Symposium Quantum Repeater (SYQR)

jointly organized by
the Quantum Optics and Photonics Division (Q),
the Atomic Physics Division (A), and
the Semiconductor Physics Division (HL)

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Overview of Invited Talks and Sessions

(Lecture rooms: Audimax, Kinosaal, and UDL 2002)

Invited Talks

SYQR 2.1	Mon	14:00–14:30	Audimax	**Protocols and prospects for building a quantum repeater** — •Peter van Loock
SYQR 2.2	Mon	14:30–15:00	Audimax	**Quantum teleportation from a telecom-wavelength photon to a solid-state quantum memory** — •Felix Bussieres
SYQR 2.3	Mon	15:00–15:30	Audimax	**Semiconductor quantum light sources for quantum repeaters** — •Peter Michler
SYQR 2.4	Mon	15:30–16:00	Audimax	**Quantum networks based on cavity QED** — •Stephan Ritter, Joerg Bochmann, Eden Figueroa, Carolin Hahn, Norbert Kalb, Martin Mücke, Andreas Neuzner, Christian Nölleke, Andreas Reiserer, Manuel Uphoff, Gerhard Rempe

Sessions

SYQR 1.1–1.7	Mon	10:30–12:15	UDL HS2002	**Flying/Stationary Qubit Conversion and Entanglement Generation**
SYQR 2.1–2.4	Mon	14:00–16:00	Audimax	**Quantum Repeaters**
SYQR 3.1–3.7	Tue	10:30–12:15	Kinosaal	**Quantum Protocols and Gates**
SYQR 4.1–4.7	Tue	14:00–15:45	Kinosaal	**Photon Sources for Quantum Networks**

SYQR 1: Flying/Stationary Qubit Conversion and Entanglement Generation

Chair: Jürgen Eschner (Uni Saarbrücken)

Time: Monday 10:30–12:15 Location: UDL HS2002

SYQR 1.1 Mon 10:30 UDL HS2002

Long distance entanglement of single trapped atoms — •Kai Redeker[1], Daniel Burchardt[1], Norbert Ortegel[1], Markus Rau[1], Julian Hofmann[1], Michael Krug[1], Markus Weber[1], Wenjamin Rosenfeld[1,2], and Harald Weinfurter[1,2] — [1]Fakultät für Physik, Ludwig-Maximilians- Universität München, D-80799 München, Germany — [2]Max-Planck Institut für Quantenoptik, D-85748 Garching, Germany

Entanglement is an essential feature of quantum mechanics. Entanglement of stationary particles like atoms forms the basis of a quantum repeater for efficient long distance quantum communication.

We present an experiment on the generation of entanglement between two separately trapped ^{87}Rb-atoms. In our scheme we use spontaneous emission that provides us with entanglement of the spin of the trapped atoms and polarization of the emitted photon together with entanglement swapping to generate entanglement between the atoms. So far we could demonstrate this scheme over a distance of 20m.[1] Additionally we could show quantum teleportation from a weak laser pulse onto the Zeeman-state of a single ^{87}Rb-atom.

Our current work is on increasing the distance of 400 m and implementing a new fast atomic state measurement with ability to randomly chose the measurement basis on a very fast timescale. Such a System can enable device independent quantum key distribution and as such forms the elementary link of a quantum repeater.

[1]J.Hofmann et al. Science 337, 72 (2012)

SYQR 1.2 Mon 10:45 UDL HS2002

High-fidelity heralded photon-to-atom quantum state transfer — •Christoph Kurz, Michael Schug, Pascal Eich, Jan Huwer, Philipp Müller, and Jürgen Eschner — Experimentalphysik, Universität des Saarlandes, Saarbrücken, Germany

A promising platform for implementing a quantum network are atom-based quantum memories and processors, interconnected by photonic quantum channels. A crucial building block in this scenario is the conversion of quantum states between single photons and single atoms through controlled absorption [1, 2] and emission [3].

We present an interface for heralded photon-to-atom quantum state conversion [4], whereby the polarization state of a single photon is mapped onto the spin state of a single absorbing ^{40}Ca$^+$ ion with >95% average fidelity. A successful state-mapping event is heralded by a single emitted photon. We record >80 s^{-1} events out of 18,000 s^{-1} repetitions.

