# TT 24: Nanomechanics

Time: Wednesday 9:30–12:45 Location: H 3005

TT 24.1 Wed 9:30 H 3005

**Dynamics of strongly coupled nanomechanical resonators** — •Benjamin A. Gmeiner, Onur Basarir, Jörg P. Kotthaus, and Eva M. Weig — Fakultät für Physik and Center for NanoScience (CeNS), Ludwig-Maximilians-Universität (LMU), Geschwister-Scholl-Platz 1, D-80539 München, Germany

In this work we study the modal interactions between two strongly coupled nanoelectromechanical (NEMS) resonators. To this end, we have fabricated a system of two doubly-clamped silicon nitride (SiN) string resonators coupled via a shared mechanical support using a series of standard clean room techniques. Each string resonator is equipped with a set of integrated electrodes allowing for an independent frequency tuning and mechanical excitation using dielectric gradient forces [1]. A shot noise-limited Fabry-Perot interferometer operating at 1550 nm has been used for the detection of the nanomechanical motion. We have characterized a set of devices with fundamental resonance frequencies around 8 MHz and quality factors of $Q > 2 \cdot 10^4$ at room temperature in high vacuum. By tuning the resonance frequencies and driving each resonator across its resonance we have observed avoided mechanical mode crossings in the high frequency spectrum, characteristic for a strongly coupled system. These experiments are the important steps in understanding strongly coupled mechanical systems and might be utilized for enhanced sensor configurations based on collective and non-linear phenomena.

[1] Q. P. Unterreithmeier, E. M. Weig, and J. P. Kotthaus, Nature (London) 458, 1001 (2009)

TT 24.2 Wed 9:45 H 3005

**Optomechanically Induced Transparency and Slow Microwaves in Circuit Nano-electromechanics** — •Xiaoqing Zhou[1,2], Fredrik Hocke[3], Albert Schliesser[1,2], Achim Marx[3], Hans Hübl[3], Rudolf Gross[3,4], and Tobias J. Kippenberg[1,2] — [1]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland — [2]Max-Planck-Institut für Quantenoptik, Garching, Germany — [3]Walther-Meißner-Institut, Garching, Germany — [4]Technische Universität München, Garching, Germany

Using a low-mass ($\approx 15$ pg), high-Q ($> 100\,000$) nanomechanical oscillator coupled to a Nb superconducting quarter wave cavity, we realize a circuit nano-electromechanical system coupling microwaves to mechanical motion oscillating at 1.45 MHz. By exciting the system on the lower motional sideband with a strong drive tone, a transparency window for a probe field is created originating from the effect of optomechanically induced transparency (OMIT) [1]. This phenomenon, analogous to electromagnetically induced transparency in Atomic Physics, arises from the interference of different excitation pathways for an intracavity probe field. We utilize the transparency window to demonstrate slow microwave propagation. A tunable delay up to 4 ms is demonstrated experimentally for a microwave pulse on resonance with the cavity. Furthermore, we systematically investigate the temporal dynamics of this transparency window when the drive tone is modulated, and the effect of the oscillator's Duffing nonlinearity on the OMIT window.

[1] S.Weis *et al.*, Science **330**, 1520 (2010)

TT 24.3 Wed 10:00 H 3005

**Optomechanically Induced Absorption and Parametric Effects in a Circuit Nano-Electromechanial System Driven on Blue Sideband** — •Fredrik Hocke[1], Xiaoqing Zhou[3,4], Albert Schliesser[3,4], Achim Marx[1], Rudolf Gross[1,2], Tobias Kippenberg[3,4], and Hans Huebl[1] — [1]Walther-Meißner-Institut, Garching, Germany — [2]Technische Universität München, Garching, Germany — [3]Max-Planck-Institut für Quantenoptik, Garching, Germany — [4]Ecole Polytechnique Fédérale de Lausanne, Switzerland

In the field of optomechanics, a light field trapped in an optical resonator is dynamically coupled to a mechanical mode, enabling cooling and amplification of mechanical motion. This concept of light matter interaction can be transferred to the microwave (MW) regime combining superconducting MW circuits with nanometer-sized mechanical beams. With such a system we demonstrate optomechanically induced absorption: In the presence of a blue-detuned pump field, constructive interference of two excitation pathways leads to a mechanically enhanced coupling of a probe field into the MW cavity. There, probe photons are dissipated to the environment, leading to reduced transmission of the probe tone. Our experimental findings quantitatively agree with model predictions, including narrowing of the absorption window with increased pump power. We also discuss parametric effects when varying the pump power and driving the mechanical system via an additional AC-field at the mechanical resonance of $f_m = 1.45$ MHz. This work is supported by the Excellence Cluster "Nanosystems Initiative Munich (NIM)" .

