The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

smr2164

Workshop on Nano-Opto-Electro-Mechanical Systems Approaching the Quantum Regime (6 - 10 September 2010)

(Miramare, Trieste - Italy)

ORGANIZERS:

Jack HARRIS	Yale, New Haven, U.S.A.
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LOCAL ORGANIZER:

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LIST OF POSTER PRESENTATION ABSTRACTS

web-page: http://agenda.ictp.trieste.it/smr.php?2164

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Organizers:
J. Harris, K. Lehnert, R. Lifshitz, J. von Delft and E. Weig

Local Organizer:
M. Kiselev

Venue:
Adriatico Guest House - Kastler Lecture Hall (lower level 1)

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(updated as of 6.9.10)

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Stefan WALTER
Non-equilibrium transport properties of a tunnel junction coupled to an harmonic oscillator in the non-markovian regime

Huaizhi WU
Dynamical multistability in a multimode optomechanical system

Interacting cavities: Single photon opto-mechanics and a set of two coupled opto-mechanical systems

Uzma Akram[1], G.J. Milburn[1],

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An example of an opto-mechanical system constitutes a cavity with a movable mirror. The cavity provides a radiation pressure force on the moving mirror subject to a linear restoring force, forming a mechanical resonator[1].
Firstly we study a coherently driven opto-mechanical system cascaded to a cavity modeled as a single photon source. We show that the probability for the additional photon to be emitted by the opto-mechanical cavity will exhibit oscillations under a Lorentzian envelope, when the driven interaction with the mechanical resonator is strong enough.
Next, we study two separate coherently driven opto-mechanical cavities coupled to each other. In this setting, we consider photons exchanged both reversibly and irreversibly between the two cavities. Each opto-mechanical cavity is described in terms of a linearised interaction in the cavity field operators by expanding around the coherent steady state field in the cavity[2]. Here we find for particular parameters, photon-phonon entanglement exists in the setup.

[1]T. J. Kippenberg and K. J. Vahala, Optics Express, **15**, 17172 (2007).
[2]S. Gröblacher, K. Hammerer, M. R Vanner, M. Aspelmeyer, Nature, **460** 724 (2009).

Title of the poster : Detection of mechanical resonances of doubly-clamped carbon nanotubes by FM techniques
Author : T. Barois *et al.*

Due to their extremely small dimensions, single wall carbon nanotubes require experimental technique to detect their mechanical. An exemple of such a detection technique is given by Sazonova *et al.* with the so called mixing technique.

We use bottum-up devices with single wall carbon nanotubes (SWNTs) in a field effect transistor configuration (SWNTs with double clamping). Our work consists of a detection method based on the use of an excitation signal with frequency modulation (FM). With FM excitation signal applied to the nanotube, one needs to bring a carrier frequency that is close to the natural mechanical resonant frequency of the nanotube. When the carrier frequency matches the resonant frequency, the nanotube returns a maximal current consistent with the modulation excitation signal. This current is rather small (tens/hundreds of pA) and can be measured using a Lock-In Amplifier.

One of the major interests of the FM excitation is the possibility to measure a current arising from the mechanical resonances only. With such a selective current signal, one can scan and fit the resonances of nanotubes. Our measurments have shown a very good agreement with a model using resonant frequencies and quality factors as free parameters of those resonantors.

Cooling and Control of a Cavity Optoelectromechanical System

Terry G. McRae[1], Kwan H. Lee[1], Glen I. Harris[1], Joachim Knittel[1], and Warwick P. Bowen[1]
[1] *University of Queensland, Australia*

Quantum mechanics is a profoundly successful theory; enabling both the description of microscopic phenomena with exquisite precision, and important new physical technologies. However, the observation and manipulation of quantum properties of macroscopic systems is notoriously difficult. Recently, due to the development of new nanofabrication techniques and a series of groundbreaking experiments it has become apparent that this regime may be realisable in cavity optomechanical systems where a complex dynamical interaction is achieved between optical and mechanical degrees of freedom via radiation pressure.

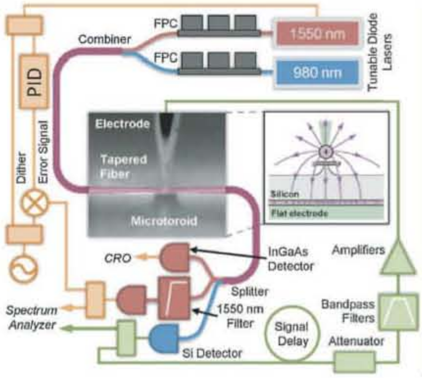

Figure 1: Experimental schematic.

The central enabling goal of this new field is to cool a macroscopic mechanical degree-of-freedom to its quantum ground state [1]. We report experiments towards this goal using a new integrated cavity opto-electromechanical system (COEMS) developed in our laboratory[1]. Feedback cooling is implemented in the experiment shown in Fig. 1. In this experiment we have achieved active cooling of an integrated cavity opto-mechanical system for the first time, with final temperature limited to 60 K by optical shotnoise. The effect of the feedback on the mechanical spectra of the device is shown in Fig. 2 (a) and (b), with the final temperature as a function of gain shown in Fig. 2 (c).

The use of whispering gallery optical resonances allows convenient motion transduction with multiple independent probe fields at different wavelengths. This enables the first independent temperature verification, and a direct comparison between temperature inferences made via in-loop and out-of-loop transduced signals. Stark differences are observed, with serious over-estimation of cooling possible in the standard in-loop inference (see Fig. 2 (c)). These results dramatically demonstrate the requirement of independent temperature verification in feedback cooling, as first demonstrated here. This is essential, not only in the regime of high feedback gain, but alsom in the critical quantum paradigm where measurement backaction itself perturbs and correlates the mechanical oscillator and transducer.

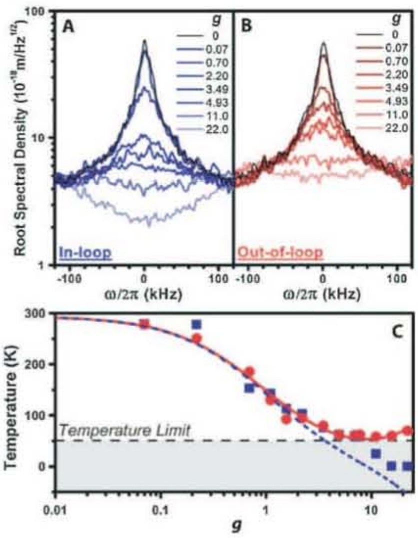

Figure 2: Feedback cooling results with varying feedback gain. (a) and (b): In- and out-of-loop transduction spectra. (c): In- (squares) and out-of-loop (circles) temperature inferences. The solid red curve and dashed blue curve, respectively, denote the theoretical predictions of actual mechanical oscillator temperature and inferred in-loop temperature.

Our results represent important progress in the control of mechanical systems at the quantum level; as well as an enabling step towards the new regime of quantum nonlinear mechanics, where strong mechanical driving of a ground-state cooled mechanical oscillator allows exploration of nonlinear quantum dynamics.

References

[1] K. H. Lee, T. G. McRae, G. I. Harris, J. Knittel, and W. P. Bowen, Phys. Rev. Lett. **104** 123604 (2010).

Key title word : optical driving, parametric amplification, coupled nanomechanical resonator, laser, amplitude modulation,

Title : Observation of nonlinear characteristics of mechanically coupled SiN nanomechanical resonator with optical actuation

Author : Sungwan Cho, Sung Un Cho, Dong-Hyun Jang, Yun Daniel Park

Abstract : Here we present all optical methods for nanomechanical resonator using optical driving and detection technique. And we also present implementation of optical and electrical driving to coupled nanomechanical beam resonator to investigate nonlinear characteristics of mechanically coupled resonator. Optical actuation technique uses laser amplitude modulation to drive micromechanical and nanomechanical structures. Coupled beam resonators are made by silicon nitride and mechanically connected but electrically disconnected. We verify the laser amplitude modulation method for optical driving by comparing optical driving and electrical driving method with optical detection technique for resonance frequency. Then we use optical and electrical driving method to drive coupled mechanical resonator simultaneously. With these results, we investigate the possibility of optical driving as a multi-driving source and nonlinear properties of coupled nanomechanical resonator like parametric amplification and synchronization.

Detecting phonon blockade with photons

arXiv:1007.4714

Nicolas Didier,[1] Stefano Pugnetti,[1] Yaroslav M. Blanter,[2] and Rosario Fazio[1]

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[2] *Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands*

By proper designing the coupling between a Cooper pair box and a nano-mechanical resonator, it is possible to reach a sufficient level on non-linearity as to make the experimental observation of phonon blockade possible. We show that phonon blockade can be observed by measuring the statistics of the light in a superconducting microwave resonator capacitively coupled to the mechanical mode. The underlying reason is the formation of an entangled state between the two resonators, ensuring a perfect match between the phonon dynamics and the photon statistics. Our scheme does also offer a way to prepare and detect entangled states between phonons and photons.

