 1.5 eV for one of spin channels. Study of dependence of electronic properties of V_3S_4 to the adsorption of various gas agents shows pronounced response to the presence of CO molecule on the surface reflecting on its conductivity. Obtained results show the prospective for V_3S_4 to be used as effective sensing materials for CO sensing and capturing.

We thank grant of Russian Foundation for Basic Research № 20-53-05009 Arm_a for support, the Center for the Information and Computing of Novosibirsk State University for computational resources.

THZ OPTOELECTRONICS AND PHOTONICS

7-10 December 2021
Chimie ParisTech, Paris

Semiconductor Surface States: Nanoscale Wavelength Converters

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Surface states generally degrade semiconductor device performance by raising the charge injection barrier height, introducing localized trap states, inducing surface leakage current, and altering the electric potential. Therefore, there has been an endless effort to use various surface passivation treatments to suppress the undesirable impacts of the surface states. We recently demonstrated that the giant built-in electric field created by the surface states can be harnessed to enable passive wavelength conversion with unprecedented efficiencies without utilizing any nonlinear optical phenomena. Photo-excited surface plasmons are coupled to the surface states to generate an electron gas, which is routed to a nanoantenna array through the giant electric field created by the surface states. The induced current on the nanoantennas, which contains mixing product of different optical frequency components, generates radiation at the beat frequencies of the incident photons. We utilized the unprecedented functionalities of plasmon-coupled surface states to demonstrate passive wavelength conversion of nanojoule optical pulses at a 1550 nm center wavelength to terahertz regime with record-high efficiencies that exceed nonlinear optical methods by 4-orders of magnitude. The presented scheme can be used for optical wavelength conversion to different parts of the electromagnetic spectrum ranging from microwave to far-infrared regimes by using appropriate optical beat frequencies.

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Billiard-like resonances in metallic nanostructures and their use for efficient ultrafast nonlinear optics

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As it is known, optical properties of metallic nanostructures may demonstrate resonant behavior because of light-induced movement of the electronic cloud close to the surface. Several types of such resonances exist, such as Mie resonances, anapole modes [1], bound states in continuum [2] and others. These resonances are related rather to light than to the bounded motion of electrons in metals and lead to optical nonlinearities, leading to, for instance, harmonic generation. Another source of nonlinearities in optics are the resonances, appearing due to quantum confinement of electrons in the finite volume of a nanoparticle. In this case, electron is trapped in a cavity formed by the nanostructure walls – the picture typical also for “quantum billiard” framework [3]. When many of such electronic levels are involved, the statistics of level spacings reveals a peak close to zero frequency. That is, many closely spaced resonances may, in certain sense, work as a single composite resonance. Although such resonances were observed in semiconductor quantum dots, they were neither considered nor observed in metallic particles. This sounds logical, since in metals the width of every particular possible transition is huge and many of such broad resonances, closely spaced, should compose rather a continuous band than a single resonance.

Here we show that, quite in contrary to the above mentioned intuition, many broad resonances, arising due to quantum confinement of electrons inside metallic nanostructures and nanoclusters form a single “super-resonance”. Such super-resonance typically lies in the low, mid-infrared (MIR) or terahertz (THz) frequency range and, as we show, plays a critical role in the optical response at those frequencies. Here we show that these resonances can be very useful in ultrafast nonlinear optics. We demonstrate, that the difference frequency mixing (DFG) process with the signal in MIR and THz, can lead to a efficient broad-band conversion at the nanometer-scale propagation distances. .

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Large HgTe nanocrystals for THz technology

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Semiconductor nanocrystals (NCs) raise more and more interest as they combine size-tuneable electronic energy levels with easy processing and transferability. They appear very promising materials for many optoelectronic applications in the visible and infrared range such as bio-labelling, single photon sources and light sources for display and low-cost infrared sensors. However, very little work has to date been focused on their potential for THz technology [1]. Among the various NCs, mercury telluride (HgTe) is an ideal material to expand the optical features towards the THz spectral range because it is a semimetal in the bulk with zero band gap. Here, we present the optical properties of self-doped large HgTe NCs in the THz spectral range. By combining microscopic modelling and measurements based on THz time-domain spectroscopy and Fourier Transform Infrared spectroscopy, we demonstrate a broad THz absorption resonance centred at ≈4.5 THz, which relies on intraband excitations of individual carriers. Our analysis reveals the absence of collective excitations in their THz optical response. Furthermore, using optical pump-THz probe experiments, we report on carrier dynamics at low energy as long as 6 ps in these self-doped large HgTe NCs [2]. We highlight evidence that Auger recombination is irrelevant in this system and attribute the main carrier recombination process to direct energy transfer from the electronic transition to the ligand vibrational modes and to nonradiative recombination assisted by surface traps. Our study opens interesting perspectives to exploit large HgTe NCs for quantum engineering at THz frequencies and for the development of THz photodetectors and emitters.

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How to use terahertz emission spectroscopy and imaging in real onsite semiconductor R&D scenes

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Terahertz emission spectroscopy (TES) and imaging (LTEM) are fundamentally different from THz-TDS. THz-TDS is used to estimate the complex refractive index of materials at THz frequencies, whereas TES discusses the emission mechanism and discloses the ultrafast optical responses of materials. Although one can observe the THz emission from a variety of materials and discuss their ultrafast carrier dynamics [1,2], killer applications for the large market are still missing. In this presentation, we provide hints on how to use TES and LTEM in real onsite semiconductor R&D scenes. To attract many scientists and engineers in the field, we have to provide them simple pictures of what we measure and characterize from the signals. Recently we have reported such simplified descriptions for the THz emission from semiconductor surfaces and MOS/MIS structures[3,4], which explain the observed properties well and make it clear how we can use the THz emission properties to characterize semiconductor parameters [5,6]. Thanks to them, we can have much higher expectations of TES and LTEM for various applications, such as wafer-scale characterization of passivation on semiconductors, wide bandgap semiconductor properties, and 3D LSI development [7-11].

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Perfectly Absorbing Optical Metasurfaces for Terahertz Applications

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Integration of plasmonic nanostructures and optical metasurfaces into photoconductive THz sources and detectors over the past several years has demonstrated the potential of photonics engineering for improving the efficiency and sensitivity of key THz technologies [1-7]. The photoconductive antenna (PCA) THz detectors is one of these technologies and it is widely used in THz spectroscopy and imaging research. Recent research in the area of PCAs have focused primarily on design and integration of plasmonic nanostructures, including interdigitated metallic contacts, nanorods and nanoantennas [8]. More recently, all-dielectric optical metasurfaces have been introduced as an alternative to plasmonic elements [3-6]. The metasurfaces can improve the efficiency of PCA detectors by exploiting the effect of perfect optical absorption, which enables highly efficient ultrafast switching of the PCA. At the same time, the metasurface geometry allows engineering the electronic properties of PCA detectors and improve the detector sensitivity [3]. In this presentation, we will discuss the impact of integrating all-dielectric metasurfaces into the photoconductive channel on the electronic properties of THz detectors. We will show the THz PCA detectors with metasurfaces require only a μWatt-level optical gate power for optimal operation [3]. The reduction of the power requirement opens possibilities for wider application of photoconductive THz detectors. We will also discuss how the perfectly absorbing metasurfaces can be exploited for generation of THz pulses.

Acknowledgment

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering. Fabrication, optical, and in part THz experiments were performed at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. O.M. and L.H. also acknowledge the support of the EPSRC.

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Vacuum-field-induced THz transport gap in a carbon nanotube quantum dot

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The control of light-matter interaction at the most elementary level has become an important resource for quantum technologies. Implementing such interfaces in the THz range remains an outstanding problem. I will present how we couple a single electron trapped in a carbon nanotube quantum dot to a THz resonator. The resulting light-matter interaction reaches the deep strong coupling regime that induces a THz energy gap in the carbon nanotube solely by the vacuum fluctuations of the THz resonator. This is directly confirmed by transport measurements.

This should be a particularly useful resource and perspective for THz quantum optics.

The absolute power meter of microwave radiation.

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A two-level quantum system, the qubit, can absorb or emit not more than one photon at a time. Using this fundamental property, we experimentally demonstrate how a qubit strongly coupled to a microwave transmission line can be used as a sensor of the photon flux. Four methods can be used for the absolute calibration of power by measuring spectra of scattered radiation from the two-level system. This type of sensor can be tuned to operate in a wide frequency range, and does not disturb the propagating waves when not in use. A range of applications are envisaged, in particular the sensor can be used to calibrate the attenuation of the transmission lines inside dilution refrigerators when designing the quantum processor.

THz self-modulated graphene perfect absorber

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The era of terahertz (THz) wireless communication opens up ahead revealing the high importance of the development of fast modulation devices operating at the THz part of the electromagnetic spectrum. Towards this direction many devices based on graphene have been proposed to modulate radiation at THz frequencies [1,2]. Here, we demonstrate a graphene based THz perfect absorber based on a cavity of monolayer graphene over a grounded dielectric that can be self-modulated using intense THz fields.

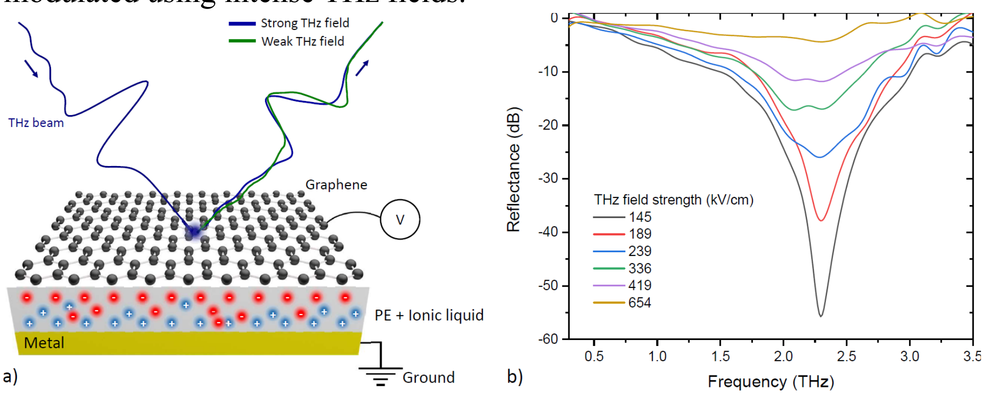

FIg. 1: (a) Schematic representation of the device. (b) Reflection spectra for various incident THz field strengths.

The cavity (Fig. 1a) is formed by a 25 μm thick porous membrane sandwiched between a monolayer graphene and a gold electrode. The porous membrane was soaked with room-temperature ionic liquid electrolyte that allowed us to fine tune the Fermi energy of graphene with an external gating. For the excitation of the device a high power THz source based on two-color filamentation was used, providing THz pulses with peak electric field strengths reaching 700 kV/cm. At low THz field strengths the device achieves an absorption of -56 dB at 2.3 THz that drops to -4 dB for high field strengths (Fig. 1b). This non-linear behaviour can be explained by an interaction of the intense THz field with the free electrons in the graphene layer, resulting in strong modulation of its conductivity via carrier heating [3]. Our results demonstrate the implementation of ultrafast nonlinear THz modulators that can find applications in future telecommunications and flat optics modulation.

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Terahertz scanning tunneling microscopy of atomically precise nanostructures

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Novel atomic-scale electronics operating at optical frequencies require new tools that can characterize them and inform device fabrication. Lightwave-driven scanning tunneling microscopy is a promising new technique towards this purpose. By coupling free-space-propagating single-cycle terahertz transients to an atomically sharp metal tip, it achieves simultaneous sub-nanometer and sub-picosecond spatio-temporal resolution [1–7]. Here, we utilize terahertz scanning tunneling microscopy (THz-STM) and spectroscopy (THz-STS) to investigate seven-atom-wide graphene nanoribbons on an Au(111) surface and unveil highly localized wavefunctions that are inaccessible with conventional scanning tunneling microscopy [7]. Three-dimensional tomographic THz-STM imaging of the electron density reveals a faster vertical decay of the valence band compared to the conduction band, paving the way for ultrafast measurements of wavefunction dynamics in atomically precise nanostructures.
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Advances in Optics of Subcycle and Unipolar Pulses

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The important part of modern physics is the generation of extremely short pulses in various spectral region [1, 2]. For example, they are actively used for control of wave packet dynamics in matter [3]. Any conventional electromagnetic pulses are bipolar – electric field strength changes its direction several times during the pulse duration [1]. Electric area of such pulses defined as $S_E(r) = \int E(r,t)dt$ [4] ($E(t)$ –electric field strength, t- time) is always zero. The limiting case of pulse shortening is generation of unipolar half-cycle pulses, containing a monopolar half-wave of the electric field and having non vanishing electric area, see review [5]. Unipolar pulses are capable of exerting a unidirectional effect on quantum systems. Acting as a short "kick" they can effectively and very fast change the state of quantum object and thus can be used for effective ultrafast control of wave packet dynamics in matter, charges acceleration etc [5-8].

The existence of such pulses in optics has long been questioned [5]. Experimentally unipolar-like pulses in THz and optical ranges can be generated so far [2,3] . The important quantity of unipolar pulses is their electric area S_E [4-8]. This area is of fundamental importance because it possess the property of conservation in 1D dissipative systems [4]. The latter is a new conservation law in physics. Next, the action of unipolar subcycle pulse on microobject is determined by the electric pulse area when pulse duration is less than characteristic wave packet oscillation time in medium [5-8].

In this talk, we revise recent approaches on unipolar subcycle pulse production in optical and THz ranges. We consider their interaction with quantum objects, discuss electric pulse area conservation law etc. This research is supported by Russian Science Foundation, project 21-72-10028.

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Optics of Two-Dimensional Materials with Tilted Dirac Cones

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We analyse the interband optical absorption of linearly polarised light by 2D Dirac semimetals hosting tilted Dirac cones in the band structure. Super-critically tilted (type-II) Dirac cones are characterised by an absorption that is highly dependent on incident photon polarisation and tuneable by changing the Fermi level with a back-gate voltage. Unlike their sub-critically tilted (type-I) counterparts, type-II Dirac cones have open Fermi surfaces meaning that there exists large regions of the Brillouin zone where both bands sit either above or below the Fermi level causing many states that would otherwise contribute to absorption to be Pauli blocked. We analyse Dirac cones featuring tilt as well as anisotropy in the Fermi velocity, yielding a wide range of qualitatively unique absorption spectra. Guided by our in-depth discussion we develop an optical recipe to fully characterise the tilt and Fermi velocity anisotropy of any 2D tilted Dirac cone solely from its absorption spectra. We also show that tilted Dirac cones allow spatial separation of carriers belonging to two different valleys under illumination by linearly polarised light, leading to novel optovalleytronic applications. Our results are used to analyse polarisation-dependent light absorption of 8-Pmmn Borophene[1,2].

This work was supported by the EU H2020 RISE project TERASSE (Grant No. 823878)

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POLARITONICS & PLASMONICS

7-10 December 2021
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Ultrastrong light-matter coupling: engineering electronic wavefunctions with single photons

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When the coupling between a confined electromagnetic mode and the electronic degrees of freedom of a solid-state system becomes large enough, the interaction can modify electronic wavefunctions and the related material properties. The hybrid polaritonic quasiparticle generated when the system absorbs a photon gets then dressed by an excitonic wavefunction which doesn't correspond to any of the unperturbed electronic states. As a first demonstration of this concept we experimentally observed a change of roughly 30% in either direction for the Bohr radius of Wannier excitons in GaAs microcavity embedded quantum wells [1], an effect originally predicted by Khurgin [2].

Investigating this technique to modify electronic wavefunctions at the single photon level we discovered the effect becomes much more dramatic in systems with continuum electronic degrees of freedom. In these systems the gapless spectra enhance the electronic compressibility, to the point that novel photon-bound excitons can be created around the photo-excited quantum well [3]. Using doped GaAs quantum wells we were then able to spectroscopically observe the existence of these predicted photon-bound excitons stabilised by the presence of the photonic cavity [4].

More recently related effects were also observed in a 2D electron gas, in which the excitation of high-momenta hybrid modes by nano-features of the resonator could launch propagative plasmons acting as a powerful damping channel [5]. This interaction with the propagative nature of the plasmons, similarly to other nonlocal effects in metals [6] or dielectrics [7], reduces the available field concentration and thus the maximal coupling achievable between light and matter, but it also allows to tune the electromagnetic field at the nanoscale.

Solid-state cavity quantum electrodynamics, after having shown its relevance in optoelectronic and more recently in chemistry, is increasingly becoming a tool for quantum material engineering, allowing us to drastically enrich the catalogue of materials available for scientific and technological applications.

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Topological photonics and topological lasers with coupled vertical resonators

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Topological Photonics is an emerging and novel field of research, adapting concepts from condensed matter physics to photonic systems adding new degrees of freedom. After the first demonstrations of topological photonic insulators [1,2], the field has moved on to study and exploit the inherent non-hermiticity of photonic systems and the interplay with their topological nature. With the envisaging [3] and realization [4-6] of topological insulator lasers it became possible to exploit topological effects to facilitate injection locking of arrays of semiconductor lasers. Topological insulator lasers have now been realized using a variety of platforms and designs as a means to efficiently couple and phase-lock extended arrays of lasers to behave like one single coherent laser. The major drawback so far is that the emission appears in the plane of the topologically protected light propagation, thus hindering light extraction. By designing a topological system which employs out-of-plane emitters such as evanescently coupled Vertical Cavity Surface Emitting Lasers (VCSELs), we can successfully separate the emission direction of the individual lasers from the propagation direction of the topologically protected mode in-plane ensuring the topological protection. In this work, we present the first experimental demonstration of a topological insulator VCSEL array [7]. Using the crystalline topological insulator model [8], we facilitate a topological gap and ensure topological mode protection at the interface of a compressed and stretched hexagonal lattice. In contrast to a range of topological photonic systems, here the topological protection is virtually independent of the wavelength or direction of lasing. The individual emitters form a lattice array measuring a few tens of microns, with each site emitting vertically, allowing for an efficient light collection and resulting in a powerful coherent laser beam. Using spatial interference measurements of the topological mode lasing within the bandgap, we highlight that the full array of 30 emitters displays an extended coherent mode emitting at a single wavelength, demonstrating that topologically protected in-plane transport can force the predominantly vertically oscillating emitters to act as one single coherent laser.