TT 24.4 Wed 10:15 H 3005

**Microwave cavity-enhanced transduction for plug and play nanomechanics at room temperature** — •Thomas Faust, Peter Krenn, Stephan Manus, Jörg P. Kotthaus, and Eva M. Weig — Fakultät für Physik and Center for NanoScience, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, 80539 München, Germany

The readout and manipulation of nanomechanical systems can be significantly enhanced by coupling them to an optical or electrical cavity. The latter has the advantage of allowing to read out a large array of resonators with only one cavity without any positioning involved. Up to now experiments employing the coupling to microwave cavities are performed at cryogenic temperatures to benefit from capacitively coupled superconducting cavities and resonators.

We present an approach based on a conventional $\lambda/4$ microstrip cavity at room temperature. It is dielectrically coupled to a doubly-clamped high stress silicon nitride beam with an extremely high mechanical quality factor of 290,000 at a mechanical resonance frequency of 6.6 MHz. Displacement detection is performed by monitoring the mechanically induced sidebands in the microwave cavity transmission signal. The sensitivity is sufficient to resolve the Brownian motion. Furthermore, the obtained coupling is strong enough to observe back-action effects of the microwave field on the mechanical resonator. We realise both cooling of the fundamental mode to 150 K as well as entering the regime of cavity-pumped self-oscillation. Thereby, an adjustement-free, all-integrated and self-driven resonator interfaced by just two microwave connectors is realised.

TT 24.5 Wed 10:30 H 3005

**Development of a Mechanical Single Electron Shuttle** — •Darren Southworth and Eva Weig — Ludwig-Maximilians-Universität, Fakultät für Physik, München

We present progress in the development of a mechanical single electron shuttle. The shuttle is composed of a gold island on a silicon nitride beam situated in a gap between source and drain electrodes. Oscillation of the beam brings the island into contact with the electrodes, and in the presence of a DC bias, charging of the island results in electron transport. The island is equipped with a gate electrode and the motion of the beam can be driven dielectrically. The current design has potential to function as a mechanical single electron transistor at 4K.

TT 24.6 Wed 10:45 H 3005

**Single-wall carbon nanotubes as nano-electromechanical resonators** — Daniel Schmid, Peter Stiller, Sabine Kugler, Christoph Strunk, and •Andreas K. Hüttel — Institute for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany

Nano-electromechanical systems realized with carbon nanotubes display outstanding both electronical and mechanical properties. We present measurements on strong coupling between single electron tunneling and mechanical motion of a carbon nanotube quantum dot. The ultra-clean, freely suspended carbon nanotube in the few carrier limit is coupled to superconducting leads. Transport measurements show the transition from strong Coulomb blockade to the Kondo regime on the electron conduction side and from Coulomb blockade to Fabry-Perot interference on the hole conduction side. Connected to these different coupling strengths, we examine the behavior of the resonance frequency of the mechanical motion, detected via dc-current measurements.

**15 min. break.**

TT 24.7 Wed 11:15 H 3005

**Cooling in the single-photon regime of optomechanics** — •Andreas Nunnenkamp[1], Kjetil Borkje[2], and Steven Girvin[2] — [1]Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland — [2]Departments of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA

Optomechanics experiments are rapidly approaching the regime where the radiation pressure of a single photon displaces the mechanical oscillator by more than its zero-point uncertainty. We show that in this limit the power spectrum has multiple sidebands and that the cavity response has several resonances in the resolved-sideband limit [1]. We then discuss how red-sideband cooling is modified in this nonlinear regime. Using Fermi's Golden rule we calculate the transition rates induced by the optical drive. In the resolved-sideband limit we find multiple cooling resonances for strong single-photon coupling. They lead to non-thermal steady states and are accompanied by multiple mechanical sidebands in the optical output spectrum. Our study provides the tools to detect and take advantage of this novel regime of optomechanics.

[1] Phys. Rev. Lett. **107**, 063602 (2011).