[1] N. Piro et al., Nat. Phys. **7**, 17 (2011)
[2] J. Huwer et al., New J. Phys. **15**, 025033 (2013)
[3] C. Kurz et al., New J. Phys. **15**, 055005 (2013)
[4] N. Sangouard et al., New J. Phys. **15**, 085004 (2013)

SYQR 1.3 Mon 11:00 UDL HS2002

Interfacing Superconducting Qubits and Optical Photons via a Rare-Earth Doped Crystal — •Nikolai Lauk[1], Christopher O'Brien[1], Susanne Blum[2], Giovanna Morigi[2], and Michael Fleischhauer[1] — [1]Fachbereich Physik und Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany — [2]Universität des Saarlandes, Saarbrücken, Germany

Superconducting qubits (SCQ) are promising candidates for scalable quantum computation. However, they are essentially stationary, which makes the transport of quantum information difficult. Telecom-wavelength photons on the other hand, are the best candidates for transporting quantum information, due to the availability of low loss optical fibers.

By interfacing telecom photons with SCQ's one can combine the advantages of both systems to build a quantum network. To this end, we propose and theoretically analyze a scheme for coupling optical photons to a SCQ, mediated by a rare earth doped crystal (REDC). In the first step an optical photon is absorbed in a controlled way into a REDC. This optical excitation is then moved into the spin state using a series of π-pulses and is subsequently transferred to a SCQ through a microwave cavity. Due to intrinsic and engineered inhomogeneous broadening of the optical and spin transitions employed in REDC for the storage of optical photons, we require a special transfer protocol using staggered π-pulses to first move the population into the microwave cavity and then from the cavity to the qubit.

SYQR 1.4 Mon 11:15 UDL HS2002

Remote entanglement generation with parabolic mirrors — •Nils Griebe, József Zsolt Bernád, and Gernot Alber — Institut für Angewandte Physik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

We develop an entanglement generation scheme which uses parabolic mirrors in a multimode and single photon scenario in order to create an entangled state between two remote material qubits. The qubits are implemented as internal states of trapped ions located in the foci of the two parabolic mirrors [1] which face each other. This configuration which might be used in free space communication causes an interesting dynamics of the two ions and the radiation field. We analyze the dynamics by using semiclassical methods and a photonic path representation of the time evolution operator. In this proposal we use the spontaneous decay as a tool for distant entanglement generation and not as an effect to evade.

[1]Alber,G., Bernád,J.Z., Stobinska,M., Sánchez-Soto,L.L., Leuchs,G.: QED with a parabolic mirror, Phys. Rev. A 88, 023825 (2013).

SYQR 1.5 Mon 11:30 UDL HS2002

Double-heralded single-photon absorption by a single atom — •José Brito, Stephan Kucera, Pascal Eich, Michael Schug, Christoph Kurz, Philipp Müller, Jan Huwer, and Jürgen Eschner — Experimentalphysik, Universität des Saarlandes, Saarbrücken, Germany

We present a single-photon single-atom interface experiment, where a heralded single photon generated by Spontaneous Parametric Down Conversion (SPDC) is absorbed by a single atom, generating a single blue (393 nm) photon in an anti-Stokes Raman process [1].

The SPDC photon-pair source [2] is stabilized and tuned to match resonantly the $D_{5/2}$–$P_{3/2}$ atomic transition of ^{40}Ca$^+$ at 854 nm [3, 4].

A single ^{40}Ca$^+$ ion is trapped in a linear Paul trap and prepared for the absorption of these photons by coherent excitation from the $S_{1/2}$ ground state to the metastable $D_{5/2}$ state. We correlate the detection of the partner photon that heralds the 854 nm SPDC photon with the blue Raman photon that heralds the absorption event. Furthermore, we explore the subsequent frequency conversion of the SPDC herald to the telecom band.

