ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

ERICE, SICILY, ITALY, JULY 31 – AUGUST 5 2016

INTERNATIONAL SCHOOL OF STATISTICAL PHYSICS

Directors of the School: P. Hänggi, F. Marchesoni

Directors of the Course: D. Vitali, F. Marin, K. Lehnert

Quantum Interfaces with Nano-opto-electro-mechanical devices: Applications and Fundamental Physics

Abstracts

Interfacing Quantum Optical, Electrical, and Mechanical Systems

PROGRAM

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<tr><td>17.30-17.45</td><td rowspan="9">Informal get-together at San Rocco's Cloister</td><td rowspan="2">Muhonen</td><td rowspan="2">Ruesink</td><td rowspan="2">Naticchioni</td></tr>
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Models of spontaneous wave function collapse and optomechanics

A. Bassi[a,b]

[a]*Department of Physics, University of Trieste, Strada Costiera 11, 34151 Trieste;*
[b]*Istituto Nazionale di Fisica Nucleare, Trieste Section, Via Valero 2, 34127 Trieste;*
e-mail: bassi@ts.infn.it

Models of spontaneous wave function collapse (collapse models) modify the Schrödinger equation by including nonlinear and stochastic terms in the dynamics of any quantum system, which describe the collapse of the wave function in space [1].

These spontaneous collapses are "rare" for microscopic systems, hence their quantum properties are left almost unaltered. At the same time, they become more and more frequent, the larger the object, to the point that macroscopic superpositions are rapidly suppressed. This is how they successfully describe the quantum-to-classical transition by providing a unified dynamics for quantum and classical systems.

I will briefly review the main features of collapse models. Next I will present an update of the most promising ways of testing them. Direct tests mainly include matter-wave interferometry.

Recently non-interferometric tests applied to optomechanics [2] have been proposed, which are able to set much stronger bounds on collapse models [3].

References:

1) Bassi, A.; Lochan, K.; Satin, S.; Singh, T.P.; Ulbricht, H.; *Rev. Mod. Phys*. **2013** *85*, 471-527.
2) Bahrami M.; Paternostro M.; Bassi A.; Ulbricht H.; *Phys. Rev. Lett*. **2014** *112*, 210404.
3) Vinante A.; Bahrami M.; Bassi A.; Usenko O.; Wijts G.; Oosterkamp T.H.; *Phys. Rev. Lett.* **2016** *116*, 090402.

Optical cavity cooling and non-linear dynamics of a functionalized silicon nitride membrane

A. Ortu[1], A. Bigongiari[1], F. Fogliano[1], A. Camposeo[2], D. Pisignano[2,3], E. Arimondo[1,4,5], F. Fuso[1,4,5], D. Ciampini[1,4,5]

[1]*Dipartimento di Fisica "E. Fermi", Università di Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy*
[2]*Istituto Nanoscienze-CNR, Euromediterranean Center for Nanomaterial Modelling and Technology (ECMT), via Arnesano I-73100, Lecce, Italy*
[3]*Dipartimento di Matematica e Fisica 'Ennio De Giorgi', Università del Salento, Arnesano I-73100 Italy*
[4]*INO-CNR, Via G. Moruzzi 1, 56124 Pisa, Italy*
[5]*CNISM UdR Pisa, Dipartimento di Fisica E. Fermi, Università di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy*

Optomechanics is a rapidly expanding field focused on the interaction between light and mechanical motion of a resonator. Optical back-action effects associated with confined electromagnetic modes in an optical cavity is used to decrease the mechanical energy of the mode, showing promise for both applications and fundamental investigation. Applying the cavity cooling method to optically active semiconductors offers additional interesting prospects, because of their internal electronic degrees of freedom. Engineered semiconductor devices enable strongly enhanced light-matter interactions, while organic materials offer a much broader dynamical range of parameters and are easier to process compared with inorganic semiconductors.

We investigate the optomechanical properties of a cavity containing, as a mirror, a multilayer membrane composed by the molecular organic semiconductor tris(8-hydroxyquinoline) aluminum (Alq_3), silver and silicon nitride, for a total thickness of 130 nm. Excitation at two laser wavelengths, 780 and 405 nm, corresponding to different absorptions of the multilayer, is examined. We observe photothermal cooling of the first oscillatory modes of the membrane, through the measure of its Brownian motion by using an external probe light and a beam deflection method.

The multiple scale dynamics induced by phototermal effects and radiation pressure is analyzed for a regime in which both radiation pressure and phototermal effects are relevant. Non-linear dynamic effects arise when the mechanical modes are heated. Multi-stable regions are observed; instabilities arise depending on the laser power and detuning from resonance. We find that in the optomechanical system under consideration the adiabatic approximation for the photo-thermal effect is no longer valid. We study the stability of the system using a model in which the response of the photo-induced forces to changes in the cavity field is described by a delay function.

