Photonic Quantum Technologies – A Revolution in Communication, Sensing, and Metrology

764. WE-Heraeus-Seminar

17 Mar - 19 Mar 2022

Hybrid
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 764. WE-Heraeus-Seminar:

In 2016 the quantum satellite 'Micius' started its successful mission, while in the same year scientists reported the first observation of gravitational waves using detectors whose sensitivity is currently enhanced exploiting squeezed states of light. Both stories impressively illustrate the transition from basic research in quantum optics to applications of photonic quantum technologies, which will have large impact to our daily life.

In this light our seminar brings together experts and next generation scientists to jointly review and discuss the state-of-the-art in photonic quantum technologies from an application-driven viewpoint. The seminar scope hereby covers the subfields of quantum communication, quantum metrology, and quantum sensing together with crosscutting challenges relevant for all subfields. In the quantum communications section of our seminar, we will discuss recent implementations and protocols for quantum key distribution, quantum communication networks and repeaters. Novel approaches such as continuous variables and device-independent schemes will be of particular interest as well as satellite-/airborne-based QKD field experiments. The quantum sensing and metrology sections include the topics of quantum imaging, quantum-enhanced super-sensitivity as well as quantum-enhanced interferometry and the realization of new standards based on quantum effects. An own section of our seminar is devoted particularly to the development of efficient and novel quantum light sources, detectors and quantum memories, representing cross-cutting challenges overarching all subfields. The application driven scope of the seminar is reflected in an industry session on Wednesday evening. Here, invited industry representatives discuss prospects and challenges for the commercialization of photonic quantum technologies in the format of a panel discussion moderated jointly by the organizers.

We invite experts and next generation scientists at all career stages to join this exciting seminar on photonic quantum technologies. Help us shaping the second quantum revolution…

Scientific Organizers:

Dr. Tobias Heindel	Technische Universität Berliln, Germany E-mail: tobias.heindel@tu-berlin.de
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Introduction

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Registration:

Martina Albert (WE Heraeus Foundation)
at the Physikzentrum, reception office
Wednesday (17:00 h – 21:00 h) and Thursday morning

Program

Program

Wednesday, 16 March 2022

17:00 – 21:00	Registration	
From 18:30	BUFFET *SUPPER / Informal get together*	

Thursday, 17 March 2022

07:30	*BREAKFAST*	
08:30 – 08:45	Scientific Organizers	**Opening remarks**
08:45 – 09:00	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
09:00 – 09:45	Harald Weinfurter	**Quantum Communication**
09:45 – 10:30	Peter Michler	**Quantum-Dot Single-Photon Sources for Quantum Photonic Networks**
10:30	*COFFEE BREAK*	
11:00 – 11:30	David Gershoni (online)	**Deterministic source of indistinguishable photons in a cluster state**
11:30 – 12:00	Paolo Villoresi (online)	**Novel photonics for Quantum Communications in Space**
12:00 – 12:30	Rinaldo Trotta	**Entanglement-based Quantum Communication with Photons from Quantum Dots**
12:30 – 12:45	**Extra Discussion**	
12:45	*LUNCH*	

Program

Thursday, 17 March 2022

14:15 – 15:00	Stephan Reitzenstein	**Deterministically fabricated quantum light sources for applications in photonic quantum technologies**
15:00 – 15:30	Fabio Sciarrino	**Photonics platform for quantum metrology, quantum walks and Boson Sampling**
15:30 – 16:00	Sara Ducci (online)	**Quantum photonics with nonlinear AlGaAs chips: biphoton state engineering and applications**
16:00 – 16:30	Thomas Jennewein (online)	**The quantum internet and why satellites will be needed**
16:30 – 16:45	**Conference photo**	
16:45 – 19:00	**Poster Session P1 and** *COFFEE BREAK*	
19:00	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, with complimentary drinks)*	

Program

Friday, 18 March 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Can Knaut	**Quantum Networks based on an Integrated Diamond Nanophotonic Platform**
09:45 – 10:30	Oliver Benson	**Enhanced Quantum-Light-Matter Interaction Using Confinement in Photonic Micro- and Nanostructures**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	Thierry Debuisschert (online)	**Wide-field magnetic imaging for applications of NV centers in diamond**
11:30 – 12:00	Marco Genovese	**First temperature measurement in neurons by ODMR techniques**
12:00 – 12:30	Stefanie Barz	**Quantum photonics: interference beyond HOM and quantum networks**
12:30 – 12:45	**Extra Discussion**	
12:45	*LUNCH*	
14:15 – 15:00	Patrick Maletinsky (online)	**Photonics and Photophysics of Nitrogen Vacancy centres in Diamond**
15:00 – 15:30	Costanza Toninelli	**Integrated molecules for photonic quantum technologies**
15:30 – 16:00	Hugues de Riedmatten	**Quantum Networking with rare-earth based quantum nodes**
16:00 – 16:30	Christine Silberhorn	**Harnessing non-linear integrated optics and pulsed light for quantum photonics**
16:30 – 19:00	**Poster Session P2 and** *COFFEE BREAK*	
19:00	*DINNER*	
20:30	**Fun Part moderated by the Organizers**	

Program

Saturday, 19 March 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Doris Reiter	**State Preparation Schemes for Solid-State Quantum Emitters**
09:45 – 10:30	Fedor Jelezko	**Quantum sensing with diamond spin qubits**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	Christopher Chunnilall	**Assessment of quantum random number generators**
11:30 – 12:00	Stefan Kück	**Single photon sources for quantum radiometry**
12:00 – 12:30	Sae Woo Nam	**tba**
12:30 – 12:45	Scientific Organizers	**Closing remarks and poster awards**
12:45	*LUNCH*	

End of seminar and departure

Posters

Posters P1

Ricardo Albiero	**Multi-port interferometer for genuine n-photon indistinguishability assessment**
Francesco Basso Basset	**Entanglement-based quantum key distribution using a deterministic quantum dot photon source**
Ghata Satish Bhayani	**Towards highly efficient entangled photon pair sources based on GaAs quantum dots using positioned circular Bragg grating cavities**
Thomas Bracht	**Off-resonant two-color excitation of a quantum emitter**
Tiff Brydges	**Integrated Photonics for Quantum Repeaters**
Oscar Camacho Ibarra	**Overcoming the integration issues between 2D materials and waveguides**
Aurelia Chenu	**Non-Hermitian formalism in a coupled quantum well and for dynamical control of open dynamics**
Justus Christinck	**Single-photon emitters based on germanium-vacancy centers in solid immersion lenses in diamond**
Martin Cordier	**Engineering the photon statistics by destructive and constructive two-photon interference**
Nicolas Fabre	**Spectral engineering of photon pairs and their measurement with Hong-Ou-Mandel and Mach-Zehnder interferometry**

Posters P1

Martin Paul Geller	**Electron-photon and electron-electron scattering as dephasing mechanisms in a single quantum emitter**
Hristina Georgieva	**Counting single photons for quantum radiometry**
Sonali Gera (online)	**Heralded Storage of Narrowband Single Photons**
Esteban Gómez-López	**The light cage: a platform for coherent interaction of light and matter**
Mauricio Gómez-Robles	**Development of photonic integrated components in a silicon carbide platform**
Lukas Hanschke	**The Origin of Antibunching in Resonance Fluorescence**
Franziska Hirt	**Sample fabrication approaches towards a cryogenic molecule-based single-photon source**
Michael Hoese	**On-Chip Quantum Devices Enabled by Shallow-Implanted Vacancy Centers in Laser-Written Waveguides in Diamond**
Caspar Hopfmann	**Maximally entangled and GHz-clocked on-demand photon pair source**
Raphael Joos	**Investigation of a Telecom C-Band QD Membrane Embedded in a Broadband Planar Optical Antenna**
Patricia Kallert	**Efficient spectral separation of single and entangled photons**

Posters P1

Yusuf Karli	**SUPER Scheme in Action: Experimental Demonstration of Red-detuned Excitation of a Quantum Dot**
Tobias Krieger	**Advances on GaAs quantum dots integrated in circular Bragg resonators on micro-machined piezoelectric substrates**
Arne Ludwig	**Progress on epitaxial growth of low noise quantum dot heterostructures**
Pablo Martinez-Azcona	**Doublons, Topology and Interactions in a 1D lattice**
Vikas Remesh	**High fidelity biexciton preparation via Adiabatic Rapid Passage in a Quantum Dot**

Posters P2

Malaquias Correa Anguita	**Quantum photo-thermodynamics on a programmable photonic quantum processor**
Mohammad Mehboudi	**Thermometry of Gaussian quantum systems using Gaussian measurements**
Max Meunier	**Photonic integrated structures for room-temperature single photon emitters in Gallium Nitride**
Battulga Munkbhat	**Nanostructured TMDs for Photonic Quantum Technologies**
Julia Neuwirth	**Multipair emission effects in quantum dot-based entangled photon sources**
Sofia Pazzagli	**Hybrid 2D material/dye molecule quantum emitter for integrated nanophotonics**
Beatrice Polacchi	**Experimental robust self-testing of the state generated by a quantum network**
Sebastian Pucher	**Atomic spin-controlled non-reciprocal Raman amplification of fiber-guided light**
Doris Reiter	**Switching of the type of photon entanglement generated by a driven quantum emitter**
Jelmer Renema	**20-mode quantum photonic processor in silicon nitride**
Lucas Rickert	**Evaluating a Quantum Key Distribution Testbed using Plug&Play Telecom-wavelength Single-Photons**
Rafael Salas-Montiel	**Waveguide lattices as photonic quantum simulators**

Posters P2

Caglar Samaner (online)	**Free-Space Quantum Key Distribution with Single Photons from Defects in Hexagonal Boron Nitride**
Marc Sartison	**Quantum Dot Imaging Localization Methodology based on Imaging**
Rebecka Sax	**Fast and Simple Integrated Quantum Key Distribution**
Eva Schöll	**Crux of Using the Cascaded Emission of a Three-Level Quantum Ladder System to Generate Indistinguishable Photons**
Frank Somhorst	**Experimental demonstration of an efficient, semi-device-independent photonic indistinguishability witness**
Tim Strobel	**Temporal evolution of line broadening in charge controlled quantum dots**
Daniel Vajner	**Towards Single Photon Quantum Communication at TU Berlin**
Lukas Wagner	**High quality quantum dot structures from hybrid MOVPE/MBE growth**
Yujing Wang	**Near-unity efficiency in ridge waveguide-based on-chip single-photon source**
Dongze Wang	**Efficient and stable fiber-to-chip coupling enabling the injection of telecom quantum dot photons into a silicon photonic chip**
Luca Zatti	**Generation of nonclassical states of light in linear and nonlinear photonic molecules**
Danilo Zia	**Black-Box Approach to High Dimensional Photonic Quantum State Engineering**

Abstracts of Lectures

(in alphabetical order)

Quantum photonics: interference beyond HOM and quantum networks

Stefanie Barz[1]

[1]*Institute for Functional Matter and Quantum Technologies & Centre for Integrated Quantum Science and Technology, University of Stuttgart*

In the first part of my talk, I will talk about recent experiments on quantum interference. I will show the impact of distinguishability and mixedness – two fundamental properties of quantum states – on quantum interference. I will demonstrate that these two properties can influence the interference of multiple particles in very different ways, leading to effects that cannot be observed in the interference of two particles alone.

In the second part of my talk, I will report on our recent work in quantum networks. I will talk about a crucial component of a photonic quantum network: Bell-state measurements and report on an experimental demonstration of a scheme that allows obtaining a success probability of more than 50%. Finally, I will show the implementation of a novel protocol for networked key exchange using cluster states as a resource.

Enhanced Quantum-Light-Matter Interaction Using Confinement in Photonic Micro- and Nanostructures

Oliver Benson

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To obtain a strong interaction of atoms or "atom-like" objects and light, either a large atomic dipole moment must be chosen, or the field amplitude must be enhanced. The latter can be achieved by confining light in certain modes in photonic micro- or nanostructures.

In this presentation we will discuss two examples how we utilize light confinement for applications in hybrid quantum/nano-photonics [1].

The first one concerns a novel light-guiding structure, a light-cage, inside an alkali (Cs) vapor cell [2]. We demonstrate electromagnetically induced transparency exploiting a light-cage and discuss the benefits of its applications in quantum technology, e.g., for the realization of quantum memories or controlled photon delays.

A second example aims at quantum sensing and concerns extreme light confinement in the near-field of plasmonic structures. We will show how this can enhance the local detection of circular dichroism and chirality perhaps down to the molecular scale [3].

References

[1] Hybrid integrated quantum photonic circuits, A.W. Elshaari, W. Pernice, K. Srinivasan, O Benson, V Zwiller, Nature Photonics **14**, 285-298 (2020).

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[3] Self-Assembly of Plasmonic Nanoantenna-Waveguide Structures for Subdiffractional Chiral Sensing, M. Rothe, Y. Zhao, J. Müller, G. Kewes, C. T. Koch, Y. Lu, and O. Benson, ACS Nano **15**, 351 (2021).