[1] C. Kurz et al., New J. Phys. **15**, 055005 (2013)
[2] N. Piro et al., J. Phys. B **42**, 114002 (2009)
[3] N. Piro et al., Nat. Phys. **7**, 17 (2011)
[4] J. Huwer et al., New J. Phys. **15**, 025033 (2013)

SYQR 1.6 Mon 11:45 UDL HS2002

Fiber-Cavity Coupled Atomic Ensembles for Photon Storage — •Miguel Martinez-Dorantes, Wolfgang Alt, Jose Gallego, Sutapa Ghosh, Lucie Paulet, Lothar Ratschbacher, Yannik Völzke, and Dieter Meschede — Universität Bonn, Institut für Angewandte Physik, Wegelerstraße 8, 53115 Bonn

Quantum networks have the potential to revolutionize the area of information technology, where the unconditionally secure transmission of information represents a prominent application. The most advanced architectures for realizing long distance quantum links rely on stationary quantum network nodes that are communicating with each other via optical photons. Here, we are experimentally implementing such network node based on small ensembles of neutral atoms coupled to high-finesse optical resonators. The fiber coupled optical cavities are formed by microscopic mirrors that we fabricate at the end facet of optical fibers [1]. Collective interaction of multiple Rubidium atoms in such a small resonator mode can allow atom-photon interface operations with increased bandwidth and fidelities. In order to effective prepare small dense atomic ensembles we start by loading tens of Rubidium atoms from a small magneto optical trap into an optical dipole "conveyor belt". Raman-cooling and adiabatic compression techniques [2] are currently investigated to further compress the atom clouds before they will be transported into a 3D optical lattice created inside an optical resonator [3]. [1] D Hunger et al New J. Phys. 12 065038 (2010) [2] Marshall T. DePue, et al, PRL 82, 11 (1999). [3] Schrader,

et al, App. Phys, B 73, 8 (2001)

SYQR 1.7 Mon 12:00 UDL HS2002

Individual addressing of multiple neutral atoms in an optical cavity — •Andreas Neuzner, Matthias Körber, Carolin Hahn, Stephan Ritter und Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

Single neutral atoms trapped in a Fabry-Perot-type optical cavity were shown to be a powerful system for the implementation of various quantum-information-processing protocols. This includes the highly efficient creation of single photons and the implementation of an optical quantum memory based on a single ^{87}Rb atom. We present recent progress on the addressing of several atoms trapped in a two-dimensional optical lattice within the resonator by means of a high-numerical-aperture objective. The addressing capability is used to quasi-deterministically load predetermined patterns of atoms and to control the interaction of individual atoms with the resonator mode. Progress towards the realization of a multi-qubit memory for a quantum repeater node will be presented.

SYQR 2: Quantum Repeaters

Chair: Harald Weinfurter (LMU München)

Time: Monday 14:00–16:00 Location: Audimax

Invited Talk SYQR 2.1 Mon 14:00 Audimax

Protocols and prospects for building a quantum repeater — •Peter van Loock — Institute of Physics, Johannes Gutenberg Universität Mainz, Germany

An overview will be given of various approaches to implementing a quantum repeater for quantum communication over large distances. This includes a discussion of systems and protocols that are experimentally feasible and thus realizable in the midterm in order to go beyond the current limit of a few hundred km given by direct quantum-state transmissions. At the same time, these schemes should be, in principle, scalable to arbitrary distances. In this context, the influence of various elements and strategies in a quantum repeater protocol on the final fidelities and rates shall be addressed: initial entanglement distribution, Bell measurements, multiplexing, postselection, quantum memories, and quantum error detection/correction. Solely on the hardware side, the differences in using just single quanta or instead employing many quanta for the flying (photons) and the stationary (atoms) qubits will be pointed out.

Invited Talk SYQR 2.2 Mon 14:30 Audimax

Quantum teleportation from a telecom-wavelength photon to a solid-state quantum memory — •Felix Bussieres — Group of Applied Physics, University of Geneva, Switzerland

Quantum teleportation is a cornerstone of quantum information science due to its essential role in several important tasks such as the long-distance transmission of quantum information using quantum repeaters. In this context, a challenge of paramount importance is the distribution of entanglement between remote nodes, and to use this entanglement as a resource for long-distance light-to-matter quantum teleportation. In this talk I will report on the demonstration of quantum teleportation of the polarization state of a telecom-wavelength photon onto the state of a solid-state quantum memory. Entanglement is established between a rare-earth-ion doped crystal storing a single photon that is polarization-entangled with a flying telecom-wavelength photon. The latter is jointly measured with another flying qubit carrying the polarization state to be teleported, which heralds the teleportation. The fidelity of the polarization state of the photon retrieved from the memory is shown to be greater than the maximum fidelity achievable without entanglement, even when the combined distances travelled by the two flying qubits is 25 km of standard optical fibre. This light-to-matter teleportation channel paves the way towards long-distance implementations of quantum networks with solid-state quantum memories.