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Polariton lasing in organic semiconductor microcavities

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Microcavities are structures composed of two mirrors placed either side of a semiconductor film. Within the strong-coupling regime, a hybridization occurs between confined photon modes and the semiconductor excitons, creating new types of quasi-particles called cavity polaritons [1]. As cavity polaritons are bosons, they can undergo a condensation process at high occupation density, creating a non-equilibrium polariton condensate that is trapped at the bottom of the 'lower polariton branch'. The emission of light from such condensates carries the same high degree of spatial and temporal coherence as the condensate itself, and represents a class of light-source called a polariton laser.

Here, I present our work on the fabrication of strongly-coupled microcavities based on fluorescent organic dyes. Organic semiconductors are of interest for polariton laser applications as their fundamental excitations (Frenkel excitons) are strongly bound and exist at room temperature. The fluorescence emission wavelength of such materials can be varied across the visible spectrum by molecular design, with their high radiative rates and high optical gain making such materials good candidates for lasing applications.

Here I present evidence for polariton condensation in BODIPY-Br based microcavities [2], and demonstrate that polariton-condensates combine a high degree of spatial coherence (up to 30 μm), long lifetimes (up to 1.2 ns) [3], with condensate emission energy being tunable through 125 meV by controlling cavity length [4]. I then show that polariton condensation and lasing can be observed in cavities based on relatively simple 'hybrid' cavity mirrors that comprise a thin silver film and a low number of dielectric layers [5]. Finally I show that polariton lasing can be observed in microcavities containing a styrylbenzene-derivative dye (DPAVB) having a high degree of photostability. Such properties make DPAVB of interest for a range of practical optoelectronic applications.

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A Quantum Annealing Approach to Optical Analogue Computing

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We theoretically implement a strategy from quantum computing to simulate all-to-all connected dissipative coupled oscillator networks. Such networks correlate to the minimum in energy of the XY Hamiltonian encoded by network coupling strengths [1,2], which in turn offers perspectives on analogue computing through heuristically solving complex graph problems, such as the NP-hard max-3-cut problem [3], and the phase retrieval problem [4].

Optical computing platforms, including polariton condensates [1,2], photon condensates [5], non-degenerate optical parametric oscillators [6] and coupled microarray lasers [7], take advantage of the systems' photonic parallelism, ultrafast timescales, and low power consumption. However, alongside these many benefits there are a handful of technical hurdles to overcome. Most graph problems that would benefit from an optical-based heuristic solver typically have high graph connectivity, which is hard to map to an optical oscillator network as finite and fully controllable coupling strengths are required between every pair of oscillators.

In this work [8], we tackle this problem by expanding a dense all-to-all connected graph to a sparse *triad graph* structure using the *minor embedding* technique practiced in the field of quantum annealing [9]. By comparing the results to a classical solver, we show that the triad graph oscillator dynamics correlate to the encoded dense graph problem. This result demonstrates the potential of future on-chip optical computing through mapping dense graph problems to a standardised hardware-friendly sparse structure. Our strategy is applicable to any system of densely coupled oscillators with a particular application in the design of hardware or software architectures to explore fundamental physics of densely connected elements, and the optimisation of computationally complex graph problems.

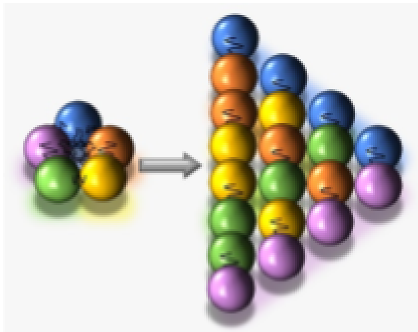

Figure 1. Schematic of all-to-all connected graph (left) expanded through minor embedding to the triad graph structure (right) [9].

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Exciton polaritons interacting with plasmons in WSe_2-Au lattices investigated using Cathodoluminescence Spectroscopy

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Semiconducting transition metal dichalcogenides (TMDC) combined with photonic cavities, exhibit strong light-matter coupling, leading to the emergence of new quasi particles [1], namely exciton-polaritons (EP). EPs have been extensively studied using near-field techniques such as SNOM and EELS for their fascinating fundamental properties [2]. These methods convey subwavelength features where EP propagations were directly imaged at monochromatic photon energies. On the other hand, plasmonic crystals such as gold lattice have been previously investigated for their optical responces and surface plasmon polaritons showing promising features for photonic systems [2].

Here, we first apply cathodoluminescence (CL) spectroscopy to probe EPs and stemming spatial correlations in atomically-flat TMDCs such as WSe_2 [4] (Fig. 1). In a second step, by depositing thin layers of WSe_2 on a gold lattice, we investigate the exciton-plasmon interactions between the TMDC and a two-dimensional periodic hole structure incorporated in a gold substrate. Cathodoluminescence spectroscopy and hyperspectral imaging are used for imaging the spatio-spectral near-field distribution of the optical modes in the visible to the near-infrared spectral ranges. Being based on spontaneous interactions, the resolved spatial interference maps are the direct proof of the spontaneous coherence associated with propagating exciton polaritons. To achieve this goal, we use electron beams (Fig. 1a) to excite optical modes of WSe_2 flakes and to investigate their spontaneous coherences by means of CL [4]. Our experimental data demonstrate a wavelength splitting on the order of 100 nm, comparable to the predicted spectral and spatial maps. In WSe_2-Au hybrid structures, experimental results fallowed by numerical simulations demonstrated additional interactions between the WSe_2 excitons and plasmon polaritons originating from the Au structures, which provide deep inside into the exciton-plasmon interaction mechanisms. This study proposes CL spectroscopy as a powerful technique for investigating photonic modes of freestanding thin WSe_2 flakes and plasmon-exciton hybrid structures.

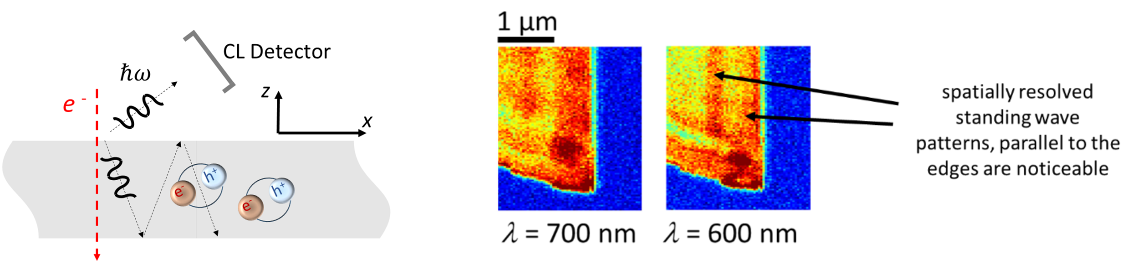

Fig.1 (a) Schematic of a thin film supporting quasipropagating optical excitations (b) Edge EP propagation along the edges.

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2D perovskites for spin-orbit photonics and topological polaritons

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In the last decade, hybrid organic-inorganic 2D perovskite have experienced a growing interest among the materials science community thanks to the great synthetic versatility that allows to tune their optical properties by modifying the chemical composition and synthesis techniques. Recently, we have shown that 2D perovskites allow the realization of exciton-photon strongly coupled devices (Figure 1A) working at room temperature with significant nonlonear properties, representing a promising pltatform for fundamental studies and electro-optical applications [1].

In this work, we show that a chemical modification of the crystalline structure of the 2D perovskite embedded in a planar microcavity allows the formation of a non-Abelian gauge field acting on the polarization of exciton-polaritons. Moreover, we demonstrate that it is possible to tune the shape of the Berry curvature [2], demonstrating the potentiality of 2D perovskite polaritons as a promising platform for the manipulation of the topological properties of light.

By adding the fluorine atom on the organic chain of the 2D perovskite crystal, we exploit the resulting strong optical birefringence of the material for breaking the cylindrical symmetry of the polariton energy band (Figure 1B-C) and inducing the onset of a non-Abelian gauge field. The non-Abelian character of the gauge field implies the existence of a non-zero effective magnetic field that affects the real space trajectories of polaritons. We directly measure the effect of this gauge field on the polariton flow, like an effective magnetic field [3], demonstrating the deviation of propagating particles according to their polarization in real space.

Moreover, we demonstrate that the band geometry of the system can be controlled through the exciton/photon fractions of the polariton mode, exploiting the multiple resonances characteristic of the 2D perovskite energy dispersion (Figure 1D-M) and that the Berry curvature shape can be actively and precise control within each band, by tuning external parameters, such as temperature, magnetic field and sample thickness.

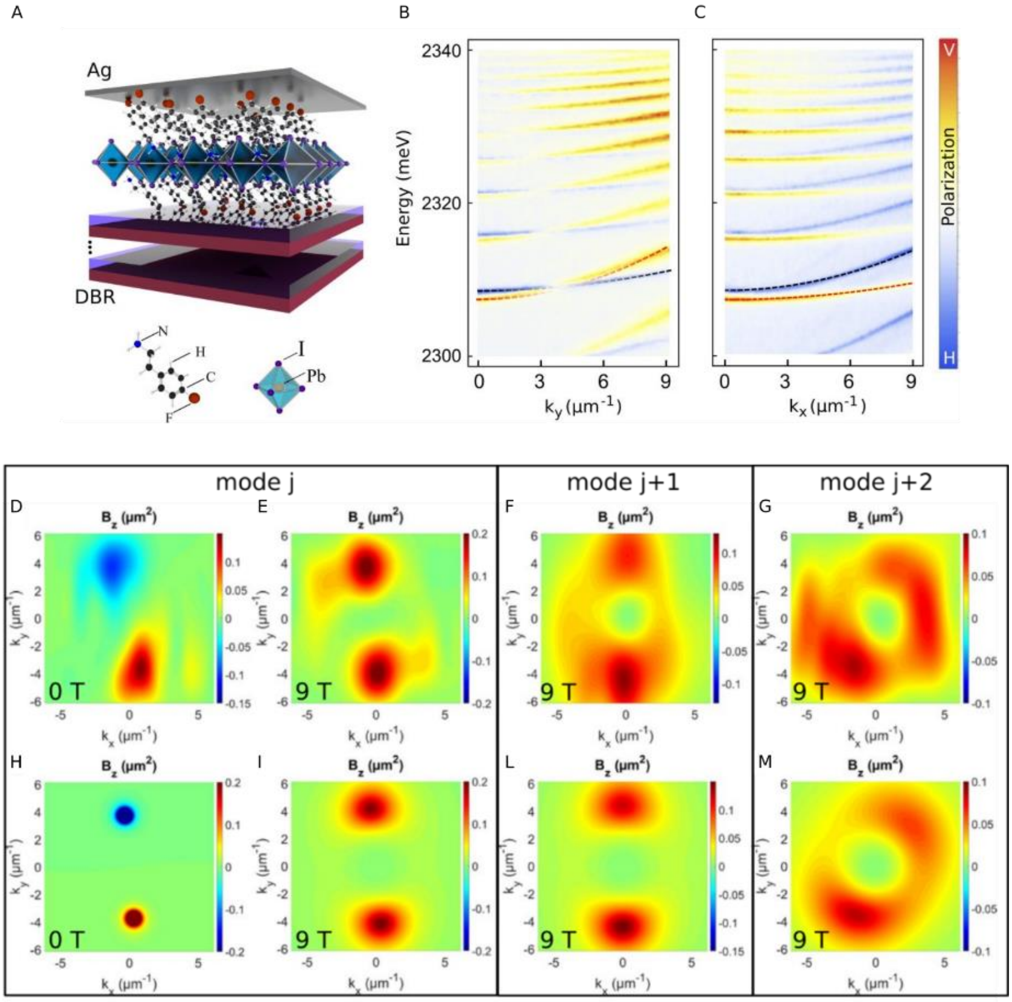

Figure 1: A) Schematic representation of a sample. Perovskite crystals are embedded in a planar microcavity made by a bottom DBR and a top silver mirror. B, C) Degree of linear polarization (H/V) of the photoluminescence signal of the lower polariton branches resolved in the energy vs ky (B) and kx (C) in-plane momentum space. The dashed lines are the theoretical dispersions. D-M) Experimental and theoretical Berry curvature extracted from the polarization-resolved measurements, increasing the excitonic fraction of the polariton mode, from j to j+2 modes.

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Towards plasmon mapping of SERS-active nanostructures obtained through thin metal film dewetting using scanning probe energy loss spectroscopy

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Conventional Raman spectroscopy suffers from low signal intensity due to the low occurrence of inelastic light scattering. Surface-enhanced Raman (SERS) overcomes this issue by enhancing the electric fields of the incident and scattered light through resonant coupling with localised surface plasmon resonances (LSPR) in metal nanostructures. As this behaviour can be complex, having an experimental technique capable of directly imaging LSPR is extremely useful for developing SERS-active substrates. This project investigates the potential of using scanning probe energy loss spectroscopy (SPELS) [1], an STM-based technique where the tip is used to field emit electrons, which are then inelastically scattered from the surface and detected by an energy analyser, to map the plasmonic behaviour of SERS-active substrates. This will aid in optimising their Raman enhancement factor and reproducibility. LSPR may be tuned by changing the nanostructure's size, shape, spacing and spatial arrangement. Such structures can be produced, for example, by thermal dewetting of silver and gold thin films. Here, we will present the results of a dewetting study of Ag and Au thin films on native SiO_2/Si substrates as a function of deposition and thermal annealing parameters. We will also report on the results of preliminary SPELS measurements of these structures, alongside simulations of the field enhancements produced around them using the finite-difference time-domain (FDTD) method. Recent SERS data measured over these structures, showing the correlation between SERS enhancement factor and the nanostructure geometry, size and interparticle separation [2] will also be discussed.

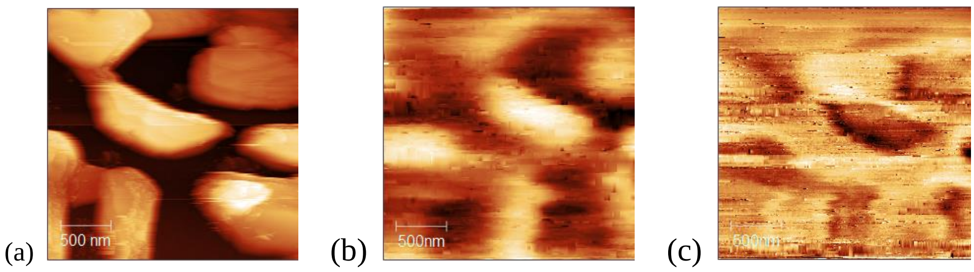

Figure. (a) STM image at -3 V and 100 pA of annealed 30 nm-thick Ag film on SiO2/Si. (b) Field-emission image of the same area as (a) at -100 V and 200 nA. (c) Backscattered electron signal from electron energy analyser.

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Advanced Functional Semiconductor Fibers and Fabrics: New Frontier of Flexible Electronics

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Fiber-based systems have been made and used by humans as they are soft, deformable, breathable, durable and washable. The demonstration of flexible functional fabrics enables the realization of wearable full-body sensing system to monitor various physiological signals. This requires the integration of functional materials such as semiconductors, conductors, and insulators into a single fiber with complex architectures and diverse functionalities. I will present our recent progress on fiber-shaped devices to enable the precise control on both functionality and device density. The hierarchical nature (fiber - yarn - fabric) makes them particularly suitable for the fabrication of wearable electronics.

Laser processing of semiconductor core fibers – device prospects

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Semiconductor core fibers, drawn using conventional fiber towers, have proven powerful platforms for optical applications, and optoelectronic and thermoelectric applications are on the horizon. Internal structuring of conventional semiconductor cores within a silica cladding has proven challenging due to the high temperatures involved, but the use of laser-driven thermal gradients has permitted segregation of the core constituents in both microspheres[1,2] and axially in continuous cores[3–6], permitting formation of structures that allow localized interaction with light. In order to provide both electrical and optical functionality, the introduction of metal elements into the core, either as dopants or electrodes is of interest. We describe propaedeutic work on the formation of axial and lateral electrodes, diodes and other structures in composite fibers.

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Molten-phase processing of multimaterial monofilaments: a route to functional fiber-embedded systems

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Fibers & Additive Manufacturing Enabled Systems Laboratory at IU Bloomington (FAMES Lab) holds a proprietary technology [1, 2], pending patent [3], for fabrication of 3D photonic and optoelectronic structures internal to fibers. In this molten-phase assembly technology, dubbed Very Large-Scale Integration for Fibers (VLSI-Fi), the fiber-photonics fabrication starts with defining the fiber cross-section through a thermal draw of the 3D printed preform [1], followed by the axial patterning of the fiber cores with a spatially coherent material selective capillary breakup, and finished by segregation-assisted dopant redistribution upon cooling and solidification of molten phase assembled structures.

In my lecture, I will describe the recent progress in substantiating VLSI-Fi as a technology that can deliver groundbreakingly impactful products.

For instance, VLSI-Fi is anticipated to deliver a new class of fibers embeddable in biomedical devices and impart them with distributed sensing and transduction [2, 4] for physiological monitoring and stimulation applicable to clinical and rehabilitation patient care. Additionally, VLSI-Fi is expected to deliver fiber-photonics that intimately and efficiently interface with emerging high-performance computing platforms. In application, for instance, to quantum computation, it will provide fiber-photonics serving as Quantum Interconnect (QuIC) [5], hybridizing the existing plethora of conventional quantum material platforms into a single information medium – "the Quantum Internet of Things" (QIoT).

