Nanophotonics

18th - 21st September 2022, Torun, Poland

Book of Abstracts

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19. **Val Zwiller**, KTH Royal Institute of Technology, Stockholm, Sweden

Programme

Sunday (Bulwar Hotel)

18.00 – 19.00 David Norris, **Optical and electronic Fourier surfaces**

19.00 – 21.00 Welcoming glass of wine

Monday (Institute of Physics, NCU)

9.00 - 9.45 Joel Cox, **Nonlinear and quantum nano-optics with atomically-thin materials**

9.45 – 10.30 Diego Martin Cano, **Optomechanics with molecules: long-lived vibrational memories and SERS principles**

10.30 – 11.00 Coffee break

11.00 – 11.45 Alexandre Bouhelier, **The case of nonlinear photoluminescence in plasmonics**

11.45 – 12.30 Achim Hartschuh, **Ultrafast microscopy of single nanostructures**

12.30 – 13.00 Joanna Niedziolka-Jonsson, **Spatial organization of silver nanowires for advanced photonics**

13.00 – 14.30 Lunch

14.30 – 15.15 Nika Akopian, **Multi-Qubit Photonic Device**

15.15 – 16.00 Doris Reiter, **Exciting quantum dots via the SUPER scheme**

16.00 – 16.30 Paweł Machnikowski, **Resonance fluorescence of a quantum system with modulated transition energy**

16.30 – 17.00 Piotr Kossacki, **Neutral and charged exciton interactions in MoSe2 monolayer**

17.30 – 19.00 Poster session (Institute of Physics, NCU)

17.30 – 19.00 Lab tour (Institute of Physics, NCU)

Tuesday (Institute of Physics, NCU)

9.00 - 9.45 Val Zwiller, **Quantum hardware for the generation, manipulation and detection of light for quantum communication**

9.45 – 10.30 Andres Ayuela, **Optical properties of quantum dots with localized states induced by impurities or being surface terminated**

10.30 – 11.00 Coffee break

11.00 – 11.45 Jakub Dostalek, **Plasmonic Nanostructures with Responsive Polymer Interfaces for Actuating and Biosensing**

11.45 – 12.30 Guillaume Baffou, **Quantitative phase microscopy for nano and bio**

12.30 – 13.15 Guillermo Acuna, **DNA-origami for nanophotonics**

13.15 – 15.00 Lunch

15.00 – 15.45 Ivan Fernandez-Corbaton, **Computing the optical response of molecular materials: from nano to device scales**

15.45 – 16.15 Łukasz Kłopotowski, **On the photoluminescence mechanism in I-III-VI colloidal quantum dots**

16.15 – 16.45 Jan Suffczyński, **Exciton-polaritons in coupled microcavities in linear and non-linear regime**

16.45 – 17.15 Grzegorz Sęk, **Recent results on epitaxial quantum dots as efficient single photon emitters at the telecommunication wavelengths**

19.00 – 22.00 Conference dinner (Bulwar Hotel)

Wednesday (check-out)

Abstracts
Invited talks

OPTICAL AND ELECTRONIC FOURIER SURFACES

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Keywords: diffractive optical element, thermal scanning-probe lithography, band engineering, quantum materials

Gratings and holograms are patterned surfaces that tailor optical signals by diffraction. Despite the long history of such structures, variants with remarkable functionalities continue to be discovered. Further advances could exploit Fourier optics, which specifies the surface pattern that generates a desired diffracted output through its Fourier transform. The required surface profile should contain a precise sum of sinusoidal waves, each with a well-defined amplitude, spatial frequency, and phase, to shape the optical wavefront. However, because fabrication techniques typically yield profiles with at most a few depth levels, complex "wavy" surfaces cannot be obtained, limiting the straightforward mathematical design and implementation of sophisticated diffractive optics. In this presentation, we will discuss a simple yet powerful approach to eliminate this design–fabrication mismatch by demonstrating optical surfaces that contain an arbitrary number of specified sinusoids [1]. Multicomponent linear gratings allow precise manipulation of the dispersion, stopbands, and coupling of electromagnetic signals. More broadly, we analytically design and accurately replicate intricate two-dimensional Moiré patterns, quasicrystals, and holograms, demonstrating a variety of previously impossible diffractive surfaces. Finally, we show that such patterns can be reduced to nanometer length scales, creating wavy Fourier surfaces for 2D electronics [2]. Therefore, this approach provides benefit for optical devices and emerging topics in photonics and 2D optoelectronics.

[1] N. Lassaline, R. Brechbühler, S. J. W. Vonk, K. Ridderbeek, M. Spieser, S. Bisig, B. le Feber, F. T. Rabouw, D. J. Norris, *Nature* **582** (2020) 506.

[2] N. Lassaline, D. Thureja, T. Chervy, D. Petter, P. A. Murthy, A. W. Knoll, D. J. Norris, *Nano Lett.* **21** (2021) 8175.

NONLINEAR AND QUANTUM NANO-OPTICS WITH AOMICALLY-THIN MATERIALS

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Keywords: Nonlinear nano-optics, Quantum nano-optics, Graphene plasmons, Polaritons

Coherent control of light and atomic systems enables fundamental explorations of quantum physics while promising disruptive applications in diverse fields, ranging from information and communications technologies to optical sensing and metrology. In this context, the intrinsically strong and actively tunable light-matter interactions available in atomically-thin materials, such as graphene and ultrathin noble metals, offer unique opportunities to trigger nonlinear and quantum optical phenomena on the nanoscale by invoking their supported polaritons and/or near field interaction with proximal quantum light emitters [1]. Here we will discuss the excellent nonlinear optical response associated with 2D plasmon polaritons in graphene [2], characterized by strong optical confinement, electrical tunability, and mechanical flexibility, as well as with plasmons in ultrathin crystalline noble metal films [3], with thickness-dependent properties and potentially lower loss than their amorphous counterparts. We shall then explore strategies to harness polariton-assisted nonlinear optical phenomena in 2D materials to resonantly couple with proximal quantum light emitters [4], mediate single-polariton-level nonlinear optical interactions on the nanoscale [5,6], and optically drive atomic systems into electrically-tunable bistable states [7].

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[2] J. D. Cox and F. J. García de Abajo, *Acc. Chem. Res.* **52** (2019) 2536.

[3] Á. Rodríguez Echarri, J. D. Cox, F. Iyikanat, and F. J. García de Abajo, *Nanophotonics* **10** (2021) 4149.

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[5] I. Alonso Calafell, J. D. Cox, M. Radonjić, J. R. M. Saavedra, F. J. García de Abajo, L. A. Rozema, and P. Walther, *Npj Quantum Inf.* **5** (2019) 37.

[6] J. D. Cox and F. J. García de Abajo, *Nano Lett.* **19** (2019) 3743.

[7] M. H. Eriksen, J. E. Olsen, C. Wolff, and J. D. Cox, arXiv:2207.12134

OPTOMECHANICS WITH MOLECULES: LONG-LIVED VIBRATIONAL MEMORIES AND SERS PRINCIPLES

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Keywords: SERS, Organic Molecules, Cavity Optomechanics, Quantum optics

The optomechanical character of molecules was discovered by Raman about one century ago. Nowadays, single organic molecules are used as probes in material science and are promising contestants for realizing quantum optical platforms [1]. Nevertheless, the highly large number of vibrational, electronic and photonic degrees of freedom interaction have limited their study to situations where some of their properties are neglected or traced out. In this talk I present our efforts to study and treat such degrees of freedom on equal footing [2,3,4,5,6]. In particular, we will show how the engineering of nanophononic structures allows us to predict enhancements of the optical coherence of solid-state molecules by orders of magnitude beyond the current experimental status [2]. Moreover, we will illustrate how we can derive Surface-Enhanced Raman scattering (SERS) interactions from the point of view of cavity optomechanics [4,5] by using first molecular principles [3,6]. Finally, we will show how our formalism allows including non-adiabatic electronic levels that enables us to show strong cooperative cavity couplings and ultrastrong vibrational responses beyond former SERS results.

[1] D. Wang, H. Kelkar, D. Martin-Cano, D. Rattenbacher, A. Shkarin, T. Utikal, S. Götzinger, and V. Sandoghdar, *Nature Physics* **15** (2019) 483.

[2] B. Gurlek, V. Sandoghdar and D. Martin-Cano, *Phys. Rev. Lett.* **127** (2021) 123603.

[3] M. Reitz, C. Sommer, B. Gurlek, V. Sandoghdar, D. Martin-Cano and C. Genes, *Phys. Rev. Research* **2** (2020) 033270.

[4] P. Roelli, C. Galland, N. Piro and T. J. Kippenberg, *Nature Nanotech.* **11** (2016) 164-169.

[5] P. Roelli, D. Martin-Cano, T.J. Kippenberg and C. Galland, *Physical Review X* **10** (2020) 031057.

[6] M. A. Martinez-Garcia and D. Martin-Cano, in preparation.

THE CASE OF NONLINEAR PHOTOLUMINESCENCE IN PLASMONICS

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Keywords: Plasmonics, ultrafast pulses, photoluminescence, hot electrons,

Upon absorption of an ultrafast laser pulse, metal nano-objects may create new up-converted photons by various plasmon-assisted nonlinear processes. Amongst them are well-known coherent mechanisms such as second or third harmonic generation. Another interesting nonlinear response is an incoherent effect traditionally referred as two-photon photoluminescence because of its (quasi)-quadratic dependence with the laser power. When present, the emission spectrum is large spanning the visible to near-IR spectrum. The origin of this continuum remains debated in the literature with various hypothesis depending if one considers that the nonlinearity arises from the absorption (multi-photon transitions) or from the emission characteristics. Here we employ a more generic term for this broad-band nonlinear response: nonlinear photoluminescence or NPL. We show in this work that NPL emitted by optical antennas is a valuable tool to study photo-generated hot carrier dynamics. We will demonstrate that the temporal response is a function of the energies of the carriers relative to the Fermi level and carries statistic of photon bunching [1]. We further show that NPL is not only locally emitting photons at the laser excitation site but is emitted by the entire body of antenna [2]. We demonstrate that such a delocalized response is mediated by the underlying surface plasmon modal landscape, enabling thereby a polariton-mediated spatial tailoring and design a nonlinear response. We will discuss the possibility to engineer the spatial distribution of the surface plasmon modes to implement advanced functionalities such as logical gates [3]. We will conclude the presentation by showing how such nonlinear responses can be controlled on-demand by a static electrical command [4] as illustrated in Fig. 1.

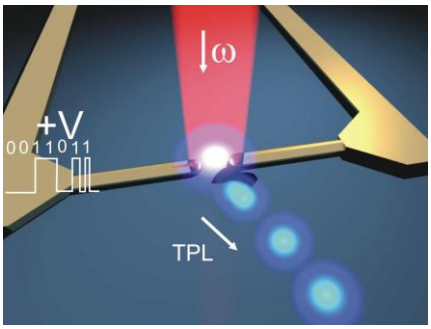

Figure 1: Scheme for electrically controlling the NPL in an optical gap antenna.

[1] R. Mejard, *ACS Phot*. **3** (2016) 1482, K. Malchow, *J. Opt. Soc. Am. B* **38** (2021) 576
[2] S. Viarbitskaya *Phys. Rev. Lett*. **115** 197401 (2015); A. Agreda, *ACS Phot*. **6** (2019) 1240
[3] U. Kumar *ACS Nano* **15** 13351 (2021), F. Dell'Ova, *Opt. Expr.* **30** (2022) 17517
[4] A. Agreda *ACS Phot*. **7** (2020) 2153

ULTRAFAST MICROSCOPY OF SINGLE NANOSTRUCTURES

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Keywords: Ultrafast spectroscopy, carbon nanotubes, plasmonics, optical antennas

Ultrafast spectroscopic techniques provide direct insight into the excited state energies and dynamics of materials. Implemented in a microscopy platform, these techniques can be utilized to establish spatio-temporal maps and to visualize photo-induced phenomena in single nanostructures.

In this talk, I will report on two different implementations we have developed to address particular sample properties. First, we combined transient interferometric scattering and time-resolved PL microscopy to study the ultrafast dynamics of excitons in single semiconducting carbon nanotubes. This allowed us to formulate a unified model by connecting unimolecular exciton decay and ultrafast exciton-exciton annihilation on a time-scale reaching down to 200 fs.

In the second implementation, we explore the non-linear response of plasmonic nanoantennas using phase-shaping of broadband laser pulses. We find that the signal enhancement provided by resonant nanoantennas can be predicted from a complex frequency dependent field enhancement factor. We then demonstrate that the spectral phase associated with this field enhancement factor can be utilized for coherent control of the non-linear response and for phase-selective confocal imaging.