Invited Talk SYQR 2.3 Mon 15:00 Audimax

Semiconductor quantum light sources for quantum repeaters — •Peter Michler — Universität Stuttgart, Institut für Halbleiteroptik und Funktionelle Grenzflächen, Germany

Exploiting the quantum properties of light has the potential of enabling many new applications in the field of photonics and quantum information technology, such as secure communication, imaging and lithography techniques beyond the diffraction limit, quantum repeaters as well as photonic quantum computing. Many of these applications require the generation of on demand indistinguishable single photons or entangled photon pairs. Resonantly excited single semiconductor quantum dots are perfectly suited to fulfill these requirements. In my talk, I will discuss the fascinating physic as well as the current status of such resonantly driven semiconductor light sources.

Invited Talk SYQR 2.4 Mon 15:30 Audimax

Quantum networks based on cavity QED — •Stephan Ritter, Joerg Bochmann, Eden Figueroa, Carolin Hahn, Norbert Kalb, Martin Mücke, Andreas Neuzner, Christian Nölleke, Andreas Reiserer, Manuel Uphoff, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Quantum repeaters require an efficient interface between stationary quantum memories and flying photons. Single atoms in optical cavities are ideally suited as universal quantum network nodes that are capable of sending, storing, retrieving, and even processing quantum information. We demonstrate this by presenting an elementary version of a quantum network based on two identical nodes in remote, independent laboratories. The reversible exchange of quantum information and the creation of remote entanglement are achieved by exchange of a single photon. Quantum teleportation is implemented using a time-resolved photonic Bell-state measurement. Quantum control over all degrees of freedom of the single atom also allows for the nondestructive detection of flying photons and the implementation of a quantum gate between the spin state of the atom and the polarization of a photon upon its reflection from the cavity. Our approach to quantum networking offers a clear perspective for scalability and provides the essential components for the realization of a quantum repeater.

SYQR 3: Quantum Protocols and Gates

Chair: Peter van Loock (Uni Mainz)

Time: Tuesday 10:30–12:15 Location: Kinosaal

SYQR 3.1 Tue 10:30 Kinosaal

Quantum key distribution with two-segment quantum repeaters — •Hermann Kampermann, Silvestre Abruzzo, and Dagmar Bruss — Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Germany

Quantum repeaters represent one possible way to achieve long-distance quantum key distribution. One way of improving the repeater rate and decreasing the memory coherence time is the usage of multiplexing. Motivated by the experimental fact that long-range connections are practically demanding, we extend the analysis of the quantum repeater multiplexing protocol to the case of short-range connections. We derive formulas for the repeater rate and we show that short-range connections lead to most of the benefits of a full-range multiplexing protocol [1].

A less demanding QKD-protocol without quantum memories was recently introduced by Lo *et al.* We generalize this measurement-device-independent quantum key Distribution protocol to the scenario where the repeater Station contains also heralded quantum memories. We assume either single-photon sources or weak coherent pulse sources plus decoy states. We show that it is possible to significantly outperform the original proposal, even in presence of decoherence of the quantum memory. We give formulas in terms of device imperfections i.e., the quantum bit error rate and the repeater rate [2].

[1] S. Abruzzo, H. Kampermann, D. Bruß, arXiv:1309.1106v1
[2] S. Abruzzo, H. Kampermann, D. Bruß, arXiv:1306.3095v1

SYQR 3.2 Tue 10:45 Kinosaal

Broadcast Classical-Quantum Capacity Region of Two-Phase Bidirectional Relaying Channels — Holger Boche, Minglai Cai, and •Christian Deppe — Technische Universität München, Fakultät für Elektrotechnik und Informationstechnik, Lehrstuhl für Theoretische Informationstechnik

The transmission of quantum states over long distances is essential for future applications such as quantum networks. The direct transmission is limited by unavoidable losses of the channel. A promising alternative for long distance quantum states distribution is the use of quantum repeaters. We analyze a quantum repeater protocol which takes advantage of bidirectional communication. We consider a three-node quantum network which enables bidirectional communication between two nodes with a half-duplex relay node. The message $m_2 \in M_2$ is located at node 1 and the message $m_1 \in M_1$ is located at node 2, respectively. Our goal is that the message $m_2 \in M_2$ is known at node 2 and the message $m_1 \in M_1$ is known at node 1, respectively. We simplify the problem by assuming an a priori separation of the communication into two phases. The capacity of the first phase (MAC) is known. We determine the capacity region of the second phase (broadcast).