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Glass additive manufacturing for specialty fiber fabrication

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In this work we present recent activities towards developing methods for additive manufacturing of glass within the Department of Applied Physics, at KTH. The main focus has been on Laser Cladding (LC) using sub-micron powders, and Direct Glass Laser Deposition (DGLD) using glass filament feedstock. Both techniques use a CO_2-laser operating at 10.6 µm wavelength. Using submicron powders having a particle diameter much smaller than the laser wavelength, shadowing effects due to particle-light interactions can largely be avoided [1]. This LC approach provides convenient means for manufacturing glass rods with tailored compositions, towards the fabrication of specialty optical fibers. Figure 1(a) shows the LC process during fabrication of a 40 mm long silica glass rod, 1.2 mm in diameter, at a glass deposition rate of up to 3.8 mm^3s^{-1}. The laser head is based on discrete coaxial powder feeding (using three powder nozzles) surrounding the central laser beam. For the DGLD technique a 4-beam system is employed to heat a centrally fed glass filament to temperatures in excess of 2000 °C. The system is very similar to a standard Cartesian FDM 3D printer for plastics, including g-code generation using commercial slicing software. The symmetric nature of both techniques has been employed to remove the quill effect during glass deposition, with subsequent improved print qualities as well as simplified programming. Figure 1(b1) shows a thin wall consisting of 4 layers. Figure 1(b2) shows silicon-core glass-clad fibers [2] printed onto the surface of a quartz glass plate, while Fig. 1(b3) shows a 5x5x5 mm^3 cube printed with 100% infill settings. As a proof of concept, Fig. 1(c) shows a microscope image of a 3D printed 125 µm diameter optical fiber. Here, a hexagonal rod was 3D printed, consisting of 68 strands of single-mode fiber. The rod was then inserted into a glass tube, which was collapsed into a preform and subsequently drawn into fiber using our in-house CO-laser based draw tower [3,4]. Both printing techniques have been shown to be applicable for optical fiber preform manufacturing, direct waveguide printing as well as construction of more complex 3D glass structures.

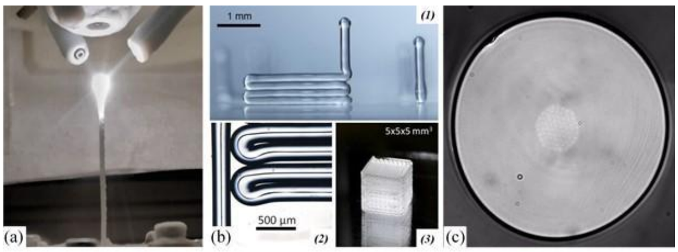

Fig. 1. Formation of (a) core rods for optical fiber fabrication using laser cladding, (b1-b3) 3D printed structures using glass filament, and (c) optical fiber with a core region composed of 68 cores. Here a 3D printed core rod was inserted into a glass tube and drawn into a 125 µm diameter fiber.

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Additive Manufacture of Single and Multi-Core Optical Fibres

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Additive manufacture of application specific optical preforms and fibres [1-3] will disrupt traditional fabrication using chemical vapour deposition (CVD) fabrication whether on the inside, typically modified (MCVD) or on the outside (OCVD). The most obvious reason is that CVD processes are on the whole constrained by a central spinning lathe that spins a tube into which material is sprayed and consolidated in various forms. This means only single and centred core preforms are fabricated from which standard optical fibres are drawn. This constraint does have some advantages in that there is a highly uniform radial symmetry to temperature and pressure properties during manufacture which offer a great deal of structural symmetry critical for low loss scattering and generating degenerate polarisation states within an optical fibre. That benefits some application specific fibres more than others – for structured optical fibres, for example, this permits simple analytical relationships describing pressure within holes and uniformity that can be integrated into a fabrication process to control their size and wall thicknesses [4]. To fabricate multicore preforms, however, multiple single core preforms are fabricated, the cores etched and then assembled (usually manually) into the desired layout. This is a highly time consuming and laborious process. Given the increasing desire for multi-core fibres playing a role in extending optical bandwidth in communications and data transfer [5], this clearly will not be tolerated longer-term. Consequently, the removal of this centre constraint in preform manufacture is a necessary requirement even though this will be accompanied by other challenges. This is where additive manufacture comes into its own by removing this constraint altogether.

I review our results on fabricating single and multicore silicate preforms and show the added complexity that arises when drawing multiple cores. In particularly, the glass softening point is reduced with increasing number of cores – this explains why more uncontrolled liquid diffusion of the core into the cladding material, varying with uneven strain and flow within and leading to irregular shapes, is observed. There are unique challenges fabricating and drawing multiple cores simultaneously including addressing the variation in uniformity of strain and heat distribution throughout the cores.

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Towards Scalable Manufacturing of Color-Changing E-Textiles

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Textiles and clothing have been a staple of human existence for millennia, yet the basic structure and functionality of textile fibers and yarns has remained unchanged. While color and appearance are essential characteristics of a textile, an advancement in the fabrication of yarns that allows for user-controlled dynamic changes to the color or appearance of a garment has been lacking. Touch-activated and photosensitive pigments have been used in textiles, but these technologies are passive and cannot be controlled by the user. The technology to be presented in this talk allows the owner to control both when and in what pattern the fabric color-change takes place. In addition, the manufacturing process is compatible with mass-producing both the user-controlled, color-changing yarns, the woven e-textiles, and the constructed end-use products.

The yarn fabrication utilizes a fiber extrusion system and a thread-coating attachment to encapsulate a metal wire inside a polymer sheath impregnated with thermochromic pigment. The color change is distinct from garments containing LEDs that emit light in various colors. The pigment itself changes its optical absorption to appear a different color. The thermochromic color-change is induced by a temperature change in the inner metal wire of each filament when current is applied. The temperature required to induce color change is near body temperature and not noticeable by touch. The prototypes already developed either use a simple push button to activate the battery pack or are wirelessly activated via a smart-phone app over Wi-Fi. The app allows the user to choose from different activation patterns of stripes that appear in the fabric continuously. The power requirements are mitigated by a large hysteresis in the activation temperature of the pigment and the temperature at which there is full color return.

The fiber fabrication process is readily scalable, and the fibers can be woven on industrial looms at commercial speeds. Furthermore, we have developed a method for quickly making the hundreds, if not thousands, of electrical connections that are necessary to produce a working product that can change between different colors and multiple patterns. This method utilizes ultrasonic welding and a multi-layer, multi-material bus that also accomplishes insulation of the electrical connections and ruggedization of the connected edge all in a single step. Rapid connectorization of the electrical components in an E-Textile has been a long-standing problem in the field, and this method aims to solve the last major hurdle in bringing this E-Textile technology to the market.

The developments to be discussed in this presentation represent a never-before seen capability: user-controlled, dynamic color and pattern change in large-area woven and sewn textiles and fabrics with wide-ranging applications from clothing and accessories to furniture and fixed-installation housing and business décor. The ability to activate through Wi-Fi opens up possibilities for the textiles to be part of the 'Internet of Things.' Furthermore, this technology is scalable to mass-production levels for wide-scale market adoption.

Stack-and-draw Revisited For The Engineering Of Multi-material Ribbon Fibers

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Here we present recent progresses in the fabrication of multimaterial fibers using glasses with intermediate T_g, including boro-phosphate glasses (T_g ~350-400°C) and soda-lime glasses (T_g ~580-620°C). More specifically, we demonstrate that the stack-and-draw technique can be expanded to unusual materials (glasses, metals) association and profile geometries to generate fiber assemblies with unprecedented functionalities. This approach relies on the stacking of flat oxide glass slides into a preform, which is then thermally elongated into tens-of-meters-long ribbon fibers with preserved cross-section ratio. Main properties and fabrication feature of the method are introduced. We believe the insertion of intermediate-T_g oxide glasses within flat multimaterial fibers will give access to a whole new range of functionalities, in electro-optics or sensing. In order to illustrate the versatility of the method, a panel of fibers with diverse applications is exposed, including click chemistry for bio-chemical sensing and experimental development of compact, all-solid fiber optical detector applied to gas analysis by means of fiber-tip plasma spectroscopy.

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Soft Electronic Fibers for Sensing and Energy Harvesting

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Fibers and fabrics are becoming an important platform to seamlessly integrate functionalities highly relevant in the context of health care, robotics, energy harvesting and sensing and monitoring. It remains however challenging to integrate onto such particular substrates the materials and required micro to nano-scale architectures to achieve advanced functionalities with robust and state-of-the-art device performance. This is particularly difficult to do so for elastomer-based fibers, in configuration when mechanical softness and stretchability are required. In this talk, we will present recent breakthroughs in the thermal drawing process in terms of fiber device design, materials, and processing to realize state-of-the-art flexible electronic systems onto soft fibers and fabrics. After a description of the materials and process requirements, we will introduce a first example of a design that allows for the detection and localization of pressure along the fiber axis[1,2]. We will then move to new designs based on the thermal drawing of thermoplastic elastomers, that enables to realize soft and deformable fibers[3]. We will show in particular electronic fibers that integrate conducting composites, and an innovative design where several liquid metal electrodes are co-drawn within an elastomeric cladding, forming distributed sensors based on transmission line principles[4]. We will also demonstrate similar architectures adapted for self-powered sensors and energy harvesters relying on the triboelectric effects[5]. Finally, we will describe how one can also integrate metallic glasses in the thermal drawing process, paving the way for novel applications in bioengineering and electrochemical sensing[6,7].

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Multifunctional Fibers for Wearable and Implantable Applications

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Smart textiles, wearable electronics, and biomedical implants can gain significant breakthrough through the invention of novel flexible devices that are capable of sensing, communicating, and interacting with humans and the environment. Among different types of flexible devices, multimaterial fibers offer unique advantages for interfacing with humans, because of their minimal footprint, scalability, high flexibility, multifunctionality, and biocompatibility. Despite the significant progress made in the fabrication of multimaterial fibers in recent years, significant challenges remain to enable wide applications in wearable and biomedical fields.

Here we present our research on developing multimaterial fibers for wearable and implantable applications. Firstly, we developed three dimensional (3D) and multifunctional deep brain interfaces based on multimaterial fibers. Human brain is a complex organ consisting of tens of billions of interconnected neurons. It is critical to understand the brain circuitry across multiple regions in the brain in order to effectively treat neurological diseases. However, mapping the brain circuitry over a large volume in the deep brain has been a major challenge. To address this challenge, we have developed a first 3D fiber-based neural probes using multifunctional fiber arrays guided through a helical multi-channel scaffold. These fiber probes enable simultaneous electrical recording, optical stimulation, and chemical delivery over a large volume in the deep brain using a small surgical burr hole for the first time.

Next, we present various wearable sensors based on multimaterial fibers. Examples include fully distributed pressure and temperature sensing fiber and fabric which can sense multi-point pressure distribution along the fiber, pressure variation, as well as continuous pressure shifting along the fabric with simple one-end connection, strain sensing fibers for multimodal extreme deformation sensing, and nano-integrated multifunctional fibers for bio-/chemical sensing. We have also developed fiber-based triboelectric nanogenerators for energy harvesting, motion and touch sensing. These fiber sensors can be woven into fabrics, and undergo multiple washing and drying cycles without degrading their performances.

In conclusion, multimaterial fibers provide a powerful platform for wearable and implantable applications. Some of the future directions include more complex and integrated functions, reduced feature sizes, increased flexibility, and facile integration with silicon electronics for signal acquisition and processing.

Smart photonic crystal fibre design for quantum technology applications

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Photonic crystal fibre (PCF), formed of a matrix of air holes running along the length of a strand of silica glass, has for the last 20 years enabled unprecedented control over the propagation of light. In PCF with a solid core, the size and distribution of micro- or nano-scale holes in the cladding controls the fibre dispersion, allowing precision engineering of nonlinear processes across brightness scales from photon-pair generation to supercontinuum sources. On the other hand, silica glass walls only tens of nanometres thick but hundreds of metres long can confine light to a hollow core in which dispersion and nonlinearity are minimized to yield high-fidelity transport of both intense ultrashort laser pulses and quantum states of light.

In this talk, I will present developments in the application of PCF to quantum technologies, where its unique capabilities have potential in all-photonic as well as photonic-enabled architectures for computation, communication, and sensing. Recent work involving the University of Bath has spanned photon-pair sources, frequency conversion for quantum interfaces, topological effects in PCF, and engineering hollow-core fibre for noise reduction in pulsed laser systems, for quantum memories in atomic vapour, and for enhancing light-matter interaction with nanoparticles. Specifically in this talk, I will focus on how four-wave mixing in PCF provides a resource-efficient frequency conversion link between nodes in a distributed quantum network [1]. I will also present preliminary experimental data showing how PCF can be engineered for ultra-tunable frequency conversion capable of unifying a wide range of wavelengths in a single device to create a truly universal quantum frequency interface [2].

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Chemi-thermal and morphologic investigation of ti(IV) isopropoxide/pvp precursor nanofibers for facile TiO_2 nanofiber preparation

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Sol-gel electrospinning is a promising technology that allows producing short and continuous ceramic nanofibers. There are two main steps in this method. First one is the preparation of an appropriate ceramic precursor solution and flowingly production of precursor nanofibers from this solution. In the second step, heat treatment process is performed to convert ceramic precursors in the nanofibers into ceramic phases and remove the products from the fibers that are produced with the degradation of the polymer and other organic parts in the nanofibers. Microstructures of the ceramic nanofibers mostly form during the heat treatment process so-called calcination process. So, the investigation of the thermal stability of precursor nanofibers is important to perform an appropriate calcination process. In this regard, sol-gel electrospinning of Ti (IV) isopropoxide/PVP nanofibers were produced and a following heat treatment process at 280ºC in air was applied to the as-spun nanofiber. Morphological analysis of both as-spun and heat treated nanofibers were conducted and it was shown that fibers were swollen after heat treatment but their uniformity were not lost. Chemical and thermal analysis of the as-spun nanofibers were performed with FTIR and TGA techniques. Chemical structures were totally changed after heat treatment process. XRD measurement revealed that the applied heat treatment temperature was not fairly enough to obtain crystalline pahses in the nanofibers and even polymeric part were not compleatelt removed from the system. But, the fibers were stabilized at the applied temperature and can be used to convert them into TiO_2 ceramic nanofibers with enhanced properties.

Keywords: Electrospinning, sol-gel, nanofibers, ceramic, Ti (IV) isopropoxide

Functional Fibers and Textiles for Biomedical Engineering

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Although nascent, regenerative medicine is gaining momentum with constant innovations of cellular-level solutions for human healthcare. Functional fibers and textiles (FFT) have a unique contribution to play in understanding the world of cells and resolving the challenges associated with their manipulation, such as 3D bioprinting, genetic modification, tissue maturation, and more. Multimaterial fiber devices can help address challenges in tissue biofabrication such as:

- the trade-off between resolution and volume
- the morphological and mechanical properties
- the selection and delivery of cell density, types, and population ratios
- the proliferation, interaction, differentiation, and cell movement
- the inhibition of bacterial contamination in cell cultures
- the introduction of different signaling pathways and/or cell growth factors
- the self-assembly and homeostasis
- the management of dangerous and infectious by-products

At the Fibers and Additive Manufacturing Enabled Systems Laboratory (FAMES Lab), the bioengineering subgroup focuses on tackling these challenges by designing a variety of fiber devices[1], such as FFT embedding microfluidics and porous compartments for delivery and controlled release of biostimulants or a combination of electroactive cores for sensing and transduction. Specifically, recent work at the FAMES Lab includes the development of fiber that disturbs quorum sensing in bacteria to mitigate the infection of tissue, having applications in surgery for deep chronic wound healing, as well as in bacteria-free bioprinting and tissue maturation. These fibers are fabricated using biocompatible materials in 3D printed polycarbonate preforms[2] and use the principles of electroceutical technology[3] to function.

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Building blocks for fiber-embedded quantum circuitry

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Photonic circuitry, in essence, a combination of resonant structures for the photons to interact with, or, mediated by, interact with each other, and waveguides, guiding the photons towards these structures, coupled appropriately for the right combinations of photons to interact.

In our previous work[1], we described a methodology for universal in-fiber manufacturing of logic circuits and sensory systems ("VLSI for Fibers" or "VLSI-Fi,") which combines 3D printing of preforms, thermal draw of fibers, post-draw assembly of fiber-embedded integrated devices utilizing material-selective spatially coherent capillary breakup of the fiber cores, and segregation-driven crystallization. Liquid-phase processing of fibers, while governed by nonlinear, often chaotic[2–4] fluid dynamics, is nonetheless expected to deliver a predictable, ordered solid-state fiber architecture. This type of capillary breakup is already extensively investigated for the assembly of photonic devices and systems, such as p-n diodes[5,6], heterojunctions[7], arrayed photodetectors[8], photonic gratings[5], and optical resonators[9].

We envision that, combined with the ability to integrate multiple material platforms[10–16], VLSI-Fi will form a complete, non-CMOS approach to fabrication of photonic circuits, addressing a number of standing challenges in Quantum Interconnects (QuIC)[17]. For QuIC it is important to note that the material-agnostic approach of VLSI-Fi is critical for quantum photonics implementation, since the performance of elements of such circuitry is material-platform dependent. Besides, it is known that in on-chip implementations of some of the quantum material platforms adversely affects decoherence times[18–20]. Fibers, on the other hand, are cylindrically symmetric and thus natural for integration with those platforms.

Through material-selective Axial Viscosity Gradient (AVG) capillary breakup, initially continuous cores in a multimaterial fiber can be selectively patterned into, for example, qubit sources, quantum memories, and quantum all-optical switches for the creation of fiber-embedded quantum devices. Moreover, AVG capillary breakup allows for the axial patterning of fiber cores both in the micron and submicron regimens. While the former is useful for the fabrication of electrically tunable whispering gallery mode spherical resonators, such as those in, the latter can be applied, for example, to create 1D photonic gratings, yet with very strict periodicity, serving as mirrors for a very-well insulated resonant cavity useful for quantum applications, as well as allowing for the tunning of interactions between photons and atoms, by coupling to them light at frequencies close to the photonic band edge.

We have developed an Axial Viscosity Gradient Instability Model (AVG-IM) which maps the the Capillary Number (Ca) and its spatial derivative into breakup position and period as one-to-one correspondence, allowing for great control over the periodicity of breakup structures through careful engineering of temperature profiles. As proof of concept, we demontrate an example of material-seclective AVG breakup where an array of spherical silicon resonators is created, with a vanadium electrode flanking along those resonators for electrical tuning of their resonant frequencies.

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THE SPECTROSCOPY TECHNIQUES IN ART

Organisers:
Olga Smolyanskaya (ITMO University)
Michael Menu (ITMO's Heritage Science Lab)

7-10 December 2021
Chimie ParisTech, Paris

Recipes and review of brass gilding practice in France : 16th - 19th centuries.

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The study and review of bibliographic sources from the 16th to the 19th centuries show an evolution in the practice of gilding. The reproduction of gilding processes gives information in the field of « use-wear » also named « traceological analysis ».