Assessment of quantum random number generators

C. J. Chunnilall[1], **R. J. Colbeck**[2], **Ke Guo**[1,2], **T. Hebdige**[2]

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[2] *University of York, York, U.K.*

Random number generators (RNGs) are important components in a variety of applications. In computer simulation, pseudo-RNGs based on deterministic algorithms are widely used because of their high generation rate and reproducibility. However, due to their deterministic nature, they are not suitable for applications where unpredictability is required. For such applications, RNGs based on physical non-deterministic effects can be used.

Given our current understanding of physics, generation of random numbers requires a quantum process. Quantum RNGs (QRNGs) generate fundamentally unpredictable (i.e. secret) and unreproducible randomness. Much progress has been made in the development of small and fast optical QRNGs, making them ideal RNG candidates for cryptographic applications.

Device-independent QRNGs do not require trusted devices and can be certified by a Bell inequality violation. However, they currently exhibit much lower generation rates compared with device-dependent QRNGs which are more common but require physical examination for a strong certification. Although generic QRNG assessment methodologies have been proposed [1-3], the experimental assessment procedures will differ for devices with different working principles. Here we introduce an assessment procedure for devices with the same working principle; this is illustrated by the evaluation of an exemplar QRNG based on the principle exploited by Sanguinetti et al. [4-5].

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Quantum Networking with rare-earth based quantum nodes

H.de Riedmatten[1, 2]

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The distribution of entanglement between the nodes of a quantum network will allow new advances e.g. in long distance quantum communication, distributed quantum computing and quantum sensing. On the ground, quantum information can be distributed across the nodes using single photons at telecommunication wavelengths traveling in optical fibers. To bridge distances much longer than the fiber attenuation length, quantum repeaters can be used. The nodes of a quantum repeater are matter systems that should efficiently interact with quantum light, allow entanglement with photons at telecommunication wavelengths and serve as a quantum memory allowing long-lived and faithful storage of (entangled) quantum bits. In addition, for efficient distribution of entanglement, the nodes should allow multiplexed operation and ideally enable quantum processing capabilities between stored qubits.

In this talk, after introducing the context I will describe our recent progress towards the realization of quantum repeater nodes with multiplexed ensemble-based quantum memories, using cryogenically cooled rare-earth ion doped solids. I will show how solid-state quantum memories can be entangled with telecom photons using non-degenerate photon pair sources [1]. I will also describe our efforts to scale up quantum repeater links. In particular, I will report an experiment demonstrating entanglement between remote multiplexed solid-state quantum memories, heralded by a telecom photon [2]. Finally, I will explain our current work to build quantum processing nodes and spin-photon interfaces using single rare-earth ions in nanoparticles embedded in fiber-based microcavities [3].

References

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[2] Dario Lago-Rivera, Samuele Grandi, Jelena V Rakonjac, Alessandro Seri, Hugues de Riedmatten, Nature **594**, 37 (2021)

[3] Bernardo Casabone, Chetan Deshmukh, Shuping Liu, Diana Serrano, Alban Ferrier, Thomas Hümmer, Philippe Goldner, David Hunger & Hugues de Riedmatten, Nature Commun **12**, 3570 (2021)

Wide-field magnetic imaging for applications of NV centers in diamond

Simone Magaletti[1], Ludovic Mayer[1], Jean-François Roch[2], and Thierry Debuisschert[1]

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NV centers are solid-state spins consisting of a substitutional nitrogen atom and a nearby vacancy in the diamond lattice. They allow the development of a wide variety of quantum sensors to measure magnetic fields and many other physical quantities with high accuracy. The possibility to control them entirely with optical and microwave fields makes them very attractive for many applications. Their internal ground states, separated by a zero-field splitting of 2.87 GHz, have equal populations at room temperature. However, it is possible to polarize them with a pump laser beam around 532 nm. Their quantum properties can then be fully exploited using a resonant microwave field. Moreover, the NV center is a color center that emits a fluorescence in the red whose intensity depends on the energy level, which allows to measure its spin state. The excellent signal-to-noise ratio of optical detection makes single spin detection possible, which has led to many applications such as scanning tip magnetometry [1].

The ability to grow large single crystal diamond samples with a very low level of impurities and a controlled level of NV doping allows measurements with ensembles of NV centers. The intrinsic parallelism of the optical detection makes wide-field imaging of the magnetic field possible. It has been exploited for many applications such as defect characterization in electronic circuits with important applications in the microelectronics industry [2]. It also opens the way to new tools to study in situ the phase transition of matter under high pressure [3]. Conversely, it is also possible to use this technique to image the frequency spectrum of an unknown radio frequency signal and to realize an instantaneous broadband spectrum analyzer for application in the telecommunication industry [4].

References

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Quantum photonics with nonlinear AlGaAs chips: biphoton state engineering and applications

S. Ducci

Laboratoire Matériaux et Phénomènes Quantiques, Université de Paris/CNRS, Paris, France

Photonic quantum technologies are a promising platform for a large variety of applications ranging from secure long-distance communications to the simulation of complex phenomena. Among the variety of material platforms under study, semiconductors offer a wide range of functionalities opening several opportunities for the development of integrated quantum photonic circuits. AlGaAs is particularly attractive to monolithically integrate active and passive components since it combines high second order nonlinearity, electro-optic effect and direct bandgap. In this talk, I will present our work on the generation and manipulation of quantum states of light in the telecom range with nonlinear AlGaAs chips working at room temperature. The seminar will be divided into three parts: in the first one I will review the developments done in terms of integrated quantum devices [1,2]; in the second one I will present our recent work on the generation and manipulation of quantum frequency states of light [3] and on the control of exchange statistics of a biphoton state leading to a fermionic, bosonic and anyonic behavior [4,5]; in the last part I will discuss the implementation of a flexible entanglement-distribution network for secure communications using an AlGaAs chip [6].

References

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First temperature measurement in neurons by ODMR techniques

G.Petrini, G.Tomagra, E.Bernardi, E,. Moreva, I.P.Degiovanni, P.Traina, P.Olivero, V.Carabelli, M.Genovese

In this talk I will present our results that demonstrate for the first time the possibility of making localized temperature measurement with precision under 0.1 K in neurons by exploiting ODMR techniques.

After a general introduction to ODMR techniques based on NV colour centers in diamond, I will present this breakthrough result that will have huge impact to biology and medicine.

In little more detail, we probe temperature variations at single-cell scale in mice neurons using NV color centers in nanodiamonds. We activate the firing of a neuronal network using a drug (picrotoxin) that stops the inhibitory mechanism. In these conditions, we detect a significant local temperature increase.

We associate the observed temperature increase to the firing state of the network, since no significant increase is observed in cases when the drug is not injected. We discuss the possible physiological mechanisms that causes the heat production leading to the observed temperature increase. This method represents a breakthrough for biological studies, allowing for the first time local measurement of temperature, that cannot be realized with other methods and it can find application in understanding various pathologies

In perspective, it will provide an extremely promising mean of indirect detection of the action potential and study of temperature variations in proximity of specific cell regions by functionalizing nanodiamonds in order to target specific cell components (e.g. specific ion channels or mitochondrions). Recent preliminary data and new lines of research in this direction will be presented.

Deterministic source of indistinguishable photons in a cluster state

Dan Cogan, Zu-En Su, Oded Kenneth and David Gershoni

The Physics Department and the Solid-State Institute, Technion – Israel Institute of Technology, Haifa, 32000, Israel

Entanglement between particles is a basic concept of quantum sciences [1]. The ability to produce entangled particles in controllable manners is essential for any quantum technology. Entanglement between light particles: photons, is particularly crucial for quantum communication due to the light's noninteractive nature and long-lasting coherence [2]. Resources producing entangled multi-photon cluster states will enable communication between remote quantum nodes [2-4], since the inbuilt redundancy of cluster photons [5] allows repeated local measurements, compensating for losses and probabilistic-Bell measurements [6]. For feasible applications, the cluster generation should be fast, deterministic, and most importantly, its photons indistinguishable, permitting measurements and clusters fusion by interfering photons. Here, using periodic excitation of a semiconductor quantum dot confined spin [7], we demonstrate the first multi-indistinguishable-photon cluster, featuring infinite length, deterministic, gigahertz generation rate, optimized for entanglement-length longer than 10 photons. Since the photons are indistinguishable, new possibilities are opened to scale up the cluster's dimensionality by fusion or time-delayed feedback [8]. Therefore, this first demonstration by far exceeds the minimal resource quality requirement needed to construct quantum repeaters for quantum communication [6,9] and possibly for building measurement-based photonic quantum computers [5, 8]. Nevertheless, further significant improvements are feasible, e.g., by using the Purcell effect [10].

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Quantum sensing with diamond spin qubits

Fedor Jelezko[1]

[1]*Institute of Quantum Optics, Ulm University, Germany*

Single nitrogen vacancy (NV) color centers in diamond currently have sufficient sensitivity for detecting single external nuclear spins and resolve their position within a few angstroms. The ability to bring the sensor close to biomolecules by implantation of single NV centers and attachment of proteins to the surface of diamond enabled the first proof of principle demonstration of proteins labeled by paramagnetic markers and label-free detection of the signal from a single protein. Single-molecule nuclear magnetic resonance (NMR) experiments open the way towards unraveling dynamics and structure of single biomolecules. However, for that purpose, NV magnetometers must reach spectral resolutions comparable to that of conventional solution state NMR. New techniques were proposed for this purpose and realized recently including technique that employs quantum memory. The ability to sense nuclear spins by NV centers also enables the transfer of polarization from optically polarized spins of NV centers to external nuclear spins. Such diamond based techniques for dynamic nuclear spin polarization are very promising for the enhancement of sensitivity of conventional MRI imaging.

The quantum internet and why satellites will be needed

Thomas Jennewein

University of Waterloo, Physics and Astronomy, Waterloo, ON, Canada

Extending today's internet, the Quantum Internet will readily transfer quantum bits, rather than classical bits, between users near and far and over multiple different channels. This network could be used for secure communications, distributed quantum computing and metrological applications. Because a crucial element of the quantum internet is the distribution of entangled photon pairs. I will discuss recent advances on implementations and tools useful for generating and distributing photonic quantum entanglement over large distances using satellites. I will also present an overview of the upcoming Canadian quantum communication satellite mission QEYSSAT.

Quantum Networks based on an Integrated Diamond Nanophotonic Platform

Can Knaut

Harvard University, Cambridge, MA, USA

Implementation of scalable quantum networks requires multi-qubit nodes that can store and process quantum information encoded in itinerant photons. Additionally, an efficient and scalable source of single photons is a necessary ingredient for optimum encoding and transmission of quantum information. In this talk, I will present our recent work on realizing these ingredients and describe our progress towards building a quantum networking platform based on Silicon-vacancy (SiV) color centers integrated into a diamond nanophotonic platform. By selectively implanting Silicon-29 ions into high-quality factor diamond nanophotonic cavities, we gain access to a two-qubit register consisting of the electron spin of the SiV center, as a communication qubit, and a strongly coupled Silicon-29 nuclear spin, which acts as a memory qubit. We demonstrate coherent control of both qubits, high-fidelity two-qubit gates, such as CNOT and SWAP, and long coherence times of our memory qubits. We furthermore show the versatility of our platform by using it as a deterministic source of arbitrarily temporally shaped single-photons with high efficiency (detection efficiency = 14.9%) and purity (g(2)(0) = 0.0168) capable of generating streams of up to 11 consecutively detected single photons. By combining efficient single-photon generation with coherent spin manipulation, our platform enables on-demand generation of streams of correlated photons such as cluster states and could be used as a resource for robust transmission and processing of quantum information.

Single photon sources for quantum radiometry

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Single photon sources have the potential to be used in a wide range of applications [1]. Well-known and widely discussed is their use in the so-called "quantum-enhanced metrology" [2], specifically quantum key distribution, quantum computing and metrology. Another important application is (quantum) radiometry [3]. This is because, in principle, single-photon sources have the potential to become a new type of standard photon source [4], as there have been so far - in the classical regime - the blackbody radiator and the synchrotron radiation source. In this presentation, I will report specifically on quantum radiometry, i.e., the use of single-photon sources for radiometric purposes. An overview of the state of the art in the application of deterministic single photon sources for the calibration of single photon detectors will be given in detail. To optimize single photon sources for this purpose, extensive research is currently being carried out at several National Metrology Institutes (NMIs) in collaboration with university partners. Several types of single-photon sources are currently being investigated, including sources based on defect centers in (nano)diamonds, molecules, and quantum dots in semiconductors. Current results for single photon sources in terms of photon flux, single photon purity, and spectral power distribution, as well as the results of single photon detector calibrations performed with these light sources will be presented, summarized, and compared.

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Photonics and Photophysics of Nitrogen Vacancy centres in Diamond

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Color center spins in diamond are a key contender for realizing scalable and practical technologies for quantum sensing [1] and quantum communication [2]. The strong interest in these platforms lies in the availability of highly coherent, optically addressable spins - even at room temperature - and the possibility to perform efficient spin-photon and subsequent, long-distance spin-spin entanglement to create quantum networks [3].