SYQR 3.3 Tue 11:00 Kinosaal

Quantum error correction in a solid-state hybrid spin register — Gerald Waldherr[1], Ya Wang[1], •Sebastian Zaiser[1], Mohammed Jamali[1], Thomas Schulte-Herbrueggen[2], Hiroshi Abe[3], Takeshi Ohshima[3], Junichi Isoya[4], Philipp Neumann[1], and Joerg Wrachtrup[1] — [1]3. Physikalisches Institut , University of Stuttgart — [2]Department of Chemistry, Technical University of Munich — [3]Japan Atomic Energy Agency, Takasaki — [4]Research Center for Knowledge Communities, University of Tsukuba, Tsukuba

Electron spins associated with solid state defects are promising systems for quantum information processing. Exploiting nuclear spins surrounding the defect as a quantum register provides a natural hybrid spin system. Such a system could be used for a fault-tolerant quantum repeater scheme [1] where the spins might be associated to nitrogen-vacancy (NV) centers in diamond. Here, we present a hybrid spin register based on a single NV defect in diamond coupled to three nuclear spins. The electron spin is used for control, and the nuclear spins as a long-lived quantum storage. We achieve high-fidelity initialization and single shot readout of the nuclear spin register. Implementation of a novel non-local gate combined with optimal control enables universal, high-fidelity control. With these techniques, we demonstrate three-qubit entanglement and quantum error correction. These experiments demonstrate the potential of solid state spin systems for quantum computation and communication. [1] L. Childress, et al., Phys. Rev. Lett. 96, 070504 (2006).

SYQR 3.4 Tue 11:15 Kinosaal

A quantum byte with 10^{-4} crosstalk for fault-tolerant quantum computing — •Christian Piltz, Theeraphot Sriarunothai, Andrés Varón, and Christof Wunderlich — Department Physik, Universität Siegen, 57068 Siegen, Germany

A prerequisite for fault-tolerant and thus scalable operation of a quantum computer is the use of quantum error correction protocols. Such protocols come with a maximum tolerable gate error, and there is consensus that an error of order 10^{-4} is an important threshold. This threshold was already breached for single-qubit gates with trapped ions using microwave radiation. However, crosstalk - the error that is induced in qubits within a quantum register, when one qubit (or a subset of qubits) is coherently manipulated, still prevents the realization of a scalable quantum computer. The application of a quantum gate - even if the gate error itself is low - induces errors in other qubits within the quantum register.

We present an experimental study using quantum registers consisting of microwave-driven trapped $^{171}Yb^{+}$ ions in a static magnetic gradient. We demonstrate a quantum register of three qubits with a next-neigbour crosstalk of $6(1) \cdot 10^{-5}$ that for the first time breaches the error correction threshold. Furthermore, we present a quantum register of eight qubits - a quantum byte - with a next-neighbour crosstalk error better than $2.9(4) \cdot 10^{-4}$. Importantly, our results are obtained with thermally excited ions far above the motional ground state.

SYQR 3.5 Tue 11:30 Kinosaal

Strain-induced active tuning of the coherent tunneling in quantum dot molecules — •Eugenio Zallo[1], Rinaldo Trotta[2], Yongheng H. Huo[1], Paola Atkinson[3], Fei Ding[1], Armando Rastelli[2], and Oliver G. Schmidt[1] — [1]Institute for Integrative Nanosciences, IFW Dresden, Helmholtzstr. 20, D-01069 Dresden, Germany — [2]Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Altenbergerstr. 69, A-4040 Linz, Austria — [3]Institut des NanoSciences des Paris, UPMC CNRS UMR 7588,4 Place Jussieu Boite courier 840, Paris 75252 Cedex 05, France

