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EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

COST Action MP1403

Nanoscale Quantum Optics

Kick-off Workshop

9-10 April 2015, Belgrade, Serbia

BOOK OF ABSTRACTS

Nanoscale Quantum Optics

Kick-off Workshop

9-10 April 2015
Belgrade, Serbia

ABTRACTS OF GUEST AND INVITED LECTURES
AND CONTRIBUTED PAPERS

Editors

Jelena Dimitrijević, Branislav Jelenković and Mario Agio

Belgrade, 2015

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Jelena Dimitrijević
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Photonics Center
Institute of Physics
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Workshop topics

- Generation, detection & storage of quantum states of light at the nanoscale
- Nonlinearities & ultrafast processes in nanostructured media
- Nanoscale quantum coherence
- Cooperative effects, correlations and many-body physics tailored by strongly confined optical fields

PREFACE

The COST Action MP1403 Nanoscale Quantum Optics (NQO) aims at promoting and coordinating forefront research in nanoscale quantum optics through a competitive and organised network, which will define new and unexplored pathways for deploying quantum technologies in nano-photonics devices within the European research area. The main vision is to establish a fruitful and successful interaction among scientists and engineers from academia, research centres and industry, focusing on quantum science & technology, nanoscale optics & photonics, and materials science. To date 25 COST Countries, 3 COST Near-Neighbour Countries and 9 COST International Partner Countries have joined the Action.

The Kick-off Workshop organised in Belgrade on April 9-10, 2015, represents the first scientific event of the Action and it is the occasion to present the research activities of its members, consolidate working groups (WG) and discuss future plans. The Kick-off Workshop will be followed by several other networking events, which will take place in the next four years. These include WG meetings, training schools, conferences and exchange visits.

The Kick-off Workshop features invited and contributed talks and poster presentations, structured in one session for Guest Speakers, four WG sessions, each introduced by WG Leaders, one session dedicated to the Industry, Education and Training and a poster session. Furthermore, it will provide a general introduction to the COST system and to the Action objectives.

This Book of Abstracts has been edited to gather and disseminate the scientific contributions presented at the Kick-off Workshop. We would like to thank all participants, the local organisers and the members of the scientific committee for their work and wish them a fruitful meeting in Belgrade.

Belgrade, April 2015

Mario Agio (Action Chair), Branislav Jelenković (MC Member for Serbia)

WORKSHOP PROGRAM

8th April – Photonics Centre

13:00 – Informal Visit to Photonics Center, Institute of Physics, University of Belgrade

9th April – Kolarac Foundation

8:30 – Welcome to Participants

Local Organizer – Brana Jelenkovic (Serbia)

Welcome Address – Viktor Nedovic (Serbia)

8:45 – Introduction to COST Association and COST Action NQO

Action Chair – Mario Agio (Germany and Italy)

Gender Balance Advisor – Irene D'Amico (United Kingdom)

Early Stage Res. Advisor – André Xuereb (Malta)

9:10 – Guest Speakers

Jelena Vuckovic (USA)

Nenad Vukmirovic (Serbia)

Dejan Pantelic (Serbia)

10:10 – Coffee Break

10:30 – Technical Session (WG1)

WG1 Leader – Félix Bussieres (Switzerland)

Invited – Mete Atatüre (United Kingdom)

Contributed – Jean-Michel Gérard (France)

Contributed – Niccolò Somaschi (France)

Contributed – Daniele Bajoni (Italy)

Contributed – Ana Predojevic (Austria)

Contributed – Andreas Engel (Switzerland)

12:30 – Free Lunch

14:00 – Technical Session (WG2)

WG2 Leader – Walther Pfeiffer (Germany)

Invited – Christoph Lienau (Germany)

Contributed – Bin Yang (France)

Contributed – Andreas Eckstein (United Kingdom)

Contributed – Johannes Feist (Spain)

Contributed – Harald Giessen (Germany)

Contributed – Jeremy Butet (Switzerland)

16:00 – Coffee Break

16:20 – Poster Session & MC Meeting

19:30 – Get together and dinner at Aero Club

10th April – Kolarac Foundation

8:50 – Industry, Education and Training

Education and Training Adv. – Darrick Chang (Spain)

Industry Adv. – Sander Dorenbos (The Netherlands)

Invited – Val Zwiller (The Netherlands)

Invited – Bert Offrein (Switzerland)

10:10 – Coffee Break

10:30 – Technical Session (WG3)

WG3 Leader – Thomas Durt (France)

Invited – Paola Cappellaro (USA and Italy)

Contributed – Vincenzo Savona (Switzerland)

Contributed – Alexander Kromka (Czech Republic)

Contributed – Lorenzo Rosa (Italy and Australia)

Contributed – Niels Israelsen (Denmark)

Contributed – Elke Neu (Germany and Switzerland)

12:30 – Free Lunch

14:00 – Technical Session (WG4)

WG4 Leader – Peter Rabl (Austria)

Invited – Giovanna Morigi (Germany)

Contributed – Tommy Hakala (Finland)

Contributed – Francesco Intravia (Germany)

Contributed – Nick Schilder (France)

Contributed – Philipp Schneeweiss (Austria)

Contributed – André Xuereb (Malta)

16:00 – Closing Remarks

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GUEST SPEAKERS

Quantum nanophotonics

Jelena Vuckovic

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By embedding a single quantum emitter inside a nanoresonator that strongly localizes optical field, it is possible to achieve a very strong light –matter interaction. The strength of this interaction is characterized by the coherent emitter-field coupling strength (g), which increases with reduction in the optical mode volume and which also sets the limit on the operational speed of such a system. With InAs quantum dots inside GaAs photonic crystal cavities, coupling strengths of 40 GHz can be reached (much greater than the record values in atom-cavity QED systems), while nanometallic cavities could increase them over 100GHz, as a result of the further reduction in the mode volume. Such a quantum dot-nanocavity platform is of interest for various quantum technologies, as well as in optical switching/computing [1,2].

Finally, alternative material systems such as impurities in silicon carbide [3] or diamond that could potentially bring the described experiments to the room temperature regime are investigated, as well as the applications beyond quantum technologies, including optical switches and biosensors.

REFERENCES

[1] On-chip generation of indistinguishable photons using cavity quantum-electrodynamics, Kai Müller, Armand Rundquist, Kevin A. Fischer, Tomas Sarmiento, Konstantinos G. Lagoudakis, Yousif A. Kelaita, Carlos Sanchez Munoz, Elena del Valle, Fabrice P. Laussy, Jelena Vuckovic (arXiv:1408.5942)

[2] Ultrafast Photon-Photon Interaction in a Strongly Coupled Quantum Dot-Cavity System, Dirk Englund, Arka Majumdar, Michal Bajcsy, Andrei Faraon, Pierre Petroff, and Jelena Vuckovic, *Physical Review Letters* 108, 093604 (2012)

[3] Visible Photoluminescence from Cubic (3C) Silicon Carbide Microdisks Coupled to High Quality Whispering Gallery Modes, Marina Radulaski, Thomas M. Babinec, Kai Müller, Konstantinos G. Lagoudakis, Jingyuan Linda Zhang, Sonia Buckley, Yousif A. Kelaita, Kassem Alassaad, Gabriel Ferro, and Jelena Vuckovic, *ACS Photonics* (2014)

Modeling of Nitride Nanostructure Based Classical and Non-Classical Light Emitters

Nenad Vukmirović[1], Stanko Tomić[2] and Žarko Gačević[3]
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Nanostructures based on III-nitride semiconductors offer certain advantages for realization of single-photon sources. Larger band offsets and effective masses lead to strong quantum-confinement effects which enable the operation of single-photon sources at higher temperatures. Wide band gap of III-nitrides leads to the emission in the blue and ultraviolet spectral range, which is not accessible with most of the other materials. In this talk, simulation insights into the classical and non-classical light emission properties of III-nitride nanostructures will be discussed.

In the first part of the talk, calculations of excitonic and biexcitonic states in self-assembled GaN/AlN quantum dots will be presented with special emphasis on the use of these dots for single-photon source applications [1]. Theoretical methodology for the calculation of single-particle states was based on 8-band strain-dependent envelope function Hamiltonian, with the effects of spin-orbit interaction, crystal-field splitting, and piezoelectric and spontaneous polarizations taken into account. Exciton and biexciton states were found using the configuration-interaction method. Optimal dot heights for their use in single-photon emitters were determined for various diameter-to-height ratios.

In the second part of the talk, electronic properties of InGaN quantum structures embedded in site controlled GaN nanowires will be presented [2]. The InGaN structures under consideration consist of two sections: the middle one, which is formed on the polar *c*-facet, and the side one, which is formed on the semi-polar *r*-facets. These structures exhibit two-color emission at 384 nm and 488 nm. We identify that the main origin of two-color emission is higher In incorporation on the nanowire polar *c*-facet, while the influences of internal electric field and strain are less significant.

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[2] Ž. Gačević, N. García-Lepetit, N. Vukmirović, et al, in preparation.

Complexity of natural photonic structures

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[1]*Institute of Physics, University of Belgrade, Serbia*
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Photonic structures are ubiquitous in nature [1] – ranging from insect eyes, cuticle and wings, bird feathers and cuttlefish bone, to stones and minerals, to mention just a few. Optically interesting features are very intricate and range from nanometer to micrometer level. They are simultaneous combination of ordered and disorder [2], resulting in complicated diffraction gratings with defects (surface, volume or layered), scatterers and photonic crystals.

Here we deal with internal complexity of biological structures in terms of their internal geometry and a number of resulting optical effects – iridescence, polarization, photonic band-gap, scattering, dispersion, fluorescence, diffraction, interference... The number of degrees of freedom is so large that there is an extremely small probability of finding two identical structures.

We propose attaching a biological structure into an item (a bill, a document, or a product), thus making it as unique as an individual human being with its fingerprint, retinal veins, or iris colour and pattern. The natural variability of biological processes guarantees the uniqueness, in the same way as no two fingerprints are identical. The uniqueness is expressed by multiple optical features randomly distributed across the structure. Furthermore, natural structures can be artificially modified or functionalized by direct laser writing to include other overt or covert information.

The advantage is that there is no need for complicated manufacturing of micro and nanostructures [3]. They grow by themselves in huge numbers, each one being unique and extremely complicated to counterfeit.

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INVITED SPEAKERS

Quantum optics with quantum-dot spins and photons

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Spins confined in solids, such as quantum dots and atomic impurities provide interesting and rich physical systems. Their inherently mesoscopic nature leads to a multitude of interesting interaction mechanisms of confined spins with the solid state environment of spins, charges, vibrations and light. Implementing a high level of control on these constituents and their interactions with each other creates exciting opportunities for realizing stationary and flying qubits within the context of spin-based quantum information science. I will provide a snapshot of the progress and challenges for optically interconnected spins, as well as first steps towards hybrid distributed quantum networks involving other physical systems.

Ultrafast Coherent Charge Transfer in Solar Cells and Artificial Light Harvesting Systems: Toward Movies of Electronic Motion

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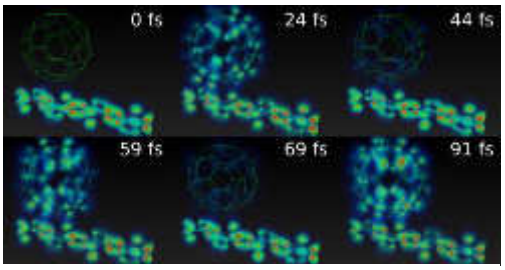
The efficient conversion of (sun-)light into electrical or chemical energy is one of the most fundamental and relevant challenges in current energy research. Our ability to construct artificial molecular or nanostructured devices that can harvest and exploit sunlight inevitably relies on an in-depth understanding of the elementary microscopic principles that govern the underlying light conversion processes. Generally, these processes happen on an exceedingly short femtosecond time scale, making real time studies of the light-driven dynamics particularly important. To elucidate these dynamics, we have recently combined coherent femtosecond spectroscopy and first-principles quantum dynamics simulations [1,2] and have used this approach to explore the primary photoinduced electronic charge transfer in two prototypical structures: (i) a carotene-porphyrin-fullerene triad, an elementary component for an artificial light harvesting system [2] and (ii) a polymer:fullerene blend as a model for an organic solar cell [1].



Real time simulation of the coherent charge transfer dynamics between polymer and fullerene moiety in a P3HT/PCBM thin film photovoltaic device

Surprisingly, our results provide strong evidence that in both systems, at room temperature, the driving mechanism of the primary step within the current generation cycle is a quantum-correlated wavelike motion of electrons and nuclei on a timescale of few tens of femtoseconds. Our results suggest that the strong coupling between electronic and vibrational degrees of freedom is of key importance for the dynamics and yield of the charge separation process. In my talk, I will present our most recent findings and their implications for the light-to-current conversion in solar cells.

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[2] C. A. Rozzi et al. Quantum coherence controls the charge separation in a prototypical artificial light harvesting system. Nature Comm. 4, 1602 (2013).

Quantum Optics with Nanowires

V. Zwiller[1, 2], K. Jöns[2], M. Reimer[2], G. Bulgarini[2], M. Bouwes Bavinck[2], L. Schweickert[2], I. Esmaeil Zadeh[2], J. Zichi[2]
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Nanowires offer new opportunities for nanoscale quantum optics; the quantum dot geometry in semiconducting nanowires as well as the material composition and environment can be engineered with unprecedented freedom to improve the light extraction efficiency.

Quantum dots in nanowires are shown to be efficient single photon sources, in addition because of the very small fine structure splitting, we demonstrate the generation of entangled pairs of photons from a nanowire.
By doping a nanowire and making ohmic contacts on both sides, a nanowire light emitting diode can be obtained with a single quantum dot as the active region. Under forward bias, this will act as an electrically pumped source of single photons. Under reverse bias, an avalanche effect can multiply photocurrent and enables the detection of single photons.

Another type of nanowire under study in our group is superconducting nanowires for single photon detection, reaching efficiencies, time resolution and dark counts beyond currently available detectors. We will discuss our first attempts at combining semiconducting nanowire based single photon emitters and superconducting nanowire single photon detectors on a chip to realize complete quantum circuits on a chip.

Photonic devices for future computing systems

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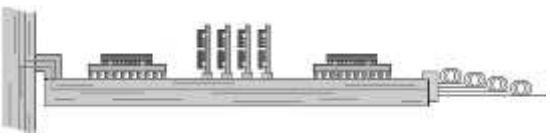
Photonic technology is now emerging in computing systems as a means to provide the required interconnect bandwidth between racks and boards. In addition to the larger bandwidth x length product as in electrical links, optical communication offers a higher interconnect density and power efficiency. To further scale the performance of future cloud, datacenter and server systems optical technology must be integrated deep into the system, closely packaged with electrical functions such as the processor, switch or memory. However, today's hybrid optical technology solutions suffer from the large number of components and associated assembly cost. Silicon photonics extends established CMOS technology with optical functions such as electro-optic modulators, detectors and wavelength filter devices for wavelength division multiplexing offering a path to a higher state of integration [1]. This opens prospects for scalable and cost-effective electro-optical functions in silicon but also at system-level, novel assembly and optical signal distribution technologies have to be established. At the Photonics group of IBM Research – Zurich we explore both aspects. Novel silicon photonics devices for power-efficient optical links were demonstrated. For example an optical modulator with <50 fJ switching energy [2] and high Q/V silicon photonics optical cavities [3]. Single mode polymer waveguides provide a scalable optical interface between silicon photonics chips and the system [4]. Exploring technologies for alternate computing concepts, we demonstrated Bose-Einstein Condensate formation at room temperature in a polymer with potential applications in quantum simulations [5].



Vision for a computing board with processor packages and memory indicating embedded electrical and optical interconnects.