SPATIAL ORGANIZATION OF SILVER NANOWIRES FOR ADVANCED PHOTONICS

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Keywords: siler nanowire, surface modification, local deposition, remote excitation

Silver nanowires (AgNWs) are unique nanoparticles due to their optical properties. They can be used as optical antennas and plasmon waveguides. While the antenna effect serves to deliver additional excitation through localized Surface Plasmons (SPs) or enhances the quantum yield, the plasmon waveguiding enables use of propagating SPs to deliver energy to remote locations along the nanowire or collect energy of a molecule coupled with it. There is however a trade-off between these two effects. Greater field enhancement, and hence fluorescence enhancement, will limit the lengths of SP propagation, whether achieved by decreased nanowire diameter or when approaching the plasmon frequency [1-3]. This gives the opportunity for controlling the optical properties of emitters, such as polymers, nanocrystals or biomolecules. The diameters of AgNWs in the range of 100 nm, are small enough to facilitate plasmonic effects over the broad spectral range, and at the same time their lengths of tens of micrometers make them visible using standard microscopy.

In this work we want to highlight the possibility of using nanowires to construct photonic systems by special organisation using optical microscopy. One such example is long nanowires connected to a drop of quantum dots emitter that be excited by illuminating the other end of the nanowire. The QD drops can also be used to transfer energy from one nanowire to the next, forming the beginning of an optical network of plasmonic wires. The waveguiding properties of nanowires can also be used for remotely controlled photocatalysis.

Efficient plasmonic waveguiding relies on the use of high quality nanowires. At present, these are achieved by chemical synthesis which allows control of the length and the diameter of the wires. Chemically synthesised NWs are monocrystalline, as opposed to those created by physical deposition methods such as sputtering. However, they are also spatially disorganised, requiring post-synthesis organisation on the sample surface.
In this talk we will give an overview of chemical synthesis of AgNWs to tune their optical properties. We will also discuss strategies for spatial organisation of the NWs and present a few examples of photonic structures studied.

The research was partially financed by the projects Sonata BIS 2016/22/E/ST5/00531 by the National Science Centre (Poland), OPUS grants 2016/21/B/ST3/02276 and 2017/27/B/ST3/02457

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MULTI-QUBIT PHOTONIC DEVICES

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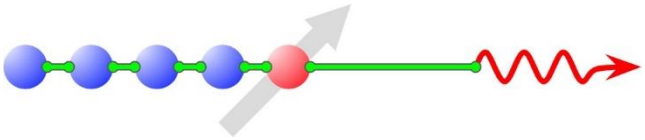
Keywords: Quantum Dots, Nanowires, Quantum Nanophotonics, Quantum Technology

Semiconductor quantum dots are one of the best on-demand sources of single and entangled photons to date, simultaneously merging the highest brightness and indistinguishability of the emitted photons. They are, therefore, among the strongest candidates for practical single-qubit quantum photonic devices. However, to exploit the full advantage of quantum physics, *multi- qubit* photonic devices are vital. This talk will present our approach to realizing practical *multi- qubit* photonic devices for quantum networks based on novel *crystal-phase quantum dots* in nanowires.



EXCITING QUANTUM DOTS VIA THE SUPER SCHEME

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Keywords: Quantum Dots, Optical Control, Photon Source, SUPER

A crucial ingredient for quantum communication is the generation of photons in either a single, entangled or Cluster state. Semiconductor quantum dots have emerged as bright source to create such photons on demand. Nonetheless, for applications it is required that the photon properties are ideal and the generation rate is sufficiently high. This has led to an ongoing search for the perfect single photon source.
In this talk, we discuss the recently proposed Swing-UP of EmitteR Population (SUPER) to excite a quantum dot [1]. The SUPER scheme is based on the coherent optical excitation using two red-detuned pulses. By this, polarization filtering can be avoided, which can enhance the rate of the generated photons by up to a factor of two. The SUPER scheme can be readily implemented using a spatial light modulator creating a pulse pair [2].
Because of the strong detuning, which indicates a dressed state splitting on the same order where the reappearance regime occurs for Rabi rotations and adiabatic rapid passage, it could be expected that phonons do not disturb this process. However, due to the strong driving the evolution along the dressed state is non-adiabatic and phonons still lead to a slight dephasing comparable to the detuning found for the Rabi scheme [3].
Therefore, the SUPER scheme is a viable and easy-to-implement alternative to Rabi rotations with the advantage of being truly off-resonant to the excitation pulse.

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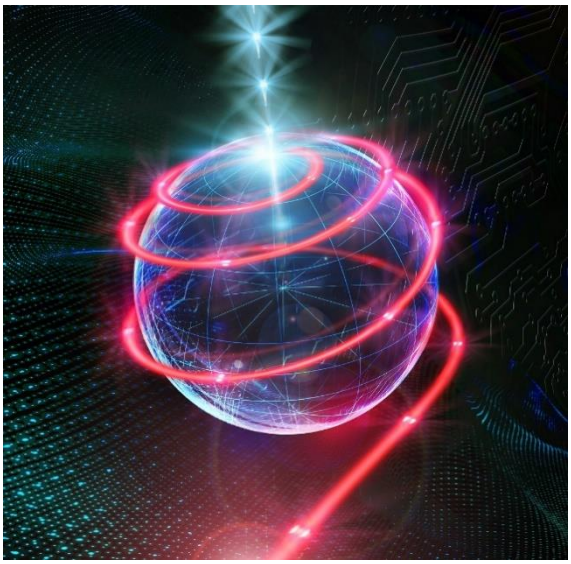

RESONANCE FLUORESCENCE OF A QUANTUM SYSTEM WITH MODULATED TRANSITION ENERGY

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Keywords: resonance fluorescence, quantum dot, surface acoustic waves, hybrid systems

I will discuss the spectra of resonance fluorescence for a two-level system in which the transition energy varies in time in a deterministic or random way. A particular system that we have studied both theoretically and experimentally is a semiconductor quantum dot interacting with the strain field of a surface acoustic wave. Such an acousto-optic control of a solid-state quantum emitter is envisaged as a step towards transduction of quantum signals from acoustic to optical domains.

I will show how a modulation with one or two acoustic tones allows one to control the frequency bin to which the photons are scattered in the weak excitation regime [1,2]. Next, I will discuss acoustic sidebands of the Mollow triplet in the strong excitation regime and show how the double dressing of quantum states leads to resonances and central line suppression under strong excitation. Finally, I will briefly report on our results concerning resonance fluorescence in the presence of random modulation by a telegraph noise.

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NEUTRAL AND CHARGED EXCITON INTERACTIONS IN MOSE2 MONOLAYER

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Monolayers of transition metal dichalcogenides (TMDs) draw a lot of attention as semiconducting materials with robust optical properties, strong Coulomb interaction and an optically accessible valley degree of freedom. Extraordinary properties of exciton complexes lead to new possibilities of exploration of nonlinear effects.

Here I will focus on femtosecond pump-probe studies of neutral and charged exciton optical response in monolayer $MoSe_2$ to resonant photoexcitation of a given exciton state. It is shown that creation of CX population in a given K,K' valley leads to the capture of available free carriers in the opposite valley and reduces the interaction of neutral X with the Fermi sea. We also observe strong broadening of X with the increasing CX population caused by efficient scattering and excitation induced dephasing in the ultrafast limit. From the valley-resolved analysis of the observed effects we are able to extract the spin-valley relaxation times of free carriers as a function of carrier density. Moreover, we analyze the oscillator strength and energy shift of X in the fermi sea regime under resonant excitation. From this we can observe the process of X decay by radiative recombination paired with trion formation effect. By analyzing the dynamics of X energy shift we observe the rapid increase of X relaxation rate with the introduction of Fermi sea of electrons.

Our findings shed light upon the complex landscape of exciton-exciton and exciton-carrier interactions in the two dimensional transitional metal dichalcogenides and lead to further development of their fundamental understanding.

QUANTUM HARDWARE FOR THE GENERATION, MANIPULATION AND DETECTION OF LIGHT FOR QUANTUM COMMUNICATION

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Keywords: Single photon generation, single photon detection, quantum technologies, photonics

We develop single photon sources based on semiconductor quantum dots to generate single photons as well as entangled photon pairs at telecom wavelengths to enable the implementation of long distance quantum communication. Operation at telecom wavelengths also allows us to implement experiments at the single photon level with off-the-shelf components such as modulators. Schemes to manipulate light on-chip, allowing for integration, scalability and higher reliability are also carried out with the aim of operating at telecom frequencies.

Single photon detectors with high detection efficiency, low noise and high time resolution are required to realize quantum communication and quantum sensing experiments. For this purpose, we develop superconducting nanowire single photon detectors, these find a wide range of applications including lidar and quantum microscopy. To allow for complex systems, integrated quantum optics circuits where we combine quantum sources and superconducting detectors are under development.

Finally, we demonstrate single photon transmission over 34 km of deployed optical fibers, paving the way to secure communication links using quantum technologies.

OPTICAL PROPERTIES OF QUANTUM DOTS WITH LOCALIZED STATES INDUCED BY IMPURITIES OR BEING SURFACE TERMINATED

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Optical properties of the quantum dots are well known to be engineered by changing their size, so that within the visible region the optical properties can be tuned between blue and red colors. However, less is known when dealing with localized states and surface terminated effects. In this talk I review results on optical spin control in nanocrystalline magnetic nanoswitches studying doped semiconductor quantum dots, which are traditionally synthesized nanostructures. Furthermore, on carbon nanostructures I am going to discuss the case of metallic carbon nanotube quantum dots with broken symmetries as a platform for tunable terahertz detection.

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PLASMONIC NANOSTRUCTURES WITH RESPONSIVE POLYMER INTERFACES FOR ACTUATING AND BIOSENSING

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Keywords: plasmonic, responsive hydrogel, biosensor, surface plasmon resonance

Metallic nanostructures support surface plasmon modes originating from collective oscillations of charge density that are associated with increased intensity of electromagnetic field and local density of optical states. Such optical resonances increasingly find use in bioanalytical technologies for efficient probing of chemical and biological species including surface plasmon resonance–based affinity biosensors as well as surface enhanced optical spectroscopy methods. The interface of metallic nanostructures needs to then facilitate several key functionalities including the specific capture of target molecular species, resistance to fouling from other abundant molecules, and their resonances need to be tuned to desired spectral windows.

The talk will cover responsive hydrogels for plasmonic biosensors and rapid actuating of plasmonic nanomaterials.[1] We will report on precise crosslinking and attachment of an open polymer network structure to the metallic surface by using UV or two-photon absorption process followed by the postmodification with desired biofunctional groups [2]. As illustrated in the Figure below, characterization of rapid swelling and collapsing of the pNIPAAm-based hydrogel thin films by the use of plasmonic heating [3], employment for dual amplification strategies [4], and reversible tuning of surface plasmon modes [5] will be discussed.

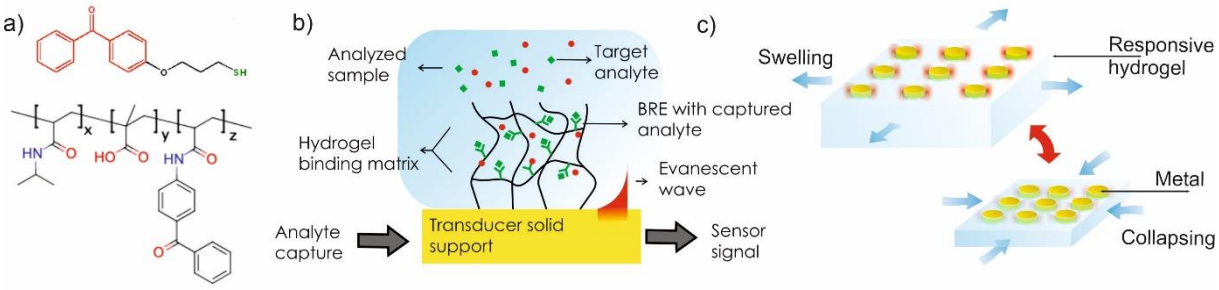

Figure: Schematics of a) polymer toolkit employed for b) construction of an affinity biding matrix and c) modulating period of gold nanoparticle arrays by external stimulus.

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QUANTITATIVE PHASE MICROSCOPY FOR NANO AND BIO

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Keywords: phase imaging, thermoplasmonics, metrology, microscopy, biology

Quantitative phase microscopy (QPM) designs a family of optical microscopy techniques capable of mapping the phase of a light beam. Oddly enough, mapping the phase of a light beam seems to be only of interest for biologists, who have been extensively using QPMs technique for two decades, not really for physicists.