Yet, optical interacting of diamond spins faces severe challenges due to diamond's high refractive index and the photophysical properties of color-center spins. The latter include a typically low yield of coherent photon emission [4] and underexplored photophysical properties that deteriorate the fidelity in optical addressing of such spins [5].

In my talk, I will describe our work in addressing these challenges by photonic engineering of diamond quantum devices [4,6,7,8] and by recent studies of hitherto unexplored aspects of the low-temperature excited state level structure of individual nitrogen-vacancy centers in diamond [5].

I will conclude with an outlook on future device developments and a highlight of specific quantum sensing applications that were recently enabled by our quantum sensing devices with enhanced photonic properties [9].

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Quantum-Dot Single-Photon Sources for Quantum Photonic Networks

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Abstract

This talk aims to provide a general introduction to the physics of semiconductor quantum dot based single-photons sources and an overview over recent exciting developments in this field. Semiconductor QDs have been identified as promising hardware for implementing non-classical light sources. This is because individual charge carriers in QDs can be generated, manipulated, coherently controlled and the QD represents a strong light-matter interface. The sources can be operated as on-demand sources of single and entangled photons with high degrees of photon indistinguishability and brightness. Moreover, miniaturized and integrated solutions with existing semiconductor technology are anticipated.

In all foreseen implementations of quantum photonic networks, photons must be able to propagate over long distances in silica fibers with limited absorption and wave packet dispersion. When propagating into silica fibers, photons in the so-called telecom C-band (1530 – 1565 nm) will experience the absolute minimum of absorption whereas in the O-band (1260 – 1360 nm) they can travel with vanishing dispersion together with limited absorption. In this tutorial we report about recent highlights achieved with quantum dots emitting in the telecom O- and C-band [1,2].

From a general perspective, in a similar way as classical computing benefited by the reduction of the device footprint, enabling the realization of highly complex chips, a range of quantum applications will sensibly improve thanks to the realization of on-chip quantum photonics [3,4]. This tutorial also reviews some of the recent progress achieved in this highly dynamic and exciting field.

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State Preparation Schemes
for Solid-State Quantum Emitters

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A prerequisite for photonic quantum technologies is the generation of specific photon states. Besides single or entangled photons, also more complex photon states like N-photon Fock states or photonic cat states are of interest. Single photons can be created by a two-level quantum emitter, which is been prepared in its excited state, while the generation of entangled photon states requires multi-level quantum systems.
In this talk, I will give an overview over different state preparation schemes for solid-state quantum emitters [1]. A major difference between atomic and solid-state emitters is the interaction with the lattice vibration, i.e., the phonons. In most applications, the phonons are detrimental to the ideal photon generation, such that parameter regimes are identified where their influence is minimal. On the other hand, phonon-assisted preparation schemes make active use of phonons.
In search for the perfect quantum light emitting device, there is still the need for new preparation schemes and I will discuss some recent examples, in particular the radically new swing-up scheme [2,3].

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Deterministically fabricated quantum light sources for applications in photonic quantum technologies

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Single photons play a prominent role in photonic quantum technologies. As flying qubits, they serve for instance as information carriers for low-loss quantum communication systems. In the case of quantum repeater networks, but also for future distributed quantum computers and global quantum networks, it is of central importance to temporarily store and retrieve the quantum information to be transmitted via stationary qubits in quantum memories. Moreover, photonic quantum computers also rely on the efficient on-chip generation and routing of single photons.

InGaAs quantum dots (QDs) are excellent single-photon emitters with close to ideal quantum nature of emission. However, extracting the photons is challenging and QDs have relatively short spin coherence times, which has a deleterious effect on their possible use as quantum memories when relying on the storage of single carriers. To circumvent these problems, QDs are usually integrated into advanced nanophotonic structures to enhance the photon extraction efficiency, and more powerful concepts that quantum dot molecules (QDMs) with storage times more than 1 ms are pursued.

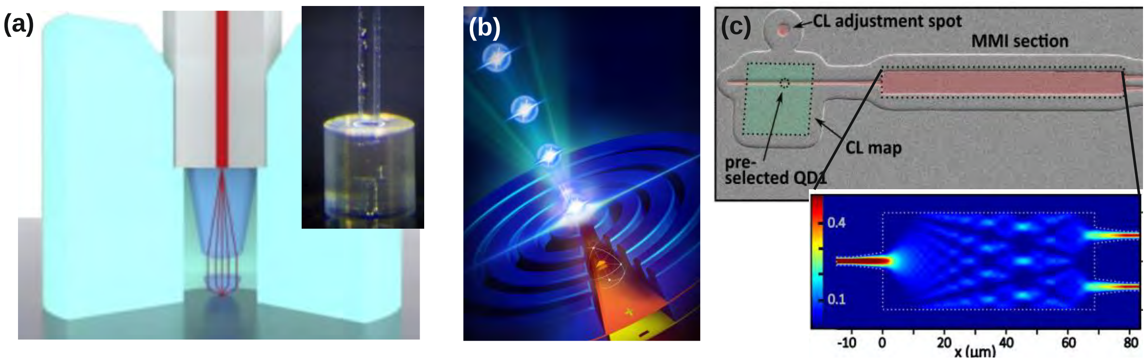

Fig. 1 (a) Fiber-coupled QD single-photon source [1]. (b) Schematic of an electrically controlled QDM device [2]. (c) Integrated quantum circuit realized by in-situ electron beam lithography [3].

We report on the development of bright fiber-coupled single-photon sources and electrically tunable single-QDM devices with strongly enhanced broadband photon extraction efficiency for applications in quantum communication networks. Moreover, we present integrated QD-based quantum circuits which aim at fully integrated Boson sampling circuits and photonic quantum gates in the future. The quantum devices are deterministically fabricated by in-situ electron beam lithography which is both very precise and flexible to realize for instance complex QD-waveguide systems with nm-accuracy.

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Photonics platform for quantum metrology, quantum walks and Boson Sampling

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In recent years, much work has been directed to the development of technologies to enable the long-term goal of scalable, universal quantum computers. This effort is motivated by the promise of quantum computational speedup in tasks such as integer factoring, quantum simulation, and solving systems of linear equations. Despite the tremendous advances in quantum technologies reported in the last few years, the implementation of a large-scale universal quantum computer is still challenging. Hence, intermediate milestones need to be identified in the long-term effort towards harnessing the computational potential of quantum systems. A first fundamental step in this direction is the achievement of the regime of quantum computational supremacy (also called quantum computational advantage).

Boson sampling is a computational problem that has been proposed as a candidate to obtain an unequivocal quantum computational advantage. The problem consists in sampling from the output distribution of indistinguishable bosons in a linear interferometer. There is strong evidence that such an experiment is hard to classically simulate, but it is naturally solved by dedicated photonic quantum hardware, comprising single photons, linear evolution, and photodetection. This prospect has stimulated much effort resulting in the experimental implementation of progressively larger devices. We will review the most recent advances in photonic boson sampling, quantum walks and quantum metrology, describing both the technological improvements achieved and the future challenges.

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Harnessing non-linear integrated optics and pulsed light for quantum photonics

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Quantum technologies promise a change of paradigm for many fields of application. However, their implementation often requires advanced setups of high complexity, which poses considerable challenges on the experimental side.

Here we review three different approaches to advance current experimental approaches for multi-dimensional photonic quantum systems: non-linear integrated quantum optics, pulsed temporal modes and time-multiplexing. Non-linear integrated quantum devices with multiple channels enable the combinations of different functionalities, such as sources and fast electro-optic modulations, on a single compact monolithic structure. Pulsed photon temporal modes are defined as field orthogonal superposition states and can constitute a high dimensional quantum system. They occupy only a single spatial mode and thus they can be efficiently used in single-mode fibre communication networks. Finally, time-multiplexed quantum walks are a versatile tool for the implementation of a highly flexible simulation platform with many modes and dynamic control of the underlying graph structures and coherence properties of the quantum network.

Integrated molecules for photonic quantum technologies

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The successful development of future photonic quantum technologies will much depend on the possibility of realizing robust and scalable nanophotonic devices. These should include quantum emitters like on-demand single-photon sources and non-linear elements, provided their transition linewidth is broadened only by spontaneous emission. However, conventional strategies to on-chip integration, based on lithographic processes in semiconductors, are typically detrimental for the coherence properties of the emitter. Moreover, such approaches are difficult to scale and bear limitations in terms of geometries. In the present contribution, we discuss an alternative platform, based on molecules that preserve near-Fourier-limited fluorescence even when embedded in polymeric photonic structures. Anthracene nanocrystals doped with dibenzoterrylene (DBT:Ac NCX) fluorescent molecules show excellent performances of single-photon emission and are naturally suitable both to deterministic positioning and to the integration in hybrid devices [1]. Three-dimensional patterns are achieved by Direct Laser Writing (DLW) of commercial photoresists around self-assembled organic nanocrystals containing fluorescent molecules [2,3]. This method enables fast, inexpensive and scalable fabrication process, while offering unique advantages in terms of versatility and sub-micron resolution. We also show optical tuning of many molecules on chip [4], unlocking two-photon interference from distinct emitters on chip [5,6]. The proposed technology will allow for competitive organic quantum devices, including integrated multi-photon interferometers, arrays of indistinguishable single-photon sources and hybrid electro-optical nanophotonic chips.

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Entanglement-based Quantum Communication with Photons from Quantum Dots

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The prospect of using the quantum nature of light for quantum communication keeps spurring the search and investigation of suitable sources of entangled photons. Among the different systems under investigation, epitaxial quantum dots (QDs) are arguably one of the most attractive. They can generate pairs of polarization-entangled photons in a nearly deterministic manner, with high efficiency, and with near-unity degree of entanglement. Despite recent advances, however, the exploitation of photons from QDs in advanced quantum communication protocols remains a major open challenge.

In this talk, I will discuss how photons generated by a GaAs quantum dot [1] can be used to implement quantum teleportation [2, 3] and entanglement swapping [4] protocols with fidelities above the classical limit. Moreover, I will present our first steps towards the construction of a quantum-dot based quantum network for secure communication within the campus of Sapienza University of Rome [5]. A discussion on future challenges and perspectives [6, 7] will conclude the talk.

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Novel photonics for Quantum Communications in Space

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As of today, quantum-key-distribution QKD is among the most advanced quantum technologies, based on the sharing of single photons, and the major European project OpenQKD is developing as the QKD testbeds across Europe.
The QKD extension to space is also envisaged in the European roadmap as well as in different continents. The addressing of the effective complementarity between ground and Space imposes challenging requirements to the space QC technology, mainly photonics, in particular where the high rate of key, the all-day availability and the long service time of operation are asked for the secure communications payloads.
In the talk I'll provide insight in the latest achievements addressing the QKD along free-space links and the technology addressing the reduction of the qubit preparation errors, aiming at the most pure transmitter for high efficiency key-rate. Indeed, as a crucial QKD parameter, Quantum-Bit-Error-Rate, or QBER, which nowadays may be pushed well under the percent [1]. The integrated photonics platform was also demonstrated as suitable for daylight QKD, with a remarkable increase in efficiency and compactness [2].
Practical terminal synchronization was obtained with a qubit correlation method, that will benefit the progresses in the experimental exchange of single photons with satellites, up to 20000 km and improved sub-ns temporal resolution [3].
Finally, space QC are also excellent tools for putting the fundament of Quantum Physics under test, paving the way to Quantum Information beyond planet Earth.

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Quantum Communication

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Photonic Technologies are at the heart of all quantum communication methods. Here, an overview will be given on the concepts and experimental demonstrations, starting from *Aunt Martha*, the first experiment on quantum key distribution, to first steps towards quantum networks.

Tba

Sae Woo Nam

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Abstracts of Posters

(in alphabetical order)

Multi-port interferometer for genuine *n*-photon indistinguishability assessment

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The generation of a large number of single-photon states is a crucial challenge of the current quantum technologies. Alongside, the quantification of the degree of indistinguishability of the generated photons is a non-trivial task. In the case of two photons, the indistinguishability can be directly measured with a Hong-Ou-Mandel experiment on a balanced beam splitter. However, when a higher number of photons is involved, performing pairwise comparisons between all the possible photon pairs is not sufficient to assess the genuine indistinguishability of the multi-photon set, only providing upper and lower bounds to the *n*-photon indistinguishability.

In this work, we propose a novel scheme for a multi-port interferometer with $N = 2n$ optical modes. We show that, upon injecting certain Fock states with n indistinguishable photons, quantum interference is observed in the output distribution with a modulation that depends on a single interferometer internal parameter. The visibility of the interference fringe coincides with the *genuine* indistinguishability of the *n*-photon set.

We experimentally demonstrate this operation for the case $n = 4$. The four-photon state is generated from a single quantum dot photonic source using a time-to-spatial demultiplexer. An eight-mode integrated interferometer is fabricated using femtosecond laser micromachining equipped with integrated micro-heaters for the thermo-optic modulation of the internal phase. We measure four-photons indistinguishability of 0.67±0.02 (0.81±0.03) without (with) spatial filtering of the single-photon source. We also show a decrease of the four-photons indistinguishability value as the polarization of one photon is altered, making it increasingly distinguishable.

