CSRC

The 4th International Workshopon
Frontiers in Quantum Optics and Quantum Information:
Optomechanics meets circuit QED

Registration

June15	14:00 ~ 17:00	Lobby of CSRC Building
June16-18	08:00 ~ 17:00	Outside the Conference Hall

Conference

June 16	9:00 ~ 12:00, 14:00 ~ 17:25
June 17	9:00 ~ 12:15, 14:15 ~ 17:35
June 18	9:00 ~ 12:15, 14:15 ~ 17:30

Conference Hall, 1st Floor, CSRC Building

June 16, 2016 (Thursday)

08:00	*Pickup from Liaoning International Hotel*
08:30	*Pickup from Hanting Hotel*
09:00 – 09:10	**Hai-Qing Lin**, *Director of Beijing Computational Science Research Center* Opening / Welcome
09:10 – 10:40 Morning Session I **Chair: Aashish Clerk**, *McGill University*	
09:10 – 09:55 (45 minutes)	**Andrew Cleland**, *University of Chicago* TBA
09:55 – 10:40 (45 minutes)	**Simon Gröblacher**, *Delft University of Technology* Quantum optomechanics experiments with photonic crystals
10:40 – 11:15	***Photo Taking*** *& Coffee Break*
11:15 – 12:00 Morning Session II **Chair: Luming Duan**, *Tsinghua University & University of Michigan*	
11:15 –12:00 (45 minutes)	**Albert Schliesser**, *University of Copenhagen* Optomechanical quantum correlations in a multimode nanomechanical membrane resonator
12:00 –14:00	*Lunch & Break*
14:00 – 15:30 Afternoon Session I **Chair: Florian Marquardt**, *University of Erlangen-Nuremberg*	
14:00 –14:45 (45 minutes)	**Hailin Wang**, *University of Oregon* Optomechanical quantum control of nitrogen vacancy centers in diamond
14:45 – 15:30 (45 minutes)	**Luming Duan**, *Tsinghua University & University of Michigan* Quantum computation and teleportation with phonons in trapped ions and diamonds
15:30 –15:50	*Coffee Break*
15:50 – 17:25 Afternoon Session II **Chair: Yanbei Chen**, *California Institute of Technology*	
15:50 – 16:35 (45 minutes)	**Franco Nori**, *Center for Emergent Matter Science, RIKEN* Parity-time-symmetric microcavities and extraordinary properties of light including the Quantum spin Hall effect of light
16:35 –17:00 (25 minutes)	**Keye Zhang**, *East China Normal University* Sensing feeble microwave signals via an optomechanical transducer
17:00 – 17:25 (25 minutes)	**Jun Zhang**, *Institute of Semiconductors, CAS* Laser cooling of lattice phonons in semiconductor materials
17:25 – 19:00	*Dinner*
19:00	*Pickup to Liaoning International Hotel & Hanting Hotel*

June 17, 2016 (Friday)

08:00	*Pickup from Liaoning International Hotel*
08:30	*Pickup from Hanting Hotel*
09:00 – 10:30 Morning Session I **Chair: Andreas Joachim Wallraff**, *Eidgenössische Technische Hochschule (ETH)*	
09:00 – 09:45 (45 minutes)	**John Teufel**, *National Institute of Standards and Technology in Boulder* Observing the nonclassical forces imparted by squeezed light
09:45 – 10:30 (45 minutes)	**Alexey Feofanov**, *Swiss Federal Institute of Technology in Lausanne (EPFL)* A dissipative reservoir for microwave light
10:30 – 11:30	*Coffee Break & Poster session*
11:30 - 12:15 Morning Session II **Chair: Hongxing Tang**, *Yale University*	
11:30 – 12:15 (45 minutes)	**Amir Safavi-Naeini**, *Stanford University* Silicon optomechanics, and heterogeneous nonlinear microwave-optical translators
12:15 - 14:15	*Lunch & Break*
14:15– 15:45 Afternoon Session I **Chair: Andrew Cleland**, *University of Chicago*	
14:15 – 15:00 (45 minutes)	**Warwick Bowen**, *University of Queensland* Probing quantum condensed matter physics with microcavity optomechanics
15:00 – 15:45 (45 minutes)	**Benjamin Huard**, *École Normale Supérieure* Extracting work with a superconducting qubit using a Maxwell demon
15:45 – 16:05	*Coffee Break*
16:05– 17:35 Afternoon Session II **Chair: Lin Tian**, *California University of Merced*	
16:05 – 16:50 (45 minutes)	**Andreas Joachim Wallraff**, *Eidgenössische Technische Hochschule (ETH) Zürich* Quantum optics with single photons in superconducting circuits
16:50 – 17:35 (45 minutes)	**Chen Wang**, *Yale University* Entangled Schrödinger cats in circuit QED
17:35 – 19:00	*Dinner*
19:00	*Pickup to Liaoning International Hotel & Hanting Hotel*

June 18, 2016 (Saturday)