In this presentation, I show how we have been using a particularly sensitive and simple QPM technique called cross-grating phase microscopy (CGM) [1] for applications in nanophotonics, opening a new route of investigation for QPM, besides biology. This contribution is aimed to explain the working principle of CGM, how the technique can be used as a temperature microscopy technique to map the temperature of gold nanoparticles under illumination [2], enabling applications in physics [3], chemistry [4] and biology [5,6] at the nano/microscale, and how CGM can be used as a metrology tool for 2D materials [7], nanoparticles [8], and metasurfaces.

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DNA-ORIGAMI FOR NANOPHOTONICS

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Keywords: nanophotonics, optical antennas, single photon emitters, plasmonics, DNA nanotechnology, DNA origami.

Over the last decade, the DNA origami technique [1] has consolidated into the state-of-the-art approach for the self-assembly of nanophotonic structures since it provides unique control and versatility to organize different molecules and nanoparticles in well-defined geometric arrangements. In particular, this technique has proven extremely useful to fabricate nanophotonic devices with specific functionality by setting single-photon emitters, such as fluorescent molecules or quantum dots, and metallic nanoparticles in precise geometries with high positional and stoichiometric control.
In this contribution, we will first introduce this technique and discuss its strengths and limitations together with a comparison with state-of-the-art top down approaches. Then we will show how this technique can be applied to study light-matter interaction at the single molecule level for enhanced spectroscopies and sensing with portable devices such as smartphones [2]. We will also show how these antennas can be engineered to manipulate the fluorescence emission, including directivity [3] and shifting the apparent fluorescence emission center [4].

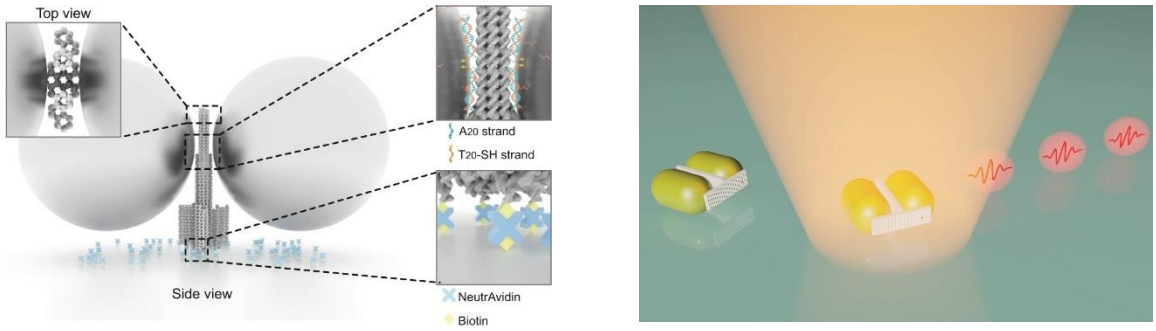

Figure 1. DNA origami based optical antennas. Dimers for light concentration exploiting two silver nanoparticles for DNA detection (left) and ultra-compact antenna based on gold nanorods for directing light (right).

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COMPUTING THE OPTICAL RESPONSE OF MOLECULAR MATERIALS: FROM NANO TO DEVICE SCALES

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Keywords: molecular materials, computational photonics, T-matrix

Advances in fabrication technologies are accelerating the rate at which we can create new materials, pointing towards a new era when materials with unprecedented properties will be tailor-made for target applications. For example, in three-dimensional laser printing, the feature size resolution is reaching the sub-micrometer and nanometer scales relevant for optical applications. Another promising class of artificial materials are molecular metal-organic frameworks (MOF), featuring nanometer-scale scaffold-like crystalline structures formed by organic molecules and metallic ions. However, for the full realization of their potential, the spectacular advances in fabrication techniques need to be matched by accurate and computationally efficient theoretical models. Such models should underpin the computer-aided design of new materials, hence partly substituting costly experimental comparisons of different alternatives, and also support the analysis and interpretation of experimental data. The multi-scale and multi-disciplinary characters of the systems at hand makes the theory challenging. Physics and chemistry are intertwined together across spatial scales ranging from nanometers to millimeters. Extra complexity is added when the materials are placed inside an optical cavity for enhancing the interaction between light and matter.

In my talk, I will present a new multi-scale methodology that we are developing at KIT to rigorously compute the optical response of devices containing molecular materials, either in isolation, on substrates, inside optical cavities, and/or in combination with metasurfaces. The methodology is based on the T-matrix and has already been used to provide a refined understanding of experimental results [1]. A new homogenization technique derived from our methodology allows one to compute the response of arbitrarily-shaped volumetric patchworks of structured molecular materials and metamaterials [2].

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ON THE PHOTOLUMINESCENCE MECHANISM IN I-III-VI COLLOIDAL QUANTUM DOTS

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Keywords: colloidal quantum dots, nanocrystals, photoluminescence, spectroscopy

Colloidal quantum dots (QDs) made of I-III-VI compounds such as $CuInS_2$ or $AgInS_2$ attract significant attention as more environmentally friendly alternatives to cadmium and lead chalcogenide QDs. Despite years of research, the optical properties of these nanostructures are not fully understood.

For $CuInS_2$ QDs most experimental results point to the free-to-bound process as the underlying mechanism of electron-hole recombination, although some theoretical and experimental reports claim that the PL can be due to an excitonic process. In the first part of the talk, I will present our results on studies of the photoluminescence (PL) mechanism in $CuInS_2$ QDs. I will show that temperature- and magnetic field-dependent PL dynamics are compatible with a recombination of a delocalized electron and a localized hole (i.e., a free-to-bound mechanism) and that the results cannot be explained by assuming a recombination of band-edge excitons.

For AgInS2 and its alloys, a donor-acceptor-pair recombination is often invoked as the PL mechanism. In the second part of the talk, I will challenge this assumption. I will show results of single dot spectroscopy studies on alloyed Ag-In-Zn-S QDs. More specifically, I will present analysis of spectra diffusion, blinking, and photon correlation experiments. These analyses suggest that - as in the case of $CuInS_2$ QDs - the PL occurs via the free-to-bound mechanism.

EXCITON-POLARITONS IN COUPLED MICROCAVITIES IN LINEAR AND NON-LINEAR REGIME

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Keywords: exciton-polariton, Bose-Einstein condensation, parametric scattering

Coupled optical microcavities embedding quantum emitters provide a multilevel system highly attractive for studies of linear and non-linear polariton related phenomena, as well as for a wide range of applications in optoelectronics and quantum information science.

Here, an epitaxial structure comprising two optical microcavities coupled through a semitransparent Bragg mirror,[1] each embedding (Cd,Zn)Te based quantum wells (QW), is designed and studied.[2] A non-magnetic QWs (NMQW) are placed in the top microcavity, whereas the second microcavity, separated by over 2 μm, contains manganese-doped QWs (MQW). The doping enhances the Zeeman splitting of MQW-confined excitons due to their *s,p–d* exchange interaction with the Mn^{2+} ions spins.

The strong light-matter coupling with a spatially delocalized optical mode results in a hybridization of distant MQW and NMQW excitons, as evidenced in photoluminescence measurements. The hybridization enables a long-distance transfer of exciton-density between the MQW and NMQW.[2] Adjustment of the relative energy order of excitons in the MQW and NMQW using magnetic field enables a control of the direction of the transfer.[2,3]

Upon transition to the non-linear regime of the non-resonant excitation, the emission from the two lowest polariton branches features a non-linear increase of the intensity, narrowing and blueshift,[4] providing an evidence for Bose-Einstein condensation of exciton-polaritons.[5] The time-resolved measurements reveal that despite that the condensates at the two lowest branches share a common condensation threshold, they do not form simultaneously following the excitation pulse. Instead, they emerge and decay subsequently one after the other. The introduced open-dissipative Gross–Pitaevskii equation based model properly describes both the time-resolved and time-integrated emission intensities with a common set of parameters.[4] A presence of the condensate triggers an energy degenerate polariton parametric scattering from the upper to the lower branch. This indicates that a non-resonantly driven polariton condensate provides an alternative to the strictly resonant pumping employed in all the previous studies of energy degenerate polariton scattering.

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RECENT RESULTS ON EPITAXIAL QUANTUM DOTS AS EFFICIENT SINGLE PHOTON EMITTERS AT THE TELECOMMUNICATION WAVELENGTHS

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Keywords: quantum dots, single photon sources, fiber networks, quantum communication

Secure quantum communication requires on-demand bright sources of single photons with high single-photon emission purity and high extraction efficiency to provide high transmission rates. Of particular interest is to transfer the developments from proof-of-principle experiments at shorter wavelengths to telecom wavelengths for compatibility with the existing low-loss fiber networks, especially for long-haul communication. In that respect, semiconductor nanostructures have been proven as prospective and flexible solid-state platform, which is a mature nanotechnology allowing for scalability and integration. It already enabled realization of many fundamental quantum optics experiments revealing the potential of epitaxial quantum dots for quantum communication and quantum networks applications. Nowadays, much effort is devoted to improvement of the emitters' performance and realization of more practical devices. In this contribution there will be overviewed our recent results on engineering the electronic and optical properties of quantum emitters suitable for the 1.3-1.55 μm spectral range, made of two different material systems of InGaAs on GaAs and InAs on InP, and further on development of efficient quantum-dot-based single photon sources within such platforms. For various classes of quantum dot materials there will be discussed the currently achievable single photon emission purity and its temperature stability, always in conjunction with the underlying physics of excitonic complexes confined in such nanostructures or the related fundamental limitations on the side of technology and fabrication. In addition, there will be elaborated the issue of photonic confinement engineering and placing quantum dots in especially designed, spectrally broadband photonic structures of various geometries for controlling the emission rates, linear polarization degree as well as improving the extraction efficiency. Eventually, there will described a solution for constructing compact, robust, portable and cryogenic-free plug&play fiber-based sources operating at telecom wavelengths.

Abstracts
Posters

SENSING OF STRAIN WAVES WITH A SPIN-1 DEFECT SYSTEM

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Keywords: color centers, quantum sensing, strain waves

The interaction between optically active color centers and magnetic fields is well explored and usually studied by applying optically detected magnetic resonance (ODMR) techniques. However, the spin states of the atomistic defects also react to the local strain of the crystal lattice. Recently, this coupling was used to demonstrate coherent control by the dynamical strain field of a surface acoustic wave (SAW) [1].

In this contribution, we discuss the possibility to use the spin-strain coupling to determine the unknown frequency of a strain wave interfaced with a spin-1 color center. The idea is to simultaneously excite the spin system with a known microwave field, which is non-resonant to any transition in the system. We then tune the spin's transition energies by applying a static magnetic field in order to find a two-quantum resonance between the ground state and one of the spin-1 states. One of the quanta is a microwave photon, and the other is a phonon from the strain wave. When scanning the magnetic field, and therefore the transition energies, we find two characteristic resonance conditions, which correspond to the sum - and difference frequency of microwave and strain field. Through the so-determined magnetic fields, we can deduce the frequency of the applied strain wave.

With this scheme, it should in principle be possible to measure the local frequency of strain field, e.g., a SAW, with an atomistic accuracy. Furthermore, the method is all-optical and does not require any electronic readout.

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THERMOMETRY OF SINGLE GOLD NANOSPHERES

Barella Mariano[1,2], Ianina Violi[3], Julián Gargiulo[3,4], Luciana Martínez[1], Cecilia Zaza[1], Germán Chiarelli[2], Florian Goschin[4], Victoria Guglielmotti[3], Diego Pallarola[3], Sebastian Schlücker[5], Mauricio Pilo-Pais[2], Guillermo Acuna[2], Emiliano Cortes[4], Stefan Maier[4], Fernando Stefani[1,6]

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A major challenge nanotechnology faces today is the rapid, accurate and non-invasive probing of temperature at the nanoscale. Temperature is a key parameter that affects several physical and chemical processes, and biological dynamics. Efforts to characterize temperature at the nanoscale are not only of fundamental interest but also critical towards the advancement of several areas of nanotechnology including nanoelectronics, opto-plasmonics, and photothermal therapeutic medicine [1, 2]. For the latter, gold nanoparticles (NPs) have received great attention due to the efficient absorption of visible and infrared light which is later dissipated in form of heat to their surroundings. However, the current thermal nanoprobing techniques either require sophisticated equipment or disturb the system, e.g., cannot be used to probe temperature profiles of NPs inside cells. Here, we present two experimental techniques that allow the photothermal characterization of plasmonic NPs and estimate the temperature field of the NPs' surroundings. By mean of Anti-Stokes thermometry [3, 4] it's possible to retrieve the photothermal coefficient of single NPs while with DNA-PAINT thermometry it's possible to determine the temperature field around it [5].