Nonlinear switching dynamics in a nanomechanical resonator

Thomas Faust, Quirin Unterreithmeier and Jörg P. Kotthaus
Fakultät für Physik and Center for NanoScience (CeNS), Ludwig-Maximilians-Universität München, Germany

Nanomechanical resonators fabricated out of high stress silicon nitride exhibit high mechanical quality factors, in the range of 10^5 at resonance frequencies in the order of 10 MHz. These resonators are ideal model systems to investigate the detailed mechanical properties of nanoscale objects, such as the nonlinear behaviour.

We report on a systematic study of the time-dependent response of a nanomechanical resonator driven well into the nonlinear regime [1]. Their bistable response allows their use as a simple mechanical memory element [2,3]. Using a constant actuation to drive the resonator into the nonlinear regime and applying short resonant RF pulses of variable phase and duration, we are able to reach arbitrary points in the phase space of the resonator and study the time-evolution of the relaxation process.

By mapping out the corresponding final state for different pulse parameters, we are able to demonstrate quantitative agreement with our perturbation calculation [Fig 1]. Our detailed understanding allows us to determine the parameters required to actively switch directly between the stable states. We experimentally demonstrate that switching thus becomes possible on time scales much shorter than the relaxation time of the resonator [Fig 2]. By implementing a completely electrical on-chip detection, integrated large-scale nanomechanical memory elements come into reach.

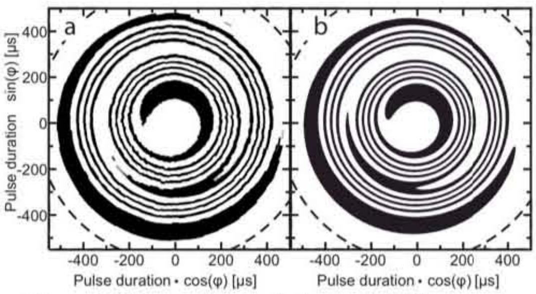

Figure 1: Measured (a) and simulated (b) final state after the application of pulses with varied phase and duration, starting from the low amplitude state and ending in the high (black) or low (white) amplitude state

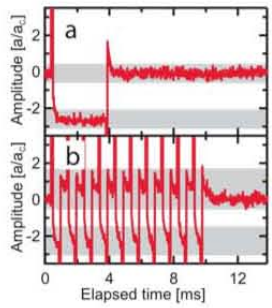

Figure 2: Time-resolved switching between the two stable states highlighted by the grey bars, a) showing no relaxation oscillations, b) demonstrating a repetition rate of 1 kHz

[1] Quirin P. Unterreithmeier, Thomas Faust and Jörg P. Kotthaus
"Nonlinear Switching Dynamics in a Nanomechanical Resonator", arXiv: 0909.3698v1 (2009)
[2] I. Kozinsky, H. W. Ch. Postma, O. Kogan, A. Husain and M. L. Roukes
"Basins of Attraction of a Nonlinear Nanomechanical Resonator", Phys. Rev. Lett. **99**, 207201 (2007)
[3] I. Mahboob and H. Yamaguchi
"Bit storage and bit flip operations in an electromechanical oscillator", Nat Nano **3**, 275 (2008)

Quantum-to-classical transition
in cavity quantum electrodynamics

J. M. Fink, L. Steffen, P. Studer, L. S. Bishop, M. Baur, R. Bianchetti, D. Bozyigit, C. Lang, S. Filipp, P. J. Leek and A. Wallraff

The quantum properties of electromagnetic, mechanical or other harmonic oscillators can be revealed by investigating their strong coherent coupling to a single quantum two level system in an approach known as cavity quantum electrodynamics (QED). At temperatures much lower than the characteristic energy level spacing the observation of vacuum Rabi oscillations or mode splittings with one or a few quanta asserts the quantum nature of the oscillator [1]. In a circuit realization of cavity QED we study how the classical response emerges from the quantum one when the system's thermal occupation is raised gradually over 5 orders of magnitude [2]. In this way we explore in detail the continuous quantum-to-classical cross-over in the spirit of Bohr's correspondence principle. We also demonstrate how to extract effective cavity field temperatures between 100 mK and 10 K from spectroscopic and time-resolved vacuum Rabi measurements. The emergence of classical physics from quantum mechanics and the role of decoherence in this process is an important subject of current research. In future experiments entanglement and decoherence at elevated temperatures can be studied in the context of quantum information.

[1] J.~M.~Fink et al.~\textit{Nature} \textbf{454}, 315 (2008). [
[2] J.~M.~Fink et al.~\textit{arXiv:1003.1161} (2010).

Progress towards observation of
radiation pressure shot noise

Nathan Flowers-Jacobs
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In cavity optomechanics, photon shot noise causes fluctuations in the radiation pressure force. This fundamental quantum effect has not yet been observed in macroscopic objects. We describe progress towards the observation of radiation pressure shot noise in an optomechanical system consisting of a high finesse (70,000) optical cavity dispersively coupled to a room temperature 50 nm thick silicon nitride membrane. The primary obstacle to direct observation is the T = 294 K thermal motion of our 1 MHz mechanical mode. We are also working towards coupling a smaller, higher-frequency silicon nitride membrane to a fiber-based cavity.

Title:
Casimir force in real MEMS/NEMS devices.

Abstract:
We propose a novel device platform to study the Casimir force in a realistic device setting, which will allow us to study the Casimir force in real MEMS/NEMS devices.

While there are several studies of the Casimir force, some limitations can be found in these experiments, which we summarize below:

(a) Device geometry limitation
Current Casimir studies largely rely on oversimplified “ideal” sample surfaces – either in the plate-plate or sphere-plate configurations.

(b) Material limitation
Silicon is the most important MEMS material and should be considered as a reference for MEMS Casimir platforms. However, to date, the Casimir force between silicon surfaces has not yet been quantified.

(c) Device scaling limitation
The lateral dimensions of most current Casimir devices remain large. The large device configuration offers a stronger signal. So far the Casimir force between two true nanoscale objects has not been measured.

To overcome these limits, we propose a macro-to-nano Casimir probe station, which utilizes the sphere-plate configuration and also our all-optical on-chip configuration.

Nanomechanical motion measured with an imprecision below the standard quantum limit using a nearly shot-noise limited microwave interferometer

J. W. Harlow, J. D. Teufel, T. Donner, M. A. Castellanos-Beltran, K. W. Lehnert

Observing quantum behavior of mechanical motion is challenging because it is difficult both to prepare pure quantum states of motion and to detect those states with sufficient precision. We present displacement measurements of a nanomechanical oscillator with an imprecision below that at the standard quantum limit [1]. We infer the motion from the phase modulation imprinted on a microwave signal by that motion. The modulation is enhanced by embedding the oscillator in a high-Q microwave cavity. We achieve the low imprecision by reading out the modulation with a Josephson Parametric Amplifier, realizing a microwave interferometer that operates near the shot-noise limit. The apparent motion of the mechanical oscillator due to the interferometer's noise is now substantially less than its zero-point motion, making future detection of quantum states feasible. In addition, the phase sensitivity of the demonstrated interferometer is 30 times higher than previous microwave interferometers, providing a critical piece of technology for many experiments investigating quantum information encoded in microwave fields.

[1] J. D. Teufel, T. Donner, M. A. Castellanos-Beltran, J. W. Harlow, K. W. Lehnert, *Nature Nanotechnology*, **4**, 820 - 823 (2009).

Synchronization in optomechanical arrays

Georg Heinrich, Jiang Qian, Max Ludwig, Björn Kubala and
Florian Marquardt

Abstract

The motion of nano- and optomechanical systems can be coupled to electromagnetic fields. Apart from their future perspective to control the quantum state of mechanical motion, these systems allow to study elaborate dynamics due to the interaction of light and mechanical motion. Recent developments have demonstrated multimode optomechanical systems comprising several coupled optical and vibrational modes, such as optomechanical crystals. The latter systems simultaneously confine optical and mechanical modes in periodically patterned structures and thus combine the concepts of photonic and phononic crystals. Here we investigate the collective dynamics in an array of coupled optomechanical cells, each consisting of a laser-driven optical and a mechanical mode. Beyond a certain threshold of the laser input power, each cell shows a Hopf bifurcation towards a regime of self-induced oscillations. We show that the phase of many such coupled optomechanical oscillators, even with different bare initial frequencies, can lock to each other, synchronizing the dynamics to a collective oscillation frequency. We present different regimes for the dynamics and describe the system in terms of an effective Kuramoto model. This allows to connect our optomechanical results to the general field of nonlinear science where synchronization constitutes an important, universal feature finding applications in fields ranging from physics over chemistry to biology.