08:00	*Pickup from Liaoning International Hotel*
08:30	*Pickup from Hanting Hotel*
09:00 – 11:15 Morning Session I **Chair: Yasunobu Nakamura**, *University of Tokyo*	
09:00 – 09:45 (45 minutes)	**Hongxing Tang**, *Yale University* Multimode strong coupling in superconducting cavity piezo-electromechanics
09:45 – 10:30 (45 minutes)	**Lars Göran Johansson**, *Chalmers University of Technology* Quantum optics and quantum acoustics in waveguide circuit QED
10:30 – 10:45	*Coffee Break*
10:45 – 12:15 Morning Session II **Chair: Liang Jiang**, *Yale University*	
10:45 – 11:30 (45 minutes)	**Yanbei Chen**, *California Institute of Technology* Testing Quantum Mechanics with Optomechanics Experiments
11:30 – 12:15 (45 minutes)	**Peter Rabl**, *Vienna University of Technology* Inhibition of ground-state superradiance and light-matter decoupling in circuit QED
12:15 – 14:15	*Lunch & Break*
14:15 – 15:45 Afternoon Session I **Chair: John Teufel**, *National Institute of Standards and Technology in Boulder*	
14:15 – 15:00 (45 minutes)	**Yasunobu Nakamura**, *University of Tokyo* Hybrid quantum systems using collective degrees of freedom in solids
15:00 – 15:45 (45 minutes)	**Eva Weig**, *University of Konstanz* Classical Stückelberg interferometry with a nanomechanical two-mode system
15:45 – 16:05	*Coffee Break*
16:05 – 17:30 Afternoon Session II **Chair: Jianqiang You**, *Beijing Computational Science Research Center*	
16:05 – 16:30 (25 minutes)	**Xiaobo Zhu**, *University of Science and Technology of China* On resonance quantum switch by longitudinal control field
16:30 – 16:55 (25 minutes)	**Tiefu Li**, *Beijing Computational Science Research Center& Tsinghua University* Multi-photon sideband transitions in an ultrastrongly-coupled circuit QED system
16:55 – 17:20 (25 minutes)	**Haohua Wang**, *Zhejiang University* Solving linear systems of equations in a four-qubit superconducting circuit
17:20 – 17:30 (10 minutes)	**Closing Remarks**
17:30 – 18:30	*Dinner*
18:30	*Pickup to Liaoning International Hotel & Hanting Hotel*

The 4th International Workshop on

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Abstract

TALK-1 of JUNE 16

TBA

Andrew Cleland

University of Chicago, USA

Quantum optomechanics experiments with photonic crystals

Simon Gröblacher

Kavli Institute of Nanoscience, Delft University of Technology, Netherlands

Mechanical oscillators coupled to light via the radiation pressure force have attracted significant attention over the past years for allowing tests of quantum physics with massive objects and for their potential use in quantum information processing. Recently demonstrated quantum experiments include entanglement and squeezing of both the mechanical and the optical mode. So far these quantum experiments have almost exclusively operated in a regime where the light field oscillates at microwave frequencies. Here we would like to discuss a recent experiment where we demonstrate non-classical mechanical states by coupling a mechanical oscillator to single optical photons. These results are a promising route towards using mechanical systems as quantum memories, for quantum communication purposes and as light-matter quantum interfaces. In addition, we will also discuss efforts to perform these quantum optomechanics experiments at room temperature, in contrast to the currently purely cryogenic environments used.

Optomechanical quantum correlations in a multimode nanomechanical membrane resonator

W. H. P. Nielsen, Y. Tsaturyan, C. Møller, A. Barg, E. S. Polzik, **A. Schliesser**

Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark

A mechanical device coupled to several electromagnetic modes simultaneously can be harnessed as a versatile coherent signal transducer,of interest both in a classical and quantum context. Ina proof-of-principle version of such a transducer, based on a high-*Q* silicon nitride membrane resonator, we have found the added noise of the transduction cascade to be proportional to the mechanical decoherence rate.

We have therefore developed nanomechanical membranes embedded in a phononic bandgap shield that suppresses mechanical decoherence by phonon tunneling. These membranes' coherence times are sufficient to realize quantum-coherent coupling to an optical resonator already at modest cryogenic temperatures (10K). They provide a promising platform for experiments in complex, hybrid systems involving several electromagnetic, mechanical or atomic degrees of freedom.

We demonstrate this potential by evidencing quantum correlations between light and a multitude of highly coherent ($Q > 10^7$) mechanical modes, as measured by means of wideband ponderomotive squeezing of the output light. A measurement rate (~90 kHz) far exceeding the decoherence rate, and a high detection efficiency enable quantum noise suppression up to -2.4dB (-3.6 dB if corrected for detection losses), the highest observed to date. While the multimode character of the mechanical resonator constitutes an additional resource for transducer applications, theoretical modeling also suggests the possibility of phonon-photon and phonon-phonon entanglement.

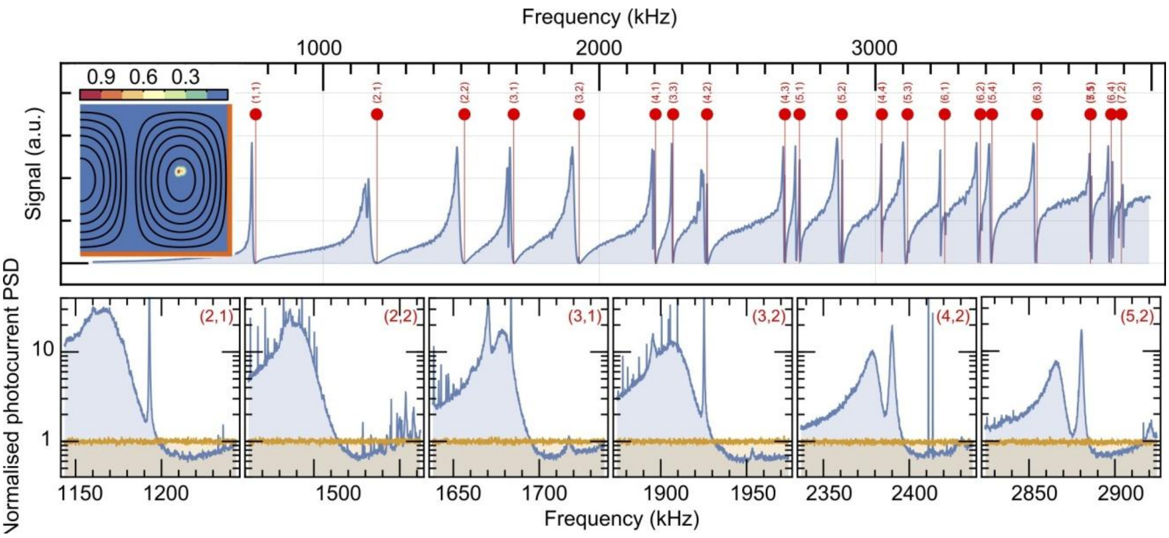

Figure 1. Top: Multimode Optomechanically Induced Transparency (OMIT) and inferred location of the optical readout beam on a membrane quadrant (inset) with clamped membrane edge indicated in orange. Bottom: Strong ponderomotive squeezing on six mechanical modes.