This device gives us direct access to the *genuine* *n*-photon indistinguishability and represents a valuable tool for characterizing multi-photon sources employed in quantum experiments.

Entanglement-based quantum key distribution using a deterministic quantum dot photon source

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Entanglement-based protocols for quantum key distribution (QKD) provide additional layers of security compared to single-photon prepare-and-measure approaches, despite presenting the challenge of a less immediate hardware implementation. As remarkable technical achievements have been used to demonstrate entanglement-based QKD over longer and longer distances [1], the main opportunity for further development is related to multiphoton emission. This is a fundamental limitation for state-of-the-art photon sources based on spontaneous parametric down-conversion, which can be solved using deterministic quantum emitters. Here we focus on semiconductor quantum dots, which can generate nearly on-demand photon pairs with record-low multiphoton emission [2] and Bell state fidelity currently up to 98% [3]. We experimentally demonstrate the viability of this technology in a realistic urban communication scenario [4]. We employ a modified asymmetric Ekert protocol and perform QKD comparing two choices of quantum channel: over a 250 m single-mode fiber and in free-space between two buildings across the campus of the Sapienza University of Rome. The key exchange is successfully performed with error rates of 3–4%, well below the protocol threshold, and with substantial violations of the Bell inequality. The results are discussed in relation to the technical solutions employed for transferring the signal and to the current state of development of the source. In this regard, an outlook is presented based on the latest and foreseen advances in source design that can lead to unprecedented pair emission rates and boost secure key exchange over long distances.

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Towards highly efficient entangled photon pair sources based on GaAs quantum dots using positioned circular Bragg grating cavities

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We present a novel approach to address the stringent requirement of efficient single and entangled photon pair sources in the context of upcoming quantum communication networks using deterministically positioned circular Bragg grating cavities on single droplet etched GaAs quantum dots. The aim of our work is to build one of the brightest, reliable and reproducible on-demand quantum sources featuring high entanglement fidelities with close to resolution limited linewidths. This is facilitated by fabrication of free-standing low Q-factor circular Bragg grating cavities centered exactly on a quantum dot using prepositioned markers. The fabrication of these structures requires several processing steps including low-temperature in-situ optical lithography, electron beam lithography, reactive ion as well as hydrofluoric acid etching of selected areas of the quantum dot sample. Rigorous experimental investigations have been carried out to optimize geometry and processing to achieve a good overlap between cavity and quantum dot for high Purcell enhancement and increased photon extraction efficiencies.

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Off-resonant two-color excitation of a quantum emitter

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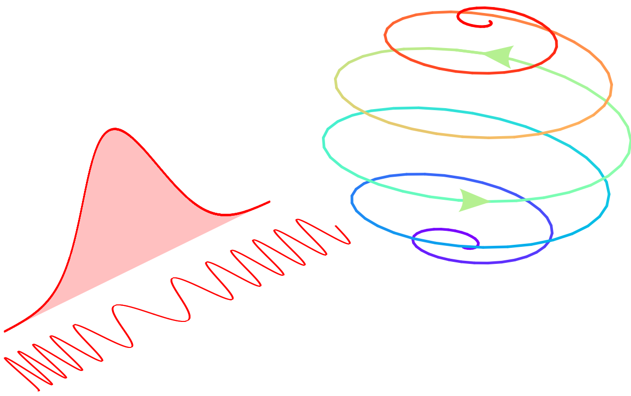
Controlled preparation of a quantum emitter is key for many of its applications, for example as a single photon source. Here, we present a scheme which uses pulses detuned significantly below the excited-state energy that lead to a swing up of the quantum emitter occupation. We show that a two-color excitation leads to high final excited-state occupation and discuss the conditions under which the scheme works. Applied to semiconductor quantum dots, the proposed swing-up scheme results in the emission of high-quality single photons. The main advantage of our scheme compared to Rabi rotations is that no filtering is needed in order to separate the resulting signal from the laser source.
Another advantage is that in contrast to off-resonant schemes relying on phonon-assisted transitions, our scheme does not depend on any auxiliary quasi-particles.
In summary, we are proposing an experimentally feasible swing-up scheme to excite a quantum emitter yielding high-quality photon emission for quantum technology.



Integrated Photonics for Quantum Repeaters

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A key component of quantum communication is the distribution of entanglement through networks. However, this comes with several challenges, in particular the limitation of transmission distance from loss through fibres [1]. A solution to this is to distribute information between two nodes in a quantum repeater architecture [2]. Current implementations of quantum repeater protocols involve the use of large, bulk optic photon sources [3]. Such large sources are impractical when moving towards a realistically implementable and scalable quantum network, where the goal is to be as compact and stable as possible. Integrated photonics is a promising solution to this problem, allowing large numbers of components to be packaged together in a compact and stable manner [4]. In particular, integrated micro-ring resonators (MRRs) have recently demonstrated excellent performance as photon sources [5, 6, 7]. They are compact, highly stable, and their heralding efficiencies have been shown to be comparable to some narrow-band bulk optic sources [7]; a crucial characteristic for scaling quantum communication to large numbers of photons [8].

This poster will present just some of the capabilities of our integrated silicon nitride MRRs, and the applications they have to future quantum networks. It will present key results from successful entanglement swapping experiments between independent integrated MRRs [6, 7], a crucial step in the distribution of entanglement in quantum networks.

In order to subsequently implement a quantum repeater architecture, we are looking to interface our MRRs with quantum memories, in particular, rare-earth ion schemes. These memories have already demonstrated the capacity for long storage time with high multimode capacity and bandwidth [9]. As such, this poster will also present some of the challenges faced in implementing this scheme, and the current work being undertaken in order to overcome them. This includes the ability for electronic frequency tuning of the generated photons, allowing for precise and stable frequency matching of the photons to the quantum memory.

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Overcoming the integration issues between 2D materials and waveguides

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To achieve fully operational quantum photonic integrated circuits, developing a scalable platform capable of supplying an efficient coupling between single-photon emitters and photonic circuitry is essential. A hybrid approach is the most favorable to integrate single-photon emitters with other on-chip components since the advantages of each material platform are exploited. Single-photon emitters hosted in 2D materials are emerging technologies and promising candidates for future scalable photonic circuits. However, the coupling of light from these emitters into waveguides remains challenging: In particular, higher coupling efficiency and reduction of spectral jitter are needed. Both issues can be simultaneously overcome by implementing a cavity in the photonic circuit. In this work, 1D photonic crystal cavities were designed and simulated for later integration of 2D emitters. These photonic crystal cavities are designed to be efficiently coupled to waveguide modes, and they possess high-quality factors and small mode volumes, resulting in prominent Purcell factors. Furthermore, the cavity geometrical structure can act as nucleation sites for strain-driven single-photon emitters, allowing a self-alignment process between emitter and cavity.

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Non-Hermitian formalism in a coupled quantum well and for dynamical control of open dynamics

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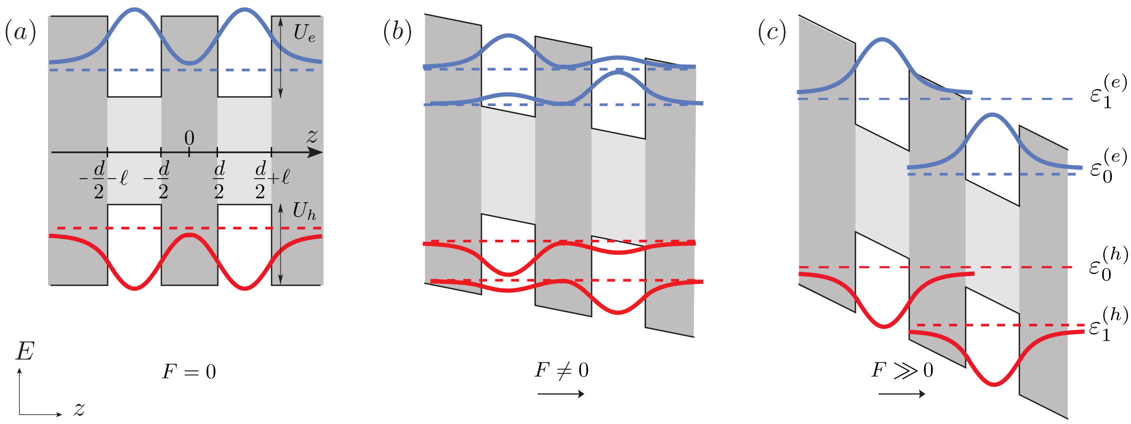
We use non-Hermitian formalism to first deal with lifetimes of polariton and dipolariton in a coupled quantum well. We consider the excitonic excitations of a coupled quantum well in the presence of an electric field and strongly coupled to photons. We show how the cavity photon lifetime and the coherence time of the carrier wave vectors influence the energies and lifetimes of the polaritonic states. While the hybrid polaritons display a spectral singularity where the eigenvalues coalesce, known as an exceptional point, that depends on detuning and lifetimes, we find that the three dipolaritonic states display an anticrossing without exceptional point due to the interaction between photons, direct, and indirect excitons.

In a second part, we extend the control techniques of shortcut sto adiabaticity to any arbitrary, open dynamics. This is possible through the use of non-Hermitian Hamiltonians [2]. We show how to use it for the fast thermalization of a harmonic oscillator [3].



Schematic representation of hybrid polariton to dipolariton in a coupled quantum well in the presence of an external electric field (from [1]).

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Single-photon emitters based on germanium-vacancy centers in solid immersion lenses in diamond

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Solid immersion lenses (SILs) have the potential to enhance the single-photon emission properties of color centers in diamond, e.g., of germanium-vacancy (GeV-) centers, due to an increase of the photon extraction from the diamond. We present the successful generation of GeV centers in bulk diamond, the fabrication of hemispherical SILs with GeV centers using a focused ion beam (FIB) and the metrological characterization of the emission of the GeV centers in SILs in terms of the spectral distribution, the single-photon purity, the saturation behavior, and the emitter's excited state lifetime. We could verify a significant increase of the detector count rate for GeV centers in SILs compared to those without a SIL. The single-photon purity and detector count rate were measured for different excitation powers and were evaluated in a combined model. This allows the possibility to distinguish between the linear background emission and multiple GeV centers in a SIL. Further details will be presented at the seminar.

Engineering the photon statistics by destructive and constructive two-photon interference

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Interference phenomena are at the origin of for many intriguing effects in physics and in particular in the field of quantum optics (e.g., double-slit experiment). Here, we experimentally demonstrate a type of quantum interference that allows us to engineer the photon statistics of a laser light field via the interaction with an ensemble of cold atoms.

When probing the ensemble with near resonant light (D2 line of Cesium), entangled photon-pairs can be generated that will interfere with the two-photon components of the incoming light [1]. Here we show how the relative amplitude and phase of these entangled photon-pairs can be tuned by controlling the number of atoms and the detuning of the laser light. Using this effect, the photon-statistics can be continuously tuned from bunching to antibunching. Our results open new routes for realizing nonclassical light sources (single photons, entangled photon-pair), based on weak, collectively enhanced nonlinearities.

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Quantum photo-thermodynamics on a programmable photonic quantum processor

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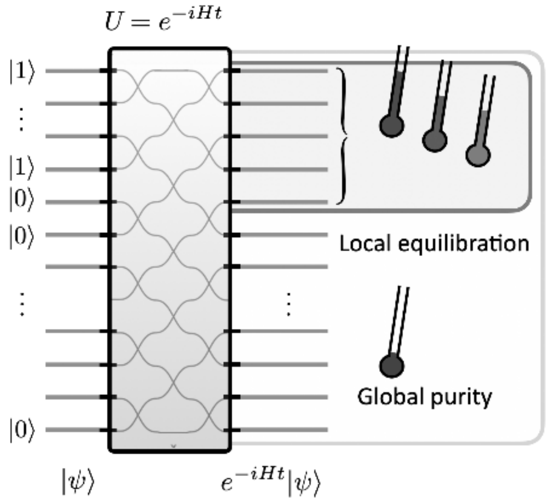

One of the core questions of quantum physics is how to reconcile the unitary evolution of quantum states, which is information-preserving and time-reversible, with the second law of thermodynamics, which is neither. The resolution to this paradox is to recognize that global unitary evolution of a multi-partite quantum state causes the state of local subsystems to evolve towards maximum-entropy states. In this work, we experimentally demonstrate this effect in linear quantum optics by simultaneously showing the convergence of local quantum states to a thermal state, while using a new, efficient certification method to demonstrate that the state retains global purity. Our quantum states are manipulated by a programmable integrated photonic quantum processor, which simulates arbitrary non-interacting Hamiltonians, demonstrating the universality of this phenomenon. Our results show the potential of photonic devices for quantum simulations involving non-Gaussian states.