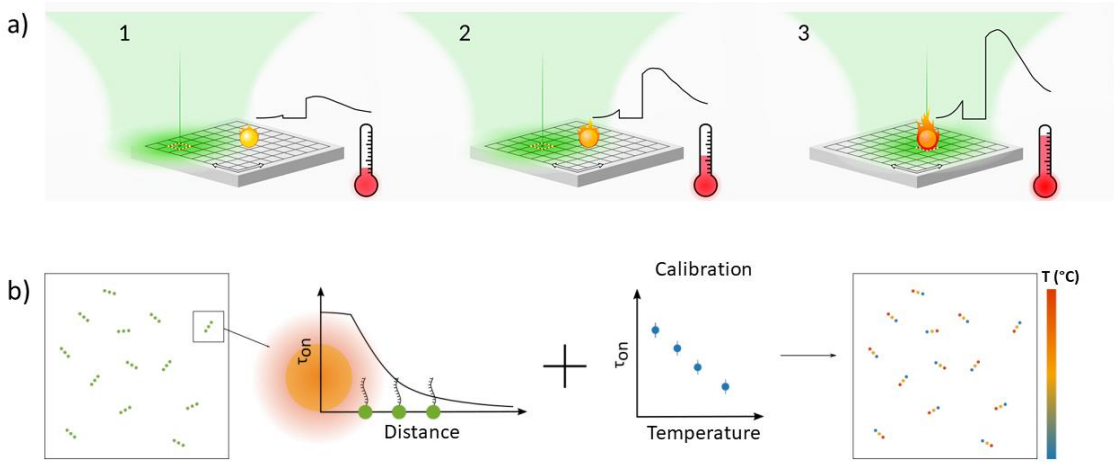

Figure 1: Thermometry techniques at the nanoscale. a) Hyperspectral Anti-Stokes Thermometry concept. b) DNA-PAINT Thermometry concept

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PRECISE MEASUREMENTS OF PROPAGATION LOSSES IN REUSABLE SILVER NANOWIRES USING QUANTUM DOTS

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Keywords: siler nanowire, surface plasmon polaritons, propagation losses, quantum dots

Surface Plasmon Polaritons (SPPs) are electromagnetic waves formed at the dielectric-metal boundary. Along elongated nanostructures, SPPs can propagate with a certain degree of evanescent. Unlike metallic structures like micrometre-wide stripes [1] or chains of metallic nanoparticles [2], silver nanowires (AgNWs) show a good trade-off between waveguide size and propagation length. Because of that, they can be utilized as a building block for optoelectronic circuits. In literature, there are few examples of measurement enabling the estimation of propagation losses in AgNWs. Most of them struggle with the same issue which is direct coverage of AgNW in fluorophore [3] or cutting and permanent decorating it with emitter [4]. Those approaches effectively exclude measured nanowires from other possible experiments.

In this work, we present an alternative and repetitive approach of estimating surface plasmon polariton propagation losses in AgNWs. This method combines the usage of movable droplets of QDs acting as emission probes and two objective fluorescence microscope allowing single excitation and single detection spots observation in real-time. Because of the physical nature of QDs and their wide optical properties we were able to construct a hybrid AgNW-QDs system where the propagation distance of surface plasmon polaritons in silver nanowires is maximized, and there is an interaction between SPPs with electronic states of QDs.

In the presented technique droplet of an emitter is spatially reorganized by physical movement to different positions at the same measured metallic nanostructure. When one end of AgNW was illuminated with a 635 nm laser beam it launched SPPs which propagated along metallic nanostructure. Because of spectral overlap between excited polariton and absorption properties of used QDs when SPPs reach placed droplet of emitter it results in a single emission spot collected by microscope objective. Thus, varying emission intensity of probe could be presented as a function of position on a single excited nanowire and allows for calculating propagation loss. Notably, the biggest advantage of this measurement method is that it does not damage measured nanostructure and allows to use them in future experiments.

The research was partially financed by the project Sonata BIS 2016/22/E/ST5/00531 by the National Science Centre (Poland).

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RESONANCE FLUORESCENCE WITH NOISY ENVIRONMENT

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Keywords: resonance fluorescence, telegraph noise, two-level system, autocorrelation function

Light-matter interaction enables us to study numerous properties of physical systems. In particular, resonance fluorescence (RF) is a very important tool, used e.g. in researching spin dynamics in semiconductor quantum dots [1-2] or interfacing and entangling spins with light [3-4]. Our work generalizes the description of RF from a periodically modulated two-level system [5-6] to random modulation in the low-excitation regime (coherent Rayleigh scattering). In our model, the transition energy of the system is subject to white noise (WN) or to an arbitrary Markovian process that shifts the transition energy between a number of discrete levels.

In order to obtain the RF spectrum we solve equation of motion for the density matrix of the system and find the two-time correlation function, the inverse Fourier transform of which yields the RF spectrum. We also take into account the finite resolution of the detector.

For the case of transition energy perturbed by WN, the RF spectrum has peaks localized at the laser frequency. As a particular case of a Markovian process we study the single-source telegraph noise (TN), where the transition frequency switches between two values. For the case of a symmetric TN and zero mean detuning value we show that the RF spectrum evolves from a triplet of broadened lines for slow switching to a sharp line for fast random switching of the transition frequency. Nonzero mean detuning shifts the non-resonant peaks. We also extend our considerations to the case of many identical noise sources.

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OPTIMIZATION OF A GRATING DESIGN ON INP/SI HYBRID WAVEGUIDE FOR UNIDIRECTIONAL AND ENHANCED QD EMISSION AT TELECOM C-BAND

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Keywords: quantum dots, photonic structures, waveguides, Bragg reflectors, single photon source

Development of the photonics-based quantum technologies would remarkably advance the processing and transfer of information [1]. Fabrication of Photonic Integrated Circuits (PIC) in which semiconductor-based components, like emitters, waveguides, detectors, built-in on a photonic-chip, allows such systems to be ultra-compact and providing better performance than those using independent optical elements. They also offer the possibility of integration with the silicon-based electronics to increase further their functionality.

We present both, the modelling and the experimental verification, for a system composed of InAs/InP quantum dots (QDs) [2] placed inside an InP waveguide (WG) hybridized with the silicon-on-insulator platform. The numerical simulations allowed designing a hybrid InP/Si WG structure in which transverse electric modes allow for low-loss light propagation - light field can be transferred efficiently to silicon WG via especially designed taper structure [3]. Next, we investigate experimentally, by using microphotoluminescence with orthogonal excitation-detection arrangement, the emission outcoupled from a cleaved sample edge from exciton and biexciton complexes confined in a single QD. Our device concept assumes incorporation of a Bragg grating along the WG for unidirectional QD emission and for enhancement of spontaneous emission (SE) rate. We have performed a series of finite difference time domain (FDTD) simulations focusing on two approaches. The first one is based on creating photonic lattice with periodic etching of nanoholes, whereas the second employs etched full stripes oriented perpendicularly to the main WG axis. The results show that for the radius of nanoholes in the range of 80 to 100 nm and period of the lattice between 200 to 240 nm we can achieve reflectivity over 90% at 1550 nm wavelength, whereas for 90 nm width of the InP stripes separated by 265 nm air gaps, and using ten grating periods, we achieve reflectivity exciding 85% at the telecom C-band. The enhancement of QD SE is estimated to exceed 6 in the best cases.

We acknowledge financial support from the Polish National Science Centre, Project No. 2020/39/D/ST5/02952.

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PLASMONIC BOOMERANG IN A SINGLE SILVER NANOWIRE: PROPAGATION LOSSES AND SUB-DIFFRACTIONAL NANOWIRE CHARACTERIZATION

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Keywords: silver nanowires, nanocrystals, up-conversion, surface plasmon polaritons, confocal microscopy

This work discusses a prototype hybrid nanostructure consisting of a femtoliter droplet of up-conversion nanocrystals (NCs) communicated with an optical system (microscope) via a single silver nanowire (NW). Due to efficient interaction between NCs and surface plasmon polaritons (SPPs), remote control of the up-conversion luminescence exclusively via polaritons is observed. Such a sample geometry allows, among the others, direct analysis of the SPPs propagation losses and estimation diameter of the NW.

The experiment was realized using a scanning confocal microscope optimized for the anti-Stokes emission and equipped with two (top and bottom) coaxial objectives. An infrared laser operating at 980 nm was focused by the top objective directly on the NCs droplet exciting nanocrystals. Consequently, excited NCs relax and launch SPPs propagating toward the opposite nanowire end. The intensities of the up-converted emission collected from the opposite (free) end of the nanowire by the bottom objective, and measured for different nanowire lengths, provide information about SPPs propagation losses. Notably, the length of the NW was gradually reduced in the experiment using a precise laser-cutting technique.

On the other hand, the up-conversion can be activated, and the luminescence can be detected using only one objective (bottom), focusing the laser/detector on the free NW end. In this configuration, excitation and detection processes are mediated by SPPs propagating there and back along a nanowire. Interestingly, in the so-called “boomerang” configuration, the complex character of interaction between a nanowire and a tightly focused laser beam can be studied. We show that the efficiency of this interaction depends on the NW geometry and thus allows sub-diffractional estimation of nanowire diameters. The presented approach shows great potential for advanced and cheap examination of metallic nanostructures for nanophotonic applications.

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CONSTRUCTION AND CHARACTERIZATION OF AN OPEN CAVITY FOR THE VISIBLE SPECTRAL RANGE

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Keywords: Tunable Open Cavity, Emitters, Bragg Reflectors.

Single photons have emerged as a topic of fundamental interest for the understanding of the nature of light, since a single-photon state exhibits some properties which cannot be explained by classical theories. In recent years, considerable efforts have been made to generate single-photon emitters that interface coherent spin with the motivation to send the information encoded in its quantum degree of freedom over long distances. Various sources have been developed, but all have different assets and drawbacks and they work only in specific conditions. Our motivation is to develop a practical, efficient, on-demand single-photon generation device that interfaces a coherent spin.

By incorporating single photon interfaces inside a cavity platform, the light-matter interaction can be significantly increased because of Purcell enhancement. In this work, we aim to build an open cavity platform that features state-of-the art figures of merit regarding collection of emission[1], while allowing us to efficiently inject ultrafast laser pulses, required for advanced time-resolved resonant spectroscopy studies. The flexible design concept of the cavity will allow us to spatially and spectrally tune the emitter into the cavity resonances in the visible range and will enable us to achieve low mode volumes and high Q-Factors simultaneously leading to high Purcell merits. We will also identify and eliminate de-coherence channels, develop high fidelity pumping schemes and finally validate their suitability for quantum technologies using tools of resonant nonlinear coherent spectroscopy.

For the early work, we started with a tunable cavity consisting of two flat DBR mirrors. The top mirror rests on a tunable mount while the bottom mirror is attached to a 3-stage piezo-actuator and carefully aligned, until Fabry-Perot modes were observed. The cavity was scanned over a tunable length via a piezo-positioner and the respective changes in the reflectivity were recorded. We were able to track down all the modes through the stopband and reach a finesse of 150. The experimental results were reproduced using transfer matrix method simulations, providing the information about the length of cavity.

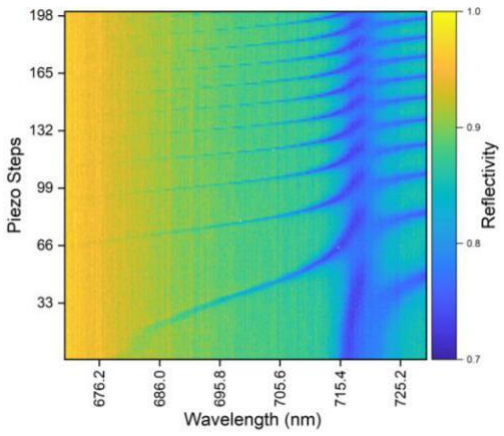

Figure 1. a) Reflectivity spectra map for varying cavity length

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THE INFLUENCE OF ZNS LAYER GROWTH TIME ON SENSITIVITY OF $CUINS_2$/ZNS NANOTHERMOMETER

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Keywords: nanothermometers, quantum dots, sensor, ternary QDs

In this study, we show colloidal $CuInS_2$/ZnS (CIS/ZnS) quantum dots (QDs) applied as a luminescent nanothermometer. We optimized the growth time of the ZnS layer for maximal sensitivity. Moreover, temperature changes affect not only the intensity of the photoluminescence (PL) but also shift the PL peak.
Our work is based on CIS QDs, due to their uniqe properties such as size dependent PL, broadband absorption and absence of photobleaching.
CIS QDs were synthesized, as reported in Ref. [1]. As-synthesized hydrophobic QDs exhibit chalcopyrite structure, pyramidal shape, and average size of 2.3 nm. To prevent QDs from degradation and to improve optical stability, we passivated/alloyed CIS with a ZnS layer, according to the method described in Ref. [2]. We examined 5 samples with ZnS synthesis times ranging from 0 to 180 min. Along with the increased ZnS synthesis time, we observed two effects: (i) enhancement of the quantum yield from 0.9% to 13%, and (ii) blue-shift of PL maximum from 673 to 606 nm. To employ CIS/ZnS as nanothermometers, it is necessary to transfer QDs to the aqueous phase. Therefore, CIS/ZnS were encapsulated by micelles, according to the method in Ref. [3]. In order to determine the optical and thermal stability of QDs encapsulated by micelles, we measured QDs PL intensity in dependence on time and temperature. To this end, in 3 heating-cooling cycles, in which temperature ranged from 20^{o}C to 54^{o}C, PL intensity decreased by less than 5-15%. Time-dependent measurements revealed that after 6 days, QDs PL intensity decreased by less than 10%. On the basis of temperature measurements, the thermometers were calibrated, by changing temperature every 2^{o}C, from 20^{o}C to 54^{o}C. At the maximum temperature, the PL intensity decreased up to 70%, and the PL maximum red-shifted up to 10 nm. Sensitivity of the thermometer reached 1.3%^{o}/C, which is comparable to other available systems. Finally, QDs were introduced into the HeLa cells, which was confirmed by images from a confocal microscope.