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[3] P. Seidler, et al., Optics Express, Vol. 21 Issue 26, pp. 32468-32483 (2013)
[4] R. Dangel, et al., Optics Express, Vol. 23 Issue 4, pp. 4736-4750 (2015)
[5] T. Stoeferle, et al., Nature Materials, 13, pp. 247–252 (2014)

Quantum Spectrometers

Paola Cappellaro[1]
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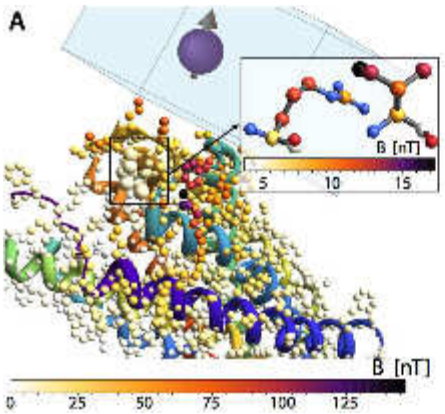
Quantum control techniques have proven effective to extend the coherence of qubit sensors, thus allowing quantum-enhanced sensitivity at the nano-scale. For example, simple pulsed dynamical decoupling schemes can protect against decoherence by acting as noise filters, while preserving the interaction with the system or field that one wishes to measure.



Nuclear spin imaging with a shallow NV center in diamond. A single NV spin at 1-2nm from the diamond surface can sense single nuclear spins in a molecule (the chemokine receptor CXCR4) anchored to the diamond. The magnetic field produced by individual C13 is in the range of nT, within reach of NV sensitivity. In the inset: the binding site of interest (atoms other than C13 are blue (O) and red (N)).

In this talk I will show how we can engineer the evolution of quantum sensor by creating more general dynamic filters that help reveal temporal and spatial information about classical and quantum sources.

The high frequency resolution achieved by these dynamical filters turns the quantum sensors into accurate spectrometers, capable of detecting the dynamics of external fields or of imaging the spatial configuration of a spin bath.

I will illustrate applications of these strategies in experimental implementations based on the Nitrogen-Vacancy center in diamond, which shows promise for the detection of biological signals and for the reconstruction of protein structures [1].

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Nano-friction in cavity quantum electrodynamics

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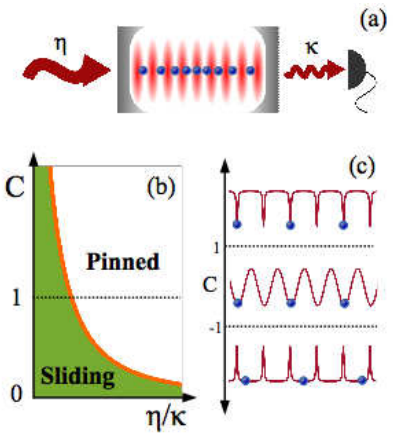
The Frenkel-Kontorova model reproduces in one dimension the essential features of the stick-slip motion which is characteristic of friction. We theoretically analyze a realization where the atomic array is an ion chain and the substrate potential is the optical lattice of a high-finesse resonator, as sketched in subplot (a). The ion transitions strongly couple with the cavity mode, and constitute a dynamically-refractive medium, which determines the potential depth. In this regime the cavity potential behaves like a deformable substrate. We characterize the properties of the stationary state, resulting from the balance between a pump driving the resonator and losses due to cavity decay, when the interparticle distance and the potential wavelength are incommensurate. While the sliding phase is essentially independent of the cavity nonlinearity C, for increasing cavity coupling the transition to the pinned phase occurs at decreasing values of the pump strength, as sketched in subplot (b), and can exhibit bistability. This dynamics represents a paradigm of competing selforganizing mechanisms at the quantum limit which can be observed in existing experimental setups [1].



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ORAL CONTRIBUTIONS

Quantum optics with photonic trumpets

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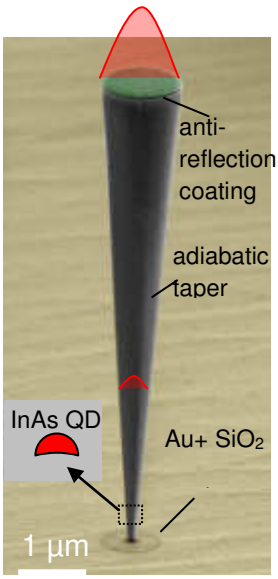
Optimizing the coupling between a localized quantum emitter and a single-mode optical channel represents a powerful route to realize bright sources of non-classical light states for QIPC. Reversibly, the efficient absorption of a photon impinging on the emitter is key to realise a spin-photon interface, the node of future quantum networks.

Besides optical microcavities, photonic wires are very attractive in this context [1]. We introduce the Photonic Trumpet [2], formed by a high-index single-mode waveguide and a conical tapering. Nearly perfect single mode emission, low-divergence Gaussian radiation pattern, linear polarization control and high efficiency single photon emission (> 0.75 photon per pulse) are reported for a single quantum dot embedded in a Photonic Trumpet. We also demonstrate a broadband tuning of the emission wavelength without efficiency loss using strain-effects. More generally, this novel photonic microstructure appears as a very promising platform to explore the unique optical properties of "one-dimensional atoms"[3] and hybrid optomechanical systems where the interaction between the two-level quantum system and mechanical modes is mediated by strain [4].



Scanning electron micrograph of a GaAs photonic trumpet.

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Electrically Tunable Bright Sources of Highly Indistinguishable Single Photons

N. Somaschi[1], V. Giesz[1], L. De Santis[1], S. L. Portalupi[1], A.K. Nowak[1], I. Sagnes[1], L. Lanco[1,2], A. Lemaitre[1], and P. Senellart[1,3]

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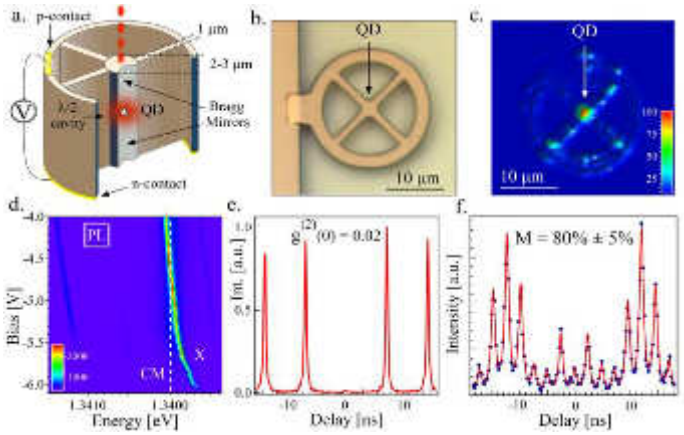
Semiconductor quantum dots (QDs) are very promising systems to build a solid state quantum network, especially with the possibility to fabricate bright sources of single and indistinguishable photons. Recently, we demonstrated single photon sources with brightness of 80% and indistinguishability as high as 92% by inserting QDs in micropillar cavities [1].



a) Schematic of the connected–pillar device. b, c) µ-scope image and PL intensity map of the device. d) PL contour plot recorded at different applied voltage showing the exciton line shift across the cavity mode. e, f) Second order autocorrelation function $g^{(2)}(\tau)$ in a an HBT(e) and HOM (f) experiment showing high single photon purity and indistinguishability of the source.

Here we report on the fabrication of electrically tunable ultrabright sources of indistinguishable single photons. We propose a novel cavity design which permits to apply an electric field while maintaining a 3D confinement for the photons: it consists of a micro-pillar cavity (2-3 µm) connected to a larger ohmic-contact

surface with four 1D-bridges and a surrounding frame (Fig. 1a). Laterally, the fundamental cavity mode (CM) of the structure is confined in the centre of the connected pillar. Vertically, the GaAs cavity is surrounded by GaAs/AlGaAs Bragg mirrors, doped in a p-i-n diode configuration. A single QD is deterministically positioned at the center of the pillar by means of an advanced in-situ optical lithography (Fig. 1b, c) [2, 3]. The strong Purcell effect obtained with such device results in a very high brightness of the single-photon source, exceeding 55%. Furthermore the application of an electric field results in a Stark shift of the QD transition over a few nm spectral range, allowing a fine spectral tuning within the mode (Fig. 1d). Under non-resonant excitation, we demonstrate a photon indistinguishability in the 70-to 80% range (Fig. 1f). This structure allows strictly resonant excitation where the photons are shown to be perfectly indistinguishable.

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[3] A. Nowak et al., Nat.Comm. 5, 3240 (2014).

Emission of entangled photons from a silicon microring resonator.

D. Grassani[1], S. Azzini[1], M. Liscidini[1], M. Galli[1], M.J. Strain[2], M. Sorel[3], J.E. Sipe[4], and D. Bajoni[5]

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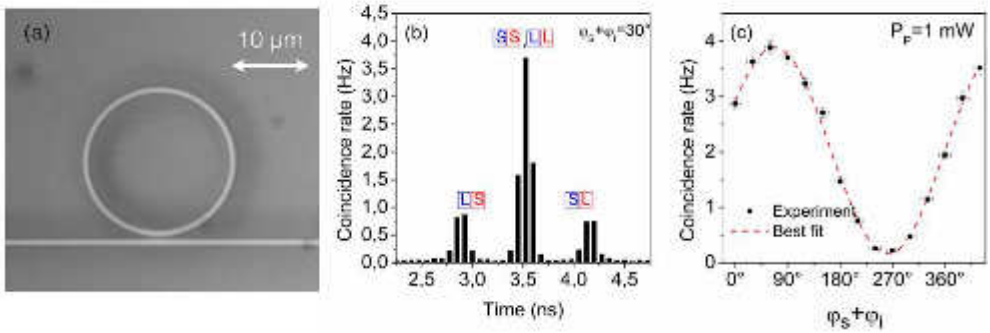

a) Micrograph of the sample. (b) Time correlation curve for a coupled pump power of 1 mW. The letters S and L refer to the paths takes by the signal and idler photons in the short (S), and long (L) arms of two independent interferometers, blue for signal and red for idler. (c). Height of the central peak from panel (b) as a function of the total phase (dots) and best fit to a sinusoid (red dashed line).

Entanglement is a fundamental tool in a wide variety of quantum information protocols, among others quantum cryptography and quantum information processing. An ideal integrated source of entangled photons should be CMOS compatible for cheap production, easily integrable with fiber networks, and highly repeatable. In this work (Optica **2** 88–94 (2015)) we report on a novel source of entangled photon pairs integrated on a silicon chip. Our sample, a silicon micro-ring with radius of 10 μm (Fig 1 (a)), emits signal and idler photon pairs by spontaneous four wave mixing. Entanglement is verified via a Franson type experiment (Fig. 1 (b)(c)). This source of entangled photons has unique characteristics. The spectral brightness per coupled pump power is remarkable, $\sim 6 \times 10^7$ nm^{-1} mW^{-2} s^{-1} , more than four order of magnitudes larger than that reported for entangled photon pairs emitted by cm long silicon waveguides. The ring small footprint has great advantages for scalability, its micrometric size making it ideal for integration with other photonic devices on the same chip.

On-demand generation of photon pairs and generation of time-bin entanglement from a single quantum dot

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Quantum information processing needs novel, efficient, and compact sources of single photons and entangled photons pairs. We report here the resonant two-photon excitation of the biexciton state of a single InAs quantum dot embedded in a micro-cavity [1]. This method allows us to generate photon pairs with nearly unit probability. The resonant nature of the excitation was confirmed by the observation of Rabi oscillations. In addition, we measured the level of quantum coherence in the ground-biexciton state superposition by performing a Ramsey interference measurement. Also, and to our knowledge for the first time, we performed a measurement of the spin-echo in such a system.

In addition, we report on an unprecedented level of time-bin entanglement [2] from a single quantum dot. The requirements to generate this type of entanglement include the suppression of the single exciton amplitude in the excitation pulse and negligible dephasing caused by the laser excitation. These conditions constitute contradictory demands on the excitation pulse-length and its intensity. We performed a study of these limitations from both an experimental and a theoretical point of view and we identified key parameters required in order to achieve a high degree of time-bin entanglement from a quantum dot system. We measured the entanglement in this optimized regime and the results yield the concurrence of 0.78(6) and fidelity of 0.88(3) to the maximally entangled state.

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Physics and Applications of Superconducting Nanowire Single-Photon Detectors

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Superconducting nanowire single-photon detectors (SNSPD) have attracted a lot of interest in recent years, due to their unique combination of characteristics. They are characterized by low-timing jitter, high count rates, high detection efficiency and low dark counts. This makes them detectors of choice for a wide variety of applications, from quantum key distribution and interplanetary communications to cancer research, to name just a few.

In order to simultaneously obtain above mentioned characteristics, it is necessary to realize various optimizations [1], e.g. the use of optical cavities to increase the photon absorption, or the reduction of thermal background radiation to reduce dark counts. These technological advances have recently been matched by an improved understanding of the detection mechanism [2, 3], which indicates that magnetic vortices are essential for photon detection in SNSPD. We will present our current understanding of the detection mechanism and highlight some results also important for applications. Furthermore, we will discuss preliminary results that give an indication of why SNSPD made from WSi show some remarkable differences as compared to SNSPD based on NbN and similar materials [4].

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Cryogenic Super-Resolution Microscopy with single molecules

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The controlled, coherent manipulation of quantum systems is an important challenge in modern science and engineering, with significant applications in quantum technologies. Solid-state quantum emitters such as single molecules, quantum dots and NV centers in diamond are among the promising candidates for realization of quantum bits. Arrays of strongly interacting solid-state quantum systems are appealing platforms for the preparation of collective delocalized states formed by the entanglement of individual emitters. For these systems, dipole-dipole coupling occurs on nanometers scale and therefore experimental schemes which optically resolve quantum emitters at this scale and allow the manipulation of their degree of entanglement are crucial.

Although the various super-resolution microscopy techniques are now commonly used at room temperature e.g. in biology, their extension to low temperatures is in its infancy, mainly because of the inherent experimental complications due to the use cryogenic systems and the non-adequacy of the photo-physics of usual markers at these temperatures. We will present two super-resolution optical microscopy techniques with single molecules. Organic molecules inserted in well-suited solid matrix at liquid helium temperature are simple two-level systems on which quantum entanglement experiments can be performed. We demonstrate a resolution down to 4 nm (FWHM) with DBATT molecules in octadecane at 2K. This technique provides the unique possibility to super-resolve single molecules having close optical resonances and can therefore bring quantum optics applications such as studying the interactions and entanglements between single molecules.

Engineering TF-mode selective quantum frequency conversion in photonic crystal fiber

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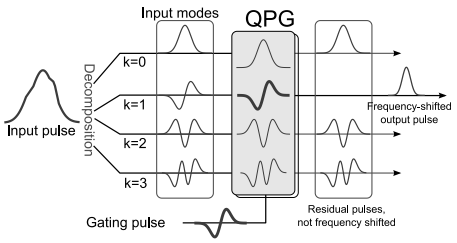
Quantum frequency conversion [1] is a promising tool to translate quantum states of light to a different wavelength regime, e. g. to improve detection efficiencies of states at the single photon level [2]. Exploiting dispersion, it is possible to implement a time-frequency (TF) mode selective conversion, quantum pulse gate (QPG) [3], in order to [de-]multiplex from/into spectrally overlapping yet orthogonal modes, boosting the transmission capacity of a single optical link while minimizing degrading effects due to chromatic dispersion. However, the requirements on phase-matching the nonlinear optical processes involved means that application is restricted to a narrow range of wavelengths.

The emergence of micro-structured photonic crystal fiber (PCF) has made it possible to tailor optical dispersion profiles to the application at hand. For four-wave-mixing, the dominant nonlinear interaction of light in silica, this means that phase-matching can be achieved in settings not accessible to standard optical fiber [4]. We explore the enlarged parameter space for implementing a QPG with the additional freedom of engineering the material dispersion function, and explore its feasibility and possible roadblocks for application in quantum state engineering.