Optomechanics with ion chains in optical cavities

T. Fogarty[a,b], C. Cormick[c], H. Landa[d], A. Buchheit[a], V. Stojanović[e], E. Demler[e], G. Morigi[a]

[a]*Universität des Saarlandes, D-66123 Saarbrücken, Germany,*
[b]*Okinawa Institute of Science and Technology, Japan,*
[c]*IFEG, CONICET and Universidad Nacional de Cordoba,*
[d]*Univ. Paris Sud, CNRS, LPTMS, UMR 8626, Orsay 91405, France,*
[e]*Department of Physics, Harvard University, Cambridge, MA 02138, USA.*

In this work we report on the optomechanical dynamics of ion chains, whose vibrations couple with the high-Q mode of an optical cavity. The dynamics results from the interplay between the long-range Coulomb repulsion and the cavity-induced interactions. The latter are due to multiple scatterings of laser photons inside the cavity and become relevant when the laser pump is sufficiently strong to overcome photon decay. We study the stationary states of ions coupled with a mode of a standing-wave cavity as a function of the cavity and laser parameters, when the typical length scales of the two self-organizing processes, Coulomb crystallization and photon-mediated interactions, are incommensurate. The dynamics are frustrated and in specific limiting cases can be cast in terms of the Frenkel-Kontorova model, which reproduces features of friction in one dimension. We numerically recover the sliding and pinned phases. For strong cavity nonlinearities, they are in general separated by bistable regions where superlubric and stick-slip dynamics coexist (Ref. 1). The cavity, moreover, acts as a thermal reservoir and can cool the chain vibrations to temperatures controlled by the cavity parameters and by the ions' phase (Ref. 2).
We then focus on the regime in which the length scale are almost commensurate and investigate how the commensurate-incommensurate transition is modified by cavity backaction.
We finally discuss how these features are imprinted in the radiation emitted by the cavity, which is readily measurable in state-of-the-art setups of cavity quantum electrodynamics.

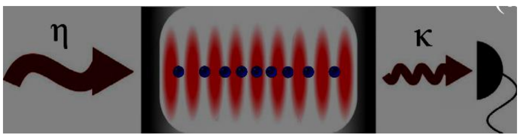

FIG. 1 An array of cold ions as a realization of the Frenkel-Kontorova model. Taken from Ref. 1).

References:

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Advanced-KWISP: investigating short-range interactions at sub-micron scales with an optomechanical sensor

G. Cantatore[a,b]

[a]*Department of Physics, University of Trieste, Strada Costiera 11, 34151 Trieste;*
[b]*Istituto Nazionale di Fisica Nucleare, Trieste Section, Via Valero 2, 34127 Trieste;*
e-mail: giovanni.cantatore@ts.infn.it

Sensitive measurements on the short range interactions between macroscopic bodies provide a window on possible physics beyond the standard model, including extra-dimensions, scalar dark matter and dilatons. The scale of distances in the sub-micron range is presently not accessible to experimental investigation, and may even hold the key to understanding at least part of the dark matter puzzle. The *a*-KWISP (*advanced*-KWISP) proposal builds on the results obtained with the KWISP opto-mechanical force sensor, designed and constructed at INFN Trieste, and enters the short-distance interaction field with the novel "double-membrane" concept. Here interaction distances can be as short as 10 nm, much below the ≈10 micron distance which is the lower limit encountered by current experimental efforts, such as the ATLAS experiment at LHC, which probes extra-dimensions down to a distance of 11 microns. *a*-KWISP reaches the ultimate quantum-limited sensitivity by exploiting an array of technologies, and by achieving sub-Kelvin membrane temperatures with a combination of cryogenic and optical cooling.
We discuss the principle of the sensor, recent results, including the current application to astroparticle physics, and possible future developments in the framework of the physics programs of CERN and other large facilities, such as underground laboratories.

Measurement-induced long-distance entanglement of superconducting qubits using optomechanical transducers

O. Cernotik[a], K. Hammerer[a]

[a]*Institute for Theoretical Physics, Institute for Gravitational Physics (Albert Einstein Institute), Leibniz University Hannover, Callinstr. 38, 30167 Hannover, Germany; e-mail: Ondrej.Cernotik@itp.uni-hannover.de*

Although superconducting systems provide a promising platform for quantum computing, their networking poses a challenge as they cannot be interfaced to light—the medium used to send quantum signals through channels at room temperature. We show that mechanical oscillators can mediate such coupling and light can be used to measure the joint state of two distant qubits. The measurement provides information on the total spin of the two qubits such that entangled qubit states can be postselected[1].

Our scheme works in analogy to experimental technique already established in the microwave domain[2] but employs an optical channel at room temperature. The use of light greatly enhances the distance over which the qubits can become entangled. The generalization to the optical domain—although relatively straightforward from the experimental point of view—is highly nontrivial and requires a systematic investigation of new sources of decoherence; thermal mechanical noise and optical transmission loss have to be analysed. Such an analysis requires adiabatic elimination of the complex transducer dynamics[3] since the Hilbert space dimension is too large to allow numerical simulations.