Spectral engineering of photon pairs and their detection with Hong-Ou-Mandel and Mach-Zehnder interferometry

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We investigate the influence of the symmetry of the biphoton wavefunction on the coincidence measurement of the generalized Mach-Zehnder (MZ) interferometer, where there are temporal and frequency shift operations between the two beam-splitters [1]. We show that the generalized MZ interferometer is the measurement of the short-time Fourier transform of the function modeling the energy conservation of a spontaneous parametric down-conversion process if the full biphoton state is symmetric, and of the symmetric characteristic distribution of the phase-matching function if the state is antisymmetric. Thus, this technique is phase-sensitive to the spectral distribution of the photon pairs. Finally, we investigate in detail the signature of a pair of anyons whose peculiar statistics can be simulated by engineering the spectrum of photon pairs [1,2]. We also present a new method to measure the spectral amplitude of single photon which takes advantage of spectral filtering, frequency entanglement between two single photons the one of interest and a reference, followed by the generalized Hong-Ou-Mandel interferometer [3]. The measurement of the coincidence probability in these different schemes reveals the chronocyclic Wigner, the pseudo-Wigner distribution and the spectrogram at the single photon level.

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Electron-photon and electron-electron scattering as dephasing mechanisms in a single quantum emitter

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We have investigated the Auger effect and the internal photo-effect in a single self-assembled quantum dot with high energy resolution using time-resolved resonant fluorescence (RF). Both effects are important scattering mechanisms that may limit the spin and photon coherence in semiconductor quantum emitters and, hence, should be suppressed for future applications in quantum information.

The Auger effect is an electron-electron scattering event, where the transition energy of one electron is transferred to another electron. Unfortunately, the Auger effect limits the spin-lifetime and suppresses the radiative trion transition. Using time-resolved resonance fluorescence measurements, we show that the Auger process influences the intensity and linewidth of the dot for certain ratios between the Auger and tunneling rates [1] and observe every Auger recombination event in real-time measurement of the random telegraph signal [2]. Moreover, by applying a magnetic field in Faraday geometry, we can suppress the Auger scattering rate by a factor of three [3]; an unexpected behavior that could help to understand how to minimize the influence of this unwanted electron-electron scattering effect.

We present another new and mostly neglected mechanism that fundamentally limits the coherence times in solid-state quantum optical devices: An internal photo-effect that emits electrons from the dot by an intra-band excitation [4]. We find a linear dependence of the optically generated emission rate that is tunable over several orders of magnitude by adjusting the excitation intensity.

Our findings show that both processes, which are well known in single atom spectroscopy, can also be observed for a solid-state quantum emitter and must be avoided or reduced to push the limits towards long qubit coherence times.

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Counting single photons for quantum radiometry

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Single-photon sources find application in many fields of quantum information processing. Therefore, there is an increasing need to ensure high accuracy and metrological traceability of measurements involving low photon fluxes. In quantum radiometry, the discrete nature of light in principle enables a direct realization of the radiometric quantities by counting photons. This work focuses on the use of a single-photon source based on a single semiconductor quantum dot in quantum radiometry, specifically, in the detection efficiency calibration of single-photon avalanche detectors (SPAD). We present a relative calibration [1], carried out with the fiber exchange technique, that reached a relative standard uncertainty of 0.7 % for the ratio of detection efficiencies of two SPADs. Moreover, an absolute calibration [2] was performed by a direct comparison of a SPAD with a low-noise analog detector via the substitution method. At high photon fluxes (up to approx. 2.6 million photons per second), the diminished nonlinearity of the apparent detection efficiency due to the sub-Poisson statistics proved the advantage of semiconductor quantum dots over laser light for applications in the field of quantum radiometry.

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Heralded Storage of Narrowband Single Photons

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Storage of single photons in quantum memories is a key step in many quantum information applications [1]. EIT-based quantum memories have many advantages but require that the stored photons have a very narrow bandwidth [2]. This is a big constraint because typical single photon sources like nonlinear crystals generate photons that are much broader in bandwidth. It has been shown that the bandwidth of generated photons can be decreased by placing the non-linear crystal in a cavity with narrow linewidth [3]. Here we show that we can store heralded, cavity-enhanced single photons in an EIT-based memory. We have a type I PPKTP crystal placed inside a cavity with a 5 MHz linewidth. The cavity is pumped with blue light at 397.5nm and the down-converted photon pairs at 795nm are split on a beam splitter. After filtering through two temperature-tuned Fabry-Perot etalons, one photon from the pair heralds the presence of the other and triggers the memory preparation. We report a spectral brightness of $\sim$ 2000 photons per mW per MHz, an improvement from production rates of similar setups.

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The light cage: a platform for coherent interaction of light and matter

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Vapor cells provide a system relatively easy to handle that allows light manipulation by creating spin-wave coherences in atomic ensemble [1]. Novel photonic structures like the hollow-core light cage [2] provide an attractive platform to boost the interaction of light and atomic vapors by confining the light field in its core while allowing a fast diffusion of atoms inside the structure.
In this work we show for the first time coherent interaction between Cs atoms and light confined in the light cage [3]. Electromagnetically Induced Transparency (EIT) and Autler-Townes Splitting (ATS) are observed. Measurements of the EIT transmission profiles show a clear deviation from the theoretical model in the weak probe approximation. We discuss these deviations and provide generalized theoretical simulations. The suitability as a quantum memory is also analyzed through the decoherence time [4] of the vapor inside the light cage. The experiments set the base for storing light pulses using EIT in a chip-integrated, easy-to-fill, device, and eventually to the implementation of a compact quantum memory for single photons using the EIT-storage scheme.

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Development of photonic integrated components in a silicon carbide platform

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The development of Photonic Integrated Circuits (PICs) has been of particular interest due to their scalability in their manufacture, their high performance, and their low cost in on-chip optical communications systems. Thanks to this, it has been possible to expand the range of applications in quantum information, such as quantum teleportation, quantum simulators and quantum metrology.
Nowadays there are several platforms for the development of PICs. The Silicon Carbide platform is one of the most promising due to the advantages it has over the silicon on insulator platform, such as low propagation losses, stability, and efficiency in third-order non-linear processes.
We present the numerical simulations carried out for the development of the basic components necessary to obtain a fully integrated circuit capable to generate any photonic quantum state. Mainly we focus our attention in the design of single photon sources using micro-ring resonators, and in the development of thermal phase shifters. We also show images of the fabrication results of some of the components.

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The Origin of Antibunching in Resonance Fluorescence

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The generation of single photons is one key component for many quantum applications. It was shown, that resonance fluorescence from a quantum two-level system, e.g. a semiconductor quantum dot, enables single photon generation with high optical quality [1,2]. Furthermore, excitation in the weak driving or the so called Rayleigh regime leads to an emission that inherits the excellent linewidth and coherence properties of the laser [3]. In addition, autocorrelation measurements of the coherently scattered light have suggested that it also gains the single photon statistics from the two-level system [4]. However, we present measurements that prove that the simultaneous observation of sub-natural linewidth and antibunching is not possible [5]. High-resolution spectroscopy reveal the sharp spectral feature of the Rayleigh regime with a vanishing component of incoherently scattered light that is limited in its linewidth by the lifetime of the excited state of the two-level system. Filtering the emission in the order of the Fourier limited linewidth leads to the loss of antibunching in the correlation measurement. Our theoretical model identifies two-photon interference between the coherent and incoherently scattered light as the origin of antibunching of the unfiltered emission [6]. This prefigures schemes to achieve a source of single photons with sub-natural linewidth.

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Sample fabrication approaches towards a cryogenic molecule-based single-photon source

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The immense progress made in quantum optical applications continuously increases the request on stable quantum emitters producing single photons on demand [1]. Dibenzoterrylene (DBT), as a polycyclic aromatic hydrocarbon (PAH), represents such one promising candidate as a single-photon emitter [2]. Photostability, a high quantum yield, short excited state lifetime and a narrow-line spectral emission predominantly in the zero-phonon line are fulfilled when embedded in a rigid organic, crystalline matrix and kept in a cryogenic environment [2, 3].

We report on different approaches concerning the fabrication towards stable molecule-based samples. The fabrication process includes the creation of a stable guest-host-system, serving for a preservation of DBT's single-photon emitter characteristics.

One approach deals with a reprecipitation method based on anthracene crystal growth containing single dibenzoterrylene molecules [4]. All components are spin coated on cover glass and covered with a protective layer made of polyvinylalcohol (PVA). We show the successful growth and following application of anthracene crystals on our substrate.

Another approach is the encapsulation of single dibenzoterrylene molecules in an ultra-stable lattice made of C_{60}-fullerenes. It is shown, that a C_{60} layer is deposited successfully on a cover slide using organic molecular beam epitaxy. Further steps of this work will be the examination of the integration and detection of single dibenzoterrylene molecules inside these carbon structures.

Detailed procedures and results will be shown at the seminar.

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On-Chip Quantum Devices Enabled by Shallow Implanted Vacancy Centers in Laser-Written Waveguides in Diamond

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Vacancy centers in diamond, such as the Nitrogen vacancy (NV^-) and the Silicon vacancy (SiV^-) center have shown enormous potential for quantum sensing and communication. Their integration into photonic structures is a key challenge on the way to build robust and scalable nanophotonic devices for application in quantum technology. Direct laser writing allows for creating arbitrarily shaped 3D photonic structures and large waveguide arrays in diamond in reliable and rapid manner.

Here, we present the functionalization of laser-written waveguides in diamond with NV^- and SiV^- centers. By shallow-implanting NV^- center ensembles into the front facet of the waveguides, we realize an integrated magnetometry platform with read-out through the waveguides [1]. Thereby, we achieve sensitivities up to 62 µT $Hz^{-1/2}$ in CW-ODMR measurements. Extending this approach to a 2D waveguide array, an integrated sensing array can be realized for time and spatially resolved magnetometry on the millimeter scale. Furthermore, we use single shallow-implanted SiV^- centers in the front facet to determine a lower bound for their quantum efficiciency of 0.153 ± 0.013 via extinction measurements [2]. Due to the non-linear character of the SiV^- - waveguide system, we observe super-Poissonian light statistics of the transmitted light, which manifests in bunching behavior of the autocorrelation function, thus confirming single photon subtraction. By extending this platform to on-chip X- or Y-beamsplitters, on-chip quantum optic experiments with SiV^- centers as coherent single photon sources become within reach.

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Maximally entangled and GHz-clocked on-demand photon pair source

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On-demand sources of entangled photons as well as quantum memories are fundamental enabling technologies for future long-range quantum network schemes. While commonly employed sources of entangled photon pairs rely on intrinsically limited spontaneous down conversion processes, quantum emitter-based sources promise greater potential - albeit with higher system complexity. Enormous progress towards practical implementations of quantum emitter-based sources and memories has been made in the past decade. However, applications of current entangled photon sources are still limited by the simultaneous realization of long quantum memory storage times as well as a set of critical parameters, which consist of the emitter clock rate, entanglement, source efficiency, photon indistinguishability and single photon purity. While each parameter has been addressed individually in specifically designed devices and experiments demonstrating a source which combines all of these parameters simultaneously in one and the same device has proven elusive.

We present a 1 GHz-clocked, maximally entangled and on-demand photon pair source based on droplet etched GaAs quantum dots using two-photon excitation [1]. By employing these GaP microlens-enhanced devices in conjunction with their substantial brightness, raw entanglement fidelities of up to 0.95±0.01 and post-selected photon indistinguishabilities of up to 0.93±0.01 are demonstrated. Thereby the suitability of these quantum dot devices for quantum repeater based long range quantum entanglement distribution schemes and interconnection to quantum memory systems is shown.

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Investigation of a Telecom C-Band QD Membrane Embedded in a Broadband Planar Optical Antenna

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Quantum communication schemes, which can prospectively guarantee secure communication by physical laws, rely on the availability of single-photons utilized as flying qubits. For this purpose, indium arsenide quantum dots (QDs) can be employed as single-photon source with excellent single-photon purity, high indistinguishability as well as entanglement of photon pairs fulfilling all principle requirements these applications pose. Particularly, QDs provide access to emission at telecom wavelengths which is highly sought-after for fiber-based applications and will, thus, most probably be the operating regime for real-world applications.
However, simple planar QD structures suffer from a low collection efficiency due to the high refractive index contrast at the semiconductor/air interface. This issue can be tackled by means of different techniques to channel the emission into a certain direction as for instance via microcavities.
This contribution deals with the optical and quantum optical investigation of a telecom C-band QD membrane embedded in a planar optical antenna following the approach of references [1,2]. In this way, the collection efficiency of the QD emission can be strongly enhanced compared to as-grown samples in a broad wavelength range by means of the optical antenna. Furthermore, the small thickness of the structure enables effective strain tuning of the QD emission by means of a piezoelectric actuator positioned underneath. This could facilitate matching the QD emission to atomic transitions, as it is of major interest for quantum networks where the latter can be used as quantum memories. On the other hand, potentially the fine-structure splitting of exciton states could be tuned by the applied strain, enabling QDs as a source of entangled photon pairs in the telecom C-band.