Mechanical and Optical Properties of Single CdS Nanowire/Nanobelt of Nanomechanical Resonators

Y.D. Kim, M. R. Cho, S. W. Cho, K. Heo, S. Hong and Y. D. Park*
*Department of Physics & Astronomy, Seoul National University, Korea

We report on the mechanical and optical properties of single CdS nanowire and nanobelt. CdS nanowire and nanobelt are synthesized by vapor-liquid- solid (VLS) method and have single hexagonal crystal structure. CdS nanowire have a typical diameter of 100~150nm and length of 3~20μm. Elastic properties are characterized by dynamic flexure measurement using optical interferometer setup and quasi-static flexure measurement using AFM. For flexural measurement, CdS nanowire and nanobelt are fashioned into suspended doubly-clamped nano-mechancial resonators with varying length 3~20μm, and cantilever with varying length 3~30μm. From dynamic and quasi-static flexure measurement, we observe a mega Hertz mechanical resonance at doubly clamped CdS nanowire resonators and mechanical quality factor in 500~600. From resonant frequency to length of resonator relation, we can assume the Young's modulus and internal stress of single CdS nanowire and nanobelt. Furthermore, from large amplitude flexure measurement, we observe mechanical nonlinear response of CdS nanowire, which is hysteresis of resonant response with frequency sweep direction. We also investigate the optical properties of CdS using freely suspended CdS nanowire and nanobelt of nano-mechanical resonator. We observe photodetector, waveguide and laser effect from CdS nanowire. From these, we expect that CdS nanowire and nanobelt of nano-mechancial resonators have great potential for nano-opto-electro-mechanical systems approaching the quantum regime.

Optomechanical coupling of ultracold atoms and a membrane

Maria Korppi[1,2], S. Camerer[1,2], D. Hunger[1,2] A. Jöckel[1,2,3], M. Mader[1,2], T.W. Hänsch[1,2], and P. Treutlein[1,2,3]

[1]*Ludwig-Maximilians-Universität, München, Germany*
[2]*Max-Planck-Institut für Quantenoptik, Garching, Germany*
[3]*Universität Basel, Switzerland*

We report the recent results of our experiment, where we couple a single mode of a high-Q membrane-oscillator to the motion of laser-cooled atoms in an optical lattice. The optical lattice is formed by retroreflection of a laserbeam from the oscillator surface. Quantum fluctuations of the lattice laser light mediate coupling between the motion of the atoms and the membrane[1]. When the trap frequency of the atoms is matched to the eigenfrequency of the membrane, the coupling leads to resonant energy transfer between the two systems. We have observed such resonant energy transfer both from the membrane to the atoms and, more significantly, the back-action of the atoms on to the membrane.

In the long term, such coupling mechanism could be exploited in developing hybrid quantum systems between atoms and solid-state devices. As another intriguing perspective, a new generation of optical lattice experiment is in sight, where the mirrors creating the laser standing waves are micromechanical oscillators which interact with the atoms, and, which ultimately must be described quantum mechanically.

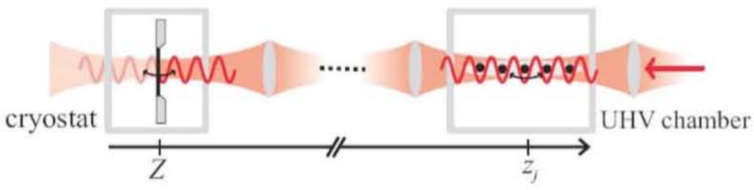

Figure : *Optical lattice mediates the coupling between ultracold atoms and a membrane placed in separate vacuum chambers.*

[1]Optical Lattices with Micromechanical Mirrors, K. Hammerer, K. Stannigel, C. Genes, P. Zoller, P. Treutlein, S. Camerer, D. Hunger, T.W. Haensch, *arXiv*:1002.4646

Quantum Detection using a Driven, Non-Linear Resonant Cavity

C. Laflamme and Professor A. Clerk
McGill University

August 20, 2010

Abstract

The nonlinear driven resonant cavity is a proposed system for making quantum measurement. This system is analysed looking at the possibility for increased measurement sensitivity as one approaches the point where cavity response is maximized (the point of bifurcation). Emphasis is given on the definition of the quantum limit, and the two types of noise which are present in the output: imprecision and back action noise. Each noise is calculated and it is found that the quantum limit is saturated, despite the fact that the gain will diverge as one approaches the point of bifurcation. This may have relevant consequences in the areas of measurement, amplification and cooling.

ENTANGLEMENT OF MECHANICAL OSCILLATORS COUPLED TO A NONEQUILIBRIUM ENVIRONMENT

MAX LUDWIG[1], K. HAMMERER[2], FLORIAN MARQUARDT[1]

Entanglement constitutes a cornerstone of quantum mechanics. Whether it persists and can be observed in systems comprising macroscopic bodies has been a hotly debated topic since the early days of quantum mechanics. The ground state of two interacting quantum systems will generically be entangled. Thus, one could naively expect that it is sufficient to simply cool two interacting, macroscopic bodies to their ground state, and thereby prepare an entangled state. However, when coupling to a dissipative bath – as is of course necessary for cooling – entanglement may be destroyed, as explored in a number of works. A slate of recent experiments has now brought a new aspect into focus: A nonequilibrium environment, consisting of either a driven optical cavity, a superconducting microwave resonator or a superconducting single electron transistor can be employed to cool the motion of mechanical resonators down to the ground state. The advances in this field may ultimately enable to test quantum mechanics in an entirely new regime and to observe entanglement of massive objects. Still it remains to resolve the issue of how the dissipative coupling to the nonequilibrium bath affects entanglement.

On this poster, we demonstrate a non-monotonic dependence of entanglement between two oscillators on the coupling strength to the nonequilibrium environment and show that there is an optimal value for the coupling to the bath. Below this value, entanglement is diminished by thermal fluctuations, and above this value, it is lost through dissipation. The striking behaviour found here is missed entirely by the commonly employed Lindblad approach to dissipative dynamics.

In order to describe it, we develop a general exact framework based on quantum Langevin equations, to analyze the entanglement between harmonic oscillators in the presence of coupling to a linear bath of arbitrary spectral density. For the case of an nonequlibrium bath we illustrate the generic behaviour in a concrete example of two mechanical resonators inside an optical cavity, being cooled by the optomechanical interaction with the light field circulating in the cavity. The theory presented here will be useful for optimizing entanglement in such systems as it predicts an optimal system-bath coupling rate. The general exact framework introduced here can be employed to discuss the entanglement of oscillators under the influence of arbitrary bath spectra, among them nonequilibrium and tailored non-standard spectral densities.

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2 Institute for Theoretical Physics, University of Innsbruck, and Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Technikerstrasse 25, 6020 Innsbruck, Austria

Prospects for quantum effects in carbon nanotube mechanical resonators

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We study a high quality mechanical resonator made from a suspended carbon nanotube driven into motion by applying a periodic RF potential using a nearby antenna. Single electron charge fluctuations create periodic modulations of the mechanical resonance frequency. A quality-factor exceeding 10^5 allows the detection of a shift in resonance frequency caused by the addition of a single electron charge on the nanotube. Additional evidence for the strong coupling of mechanical motion and electron tunneling are an energy transfer to the electrons causing mechanical damping and unusual non-linear behavior. Strikingly, we also discover that a dc current through the nanotube spontaneously drives the mechanical resonator, exerting a force that is coherent with the high-frequency resonant mechanicalmotion.

The resonance frequency of our carbon nanotube resonators is as high as 2.8 GHz (~133 mK) putting it well in the quantum regime. However, quantum signatures have not been found yet. One way of proving the quantum nature of carbon nanotube resonators would be through the observation of phonon shot noise; here quantized motion leads to quantized current which can be discerned by looking at the noise coming out of the nanotube. Another way is through the nonlinearity present. When the effective temperature is low enough it should be possible to observe tunneling from the one (low amplitude) state to the other (high amplitude) state.

A SQUID with a suspended part is a very sensitive tool to investigate mechanical motion. Combining this with the high resonance frequency, using a SQUID is a promising way to observe the zero-point motion of the nanotube. At the moment we are trying to combine the fabrication of ultraclean nanontubes with superconducting contacts.

Dynamics of phonon coupled NEMS

R. Hussein, A. Metelmann, P. Zedler, and T. Brandes
Institut für Theoretische Physik, TU Berlin, Hardenbergstr. 36, Berlin D-10623, Germany

We consider nanoelectromechanical systems that linearly couple to an oscillator mode. Our focus lies in the description of the mechanical subsystem. We derive a Langevin equation for the oscillator trajectory on the basis of the path integral formalism that we apply to the Anderson Holstein model and a modification with two quantum dots in series, for which we investigate the effective potential and the effective friction.