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OPTOELECTRONIC CONTROL OF ATOMIC BISTABILITY WITH GRAPHENE

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Keywords: quantum optics, atomic bistability, graphene, nanophotonics

The intrinsically strong light-matter interactions available in graphene—the atomically-thin carbon layer—give rise to a broadband 2.3% light absorption that can be actively modulated by electrostatic gating; recent experiments confirm that the optoelectronic tunability of graphene can enable fast dynamical control of strong near-field interactions, leading to over 1000-fold decay enhancement of erbium emitters [1]. Highly-doped graphene also supports long-lived and actively-tunable plasmons that can dramatically enhance near-field coupling, but are limit to THz and IR parts of the electromagnetic spectrum, well-below the operational frequencies of robust quantum light sources [2,3]. Here we explore the optical bistability emerging from the self-interaction of an atom mediated by an extended sheet of highly-doped graphene, which we demonstrate can be harnessed to actively drive the atom into different quantum states (see Ref. [4]). The strong electro-optical response of the graphene-atom hybrid system can be observed in the resonance fluorescence spectrum, which we predict to exhibit Mollow triplets and single Rayleigh peaks when electrically tuned through hysteresis loops. More specifically, we show that the Mollow triplets can be abruptly created or quenched in a manner reminiscent of a first-order phase transition in thermodynamics. We show that electro-optical bistability and hysteresis can manifest in the intensity, spectrum, and quantum statistics of the light emitted by the atom, which undergoes critical slowing down to steady-state. Our findings motivate further experimental studies of driven atomic light emitters, while offering a prescription for active and in situ manipulation of quantum optical states in integrated nanophotonic platforms.

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HYBRID SEMIMAGNETIC POLARITONS IN A STRONGLY COUPLED OPTICAL MICROCAVITY

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Keywords: polaritons, energy transfer, magnetic field, quantum wells

Energy transfer between excitons between semiconductor quantum wells (QW) in a single microcavity has been demonstrated so far for distances of the order of single nanometers or tens of nanometers. We expand this limit by an order of magnitude [1].
The sample studied is grown by MBE. It contains a wedge-like (Cd,Zn,Mg)Te microcavity embedded between (Cd,Zn,Mg)Te based distributed Bragg reflectors. Two sets of (Cd,Zn)Te QWs separated by 125 nm are placed in the microcavity's at the antinodes of the electric field. Each QW set has three 10 nm wells. One set of QWs is doped with 0.8% manganese, which allows tuning of the exciton energy by magnetic field.
Photoluminescence (PL) and reflectivity spectra as a function of the magnetic field at 1.8 K demonstrate anti-crossing of polariton states composed of Mn-doped and non-magnetic QWs excitons and the optical mode of the microcavity (see Fig. 1 for magneto-PL). This indicates a coupling of distant QWs mediated by the optical mode. Reference magneto-PL spectra when QW levels are detuned from the optical mode show no anti-crossing behavior. The magneto-PL results are described with the coupled oscillator model. Energy of interaction with the mode of QW excitons is determined as 8 meV. The analysis of emission intensities of magneto-PL proves polariton-mediated energy transfer between the Mn-doped and non-magnetic QWs, which direction can be altered by the magnetic field.

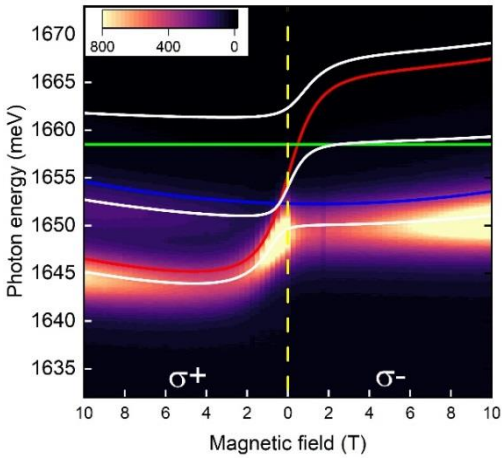

Figure 1: Photoluminescence spectra at 1.8 K as a function of the magnetic field. Solid lines represent calculated levels of: uncoupled excitons (red and blue line for the exciton in Mn-doped QWs and non-magnetic QWs, respectively), mode (green), as well as polaritons (white).

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CONDITIONS FOR SUPERLUMINAL LIGHT PROPAGATION IN A THREE-LEVEL MEDIUM

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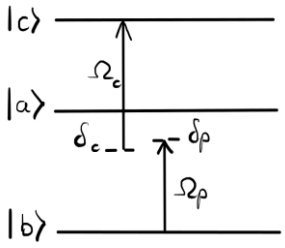
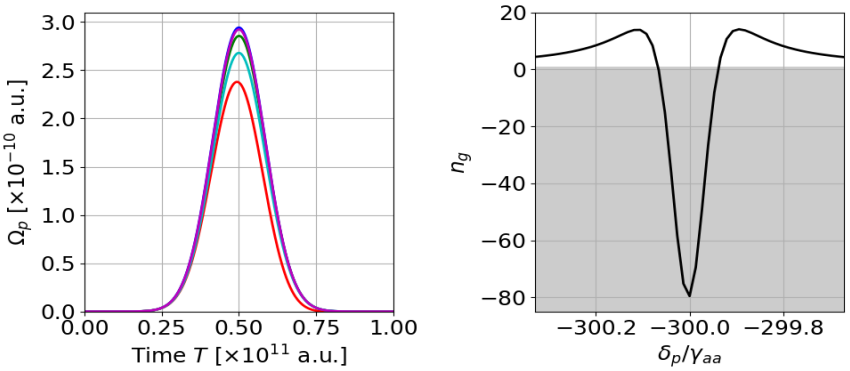
Keywords: superluminal propagation, three-level systems, group velocity

Investigation of propagation of pulses in optically dressed media is one of the most fundamental problems in optics. I will analyze a new superluminal propagation regime in ladder-type three-level systems near two-photon resonance where anomalous dispersion appears accompanied by small absorption. These conditions are necessary to achieve group velocities (v_g) greater than the speed of light in a vacuum ($v_g > c$) or negative ($v_g < 0$).



Our model is a one-dimensional medium consisting of three-level systems with the energy levels configuration as shown on the left. The lower levels are coupled by the probe field $\Omega_p(z,t)$, and the upper ones are driven by the control field $\Omega_c(z,t)$. Both fields are detuned by δ_p and δ_c, respectively. The two-photon resonance condition reads $\delta_p + \delta_c = 0$. I will show that to establish the best performance, we have to set δ_c to be hundreds of times greater than the width of the middle energy level (γ_{aa}), so we are far from the influence of the single-photon resonance.

We consider a Gaussian input pulse with the carrier frequency near two-photon resonance. The left figure below shows pulse shapes at the end of the sample for several detunings δ_p selected to be near two-photon resonance. We can evaluate the values of the group index (n_g) from these results, and since the relation between n_g and v_g reads $v_g = c / n_g$, superluminal conditions holds for $n_g < 1$. The figure on the right presents the group index as a function of detuning δ_p. Hence, we have evidence that superluminal propagation occurs as n_g values are well below 1 (grey region) for the $\delta_c = 300\gamma_{aa}$.



BROADBAND RESONANCE METASURFACE FOR SURFACE-ENHANCED COHERENT ANTI-STOKES RAMAN SPECTROSCOPY

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Keywords: Metasurface, Plasmonic, Molecular detection, Coherent anti-Stokes Raman Spectroscopy

The coherent anti-Stokes Raman spectroscopy (CARS) technique is recognized for its ability to detect and identify vibrational coherent processesat low molecular concentrations. Plasmonic metasurfaces in the metal-insulator-metal configuration provide high electric field enhancement and are among the most promising classes of plasmonic materials in the context of surface-enhanced (SE) CARS application. In this work, a metal-insulator-metal configuration metasurface with a unit cell based on two gold nanodisks supporting a broad resonance of near 200 THz width and CARS signal enhancement of 18 orders of magnitude is presented as a highly-efficient design for SECARS for various molecular species.

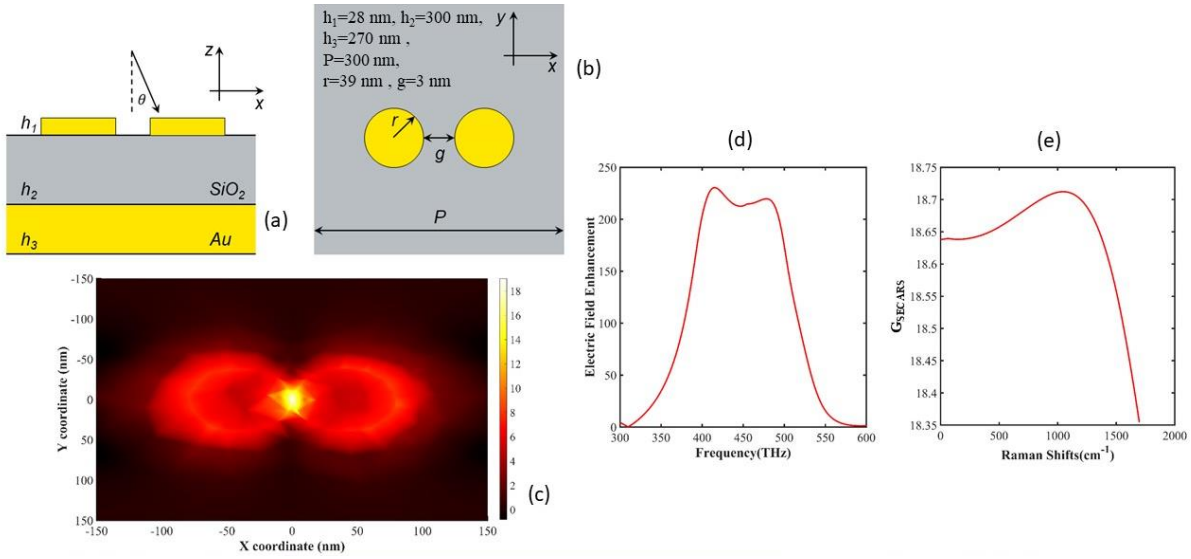

Fig. Unit cell of the proposed metasurface: side (a) and top (b) views, (c) the near field amplitude enhancement distribution on resonance $\log_{10}$[FE(r)], (d) electric field enhancement factor at strongest enhancement point (e) logarithmic local SECARS enhancement factor at strongest enhancement point.

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METAL ENHANCEMENT FLUORESCENCE OF PHOTOCHROMIC DTE MOLECULES

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Keywords: hybrid nanostructures, photochromism, silver nanowires, fluorescence

Fluorescent photochromic dithienylethene (DTE) molecules are promising materials for molecular devices as switches or high-density data storage due to high sensitivity, good thermal stability and high reversibility of photocyclization process. Combining DTE molecules with silver nanowires (AgNWs) open a possibility to control the optical properties of nearby molecules and improve efficiency of detection.
In this work we focused on DTE-py2 molecules which can have two photocyclization states open form (fluorescent) and close form (nonfluorescent). The change between two states is triggered respectively with UV light (deactivation of molecules) or with visible light (activation of molecules). The emission of fluorescence occurs in maximum at 540 nm. The photocyclization process is convertible. We studied the spectral characteristic of DTE molecules using wide-field fluorescence microscopy. We carried out the measurements to understand the process of photocyclization and plasmon interaction.
For created hybrid nanostructures we have studied the dependence on the illumination time with the wavelength of the activation light. The strong enhancement of emission and photoswitching of DTE molecules coupled to AgNWs was observed. The conducted experiments also indicate that molecules are sensitive and have different maximum intensity depends on time, illumination wavelength and number of cycles.