TT 24.8 Wed 11:30 H 3005

**Optomechanical circuits for nanomechanical continuous variable quantum state processing** — •Michael P. Schmidt[1], Max Ludwig[1], and Florian Marquardt[1,2] — [1]Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 7, D-91058 Erlangen, Germany — [2]Max Planck Institute for the Science of Light, Günther-Scharowsky-Straße 1/Bau 24, D-91058 Erlangen, Germany

Optomechanical crystals are novel on-chip realizations of an optomechanical system. Recently, Painter et. al. prepared the vibrational mode of such a structure in its quantum ground state by means of optical sideband cooling, opening the door to the investigation of its quantum dynamics. We propose and analyze an architecture, in which linear quantum operations can be performed selectively on the vibrational modes: By suitable modulation of the driving laser intensity, it is possible to generate entanglement, squeezing and state transfer between modes.

TT 24.9 Wed 11:45 H 3005

**Photon Statistics in Ultrastrong Coupling Optomechanics** — •Andreas Kronwald[1], Max Ludwig[1], and Florian Marquardt[1,2] — [1]Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 7, D-91058 Erlangen, Germany — [2]Max Planck Institute for the Science of Light, Günther-Scharowsky-Straße 1/Bau 24, D-91058 Erlangen, Germany

A standard optomechanical system consists of a laser-driven photonic mode coupled to a mechanical degree of freedom. In the ultrastrong coupling regime, where a single photon is able to strongly affect the mechanical mode, a wide range of nontrivial phenomena is expected. In this work, we focus on the full counting statistics of the photonic mode using a quantum jump trajectory method. Thereby, we observe photon antibunching as well as photon avalanches, which are induced by the ultrastrong light-mechanics coupling.

TT 24.10 Wed 12:00 H 3005

**Enhanced photon and phonon detection in ultrastrong-coupling optomechanics** — •Max Ludwig[1], Amir H. Safavi-Naeini[2], Oskar Painter[2], and Florian Marquardt[1] — [1]Institut für Theoretische Physik, Universität Erlangen-Nürnberg, Staudtstraße 7, D-91058 Erlangen, Deutschland — [2]Thomas J. Watson, Sr., Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA

The regime of ultrastrong coupling in optomechanics is reached when the optomechanical coupling rate becomes comparable to the cavity linewidth. In this regime we consider a setup comprising two cavity modes and a single mechanical mode. For mechanical frequencies nearly resonant to the optical level splitting the photon-phonon and the photon-photon interaction is boosted enabling QND phonon and photon detection.

TT 24.11 Wed 12:15 H 3005

**Adiabaticity in semiclassical nanoelectromechanical systems** — •Anja Metelmann and Tobias Brandes — Institut für Theoretische Physik, TU Berlin, Hardenbergstr. 36, D-10623 Berlin, Germany

We compare the semiclassical description of NEMS within and beyond the adiabatic approximation. We consider a NEMS model which contains a single phonon (oscillator) mode linearly coupled to an electronic few-level system in contact with external particle reservoirs (leads). Using Feynman-Vernon influence functional theory, we derive a Langevin equation for the oscillator trajectory that is non-perturbative in the system-leads coupling. A stationary electronic current through the system generates nontrivial dynamical behavior of the oscillator, even in the adiabatic regime. The 'backaction' of the oscillator onto the current is studied as well [1].

For the case of two coupled electronic levels, we discuss the differences between the adiabatic and the non-adiabatic regime of the oscillator dynamics.

[1] A. Metelmann and T. Brandes, Phys. Rev. B **84**, 155455 (2011).

TT 24.12 Wed 12:30 H 3005

**Detecting Majorana Bound States by Nanomechanics** — •Stefan Walter[1], Thomas L. Schmidt[2], Kjetil Børkje[2], and Björn Trauzettel[1] — [1]Institute for Theoretical Physics and Astrophysics, University of Würzburg, 97074 Würzburg, Germany — [2]Department of Physics, Yale University, 217 Prospect Street, New Haven, Connecticut 06520, USA

We propose a nanomechanical detection scheme for Majorana bound states, which have been predicted to exist at the edges of a one-dimensional topological superconductor, implemented, for instance, using a semiconducting wire placed on top of an $s$-wave superconductor. Existing detection schemes focus, for instance, on tunnel setups, interferometer setups and the Josephson effect. However, it is fair to say that true qualitative experimental signatures of Majorana fermions that persist in realistic systems are rather difficult to predict.

Our detection scheme, makes use of an oscillating electrode, which can be realized using a doubly clamped metallic beam, tunnel coupled to one edge of the topological superconductor. We find that a measurement of the nonlinear differential conductance provides the necessary information to uniquely identify Majorana bound states.