TALK-4 of JUNE 16

Optomechanical quantum control of nitrogen vacancy centers in diamond

Hailin Wang

Department of Physics, University of Oregon, Eugene, OR 97403, USA

Optomechanical interactions of a trapped ion in the resolved-sideband regime can enable quantum control of both the internal atomic states and the center-of-mass mechanical motion of an atom. Combining these two aspects of optomechanical quantum control has led to thus far the most successful paradigm for quantum information processing and has also enabled the generation of exotic quantum states, such as phonon number states and Schrödinger cat states. These remarkable successes have stimulated strong interest in pursuing optomechanical quantum control of artificial atoms, including quantum dots (QDs) and diamond nitrogen vacancy (NV) centers. Ground state cooling and spin entanglement via optomechanical processes in hybrid systems that couple QDs or NV centers to nanomechanical oscillators have been proposed. In this talk, I will discuss recent experimental advances toward realizing a solid-state analog of trapped ions by coupling NV centers to mechanical vibrations in diamond.

Optomechanical coupling of a NV center takes place via phonon-assisted optical transitions, i.e. sideband transitions. By coupling the NV to both optical fields and surface acoustic waves (SAWs) and also by taking advantage of the strong excited-state electron-phonon coupling in a NV center, we have realized sideband-driven Rabi oscillations as well as quantum interferences between the sideband and direct optical transitions . To take advantage of the long spin coherence time of a NV center, we also couple two electron spin states of a NV center to a common excited state via a Raman transition. Coherent population trapping (CPT) induced by both optical and sideband transitions has been achieved, demonstrating the coherent coupling between an electron spin and a SAW. These experimental progresses open the door to using resolved-sideband optomechanical coupling for quantum control of both the atom-like internal states and the motional states of a coupled NV-nanomechanical system and also to developing a phonon-based quantum network by incorporating NV centers into micro-electromechanical systems.

TALK-5 of JUNE 16

Quantum computation and teleportation with phonons in trapped ions and diamonds

Luming Duan

Tsinghua University, China & University of Michigan, USA

In this talk, I will briefly explain how to use phonons in a linear ion chain to realize scalable boson sampling, which provides a possibility to disprove the extended Church-Turing thesis. I will also explain recent experiments to use the opto-mechanical coupling in a diamond to realize quantum teleportation from photons to phonons and to use diamond defects to realize robust geometric quantum computation.

TALK-6 of JUNE 16

Parity-time-symmetric microcavities and extraordinary properties of light including the Quantum spin Hall effect of light

Franco Nori[1,2]

[1] *RIKEN, Saitama, Japan.*

[2] *University of Michigan, Ann Arbor, USA*

Optical systems combining balanced loss and gain provide a unique platform to implement classical analogues of quantum systems described by non-Hermitian parity–time (PT)-symmetric Hamiltonians. Such systems can be used to create synthetic materials with properties that cannot be attained in materials having only loss or only gain. We report PT-symmetry breaking in coupled optical resonators. We observed non-reciprocity in the PT-symmetry-breaking phase due to strong field localization, which significantly enhances nonlinearity. In the linear regime, light transmission is reciprocal regardless of whether the symmetry is broken or unbroken. We show that in one direction there is a complete absence of resonance peaks whereas in the other direction the transmission is resonantly enhanced, which is associated with the use of resonant structures. Our results could lead to a new generation of synthetic optical systems enabling on-chip manipulation and control of light propagation.

B. Peng, et al., *Parity-time-symmetric whispering-gallery microcavities*, Nature Physics **10**, 394-398 (2014). [PDF][Link][arXiv]. Supplemental: [PDF][Link]; "News & Views": [PDF][Link]

Maxwell's equations, formulated 150 years ago, ultimately describe properties of light, from classical electromagnetism to quantum and relativistic aspects. The latter ones result in remarkable geometric and topological phenomena related to the spin-1 massless nature of photons. By analyzing fundamental spin properties of Maxwell waves, we show that free-space light exhibits an intrinsic quantum spin Hall effect—surface modes with strong spin-momentum locking. These modes are evanescent waves that form, for example, surface plasmon-polaritons at vacuum-metal interfaces. Our findings illuminate the unusual transverse spin in evanescent waves and explain recent experiments that have demonstrated the transverse spin-direction locking in the excitation of surface optical modes. This deepens our understanding of Maxwell's theory, reveals analogies with topological insulators for electrons, and offers applications for robust spin-directional optical interfaces.

K.Y. Bliokh, D. Smirnova, F. Nori, *Quantum spin Hall effect of light*, Science 348, 1448-1451 (2015). [PDF] [Link] [arXiv]. Highlighted in a Perspectives [Science 348, 1432 (2015)].