Resonance Modes in InAs/InGaAlAs/InP Quantum Dot Microdisk Resonators

J. R. Mialichi[a], L. A. M. Barea[a], P. L. de Souza[b], R. M. S. Kawabata[b], M. P. Pires[c] and N. C. Frateschi[a]

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[b] Telecommunication Research Center, PUC-Rio, 22451-041 Rio de Janeiro, RJ, Brazil
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Quantum dots (QDs) can provide an efficient mechanism for stimulated emission in active region of micro-resonator lasers. Active-microdisk resonators offer great advantage in obtaining stimulated emission in small volume [1] since they support whispering-gallery modes (WGMs), which are very confined resonances with maximum intensity near the disk edge [2]. Microdisks are shown to produce a high quality factor Q [3] which may consequently lead to low laser thresholds. High-quality self-assembled QD lasers based on InAs/GaAs and InAs/InP have been demonstrated. InAs QD's on InP substrates have been shown to emit in the wavelength range of 1200–2000 nm with high efficiency, but the best results reported on InAs/InP QD lasers are limited to either optical pumping or pulsed current injection operation at room temperature. Therefore, for efficient carrier injection in the dots, a double heterostructure requires the growth of the QD structures over quaternary material. The literature reports on InAs/InGaAsP QD layers that are tuned for 1550 nm emission by the insertion of ultrathin GaAs interlayers. In this work, we describe the growth of InAs QD inside InGaAlAs/InP double-heterostructures by metal-organic chemical vapor deposition (MOCVD) to fabricate microdisk resonators. We have developed an efficient fabrication technique using focused-ion beam (FIB) milling followed by wet-chemical etching. The microdisk resonators are electrically and optically characterized showing the presence of WGMs in the C-band region, suitable for telecommunication applications.

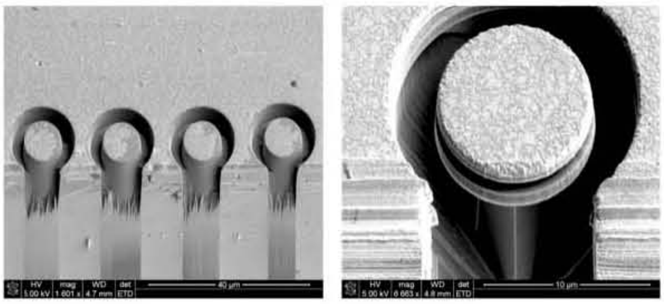

Figure 1. Microdisk-fabrication steps (a) focused-ion beam milling of disks using 1 nA at 30 KeV, for 7 minutes; (b) InP selective etching using $3HCl:1H_2O$ for 40 seconds.

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Determination of useful parameter space for a double-walled carbon nanotube based motor subjected to a sinusoidally varying electric field

S. Negi[1], M.Warrier[2] and S. Chaturvedi[2]

A molecular dynamics study has been performed for a double-walled carbon-nanotube (DWNT) based motor driven by an externally applied sinusoidally varying electric field, in the presence of a `frozen' sleeve. Brenner potential [1] is used along with Nordlund's long range interaction term [2]. Such kind of a motor is studied earlier in [3,4]. This motor consists of a DWNT where the inner carbon nanotube (CNT) behaves as a “shaft” and the outer one as a “sleeve”. The motor is stimulated by an externally applied sinusoidally varying electric field acting on two opposite charges placed on diametrically opposite atoms of the shaft. Our earlier work showed that, for a fixed frequency, it was impossible to produce full rotations of the shaft, regardless of the applied E-field amplitude due to deformation of the shaft [4]. In the present work we show that to produce unidirectional (motor-like) rotation, it is necessary to operate over a `useful' region in the parameter space defined by the amplitude and frequency of the applied electric field [5]. For a given frequency, electric field amplitudes below a threshold are not able to overcome the potential energy barriers due to interaction of the rotating shaft with the frozen sleeve. This is followed by a range of amplitudes where unidirectional motion is observed. At still higher amplitudes, distortion of the shaft increases the potential energy barriers to levels higher than those that can be overcome by the electric field. For a given amplitude, as the frequency is varied, more complex behavior is obtained, which can be broken up into four regions.

At low frequencies, large distortion of the shaft leads to an increase in potential energy barriers, hindering rotation. Over an intermediate range, unidirectional motor like behavior is observed. This is then followed by an anomalous region, where resonant excitation of a characteristic mode of the shaft leads to very large distortions, which greatly enhances the barrier. The distortion falls off with further rise in frequency. A detailed physical explanation has also been provided for the anomalous behavior in terms of resonant excitation of the characteristic modes of the shaft as in [6].

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Detuning dependence of the nonlinear resonance in coupled nanomechanical oscillators

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Nonlinear nanomechanical oscillators have attracted interest in recent years because the vibrational bistability enables the parametric amplification and stochastic resonance, which are useful for various nanomechanical applications, e.g., sensors, memories, and logics[1,2]. Coupled nonlinear oscillators are also getting an increasing attention because of their interesting physical phenomena, e.g., synchronization and chaos[3,4]. We have recently realized frequency-tunable coupled nanomechanical oscillators, which become a powerful tool for studying detailed nonlinear dynamics in coupled systems[5]. Here, we study the detuning dependence of the nonlinear resonance in coupled nanomechanical oscillators. The sample structure and the measurement setup are shown in Figs. 1(a) and 1(b), respectively. The vibrational coupling between the two elastically coupled beams can be controlled by the frequency detuning via the piezoelectric effect of AlGaAs through the top gate electrodes. Figure 1(c) shows the gate voltage (V_{T2}) dependence of the nonlinear resonance of Beam 1 measured by actuating Beam 1 with the AC gate modulation (V_{A1} = 90 mV_{rms}) while monitoring the piezoelectrically induced voltage (V_{D1}). The frequency detuning from the perfectly-tuned condition (V_{T2} = -2.15 V) leads to the abrupt change in the amplitude of the lower frequency mode, which corresponds to the symmetric vibration of the two beams. This sudden amplitude change will be able to be used for high-sensitivity detection of mass, force, charge, etc.

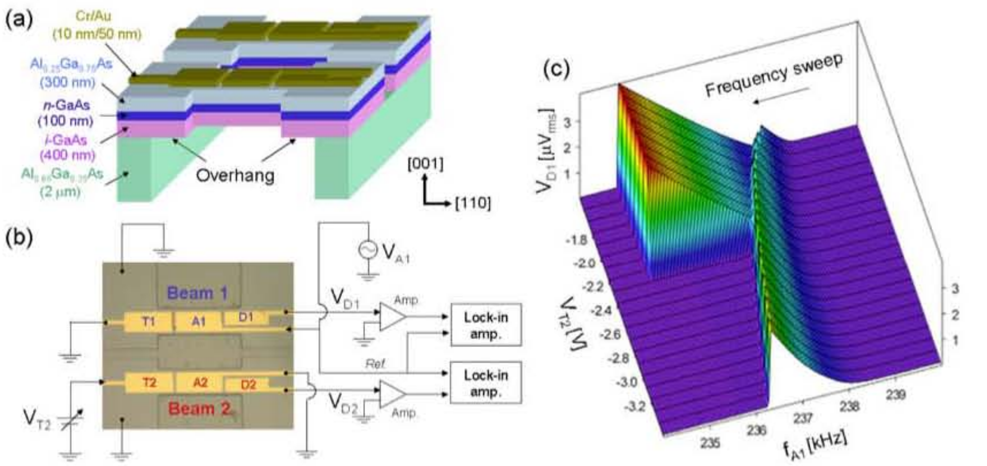

Fig.1 (a) Schematic of the two nanomechanical oscillators, which are elastically coupled via the coupling overhang. (b) Microscope image of the coupled oscillators and the measurement setup. (c) Gate voltage (V_{T2}) dependence of the nonlinear resonance of Beam 1 measured by actuating Beam 1 with the AC gate modulation (V_{A1} = 90 mV_{rms}) while the frequency was down-swept.

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Title: **Advanced MEMS Resonators for High Sensitivity Molecular Detection**

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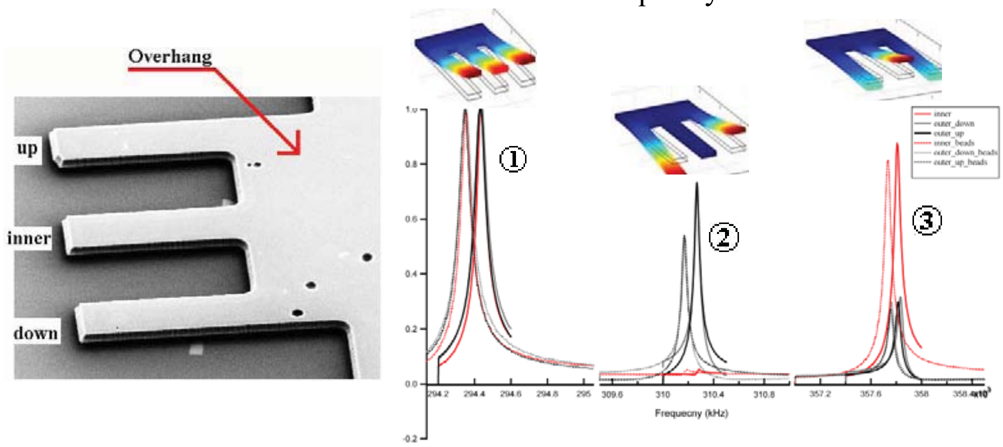
Abstract

Micro- and nanomechanical resonators can detect masses with the conventional frequency shift method. The sensitivity can be made arbitrarily large by reducing the size of the mass sensors of a proper factor but at the cost of an equivalent increase of the difficulties in the microfabrication process.
Our proposal is an alternative way to detect masses without minimizing the microcantilevers further or applying expensive equipments such as ultra high vacuum. The idea is to couple three microcantilevers at their base with the creation of a common suspended structure named 'overhang' as shown in fig. 1 (a). In this configuration, we detect the localization of the vibration modes rather than the frequency shift.