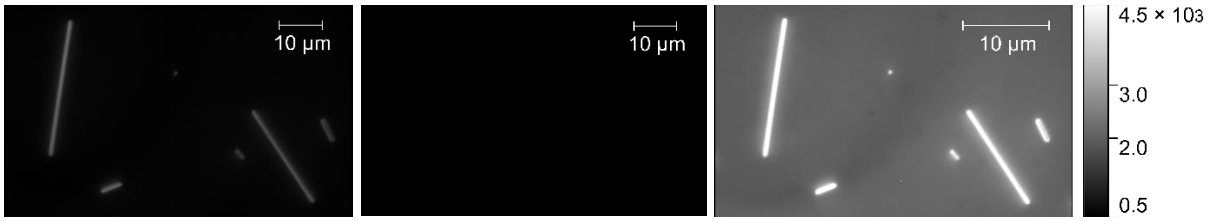

Figure 1. Fluorescence intensity maps, λ_{exc}= 405 nm, Before illumination (left), After deactivation with 360 nm for 1 s (middle), After activation with 630 nm, for 7 s (right).

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FOCUSED ION BEAM MILING AS A METHOD FOR PROCESSING EFFICINT SINGLE PHOTON EMITTERS IN THE TELECOMMUNICATION RANGE

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Keywords: single photon emitter, Xe-PFIB, semiconductor quantum dots, photonic structure

Current developments in the field of quantum technologies cause increasing demands on fabricating efficient sources of single photons, or more complex photonic states. Among several possible solutions, semiconductor quantum dots are definitely the most promising but still requiring efforts to fulfil all the practical demands. Here, we focused on development of a technological approach to process photonic structures with quantum dots as the active elements of single photon sources. We used quantum dots of two different material systems, InGaAs/GaAs and InAs/InP, offering the emission in the application-relevant range of the 2nd and 3rd telecommunication windows in view of efficient, truly nonclassical sources for quantum communication schemes in the fiber networks. We had fabricated numerous pillar-like photonic structures in function of the sample and the technological process parameters, which were then characterized by low-temperature micro-photoluminescence (μ-PL) measurements in order to optimize the emission intensity and aiming at the enhancement of the emission extraction efficiency. The developed fabrication method relies on a focused ion beam technique Xe-PFIB (xenon plasma focused ion beam) which takes advantage of high milling rate and high quality of etching of small structures of even micrometer sizes on a semiconductor material. We have tested various thicknesses of the capping layers but also protection of the surface by additional layer of carbon by sputtered by GIS (gas injection system) technique for various thicknesses in the range of 100 – 500 nm. Then we prepared a set of pillars with diameters from 2 μm to 15 μm and height of around 2 μm by Xe-PFIB milling with beam of current range from 1 nA to 15 nA and energy of 30 keV with the ion doses changed from 10^{-10} to 10^{-8} pC/μm^2. For the best cases we obtained bright emission from single quantum dots in the range of 1300-1550 nm. Our results indicate on the potential of this technological approach employing Xe-PFIB as suitable for creating photonic structures of good crystalline quality exhibiting efficient emission from embedded quantum dots in the telecommunication spectral range.

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ENERGY TRANSFER IN $CUINS_2$ COLLOIDAL QUANTUM DOT FILMS THROUGH COMPARATIVE PHOTOLUMINESCENCE LIFETIME INVESTIGATIONS

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Keywords: Colloidal Quantum Dots, Energy Transfer, Time Resolved Photoluminescence

Energy Transfer (ET) has been a key research area in Colloidal Quantum Dots (QDs) for its role in applications such as solar cells. The size dependence of optical properties is exploited to control the emission of QDs in such investigations. Tertiary QD materials like CuInS2 (CIS) provide an environmentally friendly alternative to Pb-/Cd-based QDs and have not been explored as much. CIS QDs exhibit significant Stokes shifts and their stoichiometry can be easily altered. This makes the investigation into their ET mechanism appealing. Here, signatures of ET in a CIS QD-film are demonstrated through steady-state photoluminescence (PL) and time-resolved PL (trPL).

In solution phase, the QD PL spectrum exhibits a broad full width at half maximum (FWHM) of about 100 nm and peaks at 652 nm. The QD-size distribution in the ensemble is highly inhomogeneous. The PL peak of the same ensemble when drop cast as a film has similar FWHM but is red-shifted by about 150 meV to 705 nm. This red-shift is a signature of non-radiative ET from smaller donor QDs to larger acceptor QDs within the ensemble. The spectrally integrated PL lifetime is on the order of 300 ns in solution phase, and it is shorter - on the order of 200 ns for the film. The film PL spectra decay faster via recombination channels such as ET in addition to emissive recombination. Spectrally resolved trPL shows shorter lifetimes at the red end of the spectra than at the blue end in the case of the solution as well as the film. The lifetimes at the red and blue ends are 1.3 and 0.6 times those at the PL peak energy, respectively, in solution. The spectral dependence of the solution PL lifetime is intrinsic. In the film, these lifetimes are 1.6 and 0.32 times those at the film PL peak energy, respectively. An additional spectral dependence of lifetimes in the films has been previously credited to non-radiative ET within inhomogeneous QD-ensembles [1]. Accordingly, this additional spectral dependence can be attributed to ET between donors and acceptors in the CIS QD-film. Similar ET signatures are observed in 5 other CIS QD ensembles composed of different QD sizes and Cu-to-In precursor ratios. Results for all the samples support the conclusion that ET occurs in CIS QD films. Low temperature studies should be performed to achieve more detailed insight into the photophysics of ET in CIS QD films.

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FLUORESCENCE ENHANCEMENT WITH GOLD NANOROD DIMER DNA ORIGAMI ANTENNA

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For last few years, plasmonic sensors based on gold and silver nanoparticles have been widely used in various spectral techniques, such as: CD, fluorescence and Raman spectroscopies, and colorimetric detection[1]. Main features of plasmonic nanoparticles that render them remarkably attractive sensing materials are their optical properties, namely excitation of surface plasmon resonance. Surface plasmon resonance occurs during the interaction of light and plasmonic nanoparticles and causes a significant enhancement of the electromagnetic field near the surface of irradiated nanoparticle[2]. Since the fluorescence intensity depends on the electric field strength, plasmonic nanoparticles have been widely used to enhance the signal. Importantly, the electric field is not evenly distributed around the nanoparticles. The strongest electromagnetic field enhancement occurs at the sharp edges of nanoparticles or in the gaps between them[2,3]. Therefore, for high signal amplification it is crucial to find reliable and high-precision method for fabricating plasmonic nanosensors. Because of the addressability, specificity, and nanometer precision, DNA origami becomes a natural candidate for synthesizing versatile antenna structures, especially when employing anisotropic nanoparticles. Nevertheless, still high majority of DNA origami-based sensors used in fluorescence utilize spherical gold or silver nanoparticles[4].

Here we present the synthesis of DNA origami dimer antenna based on Au nanorods enabling fluorescence enhancement of a conventional NIR dyes up to 1600 folds, that is, to the best of our knowledge, the highest values reached in a self-assembled NA with an ordinary QY dye precisely positioned in the hotspot (Figure 1). This was possible to achieve by using NRs of relatively big size (~67x20 nm) which created a higher electric field in the plasmonic hotspot, and choosing dyes with matching spectral overlap with the plasmonic near-field. Advantage of using NRs with an anisotropic shape over anisotropic NPs for fluorescence enhancement applications was demonstrated by the direct comparison of dimer AuNRs antenna with DNA origami nanonatenna containing dimer of spherical NPs of the similar volume (40 nm in diameter).Theoretical simulations performed in this study give more insights into the effects taking place in the experimental samples and indicate the importance of definition of the hotspot in comparison to the importance of the alignment of the NRs.

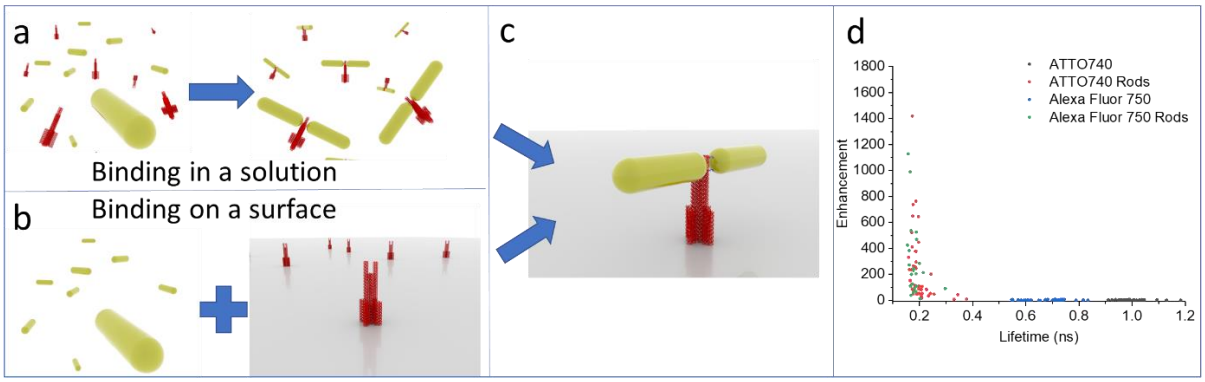

Figure 2. Schematic representation of the synthesis of AuNRs antennas for fluorescence measurements (c) by (a) solution and (b) surface binding method. (d) Fluorescence enhancement distribution of ATTO 740 and Alexa Fluor 750 with AuNRs antennas.

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EXPERIMENTAL PROPOSAL TO PROBE THE EXTENDED PAULI PRINCIPLE

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Keywords: extended Pauli principle, crystal-phase quantum dots, 3, 4

Fundamental principles in Physics — such as the well-known Pauli exclusion principle — lie at the core of the entire discipline with far-reaching implications: from the electron shell structure of atoms to the stability of matter itself, including neutron stars. The extended Pauli principle is not an exception — it too provides a fundamental constraint on the natural occupation numbers of any pure fermionic state. It is, for instance, an important benchmark for the simulation of fermionic quantum matter. So far, however, it has never been accessed experimentally.

Here, we propose an experiment [1] in a multi-quantum-dot system capable of producing the highly entangled fermionic states necessary to reach the regime, where the inequalities of the extended Pauli principle become relevant. Our proposal combines recent theoretical results revealing an onion-like structure of barriers limiting the allowed entanglement and experimental advances that enable us to transcend these barriers by carefully controlling the quantum states. The multi-quantum-dot system and coherent fermionic operations in our proposal are recently developed by us in [2].

We simulate our state preparation procedures in realistic structures, including all main decoherence sources, and find fidelities above 97%. All highly entangled states comply with the extended Pauli constraints well within error margins. The extended Pauli constraints are present in every fermionic system. Our proposal therefore opens up a standardized pathway for experimental exploration of the extended Pauli principle.

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SURFACE ENHANCED RAMAN SCATTERING FROM A MOLECULAR IMPURITY MODEL

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Keywords: molecular optomechanics, SERS, adiabatic elimination, strong-coupling,

Surface-enhanced Raman scattering (SERS) allows the fingerprinting of single molecules via their vibrational degrees of freedom. Inspired by its analogy with the field of cavity optomechanics [1], a first model was proposed considering the optomechanical dynamics between plasmonic electric fields and molecular vibrations [2]. This molecular optomechanical approach allowed both, to describe new effects in the field of SERS arising from the dynamical backaction and to offer new possibilities in cavity optomechanics due to the resulting large coupling strengths involved – orders of magnitude larger than in previous configurations. Despite recent experimental works evidencing such optomechanical nature of SERS, large spectral discrepancies have arisen with current theoretical predictions [3] that call for new mechanisms for its understanding. Inspired by the microscopic molecular Hamiltonian [4], in this work we propose an optomechanical SERS model that considers the internal mechanisms of the molecule. In this model, the electronic transitions involved in the Raman processes are treated as a set of two-level systems that mediate the interaction between plasmons and molecular vibrations via electron-vibron couplings [4]. Since such electronic levels typically lie in the ultra-violet range, we can adiabatically eliminate them and recover the original optomechanical Hamiltonian [2]. Beyond such adiabatic approximation, we further consider a near-resonant transition coexisting with the off-resonant ones, showing interesting cooperative behaviours such as enhancements of anti-Stokes lines and modifications of spectral widths. For ultrastrong interaction scenarios with electron-vibron couplings close to the mechanical frequency, we consider the resulting phonon-dressed states in the master equation that show incoherent contributions to the anti-Stokes peaks, decisive for understanding the spectrum. Our model shows the importance of treating the molecular degrees of freedom with equal footing in SERS and offers new perspectives of the mechanisms involved in molecular optomechanics.