Also it allows to inform the quantitative and semi-quantitative analysis, the metallography, and the microscopy in all its diversity. Each gilding method prints a fringe, a coloring, a patina that is unique to it and in the visible domain.

Scientific analysis can reveal additional elements such as the composition of patinas, the constitution of the gold layer. In the time allotted, we will make a point of stage of the recension work of gilding recieps, a short presentation of the principal « tracological » clues.

We will conclude with the scientific analysis requirements for this work.

The Digital Twin as a semantic-aware data-integration framework in Heritage Science

Sorin Hermon, Nikolas Bakirtzis, Svetlana Gasanova

Following on-growing requests in Europe and the world for an Open Science society, the scientific communities are more and more required to share their research data in an open and transparent way. However, whereas some research communities, such as Life Sciences have already a well-stablished tradition to operate with established protocols, common workflows and share their primary data, Heritage Science is still in its infancy in regards to data sharing, use of agreed upon protocols or canonical workflows. Moreover, its nature as an inter-disciplinary domain, combining expertise from the humanities, natural sciences and exact sciences further challenge the achievement of an open science, with inter-operable data. The presentation will present first steps towards a digital transformation of the field of Heritage Science, detailing how a digital twin may be defined. The concept will be introduced through a case-study, the pluri-disciplinary analysis of a medieval painting, namely the Crucifixion of Christ, by Giovanni Baronzio.

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Sorin Hermon is Associate Professor at The Cyprus Institute. His research interests are integration of Heritage Science and Digital Heritage research, FAIR-ification of scientific data and development of scientific visualization methods in Heritage research. He coordinates the MSc program on Digital Cultural Heritage at The Cyprus Institute.

Nikolas Bakirtzis is Associate Professor and Director of the Andreas Pittas Art Characterization Labs at The Cyprus Institute in Nicosia, Cyprus. His research and publications explore issues of heritage and cultural identity in Mediterranean cities, the development of Byzantine monasticism and the use of science and technology in art history.

Svetlana Gasanova is a chemistry graduate from Saint-Petersburg State University (Russian Federation) and PhD from the University of Duisburg-Essen in Germany. Since 2014 Svetlana is researcher at the APAC Labs, The Cyprus Institute (Cyprus) where she leads research in Heritage Science, analyzing a wide variety of archaeological and art materials including polychromed statues, medieval icons and manuscripts, oil paintings, wall paintings, terracotta objects and finds from archaeological excavations and developing the analytical lab of APAC. Her field of expertise is non-invasive analysis of pigments by spectroscopic methods (XRF, FTIR, FORS), advanced imaging techniques (IRR, XRR, multispectral imaging) and digital microscopy.

Beauty & Secrets of Lustred Majolica at Renaissance

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Lustre was one of the most sophisticated techniques for the decoration of majolica during Renaissance period. It consists of a thin metallic film containing silver, copper, and other substances like iron oxide and cinnabar applied in a reducing atmosphere on a previously glazed ceramic. In this way, beautiful iridescent reflections of different colours (gold and ruby-red, in particular) are obtained. Studies have been carried out on ancient, lustred shards using different analytical techniques (e.g. XRD, SEM–EDX, TEM–EDX–SAED, ETAAS, ICP–OES, UV–vis reflectance spectroscopy, others) to assess the lustred film properties, relating them with their chemical and physical characteristics.

Moreover, the most relevant findings from the study of excellent pieces belonging to the production of the great master Giorgio Andreoli da Gubbio, will be presented. This study was possible thanks to the collaboration of several French Museums and the use of AGLAE accelerator at C2RMF, in Paris.

Non-Destructive analysis to investigate the stone alterations at a UNESCO world heritage site: the Lalibela's churches, Ethiopia

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This study concerns the eleven monolithic churches in Lalibela in northeastern Ethiopia, a UNESCO World Heritage Site and currently the main pilgrimage site in Ethiopia. In 2019, on the initiative of Prime Minister Abyi Ahmed, the French authorities proposed their support in the management on the site of the churches. To do so the French Development Agency (AFD), in collaboration with the Ministry of Europe and Foreign Affairs and with the support of the Ministry of Culture granted a feasibility study to examine ways of restoring, conserving and developing the rock-hewn churches. The objective of the feasibility study conducted was to produce the preliminary technical diagnostics required for the preparation of the comprehensive project to restore, conserve and develop the site.

In order to propose protection and conservation solution, diagnostics and analysis of the pathology of the rocks were made during two campaigns in November 2019 and November 2020. The rock pathology teams implemented non-destructive and minimally invasive analysis. The complementary methods acquire data from the rock surface and the different forms of differential alteration of the scoriaceous basalt. The objective is to characterize, through comparative analyses the impact of a protective shelter on the alteration kinetics of the rock.

Figure 1: *Location of the tested-zones. Vew to the East*

The microclimatic monitoring implemented concerned several churches. The sensors were positioned in particular areas to jointly characterize the climate outside and inside the churches.

These microclimate variations will serve as input data (temperature T and humidity HR) when calculating the expansion of the basalt samples collected, after experimentally measuring deformations in the laboratory.

A 3D mapping was carried out with a resolution between 0.6 mm and 1 mm. The information collected is a 3D topographic image, capable of revealing texture, color, macro-roughness and any surface disorder whether anthropogenic or natural ([1]). This tool was exploited on the two zones of the eastern wall (counterscarp, see Figure 1) in Bete Maryam, the southwest angle of Bete Maryam presenting humidity indices, the investigated zone of the wall in Bete Libanos and Bete Golgotha. Finally, very conclusive tests were also carried out on the 4 bas-reliefs sculpted in Golgotha.

The transitory air permeability allows characterizing the capacity of a material to allow a fluid passage through its porosity ([2-3]). The assumption made is that is that a superficially degraded rock, by dissolution or any other mechanism, is likely to present an increase in its permeability.

The analysis coupled with on-site observations suggest that deterioration linked to liquid water and the persistence of a state of high water content is more damaging than the deterioration risk linked to the salt crystallization, a process mainly occurring areas in dry areas. This risk cannot be totally ruled out but it can be reduced by integration of current practices in stone conservation, like desalination.

As water is the key-factor in the very harmful alteration for the conservation of scoriaceous basalt as a heritage material in humid natural environments, it seems useful to fully cover the churches.

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From remote sensing and machine learning to the history of the Silk Road

Haida Liang, Su Boming,
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Automatic remote reflectance spectral imaging of large painted areas in high resolution, from distances of tens of meters, has made the imaging of entire architectural interior feasible. However, it has significantly increased the volume of data. Here we present a machine learning based method to automatically detect ‘hidden’ writings and map material variations. Clustering of reflectance spectra allowed materials at inaccessible heights to be properly identified by performing non-invasive analysis on regions in the same cluster at accessible heights using a range of complementary imaging and spectroscopy techniques. The world heritage site of the Mogao caves, along the ancient Silk Road, consists of 492 richly painted Buddhist cave temples dating from the fourth to fourteenth century. Cave 465 at the northern end of the site is unique in its Indo-Tibetan tantric Buddhist style, and like many other caves, the date of its construction is still under debate. This study demonstrates the powers of an interdisciplinary approach that combines material identification, palaeographic analysis of the revealed Sanskrit writings and archaeological evidence for the dating of the cave temple paintings, narrowing it down to the late twelfth century to thirteenth century.

Haida Liang is Distinguished Professor of Physics at Nottingham Trent University working in the field of Heritage Science. She leads the Imaging and Sensing for Archaeology, Art history and Conservation (ISAAC) Research Lab, which specialises in the development and application of advanced optical imaging, spectroscopy, long range remote sensing and data science methods to art conservation, art history and archaeology. She has a keen interest on historical global connections through interdisciplinary research.

Processing and Visualization of High Resolution Quantitative Multi-Modal Spectral Data

Ruven Pillay
C2RMF

Imaging spectroscopy techniques such as hyperspectral imaging, X-ray fluorescence, THz imaging and others can produce very large complex high resolution data sets that are difficult to manage, process and exploit. In this presentation, we will look at techniques for managing, processing and visualizing such data and show how diverse data sets can be combined and made available for online multi-modal visualization.

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Abstract

Museum curators developed preventive strategies to control their artworks environment (temperature, relative humidity, light, etc) to preserve the artworks. The environment control is for now not assisted with direct material monitoring to follow mechanical modifications or chemical reactions happening with environmental fluctuations. To complete what is lacking, we use a technique based on speckle interferometry, Digital Holographic Speckle Pattern Interferometry (DHSPI) which is a non-destructive, contactless and full-field technique. This technique allows taking images of the surface to detect possible deformation below the micrometre level. The reference arm is changed to obtain different images for the same time to increase the signal-to-noise ratio. Then, we processed the images automatically to obtain deformation maps and improve the accuracy of the maps.

Keywords: heritage science, speckle pattern interferometry, deformation map, preventive conservation.

Display Holography: a novel technological multi-tool for modern Museums

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Ultra-realistic full-color holograms (OptoClones^{TM}) offer the opportunity to researchers to study artworks from close without the need to account for transport or security of original items. Also they allow the comparative documentation of artworks before/after restoration, before/after temporary loan etc. as well as the verification of authenticity of original artifacts. A temporary travelling exhibition of such a holograms of invaluable and unmovable artworks allows the dissemination of cultural heritage within the same country or across the globe in a very safe, secure, impressive and technologically advanced way. Creation of collective thematic exhibitions using Ultra realistic holograms of artworks with a common theme or origin being dispersed among various Museum or private collections. Holographic in-situ documentation at excavation sites with the purpose of exact optical documentation and study prior or post any conservation works. Virtual optical 3D addition of missing parts with OptoClones^{TM} of either original parts located in different museums or of replica parts manufactured for the purpose of completing an artifact to its original form. Completion of collections of peripheral museums with OptoClones^{TM} of artworks which have been removed to major central museums on account of their historical value. Creation of holographic 3d moulds of archaeological findings which can be used as optical reference for texture, material, details etc. when manufacturing or repairing classical replica moulds. Production of commemorative holograms of artifacts of highest value and uniqueness for VIP giftware or collection series of limited edition. OptoClones^{TM} offer a unique impression to general public and can be used for special communication campaigns as an introduction to main temporary exhibitions, special events and presentations by combining advanced technology with historical artifacts.

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A.Sarakinos, A.Lembessis Color Holography for the Documentation and Dissemination of Cultural Heritage: OptoClonesTM from Four Museums in Two Countries, J.Imaging 2019, 5(6), 59.

Monumental worship cross of Uspenskaya Chapel, Kem Cathedral.
Renovation of author coloristic solution based on the natural science research.

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The large carved polychromic warship cross, located in the chapel of Uspensky Cathedral in the city of Kem, is the monument of the second half of the XVII century. The cross was found in 2021 by the expedition of specialists of the State Russian Museum. The aim of this work was to perform the first integrated research of the monument whereby the results allowed us to indentify precisely both the materials and the techniques applied to create the carved base and the polychromy. Upon the initial UV examination in line with the detailed UV-photos made solely in the Chapel, further X-Ray fluorescence spectroscopy revealed several types of metal coatings, as well as certain chemical pigments in paint layers. This work was continued in the Russian Museum laboratory using the methods of micro chemical tests, Fourier-transform IR-spectroscopy and polarizing microscopy. The results obtained did not contradict with the XVII-century attribution of the monument by art experts. Thus, the research result is the introduction to the open sources of another monument of the Belomorie area with the exact date attribution, while the integrated material analysis permitted to make the probable reconstruction of the author's color approach while creating this monument.
The research was carried out with the support of a grant under the Decree of the Government of the Russian Federation No. 220 of 09 April 2010 (Agreement No. 075-15-2021-593 of 01 June 2021).

Surface displacement measurements of artworks: new data processing for speckle pattern interferometry

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Museum curators developed preventive strategies to control their artworks environment (temperature, relative humidity, light, etc) to preserve the artworks. The environment control is for now not assisted with direct material monitoring to follow mechanical modifications or chemical reactions happening with environmental fluctuations. To complete what is lacking, we use a technique based on speckle interferometry, Digital Holographic Speckle Pattern Interferometry (DHSPI) which is a non-destructive, contactless and full-field technique. This technique allows taking images of the surface to detect possible deformation below the micrometre level. The reference arm is changed to obtain different images for the same time to increase the signal-to-noise ratio. Then, we processed the images automatically to obtain deformation maps and improve the accuracy of the maps.

Keywords: heritage science, speckle pattern interferometry, deformation map, preventive conservation.

A reproduction of fabrication process of Kievan Rus' ceramic tiles

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In Kievan Rus' of the 10-13th century, glazed ceramic tiles were widely used as floor coverings. The use of ceramic tiles has been archeologically identified in more than 80 architectural monuments of Kievan Rus'. The geography of mosaic floors covers all the architectural and political centers of Russia of that period. Tiles from different places have different shapes and colors, some of them have a polychrome ornament. No written evidences of the tiles production technology have yet been found. Reproduction of the technology of glazed tiles can provide useful information about the time and place of production, therefore, the purpose of this work was to create replicas of tile samples from various cities of Kievan Rus'. The tasks of this work included the study of historical tiles and the development of technology for the production of yellow glazed tiles. Studies by X-ray diffraction and EDS analysis have shown that all historical tiles have lead-tin yellow type 2 as a pigment, distributed in lead silicate glass. The thickness of the glaze layer reaches 3 mm.

To reproduce the technology, the following modifications were applied to a ceramic base:

1. Raw components of the pigment and glass
2. Raw pigment components and pre-synthesized glass powder
3. Pre-synthesized pigment and raw glass components
4. Pre-synthesized pigment and glass powder.

The samples were subjected to heat treatment at temperatures of 750-1000°C for 1-5 hours.

The obtained replica of glazed ceramics were analyzed using X-ray diffraction analysis, Raman spectroscopy; the thickness of the glass layer was determined. The obtained tiles were compared with the historical ones.

«The research was carried out with the support of a grant under the Decree of the Government of the Russian Federation No. 220 of 09 April 2010 (Agreement No. 075-15-2021-593 of 01 June 2021)»

Raman Spectroscopy Can Assess the Age of Animal Bones and Ivories

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Assessing the age of ivory is important for the proper identification of ivory objects and is also crucial for controlling illegal trafficking of elephant bones. Radiocarbon dating is the standard method of determining the age of ivories; however, it requires the destruction of a fragment of the sample. Raman spectroscopy is a non-destructive technique, and therefore can be used on artwork. Moreover, Raman measurements can be done using a portable system, and the data analysis can be performed on the spot once the groundwork is done. Ivories contain two primary components: collagen and bioapatite. Raman spectrum of ivory material is mainly a sum of the vibrational bands of these components. As collagen deteriorates with time, its Raman signal decreases, therefore the ratio of collagen-to-bioapatite peaks is smaller in the older samples compared to the younger ones, providing a basis for sample dating. We have compared the results of Raman and radiocarbon measurements applied to a set of elephant ivory fragments, and have successfully calibrated the Raman dataset using radiocarbon measurements. We found that the Raman collagen-to-bioapatite peak ratios of the samples can be used as a metric to determine their age, providing a non-destructive technique to assess the age of ivory samples. We have also used singular value decomposition (SVD) to analyse the whole Raman spectra. We observed clear separation between samples of different ages in the SVD component space, which indicates that the changes in multiple collagen and bioapatite peaks likely contribute to the differences in Raman spectra of ivory samples of different age.

Application of image processing techniques to the THz visualization of painting's inner layer

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THz imaging is a promising technology for the Heritage Science. It can provide three-dimensional information about the inner structure of the investigated object, essential for separate layers reconstruction and calculation of their width. However, THz images have rather low resolution and often contain noise. Therefore, image processing might be a useful technique in achieving better quality of visualization. For this reason, in this paper the results of THz image enhancement using basic processing methods were presented. Two methods were based on the convolution of the original image with spatial domain filters: Laplacian operator, Sobel operator, median filter, average filter, and their combination. Two others relied on low pass and high pass Fourier filtering. The obtained images and their statistical analysis proved the ability to improve THz image by means of these methods. Hence, this work has profound implications for future studies. The research was carried out with the support of a grant under the Decree of the Government of the Russian Federation No. 220 of 09 April 2010 (Agreement No. 075-15-2021-593 of 01 June 2021).

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Double Optics: the Role of Technological Research in Art History. German Painting

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Throughout history, the achievements of physics have been applied in various fields of science, including heritage studies. Not only can such a transdisciplinary research be useful for the restoration and conservation processes, it also enriches stylistic and theoretical comprehension of art. Technological analysis allows us to realize the exciting process of the creation of painting. Using the physical examination as a tool, we are able to trace the evolution of an artist's manner - compositional, coloristic and poetic. Such an efficiency can be demonstrated by several examples of painting, German in particular.

The research was carried out with the support of a grant under the Decree of the Government of the Russian Federation No. 220 of 09 April 2010 (Agreement No. 075-15-2021-593 of 01 June 2021).

Non-destructive techniques for the inlay's detection

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When working with archaeological material, preliminary diagnostics is necessary - the restorer must, in one way or another, get an idea of the object being uncovered. Traditionally, X-ray radiation is used. However, in case of an object with incrustations/inlays, the task of obtaining a contrast X-ray image of such objects is quite laborious. Especially in the case of using a film for registration of an image and its subsequent wet development. There is a need to search for alternative methods that can provide information about the structure of the archaeological object before restoration. In this work, a comparative study of possible methods for detecting incrustations is carried out.

The research was carried out with the support of a grant under the Decree of the Government of the Russian Federation No. 220 of 09 April 2010 (Agreement No. 075-15-2021-593 of 01 June 2021).

Development of Cultural Heritage Science Database

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The object database for usage in Cultural Heritage Science is being developed as a collaborative media for interdisciplinary science. In this report, the concept for such database, requirements for compatibility and interoperability, as well as the existing solutions and challenges, are discussed. In addition, working database prototype and the technologies used in development are shown.

The main activities of Oil Painting Conservation Department of the State Russian Museum

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The State Russian Museum

The State Russian Museum is one of the major research and restoration centers for the items of cultural value. The departments include the Climatological Department, Chemistry and Biology Research Laboratory, and fifteen restoration workshops, which in 2022 will celebrate their 100th anniversary. Oil painting conservation and restoration is the main area of the museum activity. For a hundred years, we have been accumulating vast experience, and we are ready to share it with our colleagues. We look forward to this international collaboration that will allow us to create new conditions for the preservation of cultural values.