Pulse-demultiplexing with a QPG: A input pulse is decomposed into the gate's mode basis, and the gating pulse selects the mode to be converted.

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Transport and harvesting of excitons mediated by strong coupling

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The transport of excitons is a fundamental process that plays a crucial rule both in natural phenomena such as photosynthesis, where energy has to be transported to a reaction center, and in artificial devices such as organic solar cells, whose power conversion efficiency can be improved significantly when the exciton diffusion length is increased. However, most systems composed of organic molecules are disordered and possess relatively large dissipation and dephasing rates, such that exciton transport typically is inefficient.

Very recently, an increase of the *electrical* conductance of an organic material was shown under strong coupling of the excitons to a cavity mode [1]. Strong coupling is achieved when the energy exchange rate between exciton and electromagnetic field modes becomes faster than the decay and decoherence rates of either constituent. Inspired by this result, we demonstrate that exciton conductance in organic materials can be enhanced by several orders of magnitude when the molecules are strongly coupled to an electromagnetic mode. Using a 1D model system, we show how the formation of a collective strongly coupled mode (a polariton) allows excitons to bypass the disordered array of molecules and jump directly from one end of the structure to the other [2].

We furthermore show that by designing the electric field profile of the electromagnetic mode that provides the strong coupling, the transport properties can be tuned to achieve exciton *harvesting*, i.e., to guide excitons from a collection area to a specific location. We demonstrate this effect using the localized plasmon resonances of a single metallic nanosphere and a three-sphere structure. The latter provides pronounced *hot spots* where the electric field is strongly concentrated. We show that excitons are efficiently transported between these hot spots, bypassing the rest of the system [3].

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Ultrafast hybrid nonlinear plasmonics

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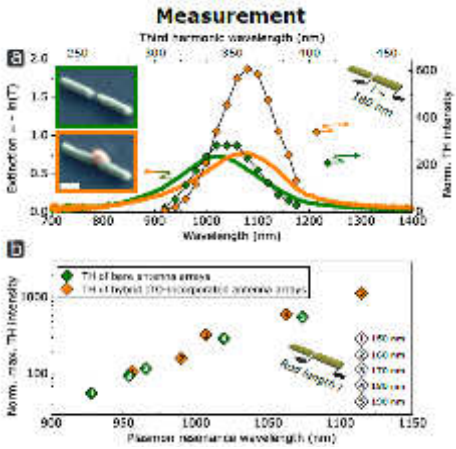
We are going to present several different concepts on ultrafast nonlinear hybrid plasmonics. Both second- and third-harmonic processes are studied. The first concept incorporates strong local nonlinearities such as nanocrystals of nonlinear materials like LiNbO3 and ITO into gaps of plasmonic nanoantennas [1]. The second concept investigates the nonlinearities of the metals itself, particularly the influence of the localized density of states in the d-band and its influence on the nonlinear optical processes [2]. The third concept uses Miller's rule to enhance the optical nonlinearity by tailoring the linear response such that the first order susceptibility is resonant with the second harmonic light [3]. This leads to a strong and reproducible enhancement of the nonlinear response.

Figure 1 depicts a typical nanostructure, as well the results of spectroscopic nonlinear experiments. The results for the nonlinear response increase largely towards the infrared, both due to larger oscillator strength as well as higher Q factors.



Our general method is particularly well suited to incorporate also localized quantum emitters into the gap and investigate nonlinear optical processes on the single particle level.
We acknowledge support by DFG, ERC (Complexplas), and BW-Stiftung.

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Second Harmonic Generation from Realistic Plasmonic Nanoantennas and Fano Metamolecules

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It is well known that metallic nanoantennas are able to enhance and control light-matter interactions down to the nanoscale. Indeed, optical antennas have the ability to concentrate the electric field inside their nanogap beating the diffraction limit. The enhancement of the electric field enables the observation of nonlinear optical processes. For instance, second harmonic generation (SHG) from metallic nanoantennas, the process thereby two photons at the fundamental frequency are converted into one photon at the second harmonic (SH), has been experimentally reported recently.

In a first part, we will discuss results obtained using a surface integral formulation extended to the case of surface SHG. Our method allows efficient evaluations of the SH near-field and far-field distributions. Calculations were performed for idealized (rectangular arms) and realistic (mesh adapted from a scanning electron microscope image) gold nanoantennas. As previously reported in the case of symmetric antennas, the SH electric field at both sides of the idealized nanogap is found oscillating out of phase indicating a non radiative behaviour (SH dark mode). This behaviour is no longer observed considering a realistic gold nanoantenna. Due to the shape asymmetry of the arms, the SH near-field distribution is more complex and the SH cross section increases because of symmetry breaking at the nanoscale. Interestingly, the dissymmetry is also clearly revealed by far-field analysis demonstrating that SHG is a promising tool for sensitive optical characterization of plasmonic nanoantennas.
In a second part, we will discuss a new strategy that we recently developed to increase nonlinear optical processes in plasmonic systems. This strategy is based on Fano resonances which stem from the coupling between a dark mode and a bright mode. Dark modes are weakly coupled to far-field radiations, resulting in a strong localization in the near-field, but need to be coupled with an optically active mode to be effectively excited. This coupling can be mediated by Fano resonances in order to increase the near-field at the fundamental wavelength. The optical properties of silver heptamers were tailored in order to observe simultaneously a Fano dip at the fundamental wavelength ($\lambda = 800$ nm) and a high order scattering peak at the second harmonic wavelength ($\lambda = 400$ nm). The observation of a Fano

dip at the fundamental wavelength ensures that the dark mode is effectively excited. This strategy effectively increases second harmonic generation. This work paves the way for the design of new plasmonic Fano systems with high nonlinear efficiencies.

Engineering non-classical states of light and matter in automatedly optimized photonic crystal structures

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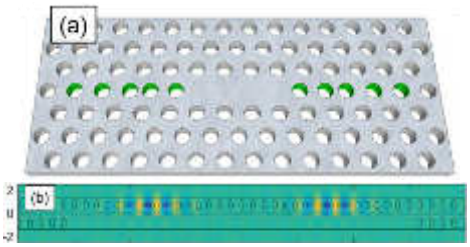
This contribution reports on two distinct but related results achieved in our group.

In the first part, I report on a novel optimization procedure for photonic crystal slab structures. The procedure combines a fast mode-expansion method with a genetic optimization algorithm, allowing exhaustive exploration of a chosen space of structural parameters [1]. When applied to silicon photonic crystal nanocavities – using the shifts of a few neighbouring holes as parameters – the method produced cavity quality factors up to 50 times higher than previous best. The resulting designs have been already successfully tested in three independent experiments [2-4], where Si L3 cavities with $Q=2\times10^6$ have been measured and record-low power threshold for optical bistability in a Si device demonstrated.



(a) Optimized L3 cavity design with $Q=5\times10^6$. (b) Double nanobeam design for remote mechanical entanglement

In the second part, I present protocols for producing non-classical states of photons and of mechanical vibrations on these optimized photonic structures. In particular, I discuss the unconventional photon blockade, and the perspective of an ultralow-power all-silicon single-photon source [5]. I then present schemes, based on realistic optimized photonic-phononic crystal structures, for the generation and readout of entangled states of mechanical vibrations at macroscopic distance [6].

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Carbon synthesis in Prague and incorporation of optically active silicon colour centres into diamond thin films

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One of the main roles of the Department of Optical Materials (Institute of Physics) is the deposition of carbon allotropes in their nano-sized form. This includes the chemical vapour deposition (CVD) of diamond thin films or their porous-like structures, and growth of carbon nanotubes and graphene by r.f. plasma CVD process combined with linear antenna microwave plasma system. Present diamond-related research topics at the department are: a) low temperature diamond growth (below 400 °C) b) optimizing an ultrasonic seeding process suitable for nearly any material type with complex 3D geometry c) diamond growth from polymer composites and/or even over polymer layers, d) growth of diamond films of electronic grade, and e) optimizing of diamond properties for biological uses such as tissue engineering and regenerative medicine.

Optically tailored diamond films and nanostructures have attracted great attention due to their remarkable properties and potential applications in several emerging technological fields, such as quantum computing, sensing, cell imaging and drug delivery. In the past few years, we have already proven usage of diamond thin films in opto-bio-electronics. Our extensive studies on optical properties of intrinsic diamond films [1-3] resulted in tailored fabrication of optical planar waveguides and photonic crystals [4, 5]. Furthermore, intentional doping of diamond with foreign atoms (silicon, nitrogen or chromium) can produce a range of colour defect centres with strong and stable fluorescence, no photobleaching and long quantum coherence times [6]. These centres can be artificially engineered in the diamond lattice during the growth process or post-processing (ion implantation, irradiation). In this proposal, we will point out the direct incorporation of silicon atoms into diamond films deposited under a wide range of growth process parameters.

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Room temperature Single Photon Sources in Silicon Carbide

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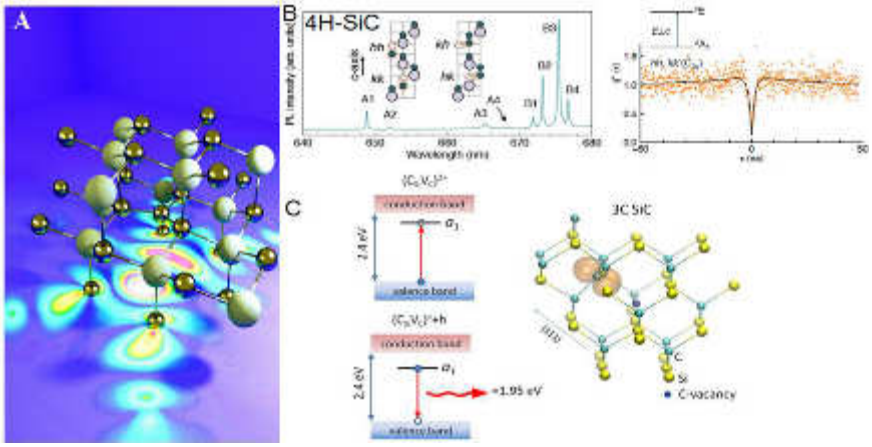
Defects are common in many materials and some were regarded for years as detrimental. Recently with the advent of ultra-sensitive detectors, quantum optical single spin magnetic resonance protocols and advanced material synthesis and doping, diamond intra-band gap defects and their nanostructured counterpart are revealed to be a disruptive discovery for the future of nanoscale sensing and quantum technologies[1]. We will report on recently studied optical centres in another wide-band gap semiconductor, such as silicon carbide (SiC). SiC harbors paramagnetic defects whose quantum properties were recently unraveled [2-7]. As occurred for similar diamond point defects[1], we have recently identified a bright single photon emission in 4H-SiC. We will show more recent results on single defects SiC nanoparticles [8], nanotetrapods [9] and other SiC quantum emission [10] providing novel information on their physics and atomistic structure. The fundamental understanding of these defects is essential for their engineering and deployment in next generation multifunctional sensors and in quantum nano-photonics.

We will discuss the potential designs of photonics cavities to further enhance some of these single photon sources.



The advance of quantum technology requires a single photon source operating at room temperature integrated in the same material where large scalability devices are ready available. Silicon carbide is satisfying this condition. The hexagonal silicon carbide lattice has been modified to host an isolated single defect identified with an intrinsic vacancy defect, providing an extremely bright single photon emission upon optical excitation. (a) Illustration of the excited state wave-function of the identified single photon source in 4h-SiC. (b) single defects in 4H[4]. (c) Isolation of equivalent defects in nanoparticles of 3c-sic emitting in the red with different photo-excitation-recombination properties[8].

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Controlled Routing of Single Plasmons at the Nanoscale

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It is possible to confine photons beyond the diffraction limit by converting them into surface plasmon excitations propagating along nanoscopic metallic wires [1]. By placing metallic wires next to each other it is possible to evanescently couple photons from one waveguide to another. Such coupling has previously been demonstrated both in the visible and the telecom spectral range, but only for pre-determined systems with a fixed coupling ratio [2,3].

We report on the experimental construction of a plasmonic beam-splitter with a tunable splitting ratio, which we tested with single photons. The beam splitter is based on evanescent adiabatic coupling between two silver nanowires supporting propagating surface plasmon polariton (SPP) modes. The individual nanowires have diameters of 88 nm. Using a scanning probe technique [4, 5], we first couple a single nitrogen vacancy (NV) center located in a nano-diamond to the SPP mode propagating along one nanowire. After this, the second wire is placed next to the first one such that the SPPs supported by the individual wires can couple to each other. As the next step we demonstrate different splitting ratios by further adjusting the gap between the two wires with a resolution better than 10 nm. The couplings found in the experiment are confirmed by finite element simulations [6].

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A low-loss, broadband dielectric antenna enabling highly efficient photon collection from a coherent NV center spin in diamond

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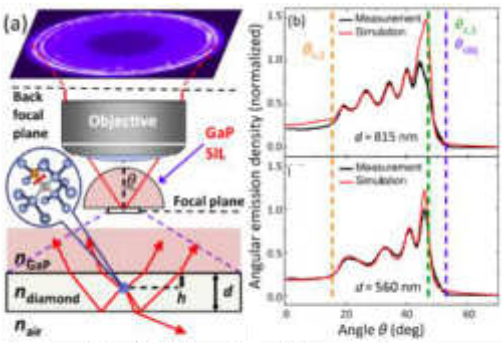
Extracting light from single quantum systems in high index, solid state materials is intrinsically challenging and highly relevant for applications in quantum information and sensing. We here introduce a novel solution to this challenge, in form of a broadband, dielectric antenna potentially enabling near unity photon collection efficiency [1]. The device efficiently redirects fluorescence of single Nitrogen Vacancy (NV) centers in a synthetic diamond membrane and thus enables efficient optical read-out of the NV's electronic spin, a process highly crucial when using the NV spin as qubit in quantum networks [2] or as magnetic sensor [3].

We implement our antenna by bonding a nanofabricated sub-Γm thick diamond membrane to a high index gallium-phosphide solid immersion lens. This procedure conserves the NV's favorable spin properties; we find coherence times T_2>100 Γs. Compared to bulk diamond, we observe strongly altered NV emission patterns in the back focal plane. These patterns allow us to demonstrate the proper operation of our antenna and to deduce a 97% efficiency of NV emission into GaP. We currently achieve single photon count rates ~1 MHz, which are limited by known loss-factors. Future improvements will allow us to further increase these rates by up to a factor of ten and thereby open exciting perspectives for quantum communication and sensing.



Schematics (left) and emission pattern (right) of the optical antenna

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Coupling effects in plasmonic nanoparticle arrays: the weak and the strong coupling regime and the effects of spin-orbit coupling

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We study the spatial coherence properties of a system composed of periodic silver nanoparticle arrays covered with fluorescent organic molecule film [1]. The evolution of spatial coherence of the structure is investigated both in weak and strong coupling regimes by systematically varying the coupling strength between the localized molecular excitons and the collective, delocalized modes of the nanoparticle array known as surface lattice resonances (SLRs). In stark contrast to pure localized excitons, the high degree of spatial coherence is maintained in the strong coupling regime, even when the mode is very exciton-like (80 %).

The effects of spin-orbit coupling are studied in periodic rectangular arrays of magnetic Ni nanoparticles [2]. We observe SLR modes in which the two directions of the lattice are coupled by the magnetic-field-controllable spin-orbit coupling in the nanoparticles. When breaking the symmetry of the lattice, we find that the optical response shows Fano-type surface lattice resonances whose frequency is determined by the periodicity orthogonal to the polarization of the incident field. In striking contrast, the magneto-optical Kerr response is controlled by the period in the parallel direction. The spectral separation of the response for longitudinal and orthogonal excitations provides versatile tuning of narrow and intense magneto-optical resonances.