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Interaction of a single photon with a single quantum system in ambient conditions

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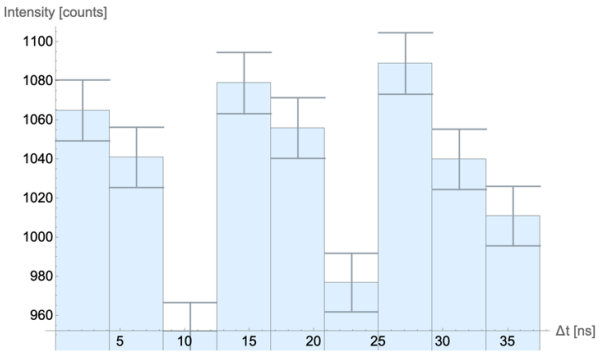

Figure 2: Fluorescence decay histogram for a single photon interacting with a single NV center.

In our work a simple, room temperature, cavity- and vacuum-free interface for photon-matter interaction is implemented. Here we report an ambient-conditions experiment in which a heralded single photon is absorbed by a single atom-like system, which is an NV center in diamond.

The experimental setup is shown in Fig. 1. The NV center is pumped with a 532 nm quantum light and subsequently the fluorescence signal, registered on a single photon detector, is compared with the idler photon detection signal and fluorescence decay is collected (Fig. 2). This scheme shows a simple platform for investigating light-matter interaction with a good control on both, the number of atom-like systems and the number of photons.

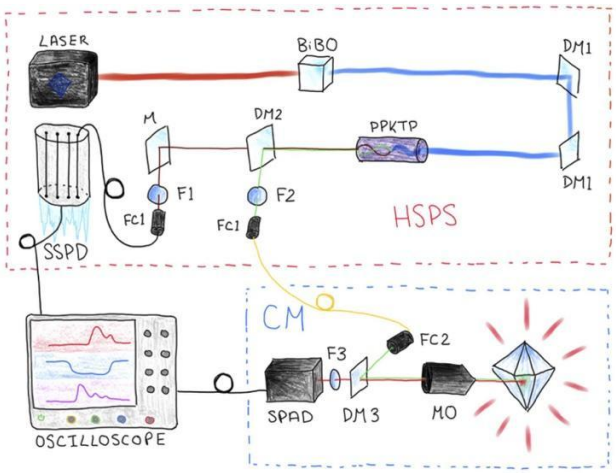

Figure 1: Experimental setup

More control over the optical illumination can provide additional information about the interrogated sample. This can be envisioned when considering an ensemble of absorbers located at distances below the diffraction limit. After laser excitation the number of emitted photons can indirectly determine the number of absorbers. However, typical single photon detectors are not photon-number-resolved, which makes this task more difficult. Illumination with a photon number state, which is well defined, could help to overcome some of these limitations.

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TUNING THE OPTICAL RESPONSE OF MOLECULAR CHAINS WITH ADATOMS

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Keywords: tight-binding model, adatom, atomic chains, nanoplasmons

The tight-binding based Su-Schrieffer-Heeger model (SSH model) has proven to accurately describe a variety of electronic and the resulting optical properties of linear organic molecules like polyenes and polyacetylenes, for instance [1]. Even though abstract to some extent, one can also artificially build chains of atom-like systems whose dynamics are goverened by similar evolution equations by fabricating quantum dots on a silicon wafer substrate [2].

In our recent papers [3,4], we study the effect of introducing an adsorbed atom (adatom) that is both electronically and optically coupled to one atom in different SSH chains and graphene nanoantennas. In [3], we specifically distinguish the metallic linear chain, the insulating dimerized chain, and the topological insulator. To that end, we apply the extended Hückel molecular orbital model [5]. Our goal is to identify the crucial parameters of the hybrid system that determine its electronic properties, and that can be altered to tailor its optical response.

In our study, we additionally investigate in detail how the localization and hybridization of the single-particle electronic states, both in the SSH chains and the adatom, are affected as coupling strength increases. Also, we perform a parity analysis of the involved states and identify which single-particle transitions are active in the optical response and how exactly they couple bilaterally. In that way, we can identify the states that we should modify to achieve desired changes in the optical response. In [4], we put emphasis on the interplay between quantum-optical phenomena like spontaneous emission and Rabi oscillations in the adatom and the electronic structure of a graphene nanoantenna. We conclude that adatoms can be readily used to substantially modify the optical properties of both linear organic molecules and graphene nanoantennas.

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ON-DEMAND SINGLE PHOTON EMISSION FROM TMD/M-LED HYBRID DEVICE

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Keywords: TMDs, single photon emission, electroluminescence, LED

Transition metal dichalcogenides are a particularly good host for naturally created or strain-engineered single-photon emission centers [1, 2]. Logically, this also provokes pertinent efforts to exploit the 2D semiconductors in designing and fabricating new optoelectronic devices of possible practical use. By extent, the operation of such devices requires direct electrical control. Controlled doping of TMD materials, though essential for the operation of conventional electroluminescent p-n diodes, remains a largely unresolved challenge [3]. Alternative methods are thus being developed that mostly rely on tunnelling mechanisms of carrier injection into the active areas of semiconductor layers. However, the complexity of manufacturing and the performance of such structures still remain not fully satisfying, especially in the context of potential industrial use.

We propose a new concept of a compact pseudo-electroluminescent device by integrating the exfoliated WSe_2 monolayer on top of the micro-(In,Ga)N-LEDs (μ-LEDs). We utilize the nanostructured surface of the μ-LEDs to deterministically create single-photon emitting centers. We show that μ-LEDs are a suitable excitation source for single-photon emitters based on atomically thin TMDs. The light emission from μ-LEDs is robust at liquid-helium temperatures which are preferential conditions for single-photon generation from TMD monolayers. Very low activation currents of the μ-LEDs facilitate broad-range tuning of the excitation intensity. We show that the ultrafast electric current modulation can be applied to the μ-LEDs, resulting in single nanosecond light pulses. With several times longer characteristic decay times of the WSe_2 single-photon emitters, our pseudo-electroluminescence hybrid device is capable of true on-demand single photon emission.

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THE MAGNETIC DIAGRAM OF MOIRÉ QUANTUM DOTS ARRAYS

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Keywords: moiré, twisted TMD bilayers, magnetism, many-body systems

Moiré patterns are formed in transition metal dichalcogenides (TMD) bilayers due to lattice mismatch of overlaid 2D lattices. Such structures have potential to be wide-tuned quantum simulators and can allow realizing exotic states of matter in the laboratory [1] like Wigner crystal states, Mott insulator, or fractional Chern insulator [2]. The effective moiré potential can form a triangular or honeycomb lattice that can be controlled by a displacement field, type of materials, and additional twist angle [3]. The many-body physics in such systems can be modelled by generalized Hubbard model with long-range interactions [4].

In our work we have focused on finite fragments of TMD twisted heterobilayer - moiré quantum dots arrays. We start from reciprocal space model for WSe2/MoSe2 [3] and using projection technique for the topmost valence band we calculate corresponding Wannier function, and from them real space Coulomb interaction parameters on a triangular lattice. We analyze electronic and magnetic properties of moir é quantum dots arrays using exact diagonalization (ED). The twist angle-filling factor magnetic phase diagrams is obtained and a range of twist angles where the system is ferromagnetic around filling factor is observed. We discuss the origin of the ferromagnetic states and potential appearance of Nagaoka ferromagnetism in these systems by comparison of results with on-site Hubbard model.

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ANTIBONDING GROUND STATES IN CRYSTAL PHASE QUANTUM DOTS

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Keywords: quantum dots, zincblende, wurtzite, excitons

The antibonding ground state is an unusual and rare feature predicted [1, 2], and observed [3, 4] in double quantum dots, and more recently in photonic crystal molecules and in adatom molecules in bulk Dirac semimetals. The antibonding ground hole state in these artificial molecules differs from the natural ordering in real diatomic molecules. It may be argued that the ground state wave-function must be non-degenerate [5], never assume the zero value, and therefore cannot be of an antibonding character. However, in semiconductor quantum dot molecules the antibonding ground state stems from the tunneling term that can change the sign due to spin-orbit interaction. More specifically, this term arises from the small contribution of the light-hole component of the hole wave function[3]. In this work, we predict – using an atomistic tight-binding approach – that the antibonding ground hole state may in fact emerge in a single crystal phase quantum dot [6] of type II confinement, which mimics molecular-like behavior [7]. To this aim, we perform a theoretical study of crystal phase quantum dots formed by an InP zincblende (ZB) section sandwiched between two InP wurtzite (WZ) sections, altogether forming a nanowire [6]. We show that coupling between two sections of wurtzite leads to the formation of quasi-molecular states with, for large dot heights and diameters, may be of antibonding character. Interestingly, even small strains due to wurtzite-zincblende lattice mismatch - which is often neglected - can strongly affect properties of lowest hole states, resulting in unusual double-peak features in the excitonic optical spectra.

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LOCATION QUBITS IN A MULTI-QUANTUM-DOT SYSTEM

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Keywords: Crystal-phase quantum dots, location qubits, qubit manipulation, quantum internet

A physical platform for nodes of the envisioned quantum internet has been long-sought. Here we propose such a platform, along with a conceptually simple and experimentally uncomplicated quantum information processing scheme, realized in a system of multiple crystal-phase quantum dots. In our work [1], we introduce novel location qubits, describe a method to construct a universal set of all-optical quantum gates, and simulate their performance in realistic multi-quantum-dot structures, including the main decoherence sources. Our results from numerical studies show that location qubits are robust against the main decoherence mechanisms, and realistic single-qubit gate fidelities exceed 99.9%. In our scheme, we take advantage of type-II band alignment in crystal-phase quantum dots and exploit spatially indirect excitons to construct all-optical initialization and coherent manipulation (single-qubit and two-qubit gates) of location qubits. Our scheme paves a clear way towards constructing multi-qubit solid-state quantum systems with a built-in photonic interface, such as a multi-qubit quantum register — a key building block of the forthcoming quantum internet.

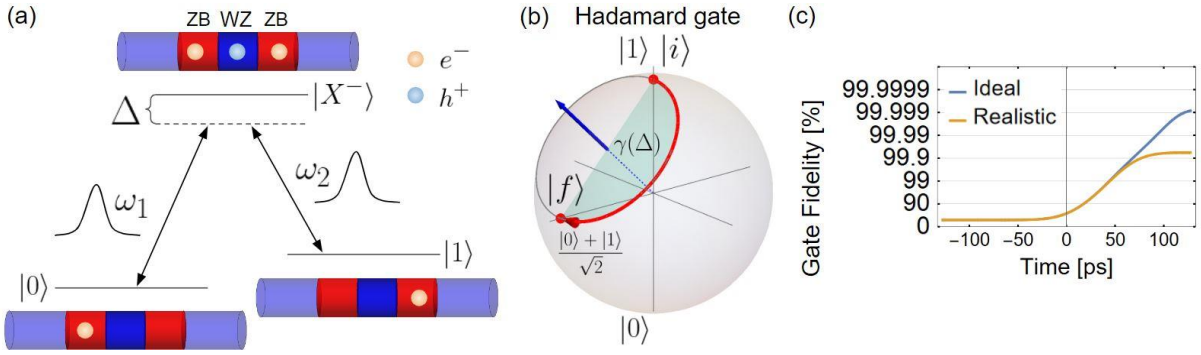

Fig. 1: *(a) The all-optical manipulation scheme of a location qubit. A section of a semiconductor nanowire (GaAs or InP) in the Wurtzite (WZ, blue) phase with a pair of crystal-phase quantum dots in the zincblende phase (ZB, red). On such a structure we define a location qubit. Two laser pulses ω_1 and ω_2 of different wavelengths drive the left and right optical transitions respectively. They are both far detuned from the common excited state by Δ. (b) Equivalent representation of the coherent manipulation scheme on a Bloch sphere. Hadamard gate is shown as an example. A state rotates with respect to an axis (blue) defined by the ratio and phase between the driving pulses. The rotation angle γ is a function of the detuning Δ. (c) The simulated Hadamard gate fidelity above 99.9% for a realistic structure.*

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Optimization of the polarization state of an ensemble of quantum dots for chiral emission

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[*]Keywords: nanophotonic waveguide, quantum dot, chiral light-matter interactions

Controlling the interaction of light and matter is the basis for many applications ranging from light technology to quantum information processing. Many of these applications are based on nanophotonic structures. As it turns out, the confinement of light in such nanostructures imposes an inherent link between its local polarization and its propagation direction, also known as spin-momentum locking of light [1]. Remarkably, this leads to altering the elementary processes of light-matter interaction. The emission and absorption of light becomes chiral, i.e., propagation direction-dependent. As a nanostructure the photonic crystal waveguide is considered promising due to a near-unity β factor that determines the fraction of emitted light coupled into the waveguide guided mode [2].