Compared to earlier proposals of optomechanical transducers, our strategy requires no time-dependent control. This simplicity leads to modest requirements on the system parameters; optomechanical cooperativity moderately larger than unity is sufficient and large transmission losses can be tolerated. The approach is scalable to generation of multipartite entanglement and represents a crucial step towards quantum networks with superconducting circuits.

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From gravitational-wave detection to quantum optomechanics

Pierre-François Cohadon

Laboratoire Kastler Brossel, ENS, UPMC, Collège de France and CNRS,
4 place Jussieu, 75005 Paris; email: cohadon@lkb.upmc.fr

Detecting gravitational waves required 4 decades of experimental effort to reach a sensitivity at the $h \sim 10^{-21}$ level, corresponding to mirror displacements below 10^{-18} m. I will review this "noise hunting" effort and give some details about the recent observation of 2 black hole mergers.

Apart from classical noise (seismic noise, thermal noise...), it was realized as soon as in the late 70s that quantum fluctuations of the light field were responsible for the Standard Quantum Limit, a sensitivity limit that second-generation gravitational-wave interferometers will reach once they operate at their design sensitivity.

A number of ideas have been considered to beat the SQL: squeezed states of the light field, tailoring the optical response function or taking advantage of the mirror mechanical response to radiation pressure. I will present the first experimental demonstrations of such ideas, either on suspended interferometers or table-top experiments.

I will also discuss how recent progress in micro/nanomechanics has allowed the emergence of the new field of quantum optomechanics, which addresses the quantum aspects of both the light field and the mechanical resonator.

Quantum electro-mechanics with dielectric oscillators

J. M. Fink

Institute of Science and Technology Austria (IST Austria), Am Campus 1, 3400 Klosterneuburg, Austria; e-mail: jfink@ist.ac.at

Superconducting circuits are at the focus of quantum engineering research because of their potential for scalable quantum information processing and simulation. One disadvantage of circuit QED systems is that they can only operate in ultra-cold environments where thermal noise and resistive losses are negligible. We are working towards an on-chip integrated microwave-photonic device, which has the potential to efficiently convert microwave to telecom wavelength photons using radiation pressure forces. Utilizing compact ultra-high impedance LC circuits suspended on dielectric nano-membranes enables efficient coupling to the mechanical modes of one-dimensional acoustic bandgap nanobeam resonators compatible with nano-photonics. With this new platform we demonstrate motional ground state cooling of the dielectric beam's fundamental mode [1], as well as mechanically mediated efficient microwave frequency conversion over 2 GHz [2]. Our most recent generation of devices is based on commercial silicon on insulator substrate [3] on which we just started to integrate superconducting qubits. This system should allow synthesizing and manipulating acoustic quantum states without the need for active cooling. Coupling these excitations to mechanical wave-guides, entanglement between itinerant multi-phonon states could be studied in analogy to quantum optical systems. Coupling to photonic crystals on the other hand would put within reach the realization of hybrid long distance quantum communication networks.

References:

1) J. M. Fink, M. Kalaee, A. Pitanti, R. Norte, L. Heinzle, M. Davanco, K. Srinivasan, and O. Painter. *ArXiv:1512.04660* **2015**

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3) P. B. Dieterle, M. Kalaee, J. M. Fink, and O. Painter. *ArXiv:1601.04019,* **2016**

High frequency nano-optomechanical disk resonators in liquids

E. Gil-Santos[a], W. Hease[b], C. Gomez[b], A. Lemaitre[b], G. Leo[a] and I. Favero[a]

[a]*Matériaux et Phénomènes Quantiques, Université Paris Diderot, C.N.R.S., Sorbonne Paris Cité, U.M.R. 7162, 10 rue Alice Domon et Léonie Duquet, 75013 Paris, France.*
e-mail: eduardo.gil-santos@univ-paris-diderot.fr
[b]*Laboratoire de Photonique et Nanostructures, C.N.R.S., Route de Nozay, 91460 Marcoussis, France.*

Vibrating nano and micromechanical structures have been the subject of extensive research for the development of ultrasensitive mass sensors for spectrometry, chemical sensing and biomedical analysis. In short, the minimum detectable mass is proportional to the effective mass of the resonator and sensitivity improves if mechanical dissipation is reduced. Device miniaturization and dissipation control are therefore crucial. In liquids, the energy losses are high and the mass sensitivity is generally diminished dramatically. To circumvent this problem, novel structures have been proposed, such as micro-channels or micro-capillars where the liquid flows directly inside the resonators. While these structures indeed show lower mechanical dissipation, they can hardly be miniaturized.

Here we demonstrate the potential of nano-optomechanical disk resonators in this context. Miniature semiconductor mechanical disks possess high-frequency radial breathing modes (GHz), with high mechanical Q even in air ($>10^3$) and low mass (pg), presenting clear assets for mass sensing applications. However, they have not been operated in liquids so far. Here, we experimentally, numerically and analytically investigate the interaction of such vibrating disk resonators with arbitrary liquids, and propose models for both the frequency shift and dissipation of their mechanical modes. Nano-optomechanical disk resonators finally emerge as probes of rheological information of unprecedented sensitivity and speed, opening applications in high frequency sensing and fundamental science.