Some related work by our group can be found in the following references:

[1] K.Y. Bliokh, F. Nori, *Transverse spin of a surface polariton*, Phys. Rev. A **85**, 061801 (2012). [PDF][Link][arXiv]

[2] K.Y. Bliokh, A.Y. Bekshaev, F. Nori, *Dual electromagnetism: helicity, spin, momentum, and angular momentum*, New J. Phys. **15**, 033026 (2013). [PDF][Link][arXiv] ISI Highly cited paper 2013-2014.

[3] K.Y. Bliokh, J. Dressel, F. Nori, *Conservation of the spin and orbital angular momenta in electromagnetism*, New J. Phys. **16**, 093037 (2014). [PDF][Link][arXiv]

[4] K. Y. Bliokh, Y. S. Kivshar, F. Nori, *Magnetoelectric Effects in Local Light-Matter Interactions*, Phys. Rev. Lett. **113**, 033601 (2014). [PDF][Link][arXiv]

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[6] A.Y. Bekshaev, K.Y. Bliokh, F. Nori, *Transverse spin and momentum in two-wave interference*, Phys. Rev. X **5**, 011039 (2015). [PDF][Link][arXiv]

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[8] K.Y. Bliokh and F. Nori, *Transverse and longitudinal angular momenta of light*, Physics Reports, Volume 592, 26 August 2015, Pages 1–38 (2015). A 38-pages review, including some of our results. URL: [PDF][Link][arXiv]

[9] K.Y. Bliokh, F.J. Rodriguez-Fortuno, F. Nori, A.V. Zayats, *Spin-orbit interactions of light*. Nature Photonics 9, p. 796–808. 13-pages review, including some of our results. [PDF][Link][arXiv]

[10] M. Antognozzi, et al., *Direct measurements of the extraordinary optical momentum and transverse spin-dependent force using a nano-cantilever,* Nature Physics , 3732 (2016). [PDF][Link][arXiv][Supplementary information]

[11] F. Monifi, J. Zhang, Ş.K. Özdemir, B. Peng, Y.X. Liu, F. Bo, F. Nori, L. Yang, *Optomechanically induced stochastic resonance and chaos transfer between optical fields,* Nature Photonics , (2016). [PDF][Link][Supplementary information]

Sensing feeble microwave signals via an optomechanical transducer

Keye Zhang[1] and Weiping Zhang[2]

[1]*Department of Physics, East China Normal University, Shanghai, P.R. China*

[2]*Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, P.R. China*

Due to their low energy content microwave signals at the single-photon level are extremely challenging to measure. Guided by recent progress in single-photon optomechanics and hybrid optomechanical systems, we propose a multimode optomechanical transducer that can detect intensities significantly below the single-photon level via off-resonant adiabatic transfer of the microwave signal to the optical frequency domain where the measurement is then performed. The influence of intrinsic quantum and thermal fluctuations on the performance of this detector are considered in detail.

Laser cooling of lattice phonons in semiconductor materials

Jun Zhang

SKLSM, Institute of Semiconductors, CAS, Beijing, 100083

Last century has witnessed a tremendous success of laser cooling technology in the fields of precision spectroscopy, time and frequency metrology, quantum optics, and solid-state optical refrigeration. Here i will report my results on laser cooling of semiconductors. By using of strong coupling between excitons and longitudinal optical phonons (LOPs), which allows the resonant annihilation of multiple LOPs in luminescence up-conversion processes, we observe a net cooling by about 40 K starting from 290 kelvin with 514-nm pumping and about 15 K starting from100 K with 532-nm pumping in a semiconductor using group-II–VI cadmium sulphide nanobelts. We also discuss the thickness dependence of laser cooing in CdS nanobelts, possibility of laser cooling in II-VI semiconductor family including CdSSe、CdSe and bulk CdS et al., Beyond II-VI semiconductor, we will present our recent progress in laser cooling of organic-inorganic perovskite materials, which show a very big cooling power and external quantum efficiency in 3D and 2D case. Furthermore, I will show a sideband Raman cooling and heating experiments of longitudinal optical phonon (LOP) with a 6.23 THz frequency in semiconductor zinc telluride nano-ribbons. When we use red-sideband laser to pump the nanoribbon, the LOP can be cooled from 225 to 165 kelvin, corresponding to an average occupation number reduced from 0.36 to 0.19. With increasing the laser power further, a normal modes splitting is observed. We also observe a LOPs heating behavior from 230 to 326 kelvin with a blue-sideband pumping.

References：

[1] J. Zhang *et al*., *Nature* (cover) **493**, 504-508 (2013)

[2] D. H. Li*, J. Zhang* *et al*., *Optics Express* **21**, 19302-19310 (2013)

[3] D. H. Li*, J. Zhang* *et al*., *Nano Letters* **14**, 4724–4728 (2014)

[4] S. T. Ha & J. Zhang *et al*., *Nature Photonics*, **10**, 115-121(2016)

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TALK-1 of JUNE 17

Observing the Nonclassical Forces Imparted by Squeezed Light

John Teufel

National Institute of Standards and Technology in Boulder, Colorado, USA

In optomechanical circuits, radiation pressure forces offer the ability to engineer strong interactions between photonic and phononic degrees of freedom. In this talk, I will describe recent experiments which explore the interaction between squeezed light and mechanical motion. First, we demonstrate how radiation pressure noise can be suppressed below the shot noise limit by interrogating a micromechanical resonator with displaced squeezed states of the microwave field. We then show how the fundamental optomechanical interaction allows the mechanical system to perform a QND measurement of the amplitude quadrature of the microwave light field. Lastly, we demonstrate that the radiation pressure forces from the correlated photons in the squeezed field can prepare the mechanical oscillator in a highly pure quantum state. Together these experiments demonstrate the utility of squeezed light and optomechanical circuits for quantum-enhanced sensing, quantum measurement and engineering nonclassical states of motion.