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Dynamics of a quantum emitter in nonlocal dissipative periodic structures

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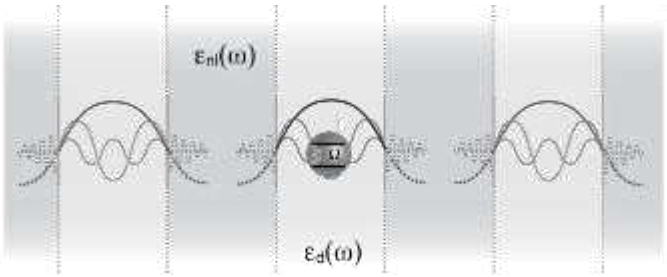
Modern technology relies more and more on the ability of building microscopic devices based on carefully designed nano-structured materials. A special class of nano-structures consists of alternating metallic and insulating layers arranged into one-dimensional periodic lattices. When carefully designed such combinations of plasmonic and dielectric materials lead—within the effective medium limit—to effective hyperbolic dispersion relations [1,2,3] that may be exploited for a number of applications such as subwavelength imaging [4], strong nonlinearities [5], emission engineering [6], and many more.

We present here [7] an approach for the description of fluorescence from optically active material embedded in these layered periodic structures. Based on an exact electromagnetic Green's tensor analysis, we determine the radiative properties of emitters such as the local photonic density of states, Lamb shifts, line widths etc.. In such systems the large wave-vector characteristics of all constituents and processes become relevant. These include the finite thickness of the layers, the nonlocal properties of the constituent metals, and local-field corrections associated with an emitter's dielectric environment. In particular, we



Sketch of the system considered in this work. An emitter placed in a dielectric layer is sandwiched between a number of identical bilayers consisting of a plasmonic and a dielectric layer. All dielectric layers are made from the same material. The plasmonic layers are also identical and different (local and nonlocal) material models are considered.

show that the corresponding effects are non-additive and lead to considerable modifications of an emitter's luminescence properties.

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Role of collective superradiant modes on the spontaneous emission in a dense cloud of atoms

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Since the pioneering work of Dicke [1] in 1954, there has been a lot of scientific interest in collective spontaneous emission by an ensemble of emitters. The decay channels of these excitations correspond to eigenstates which are described by a collective spontaneous decay rate and a collective Lamb shift, such as the super- and subradiant states [1,2].

Although the notion of collective effects has been proposed 70 years ago, there are still many open questions. In the original Dicke analysis, interactions between dipoles are not included. However, when the density of emitters is high, dipole-dipole interactions become important. In the past [2], it was thought that superradiance breaks down in the presence of dipole-dipole interaction, as that induces Van der Waals dephasing. In this work we have shown that superradiant states still exist in a mesoscopic cloud of two-level systems with a very large density, $\rho(\lambda/2\pi)^3 > 1$, with ρ the number of dipoles per unit volume. There exist superradiant states which have a given oscillatory spatial structure. Furthermore, for

a given spatial structure, they occur at the same frequency. They are very robust in the sense that the same structure is found for all microscopic realisations.

When atomic densities are large, one is tempted to introduce the concept of an effective refractive index. We propose that the above-mentioned collective superradiant modes are the most important modes for defining the effective refractive index of the cloud. To asses this hypothesis, we compare the total field scattered, the contribution of the superradiant modes and the field scattered by a homogeneous particle with the atom cloud shape and an effective refractive index. We find a very good agreement. In summary, we have found that despite the very strong interaction, superradiant modes survive in dense media. Furthermore, these superradiant modes are responsible for the usual scattering behaviour as described in the standard effective medium picture. This result establishes a connection between the collective excitation point of view of quantum optics with the macroscopic description of electrodynamics of continuous media.

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Optical diode based on the chirality of guided photons

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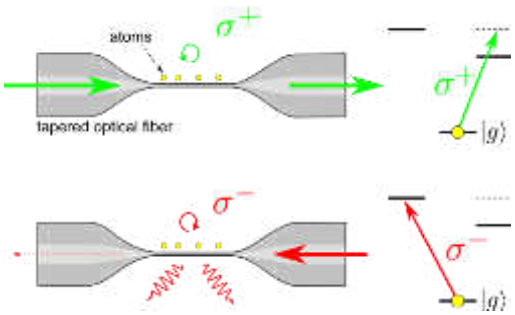
Nanophotonic components confine light at the wavelength scale and enable the control of the flow of light in an integrated optical environment. Such strong confinement leads to an inherent link between the local polarization of the light and its propagation direction [1-3], resulting in a chiral character of the light. We employ this effect to demonstrate low-loss nonreciprocal transmission of light at the single-photon level through a silica nanofiber in two different experimental schemes [4]. We either use an ensemble of spin-polarized atoms weakly coupled to the nanofiber-guided mode or a single spin-polarized atom strongly coupled to the nanofiber via a whispering-gallery-mode resonator. We observe a strong imbalance between the transmissions in forward and backward direction of about 10 dB for both schemes. Remarkably, at the same time, the forward transmissions still exceeds 70 %. The resulting optical isolator exemplifies a new class of nanophotonic devices based on the chiral interaction of light and matter, where the state of individual quantum emitters defines the directional behavior.



Optical diode exploiting the inherent link between the local polarization and propagation direction of guided light.

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Optomechanics, a platform for nanoscale quantum optics

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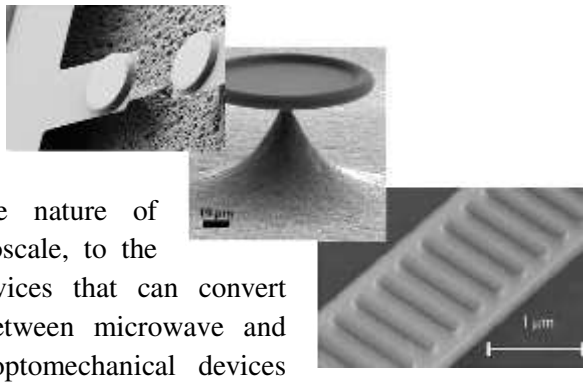
This Action brings together a wide variety of people with very different backgrounds. Rather than a technical talk, I will use my time to give an overview of optomechanics, as seen through the lens of someone actively working in the field for the last several years.



Optomechanics [1] is a thriving field that lies at the intersection between quantum optics and mesoscopic physics. It ranges in application from the very fundamental, e.g., studying the nature of quantum mechanics on the mesoscale, to the very applied, e.g., building devices that can convert classical or quantum signals between microwave and optical frequencies. Although optomechanical devices exist in a wide range of formats and sizes, a very promising approach [2] developed over the last few years brings the field into the realm of nanoscale optics and therefore closer to the central scope of this Action. In this talk I intend to briefly introduce the basic ideas underlying the field, some of its more significant theoretical and experimental results, and also the directions that the field is moving in.

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POSTER PRESENTATIONS

Evolution of 1D Airy beam propagating through a Zeeman EIT atomic medium

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We study propagation of the one-dimensional Airy beam [1] through the atomic medium with electromagnetically induced transparency (EIT) [2]. Maxwell-Bloch equations are solved numerically assuming single continuous-wave laser field resonant to the $F_g=1\rightarrow F_e=0$ hyperfine atomic transition of the ^{87}Rb D2 line. Presence of the external magnetic field removes the degeneracy of the Zeeman magnetic sublevels, bringing tripod-like atomic scheme. Characteristics of the Airy beam propagation through the EIT medium, slow-light Airy wave-packets and bullets, modulation and deflection of Airy beam, have been recently studied analytically and numerically [3, 4].

Out study analyzes how the response of the atomic medium, with induced Zeeman EIT coherences, influences evolution of the Airy beam propagation for different magnetic fields, inside or out of the EIT transparency window. Results are presented for the Airy beam intensity profile during temporal evolution and also for the deflection of the Airy beam for various propagation distances. Modulation and deformation of the Airy beam, different levels of absorption of the Airy beam lobs, while propagating through the EIT medium, are analyzed through the formation and behavior of the dark-states. Presented results suggest ways of magneto-optical control of the Airy beam and also possible applications in optical design, optical switching, optical information processing etc.

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Surface plasmons excitation in Kretschmann structure with waveguiding, amplifying and nonlinear nanoscale cover layer

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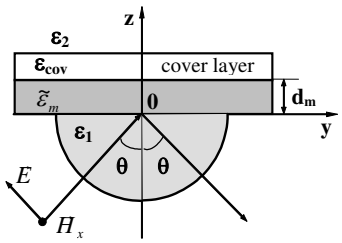

Geometry of the problem

Kretschmann structure with a dielectric covering layer of different thickness and material is analysed numerically by the method of single expression [1,2]. Surface plasmons excitation at angular interrogation is studied. The relevant Kretschmann structure with cover layer is shown in the Figure.

Thin SiO2 layer in the Kretschmann structure as a protective cover (with a thickness of few nanometers) is considered. Covering layer of around hundred nanometers thick exhibits waveguiding features and its excitation is possible at angles less than the angle of surface plasmon (SP) excitation.

Inclusion of a gain in a covering layer is analysed and compensation of intrinsic loss in a metallic layer is discussed as well. There exists minimal value of a gain for the loss compensation that is needed for the first waveguide-mode of a covering layer.

An influence of intensity-dependent refractive index change (i.e. optical nonlinearity) in the cover layer on SP excitation in Kretschmann structure is analysed. Inclusion of nonlinearity in a covering dielectric layer causes the shift of the incident wave angle of SP excitation and bistable behaviour of the angular dependence of the reflectance. At the fixed amplitude of intensive incident wave the hysteresis in the reflectance was revealed, which depends on the sign of nonlinearity. Obtained distributions of the electric field and the power flow in the nanolayers of the considered structures permit to understand the physics of nanoscale phenomena at SP excitation.

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Cavity Quantum Electrodynamics with Quantum Dots

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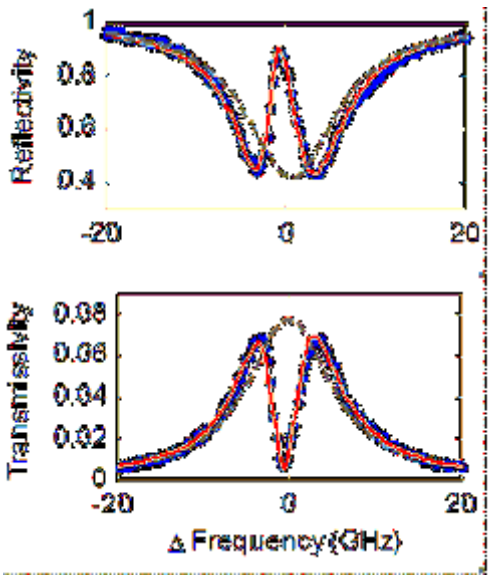
We study single InAs self-assembled quantum dots (Qdot) in a high-finesse optical cavity, in the form of an oxide-apertured AlGaAs micropillar [1]. This system is ideally suited for the generation, detection and storage of quantum states of light at the nanoscale, which is precisely the title of workgroup 1 of the COST action 'Nanoscale Quantum Optics'. This system is ideally suited because (i) it enables strong atom-field coupling, (ii) the Qdot frequency can be easily tuned with respect to the cavity via electrical contacts, (iii) the cavity can be made polarization degenerate to allow access to the polarization quantum state, and (iv) both neutral and charge Qdots can be investigated, with different level scheme and optical polarizations. Furthermore, these semiconductor systems can be integrated in opto-electronic networks with many elements and all types of functionalities, including quantum memories, quantum gates, and the potential of bosonic sampling.

The figure shows how the quantum state of a single Qdot can completely modify the reflectivity (top figure) and transmittivity (bottom figure) of an optical microcavity; the dashed curves show the corresponding measurements for an empty cavity for reference. This is just one of the many measurements that we can perform and analyze. We have also analyzed (i) avoided crossing of dressed Qdot and optical states, (ii) saturation effects at an average power of << 1 photon in the cavity, and (iii) strong hysteresis effect due to the collection of charge in nearby traps. Intriguing physics that we like to investigate further.



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Second Harmonic generation from $ZnWO_4$ single crystal and $ZnWO_4$-ZnO composites

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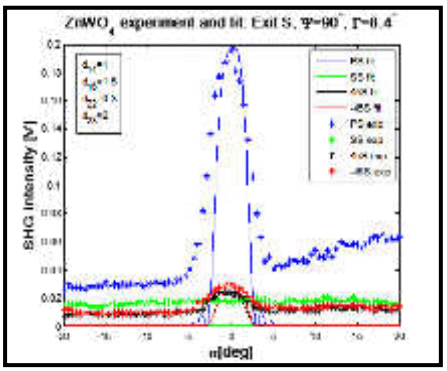
Zinc tungstate ($ZnWO_4$) has been known for its advantageous photoluminescent properties, high chemical stability and low price, and it is a promising material for various applications including scintillators, microwave devices, fiber optical communications, NO_2 sensors etc. In this work we investigate the second order nonlinear optical response from the $ZnWO_4$ single crystal samples, as well as from the two $ZnWO_4$-ZnO eutectic composites obtained by means of micro-pulling-down technique [1]. We measure second harmonic generation (SHG) in all the samples even though the known center of symmetry in the $ZnWO_4$ unit cell implies zero conversion efficiency.

In our experiment, we use a set-up similar to the one used in [2]. We fit the conversion efficiency of $ZnWO_4$ by using linear characterization from [3] and the model of *class 2* uniaxial crystals that are also monoclinic. SHG gives us an insight into the orientation of optical axis of the examined samples which is always in the surface plane. Other nonlinear processes lead to supercontinuum generation. We get the great enhancement in SHG signal for the samples with ZnO lamellas. Furthermore we are improving the fabrication process which could lead to tailoring and further control of such interesting processes in this relatively cheap and easy-to-fabricate material.



SHG from $ZnWO_4$: the s output as a function of the incidence angle α and the input polarization.

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Composite localized modes in discretized spin-orbit-coupled Bose-Einstein condensates

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The use of ultracold quantum gases, in particular bosonic and fermionic condensates, for simulating fundamental effects originating in condensed-matter physics has drawn much interest [1]. One of these effects is the spin-orbit coupling (SOC). This effect plays a major role in many phenomena and applications, including spin and anomalous Hall effects [2], topological insulators [3], spintronics [4], etc. In contrast to the complex picture found in solids, the experimental and theoretical description of SOC effects in Bose-Einstein condensate (BEC) is much simpler [5]. This has motivated our study of the impact of SOC on the immiscibility-miscibility transition in the localized complexes in BEC, which can emulate the phase transition between insulating and conducting states in semiconductor. For this purpose, we introduce a discrete model for binary SO-coupled BEC trapped in a deep one-dimensional optical lattice [6]. We consider two different types of coupling, with spatial derivatives acting inside each species, and between the species. Stable localized composite states of miscible and immiscible types are found to exist for both types of coupling. We also study how the transition between miscible and immiscible type of localized complexes depends on the SOC strength. Particularly interesting are the applications of our model to the SOC binary condensates built of infinitely heavy atoms and the binary BEC with effective atomic masses which have opposite signs.

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Controlling Coherence in Epsilon-Near-Zero Metamaterials

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The extreme-parameter metamaterials, such as epsilon-near-zero (ENZ) have attracted a great deal of attention recently. Manipulating electromagnetic waves and fields by spatially and temporally tailoring the material parameters such as permittivity and permeability offer unprecedented tools in the design of devices and components. ENZ structures "stretch" the effective wavelength inside the structure and as a result physical distances in such structures, although physically large, may behave as electrically small lengths [1, 2].

It is possible to affect the degree of coherence by spatially and temporally tailoring the material parameters. In this talk, I am going to present how an epsilon-near-zero (ENZ) medium may be utilized to increase the degree of coherence by comparing the field radiated from sources randomly vibrating in air to that in an ENZ medium.