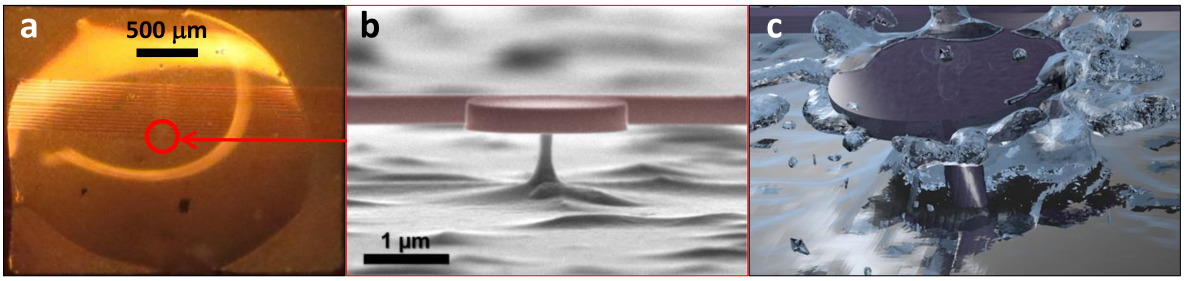

Figure 1: (a) Optical micrograph top view of a chip with an array of disk resonators, together with their optical coupling waveguides, immersed in a liquid droplet. (b) Scanning electron microscope image (side-view) of a 1 μm radius GaAs disk with a tapered waveguide. (c) Artistic illustration of the disk-liquid interaction.

Reference:

1) Gil-Santos, E.; Baker, C.; Nguyen, D. T.; Hease, W.; Gomez, C.; Lemaître, A.; Ducci, S.; Leo, G.; Favero, I. *Nature Nanotech.* **2015**, *10*, 810-816.

Experiments testing macroscopic quantum superpositions must be slow

A. Mari, G. De Palma, and V. Giovannetti

NEST, Scuola Normale Superiore and Istituto Nanoscienze-CNR, I-56127 Pisa, Italy

We consider a thought experiment where the preparation of a macroscopically massive or charged particle in a quantum superposition and the associated dynamics of a distant test particle apparently allow for superluminal communication1. We give a solution to the paradox which is based on the following fundamental principle: any local experiment, discriminating a coherent superposition from an incoherent statistical mixture, necessarily requires a minimum time proportional to the mass (or charge) of the system. For a charged particle, we consider two examples of such experiments, and show that they are both consistent with the previous limitation. In the first, the measurement requires to accelerate the charge that can entangle with the emitted photons. In the second, the limitation can be ascribed to the quantum vacuum fluctuations of the electromagnetic field. On the other hand, when applied to massive particles our result provides an indirect evidence for the existence of gravitational vacuum fluctuations and quantum gravitational radiation.

References:
1) Mari, A.; De Palma G.; Giovannetti V. *Scientific Reports* **2016**, *6*, 2277

Quantum optomechanics experiments with photonic crystals

Simon Groeblacher

Kavli Institute of Nanoscience, Delft University of Technology, Netherlands
email: s.groeblacher@tudelft.nl

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.

Microwave-mechanical-optical transducer in a dilution refrigerator

A. P. Higginbotham[a], P.S. Burns[a], R.W. Peterson[a], T. Menke[a], N.S. Kampel[a], M. Urmey[a], C.A. Regal[a], K.W. Lehnert[a]

[a]*JILA, University of Colorado and NIST, Boulder, CO, 80309-0440, USA*

An effort is underway to construct a microwave-mechanical-optical system operating in the quantum regime. Building on previously demonstrated classical electro-optic conversion [1], I will report technical improvements and discuss the outlook for upcoming quantum experiments.

References:

1) R. W. Andrews, R. W. Peterson, T. P. Purdy, K. Cicak, R. W. Simmonds, C. A. Regal, and K.W. Lehnert, Nature Phys. **10** (2014), 321–326.

Towards utilizing carbon-based NEMS as probes of helium condensates

J.-P. Kaikkonen, P. Häkkinen, A. Laitinen, A. Savin, I.A. Todoshchenko, P. J. Hakonen

Low Temperature Laboratory, Department of Applied Physics, Aalto University, PO Box 15100, FI-00076 AALTO, Finland

Suspended graphene and carbon nanotube devices are among the most precise mass, charge and force sensors. We aim at utilizing these sensitive devices in investigations of two-dimensional atomic films and bulk superfluid phases of ^{3}He. These ultra-low temperature experiments require minimal dissipation and hence, superconducting nanocarbon resonators are currently being developed. Nanocarbon resonators with proximity-induced supercurrents are further expected to be compatible with dispersive read-out techniques based on Josephson inductance. This could improve their sensitivity as probes of helium condensates but also make them promising optomechanical systems owing to their large zero-point vibrations and nonlinear nature.

This contribution presents the recent developments and discusses the future prospects of carbon-based NEMS as probes of ^{3}He condensates.