(a) (b)

Figure 1: (a) SEM-image of the triple-coupled cantilever system. (b) The different modes are represented. The red color is for the inner cantilever, grey color is for up cantilever, and the black color is for down cantilever. The shifting of the resonance frequency is due to adding few microspheres with diameter around 5µm.

Applying the finite element analysis on a triple-coupled microcantilever system, we showed that the modes become more localized after adding an extra mass. In this way, the particle can be detected while the microcantilevers are in one of the three modes.
The best performances and advantages of using a triple-coupled microcantilever system are obtained when the microcantilevers are in the 2nd mode (or anti-symmetric mode), which is shown in fig. 1 (b). Here, the inner cantilever oscillates about factor 100 less than the outer cantilevers (up or down). Simulations show that the inner cantilever is not moving in the 2nd mode, see fig. 1 (b) the image above the second curves. In principle, any kinds of disorder or additional mass can break the symmetry of the triple-coupled microcantilevers, which triggers the onset of nonzero vibration amplitude of the middle cantilever. Therefore, one of crucial step is the microfabrication process in order to fabricate perfect symmetrical structures.

The resonance frequency modes can be generated in vacuum condition by a piezoelectric actuator, which oscillate the entire chip. It is difficult to actuate independently the different modes by using piezoelectric material. Therefore, a frequency-modulated laser in a custom-built setup is used. The laser is focused on the individual overhang, see fig. 1 (a), of the triple-coupled microcantilevers. The experimental measurements showed that the laser actuation method results in narrower mode peaks since local actuation does not excite spurious modes, which are instead observed by piezoelectric actuation. The setup also allows to rotate the photodetector in order to measure the oscillation of the cantilevers both along transverse and longitudinal axes. It gives us the opportunity to decouple the transverse of the longitudinal vibrations. The results of the experiment show that there is an angle dependence of the cantilevers in the both actuation methods.

Mechanical properties of GaAs Micro- and NanoPillars

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We investigate the mechanical properties of micro- and nanopillars fabricated from single crystal GaAs by electron beam lithography followed by RIE-etching (Fig1a). Typical pillars are between 200-2µm in diameter, 3-20µm long and can include a custom taper, which allows to realize spring constants of 1N/m.. The pillars are excited via a shear piezo transducer. They are investigated in an optical setup as well as in the SEM (Fig1b). The aspect ratio of the pillars is varied so that their eigenfrequencies of the transverse fundamental mode range between 100 kHz and 30 MHz. The mechanical properties are investigated as a function of several environments variables such as pressure. The quality factors observed in vacuum are of the order of 1000.

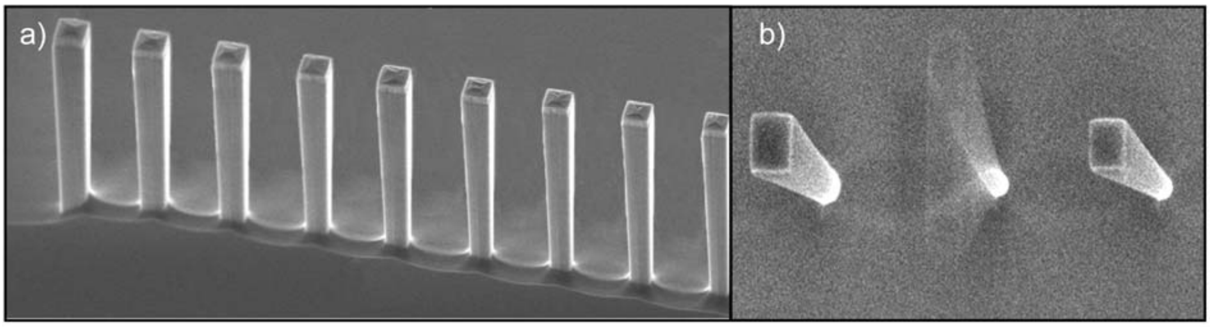
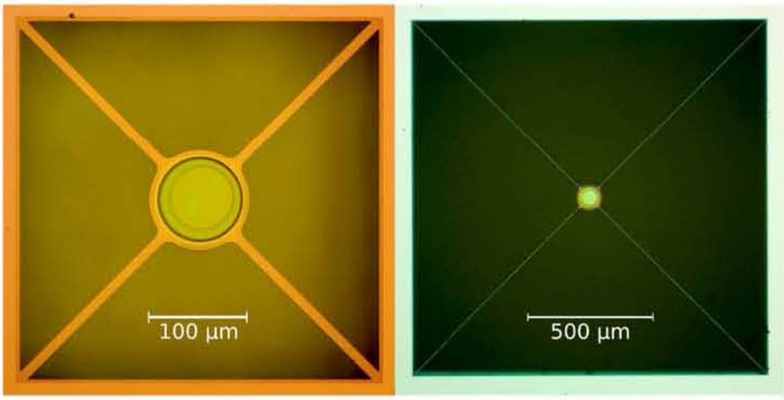


Fig1. SEM picture of GaAs pillars a) with a gradient in the radius and b) oscillating pillar at his eigenfrequency



Fabricating micro-optomechanical devices for high-finesse cavities

Brian Pepper (University of California, Santa Barbara)

Dustin Kleckner (University of California, Santa Barbara)

Dirk Bouwmeester (University of California, Santa Barbara, Leiden University)

Micro-optomechanical devices have recently been explored as a method of realizing a variety of quantum effects in mesoscopic objects. Proposed experiments include non-demolition measurements of phonon number, observation of quantum jumps, and creation of macroscopic quantum superpositions, all with strenuous requirements on optical finesse, mechanical quality factor, and temperature. We present a set of devices composed of dielectric mirrors on Si_3N_4 cross resonators, designed with macroscopic quantum superposition in mind. We describe the fabrication process and present data on optical cavities utilizing these devices.

Beyond the linear and Duffing regimes in Nanomechanics: Circularly polarized mechanical resonances of nanocantilevers

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We present here an experimental and theoretical study of the nonlinear coupling between the two polarizations of the mechanical resonances of singly clamped nanowires and nanotubes, leading to circularly polarized oscillations, as shown in Fig. 1. This regime exists for high amplitudes and beyond the frequency range of the "classical" Duffing regime. Good quantitative agreement is found with a simple theoretical model based on the first non-linear terms of the coupling. The assumptions used in the model are quite general and thus the circular movement is a universal response for nanocantilevers, which are at the center of the emerging field of the Nano Electro-Mechanical Systems (NEMS).