I will present the degree of incoherence caused by randomness in the location of electromagnetic sources and how this can be reduced and controlled by embedding these sources in an ENZ environment. The concept will be first shown numerically for a collection of dipoles with randomized positions. Furthermore, I will present this phenomenon in emission of quantum sources in ENZ metastructures such as a waveguide near its cut-off frequency. ENZ materials can open up fascinating possibilities for extending the coherence length of emitters, leading to unprecedented light-matter interaction with long spatial coherence length.

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Infrared Thermal Emission by Multipolar Nanoantennas

M. Centini, A. Benedetti, M. C. Larciprete, A. Belardini, R. Li Voti, M. Bertolotti and C. Sibilia.

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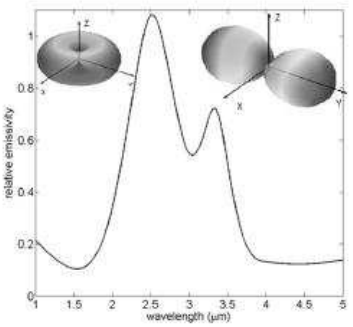
We developed a numerical model based on the fluctuational electrodynamics approach and on the discretization of the resulting volume integral equation to calculate relative emissivity and spatial emission pattern of nanoparticle ensembles smaller than the thermal wavelength $\lambda_T=hc/k_BT$ [1]. In the recent years, both metallic and dielectric nanostructures, supporting electric and magnetic resonances, have been studied in order to tailor the far field emissivity of a point source (i.e. a quantum dot) as a function of the wavelength and of the position of the feeder with respect to the antenna ensemble [2-4]. Here we show that a similar concept can be applied if thermal radiation from heated coupled nanoantennas is considered. Finally we show that the integration of designed emitters with photonic elements such as waveguides could be considered in order to manipulate the evanescent components of the emitted radiation for the creation of a new class of integrated sources.



Relative emisssissivity for an Au multipolar nanoantenna. The insets show the different emission patterns correspondind to the main peaks of emissivity.

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One-dimensional sub-wavelength atom localization via Zeeman EIT in a degenerate two-level system

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We analyze influence of the magnetic field on the 1D atom localization [1] in an atomic medium under the action of two optical fields, standing-wave and traveling-wave, probe field. Optical Bloch equations are solved numerically for the Zeeman sublevels of the hyperfine atomic transition $F_g=2\rightarrow F_e=1$ of the ^{87}Rb D1 line. For small values of the applied magnetic field, electromagnetically induced transparency (EIT) [2] can be observed. Both fields are linearly polarized, with mutually orthogonal polarizations and wave-vectors. Two configurations are considered, depending whether applied magnetic field is in the direction of the standing-wave or the probe field polarization. Information on the atom position can be achieved both from the probe field absorption and the excited state population of the atomic system i.e. overall lasers fluorescence.

Two presented configurations enable different transitions between Zeeman magnetic sublevels, thus different formation of dark-states and localization patterns i.e. atom position probability distributions within wavelength distance. Depending on the laser fields' intensity magnitudes and on the applied magnetic field, presented localization schemes provide variety of results. We analyze width and contrast of the calculated localization narrow patterns for the range of laser field intensities, both being important parameters for the experimental realization of the localization effect. It is shown that, for the choice of parameters, magnetic field can bring substantial changes on the behavior of the position-dependent atom–field interaction, dark-state population, EIT and consequently localization effect. 2D localization effect via coherent magnetic field has been recently analyzed [3] by utilizing magnetic dipole allowed transition in a triangle atomic scheme.

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Photonics of metal oxides: Formation of organic molecules over their surfaces

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Metal oxides are well known for their photo activity. The fundamental or applied research is therefore focused on their application in chemical synthesis, water or air cleaning, light converting or light harvesting systems. However, one challenging topic is focused on a little bit different problem: Their possible role in formation of organic substances in the universe. These minerals (particularly TiO_2) have been found on Mars [1],[2] or in interstellar space [3]. Therefore, one branch of our research deals with photonics over the metal oxides surfaces which may occur on various stellar bodies like terrestrial planets and/or comets [4]. We have studied several chemical reactions of inorganic molecular gases (CO_2) or simple prebiotic precursors (HCHO, $HCONH_2$) over the TiO_2 surface upon laser and broad band UV irradiation. The reaction products were analyzed with high resolution FT absorption spectrometry and GC-MS chromatography. The goal of this ongoing study is to investigate the ability of the metal oxides to produce organic molecules (hydrocarbons, sugars) under conditions of various interstellar bodies and primordial Earth. Our newest results on photonics and photochemistry of metal oxides show that basic prebiotic molecules (glycolaldehyde, sugars) and hydrocarbons (methane) are formed from simple parent molecules. The research answers fundamental questions including sugars synthesis umpolung problem or photochemical sources of methane in atmospheres.

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Photon detectors based on High Tc Superconductors

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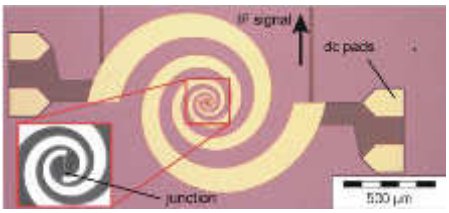
In the past years, we have been developing High-Tc Josephson nano-junctions made by ion irradiation [1]. Based on commercial $YBa_2Cu_3O_7$ thin films, this versatile and highly scalable technique opens a new route towards superconducting electronics in the temperature range between 20K and 80K. DC [2] and RF applications have been explored, with very encouraging results.

In particular, we built a heterodyne High-Tc Superconductor (HTSc) receiver in the THz range, made of a Josephson mixer embedded in a broad-band antenna, operating at 50K-60K. High-frequency mixing properties of such device up to 420 GHz has been obtained, with interesting conversion gain [3]. Accurate modeling of the detector was made using a three-ports model.



Heterodyne Josephson receiver made by ion irradiation of HTSc

We now develop a new project using ion irradiation patterning of HTSc thin films. The goal is to make HTSc Superconducting Single Photon Detectors (SSPD), operating at higher temperature and higher speed than commercially available SSPDs. Meander line nanowires are patterned on ultra-thin (10 to 30 nm thick) $YBa_2Cu_3O_7$ films, and polarized with a DC current close to the critical current. Incident photons locally destroy the superconducting state, and a voltage pulse is recorded. First DC characterization of nanowires (50 to 500 nm wide) will be presented.

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Proposal for an all-silicon integrated single-photon source by unconventional photon blockade

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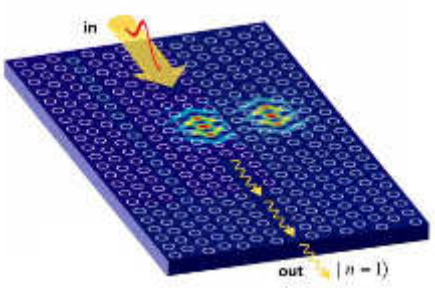
Integrated single-photon sources working in the typical telecommunication band would represent a useful building block in quantum photonics devices. Ideally, pure single-photon states require a two-level emitter as a source. Although the recent progress in fully integrated and telecom-compatible quantum photonics technologies, the ability of generating single-photon states on-chip is still lacking, owing to the lack of efficient quantum emitters at such wavelengths. As an alternative, single-photons can be generated through the photon blockade effect, but ordinary nonlinear materials require a large number of photons to produce appreciable effects, owing to the intrinsically small nonlinear susceptibilities in the bulk [1].

Here we propose an alternative all-silicon device that employs a different paradigm, namely the interplay between quantum interference and the third-order intrinsic nonlinearity of silicon in a system of two coupled optical cavities [2,3]. This *unconventional photon blockade* allows to produce single photons at extremely low input power. We demonstrate how to operate this mechanism under pulsed optical excitation, as required for device applications, and propose a state-of-art implementation in a standard silicon-based photonic crystal integrated circuit with the smallest footprint area, as schematically represented in the figure.



Representation of a single photon source integrated in a photonic crystal platform

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Micro-photoluminescence study of local emission of Quantum Dots in Core-Shell GaAs/AlGaAs Nanowires

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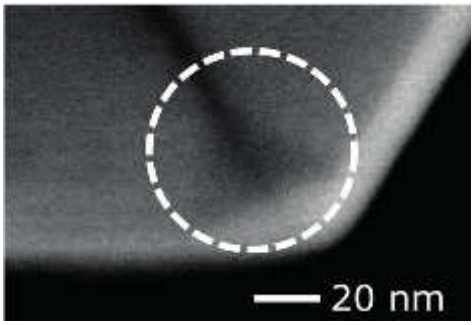
In the last few years quantum dots (QDs) have been shown as ideal components for quantum photonic devices. They are excellent candidates for controlled single-photon emitters and efficient detectors thanks to their high sensitivity to local electric and magnetic fields. In both cases, full exploitation of QD properties can be achieved if they are embedded in nanowires (NWs) [1]. Bright single-photon emitters with narrow emission lines have been recently obtained [2] by molecular beam epitaxy as self-assembled QDs embedded in GaAs/$Al_xGa_{(1-x)}As$ core/shell nanowires. They have been studied in this work by means of large-scale micro-photoluminescence at 14K in order to understand the mechanisms leading to the QD self-nucleation and consequent growth. In particular, the QD occurrence and emission energy in function of the NW radial structure and shell thickness is considered. We found that the QD density increases with the NW shell thickness in a non-monotonic way. A minimum thickness threshold is necessary to observe QD emission. We show that the deposition of an AlAs pre-deposition layer on the core facets can lower this threshold. In addition, an overlook in the QD-size growth is given by the evolution of the emission energy distributions. Being established on the analysis of several hundreds of emitters, our study provides statistically valid results. SEM investigations on fewer NWs provide a more detailed morphological insight in agreement with the statistical outcome. These results are consistent with previous explanations [2,3] of emission due to Ga-rich nano-formations in the AlGaAs shell.



HAADF-STEM image of a GaAs-AlGaAs NW cross section. Zoom of one NW corner. In the circle an Al-poor QD is visible as a triangular region in the shell.

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Addressing a single photon source by a nanowaveguide

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The integration of single photon emitters with optical buses has recently attracted great interests in the realm of photonic integration, as the generation and transfer of single photons become essential in quantum information processing (QIP) [1]. Many platforms, such as photonic crystals and cavities involving complex fabrications, have been proposed towards the collection of light from single nanoscale emitters, while only a few of them tackle the issue of effectively addressing a single photon emitter [2]. Herein we report a simple strategy to realise the localised excitation of a single photon source made of a CdSe/CdS nanocrystal using a nanowaveguide made of a single ZnO nanowire, which acts as a passive or an active sub-wavelength nanowaveguide to excite the single photon source, depending on whether we use above or below bandgap energy to couple light into this nanowire waveguide. The efficient excitation of the single photon source and the waveguiding behaviour within the nanowire in active and passive cases are

characterised using a photoluminescence set-up corroborated by FDTD simulations, as well as using a Hanbury-Brown and Twiss interferometer for photon correlation measurements. Combined with the intriguing properties of semiconductor nanowires, such integration can be extended to various applications, for instance electrically driven single photon emitter, efficient single photon detection and quantum information interconnect between nodes.

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Spectral Dynamics of NV centers in the vicinity of a mirror

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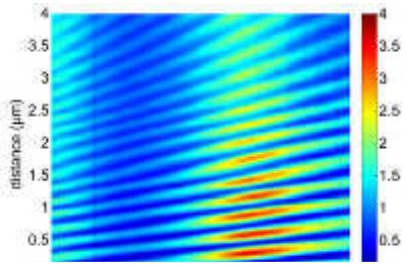
Compared to a homogeneous optical environment, the spontaneous emission rate of a dipole emitter can be strongly modified when the emitter is placed in the vicinity of a planar reflecting interface such as a silver mirror. Measurements of the spontaneous emission rate as a function of emitter mirror distance can for instance be used to determine the dipole orientation of the emitter, its internal quantum efficiency [1], and to reveal higher order transition moments [2].

In this contribution we report on strong modifications of the emission spectrum of nitrogen vacancy (NV) centers placed in the vicinity of a planar silver mirror. NV center ensembles were prepared via nitrogen implantation and annealing about 10 nm below the surface of an electronic grade diamond sample. Silver was deposited on the end facet of a cleaved optical fiber, and the fiber was placed with a piezo stage in the vicinity of the diamond.



Experimentally measured spectral enhancement of NV centers vs. distance to a planar silver mirror.

We model the vibronic spectrum of the NV center by applying the Franck-Condon principle, and use a rate equation model to determine the spectral enhancements.

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Nonequilibrium terahertz conductivity in materials with localized electronic states

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A broad range of disordered materials contain electronic states that are spatially well localized. In this work [1] we studied the electrical response of such materials to external terahertz electromagnetic field. We obtained expressions for nonequilibrium terahertz conductivity of a material with localized electronic states and weak electron-phonon or electron-impurity interaction. The expression is valid for any nonequilibrium state of the electronic subsystem prior to the action of external field. It gives nonequilibrium optical conductivity in terms of microscopic material parameters and contains both coherences and populations of the initial electronic subsystem's density matrix. Particularly, in the case of incoherent nonequilibrium state of the electronic subsystem, the optical conductivity is entirely expressed in terms of the positions of electronic states, their nonequilibrium populations, and Fermi's golden rule transition probabilities between the states. The same mathematical form of the expression is valid both in the case of electron-phonon and electron-impurity interaction. Moreover, our result for the nonequilibrium optical conductivity has the same form as the expressions previously obtained for the case of equilibrium. Our results are expected to be valid at sufficiently high frequencies, such that the period of the external field is much smaller than the carrier relaxation time. We apply the derived expressions to two model systems, a simple one-dimensional Gaussian disorder model and the model of a realistic three-dimensional organic polymer material obtained using previously developed multiscale methodology [2]. We note that the simple one-dimensional model captures the essential features of the mobility spectrum of a more realistic system. Furthermore, our simulations of the polymer material yield the same order of magnitude of the terahertz mobility as previously reported in experiments.

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Controlling the emission quantum efficiency of Er^{3+} ions by near-field coupling with plasmonic nanohole array

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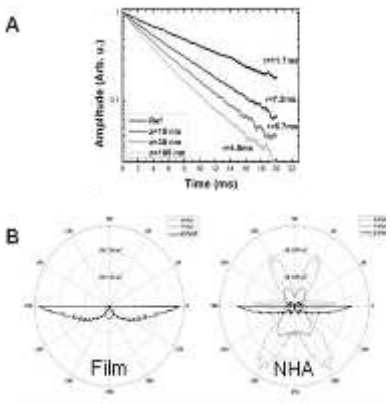
Due to its intense room temperature emission at λ_{em}=1.54 μm, the Er^{3+} ion is the main optical dopant for many optoelectronic applications. The long lifetime of characteristic transition $^4I_{13/2} \rightarrow ^4I_{15/2}$ of Er ions (about 12 ms) is one of the major limitations in the realization of photonic and optoeletronic devices based on Er-doped materials, because the long permanence of the ion in the excited state makes it prone to non-radiative decay processes such as energy migration, cooperative up-conversion and concentration quenching [1]. Since the early work of Purcell [2], it is well known that the variation of the local photonic density of states can modify the spontaneous emission rate of the emitter.



(A) Variation of the Er^{3+} PL decay curves at λ_{em}=1540 nm as a function of the distance from a Au NHA. (B) FEM simulated angularly resolved power outflow of Er emitter placed 50 nm below a Au film and a NHA

In the present work, we investigated the variation of the emission quantum efficiency of Er^{3+} ions in silica layers due to the interaction at sub-wavelength distance with Au plasmonic nanohole arrays (NHA), whose Extraordinary Optical Transmission (EOT) peak is resonant with the Er^{3+} emission wavelength [3]. Time-resolved photoluminescence (PL) measurements have shown a strong decrease of the Er lifetime. The modification of the local density of states arising from EOT and a resonant coupling with surface plasmon polariton modes is investigated experimentally and by finite-element method (FEM) electrodynamic simulations.