Quantum dot molecules (QDMs) are formed by orbital hybridization of wavefunctions in two closely positioned quantum dots (QDs), and they are important for a coherent manipulation of qubits in quantum information applications. The coupling strength is the key parameter determining the operation rate of quantum gates based on QDMs. Recently, ultrafast optical control of the entangled state of two electron spins interacting through tunneling in a QDM was demonstrated. Despite the extensive efforts in the community, it is a formidable task to actively tune the tunnel coupling in a single QDM obtained by vertical stacking of two semiconductor quantum dots. In this presentation, a novel class of devices that allow large strain and electric fields to be applied to single QD and QDM will be introduced first. Then, the experimental achievement of this active tuning will be demonstrated. By means of externally induced strain fields the coupling strength of holes confined in vertically coupled InGaAs/GaAs QDs was varied by more than 14%.

SYQR 3.6 Tue 11:45 Kinosaal

Harnessing the diamond spin bath — Jan Honert[1], Martin Hohmann[1], Nan Zhao[2], •Helmut Fedder[1], and Jörg Wrachtrup[1] — [1]3. Physikalisches Institut and Research Center SCoPE, University Stuttgart, Germany — [2]Beijing Computational Science Research Center, Beijing, China

^{13}C nuclear spins in diamond are the predominant source of decoherence for electron spin qubits such as the NV center [1] or ST1 [2] defect. At the same time, they are a valuable resource for the implementation of nuclear spin quantum registers [3]. Addressing distant and thus weakly coupled bath spins would enable us to scale up nuclear spin registers to sizes relevant to small scale quantum algorithms such as stabilizer codes that are particularly relevant to quantum repeaters. In here we show that dynamical decoupling techniques can be used to detect a single ^{13}C nuclear spin that is coupled to an NV center with a dipole coupling strength as weak as 400 Hz. We discuss protocols for initializing and coherently controlling such weakly coupled bath spins.

[1] P. Neumann et al. Multipartite entanglement among single spins in diamond. Science 320, 1326 (2008)
[2] S.-Y. Lee et al. Readout and control of a single nuclear spin with a metastable electron spin ancilla. Nature nano. 8, 487 (2013)
[3] G. Waldherr et al. Quantum error correction in a solid-state hybrid spin register. arXiv:1309.6424v2 (2013).

SYQR 3.7 Tue 12:00 Kinosaal

Towards long coherent time quantum memory based on NV center in low temperature — •Sen Yang[1], S. Ali Momenzadeh[1], Thai Hien Tran[1], Ya Wang[1], Naofumi Abe[2], Hideo Kosaka[2], Helmut Fedder[1], Philipp Neumann[1], and Joerg Wrachtrup[1] — [1]3rd Physics Institute, Universitaet Stuttgart, Germany — [2]Research Institute of Electrical Communication, Tohoku University, Japan

The Nitrogen-Vacancy (NV) center in diamond is a promising system for quantum communication/computation. Low temperature gives us not only ultralong spin lifetime but also the ability to address excited states individually. Optically resonant excitation of spin-selective transitions and single shot readout of electron spin in low magnetic field improve initialization and readout fidelity. This opens up the opportunities of making quantum devices based on the fine structure of excited states and photon NV interaction. Long coherence time makes nuclear spin a good choice as quantum memory. $M_s = \pm 1$ ground states and A1 excited state form Λ system which make optical writing possible. Here, we presents recent results of this quantum memory scheme. this quantum memory could be an important component for building quantum repeater based on NV center in diamond.

SYQR 4: Photon Sources for Quantum Networks

Chair: Dieter Meschede (Uni Bonn)

Time: Tuesday 14:00–15:45 Location: Kinosaal

SYQR 4.1 Tue 14:00 Kinosaal

High efficient generation of single mode narrow-band photon pairs — •Michael Förtsch[1,2], Gerhard Schunk[1,2], Josef U. Fürst[1,2], Dmitry Strekalov[1,2], Florian Sedlmeir[1,2], Harald G. L. Schwefel[1,2], Thomas Gerrits[3], Martin J. Stevens[3], Sae Woo Nam[3], Gerd Leuchs[1,2], and Christoph Marquardt[1,2] — [1]Max Planck Institut für die Physik des Lichts, Günther-Scharowsky-Str. 1, Bau 24, 91058, Erlangen, Deutschland — [2]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, Staudtstraße 7/B2, 91058, Erlangen, Deutschland — [3]National Institute of Standards and Technology, 325 Broadway, Boulder, CO, 80305, USA

