CSRC

# The 4th International Workshopon

# Frontiers in Quantum Optics and Quantum Information:

# *Optomechanics meets circuit QED*

## 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

## Poster Session

June 17  10:30~11:30

Lobby of CSRC Building

*Required Poster Size: 120cm Height * 90cm Width*

*Poster Put-up: Thursday Afternoon (June 16), Friday Morning (June 17)*

# Abstract of Posters

## Transfer of a quantum state through a thermal channel

Zeliang Xiang[1], Liang Jiang[2], and Peter Rabl[1]

[1]*Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria*
[2]*Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520, USA*

We propose a new scheme to achieve perfect state transfer between two qubits through a thermal channel. We show that by mapping the qubit state onto a harmonic oscillator with time-dependent coupling to a thermally occupied waveguide, the quantum state can still be transmitted with perfect fidelity, even though the number of thermal photons is much larger than one. We discuss applications of this scheme for transmitting the state of superconducting qubits between two separated dilution refrigerators over a 4 Kelvin transmission line. By using the error-correcting code, the unexpected error could be effectually prevented. These findings would enable reliable state transfer or sharing entanglement among spatially distant superconducting qubits, even then a large fault-tolerant hybrid quantum network.

## Optomechanical cooling in non-Markovian regime

Wenzhao Zhang, Jiong Cheng, and Ling Zhou

*School of Physics and Optoelectronic Technology,Dalian University of Technology, Dalian 116024, P. R. China*

Recently, it is widely recognized that optomechanical devices can be used as gravity wave detection, the quantum-to-classical transition, high precision measurements and quantum information processing. Cooling the mechanical oscillator to its quantum ground state is the prerequisite for realizing some quantum processing. We propose a scheme to realize the cooling of mechanical resonator by exposing the optomechanical system in non-Markovian environment. Because of the backflow from the engineering environment, the mean number of the mechanical oscillator is capable of breaking the conventional cooling limit of Markovian environment. Employing the spectrum density in recent experiment [Nature Communications **6**, 7606 (2015)], we show that the cooling process is highly effective by engineering non-Markovian environment. The mechanism of cooling under non-Markovian environment is analyzed in the condition of optomechanical single-photon weak coupling. We provide an analytical approach fully taking into account the non-Markovian memory effects. It is shown that the non-Markovian memory effect do benefit the cooling process, even the non-Markovian environment is in high temperature region. Our study provides a new method for the ground state cooling of mechanical oscillator.

**References:**

[1] J. Cheng, W.-Z. Zhang, L. Zhou, and W. Zhang, Sci. Rep. **6**, 23678 (2016).

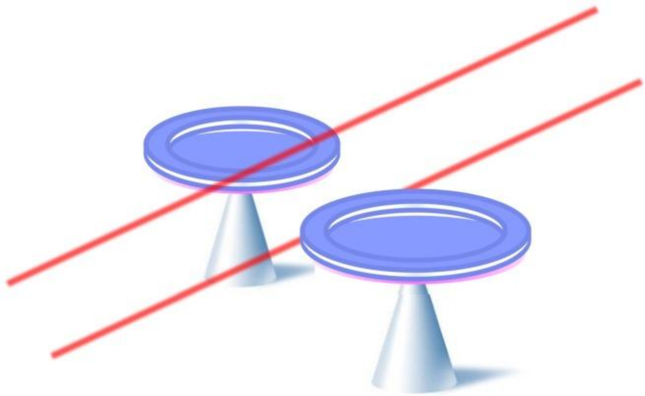
[2] W. Zhang, J. Cheng, W. Li, and L. Zhou, arXiv: 1605.00753 (2016) has been revised.