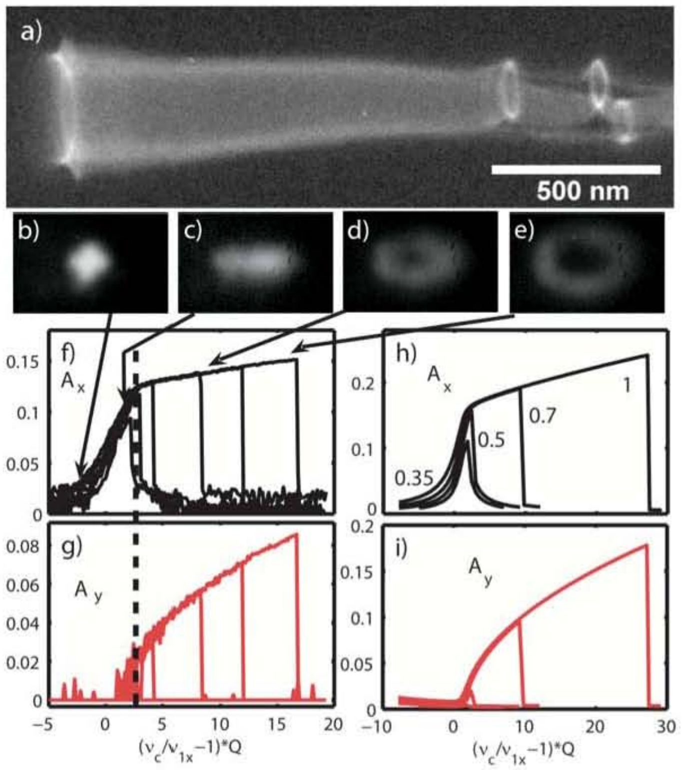

FIG. 1: Elliptical response of the first eigenmode: a) TEM image showing time averaged response of a MWNT with the apex tracing out an elliptical movement. (Several defects along the the MWNT also trace out ellipses) b)-e): Field Emission Microscopy images showing response of the apex of an SiC-NW to increasing excitation. First we observe the linear polarization in the horizontal x direction, then the system transits to an elliptical polarization which becomes more circular with increasing excitation. f)-g) Experimental and h)-i) simulated frequency responses for x ans y amplitudes A_x and A_y, for increasing excitation amplitude near the x polarization eigenfrequency ($\nu_{1y} = 0.989\nu_{1x} = 1.527MHz$, $Q \simeq 2000$). The excitation forces normalized to EI/L^2 were 0.35, 0.5, 0.7 and 1 for the simulated data. A_x is Lorentzian for low excitation and "hard spring" non-linear for intermediate excitation. At high excitation amplitudes V_c and frequencies ν_c one observes "hard spring" elliptically polarized response with the eccentricity decreasing with ν_c until circular polarization is almost reached, delimited in f) and g) by the vertical dashed line. Excellent agreement can be seen between the measured and the simulated data.

Theory of optically levitating nanodielectrics in the quantum regime

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We develop a full quantum theory to consistently describe the coupling of light to the motion of general dielectric objects in high-Q cavities. We derive the Hamiltonian describing the motion of the dielectric, the cavity photons and the interaction between the two and show that it can be fully described by a master equation. While this theory applies to a wide range of systems, we want to use it to explicitly study a recent proposal to use optically levitating nanodielectrics inside an optical cavity as an optomechanical system, [1, 2]. We show that the center of mass motion of such objects decouples from its vibrational excitations within a theory of quantum elasticity. Hence, this degree of freedom is isolated and can be treated separately. We study its dynamics and its main heating mechanisms. Besides, quantum effects such as the renormalization of the Hamiltonian through virtual photons exchange processes, are taken into account. We show that this mechanical system can in principle be cooled down to its ground state and show how protocols to create non-Gaussian states can be applied.

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SUB-POISSONIAN PHONONIC POPULATION IN A NANOELECTROMECHANICAL SYSTEM

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Nano-electromechanical systems (NEMS) are a class of nanodevices in which electrical and mechanical degrees of freedom have comparable energy scales and are strongly coupled, like for example micron-size cantilevers capacitively coupled to quantum dots [1] or carbon nanotubes suspended between two metallic gate and used as oscillating nanowires [2]. In this work, employing the Anderson-Holstein model, we study [3,4] a quantum dot coupled to a single vibrational mode with frequency ω and coupling parameter λ. The states of the system are labeled according to the occupation numbers of the electronic and of the oscillator levels (denoted by n and l respectively). The dot is tunnel-coupled to external leads to which a bias V is applied. Exploiting a generalized master equation approach in the sequential tunneling regime, we derive a dynamical equation for the reduced density matrix of the dot+oscillator system obtaining numerically the stationary solutions. In order to characterize the out of equilibrium phonon distributions, we define the phonon Fano factor $F_{ph} = var(l)/\langle l \rangle$. In analogy with quantum optics, we can distinguish between super- and sub-Poissonian distributions according to $F_{ph} > 1$ or $F_{ph} < 1$. The latter case signals a non-classical behaviour of the system. Exploring a wide range of parameters we have found that, although in most cases the phonon distributions induced by tunneling are super-Poissonian, in the presence of asymmetric tunneling barriers sub-Poissonian distributions may appear in selected transport regimes and for not too large λ . The sub-Poissonian Fano Factor is originated by a peculiar, selective phonon distribution, i.e. a situation in which the first two phononic levels $l=0,1$ are almost equally populated and states with $l>1$ have much lower populations

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Phonon assisted transport through suspended carbon nanotube quantum dots in electric and magnetic fields

G. Rastelli, M. Houzet, F. Pistolesi, L. Glazman

We study the phonon assisted electronic transport through a suspended carbon nanotube quantum dot.
The electrons interact with the transverse modes via the electrostatic coupling with the near metallic gate and, in presence of a uniform magnetic field B, via the Laplace force acting on the current carrying wire. To study the problem, we consider the expansion in the tunnelling taking into account the first-order sequential processes and the second-order cotunneling processes.
At sequential order, we find that the electrostatic interaction and the magnetic interaction are completely equivalent. The removal of spin degeneracy changes significantly the current-voltage characteristic as compared to the phonon-assisted transport at B=0.
The difference between the two interactions appears at the cotunneling order. We discuss in details the off-resonance regime, where the cotunneling current overcome the sequential current, at low temperatures for the vibrational modes.

Investigation of a nanomechanical system with scanning probe microscopy

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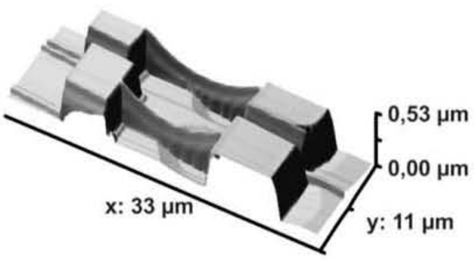
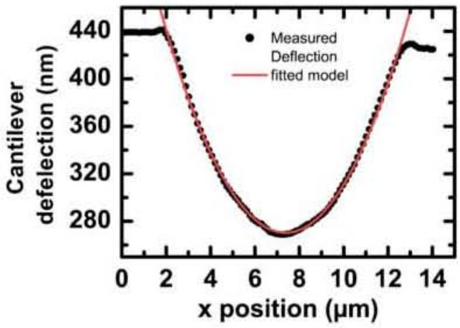
Center for Nanoscience and Department of Physics LMU München - Germany

The atomic force microscope has become an extremely powerful tool for the investigation of nanoscale structures. In addition to providing information about a sample's topography, it allows spatially resolved measurements of certain local properties such as spring constants, magnetization, capacitance, etc. The development of small mechanical elements for this application has ultimately led to the rapidly evolving field of nanomechanics.

Here we report on the investigation of the mechanical properties of a doubly clamped silicon nitride beam under high tensile stress by means of atomic force microscopy (we use an Attocube AFMI). From constant force measurements we are able to extract the intrinsic tensile stress of the material in excellent agreement with the value obtained by a measurement of the linear frequency dependant amplitude response of the resonator. In the future, we plan on utilizing the setup to gain access to dynamical properties of the nanomechanical system such as the mode shape of the driven beam or the frequency response of a resonator subject to an additional force exerted by the AFM-cantilever.





Left: Contact mode image of two doubly clamped silicon nitride beams. **Right:** Cut of the data along the beam in the front of the image to the left. The model of a string under tensile stress yields a quadratic behaviour and was fitted to the data, yielding a tensile stress of 62 MPa.

Nonlinear Optomechanics and Progress Toward Laser-Cooling to the Mechanical Ground State

Jack C. Sankey, Andrew M. Jayich, Cheng Yang, Benjamin M. Zwickl, Nathan E. Flowers-Jacobs, Andrei A. Petrenko, Scott W. Hoch, J. G. E. Harris

In the field of optomechanics, a major goal is to observe (and eventually control) quantum behavior in a solid mechanical resonator coupled to an optical cavity. Work towards this goal generally has focused on increasing the strength of the coupling between the mechanical and optical degrees of freedom; however, the form of this coupling is crucial in determining which phenomena can be observed in such a system. Here we demonstrate several different forms of the optomechanical coupling, realized at avoided crossings in the spectrum of an optical cavity containing a flexible dielectric membrane. These couplings include cavity detunings that are (to lowest order) linear, quadratic, or quartic in the membrane's displacement, and a cavity finesse that is linear in the membrane's displacement. All these couplings are realized in a single device with extremely low optical loss and can be tuned over a wide range in situ. In particular, we find that the quadratic coupling can be increased three orders of magnitude beyond previous devices. As a result, the device presented here should be capable of resolving the phonon shot noise (an inherently quantum phenomenon) of a membrane that is mechanically driven from the ground state to large amplitude. In an effort to prepare the membrane in its ground state, we have pre-cooled the entire system in a 300-mK cryostat and are attempting to laser-cool the membrane's thermal motion to <10 uK at which point the average phonon occupancy will be less than one.

Cooling of the vibrations of a DC-biased nanomechanical resonator determined by quantum interference effects

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One of the major topics of the current research activity on nano-electromechanical systems (NEMS) is the investigation of the physical conditions under which the dynamics of nanometer-sized mechanical oscillators has to be described by quantum rather than classical mechanics. For a mechanical system, quantum features are expected to become experimentally accessible when the thermal energy is smaller than the quantum of vibrational energy.