Microfabrication of high-stress SiN membranes with arbitrary shape for optomechanical applications

Serra E.,[a, b] Bawaj M.,[c, d] Borrielli A.,[a, e] Di Giuseppe G.,[c, d] Forte S.,[b, f] Kralj N.,[c] Malossi N.,[c, d] Marconi L.,[g, h] Marin F.,[i, g, h] Marino F.,[h, j] Morana B.,[b] Natali R.,[c, d] Pandraud G.,[b] Pontin A.,[g, h] Prodi G.A.,[a, f] Rossi M.,[c] Sarro P.M.,[b] Vitali D.,[c, d] and Bonaldi M.[a, e]

[a] *Istituto Nazionale di Fisica Nucleare, TIFPA, 38123 Povo (TN), Italy*
[b] *Delft University of Technology, Else Kooi Laboratory, 2628 Delft, The Netherlands*
[c] *Physics Division, School of Science and Technology, Università di Camerino, 62032 Camerino*
[d] *INFN, Sezione di Perugia, 06123, Perugia, Italy*
[e] *Institute of Materials for Electronics and Magnetism, Nanoscience-Trento-FBK Division, 38123*
[f] *Dipartimento di Fisica, Università di Trento, 38123 Povo (TN), Italy*
[g] *Dipartimento di Fisica e Astronomia, Università di Firenze, Via Sansone 1, 50019 Sesto Fior*
[h] *INFN, Sezione di Firenze, Via Sansone 1, 50019 Sesto Fiorentino (FI), Italy*
[i] *LENS, Via Carrara 1, 50019 Sesto Fiorentino (FI), Italy*
[j] *CNR-INO, L.go Enrico Fermi 6, 50125 Firenze, Italy*

Optomechanical setups span a vast range of sizes and masses, as do their applications and aims – from testing the foundations of the quantum theory to precision sensing and detecting gravitational waves[1)-5)]. More generally speaking, these experiments are performed not only in the optical, but also in the microwave domain. The two meet in efforts to develop an optical-to-microwave transducer, which would, in turn, be of use in quantum computing. In view of the integration of membrane resonators with more complex microelectromechanical systems (MEMS)[6)], we developed a general fabrication procedure for circular shape SiN_x membranes using deep reactive ion etching (DRIE)[7)]. The membranes were used as resonators in a Michelson interferometer and a Fabry-Pérot cavity to study their properties. Albeit the fabrication procedure has yet to be optimized, both mechanical quality factors and optical roughness are comparable to those of commercially available membranes, while the optical absorption is almost an order of magnitude lower.

References

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7) Serra, E.; Bawaj, M; Borrielli, A.; Di Giuseppe, G.; Forte, S.; Kralj, N.; Malossi, N.; Marconi, L.; Marin, F.; Marino, F.; Morana, B.; Natali, R.; Pandraud, G.; Pontin, A.; Prodi, G. A.; Rossi, M.; Sarro, P. M.; Vitali, D.; Bonaldi, M. *AIP Advances*, **2016**, *6*, 065004

Mechanically-Induced Transparency in a hybrid electromechanical system

Moaddel Haghighi I., Malossi N., Natali R., Di Giuseppe G., Vitali D.

Physics Division, School of Science and Technology, Università di Camerino, 62032 Camerino
INFN, Sezione di Perugia, 06123, Perugia, Italy, email: imanmoaddel.haghighi@unicam.it

We study an electromechanical hybrid system consisting of a radiofrequency (rf) resonator coupled to a mechanical resonator. The oscillation of the mechanical resonator can alter the capacitance of the radiofrequency resonator leading to the modulation of transmitted signal. The coupling between the two resonators manifests itself by an effect called Mechanically-Induced Transparency (MIT), which is an interference effect like the well known phenomenon Electromagnetically-Induced Transparency (EIT). In our study the rf resonator is an LC with variable resonance frequency between 100 kHz -1MHz. The quality factor of the resonator is around 130. The hybrid system is obtained by coupling the LC resonator to a metalized high stress, 1×1 mm^2, 50 nm thick, stoichiometric Silicon Nitride Membrane. We drove the electronic resonator with an rf signal and observed an MIT transparency window in the transmitted signal. We measured the coupling rate in two independent ways using the electronic signal as well as the reflected optical signal .

Cavity optomechanics with extreme coupling rates in silicon photonic crystal

J.T. Muhonen, R. Leijssen, L. Freisem, G. la Gala, and E. Verhagen

Center for Nanophotonics, FOM Institute AMOLF, Science Park 104, 1098 XG Amsterdam, The Netherlands; e-mail: j.muhonen@amolf.nl

We present a cavity optomechanical system that utilizes subwavelength optical confinement to achieve photon-phonon coupling strength of tens of megahertz and single-photon cooperativities exceeding 1000. With these parameters, room-temperature Brownian motion drives the system far into the non-linear regime of optical response. At 300 Kelvin, the frequency modulation of the optical cavity induced by thermal motion is ~5 times larger than the cavity linewidth, leading to thermal motion-limited apparent optical linewidth characterized by a Gaussian resonance profile. This apparent linewidth decreases with temperature as expected between room temperature and 3 Kelvin. Operating at bad cavity limit, our structure combines fast measurements with high coupling rates and is ideally suited for measurement based quantum state preparation schemes.