## Single Photon Router based on Polariton Blockade of two mode optomechanics

Li Xun and Ling Zhou

*School of Physics and Optomelectronic Technology, Dalian University of Technology, Dalian 116024, P.R. China*

We demonstrate the polariton blockade in two coupled optomechanical system shown in Fig.1, which is generated from nonlinear interaction of radiation pressure. By solving Schrodinger equation with effective Hamiltonian, we show that the polariton blockade can be observed. Through coupling the two optomechanical system with two waveguides, a router with four ports is formed. Our investigations show that the four ports router can be used to control the single photon transport by adjusting the phase difference of input photon.



## Measuring work and heat statistics in Superconducting Quantum Circuits

Quentin Ficheux[1,2], Sébastien Jezouin[1,2], Philippe Campagne-Ibarcq[1,2], Nathanaël Cottet[1,2],

Pierre Six[2], Alain Sarlette[2], Pierre Rouchon[2], and Benjamin Huard[1,2]

*[1]Laboratoire Pierre Aigrain, Ecole Normale Supérieure, Paris, France*
*[2]Quantic Team, INRIA, ENS, MINES PARITECH, UPMC, CNRS, Paris, France*

Owing to the large detection efficiency of microwave amplifiers and to the controllability of superconducti circuits, it is now possible to follow the state a a quantum system in a single realization of an experiment inste of average quantities only. After measuring a large number of these quantum trajectories, one has access to t distribution of various thermodynamics quantities such as heat, work and entropy.

In our experiment, we perform weak and continuous measurement of superconducting qubits and access mo than 30% of the total information leaking from the system. In the experiment, we measure both the fluorescen emitted by the qubit and the population of the excited state of the qubit in time. We will highlight the impact the detector type on the distribution of heat and work as a function of time. By tuning the strength of t population measurement we should observe a continuous transition between two kinds of heat and wo distributions.

## Ground-state phase diagram of a spin-orbit-coupled bosonic superfluid in an optical lattice

Zhaoxin Liang

*Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Wenhua Road, 72, Shenyang, China*

In recent experiments, spin-orbit-coupled (SOC) bosonic gases in an optical lattice have been successfully prepared into any Bloch which promises a viable contender in the competitive field of simulating gauge-related phenomena. However, the ground-state phase diagram of such systems in the superfluid regime is still lacking. Here we present a detailed study of the phase diagram in an optically trapped Bose gas with equal-weight Rashba and Dresselhaus SO coupling. We identify four different quantum phases, which include three normal phases and a mixed phase, by considering the wave vector $k1$, the longitudinal $\langle\sigma z\rangle$, and the transverse $\langle\sigma x\rangle$ spin polarizations as three order parameters. The ground state of normal phases is a Bloch wave with a single wave vector $k1$, which can position in arbitrary regions in the Brillouin zone. By contrast, the ground state of the mixed phase is a superposition of two Bloch waves with opposite $k1$, which, remarkably, may lack periodicity even though the system's Hamiltonian is periodic. This mixed phase in the lattice setting can be seen as the counterpart of the stripe phase associated with the uniform SOC gas. Furthermore, due to the lattice-renormalized SOC, the phase diagram of the model system becomes significantly different from the uniform case when the lattice strength grows. Finally, a scheme for experimentally probing the mixed phase using Bragg spectroscopy is proposed.

**Reference:**

Z. Chen and Z. Liang, Phys. Rev. A **93**, 013601 (2016)

# Efficient Scheme for Perfect Collective Einstein-Podolsky-Rosen Steering

Meng Wang[1,2], Qihuang Gong[1,2], Zbigniew Ficek[3], and Qiongyi He[1,2]

*1 State Key Laboratory of Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, P. R. China.*
*2 Collaborative Innovation Center of Quantum Matter, Beijing 100871, P. R. China.*
*3 The National Center for Applied Physics, KACST, P.O. Box 6086, Riyadh 11442, Saudi Arabia.*

A practical scheme for the demonstration of perfect one-sided device-independent quantum secret sharing is proposed[1,2]. The scheme involves a three-mode optomechanical system in which a pair of independent cavity modes is driven by short laser pulses and interact with a movable mirror. We demonstrate that by tuning the laser frequency to the blue (anti-Stokes) sideband of the average frequency of the cavity modes, the modes become mutually coherent and then may collectively steer[3,4] the mirror mode to a perfect Einstein-Podolsky-Rosen state. The scheme is shown to be experimentally feasible, it is robust against the frequency difference between the modes, mechanical thermal noise and damping, and coupling strengths of the cavity modes to the mirror.