Over the past ten years the interest in resonator assisted spontaneous parametric down-conversion (RA-SPDC) has increased significantly since it offers the possibility to efficiently generate narrow-band heralded single photons, which are directly compatible with atomic transitions. One still remaining challenge with RA-SPDC based systems is the efficient photon generation in exactly one spatiotemporal mode, which up to now is often accompanied with additional lossy filtering. Here we experimentally demonstrate a narrow-band RA-SPDC source based on a crystalline whispering gallery mode resonator, which emits photons in exactly one mode. The unique phase-matching conditions make additional filter cavities unnecessary and results to the best of our knowledge in the highest reported single mode pair-production rate. In combination with the unique wavelength and bandwidth tuning possibilities, our setup is ready to serve as the heralded single photon source in a large variety of proposed quantum-repeater networks.

SYQR 4.2 Tue 14:15 Kinosaal

Electro-mechanical engineering of Non-classical Photon Emissions from Single Quantum Dots — •Bianca Höfer[1], Eugenio Zallo[1], Jiaxiang Zhang[1], Rinaldo Trotta[2], Armando Rastelli[2], Fei Ding[1], and Oliver G. Schmidt[1] — [1]Institute for Integrative Nanosciences, IFW-Dresden, Helmholtzstrasse 20, D-01069 Dresden, Germany — [2]Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Altenbergerstrasse 69, A-4040 Linz, Austria

Indistinguishable photons and entangled photon pairs are the key elements for quantum information applications, for example, building a quantum repeater. Self-assembled semiconductor quantum dots (QDs) are promising candidates for the creation of such non-classical photon emissions, and offer the possibility to be integrated into solid state devices. However, due to the random nature of the self-assembled growth process, post-growth treatments are required to engineer the exciton state in the QDs (e.g. energies, exciton lifetimes, and fine structure splittings). In this work, we study the electro-mechanical engineering of the exciton lifetime, emission energy in the QDs, with the aim to produce single photons with higher indistinguishability. Also we present a recent experimental study on the statistical properties of fine structure splittings in the QD ensemble, in order to gain a deeper understanding of how to generate entangled photon pairs using semiconductor QDs.

SYQR 4.3 Tue 14:30 Kinosaal

Two Photon Interference from Remote Quantum Dots with Inhomogeneously Broadened Linewidths — •Peter Gold[1], Alexander Thoma[1], Sebastian Maier[1], Stephan Reitzenstein[1,2], Sven Höfling[1,3], Christian Schneider[1], and Martin Kamp[1] — [1]Technische Physik, Universität Würzburg, Am Hubland, D-97074, Würzburg, Germany — [2]present address: Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany — [3]present address: SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, KY16 9SS, United Kingdom

The interference of single, indistinguishable photons is at the heart of long distance quantum repeaters. Here, we investigate the influence of non-resonant and quasi-resonant excitation on the interference properties of single photons emitted from semiconductor quantum dots (QDs). For the quasi-resonant excitation scheme, we observe an increase of interference visibility for consecutively emitted photons from the same QD of 69% compared to 12% for non-resonant excitation. In addition, we demonstrate quantum interference of photons emitted from separate QDs simultaneously excited into their p-shell. We can extract a two photon interference visibility as high as $(39\pm2)\%$ for non-postselected coincidences. This value exceeds the predicted value based on coherence and radiative decay times of the quantum dot emission ($\approx 25\%$). We account for this by treating the emission of both quantum dots as inhomogeneously broadened ensembles of Fourier limited photons and observe good congruence between experiment and model.

SYQR 4.4 Tue 14:45 Kinosaal

Interfacing telecommunication and UV wavelengths — •Helge Rütz, Kai-Hong Luo, Hubertus Suche, and Christine Silberhorn — Universität Paderborn, Integrierte Quantenoptik, Warburger Str. 100, D-33098 Paderborn

Changing the color of a photonic quantum state by means of coherent frequency conversion allows to interface short-wavelength stationary qubit systems and low-loss photonic channels at telecommunication wavelengths.