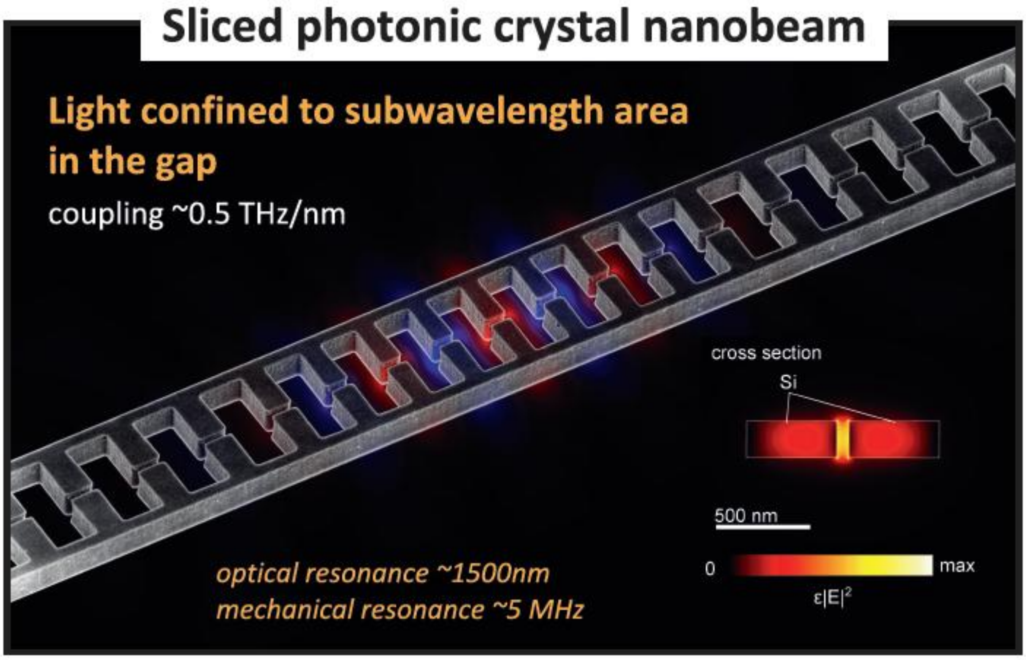

Figure 2: Schematic of the structure

Ponderomotive squeezing of light: overcoming the standard quantum limit in the detection band of interferometric gravitational wave detectors

L. Naticchioni[a,b,e], E. Calloni[c,d], M. De Laurentis[c,d], S. Di Pace[a,b], P. Puppo[b], F. Ricci[a,b]

[a]*Department of Physics, University of Rome Sapienza, P.le Aldo Moro 5, 00185 Roma IT;*
[b]*I.N.F.N. Roma, Pl.e Aldo Moro 2, 00185 Roma IT;*
[c]*University of Naples Federico II, Corso Umberto I 40, 80138 Napoli IT*
[d]*I.N.F.N. Napoli, Ed.6 M.S. Angelo, Via Cintia, 80126 Napoli IT;*
[e]*e-mail: luca.naticchioni@roma1.infn.it*

Shot noise and radiation pressure-induced fluctuations due to the Poisson's distribution of photons introduce an intrinsic limitation on the accuracy in the position measurement of a free mass using coherent light. If the uncertainty related to these two contributions is equal, then the limit is known as Standard Quantum Limit (SQL) [1]. It is possible to overcome this limit by squeezing the uncertainty on a quadrature increasing that of the other quadrature (e.g. phase vs. amplitude) without breaking the Heisenberg uncertainty principle. Starting from the first optical squeezing experiments, the parametric processes in Kerr medium with an optical feedback (Optical Parametric Oscillator, OPO) has been demonstrated so far the most efficient squeezing generators [2]. Moreover, in the recent years, different gravitational waves groups have demonstrated squeezing generation in the audio-frequency range down up to 150 *Hz*, improving the sensitivity of the Gravitational Wave Detectors GEO600 and LIGO by introducing vacuum squeezed states into the interferometer output. Nevertheless at very low frequencies (tens of hertz) the OPOs are affected by experimental limitations, mainly due to the photo-thermal fluctuations caused by the high power circulating in the optical cavities and by the parasitic optical interference, which easily hides the vacuum noise. The lower observed frequency limit at the moment is 1 *Hz,* for a very short observation time. An alternative approach is the ponderomotive squeezing generated in cavities and interferometers with suspended mirrors. The optomechanical coupling between the impinging coherent light and the motion of the mirrors, due to the radiation pressure of the same light, causes a phase shift of the reflected light proportional to the light intensity: this correlation generates the desired squeezing effect. The POLIS [3] experiment is a suspended interferometer designed to achieve a frequency-dependent and stable squeezing below 1 *kHz*, with the aim to demonstrate the feasibility of the ponderomotive technique in the audio band and its potential integration to the future generation of the Gravitational Wave Detectors.