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Efficient spectral separation of single and entangled photons

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Experiments and protocols based on single-photons with different properties are crucial to develop photonic quantum technologies. Semiconductor quantum dots are a promising platform for the emission of single, indistinguishable, and entangled photons. The efficient routing and filtering of frequency mismatched photons, for example, from the biexciton-exciton cascade, is crucial to facilitate the full potential of quantum dots. The separation of photons of different energies allows for efficient entanglement swapping and teleportation experiments, which rely on multiphoton coincidences. Spectral separation and simultaneous detection of adjacent wavelengths are complex to realise. Here we exploit a strategy to build a blaze grating-based transmission spectrometer with outstanding figures of merit. We shed light on the basic principle and the pitfalls that lead to a severe decrease in the efficiency or deterioration of the resolution and how to overcome them. Balancing the main properties, our overall efficiency exceeds 66 %, and our resolution is 21 GHz. Simultaneously, wavelengths distanced by 0.2 nm can be separated. Our self-built setup offers all functionalities to characterise single-photon sources and efficiently incorporate them in modern quantum optics experiments.

SUPER Scheme in Action: Experimental Demonstration of Red-detuned Excitation of a Quantum Dot

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The future of photonic quantum technologies relies on bright, photostable, and on-demand sources of single and indistinguishable photons. In the search for such perfect quantum light sources, semiconductor quantum dots have emerged as a promising platform with excellent performance characteristics [1,2]. Quantum dots benefit from their excellent photostability, near Fourierlimited emission linewidth, and growth technologies that allow easy integration into nanoscale devices [3]. To operate as an on-demand single-photon source, the quantum dot has to be prepared in its exciton state, which recombines to emit a single photon. The usual above-band optical or electrical excitation, which are very appealing from a practical point of view, have severe drawbacks due to preceding non-radiative relaxation processes, intrinsic time jitter, and charge fluctuations by excess carriers, which affect the properties of the emitted photons. In addition, several resonant or near resonant excitation schemes like Rabi rotations, chirped excitations exploiting the adiabatic rapid passage effect [8], dichromatic excitation [5,6], or phonon-assisted excitation [9] have been developed.

In this work, we use two red-detuned pulses in the recently proposed [4] swing-up of quantum emitter population (SUPER) scheme to excite a quantum dot. It is rather surprising that this is possible at all, because neither of the two pulses alone will yield a significant exciton occupation. The SUPER scheme uses the coherent coupling of two laser fields to a quantum emitter to swing-up the system to full inversion. The decisive advantage over the dichromatic scheme [5,6] is that both pulses are red-detuned and therefore, no higher-lying states of the quantum dot will be directly addressed. Because it operates below the band gap but yet coherently. We experimentally demonstrate that, under optimized detuning and intensity, a red-detuned, phase-locked pulse pair can populate the exciton state in a quantum dot relying on the SUPER mechanism. We also perform photon quality measurements and contrast the results with that of resonant excitation. Our results contribute towards an effortless method for generating high purity single photons, with the proof-of-concept performance on par with the resonant excitation scheme, yet most importantly, removing the need for stringent polarization filtering. The red detuned, pulse-pair excitation could have wider implications, especially for probing the coherent dynamics of multi-excitonic systems.

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Advances on GaAs quantum dots integrated in circular Bragg resonators on micro-machined piezoelectric substrates

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Over the last two decades, semiconductor quantum dots have proven to be promising building blocks in nodes of quantum information networks due to their capability of emitting pairs of polarization-entangled photons featuring a near unity degree of entanglement, near-zero multi-pair emission probability and a high photon indistinguishability [1]. However, as-grown quantum dots lack of sufficient photon yield due to total internal reflection within their embedding matrix. In addition, their random position on the substrate and the spread in emission wavelength hinder the scalability of the “quantum dot hardware”. The circular Bragg resonator has been recently reported to show outstanding properties in terms of extraction efficiency while also enhancing the spontaneous radiative emission rate via the Purcell effect [2]. Within this poster, we present promising results on the combination of this photonic cavity together with piezoelectric actuators. The use of a quantum-dot detection-system based on photoluminescence imaging employing numerical image processing and relying on reference-markers allows for the deterministic fabrication of circular Bragg resonators in a reactive-ion dry-etching process. The measured extraction efficiency of the device is substantially increased in contrast to out-of-cavity emitters and a Purcell enhancement is observed. Consequently, the device grants control of the in-plane strain tensor of the quantum dot to decrease the excitonic fine structure splitting and achieve a high degree of entanglement, as well as to control the emission energy to match the cavity mode and tunability for interfacing remote emitters.

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Progress on epitaxial growth of low noise quantum dot heterostructures

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A key component for integrated photonic quantum devices is a deterministic source of high-fidelity photonic qubits, a single photon source (SPS) [1]. A promising route to create such a device employs semiconductor quantum dots (QDs) in tuneable cavities, photonic cavities, and waveguides. These approaches exploit the exquisite toolbox of semiconductors, in particular scalable manufacturing.

Decoherence and noise processes hampering these approaches have been identified [2]. A main contributor to decoherence is noise from a fluctuating electrostatic environment, so called charge noise. One way to efficiently suppress this to such a degree that fully coherent single-photon emission lines are routinely observed, is to embed the QDs in the undoped region of a p-i-n-diode [3,4]. This approach combined with a tuneable cavity has been pursued to realize a highly efficient fiber-coupled SPS with an end-to-end efficiency of 57% [5].

In the presentation, the methods developed to calm the embedding heterostructures environments will be presented [6]. We reveal the strategies to achieve low-noise heterostructures with little photon absorption by strategic placement of n- and p-gates and by using appropriate doping and alloy matrix concentration during molecular beam epitaxial growth.

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Doublons, topology and interactions in a one-dimensional lattice

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Topology and many-body physics are two concepts which have gained much attention recently. To study the interplay between them, we investigate theoretically the Bose–Hubbard version of the celebrated Su-Schrieffer-Heeger topological model, which essentially describes a one-dimensional dimerized array of coupled oscillators with on-site interactions. We study the physics arising from the whole gamut of possible dimerizations of the chain, including both the weakly and the strongly dimerized limiting cases.

Focusing on two-excitation subspace, we systematically uncover and characterize the different types of states which may emerge due to the competition between the inter-oscillator couplings, the intrinsic topology of the lattice, and the strength of the on-site interactions. In particular, we discuss the formation of scattering bands full of extended states, bound bands full of two-particle pairs (including so-called 'doublons', when the pair occupies the same lattice site), and different flavors of topological edge states. The features we describe may find many applications in photonic quantum technologies and provide perspectives on topological many-body physics.

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Thermometry of Gaussian quantum systems using Gaussian measurements

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We study the problem of estimating the temperature of Gaussian systems with feasible measurements, namely Gaussian and photo-detection-like measurements. For Gaussian measurements, we develop a general method to identify the optimal measurement numerically and derive the analytical solutions in some relevant cases. For a class of single-mode states that includes thermal ones, the optimal Gaussian measurement is either Heterodyne or Homodyne, depending on the temperature regime. This contrasts with the general setting, in which a projective measurement in the eigenbasis of the Hamiltonian is optimal regardless of temperature. In the general multi-mode case, and unlike the general unrestricted scenario where joint measurements are not helpful for thermometry (nor for any parameter estimation task), it is open whether joint Gaussian measurements provide an advantage over local ones. We conjecture that they are not useful for thermal systems, supported by partial analytical and numerical evidence. We further show that Gaussian measurements become optimal in the limit of large temperatures, while photo-detection-like measurements do it for when the temperature tends to zero. Our results therefore pave the way for effective thermometry of Gaussian quantum systems using *experimentally realizable measurements*.

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Photonic integrated structures for room-temperature single photon emitters in Gallium Nitride

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In the last 20 years, Gallium Nitride (GaN) has become one of the most widely used semiconductor for optoelectronics applications [1]. This interest is principally due to the fabrication of efficient LEDs and lasers operating from the visible range to the ultraviolet. In terms of materials processing, GaN can thus rely on a mature technology, enabling the fabrication of all necessary elements to build integrated photonic circuits such as waveguides, couplers, gratings, antennas or micro-disks.
More recently, single photon emitters in GaN have aroused great interest as they operate at room temperature, and can emit both in the telecom [2] and near-IR (typically around 700 nm [3]) ranges. The nature of the emitters is still subject to debate, with hypothesis going from point defects in the vicinity of 1- or 2-D structural defects in the GaN (respectively dislocations [4] or stacking faults [3]), to defects created only for one polarity of the GaN matrix [5]. In any case, the integration of these emitters within photonic devices needs yet to be demonstrated.
In this work we study the growth conditions that enable the presence of these room-temperature single emitters in GaN, and address the fabrication of different GaN photonic circuits at the corresponding operating wavelengths. In particular, we discuss the fabrication of bullseye nano-antennas, as well as of a more complex system that includes a waveguide cavity surrounded by two asymmetric Distributed Bragg Reflectors (DBR), which enable the coupling to an auxiliary waveguide terminated by a grating out-coupler.

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Nanostructured TMDs for Photonic Quantum Technologies

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Transition metal dichalcogenides (TMDs) have attracted significant attention as a unique excitonic platform for advanced optical and electronic functionalities. However, in spite of intense research efforts, it has not been widely appreciated that, in addition to displaying rich exciton physics, bulk TMDs also possess a very high refractive index [1-5]. This opens the possibility of utilizing these materials to construct resonant nanoantennas based on subwavelength geometrical modes [1-5]. Here, we show various photonic cavities based on nanostructured TMDs that can be exploited for nano and quantum photonics. First, I will discuss interesting pronounced optical modes in nanostructured TMDs. These optical modes could be tuned over the visible and near-infrared spectral range with precise nanopatterning [2, 4, 5]. Second, I will also discuss novel nanofabrication methods for TMDs [4-5], including a facile and controllable anisotropic wet etching method that allows scalable fabrication of TMD metamaterials with atomic precision. The resulting TMD nanostructures can potentially impact several research fields, e.g., nanophotonics, optoelectronics, quantum photonics, and on-chip optical circuits. Lastly, I will present our new quantum optics laboratory at DTU Fotonik and our experimental research activities on quantum light sources based on various platforms, e.g., III-V quantum dots TMDs.

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Multipair emission effects in quantum dot-based entangled photon sources

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During recent years, quantum dots have become an increasingly established source of highly entangled photons [1], [2]. The main motivation for the development of this technology has resided in the expectation that a resonantly driven quantum emitter can offer a path towards on-demand photon pair generation [3], [4]. In fact, state-of-the-art sources relying on spontaneous parametric down-conversion intrinsically suffer from multipair emission at high pair generation rates, which causes a tradeoff between brightness and degree of entanglement [5]. Despite the key importance of this aspect, the experimental study of how multiphoton emission affects the entanglement properties of quantum dot-based sources has received surprisingly little attention. On this poster, we address the matter and investigate the figures of merit of the source in a wide range of excitation powers under quasi-deterministic resonant two-photon excitation. The weight of multiphoton emission is inferred from the second-order correlation function at zero-time delay. By critically revising previous work in the field, which directly associated variations in this quantity to the polarization density matrix of the photon pair, we propose a model which identifies the actual relationship to the experimental quantum state tomography. Ultimately, we are able to demonstrate that the degree of entanglement of the source is unaffected by multiphoton emission in the whole range of coincidence rates given by Rabi oscillations up to 5π pulse area. Our work confirms that quantum dots can deliver their promise of generating multipair-free entangled photons and helps the design of efficient photon sources for quantum information and communication technologies.

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Helium-4 optically pumped magnetometers for functional brain imaging

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Our startup develops a brain functional imaging tool based on magneto-encephalography (MEG). In order to democratize MEG, which currently relies on cumbersome and expensive SQUID systems requiring cryogenic cooling, we use quantum sensors, namely optically pumped magnetometers (OPM) based on a gas of metastable helium-4. This kind of quantum magnetometer works at any temperature, needing no cooling nor heating, unlike SQUID or alkali OPM based on the SERF effect. This allows setting the sensors in contact with the surface of the body, as close as possible to signals to be observed in medical imaging. As a result the amplitude of the observed signals is significantly better than with other technologies.

After a first proof-of-concept MEG recording [1], we developed a new generation of sensors with improved footprint to be set in arrays. In contrast with other OPM we pump the atoms with linearly polarized light. This configuration allows measuring the component of the field radial to the head using light that propagates radially [2], which allows closer packing and a simpler optical setup. Our sensors currently have 2 kHz bandwidth, a dynamic range of several hundredths of nanotesla and resolutions better than 30 $fT/Hz^{1/2}$ in multi-axis mode. We demonstrated array operation of closely-packed sensors in closed-loop and automatic correction of the cross-talks between the sensors [3].

We now aim to develop for 2023 a commercial product consisting in an array of 64 OPMs with all its associated electronics for hospitals and biomedical research centers.