Most research has focused on the directional emission from a single quantum dot with circularly polarized transitions. Unidirectional (chiral) emission of light from a circular dipole emitter into a waveguide is only possible at position of perfect circular polarization (C points). When elliptical dipoles are used instead of circular ones, the size of the region that is appropriate for chiral emission typically increases (by a factor of about 30 [3]). Moreover, a successful experimental realization requires precise deposition of a quantum dot to the area where C points occur.

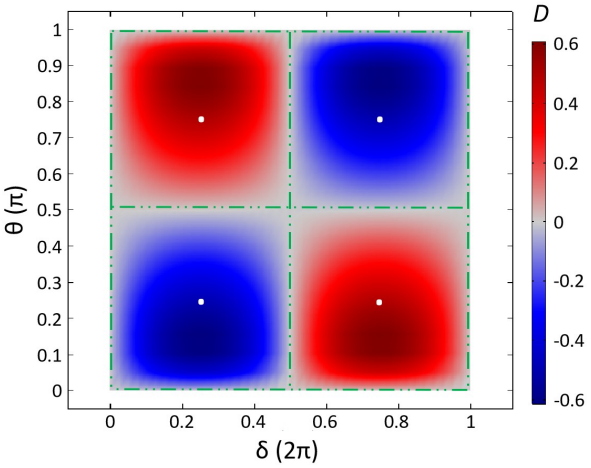

Figure 1: *Net directionality D of QD ensembles as a function of polarization state of dipole moment determined by two angles. The green dash lines mark the cases of linear polarization and four white dots mark circular polarization.*

In this presentation, we consider the photonic crystal waveguide coupled to an ensemble of quantum dots and find the polarization state of such an ensemble that optimizes the net unidirectionality. It turns out that maximum unidirectionality is reached for elliptical polarization states (Fig. 1). At this figure two angles describe the polarization state of a dipole transition moment. Six green dash lines mark the cases of linear polarization and four white dots mark circular polarization state. For other pairs of angles the polarization is elliptical.

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BENCHMARKING SPATIAL METROLOGY: PITFALLS IN STM DOPANTS MODELLING

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Keywords: dopant-based devices, quantum computing,
scanning tunnelling microscopy, tight-binding

Design, modelling and analysis of atom-based nanoscale devices relies on the ability to determine the precise locations of phosphorous dopants in such systems and predict the properties of any given dopant configuration. Knowledge of the number and precise positions of the dopants in a fabricated device is needed to validate, model, and understand the connection between device performance and dopant arrangement. Recently, several papers showed that a metrology of scanning tunnelling microscopy (STM) imaging combined with atomistic tight-binding simulations could be used to determine coordinates of a dopant buried close to a Si surface.

Using a multi-million atom tight binding approach combined with the use of Slater-type orbitals, we perform a thorough analysis of different dopant configurations. By evaluating different aspects of modelling, such as the choice of the tight-binding model, surface reconstruction and passivation, dangling bond treatment and STM tip composition, we identify the effects which play a crucial role in the simulation of STM images and have to be precisely modelled for STM imaging of buried dopants and multi-dopant clusters to provide reliable position information. In contrast to previous work, we demonstrate that a metrology combining STM imaging with tight-binding simulations may lead to pronounced uncertainty due to tip orbital model, effects of dangling bonds and choice of local atomic basis for the tight-binding representation.

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Simulation of optical fields in photonic honeycomb structures

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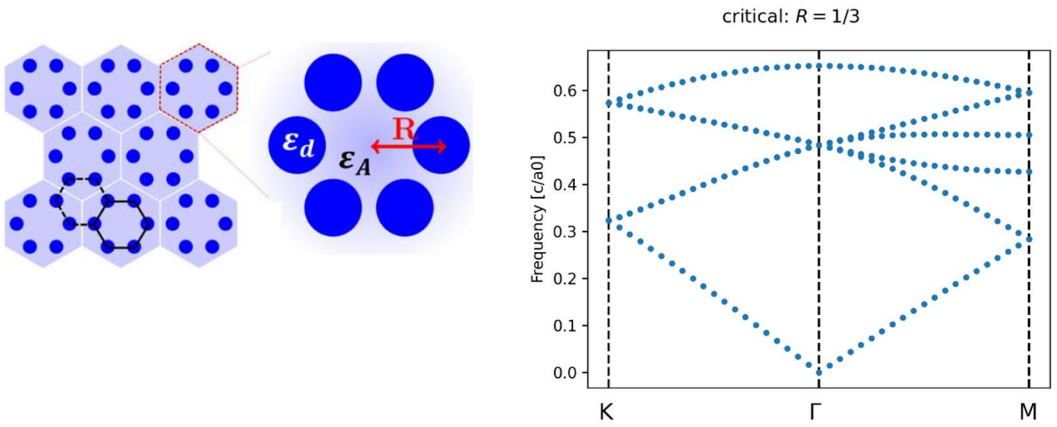
Keywords: photonic crystal, honeycomb lattice, photonic Dirac points

Photonic structures, consisting of repetitive patterns of dielectric materials, are used to manipulate the properties of electromagnetic fields. If one operates on the nanoscale, the effects manifest in the optical regime, giving rise to the field of nanophotonics. Different nanopatterns are used to tailor the band structure of the electromagnetic modes creating for example topological nanophotonic structures. One prime example are honeycomb structures made of dielectric nanospheres, which can exhibit a photonic band structure with photonic Dirac points.

We simulate TiO_2-Nanospheres in a hexagonal pattern with the distance of the spheres from the center as parameter R. At a critical value R_{crit} the structure reaches a higher symmetry. This can be seen in the photonic band structure as the emergence of a Dirac Point, where formerly independent bands touch. Introducing a perturbation to R_{crit} opens a band gap. Here, we study the band structure of honeycomb lattices using simulations with the MPB solver (MIT photonic bands). We show that depending on R topological structures can be found. This allows one to combine structures with different R generating topological waveguides.

Our simulations help in designing and fabricating the honeycomb structures of TiO_2-spheres in experiment [1] with the goal of fabricating nanophotonic topological structures.



Band structure of the honeycomb lattice

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ELONGATED SILVER NANOPARTICLES AS SENSING PLATFORM FOR DETECTING PHOTOACTIVE PROTEINS

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Keywords: silver nanowires, single protein, microfluidic channels, wide-field microscopy

In this work, we describe a method of detecting photoactive proteins using silver nanowires (AgNWs) as a sensing platform. On the other hand, we develop a method of aligning silver nanowires using microfluidic channels. The advantages of using AgNWs are: simple synthesis, the possibility to observe them by optical microscope, plasmonic resonance, and surface modification. We apply conjugation of our photoactive proteins to the AgNWs either via streptavidin-biotin interaction. Advanced experiments was carried on using a fluorescence wide-field microscope enables on register a of real-time fluorescence imaging upon deposition of a protein-containing droplet on silver nanowires. The figure shows a fluorescence image of protein attachment to AgNWs with a corresponding transmission picture with AgNWs positions. We observed that the emission intensity of the protein is strongly enhanced through plasmonic interactions.

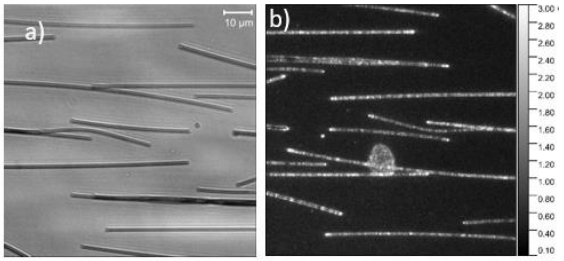

Figure 3 Transmission image of aligned AgNWs with a corresponding image showing fluorescence of proteins attached to aligned silver nanowires.

The results of comprehensively designed and performed experiments imply that metallic silver nanowires offer considerable potential for sensing photoactive bio(molecules) in real-time. This solution can be implemented in biosensing other analytes as well.

This work was supported by grants from the National Science Centre (Poland) within the OPUS grants 2016/21/B/ST3/02276, 2017/27/B/ST3/02457, and 2017/26/E/ST3/00209, and project nr POWR.03.05.00-00-Z302/17 “Universitas Copernicana Thoruniensis In Futuro” (2018-2022).

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SIMULATION TOOLBOX FOR ELECTROOPTICAL PROPERTIES OF 2D MATERIAL NANOFLAKES

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Keywords: nanomaterials, graphene, python, tight-binding model

GRANAD is a non-commercial, object-oriented code written in Python. It serves as a tool to model the electronic and optical properties of graphene nanoflakes with adatoms [1,2], based on the tight-binding model combined with the master equation approach similar to the one introduced in [3]. I have generalized and extended it to include models of two other two-dimensional materials: hexagonal boron nitride (hBN)[4] and molybdenum disulfide (MoS_2)[5], both of which are characterized by a hexagonal spatial structure, correspondent to that of graphene. Especially complicated proved to be the case of molybdenum disulfide, consisting of 3 layers of atoms, unlike the other two materials, which required a set of non-trivial adjustments. We will discuss these in further detail.

In this context, we will also supply an analysis of the fundamental analytical issues and concepts pertaining to the program and the computations it conducts alongside the integral characteristics of the selected chemical compounds. The subsequent descriptions will aim to justify the selection of these particular substances highlighting the similarities and differences between them.

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TWO-PHOTON DRESSING OF QUANTUM EMITTERS FOR CAVITY-ASSISTED GENERATION OF STEADY-STATE ENTANGLEMENT

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Keywords: entanglement generation, dipole-dipole coupling, nanostructures, cavity engineering

In this work we show how driving the two-photon resonance of a system of interacting quantum emitters can be exploited for the generation of cavity-assisted steady state entanglement. The fact that two interacting emitters can be coherently driven via two-photon processes has been exploited, e.g., to estimate interaction strengths and inter-molecular distances at the nanometer scale [1]. It has also been shown that, under a strong two-photon drive, the emitters can be dressed with photon pairs from the drive, developing a rich family of energy levels that translate into a complex structure in the spectrum of resonance fluorescence [2].

By coupling the dressed system to a cavity in the bad cavity limit, new processes among the two-photon dressed energy levels can be engineered. We show that, by placing particular dressed-state transitions in resonance with the cavity, these novel decay processes can stabilize the system into a highly entangled state. Since the energy of the dressed states can be tuned through the Rabi frequency of the drive, the system can be optically tuned in and out of these resonances. We also show that the stabilization of entanglement translates into particular features in the quantum optical properties of the light emitted by the system at frequencies that are well detuned from the drive, allowing to isolate the optical signatures of entanglement by simple spectral filtering.

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POWER-DEPENDENT DYNAMICS OF THE UP-CONVERSION PROCESS IN ER^{3+}/YB^{3+}-DOPED SINGLE NANOCRYSTALS

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Keywords: anti-Stokes emission, rate equations, confocal microscopy, nanoparticles

This work analyzes the kinetics of the up-conversion process occurring in the single $NaYF_4$ nanocrystals (NCs) doped with Er^{3+} and Yb^{3+} ions under varying excitation laser power. We used a confocal microscope to collect the time-dependent luminescence of erbium ions ($^4F_{9/2}\rightarrow{}^4I_{15/2}$), which can be activated by a laser operating at 980 nm. A strong correlation between the shape of the decay profile and the power of the excitation laser was noticed. For low laser power (c.a. 100 μW), a relatively slow rising part preceding a proper luminescence decay profile is observed. However, for high laser power (c.a. 1 mW), no rising part is observed, and transient intensity peaks immediately. Additionally, we noticed a decrease in the average decay time with the increasing power of the excitation laser.

In order to explain this phenomenon, a semi-empirical model of time-dependent kinetic rate equations of the erbium-ytterbium system was developed. Our simulations show that for low laser power, the dominant contribution in the excitation process comes from the nonradiative energy transfer from Yb^{3+} to Er^{3+} ions. Instead, the up-conversion luminescence is activated mainly due to direct absorption of photons in the excited state absorption process for high laser power. We also identified an additional nonradiative decay channel depopulating the emitting level, attributed to the presence of surfactants stabilizing NC. The efficiency of this channel depends on the local temperature, controlled by the laser, and requires overcoming a potential barrier. Moreover, the channel activity can be reduced by coating NCs with an additional optically passive shell, insulating the active core from the environment. The proposed kinetic model, including the interaction of erbium ions with the surface of the NC, allowed us to estimate correct fits to the experimental luminescence decay profiles. We also extracted the power-independent radiative lifetime of the red emission level. We found the presented approach valuable for the dynamics of the up-conversion processes analysis.

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