Leading specialist of the Oil Painting Conservation Department, oil painting restorer, art restoration and conservation historian.

Since 1992 has worked in the State Russian Museum, since 2000 – in the Oil Painting Conservation Department.

In 2008, graduated from Ilya Repin St. Petersburg State Academic Institute for Painting, Sculpture and Architecture with a master’s degree in theory and history of fine arts.

The area of scientific interests includes the history of Russian and international art restoration and conservation, restoration and conservation research, new technologies and their applications. Has authored a series of lectures “Oil Painting Conservation. Art, craft or science?” and is a coordinator for the international scientific-practical conference “NERADOVSKY READINGS: Storing and Restoring Exhibitions in a Museum of Art. *History, current state and prospects for development*”. Lives and works in Saint Petersburg.

Laser painting as a new direction of modern art

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Light is the main source of art around us. It allows us to see colors, and moreover, light itself can be a tool for creating unique pieces of art and designs. Here we demonstrate that a laser acts as a multifunctional and effective tool for creation of masterpieces in a way similar to that of classical paints and brushes. To make analogies between the processes of an artist creating a canvas and laser painting an artwork, we investigate the interaction between focused laser irradiation and metallic surfaces and analyze deeply the interferntial optical effects in thin oxide films. For this, we describe the nature of three main artistic operations, which are color making, multiple color change, and erasing managed by a nanosecond laser. These processes are possible due to the material heating above the evaporation point and are proved to be dependent on the cooling rate according to the obtained experimental and theoretical results. Therefore, our paper is the first attempt to present the concept of interference-based laser painting, which sets new perspectives for modern art and design.

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DOI: 10.1364/OPTICA.386574.

Digital technologies for Cultural Heritage

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The concept of development of digital services for Heritage science based on modern technologies is discussed. Preliminar results achived in database design, image improving and machine vision are pointed out. The strategy to use open source products and open codes solutions is declared.
The research was carried out with the support of a grant under the Decree of the Government of the Russian Federation No. 220 of 09 April 2010 (Agreement No. 075-15-2021-593 of 01 June 2021)

The application of optical and spectroscopy methods for the study of paintings by Russian avant-garde artists of the 1910s

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The article shows the possibilities of using optical and spectroscopy methods to study the paintings of the Russian avant-garde of the 1910s in the museum collection. The issues of examination and restoration in the framework of technological research were also considered. Routine research consists of a complex study approach, including optical microscopy, UV luminescence, IR reflectography, X-ray radiography, XRF analysis, FTIR analysis in the mid-IR region.

The research was carried out with the support of a grant under the Decree of the Government of the Russian Federation No. 220 of 09 April 2010 (Agreement No. 075-15-2021-593 of 01 June 2021).

Photogrammetric digitizing of a three-dimensional image of the object surface reconstructed from a display hologram

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We propose a novel approach to digitize the information stored in analog display holograms. It implies the conversion of a 3D image reconstructed from a hologram to electronic form by photogrammetry. The original object and the object wavefront of the analog display hologram were digitized by the photogrammetry method. The similarity of the three-dimensional models had been evaluated. Proposed approach can be used to solve problems for the long-term storage of information about cultural heritage facilities.

NANOPHOTONICS

7-10 December 2021
Chimie ParisTech, Paris

Spatio-Temporal Near-Field and Quantum Dynamics of Large-Area Semiconductor Lasers and Nano-Confined Quantum Emitters

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A long-standing challenge for high-power semiconductor lasers is to tame the inherent notoriously complex and frequently chaotic spatio-temporal instabilities in edge-emitting [1] and vertical-cavity surface emitting [2] semiconductor lasers [3]. General wisdom and most strategies proposed and technologically applied to date all seek to reduce the level of complexity by reducing the number of lasing modes, for example by optical injection, delayed [4] or delayed structured and filtered optical feedback [5] or, more recently, through super-symmetry in semiconductor laser arrays [6]. Based on a radically different strategy involving fighting laser chaos with quantum-chaotic or nano-disordered cavities we have recently shown that near-field and quantum chaos on the nanoscale leads to disorder which disrupts the formation of self-organized structures such as filaments that would normally lead to instabilities [7].

The talk will give an overview of the foundations and development of theoretical approaches to simulate and understand the spatio-temporal near-field and quantum dynamics of large-area semiconductor lasers and nano-confined quantum emitters. We will discuss how microscopic and dynamic materials-based simulations are the basis for an interpretation of the quantum chaotic dynamics [7], and how an innovative cavity design can be used to advance ultrafast parallel quantum noise 'harvesting' by spatio-temporal many-mode and quantum chaotic lasing dynamics in semiconductor lasers forms the basis for a new paradigm for greatly accelerated quantum random bit generation [8]. We will also show how through nanoplasmonic nano-cavity design lasing and near-field control quantum dynamics can be supported down to the extreme nano-scale [9]. We will highlight recently demonstrated room-temperature strong coupling of single molecules in a plasmonic nano-cavity [10] and near-field generated strong coupling of single quantum dots [11] as well as near-field enhanced single-photon emission and dynamic quantum entanglement [12].

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Harmonic Scattering Optical Activity: a new nonlinear optical probe for chiral materials

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Current drug discovery is facing numerous challenges; from antimicrobial resistance – one of the top ten global public health threats, to the increased risk of future pandemics from globalization, to the spiralling costs involved in bring a new drug to market. High-throughput (HT) synthesis with robotised operations driven by AI algorithms is recognized as a significant opportunity that could help accelerate drug discovery and development, but it requires miniaturized sample volumes and HT analysis. Therefore, new experimental tools are needed for analysing reaction products in tiny volumes, especially when it comes to chiral drugs.

In 2019, our group "made history" by first demonstrating a chiroptical effect that had eluded scientists for 40 years.[1,2] This effect can be referred to as "harmonic scattering optical activity". The effect states that *in chiral light scatterers* (those that lack mirror symmetry) *the intensity of light, scattered at the harmonic frequencies, is proportional to the chirality*. The effect is general. So far, it has been observed in chiral plasmonic nanoparticles,[1,3,4] in chiral organic molecules[5] and in chiral semiconductor nanoparticles.[6] Moreover, it was demonstrated both for second harmonic[1,3,5] and for third harmonic scattering.[4,6] Additionally, it was reported both for nonlinear Rayleigh [1,3-5] and nonlinear Mie scattering.[6]

The new effect requires minuscule volumes of illumination and has allowed the first chiroptical characterization of a single nanoparticle, floating freely in an isotropic liquid.[3] Unlike other nonlinear chiroptical effects, the harmonic scattering optical activity is technologically straightforward. It offers access to intricate optical properties (hyperpolarizabilities) that are essential for our understanding of light-matter interactions across inorganic and organic materials. This new effect paves the way towards a miniaturized but straightforward analysis tool that could, in the future, be used to automate workflows in future (chiral) therapeutics.

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Active metasurfaces based on phase change materials and hydrogels

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By changing a phase of the phase change material or the state of hydrogel near a functional building block of a metamaterial, it is possible to realize (re)configurable, time dependent and (re)programmable materials. Phase change materials are materials in which phase transitions can be induced quickly and reversibly, resulting in pronounced changes in their physical properties. Hydrogels are macromolecular cross-linked networks swollen by the solvent in which they are dissolved. The unique property of hydrogels is their ability to dramatically change volume in response to external stimuli. Here we report on our recent developments of a multiphysics description of complex composite metasurfaces incorporating phase change materials and hydrogels as their building blocks. Such a multiphysics description requires self-consistent treatment of the electromagnetic, heat transfer, mechanical deformation and phase transition models. Possible applications in the field of mid-infrared and microwave metasurfaces are discussed.

Chiral Superstructure Printing by Circularly Polarized Light

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Recent progress in additive manufacturing using light to cure the polymer resins enables to generate various 3D metamaterials with structural complexity. However, for stronger optical responses from the metamaterials, implementing inorganic materials and breaking optical symmetry is inevitable, which can be represented by chiral inorganic metamaterials. Most of manufacturing chiral inorganic superstructure on substrates rely now on the high-cost and time-consuming fabrication methods, which require either multistep lithography or depositions by instrumentation with high temperatures and/or low pressures. Using solution-processed chiral nanoparticles (NPs) can be a good alternative approach that is simpler and faster. Furthermore, the NP self-assembly processes can substantially expand the spectrum of the materials by including almost any type of inorganic material- metallic, semiconductor and ceramic as well as the combinations thereof. However, although many complex structures in colloids have been accomplished, solution-processed chiral structures on the surface/interface hitherto remains virtually unexplored.

Illumination of nanoparticles (NPs) with circularly polarized light (CPL) can strongly change the interaction forces between them due to light-induced polarization. [i] It will be attractive to utilize the ability of light to guide the self-organization processes of NPs to ‘sculpt’ chiral structures at interfaces. Here, we show that the strong optical activity of plasmonic materials under CPL afford photon to matter chirality transfer, fabricating silver nanohelices (AgNH) over the centimeter scale area in minutes. The rotational axis of the AgNH is oriented perpendicularly to the surface of the substrate, ensuring their chiroptical efficiency, the high g-factor. The handedness of the AgNH is altered from left to right when circular polarization of the incident photons changed from right to left, showing opposite polarity in their circular dichroism (CD) spectra. The wavelength of light source determined the size of the final superstructure as well as their surface plasmonic resonance (SPR) and CD band wavelength. Electron microscopy images for its intermediate growth stages showed vivid handedness of the rotational assemblies of NPs. The experimental evolution of CD peaks in different growth stages correlated well with those calculated for assembled nanostructure models with complex geometry, as established by prediction of deposition/assembly pattern by electromagnetic simulations. The chiral patterns were also fabricated on a polydimethylsiloxane (PMMA) stamp to demonstrate the simplicity and universality of these photosynthetic routes to direct construction of metallic 3D chiral metamaterials on arbitrary substrates with controlled chirality. More importantly, we successfully built a preliminary demo for a fast chiral surface printing system by implementing programmable motorized stage. The writing pattern showed a good CD signal (hundreds mdeg) of which handiness is distinguishable through Mueller matrix polarimetry. These simple and versatile architected metamaterials can be used for extensive applications, including but not limited to photonic, optoelectronic, and electromechanical devices as well as enantioselective catalytic and sensing systems.

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QUANTUM OPTICS AND QUANTUM METROLOGY

7-10 December 2021
Chimie ParisTech, Paris

Nonlinear quantum optics with trion-polariton in 2D materials

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Monolayers of transition metal dichalcogenides (TMDC) coupled to optical cavities offer a powerful platform for nonlinear optics. Being the direct bandgap type semiconductors with relatively large effective masses of carriers, TMDCs host strongly bound excitonic states with binding energies that allow for robust exciton formation. In fact, excitons dominate an optical response of TMDCs even at room temperature, thus paving a route to future optoelectronic devices. Importantly, in the presence of an access of free electrons (doping), the charged excitons – trions – can be formed. These quasiparticles can couple strongly to cavity photons and result into hybrid exciton- and trion-polariton modes that are both coherent and nonlinear.

In my presentation, I will discuss recent theoretical and experimental results that reveal strong nonlinear response of trion-polaritons and describe their microscopic nature. First, using a monolayer of $MoSe_2$ as an example, I will show that phase space filling effects lead to large renormalization of trion-polariton Rabi frequency and an effective blueshift for the lower polariton mode [1]. The observed nonlinearity represents the state-of-the-art value for planar microcavity nonlinear response with 2D materials. Next, I will describe a theory and numerical simulations that account on equal footing for exciton-polaron and trion effects, revealing qualitative spectral changes at increasing doping levels [2]. This extends the results from the electron-dressed excitonic states that have significant nonlinearity [3]. Finally, I will also show that the large nonlinearity and long coherence can facilitate quantum effects with trion-polaritons, and ultimately offer single-photon emission sources in a controllable system that is easy to fabricate.

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Quantum Sensors for Electromagnetic Induction Imaging: from Atomic Vapours to Bose-Einstein Condensates

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Electromagnetic induction imaging (EMI) allows mapping of the conductivity of target objects and, when combined with appropriate algorithms, the generation of full 3D tomographic images. Despite its tremendous potential, and the wealth of possible applications, for a long time the use of EMI was hampered by the lack of suitable sensors, with high sensitivity at low frequency. The use of atomic magnetometers (AMs) was shown to overcome such a limitation and, in conjunction with machine learning techniques, opened the path to new applications of EMI. Most of the EMI-AMs demonstrations reported thus far rely on atomic vapours as sensing media. This talk discusses recent results obtained with ultra-cold atoms and Bose-Einstein condensates, highlighting the potential extreme resolution obtainable.

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A Nanoscale Continuous Quantum Light Source

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Regular arrays of two-level emitters at distances smaller than the transition wavelength collectively scatter, absorb and emit photons. The strong inter-particle dipole coupling creates large energy shifts of the collective delocalized excitations, which generates a highly nonlinear response at the single and few photon level. This should allow to implement nanoscale non-classical light sources via weak coherent illumination. At the generic tailored examples of regular chains or polygons we show that the fields emitted perpendicular to the illumination direction exhibit a strong directional confinement with genuine quantum properties as antibunching. For short interparticle distances superradiant directional emission can enhance the radiated intensity by an order of magnitude compared to a single atom focussed to a strongly confined solid angle but still keeping the anti-bunching parameter at the level of $g^{(2)}(0) \approx 10^{-2}$.

Quantifying the breakdown of the Rotating-Wave Approximation in Superradiance

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We study quantitatively the breakdown of the rotating-wave approximation in the light-matter interaction for the description of inter-emitter interactions. As our main case study, we calculate collective light emission of quantum emitters. We employ a known multiple-scattering formalism where the full light-matter interaction leads to induced inter-emitter interactions described by the classical Green function. Within the RWA, however, these induced interactions differ in the near field, and for free space we find a reduction by up to a factor of two. By contrast, for a corresponding scalar model the corresponding relative RWA error for the inter-emitter interaction even diverges in the near field. For two identical emitters, the errors due to the RWA in collective light emission will show up in the emission spectrum, but not in the sub- and superradiant decay rates. In case of two non-identical emitters, also the collective emission rates will differ by making the RWA. For three or more identical emitters however, RWA errors in the interatomic interaction in general affect both the collective emission spectra and decay rates. Our results show more generally how the RWA becomes inaccurate already outside of the ultrastrong-coupling regime, that is long before the inter-emitter interactions would become of the order of the emission frequencies.

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Raman cooling in submicron attenuators, doped with optically active impurities

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The development of integrated waveguide optics and its miniaturization set new challenges for physics, microelectronics, and materials science. Microelectronic technology implementation into optics systems leads to a size decrease of optical elements on a chip and an increase in the density of elements. The task is to increase the efficiency of heat distribution in optical chips, and this task is very urgent in integrated optics.

Heat dissipation problem is a critical in quantum key distribution (QKD) systems. Attenuators with a large attenuation of tens of decibels are used in QKD systems to provide a quasi-single-photon mode [1, 2]. The attenuators are strongly heated under the powerful laser radiation. Due to heating, the attenuation coefficient changes and leads to a violation of the single-photon regime.

It is shown in [3], using the example of spliced fiber attenuators, that external laser action can lead to a violation of the single-photon regime in QKD systems. The pulses become multiphoton, which makes the QKD protocol vulnerable to a photon splitting attack.

With the progress of optical systems on a chip, miniaturization of elements is accompanied by a heat dissipation deterioration and worsening heat problems. The classical thermal conductivity of materials becomes insufficient for effective heat dissipation. The challenge is to develop smart materials that can dissipate heat through more efficient physical processes.

Heating is caused by the dissipated optical power, which can transfer energy to vibrations of atoms, for example, through Raman scattering. There are optically active vibrations, for example, molecular vibrations of Si-O, which absorb the power of optical radiation and transfer it to acoustic phonons, with which they interact well. As a result, the Raman spectrum for such vibrations broadens.

A feature of phosphorus-doped SiO_2 is strong Raman scattering of light. In the presence of phosphorus impurity in SiO_2, optically active P-O vibrations weakly interact with the SiO_2 lattice, which demonstrates a sharp peak in the Raman spectrum (see Fig. 1). Optically active P-O vibrations can effectively redistribute energy in a material, reducing its conversion to heat.

Although the intensity of spontaneous Raman scattering is rather low, it should be taken into account that high intensity of optical radiation leads to stimulated scattering. The intensity of stimulated Raman scattering increases by several orders of magnitude and can become comparable to the pump intensity.

Moreover, Raman scattering can occur both in the Stokes regime and in the anti-Stokes regime. Anti-Stokes scattering is associated with an increase in the photon energy due to the absorption of energy from the phonon subsystem. Anti-Stokes scattering can effectively cool the attenuator. Thus, scattering by dopants can significantly change the energy redistribution in optical elements, ensure efficient energy transfer, and reduce local heating.

For the case of planar waveguides made with an epitaxial crystal lattice, this effect is described in terms of selective pumping of the optical phonon subsystem. The dissipated optical power causes local heating due to the energy transfer to acoustic phonons through Raman scattering (RS) of light. Selective pumping of a phonon system by optical phonons leads to efficient energy extraction from the region with a high optical density.

We study attenuators based on phosphorus-doped SiO_2, in which the role of Raman scattering by molecular P-O vibrations is essential. Preliminary measurements of spliced fiber attenuators demonstrated that strong attenuators based on standard fiber are susceptible to damage at a radiation power of 2.5 W. The attenuation coefficient is reduced by 20-25dB. This effect was confirmed in [3].

Next, we used a phosphorus-doped fiber, and the power threshold has increased to 3.6 W. This is evidence of efficient energy transfer by impurity vibrations.