Here we present the theoretical analysis of a novel procedure to achieve ground-state "cooling" of a beam-shaped nanoresonator.

The NEMS that we consider is a doubly clamped suspended metallic carbon nanotube in which extra charge is injected from the tip of a scanning tunneling microscopy (STM). The position-dependent tunneling amplitude between the STM tip and the nanotube and the electrostatic force controlled by the bias voltage provide two different mechanisms of coupling the mechanical and electronic degrees of freedom of the system.

The inelastic tunneling processes activated by the electromechanical coupling induce a non-thermal equilibrium population of the vibronic states in the nanotube.

Our analysis shows that the probability amplitudes for the emission and absorption of vibrons are affected by quantum interference between different electron tunneling paths which can be controlled by the bias voltage. We find that this interference effect can be made constructive (destructive) for the processes involving absorption (emission) of vibrons when the bias voltage is below the Coulomb blockade threshold, so that the transport of charge is activated by the finite temperature of the electronic reservoirs.

Under this condition, the probability of tunneling processes involving emission of vibrons can be significantly reduced in comparison to the probability of processes characterized by absorption. As a result, a net "cooling" of the vibrational degrees of freedom can be achieved. We remark that the abovementioned kind of electromechanical coupling can also drive the system into the regime of "shuttle-like" electromechanical instability if the bias voltage is above the Coulomb blockade threshold.

In order to evaluate the performance of the proposed "cooling" mechanism, we describe the coupled dynamics of electronic and mechanical degrees of freedom by means of a suitable rate equation and calculate the stationary probability distribution for the occupancy of the vibron states. Our analysis shows that the optimal "cooling" effect that can be achieved corresponds to an average number of vibrons in the excited states of $\langle n \rangle \sim 0.2$.

Quantum fluctuations as the origin of classical shuttle instability

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In presented work we considered the effect of classical shuttle instability in the single-level "vibrating" quantum dot (QD), connected with "Fermi" leads by two tunnel barriers, when strong electron-vibron interaction in the QD takes place. In our model, quantum fluctuations of the QD's coordinate are able to affect the electron tunneling through the system by means of electron-vibron interaction in the QD, and due to the "softness" of tunnel barriers. As the result, quantum fluctuations of "charged" QD under the "driving" bias voltage applied, could "swing" the QD classically in a self-consistent way. This effect leads the "classical" movement of the QD to the regime of shuttle instability, which differs distinctly from the classical instability regime without quantum fluctuations (see Fig.2 on the right). We established, for the first time, that the increment of shuttle instability in considered system is a nonmonotonic function of a "driving" voltage applied (see solid line on the Fig.2). In particular, we show, that the interplay of the two opposite effects: nonelastic electron tunneling through many "vibron" channels, and "polaronic" blockade effect in each channel – leads, at low temperatures, to the strong oscillations of the increment value on the energy scale of the order of vibron energy (see Fig.2 on the right). Also we revealed the strong dependence of the shuttle instability existence in described model (i.e. – of the maximal increment value) on the "tunnel length" of electron (- "under" the tunnel barrier between the QD and the leads).

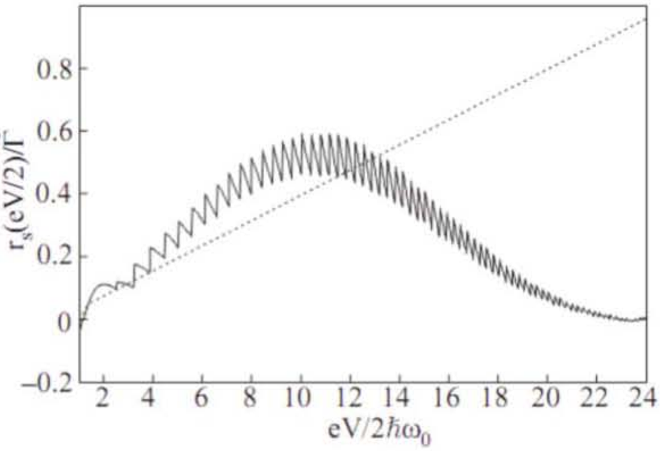

Fig. 2. «Weak» shuttle instability. The increment of shuttle instability (in the units of $\Gamma/\hbar\omega_0$) as a function of bias voltage for $\lambda_t = x_0/l_t = 0.2$; $r_d = x_0/d = 0.2$ (solid line) and $\beta^{-1} = k_B T/\hbar\omega_0 = 0.2$. The dotted line represents the result of Ref. 9 extended to the region of strong electromechanical coupling.

Cooling of a suspended nanotube by an AC Josephson current flow

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We consider a nanoelectromechanical Josephson junction, where a suspended nanowire serves as a superconducting weak link, and show that an applied DC bias voltage can result in suppression of the flexural vibrations of the wire. This cooling effect is achieved through the transfer of vibronic energy quanta first to voltage driven Andreev states and then to extended quasiparticle electronic states. Our analysis, which is performed for a nanowire in the form of a metallic carbon nanotube and in the framework of the density matrix formalism, shows that such self-cooling is possible down to a level where the average occupation number of the lowest flexural vibration mode of the nanowire is 0.1.

Cavity-Optomechanics at Subwavelength Scale

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Recent work in optomechanics has shown that low mass mechanical resonators and small optical mode volume are beneficial for observation of strong optomechanical coupling in experiments [1, 2]. This calls for downscaling of the mechanical resonators: Subwavelength nanomechanical resonators are introduced into the confined mode of an optical microcavity (as depicted in fig. 1) where they interact with cavity photons [3]. Our approach follows such scheme by combining a high finesse fibre based micro cavity and a carbon based nanomechanical oscillator.
In initial experiments we have employed electron beam deposited, singly clamped carbon rods with a diameter of about 120 nm and a length of 5 µm as mechanical resonators. Piezo-electric excitation is used to characterize their mechanical resonance frequencies and quality factors [4]. Brownian motion of the nano resonator has been observed in the noise spectrum of the light transmitted through the cavity [5]. A subsequent miniaturization and optimization will involve the development of CNT resonators.

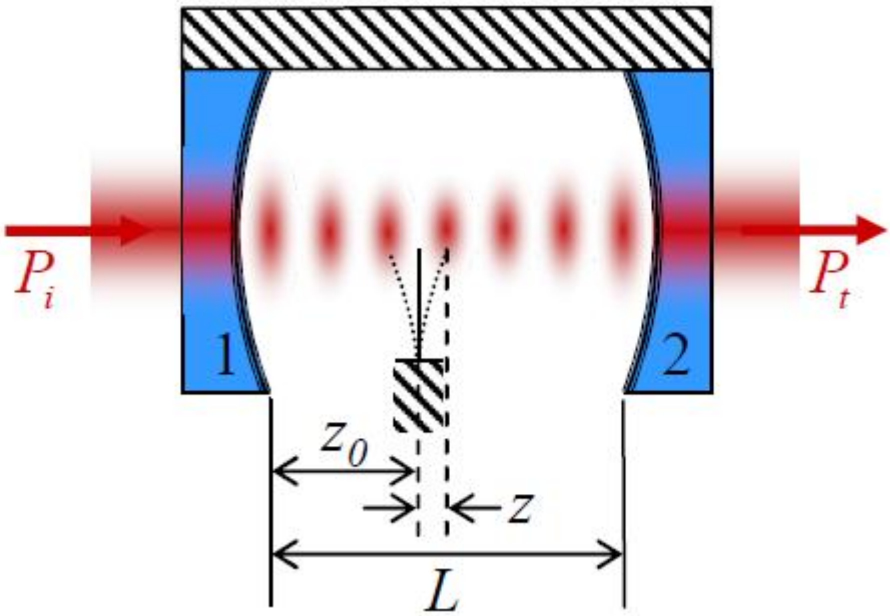

Figure 1. A nanomechanical resonator placed in the confined mode of an optical microcavity.

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[3] I. Favero *et al.*, New J. Phys. 10, 95006 (2008)
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Opto-mechanical transducers for quantum information processing with solid-state qubits

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We describe a new scheme to interconvert stationary and photonic qubits which is based on indirect qubit-light interactions mediated by a mechanical resonator. This approach does not rely on the specific optical response of the qubit and thereby enables optical quantum interfaces for a wide range of solid state spin and charge based systems. We discuss the implementation of state transfer protocols between distant nodes of a quantum network and show that high transfer fidelities can be achieved under realistic experimental conditions. We further describe how the interface can mediate short-range interactions between qubits located on the same chip.