Here, we report on such an interface for quantum states of light between trapped ions at 369.5 nm and telecommunication wavelengths around 1310 nm. More specifically, we employ a single-pass quasi-phasematched second-order nonlinear interaction in a periodically poled Potassium Titanyl Phosphate- (KTP-) waveguide in conjunction with a strong cw-pump field at 515 nm.

We present experimental details of our interface, showing bright-light conversion efficiencies of up to 10%. Non-phasematched spontaneous parametric downconversion of pump photons is identified as the major limitation in the achievable signal-to-noise-ratio on the single-photon-level.

Finally, the potential use of our frequency conversion interface in quantum information technology is discussed.

SYQR 4.5 Tue 15:00 Kinosaal

Frequency Conversion of Single Photons from a SPDC Source — •Andreas Lenhard, Stephan Kucera, José Brito, Jürgen Eschner, and Christoph Becher — Universität des Saarlandes, FR 7.2 Experimentalphysik, Campus E2.6, 66123 Saarbrücken

Many quantum repeater schemes rely on the transfer of single photons or entangled states. Thus, long-range transmission in fibers requires photons at low-loss telecommunication wavelengths. We have recently demonstrated the frequency conversion of photons generated by a single quantum emitter in the near-infrared spectral region to the telecom bands via frequency down-conversion in a nonlinear medium [1]. The frequency conversion of an entangled photon is another basic building block to establish quantum networks.

Here we report on the frequency down-conversion of single photons from a photon pair source, resonant with an atomic transition of a quantum repeater node. The pairs are generated by a type-II spontaneous parametric downconversion process in a bulk KTP crystal. One photon of the pair is spectrally filtered to fit a transition of $^{40}Ca^{+}$-ions at 854 nm and used as a herald [2]. By mixing with a pump field at 2.5 μm in a nonlinear waveguide the partner photon is converted to the telecom O-band at 1313 nm with an over-all efficiency around 10 %. We show that the temporal correlation between the photon pairs is preserved in the conversion process by measuring the photon correlation functions.

1. S. Zaske et al., Phys. Rev. Lett. **109** (2012), 147404
2. N. Piro et al., Nat. Phys. **7** (2011), 17-20

SYQR 4.6 Tue 15:15 Kinosaal

Quantum teleportation and entanglement swapping of matter qubits with multiphoton signals — •Juan Mauricio Torres[1,2], József Zsolt Bernád[1], and Gernot Alber[1] — [1]Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Germany — [2]Departamento de Investigación en Física, Universidad de Sonora, Hermosillo, México

We introduce a probabilistic Bell measurement of atomic qubits based on two consecutive photonic field measurements of two single mode cavities with which the atoms interact in two separate stages. To this end, we solve the two-atoms Tavis-Cummings model and exploit the property that the antisymmetric Bell state is insensitive to the interaction with the field. We consider implementations for quantum teleportation and for entanglement swapping protocols both of which can be achieved with 25% success probability and with unit fidelity. We emphasize possible applications for hybrid quantum repeaters where the aforementioned quantum protocols play an essential role.

SYQR 4.7 Tue 15:30 Kinosaal

Rydberg gases at room temperature - pulsed four-wave-mixing down to volumes of a few cubic micrometers — •Andreas Kölle, Bernhard Huber, Fabian Ripka, Robert Löw, and Tilman Pfau — 5. Physikalisches Institut, Uni Stuttgart

The van-der-Waals interaction between Rydberg-excited atoms provides an interaction range on the micrometer scale. Various experiments in cold atomic clouds demonstrated the feasibility of using Rydberg states for quantum devices like single photon sources. In our experiments, we want to transfer these results to thermal vapor cells of the size of the Rydberg-Rydberg interaction length scale, which are more favorable in terms of scalability and handling. In comparison to an ultra-cold atomic cloud, thermal cells have the disadvantage of thermal atomic motion and the resulting Doppler shift. To overcome this effect we perform our excitation to the Rydberg state on the nanosecond timescale. We present our results of a pulsed four-wave-mixing scheme via a Rydberg state. We observe four-wave-mixed light emission on a nanosecond time scale with a non-trivial temporal evolution which can be described by a coherent interference within the Doppler ensemble. Furthermore we discuss our experimental effort to reduce the excitation volume to a sub micrometer length scale in all 3 dimensions.