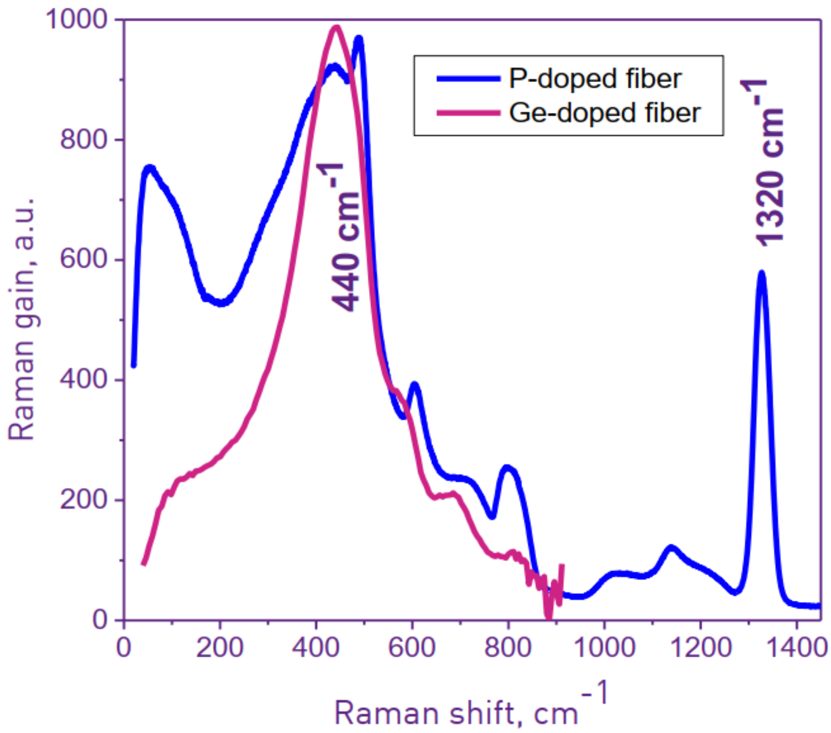

Fig. 1. The Raman scattering spectrum in a doped fiber with phosphorus and germanium impurities.
The maximum at 400 cm^{-1} corresponds to scattering by Si-O vibrations.
The maximum at 1320 cm^{-1} corresponds to P-O vibrations.

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Laser anti-Stokes Raman cooling of diamond single photon source

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Molecules interaction with light is usually followed by raman scattering that very often applied to investigated these molecules in raman spectrometers [1]. Stimulated Raman light scattering is actively used in fiber-optic systems [2], on the basis of which Raman lasers and amplifiers have been created [3]. Stimulated Raman scattering is a purely non-linear effect due to the stimulation of the Stokes transition by photons in the fibers. It is noteworthy that such stumulated radiation increases the probability of the raman scattering from the value of spontaneous scattering from 10^{-6} to 10^{-1}, i.e. by 5 orders of magnitude [4]. On the one hand, such a sharp increase in probability is due to the large number of photons in the fiber, on the other hand, we should expect a coherent stimulated emition in the phonon subsystem as well. Optical phonons (more precisely, polaritons), unlike photons, are practically immobile and retain their states for quite a long time (~ 2.1 ps, as can be determined by the half-width of Stokes peaks in the Raman spectra [5]). However the light scattering can be not only used in Stokes mode but anti-Stokes also. Recently a laser anti-Stokes cooling was realized in solid single crystals [6], coloidal quantum dots [7], ytterbium-doped silica glasses [8]. In this report we propose to use it for single photon sources in diamond N-V centers. Single-photon sources based on N-V centers in diamond are manufactured in the process of ion implantation of nitrogen atoms into a diamond film with its subsequent annealing [9]. For a single-photon source to work, it is necessary to pump a single center with a green laser (575 nm, see item 6 in Fig. 1). After that, its luminescence is observed in a fairly wide range against the background of the luminescence of the diamond crystal associated with the Stokes component of Raman scattering, which leads to parasitic source noise. To reduce noise, it is proposed to use Raman laser cooling. To do this, an additional laser is built into the setup (item 10 in Fig. 1(b)), which emits at a frequency ω_r exceeding the frequency of the pump laser ω_p, so that the difference between the photon energies corresponds to the energy of the diamond optical phonon $\hbar\omega_d$: $\hbar\omega_r - \hbar\omega_p = \hbar\omega_d$.

(a) (b)

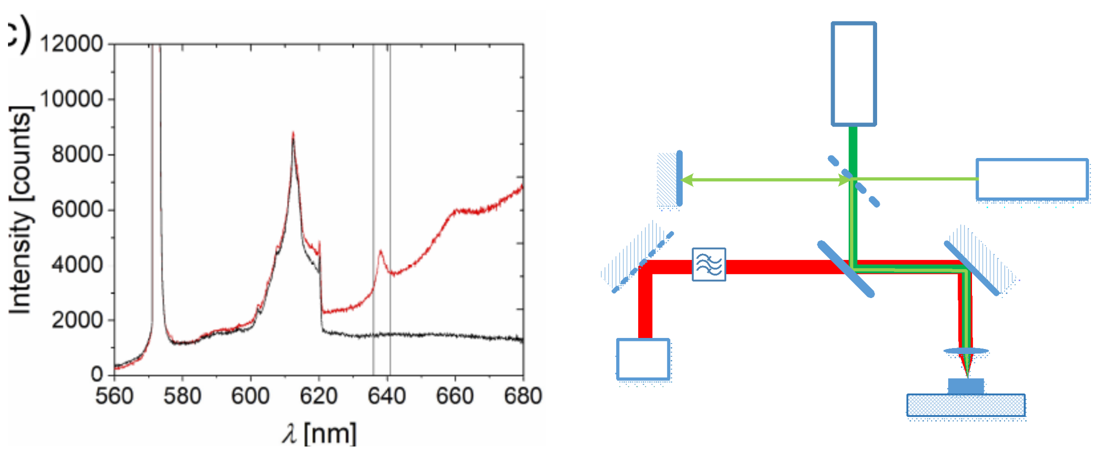

Fig. 1. (a) The micro photo-luminescence spectra of the single N-V center and diamond film are shown as red and black curves accordingly. (b) The experimental set-up consist of the following items: 1 – moveable table; 2 – diamond film with N-V centers; 3 – lens; 4 – mirror; 5 – dichronical mirror; 6 – pump laser; 7 – filter; 8 – mirror with diffraction grid; 9 – spectrometer; 10 – additional laser for cooling; 11 – semi-transparent diffraction grid.

The light of an additional laser will stimulate anti-Stokes scattering in the region of a single N-V center, which will lead to its local cooling and a decrease in the noise of a single-photon source. To adjust the optical scheme so as to create a general confocality of radiation, it is necessary to use a diffraction semi-transparent grid (item 11 in Fig.~1(b)). The grid period is selected for effective refraction and reflection of the additional laser radiation in the direction of propagation of the pump laser radiation.

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Non-Gaussian interactions in electromechanical systems: limitations and applications

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In this talk, I will consider a nonlinearly coupled electromechanical system [1], and develop a quantitative theory for two-phonon cooling. In the presence of two-phonon cooling, the mechanical Hilbert space is effectively reduced to its ground and first excited states, allowing for quantum operations at the level of individual phonons and preparing nonclassical mechanical states with negative Wigner functions. I will describe a scheme for performing arbitrary Bloch sphere rotations, and derive the fidelity in the specific case of a \pi-pulse. I characterise detrimental processes that reduce the coherence in the system, and demonstrate that our scheme can be implemented in state-of-the-art electromechanical devices. The talk is based on the results presented in Ref. [2]

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ENERGY HARVESTING AND PHOTOVOLTAICS

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Strategies for Efficiency Enhancement of Thin-Film Solar Cells

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Small-scale photovoltaic generation of energy must become ubiquitous to satisfy the global demand for eco-responsible sources of cheap energy for the betterment of an ever-increasing fraction of the human population. Thin-film solar cells are a viable option in addition to crystalline-silicon solar cells due to low cost and ease of manufacturing. But their efficiencies have to be higher for commercial viability. A coupled optoelectronic model was formulated and implemented along with the differential evolution algorithm to assess the efficacy of grading the bandgap of the absorber layer in three thin-film solar cells [1]. Optimal nonlinear grading is predicted to deliver 27.7% efficiency with a 2200-nm-thick CIGS absorber layer in the CIGS solar cell, 21.7% with a 870-nm-thick CZTSSe layer in the CZTSSe solar cell, and 34.5% with a 2000-nm-thick AlGaAs layer in the AlGaAs solar cell. For a solar cell with two bandgap-graded absorber layers, 34.45% efficiency is predicted with a 300-nm-thick CIGS layer and a 870-nm-thick CZTSSe layer. The use of these solar cells in concentration phototovoltaic systems can enhance the efficiency further. For colored solar cells to be used in building-integrated photovoltaic systems, efficiency loss is predicted to range between 10% and 20%, depending upon the percentage and spectral range of incoming solar photons rejected.

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Investigation of optimum sintering conditions for cold compact nanostructured bismuth telluride thermoelectric material

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Successful scaling of thermoelectric materials requires an optimum sintering environment and method that is simple, quick, scalable, and cost-effective. Our work examines the optimum sintering technique and temperature to treat and improve the proficiency of cold compact bismuth telluride thermoelectric material. Three diverse types of annealing techniques namely, conventional (box), microwave, and tube sintering were used to treat both p and n-type bismuth telluride thermoelectric material. The annealing temperatures were set at 250ºC, 300ºC, 350ºC, and 400ºC. A comprehensive analysis of these techniques was done by testing both pristine and sintered specimens for their structural, morphological, electrical, and thermal properties. "Broadband Dielectric Spectroscopy (BDS)" or otherwise known as "Impedance Spectroscopy" was used to comprehend the dielectric properties of the specimens. Through our investigation, even though each method had its benefits and drawbacks, the most advantageous conditions for magnified electrical and thermal properties were found in the microwave at 250ºC sintering temperature, followed by tube and box sintering. The p-type samples annealed through microwave sintering at 250ºC had extremely low-thermal conductivity of ~0.4 W/m/K at room temperature. The results of XRD, SEM, and EDX indicated the formation of oxide phases beyond 300ºC sintering temperatures in all three furnaces. The size of the nano to sub-micron particles calculated from the Debye-Scherrer formula was in the range of 400 nm to 1000 nm. The increase in annealing temperature from 250ºC to 400ºC resulted in the growth of crystalline and coarse structures and a decrease in DC electrical conductivity. Conversely, the increase in annealing temperatures led to an increase in thermal conductivity. The EDX spectrum confirmed the occurrence of tellurium deficiency due to its volatile nature at higher temperatures. The response of AC electrical conductivity at different frequencies 1 MHz, 1 kHz, 1 Hz, and 10 mHz indicated the introduction of defects beyond 250ºC measuring temperature. The BDS response confirmed that the samples demonstrated more glass-like characteristics.

Keywords: Thermoelectric, bismuth telluride, microstructures, broadband dielectric spectroscopy.

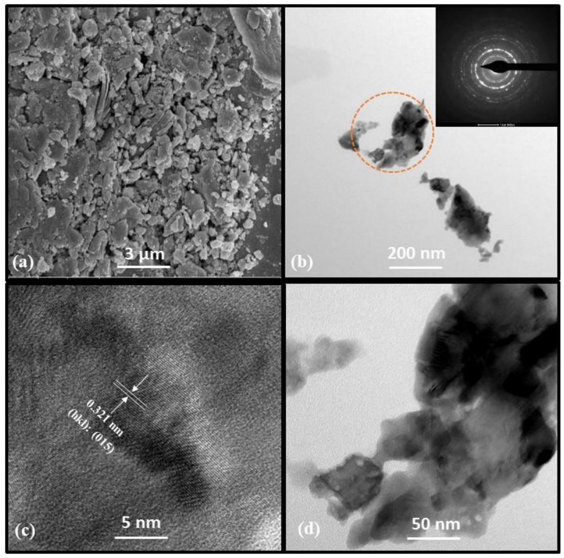

Figure 1. (a) Scanning electron microscopy (SEM) image of the MP250 (microwave sintered p-type Bi_2Te_3 at 250ºC sintering temperature) at 3 µm, (b) low magnification transmission electron microscopy (TEM) image with SAED pattern (selected area electron diffraction) shown in the inset of the MP250 pellet at 200 nm resolution, (c) High-resolution TEM (HRTEM) image of MP250 pellet at 5 nm, (d) Zoom in TEM image at 50 nm resolution.

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Aerosol Treatment for Efficient and Stable Perovskite Solar Cells

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Solvent annealing has been shown to be an effective and simple post-deposition treatment for perovskite solar cells (PSCs) that does not rely on complex chemical modification on the precursor solution or on the as-deposited films.[1] The ability to improve the efficiency of a PV device through such a simple process is therefore in principle an attractive approach. However, due to a lack of uniformity and reproducibility, this process is not widely used for the production of high-efficiency devices, nor seems likely to be highly relevant for commercial applications.

We have demonstrated a new approach to solvent-based post-treatment of perovskite films that addresses these major issues with reproducibility and uniformity, and have shown the applicability of this approach to large-scale processing of PSCs.[2] This is achieved by controllably passing a solvent aerosol across the film surface within a bespoke reactor. By controlling the aerodynamic processes, a boundary layer forms though which the solvent diffuses towards the film surface, leading to a highly-uniform and controllable exposure to the solvent.

Gaining such high level of control of the process has allowed us to not only achieve a power conversion efficiency (PCE) enhancement of p-i-n structured photovoltaic devices to over 20% using conventional methylammonium lead iodide ($MAPbI_3$) as the active layer, but also, more significantly, we have achieved large improvements in uniformity of film morphology after treatment over the whole reactor area (~30 cm^2), which also translates to reduced PCE variability of devices produced from treated films. This improved large-area uniformity leads to a much less marked efficiency drop when scaling up device area to 1 cm^2 compared to untreated films as well as increased stability under continuous maximum-power-point tracking in both N_2 atmosphere and ambient air. Furthermore, we also demonstrate that the technique can be applied to a wide range of perovskite compositions and cell architectures, including Cs-FA, triple cation, Br-containing, ‘conventional’ (n-i-p), and HTL-free architectures, with efficiency enhancements in all cases.

Expanding beyond solvent post-treatment, we have also applied this technique to pure formamidinium lead iodide ($FAPbI_3$). Using aerosol-assisted crystallization (AAC) of the $FAPbI_3$ films we are able to crystalise pure black-phase α-$FAPbI_3$ in only 2.5 minutes at 100°C, compared to 20 minutes at 150°C for conventional thermal annealing. Not only does this open up wider processing options for the material, but we demonstrate improvement in PCE and, importantly, phase stability of pure α-$FAPbI_3$ compared to thermally annealed control samples. Using X-ray diffraction, X-ray scattering and density functional theory simulation, we identify that relaxation of residual tensile strains due to the lower annealing temperature and post-crystallization crystal growth during AAC are key factors that facilitate the formation of phase-stable α-$FAPbI_3$.

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Comparative studies of optoelectrical properties of prominent PV materials: Halide perovskite, CdTe, and GaAs

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Impressive performance in PV application of halide perovskite $MAPbI_3$ and related materials is often attributed to their similarity in electronic properties with well-known PV materials like GaAs and CdTe that have had a much longer development history. However, objective comparison is rarely available. We compare three representative high performance PV materials: halide perovskite $MAPbI_3$, CdTe, and GaAs, in terms of photoluminescence (PL) efficiency, PL lineshape, carrier diffusion, and surface recombination and passivation, over multiple orders of photo-excitation density or carrier density appropriate for different applications [1]. The results indicate that on the one hand the $MAPbI_3$, even without surface passivation, can be superior than the best CdTe and GaAs double heterostructures with passivated surfaces in PL efficiency at low excitation density near and below 1 sun equivalent, indicating that the halide perovskite is more immune to both surface and bulk Shockley–Read–Hall (SRH) recombination loss; on the other hand, the polycrystalline $MAPbI_3$ samples, which are similar to those typically used for the high performance PV devices, have much shorter carrier diffusion lengths than the CdTe and GaAs samples use for the comparison. Additionally, as an organic-inorganic hybrid material, $MAPbI_3$ is structurally disordered and much less unstable, in contrast to the inorganic counterparts as well as another group of II-VI based organic-inorganic hybrid materials that have been found to be nearly perfectly ordered in structure and exhibit over 15 years shelf stability [2]. An analytic model that takes into account the radiative and SRH recombination is used to describe the excitation density dependence of PL intensity and extract the internal PL efficiency, occupation fraction of the SRH centers, and multiple pertinent recombination parameters, allowing for making quantitative comparison between different materials. This comparative photovoltaics study provides more insights into the fundamental material science and the search for optimal device designs by learning from different technologies.

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Stability of Nonfullerene Organic Solar Cells: from Built-in Potential and Interfacial Passivation Perspectives

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Remarkable progress has been made in the development of high efficiency solution-processable nonfullerene organic solar cells (OSCs). However, the stability of the nonfullerene (NFA) OSCs is not fully understood yet. In this talk, we report our effort to understand the stability of NFA OSCs, made with the binary blend poly[(2,6-(4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)-benzo[1,2-b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c']dithiophene-4,8-dione)] (PBDB-T) : 3,9- bis(2-methylene-(3-(1,1-dicyanomethylene)-indanone))-5,5,11,11-tetrakis(4-hexylphenyl)-dithieno[2,3-d:2',3'-d']-s-indaceno[1,2-b:5,6-b'] dithiophene (ITIC) system and poly[(2,6-(4,8-bis(5-(2-ethylhexyl-3-fluoro)thiophen-2-yl)-benzo[1,2-b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c'] dithiophene-4,8-dione)] (PM6) : 3,9-bis(2-methylene-((3-(1,1-dicyanomethylene)-6,7-difluoro)-indanone))-5,5,11,11-tetrakis(4-hexylphenyl)-dithieno[2,3-d:2',3'-d']-s-indaceno [1,2-b:5,6-b']dithiophene (IT-4F) system. It shows that a continuous vertical phase separation process occurred, forming a donor-rich top surface and an acceptor-rich bottom surface in BHJ during the aging period. It is found that a gradual decrease in the built-in potential (V_0) in the regular configuration NFA OSCs, due to the interfacial reaction between the poly(3,4-ethylenedioxythiophene)- poly(styrenesulfonate) (PEDOT:PSS) hole transporting layer (HTL) and NFA acceptor, is one of the reasons responsible for the performance deterioration.[1] The impact of interfacial modification, molybdenum oxide (MoO_3) induced oxidation doping of the PEDOT:PSS HTL, on the operational stability of PM6:IT-4F nonfullerene OSCs has been studied.[2] The MoO_3-induced oxidation doping in PEDOT:PSS can effectively suppress the interfacial chemical reactions between NFA acceptor and PEDOT:PSS. Our findings highlight that retaining a stable and high V_0 across the BHJ via interfacial modification and device engineering is a prerequisite for efficient and stable operation of the nonfullerene OSCs.

