Q 4: Hybrid Quantum Systems

Time: Monday 11:00–13:00 Location: HS 1199

Q 4.1 Mon 11:00 HS 1199

Cavity optomechanics with polymer-based multi-membrane structures — •Lukas Tenbrake[1], Sebastian Hofferberth[1], Stefan Linden[2], and Hannes Pfeifer[3] — [1]Institute of Applied Physics, University of Bonn, Germany — [2]Institute of Physics, University of Bonn, Germany — [3]Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden

Despite their application in multiple fields, ranging from quantum sensing to fundamental tests of quantum mechanics, conventional state-of-the-art cavity optomechanical experiments have been limited in their scaling towards systems with multiple resonators. 3D direct laser writing offers a new approach of fabricating multi-membrane structures that can be directly integrated into fiber Fabry-Perot cavities. Here, we experimentally demonstrate direct laser-written stacks of two or more coupled membranes – with normal-mode splittings of up to a MHz – interfaced by fiber cavities. We present finite element simulations for the optimization of the mechanical coupling and investigate the collective optomechanical coupling of multi-membrane stacks (with single-membrane vacuum optomechanial coupling strengths of $\gtrsim 30\,\mathrm{kHz}$). We present our first experimental results and give an outlook on the scalability of the system to an even larger number of coupled mechanical oscillators. Aside from tests of fundamental properties of multimode optomechanical systems, applications for sensing or routing of vibration in acoustic metamaterials and circuits are envisaged.

Q 4.2 Mon 11:15 HS 1199

Theory of phase-adaptive parametric cooling — •Pardeep Kumar[1], Alekhya Ghosh[1,2], Christian Sommer[3], Fidel G. Jimenez[4], Vivishek Sudhir[5,6], and Claudiu Genes[1,2] — [1]Max Planck Institute for the Science of Light, Staudtstraße 2, D-91058 Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstraße 7, D-91058 Erlangen, Germany — [3]AQT, Technikerstraße 17, 6020, Austria — [4]Pontificia Universidad Católica del Perú, Av. Universitaria 1801, San Miguel 15088, Peru — [5]LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA — [6]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

An adaptive phase technique has been proposed for the parametric cooling of the mechanical oscillators. The method calls for a sequence of periodic adjustments of the phase of a parametric modulation of the mechanical oscillator that is conditioned on measurements of its two quadratures. This technique indicates a pure exponential loss of the thermal energy at initial high occupancies. As the quantum ground state is approached, the phase adaptive scheme leads to residual occupancies at the level of a few phonons owing to the competition between parametric amplification of the quantum fluctuations and the feedback action. In contrast to available parametric feedback cooling techniques, the proposed phase-adaptive technique remains immune from the extraneous heating arising from direct modulation of the radiation pressure force.

Q 4.3 Mon 11:30 HS 1199

Interfacing Rydberg atoms with an electromechanical oscillator at 4K — •Cedric Wind, Johanna Popp, Leon Sadowski, Julia Gamper, Valerie Mauth, Wolfgang Alt, Hannes Busche, and Sebastian Hofferberth — Institute of Applied Physics, University of Bonn, Germany

We currently construct a novel setup to interface optically controlled Rydberg atoms with an on-chip electromechanical oscillator at 4K. This talk discusses the prospects of implementing this hybrid quantum system and presents our progress on the construction of the cryogenic setup. As a first experiment, we will explore the cooling of a GHz mechanical mode to its quantum mechanical ground state by extracting phonons via a dissipative extraction of microwave photons via Rydberg atoms.

Our system combines a closed-cycle cryostat with vibration isolation with a classical room-temperature setup from which ultra-cold atoms are magnetically transported into the cryo-region. Besides providing the suppression of thermal noise required to study electromechanical oscillators near their ground state, the enhanced vacuum condition due to cryo-pumping eliminates the need to bake the vacuum system and enables fast exchange and cooling of samples in the experiment region. We will discuss how the setup, the on-chip superconducting magnetic trap and the electromechanical oscillator design have been optimized for the planned experiment.

Q 4.4 Mon 11:45 HS 1199

Waveguide QED with Rydberg superatoms — •Lukas Ahlheit, Daniil Svirskiy, Jan de Haan, Christoph Biesek, Nina Stiesdal, Wolfgang Alt, and Sebastian Hofferberth — Institute of Applied Physics, University of Bonn, Germany

The field of Waveguide QED investigates how light in a single mode propagates through a system of localized quantum emitters. If the coupling between individual photons and emitters is sufficiently strong, the photons mediate an effective interaction between the emitters, creating a many-body system.

We use Rydberg superatoms as quantum emitters. These are ensembles of $N \sim 10\,000$ atoms confined to within the Rydberg blockade volume, such that each ensemble only supports a single excitation. Every collective emitter has highly directional emission, and couples strongly to even few-photon fields. The directed emission into the mode of the driving field realizes a waveguide-like system in free-space without any actual light-guiding elements.

This talk will discuss how we scale our system from one to few strongly coupled superatoms with low dephasing. We use a magic wavelength optical lattice to trap atoms in both the ground- and the Rydberg state. This reduces atomic motion and limits dephasing of the collective excitation. With extended coherence times, we will be able to show how the propagation of quantized light fields through a small emitter chain results in photon-photon correlations and entanglement between the emitters.