TALK-2 of JUNE 17

A dissipative reservoir for microwave light

L. D. Tóth, N. R. Bernier, A. Nunnenkamp, E. Glushkov, **A. K. Feofanov**, T. J. Kippenberg

Swiss Federal Institute of Technology in Lausanne (EPFL), Switzerland

Isolation of a system from its environment is often desirable, from precision measurements to control of individual quantum systems; however, dissipation can also be a useful resource. Remarkably, engineered dissipation enables the preparation of quantum states of atoms, ions or superconducting qubits as well as their stabilization. This is achieved by a suitably engineered coupling to a dissipative cold reservoir formed by electromagnetic modes in either the optical or microwave domain. Similarly, in the field of cavity electro- and optomechanics the control over mechanical oscillators utilizes the inherently cold, dissipative nature of the electromagnetic degree of freedom. Breaking from this paradigm, recent theoretical work has considered the opposite regime in which the dissipation of the mechanical oscillator dominates and provides a cold dissipative reservoir to the electromagnetic degree of freedom. This novel regime allows for manipulation of the electromagnetic mode and enables a new class of dissipative interactions. Here we report the experimental realization of this reversed dissipation regime in a microwave cavity optomechanical system and realize a quasi-instantaneous, cold reservoir for microwave light. We evidence this regime by decreasing or increasing the damping rate of the cavity on demand that corresponds to amplification and de-amplification of the microwave field. Additionally, we observe the onset of parametric instability, that is, the stimulated emission of microwaves (masing). Moreover, we employ the engineered cold reservoir to implement a low-noise, large-gain phase-preserving amplifier. Beyond offering the manipulation of microwave fields, such a dissipative reservoir for microwave light, when coupled to multiple cavity modes, forms the basis of microwave entanglement schemes, electromechanical amplifiers with unlimited gain-bandwidth product and dissipative quantum phase transitions. Equally important, combining such reservoir-mediated interaction with coherent dynamics allows for the realization of recently predicted non-reciprocal devices, which would extend the available toolbox of quantum-limited microwave manipulation techniques.

Silicon optomechanics, and heterogeneous nonlinear microwave-optical translators

Amir Safavi-Naeini

Department of Applied Physics, Stanford University, USA

In this talk I will outline two ongoing experiments at the intersection of optomechanics, nonlinear optics, and quantum electromechanics. First I will show our results on simultaneous confinement of acoustic and optical waves on the surface of silicon-on-insulator (SOI) chips. While silicon on insulator (SOI) is a natural platform for photonics, it is not as well suited for on-chip phononics and acoustic waveguiding. The high index contrast between silicon and silica glass readily allows for confinement of optical fields to the silicon device layer. But silicon's relative stiffness -- and therefore high sound velocity -- makes guiding acoustic waves challenging. The intuition of ``index-guided" confinement of mechanical modes fails for sub-wavelength structures. The second effort I will present is our work on heterogeneous integration of Lithium Niobate with silicon photonic and superconducting circuits for implementation of microwave-to-optical converters.

TALK-4 of JUNE 17

Probing quantum condensed matter with microcavity optomechanics

D. L. McAuslan, G. I. Harris, C. Baker, Y. Sachkou and **W. P. Bowen**

Australian Centre for Engineered Quantum Systems, University of Queensland, Australia

Emergent quantum phenomena such as superconductivity, quantum magnetism, and superfluidity arise due to strong interactions between elementary excitations in condensed matter systems. In superfluids, the elementary excitations are phonons and rotons; with techniques such as neutron and light scattering used to probe their behaviour since the 1960s. However, quite generally, such techniques have been limited to measurements of average properties of bulk superfluid; or to observations of the driven response far out of thermal equilibrium. In this talk I will discuss experiments where approaches from cavity optomechanics are used to directly probe and control superfluid excitations in real time[1]. This allows the observation and cooling of thermomechanical fluctuations of third sound modes (Fig. 1), as well as probing of phonon-vortex interactions.

The ability to probe excitations in real time may provide a new approach towards understanding the microscopic behaviour of superfluids, including quantum turbulence, quantum vortices, and two dimensional quantum phenomena such as the Berezinskii-Kosterlitz-Thouless transition. Furthermore, our results demonstrate that superfluid films have significant prospects for quantum optomechanics, including strong optomechanical coupling, femto- to pico-gram effective mass, high mechanical quality factor and strong phonon-phonon interactions; potentially enabling the realisation of macroscopic nonclassical states, superfluid phononic circuits, optomechanics with quantized vortices, and applications in superfluid force and inertial sensing.

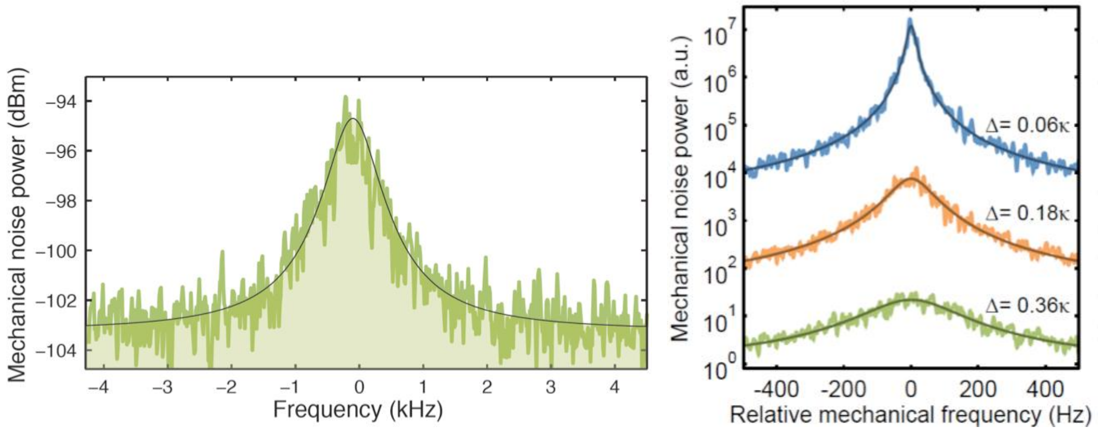

Figure 1: Left: Thermal motion of a third sound mode in a thin superfluid film. Right: Laser cooling, as a function of cavity detuning Δ.