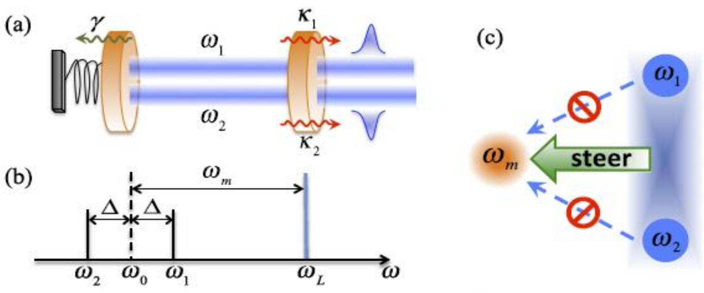



Figure 1. Schematic diagram of a three-mode optomechanical system for realization of perfect EPR collective steering. (a) The system consists of two nondegenerate cavity modes of frequencies $\omega_1$ and $\omega_2$, separated by $2\Delta = \omega_1 - \omega_2$, and a single mode of frequency $\omega_m$ associated with the oscillating mirror. The cavity modes are driven by a pulse laser with duration time $\tau$ and are damped with rates $\kappa_1$ and $\kappa_2$, respectively. The damping rate of the vibrating mirror is $\gamma$. (b) The laser frequency $\omega_L = \omega_0 + \Delta$ is tuned to the blue (anti-Stokes) sideband of the average frequency $\omega_0$ of the cavity modes. (c) Two cavity modes can collectively steer the quantum state of the oscillator (indicated by green arrow), while the cavity modes cannot steer the mirror individually (indicated by red stop sign).

**References:**

1. C. Branciard, E. G. Cavalcanti, S. P. Walborn, V. Scarani, and H. M. Wiseman, Phys. Rev. A **85**, 010301(R) (2012).

2. S. Armstrong et.al, Nat. Phys. **11**,167–172 (2015).

3. Q. Y. He and M. D. Reid, Phys. Rev. Lett. **111**, 250403 (2013).

4. M. Wang, Q. H. Gong, and Q.Y. He, Opt. Lett. **39**, 6703 (2014).

## Electron spin control and torsional optomechanics of an optically levitated nanodiamond in vacuum

Thai M. Hoang[1], Jonghoon Ahn[2], Jaehoon Bang[2], and Tongcang Li[1, 2, 3, 4]

[1]*Department of Physics and Astronomy, Purdue University, USA*
[2]*School of Electrical and Computer Engineering, Purdue University, USA*
[3]*Birck Nanotechnology Center, Purdue University, USA*
[4]*Purdue Quantum Center, Purdue University, USA*

Electron spins of diamond nitrogen-vacancy (NV) centers are important quantum resources for nanoscale sensing and quantum information. Combining such NV spin systems with levitated optomechanical resonators will provide a hybrid quantum system for many novel applications. Here we optically levitate a nanodiamond and demonstrate electron spin control of its built-in NV centers in low vacuum. We observe that the strength of electron spin resonance (ESR) is enhanced when the air pressure is reduced. We also observe that oxygen and helium gases have different effects on both the photoluminescence and the ESR contrast of nanodiamond NV centers, indicating potential applications of NV centers in oxygen gas sensing. For spin-optomechanics, it is important to control the orientation of the nanodiamond and NV centers in a magnetic field. Recently, we have observed the angular trapping and torsional vibration of a levitated nanodiamond, which paves the way towards levitated torsional optomechanics in the quantum regime.