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Absence of mutual polariton scattering for strongly coupled surfa ce plasmon polaritons and dye molecules with a large Stokes shift

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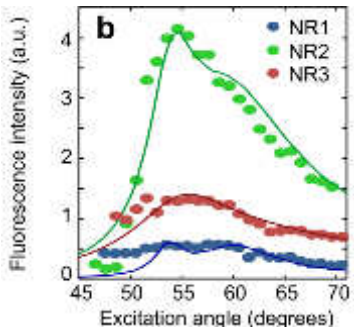
During the last decades surface plasmon polaritons (SPPs) have attracted vast interest due to promises of optics beyond the diffraction limit. Of particular interest is also strong coupling between SPPs and molecular excitations (ME) arising from the strongly enhanced light-matter interaction, and manifesting itself through a formation of new SPP-ME hybrid modes exhibiting Rabi splitting even up to several hundreds of meV [1,2]. These modes could provide the missing non-linearity to enable interactions needed for any optical component. Also the dynamics of these modes can differ dramatically from the dynamics of either SPP or ME, and can significantly affect the chemical properties of the molecules involved [3].

We have demonstrated strong coupling between SPPs and various molecules [2], and in all of them the fluorescence of MEs reveals the coexistence of the strongly coupled polariton modes and non-coupled MEs. As the molecular fluorescence is directly related to the ME occupation, it provides an ideal tool for studying the polariton dynamics. Here we have utilized dye molecules with an especially large Stokes shift, i.e. Nile Red (NR), to demonstrate the absence of scatterings among the polariton branches and to show that the modes decay directly via dephasing and internal relaxation of the molecules to a fluorescing state [4]. This result provides essential information on the dynamics of the strongly coupled modes.



Measured fluorescence (circles) for three NR-samples together with the quantum mechanical model (solid lines)

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Nanostructuring of multilayered thin films by femtosecond laser beam

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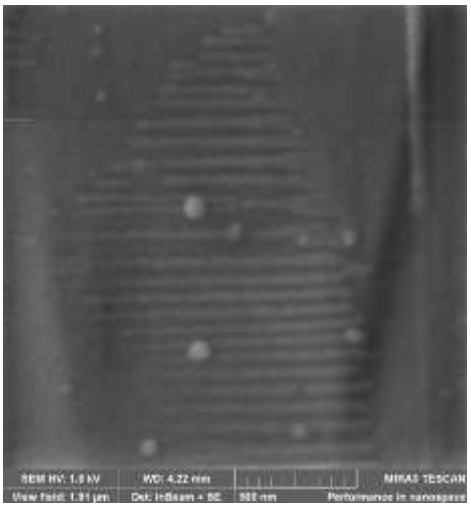
Thin films have a wide area of application, from semiconductor technology to other fields like optics, chemistry, mechanics: coatings for reflection/antireflection, filtering, protection, diffusion barriers, waveguiding, sensing and decorative purposes. Thin films can enhance characteristics by structuring. The use of ultrafast laser beams to generate structures on thin films gains more and more interest. Such interaction yields the generation of nanoparticles which tend to regroup on the surface and form the structures. Nanoparticles are of great interest due to their position between bulk materials and atomic/molecular structures. We have used low-fluence femtosecond beam of various wavelegths and expositions on thin film samples: Al on Si, Al/Ti multilayer on Si and multilayer graphene on SiO_2. Graphene is a material of outstanding electronic, optical, magnetic, thermal and mechanical properties, and Al/Ti films have an important mechanical applications due to their extraordinary wearing behavior and corrosion resistance. The exposition yielded the generation of nanoparticles and the formation of subwavelength laser-induced periodic surface structures (LIPSS). In Al and Al/Ti samples, preferential radius of nanoparticles was ~25–75 nm; spatial period and width of LIPSS were ~320 nm and ~200–220 nm, respectively [1]. In graphene, preferential radius of nanoparticles was ~18 nm; spatial period and width of LIPSS were ~70–100 and ~35 nm, respectively [2].



LIPSS on multilayer grapheme.

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High intensity broadband source of energy-entangled photons for spectroscopy

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When pumped by a narrowband laser, photon pairs produced by spontaneous parametric downconversion can show strong correlations in energy, i.e. the energy of both photons from the pair sums up to the energy of the pump laser, which is well defined. On other hand the energy of each photon from the pair can take any value from a large spectrum, depending of the phase matching in the emission process. Therefore broadband energy entangled photons possess simultaneously broadband and narrowband features. It has been theoretically predicted that using such quantum light for two-photon spectroscopy allows to reveal spectroscopic features not accessible with classical light [1]. However no experimental demonstration has been realized up to now because it requires a high flux of entangled photons together with the capability to manipulate their spectrum. We are presenting here a high flux source of highly entangled photons, pushing the creation rate to the limit of multiple pair emission. The photon pairs are subsequently manipulated in their energy spectrum by means of a pulse shaper, inspired from ultrafast optics setup. In order to characterize the source and the spectral manipulation capabilities, the photons are detected by sum frequency generation in a non-linear crystal. This allows to study the two-photon state with femtosecond resolution. The temporal correlation function of the two-photons can thus be measured. Moreover the influence of dispersion on the state can be demonstrated. Because the entanglement content of those states is intrinsically very large [2], they are suited to study entanglement between highly dimensional states. With our setup we demonstrated the implantation of quantum state tomography on frequency-bin entangled qutrits and ququarts and the measurement of Bell operators as entanglement witnesses [3]. Moreover the scheme can be extended to other discretization procedures [4].

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Single molecule fluorescence coupled to dielectric waveguides: a new route towards integrated single photon sources

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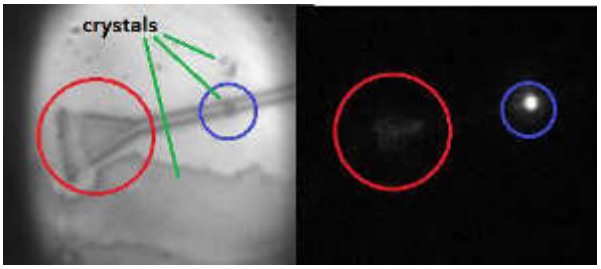
We here discuss a new kind of solid-state single-photon source based on organic molecule emitters efficiently coupled to dielectric waveguides [1]. We investigate a simple device consisting of single emitters (Dibenzoterrylene molecules (DBT) hosted in anthracene crystals [2,3]) placed very close (tens of nanometers) to dielectric Si_3N_4 waveguides. In this work we present a first evidence of molecules excitation through light coupled into a waveguide.



CCD images of one waveguide with DBT:Ac crystal: white light image (left) and DBT fluorescence detection (right). Confocal laser excitation is focused on the coupler (red circle). The blue circle indicates the crystal responsible for the fluorescence (15 um apart from the illuminated region).

The potentiality of this approach is also explored by means of numerical simulations aimed at finding the optimal guiding structure for this application. Single emitter photon coupling into a single waveguide mode up to 30% is anticipated.

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One-dimensional superconducting photonic crystal with dielectric defect layer

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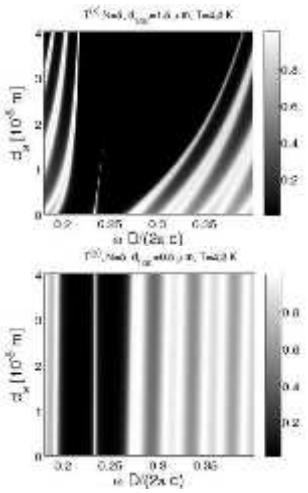
Investigation of the superconducting (SC) photonic crystals (PCs) is one of intensively developing directions in modern photonics [1]. The majority of publications devoted to SCPC, refers to study of the ideal PCs with regular structure. It is well known that periodicity violation leads to appearance of the defect modes inside the photonic band gaps. In our papers [2, 3] we investigated 1D PC with complex defect composed of dielectric and SC layers and showed strong dependencies of the defect mode's intensities and positions on the thickness of SC layer and temperature. In this communication, we present the theoretical analysis of the spectra for the inverse PC, namely, ternary SCPC with a dielectric defect layer. We calculated the variation of transmitted spectra of the SCPC of the structure $(ASB)^5D_B(BSA)^5$, where A is strontium titanate $SrTiO_3$, B is aluminium oxide Al_2O_3, and S is high-temperature superconductor $YBa_2Cu_3O_7$. The dependence of transmission spectra for two polarizations of light on the thickness of SC constituent for the fixed thickness of defect layer is presented below.



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Entanglement with negative Wigner function of 3000 atoms heralded by a single photon

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For measurements on N uncorrelated atoms in a coherent spin state (CSS), quantum projection noise sets the limit of precision known as the standard quantum limit, which scales as $1/\sqrt{N}$. Entangled states can reduce projection noise and overcome this limit, and are now recognized as a resource for quantum information processing, secure communication and precision metrology. Hence an important goal is to create the entangled states of many-particle systems while retaining the ability to characterize the quantum state and validate entanglement. In our work we generate entanglement of several thousand atoms by detection of a single photon that has interacted with the ensemble. We reconstruct a negative-valued Wigner function, an important hallmark of non-classicality, and verify an entanglement depth of 90% atoms in the ensemble.

An ensemble of 3100 ± 300 laser-cooled ^{87}Rb atoms with total spin S is confined in an optical cavity and prepared in a CSS along **x**-axis, with quantization **z**-axis determined by a magnetic field along the cavity. A 780-nm probe laser is coupled into the cavity with single-atom cooperativity $\eta < 1$. A single vertically-polarized (along **x**) probe photon with detuning Δ from the atomic resonance passes through the cavity and experiences Faraday rotation. If the photon is detected with horizontal polarization upon exiting the cavity, the atomic ensemble is projected into non-Gaussian entangled state of collective atomic spin, i.e., the first excited Dicke state [1] along **x**, which displays a negative-valued Wigner function of -0.36 ± 0.08 and entanglement depth of 2910 ± 190 out of 3100 atoms. This is the first time a negative Wigner function and the mutual entanglement of virtually all atoms have been attained in an ensemble containing more than a few particles.

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A Pulsed Nonclassical Light Source Driven by an Integrated Electrically Triggered Quantum Dot Microlaser

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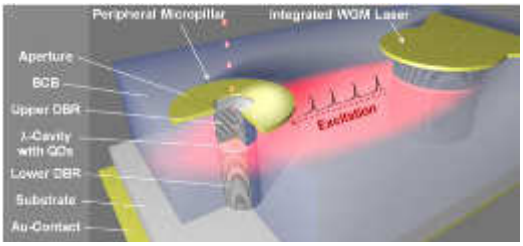
The generation, manipulation, and detection of single photons on an integrated platform is actively pursued within the nanophotonics community [1]. Linear optics-based quantum information processing [2] and quantum cryptography schemes [3] utilizing, e.g., the polarization of single photons, would greatly benefit from the compactness and efficiency afforded by such architectures.



Schematic of the device, showing the peripheral target micropillar which is laterally excited by an electrically triggered WGM microlaser.

Here, we present a novel compact nanophotonic device consisting of a nonclassical light source excited by a monolithically integrated and electrically driven quantum dot (QD) microlaser. Our device concept is based on self-assembled InGaAs QDs embedded in micropillar cavities. Electrically driven micropillars act as whispering gallery mode (WGM) microlasers operated either in continuous or pulsed mode, with repetition rates up to 150 MHz. These microlasers are used as on-chip excitation sources to laterally excite individual QDs in nearby micropillars, which in turn act as vertically emitting nonclassical light sources. We demonstrate the generation of antibunched light in continuous and pulsed operation, demonstrating the potential of our compact solid-state platform for the generation of triggered single photons on a highly integrated chip.

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Wavelenght filtering of the emission at 1.3 µm of a single InAs quantum dot by using a tunable fibre Bragg grating

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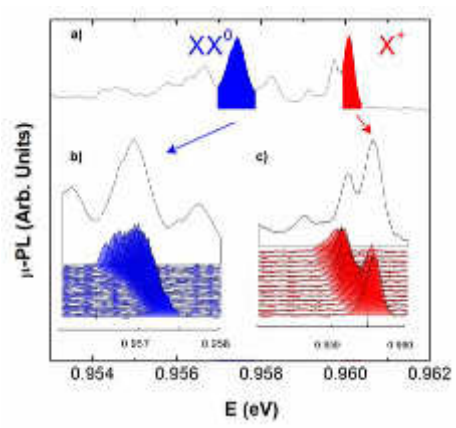
We propose a novel µ-Photoluminescence (µ-PL) characterization technique of single Quantum Dots (QDs) based on the light filtering through a wavelength tunable Fiber Bragg Grating (FBG) instead of a standard monochromator [1]. The wavelength tuning capability (figure 1), together with the increased light collection efficiency of the FBG, offer a great advantage to study transient µ-PL (µ-TRPL) of the different excitonic transitions, by using conventional InGaAs APD detectors. Along with these operational improvements, the wavelength tunable FBG offers an efficient, but easy and cheap alternative characterization tool, which could be easily integrated into more complex signal treatment schemes, as phase or amplitude modulators. With the help of our set-up improvement, we studied µ-TRPL from single QDs emitting at 1.3 µm (grown by MBE on metamorphic substrates [2]) at low temperatures. The efficient FBG filtering could be used to improve the signal to noise ratio in photon correlation experiments, and develop a more efficient single



Wavelenght filtering of the µ-Photoluminescence emission from XX^0 (b) and X^+ (c) QD optical transitions with Fiber Bragg Grating. Black lines corresponds to the standard monochromator adquisition.

photon collection in the telecom wavelengths (1300 – 1500 nm) with standard InGaAs APD detectors.

In future applications, our FBG filtering method applied to the XX^0-X^0 cascade emission could be used to force the entanglement [3], and, hence to demonstrate that our QDs can be used as a single photon emitters (preliminary results of HBT experiments will be presented), or sources for polarization photon entanglement.

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Propagation of Raman–Ramsey pulses through Rb buffer gas cell under condition of Zeeman Electromagnetically Induced Transparency

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Experimental and theoretical investigation of time development of Zeeman electromagnetically induced transparency (EIT) [1] during propagation of two time separated polarization laser pulses through Rb vapour is presented [2,3]. The laser pulses were produced by modifying laser intensity and degree of elliptical polarization. The single laser beam is frequency locked to the hyperfine Fg=2 → Fe=1 transition of the D_1 line in ^{87}Rb.

Transients in the intensity of the σ^- component of the transmitted light are both measured and calculated at different values of the external magnetic field, during the first (preparatory) and the second (probe) pulse. Zeeman EIT resonance at a particular time instant of the pulse propagation is reconstructed by taking normalized σ^- transmissions at various magnetic fields at given time. From these results, the dependence of EIT line shapes, amplitudes and linewidths on the laser intensity, Ramsey sequence and the Rb cell temperature are examined.

It is shown that at early times of the probe pulse propagation, several Ramsey fringes are present in EIT resonances, while at later moments a single narrow peak prevails. Time development of EIT amplitudes are determined by the transmitted intensity of the σ^- component during the pulse propagation.