Keywords quantum optomechanics, superfluid helium, laser cooling

References:

[1] G. I. Harris et al, Nature Physics (2016); D. L. McAuslan, PRX (2016)

Extracting work with a superconducting qubit using a Maxwell demon

Benjamin Huard

Laboratoire Pierre Aigrain, Ecole Normale Supérieure, Paris, France

Quantum thermodynamics of information addresses the link between information and energy in the quantum regime. Entanglement and measurement backaction are known to deeply affect information processing and their impact on quantum thermodynamics has attracted a lot of theoretical activity. A basic illustration of these ideas consists in devising a quantum version of the Maxwell demon that uses information on a system to extract work from it.

In this talk, we will discuss an elementary thermal machine able to extract work from a superconducting quantum bit from the knowledge it acquires. We have realized such a machine using superconducting circuits in two manners. First, by measurement based feedback, a macroscopic observer acquires information about the quantum system and reacts on it. Second, using a microwave mode as a quantum Maxwell demon, we are able to directly measure the extracted work from a thermalized qubit. We track quantitatively the flows of energy and entropy at any step of the process owing to the high level of controllability of superconducting circuits. When the qubit starts in a coherent superposition, this work gives a direct picture of the power flows out of a qubit during a coherent evolution and a measurement.

Quantum optics with single photons in superconducting circuits

A. Wallraff

ETH Zurich, Zurich, Switzerland

In our lab, we design, manufacture and explore quantum electronic circuits in which we create, store, and manipulate individual microwave photons. We realize our circuits structuring superconducting thin films with modern micro and nano-fabrication techniques. Achieving strong coherent interaction between photons and superconducting quantum two-level systems we probe fundamental quantum effects of microwave radiation and develop components for applications in quantum technology. In this presentation, I will discuss method for creating, manipulating and characterizing single photons [1, 2, 3]. In particular, I will discuss our progress in the creation of single photons with controlled envelopes [4]. I will also discuss a recently developed, lossless microwave switch, which we integrate with other quantum circuits on the same chip. With this switch, we demonstrated the routing of signals from the single photon level to large coherent fields with near-unity efficiency and a bandwidth of 150MHz, a 1dB compression point of −80 dBm, turn-on/off times of about 5 ns and on/off power ratios reach values of approximately 30 dB. We expect that our device will find use in (de)multiplexing of control and readout in superconducting circuits and routing of microwave fields in quantum optical experiments and quantum communication applications. The methods which I present are not only applicable in the context of superconducting circuits but may be used to route and characterize radiation emitted from any source of microwave frequency radiation, such as that emitted by electron inelastic tunneling in semiconducting nano-structures [5], for example.

References:

[1] D. Bozyigit et al., Nat. Phys. **7**, 154 (2011)

[2] C. Lang et al., Phys. Rev. Lett. **106**, 243601 (2011)

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Entangled Schrödinger cats in circuit QED

Chen Wang,[1] Yvonne Y. Gao,[1] Philip Reinhold,[1] R. W. Heeres,[1] Nissim Ofek,[1] Kevin Chou,[1]
Christopher Axline,[1] Matthew Reagor,[1] Jacob Blumoff,[1] K. M. Sliwa,[1] L. Frunzio,[1] S. M. Girvin,[1]
Liang Jiang,[1] M. Mirrahimi,[1,2] M. H. Devoret,[1] R. J. Schoelkopf[1]

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78153 Le Chesnay cedex, France

Quantum superpositions of distinct coherent states in a single-mode harmonic oscillator, known as "cat states", have been an elegant demonstration of Schrödinger's famous cat paradox. Here, we realize a two-mode cat state of electromagnetic fields in two microwave cavities bridged by a superconducting artificial atom, which can also be viewed as an entangled pair of single-cavity cat states. We present full quantum state tomography of this complex cat state over a Hilbert space exceeding 100 dimensions via quantum non-demolition measurements of the joint photon number parity. The ability to manipulate such multi-cavity quantum states paves the way for logical operations between redundantly encoded qubits for fault-tolerant quantum computation and communication.

Multimode strong coupling in superconducting cavity piezo-electromechanics

Hongxing Tang

Yale University, USA

High frequency mechanical resonators subjected to low thermal phonon occupancy are easier to be prepared to the ground state by direct ryogenic cooling. Their extreme stiffness, however, poses signifcant challenge for external interrogations. Here we demonstrate a superconducting cavity piezo-electromechanical system in which multiple modes of a bulk acoustic resonator oscillating at 10 GHz are coupled to a planar microwave superconducting resonator with a cooperativity exceeding 2E3, deep in the strong coupling regime. By implementation of the non-contact coupling scheme to reduce mechanical dissipation, the system exhibits excellent coherence characterized by a frequency-quality factor product of 7.5E15 Hz. Interesting dynamics of temporal oscillations of the microwave energy is observed, implying the coherent conversion between phonons and photons. The demonstrated high frequency cavity piezo-electromechanics is compatible with superconducting qubits, representing an important step towards hybrid quantum systems.