Quality Factors of Nanomechanical Resonators

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The study of nanomechanical resonant motion is a rapidly advancing field of science with prospects in fundamental studies and application. For many aspects, a low mechanical friction (or high quality factor) is advantageous. It has been experimentally shown that silicon nitride resonators under high uniform tensile stress exhibit significantly higher quality factors when compared to unstressed ones of the same resonance frequency. The underlying mechanism however is yet to be known.
In order to reproduce the measured room-temperature quality factors of the fundamental and higher harmonic modes of our high stress SiN nanomechanical oscillators with cross sections of 200x100 nm and lengths ranging from 35 to 5 micrometer, we apply a damping model based on continuum mechanics.
We assume the friction throughout volume of the resonator to be caused by the local strain as the beam oscillates and are thereby able to quantitatively model the observed quality factors introducing a frequency independent imaginary part of the Youngs modulus [Fig. 1]. Based on our calculations we can deduce that the high mechanical quality factors are caused by the increase in elastic energy rather than a decrease in energy loss with increasing tensile stress. Therefore, we expect that resonators consisting of nearly any material will exhibit higher quality factors when stressed.

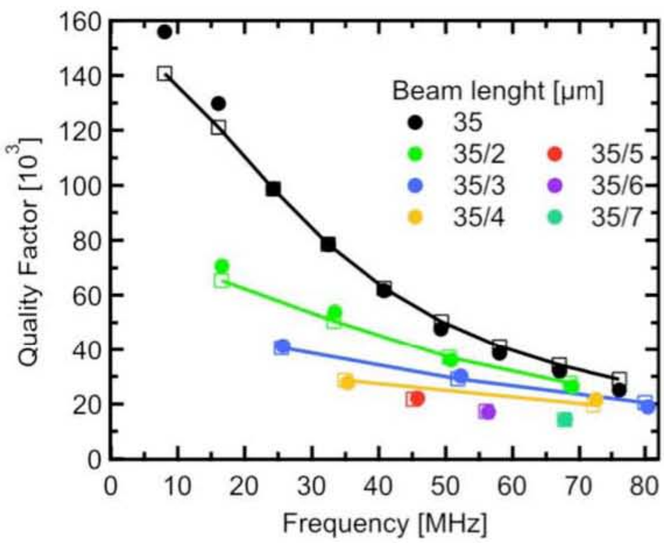

Fig. 1: Frequency and mechanical quality factors of the measured resonances (solid dots); the lengths of the beams are colour-coded. The hollow squares represents our modelling of the resonance frequencies as well as the quality factors, as a guide to the eye, the various harmonics corresponding to the same beam are connected.

Reference:

Q. Unterreithmeier, T. Faust and J. Kotthaus "Damping of Nanomechanical Resonators", Phys. Rev. Lett. **105,** 027205 (2010).

Cavity Optomechanics with 150nm-thick GaAs Membrane

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Abstract

Optomechanical properties of 150nm-thick GaAs membrane are studied for exploring its potential use in membrane-in-the-middle approach of cavity optomechanics [1, 2]. GaAs posseses many interesting properties [3]; direct band gap transition, high mobility of electrons, and strong piezoelectric properties to name just a few. These extra properties may be found favorable to approach the quantum regime with optomechanical system. Investigating opto-nanomechanical properties of the semiconductor may also be beneficial for advancing already-mature optoelectrical, electrical, and electromechanical semiconductor integrated devices further.

To investigate the optomechanical properties of a fabricated 150nm-thick intrinsic GaAs membrane (1.3mm×1.9mm) a 975nm-laser (below band gap) is used to probe the mechanical resonances via beam deflection method. An 810nm-laser (above band gap), which is mode-coupled to a Fabry-Pérot cavity formed between the membrane and a mirror (Finesse: ∼24) inside a vacuum chamber (∼10^{-7}Torr), is used to lock the cavity length at the cavity resonant slope and to induce mechanical oscillations by modulating the intensity from the offset level for ring down measurements.

We observe the cavity cooling of the mechanical modes when the cavity is locked at the blue-side of the slope. The instability is set in when the cavity is around the red-side of the slope or the cavity input exceed 50μW and prevents us from using these conditions for the ring down measurements. The mechanical ring down time, τ, decreases as the cavity input power is increased from 5μW to 45μW (cavity cooling). The measured ring down times are extrapolated down to zero cooling power to evaluate the intrinsic mechanical quality factor Q of the membrane, which is found to be 0.5×10^6 for ν=23.4kHz fundamental mode at room temperature. Up to 150kHz the νQ products are measured to be nearly constant (around 3×10^{10}Hz). From the ratio of the extrapolated intrinsic ring down time to that at 50μW the cooling factor can be evaluated for each mode. For the fundamental mode it is found to be as large as 12 meaning that the effective temperture of the mode is cooled down to 25K. We believe that the main cause of the cooling is neither the radiation pressure nor the photothermal effect given the relavant physical parameters.

We will report the progress of the experiments aiming to reveal the underlying cavity cooling mechanism of the GaAs membrane.

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Interacting vibrational modes in clamped-clamped mechanical resonators

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The coupling between the flexural resonance modes in clamped-clamped mechanical resonators is investigated by theory and experiment. In a clamped-clamped resonator, a nonzero displacement amplitude implies elongation of the resonator, and this is accompanied by a tension force. The effect of the displacement-induced tension on its own resonance frequency is well-known: it leads to the Duffing nonlinearity in clamped-clamped resonators. The tension however also affects all the other modes, and this mechanism couples all the flexural vibrational modes of the resonator.
The coupling between the flexural modes is experimentally investigated by detecting the response of a clamped-clamped silicon resonator while simultaneously driving two flexural resonance modes. For small amplitudes, a quadratic dependence is found between the shift in resonance frequency of the detector mode and the amplitude of the mode to be detected, as shown in Fig. 1. When multiple modes are driven strongly, i.e. in the regime where for each mode multiple amplitudes are stable, complex dynamics are observed. A model which couples the modes via the beam extension quantitatively captures all these experimentally observed features [1].
Based on the coupled modes several applications are envisioned. Using the self-detecting principle, resonance modes can be detected that would be otherwise inaccessible by the experiment, such as the even resonance modes in a magnetomotive measurement. Another application is to control the switching between stable amplitudes of one mode by modulating the tension induced via another mode, as shown in Fig 2; this enables the implementation of signal processing functions in a single mechanical resonator.

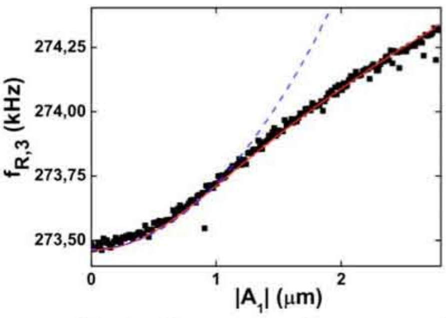

Fig.1. Resonance frequency of mode 3 as a function of the amplitude of mode 1.

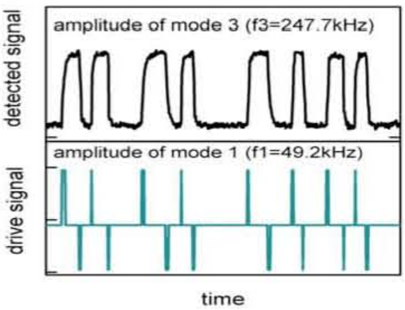

Fig.2. Controlling the state of mode 3 by mode 1 via modal interactions.

Non-Equilibrium Transport Properties of a Tunnel Junction Coupled to an Harmonic Oscillator in the Non-Markovian Regime

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We are interested in the true quantum behavior of the coupled system of a quantum harmonic oscillator and a tunnel junction beyond Born and Markov approximation. The transport properties of the tunnel junction (I-V characteristics and finite frequency noise) are perturbatively calculated in the tunneling Hamiltonian using the Keldysh formalism.

We find that the non-equilibrium transport properties of the tunnel junction significantly dependent on the properties of the oscillator (such as its frequency, position and momentum). This can, in principle, be used to manipulate and read out the quantum state of the oscillator.

In addition, we recover for a non-stationary oscillator a complex noise which complements the proposal for a momentum detector in Ref. 1.

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Dynamical multistability in a multimode optomechanical system

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Abstract

Optomechanical systems couple mechanical motion of macroscopic objects to electromagnetic fields. The standard setup comprises a laser-driven cavity with a movable end-mirror whose motion changes the optical resonance frequency and thus acts back on the light field. Studies of the complex nonlinear dynamics for this system revealed several dynamical attractors due to phase locking between the mechanical oscillations of the mirror and the ringing of the light intensity. Here we study such dynamical multistability for a novel setup where a moveable membrane is placed in the middle between two high-finesse mirrors. The membrane couples two optical modes residing in the left and right half of the cavity, respectively. Its motion is determined by the coupled light-field dynamics that was recently studied elsewhere and shows two-level dynamics such as Autler-Townes splittings and Landau-Zener-Stueckelberg oscillations. Here we discuss the result of these effects on the nonlinear dynamics in terms of the attractor diagram for different parameter regimes. This is the first study of dynamical multistability in one of the exciting new setups with multiple coupled optical (and vibrational) modes that have been developed recently.

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