Q 4.5 Mon 12:00 HS 1199

Quantum repeater node with free-space coupled photons from trapped $^{40}\mathrm{Ca}^{+}$ ions — •Max Bergerhoff, Omar Elshehy, Stephan Kucera, Matthias Kreis, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

The quantum repeater cell according to [1] is a fundamental building block for the realisation of large distance quantum networks. By dividing a transmission link in asynchronously driven segments it is possible to overcome the loss scaling of direct transmission. The advantage of this protocol has already been demonstrated with single atoms [2] in a cavity and single ions in a large cavity [3]. We report on the implementation of a quantum repeater cell with free-space coupled photons from two $^{40}\mathrm{Ca}^{+}$ ions in the same Paul trap as memories. Atom-photon entanglement is generated asynchronously [4] by controlled emission of single photons from the individually addressed ions, and separate single-mode fiber coupling. Photon-photon entanglement is then generated by a Mølmer-Sørensen gate [5] on the ions. We discuss the probability and rate scaling due to the asynchronous sequence, as well as the fidelity of the final photon-photon state. In this context the perspective of a new ion trap setup with integrated sub-mm cavity is discussed and its implementation status is presented.

[1] D. Luong et al., Appl. Phys. B 122, 96 (2016)
[2] S. Langenfeld et al., Phys. Rev. Lett. 126, 30506 (2021)
[3] V. Krutyanskiy et al., Phys. Rev. Lett. 130, 213601 (2023)
[4] M. Bock et al., Nat. Commun. 9, 1998 (2018)
[5] K. Mølmer and A. Sørensen, Phys. Rev. Lett 82, 1835-8 (1999)

Q 4.6 Mon 12:15 HS 1199

optical microcavity with coupled single SiV and GeV centers in a nanodiamond for a quantum repeater platform — •Selene Sachero[1], Robert Berghaus[1], Gregor Bayer[1], Florian Feuchmayr[1], Andrea B Filipovski[1], Patrick Maier[1], Lukas Antoniuk[1], Niklas Lettner[1], Marco Klotz[1], Richard Waltrich[1], Viatcheslav Agafonov[2], and Alexander Kubanek[1] — [1]Institute for Quantum Optics, Ulm University, Germany — [2]Tours University, France

Quantum repeater are essential building block to create a large scale quantum communication network. An ideal quantum repeater nodes efficiently link a quantum memory with photons serving as flying qubits. By coupling group defect centers to an open Fabry-Perot cavity, such an interface can be created.

As such a platform, we propose a fully tunable cavity, composed by two Bragg mirrors, which allows short cavity lengths, and provides efficient coupling of quantum emitters at 4 K.

Here, we show the good optical properties of a single germanium vacancy (GeV-) and its transfer to a Fabry-Perot cavity. The coupling of the GeV- into the resonator is achieved maintaining a high finesse.

Moreover, we couple an individual SiV- into our resonator. We perform resonant photoluminescence measurements, and observe a spectrally stable emitter with a linewidth close to the Fourier limit. We demonstrate coherent optical driving and all-optical initialization and readout of the electron spin in a high external magnetic field.

Q 4.7 Mon 12:30 HS 1199

Hybrid Quantum Photonics With One Dimensional Photonic Crystal Cavities and Silicon Vacancy Centers In Nanodiamonds — •Lukas Antoniuk[1], Niklas Lettner[1,2], Anna P. Ovvyan[3,5], Daniel Wendland[3], Viatcheslav N. Agafonov[4], Wolfram H.P. Pernice[3,5], and Alexander Kubanek[1] — [1]Institute for Quantum Optics, Ulm University, Germany — [2]Center for Integrated Quantum Science and Technology (IQst), Ulm University, Germany — [3]Institute of Physics and Center for Nanotechnology, University of Münster, Germany — [4]Universite F. Rabelais, 37200 Tours, France — [5]Heidelberg University, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany

Efficient connection of stationary- and flying qubits posts a formidable challenge, yet is one of the demands for the development of applications like quantum networks, distributed quantum computing and quantum communication. Cavity quantum electrodynamics provides enhanced light-matter interaction, hence serving as an attractive tool for spin-photon interfaces. Here, we present our progress of a hybrid quantum photonic interface which interconnects chip-integrated one-dimensional photonic crystal cavities in silicon nitride with negatively charged silicon vacancy centers (SiV) in nanodiamonds. We elaborate on the unique possibilities of dipole alignment by nanomanipulation [1] and show our results on Purcell broadened optical access to the SiV centers electron spin [2].

[1]Lettner et al., arXiv:2310.17198

[2]Antoniuk et al., arXiv:2308.15544

Q 4.8 Mon 12:45 HS 1199

Towards coherent single praseodymium ion quantum memories in optical fiber microcavities — •Sören Bieling[1], Nicholas Jobbitt[1], Roman Kolesov[2], and David Hunger[1] — [1]Karlsruher Institut für Technologie, 76131 Karlsruhe, Germany — [2]Universität Stuttgart, 70569 Stuttgart, Germany

Rare earth ions doped into solids show exceptional quantum coherence in their ground-state hyperfine levels. These spin states can be efficiently addressed and controlled via optical transitions and are thus ideally suited to serve as quantum memories and nodes of quantum networks. However, while long storage times, high storage efficiencies and storage on the single photon level have all been demonstrated separately, they could not yet be achieved simultaneously.

We aim to demonstrate both long and efficient single quantum storage in the ground-state hyperfine levels of single Pr^{3+} ions doped into yttrium orthosilicate (YSO) by integrating them as membrane into optical high-finesse fiber-based Fabry-Pérot microcavities. This allows for efficient addressing and detection of individual ions. We report on the design, commissioning and characterization of a next-gen cryogenic scanning microcavity with an integrated, few-μm thick Pr:YSO membrane. First cryogenic, cavity enhanced photoluminescence excitation measurements of a doped Pr:YSO membrane will be reported. Together with the Purcell enhanced emission and ultrapure Pr:YSO membranes this strives to realize efficient and coherent spin-photon interfaces suitable for deployment in scalable quantum networks.