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Transfer of Direct to Indirect Bound Excitons by Electron Intervalley Scattering in $Cs_2AgBiBr_6$ Double Perovskite Nanocrystals

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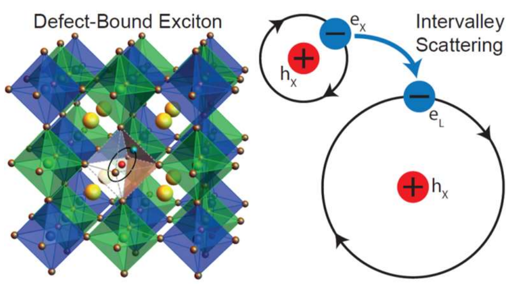
Lead halide perovskites have gained a lot of popularity in the field of optoelectronics in recent times. Where the toxicity of lead remains a major issue, an emerging non-toxic alternative proposed is lead-free double perovskites with the generic stoichiometric formula $A_2M^IM^{III}X_6$. In double perovskite the divalent lead is replaced with one monovalent (M^I) and one trivalent (M^{II}) metal cation. $Cs_2AgBiBr_6$ is one the stable double perovskite with an indirect bandgap where the optical properties and the charge carrier relaxation processes are not fully understood.
We applied time-resolved photoluminescence and differential transmission spectroscopy to explore the photo-excited charge carrier dynamics within the indirect band structure of $Cs_2AgBiBr_6$ nanocrystals. We observed a high energetic emission at the direct bandgap, alongside the emission from the indirect bandgap transition. We assigned this emission to the radiative recombination of the direct bound excitons originating due to trapping of holes. Due to the electron intervalley scattering process, the emission maximum from this direct bound excitons redshifts over 1 eV within 10 ps, leading to its transfer from direct to indirect bound exciton. We conclude that this direct bound exciton has giant oscillator strength which causes the higher energetic emission to occur at the direct bandgap despite the prevailing intervalley scattering process. These results expand the current understanding of the optical properties and the charge carrier relaxation process in double perovskites family, thus, facilitating the further development of optoelectronic devices harnessing lead-free perovskites.



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Solution-based synthesis of Barium Titanate-Hematite Nanocomposite Thin Films for Enhancement of Photocatalytic Activity

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The study of novel photocatalyst and photo-electrocatalysts (PEC) for solar energy has gained great attention, aiming to use solar energy to directly split water into hydrogen and oxygen to produce solar fuels. In order to achieve unassisted water splitting, new low-cost, stable and high- efficiency PEC systems are being explored. Recent research has focused on a wide range of materials such as Fe_2O_3, $BiVO_4$, $CuWO_4$, with bandgaps in the range of 2-2.5 eV, which allow visible light absorption, unlike the traditional photocatalyst, TiO_2. However, these materials generally present high level of surface or bulk recombination and low carrier mobility[1]. The electric field associated with ferroelectric polarization has emerged as novel strategy in photocatalysis to induce opposite band bending at material surfaces facilitating charge migration towards different sites and promoting selective redox reactions in the respective locations[2]. In the present work, we develop and investigate a nanostructured, composite thin film, obtained combining ferroelectric $BaTiO_3$ with the photocatalyst Fe_2O_3 in parallel at the nanoscale to improve the photocatalytic performance. The ferroelectric polarization can aid effective charge separation while narrow bandgaps and good charge transport properties of the photocatalyst are needed for light absorption and carrier extraction. Porous $BaTiO_3$ (pBTO) thin films are synthesized by a surfactant-assisted sol-gel method. Using different concentrations of organic template, the porosity of pBTO thin films has been controlled in order to obtain suitable thin films for photocatalyst integration. SEM analysis and ellipsometry allow the determination of overall porosity of pBTO thin films. The tetragonal (ferroelectric) phase of pBTO thin films is confirmed by XRD analysis and Raman spectroscopy.The switching of spontaneous polarization of $BaTiO_3$ thin films by an electric field is verified by PFM. In addition, the alignment of polar dipoles to the ferroelectric surface ($\vec{P}_{up}$or $\vec{P}_{down}$) is evaluated by testing PEC performance of pBTO thin film after electrochemical (EC) poling at ±8V. XPS analysis does not reveal a considerable alteration of pBTO thin film due to EC poling. Lastly, the pBTO/Fe_2O_3 composite photocatalyst thin film shows an enhancement of the photocurrent density compared to either the bare Fe_2O_3 (by ~2 times) and pBTO thin films (by ~20 times), which could be correlated to the upward band bending induced by the ferroelectric polarization of pBTO leading to improved charge separation and injection in pBTO/Fe_2O_3 thin films. The possibility to regulate the PEC response in pBTO/Fe_2O_3 by changing the polarization direction in pBTO is verified using EC poling, which does not significantly affect the Fe_2O_3 layer, as confirmed by XPS analysis. This research work shows a facile and low-cost approach for the development of novel ferroelectric/photocatalyst photoanodes with switchable control of their PEC performance, which possess a great potential for photoelectrochemical applications.

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P-N junction-based ZnO textile nanogenerator for wearable energy-harvesting

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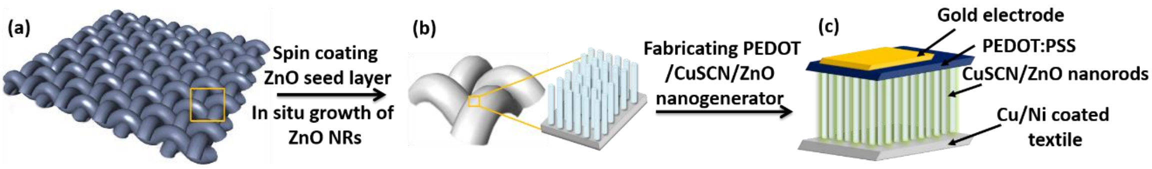
To solve the issue of clean energy availability and environmental pollution issue, for example through battery disposal, mechanical energy is considered as one of the most promising resources because it is abundant and accessible in various environments such as body movements, vibration, flowing air and muscle stretching. Zinc oxide (ZnO) nanostructures have been extensively investigated for harvesting mechanical power owing to the large piezoelectric coefficient and easy synthesis. In addition, with increasing development of portable/wearable electronic devices such as smart watches, health or activities monitors, it is particular desire to research a flexible energy harvester that can capture multiple forms of mechanical energy with enhanced energy conversion efficiency, which holds great promise in personal smart devices.

Herein, p-n junction-based ZnO textile nanogenerator has been designed to combine the advantage of ZnO piezoelectricity and textile flexibility. ZnO nanorods were synthesized on copper-nickel plated textile. A P-N junction was established between PEDOT:PSS and ZnO nanorods to reduce the rate of screening to achieve higher performance output, which can generate increasing output voltage from 0.2 V to 1.81 V as the shaking frequency increases from 19 Hz to 26 Hz. The device also show high stability and durability under 26000 cycles test by shaking at 26 Hz. The output voltage from the device can activate an LCD screen display by shaking at its resonant frequency. The device is able to harvest energy from mechanical forces different impacting force, flicking from different direction and gentle finger tapping and bending. Our results can be utilized for future flexible self-powering nanogenerator design to harvest a larger amount of electricity from the environment.



Scheme 1. Fabrication process of PEDOT:PSS/CuSCN/ZnO textile nanogenerator. (a) Cu/Ni coated textile, (b) enlarged section of textile with grown ZnO nanorods, (c) schematic of nanogenerator.

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EARLY CAREER

7-10 December 2021
Chimie ParisTech, Paris

Non-Abelian Topological Charges of Nodal Links in Dielectric Photonic Crystals

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For the last two decades, point degeneracies, such as Dirac or Weyl points, have been widely studied in topological physics. It is also well-known that Weyl points are formed when one of space-time inversion (P and T) symmetries is broken. In contrast, a perturbation preserving P and T symmetries can generate a line degneracy, called a nodal line, rather than the Weyl points [1]. This means that nodal lines are very closely linked with Weyl points but exhibits different topological properties. Therefore, extensive efforts on the nodal lines have been recently made in condensed matter physics, for example on topological semimetals [2] and metals [3].

In photonics, diverse nodal shapes such as nodal chains and links were realized in metallic photonic crystals [4,5]. However, there has not been a dielectric photonic crystal exhibiting nodal chain or link, in spite of the advantage of dielectric structures such as the frequency scalability.

In this work, we propose a dielectric double-diamond photonic crystal as a design for non-Abelian charges of nodal lines [6]. Based on numerical simulations, we show that the proposed design has nodal links, composed of two nodal rings, in the momentum space. Then we show the topological charges of the nodal lines are non-Abelian that can be described by quaternion numbers. This is done by considering a loop which encloses the section of the link(s) and observing the correlation vectors of the eigenstates.

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Low-cost, asymmetric metasurfaces for chirality at the nanoscale

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Plasmonic asymmetric nanostructures can tailor chiro-optical phenomena at the nanoscale [1], leading to applications spanning from chiral sensing [2] to circularly polarized light emission [3]. Here we combine the cost- and time-effective nanosphere lithography [4] with a tilted metal deposition to fabricate various asymmetric plasmonic nanostructures organized in metasurfaces. We characterize them with different optical and photo-thermal techniques, and we gain insight into the electromagnetic behavior at the nanoscale by modelling.

We previously used photo-acoustic technique to characterize metasurfaces made of polystyrene nanospheres (PSN) covered by asymmetric plasmonic layer [5]; we showed the extrinsic chiral behavior at 633 nm. Next, we noticed that the tilted metal deposition leaves an elliptical nanohole array (ENHA) on the substrate, which can give the chiral behavior itself, even at normal incidence [6]. Indeed, we measure intrinsic chirality in similar metasurfaces without PSN, which consist of ENHA in 50 nm of Ag [7]. As the numerical modelling provides good fit with experimental data, we use the same approach to design ENHA coupled with achiral quantum emitters, for tunable, chiral light emission in the visible and near-infrared [8]. Furthermore, we perform broadband extrinsic chirality characterization in the near-infrared range in PSN-based metasurfaces; we demonstrate rich, resonance-governed, spin-dependent extinction [9]. Most recently, we characterize similar metasurfaces in the blue range by means of photo-deflection technique, and demonstrate strong chirality in diffracted beams [10].

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Thermal and nonthermal mechanisms of hot electron chemistry

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Here, I will discuss two experimental systems, both probing the activation of chemical reactions by hot electrons. Hot electrons can induce chemical reactions by thermal or a non-thermal pathways and the interplay between these mechanisms is subject to much debate in literature [1].

1. STM induced hot-electron chemistry. The tip of a scanning tunnelling microscope is a local tunable source of hot electrons. Recently, a new manipulation technique where the target is a few nanometres away from the STM tip, nonlocal manipulation [2], has come in the spotlight. In nonlocal manipulation, charge injected from the STM tip is transported across the surface causing the apparent-simultaneous manipulation of hundreds of molecules with a single pulse of charge carriers. The manipulation process is in effect parallelised and completely decoupled from the STM tip. However, a key question remains: *What exactly is the molecular manipulation mechanism?*

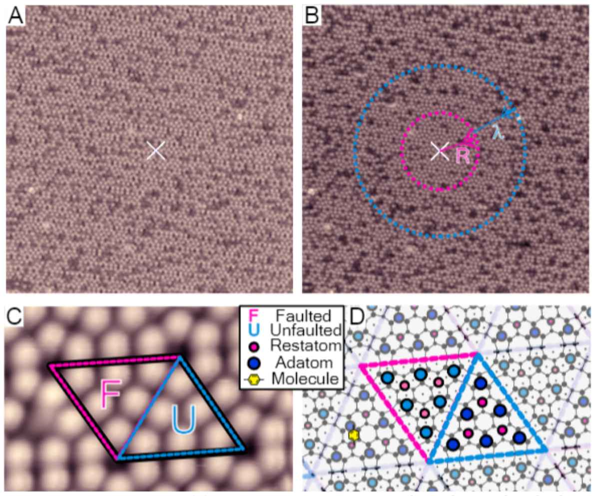

*Figure SEQ Figure * ARABIC 1* A,B Nonlocal manipulation of toluene molecules on Si(111)-7x7. C,D STM image and corresponding schematic of the Si(111)-7x7 surface reconstruction.

Here we quantitatively link the voltage dependence of the nonlocal manipulation probability to the integrated local density of surface states of the Si(111)–7×7 surface. Our results further corroborate the previously proposed ballistic-diffusive transport model.[3] We show that the measured increase in the probability of nonlocal manipulation with injection bias voltage is not due to an energy dependence of the molecular manipulation process. Instead, it is caused by an increase in the fraction of the tunnelling current that is captured by the surface state mediating nonlocal manipulation. This result is an important breakthrough in the understanding of hot electron chemistry and should allow us to tailor the energy band structures of catalytic systems.

2. Thermoplasmonically activated atomic dispensers. Alkali metal vapors enable access to single electron systems, suitable for demonstrating fundamental light-matter interactions and promising for quantum logic operations, storage and sensing. However, progress is hampered by the need for robust and repeatable control over the atomic vapor density and over the associated optical depth. Until now, a moderate improvement of the optical depth was attainable through bulk heating or laser desorption – both time-consuming techniques. Here, we use plasmonic nanoparticles to convert light into localized thermal energy and to achieve optical depths in warm vapors, corresponding to a ~16 times increase in vapor pressure in less than 20 ms, with possible reload times much shorter than an hour. Our results enable robust and compact light-matter devices, such as efficient quantum memories and photon-photon logic gates, in which strong optical nonlinearities are crucial. [4]

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Analytical models for quality of transmission applied for ultrawideband system analysis and design

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The throughput of the currently employed fibre-optics infrastructure is reaching its limits, and new ideas are needed to meet ever-growing data demand. One of the promising and cost-effective directions is maximizing the usage of currently employed fibre infrastructure by utilizing the entire transparency window of silica fibre. This approach, known as ultrawideband transmission, can bring 50 THz overall bandwidth, compared to 5 THz one for the conventional C band. This methodology requires the development of amplifiers and transceivers for additional wavelengths. Additionally, ultrawideband transmission suffers from the severe impact of interchannel stimulated Raman scattering (ISRS), which leads to power transfer between channels and non-uniform signal-to-noise (SNR) distribution across the transmission window [1].

To study the performance of optical communication systems, traditionally simulation tools of signal propagation in the optical fibre are used. However, the design of ultrawideband transmission systems involves the adjustment of a multitude of system parameters, including modulation format, channels spacing and sampling, amplification gain profile. Furthermore, fibre parameters, e.g., chromatic dispersion or attenuation, depend on channel wavelength. Because of this, extensive simulation of all possible input waveforms and parameters is not practical. Instead, one can use analytical or semi-analytical models for the estimation of the quality of transmission metrics. The Gaussian noise model [2] applies the perturbation approach and the statistical properties of input signals and impairments impact, to provide SNR estimation for a given transmission system. Its generalization, which accounts for ISRS [3], allows studying ultrawideband scenarios in an accurate and computationally cost-effective way.

We demonstrate the advantage of the analytical models for optimising communication systems. We show it being applied for three different scenarios; for throughput maximisation by means of power tilting [4]; for the validation of different bands performance; and for the analysis of experimental transmission systems aimed at maximizing transmission throughputs [5].

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POSTER SESSION

7-10 December 2021
Chimie ParisTech, Paris

Hydrogen isotopes discrimination with SAW sensors

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Among the green energy sources, hydrogen technologies are a very promising option. However, while using, handling and storing hydrogen, safety precaution have to be carrefully taking care and sensors are presently a key issue in the present technological development. However, gas discrimination is a major problem of the existing sensors, beside ambient factors influences and other ambiental conditions.

Surface Acoustic Wave (SAW) sensing is among the technques with best performances in terms of detection limit. It is using acoustic waves propagating over a piezoelectric surface and are basing their functionality on the 'active layer' material mechanical properties change. For sensor fabrication we use ZnO nanowires layers, as a versatile wide bang-gap semiconductor with a high surface-to-volume ratio, and a good absorption of hydrogen and its isotopes. We grow ZnO single crystal [0001] nanowires on sensor surface as an active leyer using Pulsed Laser Deposition (PLD) - Vapour-Liquid-Solid (VLS) techniques. On one hand, discrimination process used by our sensors relays on different mass and similar sorbtion mechanisms of the hydrogen isotopes into the active layer. On the other hand a multi-frequency scan is a way to discriminate the active layer different behaviour for each analyt. Experimental results are presented together with a theoretical modelling of the sensor response results.

Development of a sustainable biosensor to detect respiratory infectious diseases

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The Covid-19 pandemic brought the need to use social masks to prevent the spread of the virus. However, no reliable and fast method were yet established to detect viral particles and to improve the protective ability of social masks. The new Sars-Cov-2 has a second pathway of entry into the cells of the human body – the sialic acid (SA) receptor. Gold nanoparticles (AuNP) are known to have excellent optical properties and huge research potential. Through color changes, colorimetric biosensors can be used as a rapid and easily approach to detect virus. Here, we develop a colorimetric biosensor based on the functionalization of AuNP by SA (SA-AuNP), as a new and effective textile coating layer, to provide a direct indication of the protective capacity of social masks. This biosensor will provide information about the state of contamination by Sars-Cov-2 and other viruses that cause breathing problems. To do that, AuNPs (10 nm) were functionalized with SA (SA-AuNP), in three different concentrations (50-50, 30-70 and 20-80, respectively) to select the optimal concentration for respiratory virus detection. Fourier-transform infrared spectroscopy (FTIR) and Scanning Electron Microscope with a Transmission Detector (STEM) analyses confirmed SA-AuNPs binding. FTIR results showed a well-established bond, through matches of peaks of SA-AuNPs. Bindings between the compounds were more evident in 50-50 concentration of SA-AuNP. In the 30-70 SA-AuNP the STEM images show some superposition of the nanoparticles and not so evident binding, as in the 20-80 concentration. Still, between these last two concentrations, the 30-70 is the one that shows the best results since it is visible some circular points larger than the others. In order to achieve the goal, the concentrations 30-70 and 50-50 of SA-AuNP were impregnated (Textile Foulard) in two substrates of different compositions, a cellulosic and a synthetic one. However, in this technique there are many parameters, such as drying time and temperature, which were varied in order to understand which was the best procedure to obtain the biosensor. The development of these smart mask demonstrated as a sensitive, rapid, and simple way to ensure a greater individual protection against viruses that attack the respiratory tract, and further reduce their contagion and preventing their spread.