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Hybrid 2D material/dye molecule quantum emitter for integrated nanophotonics

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We present preliminary results on the photophysical properties of a novel hybrid solid-state quantum emitter based on single dye molecules encapsulated between two monolayers of 2D materials. The latter are supposed to provide surface passivation and dye protection against photobleaching agents as, e.g., oxygen [1, 2]. At cryogenic temperatures, low spectral diffusion and an accordingly narrow emission linewidth of the molecules are expected. Being nanometer thin, this novel quantum emitter would efficiently couple to the evanescent field surrounding nanophotonic devices, such as tapered optical fibers with a nanofiber-waist and on-chip high-Q microresonators, relying on the well-established all-dry viscoelastic deterministic transfer method [3, 4]. Strong light-matter interaction would be ensured as the emitter can be placed directly onto the surface of the nanostructure while causing only minimal scattering losses. The system thus represents a promising alternative to the currently available solid-state quantum emitters based on sub-micrometric size crystals which are doped with single dye molecules [5, 6].

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Experimental robust self-testing of the state generated by a quantum network

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Within the last decades, several quantum resource-based protocols have been designed, with a wide range of applications. In such a context, it is pivotal to have certification procedures to discriminate whether a device claiming to perform a quantum task is truly exploiting quantum behaviours, and not just simulating them. However, this is not trivial. Indeed, the apparatus may be affected by imperfections that are not under its user's control, and that may be exploited by an untrusted party to sabotage its operation. In order to address this issue, the device independent (DI) approach for certification procedures was introduced [1], that allows validating a device operation only relying on input/output statistics, and without assuming anything about its functioning details.

In this work [2], we implement a versatile DI protocol, in particular a self-testing [3], that provides lower bounds on the fidelity between arbitrary target states and unknown states generated by two different photonic building blocks for quantum networks. For its experimental realization, we use a scalable photonic platform that allows performing separable measurements on the states generated by independent sources located in different laboratories. Then, we obtain lower bounds on the fidelity through semidefinite programming. The main novelty of our method lies in its intrinsic robustness to noise, since it is tailored to experimental data. Moreover, due to its versatility, it can be easily adapted to the certification of larger and more complex networks, towards the realization of a quantum internet.

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Atomic spin-controlled non-reciprocal Raman amplification of fiber-guided light

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In a non-reciprocal optical amplifier, gain depends on whether the light propagates forwards or backwards through the device. Typically, one requires either the magneto-optical effect, a temporal modulation, or an optical nonlinearity to break reciprocity [1]. By contrast, here, we demonstrate non-reciprocal amplification of fiber-guided light using Raman gain provided by spin-polarized atoms that are coupled to the nanofiber waist of a tapered fiber section [2]. The non-reciprocal response originates from the propagation direction-dependent local polarization of the nanofiber-guided mode in conjunction with polarization-dependent atom-light coupling [3]. We show that this novel mechanism does not require an external magnetic field and that it allows us to fully control the direction of amplification via the atomic spin state. Our results may simplify the construction of complex optical networks. Moreover, suitable solid-state based quantum emitters provided, our scheme could be readily implemented in photonic integrated circuits.

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Switching the type of photon entanglement generated by a driven quantum emitter

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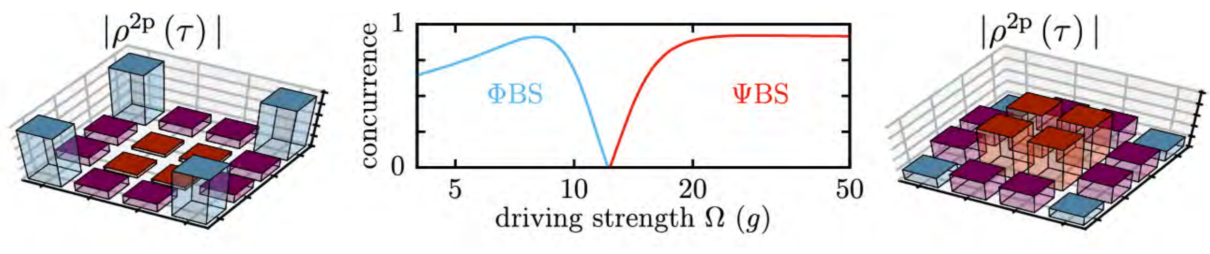
The generation of entangled photons is essential in quantum communication. In a four-level emitter as found in a semiconductor quantum dot, entangled photon pairs can be created that are in one of the four Bell states. When staying in the same basis, the type of the Bell state can be changed, if the emitter is placed inside a photonic cavity and driven from the side by an external laser pulse. We show that different types of entanglement are obtained for different conditions and compute the corresponding two-photon density matrices [1]. A very handy tuning knob is the driving strength of the external laser pulse. Using this knob, we propose a scheme to switch the type of photon entanglement on a nanosecond time-scale [2].



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High Fidelity Biexciton Preparation via Adiabatic Rapid Passage in a Quantum Dot

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Semiconductor quantum dots are bright, on-demand single-photon sources suitable for realising scalable quantum communication devices. An important prerequisite to this end is the high-fidelity preparation of the biexciton (XX) state via a two-photon excitation (TPE), since the subsequent radiative decay results in entangled photon pair production. Here we investigate the robustness of Adiabatic Rapid Passage (ARP) via chirped pulses as an alternative scheme towards deterministic generation of single photons from GaAs/AlGaAs quantum dots. Our results also demonstrate the challenges in achieving the ARP regime, due to the high chirp values required.

20-mode quantum photonic processor in silicon nitride

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Quantum photonic processors, i.e., large-scale, low-loss multimode interferometers are a crucial component of photonic quantum computers, whether of the near-term boson sampling-based variant or in universal architectures. In this work, we introduce a 20-mode quantum photonic processor – the largest reported on to date. The processor has optical losses of 2.9 ± 0.2 dB, where the spread is over different modes, and a fidelity (excluding phase) of 0.935 ± 0.017 over 1000 Haar-random unitary matrices. The processor has a design wavelength of 1550 nm and is realized in TriPleX silicon nitride. We show experimentally that the processor preserves Hong-Ou-Mandel interference at any node on its structure. This processor will find application in state-of-the-art quantum optics and quantum information processing experiments.

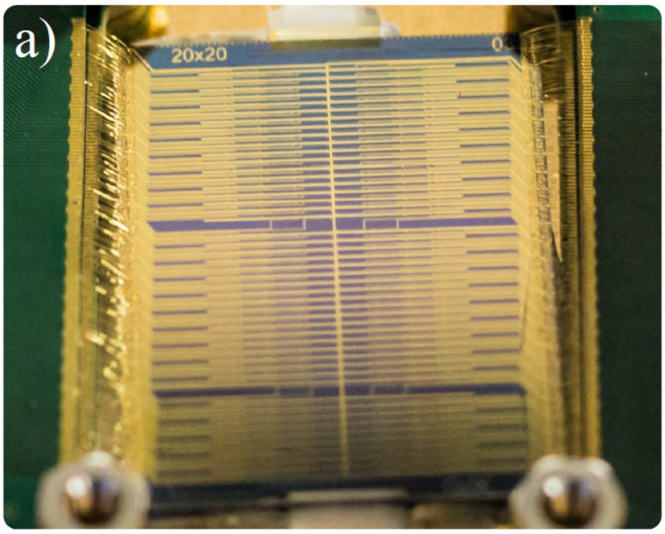

Figure 1: the 20 x 20 quantum photonic processor chip

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Evaluating a Quantum Key Distribution Testbed using Plug&Play Telecom-wavelength Single-Photons

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Quantum light sources are key building blocks for advanced photonic quantum technologies and quantum communication in particular. Among the plethora of available solid-state based quantum emitters, semiconductor quantum dots (QD) stand out, as they allow to simultaneously achieve high single-photon purities, in terms of $g^{(2)}(0)$, and high photon indistinguishabilities of single- and entangled-photon states both at large photon collection efficiencies. In addition, their relatively short radiative lifetime enables high clock rates, as demonstrated in first proof-of-concept QKD experiments using QD single-photon sources (SPSs) under pulsed optical [1] and electrical pumping [2]. A drawback of almost all QD-based SPSs, however, was the need for bulky cryotechnology often requiring liquid helium infrastructure. To resolve this, an innovative concept combining directly fiber-pigtailed deterministically fabricated QD-devices with compact Stirling cryocoolers was recently introduced [3].
In this contribution, we present QKD tests using a 19-inch benchtop single-photon source at 1321 nm based on a fiber-pigtailed quantum dot (QD) integrated into a Stirling cryocooler. Emulating the polarization-encoded BB84 protocol, we achieve an antibunching of $g^{(2)}(0) = 0.10 \pm 0.01$, a raw key rate of up to (4.72 ± 0.13) kHz, and a maximum tolerable loss of 23.19 dB exploiting optimized temporal filters in the asymptotic limit [4]. The results are discussed in comparison to previous works on QD-based single photon sources used for QKD experiments, and an outlook with further improvements for compact quantum light sources is provided.
Our study represents an important step forward in the development of fiber-based quantum-secured communication networks exploiting sub-Poissonian quantum light sources.

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Waveguide lattices as photonic quantum simulators

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Quantum mechanics phenomena could lead to revolutionary applications in quantum technologies such as in quantum computation, communication, metrology, and simulation. However, the implementation and control of such phenomena are still difficult to achieve and problematic to implement on a large scale. Integrated photonics is a key enabling technology for the implementation of quantum simulators. Indeed, integrated quantum nanophotonics, implemented via waveguide lattices, mimic physical quantum mechanics systems due to their mutual equivalence [1,2].

In this work, we aim at developing scalable programable quantum simulators with the use of waveguide lattices. The dynamics of quantum system can be mapped into space domain and thus, implemented with the help of waveguide lattices [3-5]. Here, we present the numerical simulations that mimic the dynamics of a quantum system, namely the Heisenberg spin chain, where coherent transport of quantum states is seen. A coherent transport was achieved with a fidelity higher than 99%. The fabrication of the quantum simulator in a silicon nitride platform is presented as well as preliminary characterization of the device.

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Free-Space Quantum Key Distribution with Single Photons from Defects in Hexagonal Boron Nitride

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On-demand, bright, and stable single-photon emitters at room temperature have the potential to both reduce the cost and increase the security of quantum key distribution (QKD) systems. In the last two decades, several single-photon sources have been used in QKD demonstrations, including quantum dots and diamond color centers [1-2]. Hexagonal boron nitride (hBN) is a two-dimensional material hosting several optically active defect types which are capable of single-photon generation at room temperatures [3]. Bright and optically stable nature of these emitters makes them a good candidate for room temperature QKD applications compared to alternatives. Here we present our recent activities on demonstration of free-space QKD with a single emitter of hBN at room temperature. Basic optical properties of the selected emitter are characterized via confocal micro-photoluminescence setup, and the quantum nature of the emission is shown by second-order photon correlation measurement. Finally, the emitter at hand is integrated into a stand-by QKD system based on the B92 protocol, which uses the polarization of single photons to generate a secure key. Our results show that hBN promises to be a new single-photon source for QKD experiments without the need for cryogenic conditions.

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Quantum Dot Imaging Localization Methodology based on Imaging

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Since the discovery of the triggered generation of single photons in 2000, quantum dots have proven to be one of the most versatile quantum light sources for pure, indistinguishable, entangled photons while maintaining high brightness. Before developing deterministic integration techniques, high yield in device fabrication remained elusive due to the statistical growth properties in high-quality self-assembled growth modes. Several methods have been developed, providing the quantum dot location and its spectral information, namely in-situ optical lithography[1], in-situ electron beam lithography[2], and quantum dot localization using quantum dot imaging[3]. Our work describes a methodological workflow using computational and image processing approaches in python to precisely determine the quantum dot position concerning pre-deposited metal marker structures. Here, we investigate different hardware, marker geometries, and software methods. Furthermore, we quantify the expectable upper bound accuracy for device integration. Importantly, our presented methods are not developed for a fixed emitter wavelength or type. With the right choice of optical elements within the setup, it is possible to cover the wavelengths from the visible up to the telecom C-band. The presented technique can, in principle, be applied to any solid-state quantum emitter type.

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Fast and Simple Integrated Quantum Key Distribution

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Confidentiality and protection of the transmission of online data is becoming a more and more relevant area of concern. Today, algorithms used to encrypt and decrypt data are based on computationally hard problems. However, with the advancement of quantum computers such algorithms will no longer be secure, ergo an urgent need of an alternative solution. One such is the use of quantum key distribution (QKD), which, with the help of the laws of quantum mechanics, is proven to be information-theoretically secure.

QKD has been extensively experimentally demonstrated, from the first one with users separated on an optical table using the free space as the quantum channel [1], to their separation at distances of hundreds of kilometers through optical fibers [2] and even to the usage of satellites [3]. The setups have gone from bulk to integrated [4], to allow for a straight-forward and cost-friendly integration of QKD into existing metropolitan fiber-networks.

We present a time-bin encoding QKD setup using several different integrated photonic technologies for the transmitter (Alice) and receiver (Bob). A secret key exchange is performed at a rate of 2.5 GHz, which is the fastest (to our knowledge) rate performed using integrated QKD. Secret keys with low QBERs at reasonable metropolitan distances were obtained, applying the three-state BB84 protocol with 1-decoy state. The integrated part of Alice is based on silicon and consists of an interferometer, an intensity modulator and variable attenuators, all integrated onto one chip. Regarding Bob, two integrated versions were made, both consisting of a passive beam splitter and an interferometer, based either on silica planar light circuit or fabricated using a femtosecond laser micromaching technique on silica. Bob is polarization insensitive, and Alice and Bob are separated with dedicated optical fibers.