Quantum optics and quantum acoustics in waveguide circuit QED

Göran Johansson

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In this talk, I'll discuss the physics of microwave photons moving in a coplanar waveguide (1D transmission line) interacting with one or more artificial atoms. Compared to the optical regime, the microwave regime allows for strong and stable coupling of the photons to (artificial) atoms. In particular, I'll discuss the possibility of using the giant cross-Kerr effect for QND detection of propagating microwave photons. I'll also discuss robust designs for broadband single photons sources. Motivated by recent experiments, I'll also discuss what happens when the microwave photons are replaced by surface acoustic wave (SAW) phonons. The phonon velocity is five orders of magnitude slower, implying also that the atom is now substantially larger than the wavelength for its spontaneous emission. This results in a strongly frequency dependent coupling between the atom and the waveguide.

The presentation is primarily based on the following references:

[1] *"Detecting itinerant single microwave photons"*,
Sankar Raman Sathyamoorthy, Thomas M. Stace, Göran Johansson, e-print arXiv:1504.04979

[2] *"Non-absorbing high-efficiency counter for itinerant microwave photons"*,
Bixuan Fan, Göran Johansson, Joshua Combes, G. J. Milburn, Thomas M. Stace,
Phys. Rev. B **90**, 035132 (2014).

[3] *"Quantum nondemolition detection of a propagating microwave photon"*,
Sankar R. Sathyamoorthy, L. Tornberg, Anton F. Kockum, Ben Q. Baragiola, Joshua Combes, C.M. Wilson,
Thomas M. Stace, G. Johansson, Phys. Rev. Lett. **112**, 093601 (2014).

[4] *"Simple, robust and on-demand generation of single and correlated photons"*,
Sankar Raman Sathyamoorthy, Andreas Bengtsson, Steven Bens, Michaël Simoen, Per Delsing,
and Göran Johansson, e-print arXiv:1511.03038, to appear in Phys. Rev. A (2016)

[5] *"Propagating phonons coupled to an artificial atom"*,
Martin V. Gustafsson, Thomas Aref, Anton F. Kockum, Maria K. Ekström, Göran Johansson,
Per Delsing, Science **346**, 207 (2014).

[6] *"Designing frequency-dependent relaxation rates and Lamb shifts for a giant artificial atom"*,
Anton Frisk Kockum, Per Delsing, Göran Johansson, Phys. Rev. A **90**, 013837 (2014).

[7] *"Quantum Acoustics with Surface Acoustic Waves"*,
Thomas Aref, Per Delsing, Maria K. Ekström, Anton Frisk Kockum, Martin V. Gustafsson,
Göran Johansson, Peter Leek, Einar Magnusson, Riccardo Manenti,
Chapter 9 in *Superconducting Devices in Quantum Optics*,
Eds. R. Hadfield and G. Johansson, Springer International Publishing (2016)

Testing Quantum Mechanics with Optomechanics Experiments

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With recent advancement of experimental physics, macroscopic objects, which are typically well-described by classical physics, can now be isolated so well from their environment, that their quantum uncertainties can be studied quantitatively. In the research field called “optomechanics”, mechanical motions of masses from picograms to kilograms are being prepared into nearly pure quantum states, and observed at time scales ranging from nanoseconds to milliseconds. In practice, optomechanics experiments have been constructed to measure extremely weak classical forces, e.g., due to gravitational waves, acting on macroscopic test objects. In this case, experiments must be designed in such a way that quantum uncertainties of the test objects are avoided as much as possible --- often by employing the quantum correlations between the state of light and the motion of the test object, which can build up during the measurement process. Optomechanics experiments can also be used to search for possible deviations from standard quantum mechanics when macroscopic objects are involved. In this case, experiments are designed to highlight as much as possible the quantum-state evolution of the macroscopic objects. It is hoped that these macroscopic quantum mechanics experiments will either lead our way toward new physics, or put experimental constraints on how standard quantum mechanics might be modified.

Inhibition of ground-state superradiance and light-matter decoupling in circuit QED

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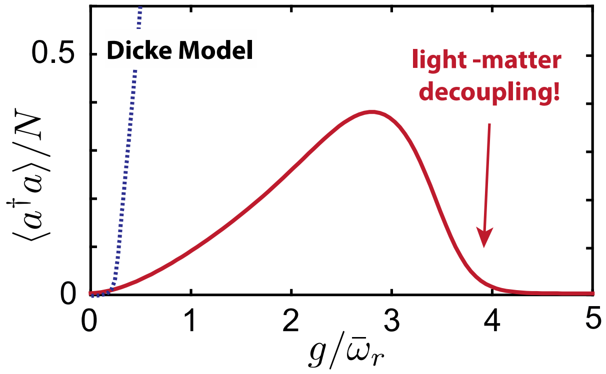
We study effective light-matter interactions in a circuit QED system consisting of a single LC resonator, which is coupled symmetrically to multiple superconducting qubits. Starting from a minimal circuit model, we demonstrate that in addition to the usual collective qubit-photon coupling the resulting Hamiltonian contains direct qubit-qubit interactions, which prevent the otherwise expected superradiant phase transition in the ground state of this system. Moreover, these qubit-qubit interactions are responsible for an opposite mechanism, which at very strong couplings completely decouples the photon mode and projects the qubits into a highly entangled ground state. These findings shed new light on the controversy over the existence of superradiant phase transitions in cavity and circuit QED systems, and show that the physics of ultrastrong light-matter interactions in two- or multi-qubit settings differ drastically from the more familiar one qubit case.



Reference:

Inhibition of ground-state superradiance and light-matter decoupling in circuit QED, T. Jaako, Z.-L.Xiang, J. J. Garcia-Ripoll, and P. Rabl, arXiv:1602.05756.