## Gain competition induced mode evolution and resonance control in erbium-doped whispering-gallery microresonators

Xiaofei Liu[1], Fuchuan Lei[1], Xu Yang[1], Chuan Wang[2], and Guilu Long[1]

*[1]State Key Laboratory of Low-dimensional Quantum Physics and Department of Physics, Tsinghua University, Beijing 100084, P.R. China*

*[2]State Key Laboratory of Information Photonics and Optical Communications and School of Science, Beijing University of Posts and Telecommunications, Beijing 100876, P. R. China*

Precise control of resonance features in microcavities is of significant importance both for fundamental researches and practical applications. Exploiting the doping rare earth ions or Raman gain, the control of resonance features in microcavities can be achieved through changing the power of a pump laser. Here, we experimentally realized resonance modulation of a probe signal by introducing a control signal which is also in the emission band of erbium while the pump is kept unchanged. When we tune the control signal, the transition of Lorentz peak, Fano-like resonance and Lorentz dip can be observed from the transmission spectra of the probe signal. From the measured results, we reconstructed the theory based on coupled-mode theory and laser rate equations by setting the optical gains as time-dependent. Further analyses reveal that gain competition plays an important role during this process. We provide a new and effective method to control resonance features without modifying the pump, which can be used in the precise control of transmission spectra and the coupling condition between the waveguide and microcavities. Also, the experiment opens up new opportunities to control the dynamic property of optical gains in erbium-doped microcavities which may have significant applications in the implementation of non-reciprocal optical devices.

## POSTER-9

### Optomechanical Self-Oscillations in Anharmonic Potentials

Niels Lörch, Manuel Grimm, and Christoph Bruder

*University of Basel Switzerland*

We study self-oscillations of an optomechanical system, where coherent mechanical oscillations are induced by a driven optical cavity. For the case where the mechanical oscillator has a nonlinear potential, a semiclassical analytical model is developed for characterization of the limit cycle. The model is valid for large mechanical amplitudes corresponding to a weak nonlinearity. Based on this model we predict conditions to achieve subpoissonian phonon statistics in steady state, indicating classically forbidden behavior. We compare with numerical simulations and find very good agreement.

## Generating giant and tunable nonlinearity in a macroscopic mechanical resonator from a single chemical bond

Pu Huang[1,2,*], Jingwei Zhou[1,2,*], Liang Zhang[1,2,*], Dong Hou[1,2], Shaochun Lin[1,2], Wen Deng[1,4], Chao Meng[1,2], Changkui Duan[1,2], Chenyong Ju[1,2], Xiao Zheng[1,2], Fei Xue[4], and Jiangfeng Du[1,2]

[1]*Hefei National Laboratory for Physics Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, P. R. China*
[2]*Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, P. R. China*
[3]*High Magnetic Field Laboratory, Chinese Academy of Science, Hefei 230026, P. R. China*

Nonlinearity in macroscopic mechanical systems may lead to abundant phenomena for fundamental studies and potential applications. However, it is difficult to generate nonlinearity due to the fact that macroscopic mechanical systems follow Hooke's law and respond linearly to external force, unless strong drive is used. By using the anharmonicity in chemical bonding interactions, we have proposed and experimentally realized high cubic nonlinear response in a macroscopic mechanical system. We demonstrate the high tunability of nonlinear response by precisely controlling the chemical bonding interaction, and realize, at the single-bond limit. This enables us to observe the resonator's vibrational bi-states transitions driven by the weak Brownian thermal noise. This method can be flexibly applied to a variety of mechanical systems to improve nonlinear responses, and can be used to explore macroscopic quantum mechanics with improvements.