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Propagation and survival of frequency-bin entangled photons in metallic nanostructures

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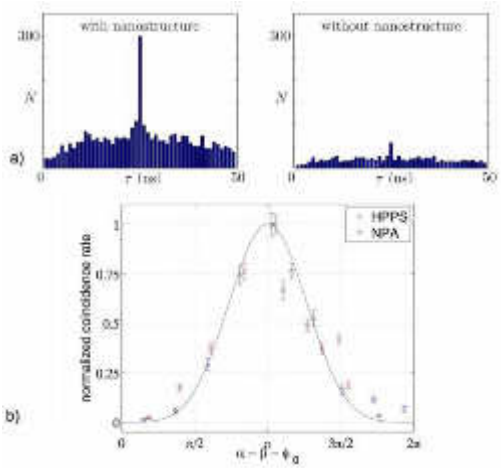
Here we present an analysis of interactions of frequency-bin entangled photons with different plasmo- photonic nanostructures i.e. a nanosphere (HPPS) array and a nanopillar (NPA) array respectively. Specifically, in this study we address two pivotal questions. First, in which cases and to what extent does frequency-bin entanglement survive when a photon is subject to a plasmonic conversion? Second, could the nature of a resonance affect the coherence of the photon-plasmon-photon conversion process? Figure a shows typical results performed on our structures. Experimental measurements extracted from coincidence peaks (Figure b) are in good agreement with the predictions. After subtraction of the background noise, large net visibilities are obtained. In conclusion, we find no evidence for decrease of coherence when photons are converted to mesoscopic electronic excitations. Indeed the only parameter that seems to influence the results are the losses of the samples, which are much higher for a flat gold film than for the investigated plasmonic structures due to the existence of plasmonic resonances.



Electromagnetically induced transparency in spherical quantum dot with on-center hydrogen impurity in magnetic field

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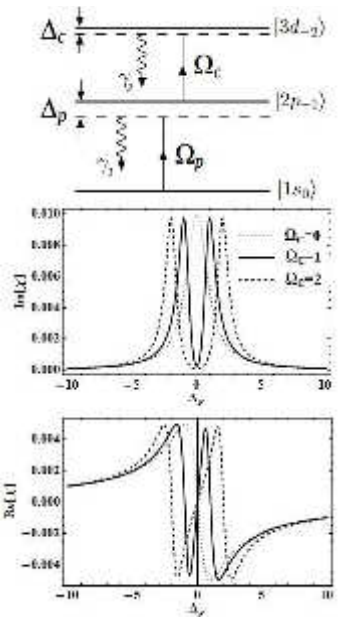
Electromagnetically induced transparency (EIT) is an atomic coherent effect that permits propagation of electromagnetic radiation without attenuation through otherwise opaque medium [1]. In recent years, this phenomenon has been investigated in nanostructures such as semi-conductor quantum wells and quantum dots (QD) due to their practical applications (e.g. in telecommunications, optoelectronic devices, EIT-based quantum memories) [2 - 4].

In this paper we have analyzed the realization of EIT with hydrogenic impurity located in the center of 3D spherical QD in the presence of static magnetic field at intermediate strength. The energy levels of impurity $1s_0$, $2p_{-1}$ and $3d_{-2}$, which are included in consideration, together with probe and control laser fields, inducing σ^- transitions, form a ladder-type three-level atom. The optical Bloch equations in steady-state regime are solved and it is discussed dependence of the susceptibility on the QD radius R_0, Rabi frequency of coupled field $\mathbf{\Omega_C}$, detuning of the probe field Δ_p and magnetic field strength B_0.



Imaginary and real part of susceptibility vs. probe field detuning with R_0=8 a.u.* and B_0=0.5 a.u.* .

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Perforated SOI Microring Resonators for Enhanced Light Matter Interaction

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A novel perforated microring resonator structure with low relative permittivity material defects has been proposed for enhancement of light matter interaction, sensing and applications in nanoscale quantum optics. The device fabricated on a Silicon-on-Insulator (SOI) platform. We present numerical simulations of the perforated optical microring resonator based finite-difference time domain (FDTD) and finite-element methods (FEM). The bottlenecks of simulation time for FDTD method were resolved by harnessing graphical processing unit (GPU) computation techniques. It was shown that GPU based FDTD implementation performs the same simulation task up to 18 times faster.

The performance in enhancement of light matter interaction of perforated microring resonator in bulk and surface sensing schemes has been analyzed. We show that our proposed refractive index sensor based on a modified microring resonator significantly outperforms ordinary microring resonators. The presented perforated microring resonator allows for variation of both, the quality factor and the sensitivity, making it applicable in many optical applications. Our design not only achieves high sensitivity, but also increases the total area of the interface between the microring resonator and the surrounding medium, which enhances the light matter interaction, and has high potential in nanoscale quantum optics applications.

The initial device fabrication results are discussed. It is shown that microring resonator with sub wavelength perforations enhances SOI ring sensor sensitivity 3-5 times. The microring resonator with a first order Bragg grating and a defect mode has large spatial detection resolution and wider free spectral range (FSR). On the other hand, if the microring is modified with a second order Bragg grating, the resulting structure can be used for vortex sensors and micro-manipulation of particles.

Different strategies towards the deterministic coupling of a Single Quantum Dot to a Photonic Crystal Cavity Mode

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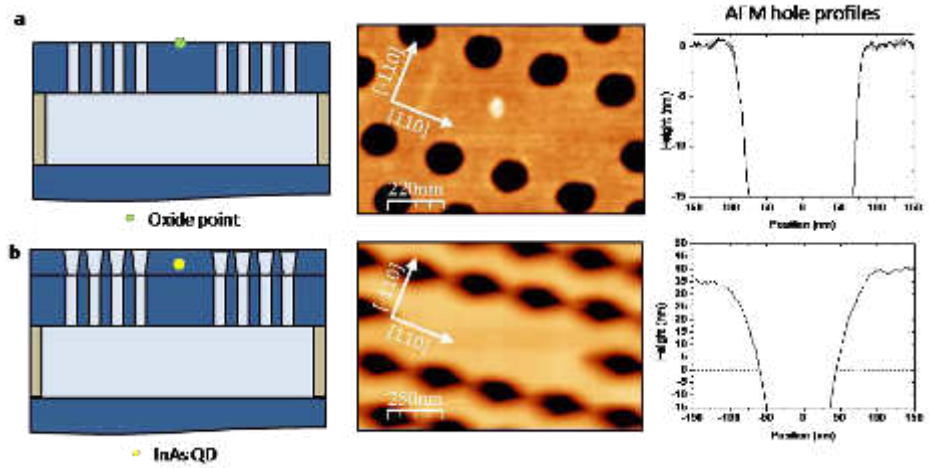
In this work we present two strategies for coupling of InAs site-controlled QD with the mode of GaAs- based PC nanocavities. In both approaches InAs QD are formed at specific sites of the GaAs surface defined by the presence of nanoholes formed after desorption of the GaAs oxide points obtained by AFM local oxidation lithography. These site-controlled nanostructures show good optical emission properties and are efficient quantum emitters operating as single photon sources. In both approaches the photonic crystal nanocavities are fabricated by *e*-beam lithography and dry etching on GaAs epitaxial layers grown by molecular beam epitaxy.



Site controlled InAs QD fabrication at the maximum of the electric field of a pre-patterned photonic crystal cavity. (a) Fabrication of the photonic crystal structure and GaAs oxide dot (AFM local oxidation); (b) The structure is completed by a regrowth process up to 140nm thickness with an embedded site-controlled InAs QD placed 20nm below the surface.

Polaron transport in nanocrystal solids

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Colloidal quantum dot supercrystals are novel nanostructured materials which appear very promising in potential optoelectronic applications and for fundamental study of electronic transport properties in condensed matter physics. Recent fabrication of high quality supercrystals with relatively strong inter-site electronic coupling and high size monodispersity enabled high carrier mobilities that slightly increase with decreasing temperature. Due to such temperature behaviour it is believed that such transport is so called coherent band-like transport.

We developed an accurate model accounting for electron-phonon interaction in colloidal quantum dot supercrystals that allowed us to identify the nature of charge carriers and the electrical transport regime. We find that in experimentally relevant CdSe nanocrystal solids the electron-phonon interaction is sufficiently strong that small polarons localized to single dots are formed. Charge-carrier transport occurs by small polaron hopping between the dots with mobility that decreases with increasing the temperature. While such a temperature dependence of mobility is usually considered as a proof of band transport, we show that the same type of dependence occurs in the system where transport occurs by small polaron hopping.

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Directional couplers based on open and closed waveguide arrays

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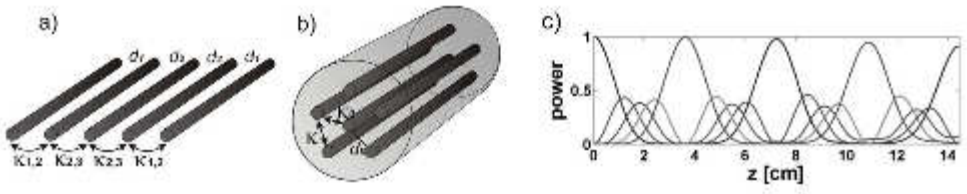
Multiport optical couplers are of great interest as interferometric beam splitters in quantum optics and sensing [1]. They are realized by concatenating or nesting single-mode two-port couplers, or by using multimode interference. Here, we propose alternative multiport optical couplers based on open and closed finite waveguide arrays in two compact architectures: planar waveguide arrays (WGA) and circular multicore fibers (MCF). Directional coupling is based on periodic energy exchange between waveguides achieved by engineering their coupling coefficients to yield the eigenvalues of the system coupling matrix commensurable.



a) WGA, b) MCF, c) an example of periodic energy transfer in a realistic 5-guide open array.

Equal coupling coefficients render periodic propagation dynamics in the case of M=2,3 for WGA and M=2,3,4,6 for the circular array, where M is the number of cores. Starting from the eigenvalue commensurability condition, we derive ratios between the coupling coefficients that render periodicity for M=4,5 WGAs, [2]. We also consider adding the central core to the MCF and derive an additional condition for the coupling coefficients that should be fulfilled to achieve periodic dynamics.

We use these findings to design 1x2, 1x4 and binomial directional couplers. They are of interest for optical circuits, multipath interferometers and coherent energy transport. The results are corroborated by numerical simulations of realistic WGAs.

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Operating Quantum Dot Single-Photon Sources Using a Compact Stirling Cryocooler

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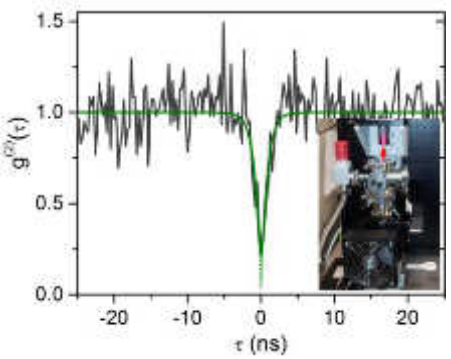
The emerging field of quantum information technology has become a major driving force for the development of easy-to-operate single-photon sources (SPSs) [1] and detectors [2]. To realize practical solid state based SPSs, mainly two different routes can be pursued: first, specific materials can be used to achieve room temperature operation, and second, an easy-to-handle cooling technique can be applied to operate readily available high-quality single-photon emitters at cryogenic temperatures.

Here, we report on the application of a compact and user-friendly Stirling cryocooler (c.f. Figure inset) in the field of nanophotonics. The Stirling cryocooler is used to operate a single quantum emitter constituted of a semiconductor quantum dot (QD) at a temperature of (28.79 ± 0.07) K [3]. Proper vibration decoupling of the cryocooler and its surrounding enables free-space micro-photoluminescence spectroscopy to identify and analyze different charge-carrier states of a single quantum dot. As an exemplary application in quantum optics, we perform Hanbury-Brown and Twiss experiments demonstrating a strong suppression of multi-photon emission events with $g^{(2)}(0) < 0.04$ from this Stirling-cooled single quantum emitter (c.f. Figure).



Photon-autocorrelation measurement of a single quantum dot operated with a plug-and-play Stirling cryocooler (see inset).

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White light generation and non-linear optical properties of Ag nanoclusters and nanoparticles dispersed in the glass host

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Ag- doped bulk oxyfluoride glasses have been prepared by conventional melt-quenching method. The photoluminescence excitation and emission spectra of the as-prepared glass cover wide range from 300 to 500 nm and from 400 to 900 nm, respectively, corresponding to the typical spectra of Ag nanoclusters with size less than 1.2 nm [1, 2]. The particular preparation conditions result in a glass with white light luminescence based solely on emission of Ag nanoclusters under excitation in UV [3]. Likewise, the white light generation may be achieved via co-doping with Tm^{3+} ions emitting in the blue region [4]. The quantum yield of the prepared glasses was found to be up to 70% [1]. The as-prepared glasses were heat-treated at 350 ^{o}C (below glass transition temperature) preserving glassy state of the samples. Under heat-treatment the Ag nanoclusters coalesce into the amorphous nanoparticles larger than 2 nm exhibiting a broad surface plasmon absorption band centered at 480 nm in the visible range. These amorphous Ag nanoparticles do not emit light due to the ascribing plasmonic properties. Open aperture z-scan experiments were conducted using 480 nm nanosecond laser pulses. These experiments revealed that the Ag nanoclusters and nanoparticles exhibit non-saturated and saturated non-linear absorption with large non-linear absorption indices, respectively [5]. The prepared glasses may be applied for white light generation under UV excitation, optical limiting and object's contrast enhancement.

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Slow-Light Metamaterials

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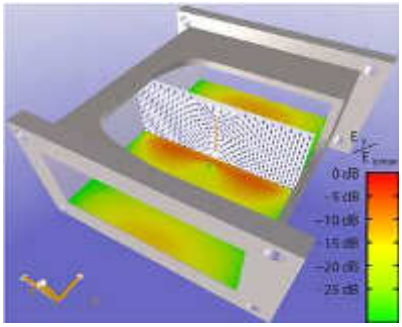
I will discuss the state-of-the-art in slow-light metamaterials [1], i.e., effective media in which light propagates at a group velocity much smaller than the speed of light in vacuum. Slow-light metamaterials are based on a classical analogue of electromagnetically induced transparency. The metamaterials consists of a radiative meta-atom coupled by near fields to a dark meta-atom that traps the optical energy [2-3]. Two important aspects of slow-light metamaterials will be discussed: the design of the dark meta- atom (minimizing radiation loss) and the choice of material (minimizing dissipative loss) [4]. This will culminate in our latest designs based on dielectric metamaterials excited by nonresonant antennae [5].



Design of a slow-light metamaterial.

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Bright Emission of Indistinguishable Photons from Deterministically Fabricated Quantum Dot Microlenses

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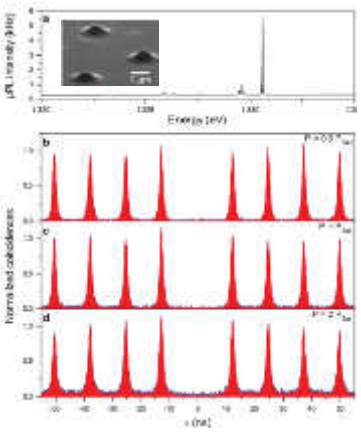
Bright non-classical light sources emitting single and indistinguishable photons on demand constitute essential building blocks towards the realization of quantum communication networks [1]. In this work we report on efficient single photon sources based on deterministically fabricated single quantum dot (QD) microlenses. Close to ideal performance of the non-classical light-sources in terms of photon extraction efficiency, high suppression of multi-photon events and a high degree of indistinguishablility is ensured by applying in-situ electron beam lithography [2] with high process yield of >90%.

In our concept we combine cathodoluminescence spectroscopy with advanced in-situ 3D electron-beam lithography at cryogenic temperatures to pattern monolithic microlenses precisely aligned to pre-selected single QDs. Here, the microlenses allow for a broadband enhancement of the extraction efficiency, which can reach values beyond 80 % if combined with a lower Au mirror. The quantum character of emission is tested by photon-autocorrelation measurements and reveals very high suppression of multi-photon emission events with $g^{(2)}(\tau) \leq 0.01$ even for optical pump powers of two times the saturation power (cf. Figure). Moreover, performing Hong-Ou-Mandel experiments under pulsed p-shell excitation allows us to demonstrate an interference visibility exceeding 80 %, which reveals a very high degree of indistinguishability of the emitted photons.