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Highly efficient organic photovoltaics using non-toxic solvents for large scale applications

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Organic photovoltaics using non-fullerene acceptors have now reached 18% efficiencies[1]. These devices offer advantages over their inorganic counterparts such as lower cost, shorter energy payback time, solution processability and tuneability of energy levels. However, these materials are usually processed using chlorinated, toxic solvents that cannot be used in industrial settings. The solvent used during fabrication has a significant impact on the active layer morphology, meaning that a fundamental first step towards industrialization is to find donor/acceptor material blends that are soluble in greener alternatives such as tetrahydrofuran and o-xylene. The purpose of this work is to fabricate lab-scale (spin-coated) devices with the poly[(2,6-(4,8-bis(5-(2-ethylhexyl-3-fluoro)thiophen-2-yl)-benzo[1,2-b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c'] dithiophene-4,8-dione)] (PM6):2,2'-((2Z,2'Z)-((12,13-bis(2-butyloctyl)-3,9-diundecyl-12,13-dihydro-[1,2,5]thiadiazolo[3,4-e]thieno[2",3'':4',5']thieno[2',3':4,5]pyrrolo[3,2-g]thieno[2',3':4,5]thieno[3,2-b]indole-2,10-diyl)bis(methanylylidene))bis(5,6-difluoro-3-oxo-2,3-dihydro-1H-indene-2,1-diylidene))dimalononitrile (BTP-4F-12) blend with green solvents, and to compare their performance to devices made with the traditionally used chlorinated solvents. This will provide insight on how high efficiencies can be reproduced with low-toxicity and large-scale compatible solvents.

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Cyanographene@Ag Nanocomposite: Synthesis and Antibacterial Activity

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The ability of bacteria to develop resistance to conventional antibiotics as well as to silver and silver nanoparticles is threatening one of the pillars of modern medicine. To mitigate the risk of returning to the pre-antibiotic era, effective agents against pathogens are needed to be developed. Silver nanoparticles strongly bound to cyanographene (GCN/Ag) show high antibacterial activity at very low concentrations (0.2-2 ppm of Ag). Such strong antibacterial activity is higher even than that of ionic silver. Furthermore, GCN/Ag overcomes resistance mechanisms of multi-drug-resistant, and silver-nanoparticle-resistant bacteria, which has been so far an unmet challenge. Due to the strong dative bond between the nitrile groups of GCN and silver there is minimum leaching and thus record cytocompatibility to human cells. This work offers the opportunity to exploit suitably functionalized graphene as a covalent trap for silver, surpassing the antibacterial activity of Ag ions, keeping good biocompatibility and preventing Ag ion leaching and bacterial resistance.

The authors gratefully acknowledge the support provided by the project No. 19-22720S of the Czech Science Foundation.

Development of Epirubicin-Loaded Biocompatible Polymer PLA–PEG–PLA Nanoparticles: Synthesis, Characterization, Stability, and In Vitro Anticancerous Assessment

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Epirubicin (EPI) is an anti-cancerous chemotherapeutic drug that is an effective epimer of doxorubicin with less cardiotoxicity. Although EPI has fewer side effects than its analog, doxorubicin, this study aims to develop EPI nanoparticles as an improved formula of the conventional treatment of EPI in its free form. Methods: In this study, EPI-loaded polymeric nanoparticles (EPI-NPs) were prepared by the double emulsion method using a biocompatible poly (lactide) poly (ethylene glycol) poly(lactide) (PLA–PEG–PLA) polymer. The physicochemical properties of the EPI-NPs were determined by dynamic light scattering (DLS), transmission electron microscopy (TEM), differential scanning calorimetry (DSC), entrapment efficiency and stability studies. The effect of EPI-NPs on cancer cells was determined by high throughput imaging and flow cytometry. Results: The synthesis process resulted in monodisperse EPI-NPs with a size of 166.93 ± 1.40 nm and an elevated encapsulation efficiency (EE) of 88.3%. In addition, TEM images revealed the spherical uniformness of EPI-NPs with no aggregation, while the cellular studies presented the effect of EPI-NPs on MCF-7 cells' viability; after 96 h of treatment, the MCF-7 cells presented considerable apoptotic activity. The stability study showed that the EPI-NPs remained stable at room temperature at physiological pH for over 30 days. Conclusion: EPI-NPs were successfully encapsulated within a highly stable biocompatible polymer with minimal loss of the drug. The used polymer has low cytotoxicity and EPI-NPs induced apoptosis in estrogen-positive cell line, making them a promising, safe treatment for cancer with less adverse side effects.

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Systematic errors of THz absorption gas spectroscopy due to interference in a multipass cell

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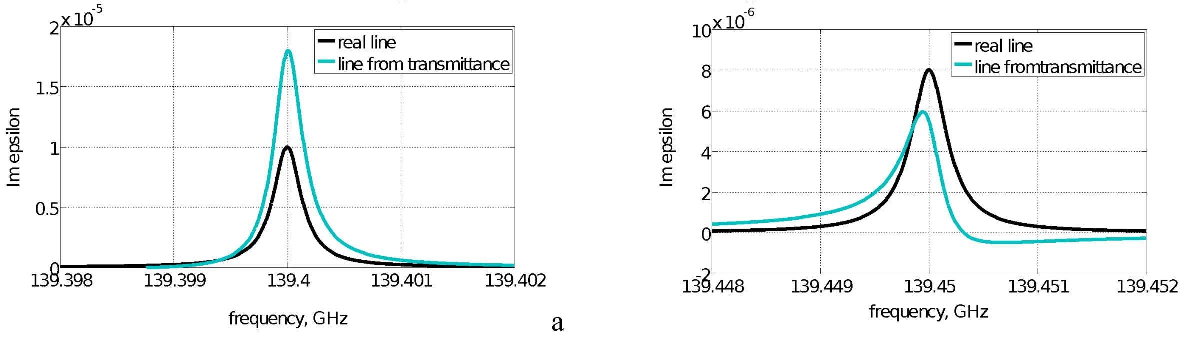
THz spectroscopy has tremendous potential for analysis of multicomponent gas mixtures with actual applications in medical diagnostics [1−3], food control [4] and security [5]. As the width of THz absorption lines is minimal at pressures about few Pa [1, 2], cells filled with absorbing gases are used for low-pressure measurements. Multipass cells enable to achieve optical path length of 1 to 10 meters in a relatively compact spectroscopic setup [3].

The transmittance spectrum of a gas cell is determined both by the absorption of the gas molecules and by the intrinsic transmittance of the cell. Commonly, it is considered that the cell impacts only on the slow part of the frequency dependence of the transmittance, while the absorption of the gas molecules results in the fast part. However, careful calculations have revealed a more complex picture, at least for the cells with significant interference (Fig. 1).

In the presented simulation, the cell was treated as a Fabri-Pérot interferometer with the intrinsic frequency response curve shown in Fig. 2. To test the model and observe its behavior in different conditions, we introduced a gas absorption line at an arbitrary frequency from 132 to 140 GHz. The line was at a resonant extreme of the frequency response curve or in between. We took care of examining all the position cases, so that real gas lines should fall into one of them.

The simulations revealed two effects, the perturbation of the shape of the observed line and the overestimation of its strength. The first reveals if the central frequency of the absorption line corresponds to the slope of the frequency dependence of the transmittance. The second one could be observed if the central frequency of the absorption line corresponds to the extreme of the transmittance.

Once confirmed in an experiment, the obtained results may reflect on the methods of numerical processing of THz transmission spectra measured with multipass cells.



a

b

Fig. 1. An absorption line of the model gas used in the simulations is plotted with the solid curve. An absorption line calculated from the difference between the transmittance of an empty cell and of the cell filled with the model gas is the dashed curve. (a) The absorption line is at the cell transmittance extreme. (b) The absorption line on the slope of the cell transmittance.

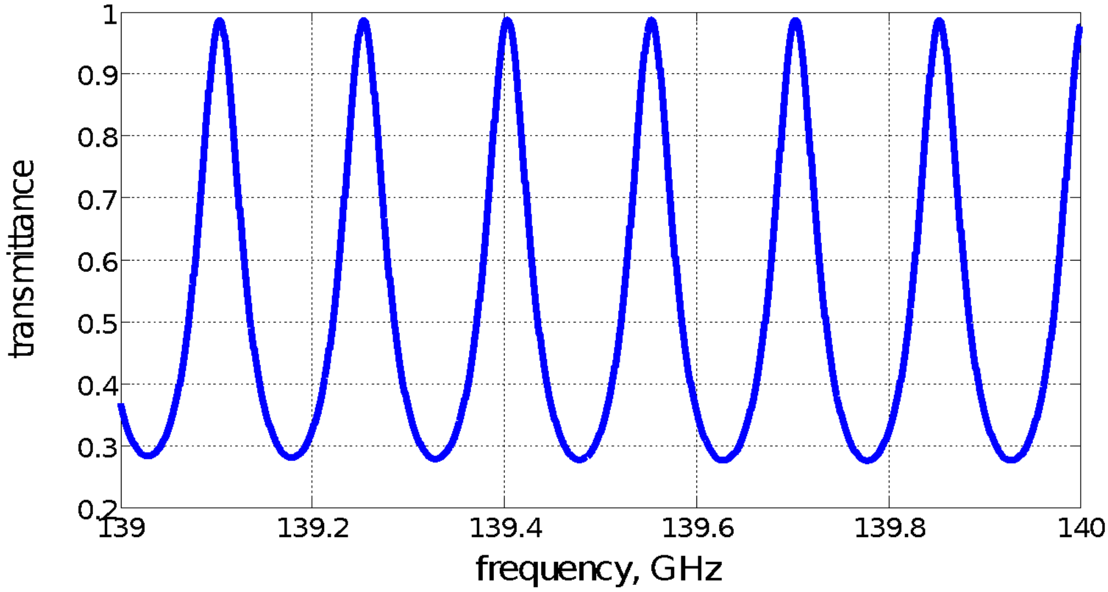


Fig. 2. The frequency dependence of the intrinsic transmittance of the cell (TM-polarization).

Acknowledgements

This research was funded by the Russian Science Foundation, grant No. 21-19-00357, https://rscf.ru/en/project/21-19-00357/

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Hydrogen sorbtion in ZnO nanostructures

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While sensors are a key issue in the present technological development, decreasing the detection limit in gas sensing is just one of the main directions of the development for a wide range of application worldwide including green anergy. Hydrogen is one of the serious green energy candidates for reducing carbon dioxide polution but with serious safety issues, needing a rigurous monitoring of its presence into the atmosphere. ZnO is a versatile wide bang-gap semiconductor with a good sorbtion of various gases including hydrogen isotopes, and presently used in a wide range of sensor applications. For a ZnO sensor case with application in hydrogen detection, decreasing of the sensor detection limit relays mostly on the increasing of the sensor active area surface and the main way of doing that is using ZnO nanostructures as alternative to bulk material for sensing applications. Controlled morphology nanowires are used as ‘building blocks’ for such an active layer. On the other hand ZnO nanostructures presents a series of enhanced properties related with the bulk materials, due to the high surface-to-volume ration, and, it is relatively easy to grow on many materials. In the present work, using LAMP open-source software, theoretical simulation on ZnO nanowire gas absorption were performed. Theoretical simulations for hydrogen gas and its isotopesand are presented together with some experimental gas detection results using SAW sensors. Results are aimed for device applications in gas detection and possible discrimination as well as pressure measurements.

Different sizes of gold nanoparticles in a self-assembling plasmonic film as a SERS substrates

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Surface-enhanced Raman scattering (SERS) is a powerful analytical method for studying the composition of various analytes. It can be used in chemistry, medicine, biology, material sciences and other areas of life [1]. SERS has two main types of enhancing media. They are colloidal suspensions of plasmonic nanoparticles and solid substrates with immobilized plasmonic nanoparticles on their solid surfaces. Each has associated advantages and disadvantages. The main problem of colloidal suspensions is time-dependences of enhancing factors. Most solid substrates have irreproducible surface distributions of enhancing factors. Regularly patterned surfaces obtained via lithographic techniques or thermal evaporation can solve problems of irreproducible surface distribution, but they are expensive to synthesize. Self-assembled plasmonic films (SPF) have been studied as potential SERS active substrates. This method of the enhancing substrate synthesis combines the simplicity of synthesis, the regularity of the resulting structure, the absence of the dependence of the enhancing factor on time. SPF are metal films at the interface between an aqueous gold colloid and a solution of a modifier in an organic solvent. The main types of modifiers are transition metal complexes, thiols, quaternary ammonium and arsonium salts crown ethers, etc [2].

Colloids with different sizes of gold nanoparticles (Au-NP) were synthesized by the citrate method with varying the content of sodium citrate in the reaction mixture [3]. SEM and DSL studies were carried out to determine the particle size of the obtained colloids. Colloid № 1 (C1) contained spherical particles 40 nm in size. Colloid № 2 (C2) consisted of lamellar particles with an approximate size of 60x30x15 nm. Colloid № 3 (C3) contained spherical particles of 15 - 20 nm in size. The zeta potential of the obtained colloid Au-NPs is equal to - 20.7 mV, - 37.6 mV and -8 mV for C1, C2 and C3, respectively. C1 and C3 were unstable. The film was obtained from freshly prepared colloids. SEM and DLS results were obtained at the same time with obtaining film, and the absorption spectrum was recorded later only for stable C2. However, SPF also formed from aggregated colloids. Three obtained colloids were used to obtain SPF. Three samples were prepared on a glass substrate for the comparison of enhancement substrates study. Pseudoisocyanine iodide (1,1'-diethyl-2,2'-cyanine iodide) was selected as the analyte. The intensity distribution map (IDM) of samples with an area of 2025 μm^2 was obtained on a Renishaw micro-Raman spectrometer. Average intensity of IDM and IDM gates were calculated for C1, C2 and C3. These quantities for C1 are 5393 counts and 3523 counts (5393±3523 counts further), for C2 are 9398±1838 counts and for C3 are 2414±1274 counts. This corresponds to analytical enhancing factors [1] $5 \cdot 10^4$, $9 \cdot 10^4$, and $2 \cdot 10^4$ for samples C1, C2, and C3, respectively. The best enhancement will be determined in future works. Optimization of the ratio of the reaction mixture components in the SPF preparation will be carried out in these works.

This work was supported by the Russian Science Foundation (Agreement 20-72-00114).

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Electronic Nose based on Organic Field Effect Transistors

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Real-time quantitative analysis of various gaseous mixtures such as indoor and outdoor air atmosphere, exhaled breath, food aromas, etc., are becoming more and more important from both safety and personal medicine points of view. Modern solid-state gas sensors are approaching limit of detection of a few ppbs while their cost is much less then ones utilizing benchmark optical and mass-spectroscopy methods. Thin-film organic field effect transistors (OFETs) are notably promising for gas sensing due to their high sensitivity at room temperature, low power consumption and architectural versatility. Such high sensitivity achieved due to direct contact between the thin current-carrying layer and the analyte in the OFETs leasing to the strong dependence of the OFETs electrical properties on the environment. [1] However, due to non-covalent sensing mechanism, single OFET sensors responses to a different of analytes including water vapors, are rather similar what leading to their main drawbacks – poor selectivity and environmental instability.[2] To overcome such problems usually the “electronic nose” approach based on a combination of cross-selective sensors array with pattern recognition algorithms is used, however up to now it was rarely reported for OFETs.

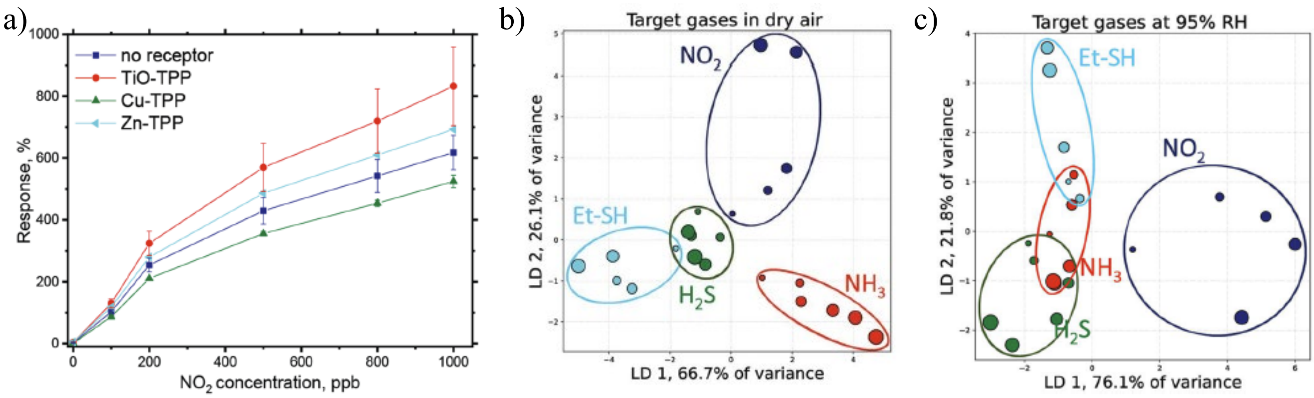

Figure 1. (a) Response of sensors with different receptors. LDA diagrams for target gases in (b) dry and (c) humid air.

We present the first fully integrated, compact and portable electronic nose based on array of OFETs gas sensors with varied cross-sensitivity. We developed a simple, affordable and versatile approach for fabrication of such array on a single substrate. This approach is based on partial modification of the substrate with a set of receptor molecules by easy-processable and rather fast Langmuir technique. Fabricated sensors were found to be very stable and have a limit of detection down to 30 ppb of NO_2 in a wide range of air humidity from 0 to 95%. Electronic nose also demonstrated great ability of distinguishing low molecular gases such as NH_3, NO_2, H_2S and Et-SH at the same humidity range (Fig.1). The device have a great potential in a wide range of practical applications such as environmental monitoring and food spoilage detection.[3]

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