## Non-reciprocal Radio Frequency Transduction in a Parametric Mechanical Artificial Lattice

Pu Huang[1, 2, †], Liang Zhang[1, 2, †], Jingwei Zhou[1], and Tian Tian[1],

Peiran Yin[1], Changkui Duan[1, 2], and Jiangfeng Du[1, 2, *]

[1]*Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, P. R. China.*
[2]*Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, P. R. China.*

Generating non-reciprocal radio frequency transduction plays important roles in a wide range of researches and applications, and an aspiration is to integrate this functionality into micro-circuit without introducing magnetic field, which, however, remains challenging. By designing a 1D artificial lattice structure with neighbor-interaction engineered parametrically, we predicted a non-reciprocity transduction with giant unidirectionality. We then experimentally demonstrated the phenomenon on a nano-electromechanical chip fabricated by conventional complementary metal-silicon processing. A unidirectionality with isolation as high as 24 dB is achieved and several different transduction schemes are realized by programming the control voltages topology. Apart from being used as a radio frequency isolator, the system provides a way to build practical on-chip programmable device for broad researches and applications in radio frequency domain.

## Dark-like states for multi-photon and multi-qubit Rabi systems

Jie Peng

*School of Physics and Optoelectronics, Xiangtan University, Xiangtan, Hunan, P. R. China*

There are famous "dark state" in the even-qubit Dicke systems, formed by the product of the two-qubit singlet, where the qubit are decoupled from the photon field. These "dark state" can preserve entanglement even under dissipation, driving and dipole–dipole interactions, pointing to their use for storing quantum correlations. One characteristic for these "dark state" is that it corresponds to a horizontal line in the energy spectra, that is, the energy is independent of the qubit-photon coupling strength.

Recently, we have found a novel kind of dark-like states for multi-photon and multi-qubit Rabi systems, whose eigenenergy is also constant in the whole coupling regime, but unlike "dark state", these eigenstates are coupling dependent, and the qubits and photon are not decoupled. These dark-like states has similar property as "dark state", and very special structure with photon number bounded from above even in the Rabi systems, so they may have interesting application in quantum information. For example, for the two-qubit Rabi system, one dark-like state reads

$$|\psi\rangle = \frac{2(\Delta_1 - \Delta_2)}{g_1 + g_2}|0,\uparrow,\uparrow\rangle - |1,\uparrow,\downarrow\rangle + |1,\downarrow,\uparrow\rangle,$$

where $2\Delta_1, 2\Delta_2$ are the energy splitting of the two qubit respectively. $g_1$ and $g_2$ are the coupling strength for the two qubit respectively. Meanwhile, the existing condition is just $\Delta_1 + \Delta_2 = \hbar\omega$ and $g_1 = g_2$, where $\hbar\omega$ is the single photon energy, so this state may be easily realized in experiment[1].

**Reference:**

Jie Peng, Zhongzhou Ren, Daniel Braak, Guangjie Guo, Guoxing Ju, Xiaoyong Guo and Xin Zhang, "Solution of the two-qubit quantum Rabi model and its exceptional eigenstates", J. Phys. A: Math. Theor. **47**, 265303 (2014) Chosen as **IOPselect** .

## POSTER-13

### Subluminal and Superluminal Pulse in the slab system doped with Graphene *

Lin Wang, Jisen Wen, and Ligang Wang

*Department of Physics, Zhejiang University, Hangzhou 310027, P. R. China*

The characteristics of light propagation have been investigated in the slab system doped with graphene. Two different physical mechanisms are presented to realize the efficient switch of reflected light pulse from subluminal to superluminal. It is shown that the group delays of reflected light pulse are sensitive to the thickness of gap and incident frequency. The optimal thickness and incident frequency are found. Near the optimal point, the group delays of the reflection show the opposite behaviors. Furthermore, the transition between subluminal pulse and superluminal pulse can also be controlled via the chemical potential.

* This research is supported by NSFC grants (Grants No. 11274275 and No. 61078021) and by grants of the National Basic Research Program of China (Grants No. 2012CB921602).