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Graphene optomechanics in a cryogenic environment

A. Noury[a], J. Güttinger[a], P. Weber[a], J. Vergara-Cruz[a], J. Moser[a], C. Lagoin[a], C. Eichler[b], A. Wallraff[b], M. Eriksson[c], A. Isacsson[c] A. Bachtold[a]

[a]ICFO – Institut de Ciencies Fotoniques & BIST - The Barcelona Institute of Science and Technology. 08860 Castelldefels (Barcelona), Spain; e-mail: adrien.noury@icfo.es, adrian.bachtold@icfo.es
[b]Department of Physics, ETH Zürich, CH-8093 Zürich, Switzerland
[c]Chalmers, Department of Physics, SE-41296 Gothenburg, Sweden

When a graphene layer is suspended over a circular hole, the graphene vibrates as a music drum. However, the graphene drum has an extremely small mass, since the graphene is only one atom thick. Another difference is the quality factor Q, which becomes extremely large in graphene resonators at cryogenic temperature (Q above 1 million[1]). Because of this combination of low mass and high quality factor, the motion is enormously sensitive to external forces, such as the radiation pressure of photons. Here, we couple the graphene resonator to a superconducting cavity via a radiation pressure-like force[2]. We sideband cool the graphene motion to an average phonon occupation of 7.2 phonons, approaching the quantum ground-state[3]. The superconducting cavity is also used as an efficient transducer of the graphene motion with a displacement sensitivity of 1.3 fm/Hz$^{1/2}$. In particular, it allows us to use the graphene resonator as a fantastic force sensor with a sensitivity of 390 zN/Hz$^{1/2}$, approaching the fundamental limit imposed by thermo-mechanical noise. The efficient transduction also allows us to probe the energy decay in atomically-thin mechanical resonators with an unprecedented accuracy. We find that energy decays in a way that has thus far never been observed nor predicted[1].

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Cooling and Squeezing in pulsed optomechanics

G. M. Palma

3NEST, Istituto Nanoscienze-CNR and Dipartimento di Fisica e Chimica, Università degli Studi di Palermo, via Archirafi 36, I-90123 Palermo, Italy, email: massimo.palma@unipa.it

The optomechanical coupling between micromechanical oscillators and light allows not only for the cooling of the fluctuations of the mechanical mode but also for the engineering of non trivial joint states of the field and the mechanical modes characterized by entanglement and squeezing. In this talk we will show how the amount of cooling, squeezing and entanglement can be controlled by a suitable pulsed pumping of the field mode. Furthermore we will show how the effect such pulsed pumping can be viewed as a tool to engineer an effective bath for the mechanical mode.

Quantum-limited estimation of continuous spontaneous localisation in hybrid optomechanical systems

M. Paternostro

School of Mathematics and Physics, Queen's University, Belfast BT7 1NN, UK
email: m.paternostro@qub.ac.uk

In this talk I will apply the formalism of quantum estimation theory to extract information about potential collapse mechanisms of the continuous spontaneous localisation (CSL) form. In order to estimate the strength with which the field responsible for the CSL mechanism couples to massive systems, I will consider the optomechanical interaction between a mechanical resonator and a cavity field, demonstrating the experimental viability of strategies for the estimation of the coupling strength by either probing the oscillator or the electromagnetic field that drives its motion. In particular, I will concentrate on all-optical measurements, such as homodyne and heterodyne measurements and compare the performances of such strategies with those of a spin-assisted optomechanical system, where the estimation of the CSL parameter is performed through time-gated spin-like measurements.

Optomechanical quantum non-demolition measurement of optical field fluctuations

A. Pontin[1, 2], M. Bonaldi[3, 4], A. Borrielli[3, 4], L. Marconi[5], F. Marino[2, 5], G. Pandraud[6], G. A. Prodi[4, 7], P.M. Sarro[6], E. Serra[4, 6], F. Marin[1, 2, 5, 8]

[1]Dipartimento di Fisica e Astronomia, Università di Firenze, Via Sansone 1, I-50019Sesto Fiorentino (FI), Italy

[2] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Firenze, Via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy

[3]Institute of Materials for Electronics and Magnetism, Nanoscience-Trento-FBK Division, 38123 Povo, Trento, Italy

[4] INFN, Trento Institute for Fundamental Physics and Application, I-38123 Povo, Trento, Italy

[5] CNR-INO, L.go Enrico Fermi 6, I-50125 Firenze, Italy

[6] Delft University of Technology, Else Kooi Laboratory, 2628 Delft, The Netherlands

[7] Dipartimento di Fisica, Università di Trento, I-38123 Povo, Trento, Italy

[8] European Laboratory for Non-Linear Spectroscopy (LENS), Via Carrara 1, I-50019 Sesto Fiorentino (FI), Italy

According to quantum mechanics, there exists a class of observables for which is possible to confine the perturbation produced by a continuous measurement to the conjugate variable. Therefore, it is possible to devise experimental schemes that allow estimating the observed variable with arbitrary accuracy, or preparing it in a well-known state. Such schemes are referred to as quantum non-demolition measurements (QND). Among these observables there is the amplitude of the light field. Indeed, it is possible to exploit a movable mirror to implement a QND scheme[1)]. Intensity fluctuations of an optical field impinging on it are not affected by the interaction. However, the movable mirror is excited by the associated radiation pressure. This, in turn, affects the phase of the field.