Micro-photoluminescence emission spectrum and power dependent photon-autocorrelation measure-ments of a QD microlens (cf. inset).

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Azophenylcarbazoles: isomerization and application to functionalize GaN surface.

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If a material with initial centrosymmetric structure irradiated with fundamental ω and its second harmonic 2ω beams is able to absorb these beams, quantum interference between two ω photons and one 2ω photon to same energy level can be achieved. Thus depending on phase difference between these two beams poling electric field inside the material can be created. Such oriented distribution makes molecules bleached out towards direction of the electric field polarization. This induced molecular orientation breaks the initial centrosymmetric structure inside material creating quasi-phase-matched grating of nonlinear second-order susceptibility $\chi^{(2)}$ applicable to second harmonic generation. That's the basis for all-optical poling – a method used to investigate optical storage materials. Key point for optical storage application is to fix molecules oriented in the host matrix. To be successful one needs to overcome problems like photoinduced (reading) and thermally driven relaxation. Increase of the first leads to a dramatic "wash-out" of the non-centrosymmetry [1]. Temperature measurements were performed to investigate thermoisomerization phenomena. For azophenylcarbazoles in polycarbonate a model describing all-optical poling transients using an approach of three relaxation rates was applied to interpret the experimental results measured in a wide range of temperatures 300 K–150 K, thus covering the β transition for the host [2]. The rates for thermoisomerization (10^{-5}–10^{-2} s^{-1}) and for orientational diffusion of *trans* isomer (10^{-6}–10^{-4} s^{-1}) exhibited diverse temperature dependent behavior manifesting non-Arrhenius type dependence for the highest rate interpreted using a geometry "adjustment" model. At temperatures far below T_g we were able to

uncover the situation when the orientational randomization is suppressed considering the azochromophores as "frozen". Highest values of $\chi^{(2)}$ (0.72 pm/V) and lowest mobility were obtained for the most branched azophenylcarbazoles [3]. To enhance the interaction with host matrix genuine molecular glasses were investigated [4].

Combined with the prominent optoelectronic material GaN the fascinating isomerization properties of azochromophores may provide a great potential for developing hybrid multifunctional devices. Smart surfaces and interfaces are the basis for sensors and FETs. Our interest extended towards azochromophore self-assembled monolayers (SAM) on GaN. By means of surface hydroxylation assemblies of azophenylcarbazole molecules were chemisorbed and aligned in closely-packed SAMs on GaN due to intermolecular forces. Since self-assembly and homogeneity of coverage of gallium nitride surface by azochromophores aren't simple tasks, several configurations of surface active headgroups have been tested. Wetting behavior, XPS and work function investigations provided indication that GaN surface was successfully functionalized by azophenylcarbazole SAMs [5]. Modulation of gallium nitride work function via resonantly photoinduced *trans→cis* isomerization confirmed the latter process. Depending on the molecule architecture the attachment quality was predicted and the results will be discussed.

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Metamorphic InAs/InGaAs nanostructures for single QD emission in the telecom range

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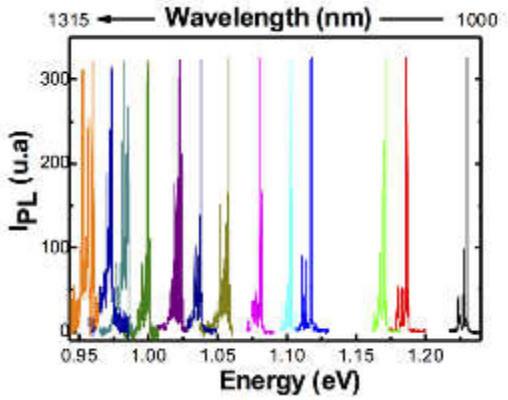
InAs self-assembled semiconductor quantum dots (QDs) can be viable sources of single photons, but strong research efforts are still needed to engineer the structure to tune the emission in the telecom window (1.3 - 1.55 µm). [1]

We present the design, the MBE growth and the optical characterization of metamorphic InAs/$In_xGa_{1-x}As$ QDs with a density low enough for single QD characterization. [2] The MBE growth is based on the deposition of InAs sub-critical coverages on $In_xGa_{1-x}As$ metamorphic buffers (MBs): QD emission is redshifted due to the reduction of QD strain and QD-MB band discontinuities, as verified by model calculation carried on with the Tibercad software. [3]

Optical properties were studied by ensemble PL at 10K and by µ-PL at 4K and single QD emission was detected from 1000 to 1315 nm: most of the excitonic species at the ground state were detected. In conclusion, our results show that metamorphic InAs/InGaAs QDs can be effective single photon sources emitting at 1.3 - 1.55 µm at low temperature.



µPL QD spectra from QDs on $In_{0.15}Ga_{0.85}As$ MBs

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Progress in the fabrication of open-access microcavities using focused ion beam milled substrates

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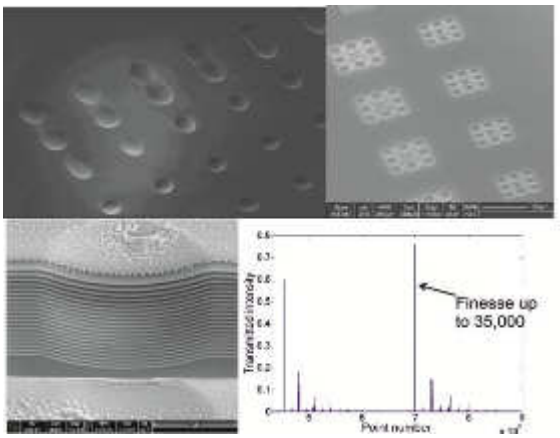
Open access microcavities have become popular in recent years for cavity QED of both atomic and solid state systems, due to their ready tunability, ease of access to the confined cavity mode, as well as high finesses and small mode volumes. A number of techniques have been used to fabricate the concave substrates of such cavities including chemical etching [1], laser processing [2], and focused ion beam milling [3]. This latter method has the advantage of offering precision shapes at length scales much shorter than the optical wavelength, thereby offering the smallest mode volumes and ready engineering of new structures such as coupled cavities, whilst providing finesse comparable with the best of other methods.



SEM micrographs of FIB milled substrates; cross sectional micrograph of a 7 μm radius of curvature substrate with DBR coating; and transmission spectrum of a high finesse cavity.

We will present some of the latest developments in the fabrication of cavities using focused ion beam methods, along with some recent work on coupling of emitters such as single nitrogen-vacancy centres in diamond to cavity modes.

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Near-Field Optical Detection of Plasmon Resonances

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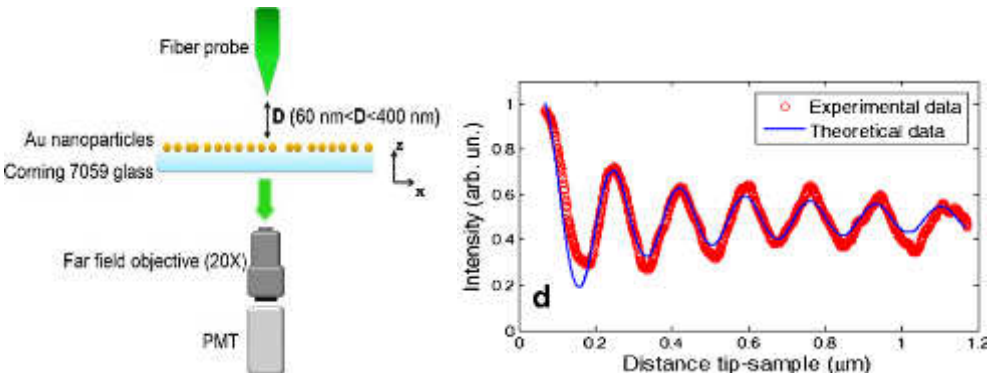
The plasmons properties depend on many factors, such as composition, size, shape and arrangement of nanoparticles. In this talk, we propose a method to obtain an indirect precise measure of the nanoparticle dimension from the backscattering. The method basically consists in excite the plasmon resonance by means of a near field aperture probe collecting in the far field the interference arising from the incident field and the superimposed scattered one. The interaction between the incident and the scattered field in backscattering zone as a function of tip–sample distance has been resorting to multipolar expansion of of the fields and on T-matrix approach[1]. To validate the model we studied the optical properties of gold nanoparticles deposited by pulsed laser ablation [2] and investigated by near-field optical microscopy (SNOM) in a transmission far-field collection scheme [3]. The theoretical model almost accurately reproduces the experimental data and makes us confident that the used method is suitable to describe more complex systems of metal nanoparticles.



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Quantum Communications along free-space and satellite channels: a workbench for Nanoscale Quantum Processes

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Quantum Communications represent a paradigm shift with respect to classical counterpart allows envisaging demonstrations of test of Quantum Mechanics over planetary scale as well as protocols of Quantum Information, quantum teleportation along satellite-to-ground or intersatellite links. The sharing of quantum states among ground and orbiting terminal may be considered as feasible with present optical means [1,2]. However, the extension of the Quantum Communications and Technologies to long distances, on the surface of the Earth as well as from the Earth to an orbiting terminal in Space, is influenced by difficulties, among which the moving terminals, the large losses, the effects on the optical propagation of the turbulent medium.

The development of novel scheme for quantum devices in the nanoscale for generation, detection and storage of quantum states is expected to provide a great impulse in the area.

To present the actual state of the research, we will present the experimental studies on the faithful transmission of qubits from Space to ground and from distant terminals on the Earth which demonstrates the means for realizing Space Quantum Communications [3].

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Ab initio dielectric responses as a basis for computational plasmonics and photonics

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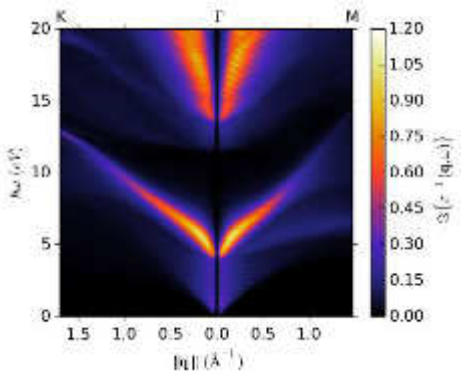
Theoretical simulations offer complementing insight into physical properties compared to experimental set-ups. In the field of optics we are often confronted with multi-scale problems. The fundamental dielectric response of a system is determined by the electronic properties of a material on an atomistic scale. Modern Density Functional Theory (DFT) and its time-dependent extensions (TD-DFT) allow us to compute the linear dielectric response of a solid for the complete electro-magnetic spectrum. In the case of molecular systems, TD-DFT even allows for the real-time simulation of linear and non-linear dielectric responses.



Electron Energy Loss Spectrum of Graphene as a function of energy and momentum transfer

This fundamental ab-initio numerical data is used as input for plasmonic or photonic simulations of systems with specific geometries and/or dimensions.

It turns out that graphene is an excellent benchmark for the optical properties and potential applications of low-dimensional materials. Unfortunately, its optical properties are very sensitive to the quality of the samples under examination. The plasmonic properties of graphene in the THz region are of great technological interest. We therefore present results of low-energy dielectric response calculations for a perfect graphene sheet, and we track the changes in the dielectric response caused by defects and impurities.

Accurate dielectric response data is also crucial for plasmonic-photonic devices. We briefly describe our current research to supply the standard frequency and time domain methods of computational electrodynamics with proper ab initio data, and we discuss some results concerning the photonic band structures of plasmonic photonic (quasi)-crystals.

Analytical formalism for the interaction of two-level quantum emitters with plasmonic nanoresonators

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Much theoretical study has been conducted on the optical response of the composite structure made of quantum emitters (QEs) and resonant plasmonic nanostructure [1]. As shown recently, the scattering and absorption cross-sections of the hybrid system can exhibits Fano resonances resulting from the interaction between the QEs and the plasmon resonance, being dramatically different from the bare (without QE) resonant plasmonic nanostructure [1].

Coupling coefficients between injected field, QE and nanoparticles are obtained by brute-force fully-vectorial electromagnetic calculations. The approach is accurate indeed, but much physics remains hidden. Besides, these numerical simulations have to be entirely redone whenever an excitation parameter is changed (angle of incidence, frequency of the pump beam, relative position of the QE). Consequently, a reliable framework for understanding and designing the properties of composite structures is lacking.

The quasi-normal mode (QNM) expansion recently proposed for plasmonic nanoresonators [2,3], allows us to compute analytically the key parameters that describes the QE/nanoparticle interaction (including the spontaneous decay rate of QE). As a result, a semi-analytical description of the optical response of the composite can be derived and further allows intuitive understanding and even optimization of its optical properties. Importantly, the formalism allows the derivation of accurate closed-form expressions for the Fano factor that determines the Fano spectral responses of hybrid systems.

The theoretical formalism, which explicitly relies on the natural resonances of the plasmonic nanoresonator, represents an enabling approach for the description of plasmon-exciton interactions in complex systems.

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Generation and Detection of Single Photons: Applications in Quantum Communication

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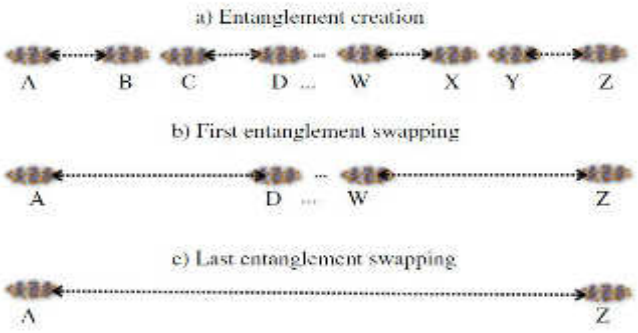
Single Photons Sources and Single Photon Detectors are obviously important tools for research and in quantum optics, and an important part of the action WG 1 is dedicated to their development. There are also many potential applications in a wide range of fields, in particular for the detectors.

In this short talk, I would like to highlight the importance for these tools in the field of Quantum Communication. Quantum Key Distribution is the most advanced technology, but very is an active research worldwide on Quantum Repeaters, with the promise of long distance quantum communication. I will discuss, to which extent single photon sources on demand can improve the performance of Quantum Repeater with respect to entangled photon pair sources [1]. I will also show the essential role of highly efficient single photon counters and give a brief overview of their state of the art.



Principle of quantum repeaters: Entanglement swapping operations are then repeatedly performed between neighboring links until it is extended over the desired distance.

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Parametric non-degenerate four wave mixing in hot potassium vapor

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Parametric non-degenerate four wave mixing (4WM) is a nonlinear process in which two pump photons mix in order to create photons with different frequencies. This process is realized via double lambda scheme by stimulating a four-stage cyclical transition resulting in the emission of amplified probe and conjugate photons. Photons created by this process are time-correlated and produce relative intensity squeezed beams [1] enabling measurements beyond the shot-noise limit [2].

In our experiment double lambda scheme is realized at D1 line of potassium isotope ^{39}K. We have investigated the influence of the density of potassium atoms, intensity of the pump beam, intensity of the probe beam, angle between the pump and the probe beam, one photon detuning and two photon detuning on the 4WM gain.

The laser frequency is locked at various detunings (250 MHz to 2500 MHz) from the $4S_{1/2}F_g=1$ -> $4P_{1/2}$ transition. The probe is detuned at 460 MHz (ground state hyperfine splitting) in respect to the pump beam and scanned around the Raman resonance. The vacuum potassium vapor cell,is heated up to 150^{o}C. The pump and probe beam intersect at small angle (2- 10 mrad) determining the phase matching condition.

The efficiency of 4WM process is studied by simultaneously measuring the conjugate and the probe beam amplification. The highest gain we measured is 80 and to the best of our knowledge it is the highest gain obtained in FWM process in alkaline vapor cells. The maximal gain was achieved at 120^{o}C and for -6 MHz two photon detuning. We believe this will significantly improve the results in further investigation on relative intensity squeezing.

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