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Crux of Using the Cascaded Emission of a Three-Level Quantum Ladder System to Generate Indistinguishable Photons

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Single and indistinguishable photons are basic building blocks for many quantum technology applications. Photons emitted from the radiative cascade of a three-level quantum ladder system show excellent single-photon purity[1]. Here[2], we investigate the degree of indistinguishability of cascaded photons emitted from such a system; in our case the biexciton-exciton cascade of semiconductor quantum dots. We theoretically show that the indistinguishability for both emitted photons is inherently limited by the ratio of the lifetimes of the excited and intermediate states. We confirm this finding both experimentally and with quantum optical simulations by comparing the quantum interference visibility of cascaded and noncascaded emission of the same quantum dot. Based on our model, we propose photonic structures or stimulated emission from the excited to the intermediate state[3] to optimize the lifetime ratio and overcome the limited indistinguishability.

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Experimental demonstration of an efficient, semi-device-independent photonic indistinguishability witness

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Efficient and reliable measurements of photonic indistinguishability are crucial to solidify the claims of a quantum advantage in photonics. Existing indistinguishability witnesses may be vulnerable to implementation loopholes, showing the need for a measurement which depends on as few assumptions as possible. Here, we introduce a semi-device-independent witness of photonic indistinguishability and measure it on an integrated photonic processor, certifying three-photon indistinguishability in a way that is insensitive to implementation errors in our processor [1,2].

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High photon number entangled states and coherent state superposition from extreme-UV to far-IR

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We present a theoretical study on the generation of entangled coherent states and of coherent state superpositions, with photon numbers and energies, orders of magnitude higher than those provided by the current technology [1]. This is achieved by utilizing a quantum mechanical multimode description of the single- and two-color intense laser field driven process of high harmonic generation in atoms. It is found that all field modes involved in the high harmonic generation process are entangled, and upon performing a quantum operation, leads to the generation of high photon number non-classical coherent state superpositions spanning from the extreme-ultraviolet to the far infrared spectral region. These states can be considered as a new resource for fundamental tests of quantum theory and quantum information processing.

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Temporal evolution of line broadening in charge-controlled quantum dots

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Self-assembled semiconductor quantum dots (QDs) present themselves as an attractive platform for the implementation of scalable hybrid quantum-information schemes [1]. On-demand emission of high-quality single photons demonstrates the potential of such systems [2,3]. Sources of noise, caused by the interaction with the solid-state environment can lead to an inhomogeneous broadening of the emission line [4]. The magnitudes and timescales of such dephasing mechanisms vary strongly with the material composition and heterostructure of a sample. Here, we employ photon-correlation Fourier spectroscopy as a powerful experimental method to study the spectral dynamics of single emitters, with high spectral and temporal resolution [5]. In particular, the broadening mechanisms of QDs embedded in a novel type of gated structure, based on a n-i-n-diode are investigated.

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Single Photon Quantum Communication at TU Berlin

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The quantum internet promises secure communication at a global scale and the ability to perform distributed quantum computations. While its physical implementations will rely on many different building blocks, photonic quantum technologies will play a major role, especially in the distribution of quantum information. Over the last decades significant progress has been made towards this goal [1].

Our group at Technical University Berlin studies different types of quantum emitters, to develop practical quantum light sources and implement quantum information protocols. Epitaxial semiconductor quantum dots are thereby serving as a mature technology platform [2]. Integrated in highly functional devices, the source efficiency and the quality of the emitted photons can be optimized [3]. Moreover, combining direct fiber coupling [4] and compact cryotechnology [5], practical quantum light sources can be realized. Furthermore, we pursue implementations of quantum communication using novel types of quantum emitters, such as strain-centers in atomically-thin transition metal dichalcogenides [6] and non-linear effects in atomic ensembles [7]. In addition, our group strives for implementations of measurement-device independent QKD and other cryptographic primitives beyond QKD. Based on these efforts, our group works on setting up a quantum local area network at the campus of Technical University Berlin.

This poster presentation reviews recent advances of our group, including the first quantum communication tests using atomically-thin single-photon sources.

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High quality quantum dot structures from hybrid MOVPE/MBE growth

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Semiconductor-quantum dots are promising candidates as single photon sources for quantum information technologies. Photonic quantum operations often require indistinguishable photons from remote sources, ideally with high brightness. For these purposes, quantum dots embedded in diode structures provide several advantages: these gated samples allow for the application of electric fields to the quantum dots which alters the emission wavelength making the emission spectrally tunable. This is especially useful for two photon interference experiments using two distinct sources. In addition, an applied electric field stabilizes the charge environment enhancing the emitted photons coherence. The growth of self-assembled semiconductor quantum dots is usually carried out utilizing epitaxial processes like metal-organic vapor-phase epitaxy (MOVPE) or molecular-beam epitaxy (MBE). This work presents a novel approach for a hybrid growth of semiconductor quantum dot samples utilizing MOVPE for the distributed Bragg mirrors and MBE for growth of high-quality quantum dots, embedded into a diode structure. This provides InAs quantum dots with high emission rate, narrow emission linewidth and wavelength control. Indeed, the sample is electrically tunable due to its gated structure and the excitonic states can be selectively initialized depending on their charge state. The novel sample is a high-quality single-photon source that allows two-photon excitation (TPE) with many visible Rabi oscillations and good $g^{(2)}(0)$ values as shown in figure 1.

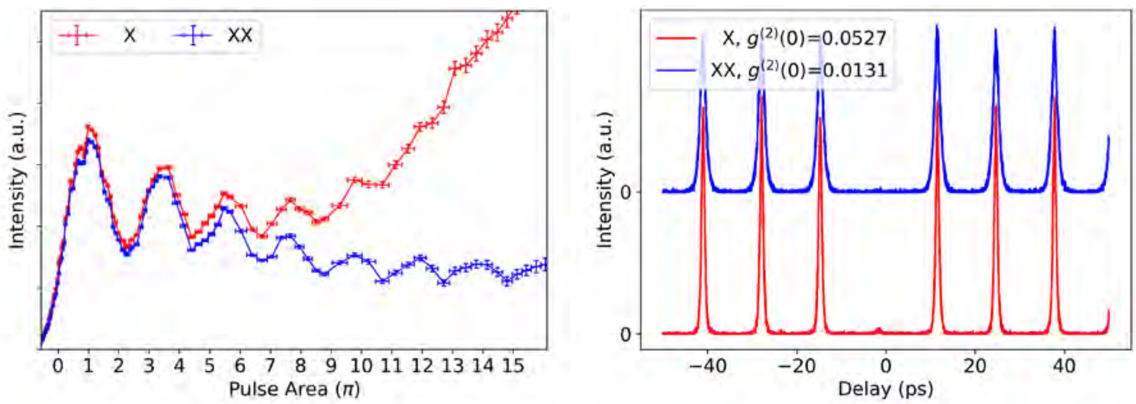

Figure 1: Two-photon excitation (TPE) at 6K of the biexciton-exciton cascade shows many Rabi oscillations (left) and good dark count corrected $g^{(2)}(0)$ values (right) for the excitonic (X) and biexcitonic (XX) state.

Near-unity efficiency in ridge waveguide-based on-chip single-photon source

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We report a design procedure of pursuing a near-unity coupling efficiency in quantum dot-cavity ridge waveguide single-photon source, whose structure is shown in Figure 1. We investigate the impact of different design configurations on the emission and collection properties in the same base platform by performing numerical simulations with the Finite Element Method [1-2]. Our optimum design achieves a high source efficiency β_{xy} of 97.7% for an isotropic in-plane dipole, together with a remarkable Purcell factor of 38. Furthermore, we analyze the bottleneck of the proposed platform and accordingly present the optimization recipe of an arbitrarily high-efficiency on-chip single-photon source for large-scale quantum information processing. Finally, we discuss the robustness of the system under the consideration of realistic fabrication imperfections.

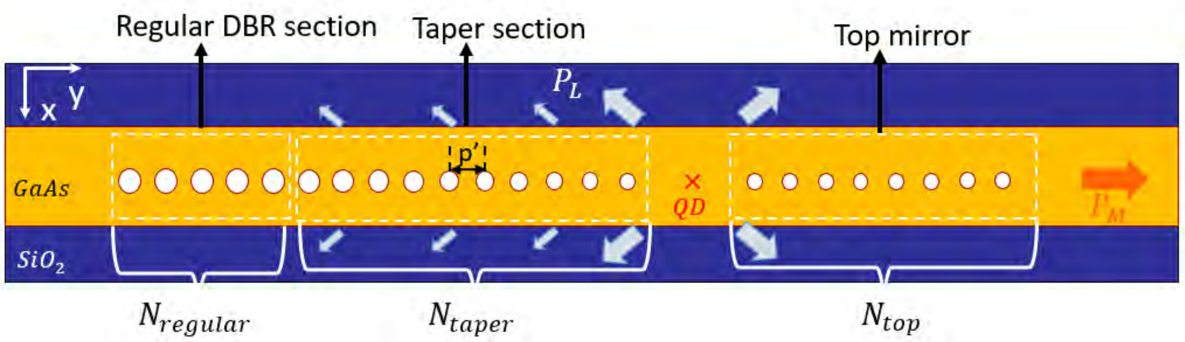

Figure 1. Top view of the QD- taper cavity waveguide structure. The bottom mirror is divided into a taper section and a regular DBR section, whose number of holes are described by N_{taper} and $N_{regular}$.

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Efficient and stable fiber-to-chip coupling enabling the injection of telecom quantum dot photons into a silicon photonic chip

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Generation of nonclassical states of light in linear and nonlinear photonic molecules

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Integrated quantum optics allows for new possibilities of improving the light-matter interaction and increasing the efficiency of the generation of nonclassical light via nonlinear parametric processes, such as spontaneous parametric down conversion and spontaneous four-wave mixing. In this respect, spatial and temporal confinement of light in micro and nano resonators is fundamental to control the generation efficiency and mitigate the effect of parasitic processes or unwanted nonlinear phenomena.

Here we focus on the generation of photon pairs via parametric fluorescence in two different systems. The former is composed of two resonators that are strongly coupled to exploit the resonances arrangement of a photonic molecule [1] (Figure 1 (a)). The latter consists of two linearly uncoupled (but coupled through non-linear interaction) resonators that allow for a flexible and precise control of the resonant field enhancement [2] (Figure 1 (b) and (c)). We show that the first strategy allows to suppress parasitic processes and reach record levels of squeezing on Si_3N_4 chips. At the same time, we demonstrate that linearly-uncoupled resonators in integrated devices control the quantum properties of the generated light [3,4].

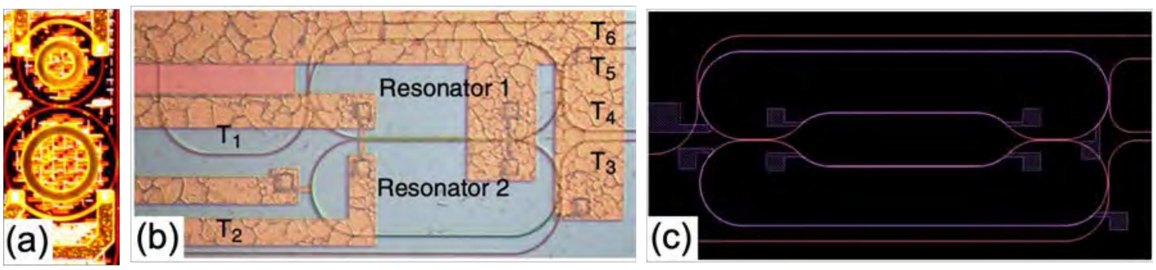

Figure 1: (a) Strong coupling in a photonic molecule. (b) Linear uncoupling via directional coupler. (c) Linear uncoupling via Mach-Zehnder interferometer.

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Black-Box Approach to High Dimensional Photonic Quantum State Engineering

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The engineering of arbitrary high-dimensional quantum states is a pivotal task in quantum information science. In particular, the ability to produce the desired state with high fidelity and independently of the environmental situation is a highly demanded feature in quantum communication and cryptography protocols. Several strategies and platforms have been proposed and adopted to accomplish this task. However, the inevitable presence of noise and the lack of an accurate characterization of the apparatus significantly decrease the generation performances. In this work [1], we showcase the use of an adaptive optimization protocol for the engineering of Orbital Angular Momentum (OAM) states. Working in a fully black-box scenario [2], the protocol tunes the relevant experimental parameters relying only on the measured fidelity between the produced state and the target one, without needing a description of the generation setup. We experimentally implemented the protocol using the evolution of a Quantum Walk in the angular momentum of light for both laser source and single photon states. The protocol is demonstrated to be able to optimize the engineering process from a noisy output statistic for several four-dimensional OAM states, reaching high values for the fidelities. Moreover, we investigated the adaptability of the protocol by introducing noise as external perturbation on the values of the parameters. We observed that high fidelities are reached even when the environmental conditions change.

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