Hybrid quantum systems using collective degrees of freedom in solids

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Collective excitations in solids sometime have long coherence times useful for quantum information processing. Superconducting qubits are the most advanced and successful example among them. In addition to long-lived harmonic oscillator modes found in superconducting resonators and cavities, nonlinearity brought by Josephson junctions plays a crucial role in quantum state control and measurement in superconducting quantum circuits.

Now it is natural to apply the excellent quantum tools to other quantum systems. We are particularly interested in controlling other collective excitations in solids. It will expand the territory of our quantum empire and give rise to quantum interfaces and transducers between various physical systems with different energy scales, which could be useful for quantum communication and sensing.

In this talk, I will review our recent activities on quantum magnonics using a millimeter-scale ferromagnetic sphere as an example of such hybrid quantum systems. The collective spin excitations in the sphere, in particular the uniform spin precession, are strongly coupled with a microwave cavity mode [1] and then indirectly with a superconducting qubit [2]. The magnon-induced vacuum Rabi splitting observed in the system indicates that we can readily apply the well-established schemes of cavity (circuit) QED to magnons and manipulate and measure their quantum states. I will also discuss interaction between the collective spin excitations and infrared light and present experimental results on optomagnonics [3, 4].

References:

[1] Y. Tabuchi *et al.*, Phys. Rev. Lett. **113**, 083603 (2014).

[2] Y. Tabuchi *et al.*, Science **349**, 405 (2015); arXiv:1508.05290.

[3] R. Hisatomi *et al.*, arXiv:1601.03908; to appear in Phys. Rev. B.

[4] A. Osada *et al.*, arXiv:1510.01837; to appear in Phys. Rev. Lett.

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Classical Stückelberg interferometry with a nanomechanical two-mode system

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Classical nanomechanical resonators can exhibit millisecond coherence times, and are thus interesting model systems to explore coherent phenomena. Here, I will focus on the in- and out-of-plane fundamental flexural vibration mode of a pre-stressed silicon nitride string resonator. Both modes feature high room temperature quality factors of several 100,000 in the 10 MHz eigenfrequency range. Furthermore, the modes are strongly coupled and can be coherently controlled by means of an inhomogeneous field applied between two adjacent gold electrodes enabling dielectric transduction [1].

We have investigated the dynamics of these strongly coupled nanomechanical modes, which can be described as a classical two-mode system exhibiting a pronounced avoided crossing. A single passage through the avoided crossing gives rise to classical Landau-Zener dynamics. Thus, the normal modes can be initialized via adiabatic transitions, enabling to analyze the coherence of the system via Rabi-, Ramsey- and Hahn-echo-type experiments. Going beyond a single passage through the avoided crossing, self-interference effects become apparent. For example, a double passage through the avoided crossing will lead to destructive or constructive interference depending on the amplitude and speed of the applied tuning ramp. This effect has been described in a quantum mechanical context by Stückelberg in the 1930s [2], and is well-known in quantum mechanical two-level systems. We demonstrate classical Stückelberg interferometry, and show that the observed interference pattern is described by an exact theoretical solution of the classical Stückelberg problem which coincides with the quantum mechanical case [3].

References:

[1] T. Faust et al., Nature Physics 9, 485 (2013)

[2] E. C. G. Stückelberg, Helvetica Physica Acta 5, 369 (1932)

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On resonance quantum switch by longitudinal control field

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In quantum optics and atomic physics, the longitudinal coupling and control between electromagnetic fields and atoms are normally ignored. In artificial systems, e.g., superconducting quantum devices, all directional couplings can be engineered in principle. However until now only transverse coupling field is well studied, since the longitudinal coupling field is usually thought useless, in particular, for building large scale quantum computers or simulators, in which switchable or tunable coherent coupling among qubits or data buses is most important problem for realizing universal gate. In this talk we will show dynamical switching on or fully off by a longitudinal control field for the resonant coupling between the qubit and the quantized single-mode microwave field, while the qubit always keeps working at the coherence optimal point. This approach suggests a new way to control coupling among qubits and data buses by longitudinal control fields, and can be scaled up to large scale quantum chips without any auxiliary circuit and free of the frequency crowding problem.

Multi-photon sideband transitions in an ultrastrongly-coupled circuit QED system

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Ultrastrong coupling in circuit quantum electrodynamics systems not only provides a platform to study the quantum Rabi model, but it can also facilitate the implementation of quantum logic operations via high-lying resonator states. Here we report the experimental observation of multi-photon sideband transitions of a superconducting flux qubit coupled to a coplanar waveguide resonator in the ultrastrong-coupling regime. With a coupling strength reaching about 10% of the fundamental frequency of the resonator, we obtain clear signatures of higher-order red-sideband transitions and the first-order blue-sideband transition in a transmission spectroscopic measurement. This study advances the understanding of driven ultrastrongly-coupled systems and paves the way to further studies of high-order processes with quantum Rabi model.

Solving linear systems of equations in a four-qubit superconducting circuit

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In this talk, I will review our recent activities with our collaborators on designing and fabricating various superconducting circuits for scalable quantum information processing. In particular, I will introduce a circuit QED processor which integrates four individually-accessible Xmon qubits that are arranged in a chain. Neighboring qubit couplings can be flexibly turned on and off by tuning the qubits' resonance frequencies. With this processor we demonstrate a simplest instance, i.e., solving 2 by 2 linear equations, of a quantum algorithm that could solve linear systems in a time scale of order log(N), where N is the number of variables. The experimental sequence is one-microsecond long, which consists of 9 single-qubit gates and 9 two-qubit entangling gates in total. For eighteen input vectors, execution of the sequence in our four-qubit circuit yields solutions for the linear equations with reasonably high fidelities ranging from 0.84 to 0.92.