We have performed an optomechanical experiment, based on a Fabri-Pérot cavity in which the end mirror is a high Q micro-mechanical device[2)], where we have simultaneously measured intensity fluctuations of the field reflected by the cavity and the mirror motion imprinted in the phase fluctuations. By exploiting the correlations between these variables, we demonstrate a reduced uncertainty on intensity fluctuations actually reaching a sub-shot noise level.

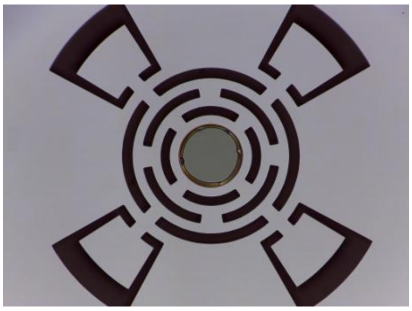

Fig. 1 SEM image of the micro-mechanical device with the central, 0.4 mm diameter, mirror.

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Integrated optomechanics and linear optics quantum circuits

M. Poot[a,b], H. X. Tang[c]

[a]*Yale University, Department of Electrical Engineering; 55 Prospect St., New Haven, Connecticut, U.S.A., CT 06511 e-mail: menno.poot@yale.edu*
[b]*Delft University of Technology, Kavli Institute of Nanoscience; Lorentzweg 1, 2628CJ, Delft, The Netherlands*
[c]*Yale University, Department of Electrical Engineering; 55 Prospect St., New Haven, Connecticut, U.S.A., CT 06511 e-mail: hong.tang@yale.edu*

Integrated optics provides unprecedented flexibility, scaling possibilities, and stability in the design of optical circuits. In this talk I will address two topics in this rapidly developing field. By combining movable structures with electrostatic actuation we developed a opto-electromechanical platform that can be employed as a broadband integrated phase shifter[1]. These devices are also an excellent test ground for optomechanics experiments directed towards the quantum regime. In vacuum, quality factors up to 300 000 are observed in this device. Using nonlinear feedback in combination with parametric squeezing we prepare the resonator in (classical) non-Gaussian states[2]. However, when increasing the parametric driving strength, instabilities occur that limit the amount of squeezing that can be realized. However, by parametrically driving in the presence of a real-time stabilization of the unstable quadrature, 15 dB of thermo-mechanical noise squeezing is demonstrated[3]. Extensions of this technique towards quantum squeezing are discussed.

In the second part, I will discuss our efforts[3,4] towards fully-integrated linear-optics quantum circuits. Optomechanical devices play an important role in this research. In our vision, superconducting single photon detectors are monolithically embedded on the same chip as the quantum circuitry. To prepare the qubits and to perform tomography on them, our optomechanical phase shifters are employed. We show the design, fabrication, and characterization of the important elements, including directional couplers, photonic CNOT gates, phase detection, and SSPDs.

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From photon-phonon correlations towards fundamental tests of standard quantum theory

R. Riedinger[a], S. Hong[a], D. Grass[a], U. Delic[a], L. Magrini[a], J. Hofer[a], P. Köhler[a], R. A. Norte[b], J. A. Slater[a], N. Kiesel[a], J. Shang[c], A. G. Krause[b], V. Anant[c], S. Gröblacher[b], M. Aspelmeyer[a]

[a]*Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Wien, Austria; e-mail: ralf.riedinger@univie.ac.at*
[b]*Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628CJ Delft, The Netherlands; e-mail: s.groeblacher@tudelf.nl*
[c]*Photon Spot Inc., Monrovia, 142 W. Olive Ave. California 91016, USA,; e-mail:* v*ikas.anant@photonspot.com*

The concept of a photon-phonon mechanical quantum transducer requires quantum correlations of a mechanical element and the electromagnetic field. For microwave fields optomechanical entanglement was demonstrated for continuous variables[1]. Here we report the observation of non-classical correlations between a nanomechanical resonator and an optical field on the single quantum level[2].

While the mechanical states generated in these experiments have genuine quantum features, the displacement is limited and fundamental tests of the quantum theory hard to achieve. This can be overcome by changing to non-clamped mechanical resonators, where dynamic reshaping of the potential landscape is possible. We report on recent advancements in optically and magnetically levitated systems.

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Magnetic Levitation in Quantum Nanomechanics: New Opportunities

Oriol Romero-Isart

Institute for Quantum Optics and Quantum Information of the
Austrian Academy of Sciences and Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria; e-mail: oriol.romero-isart@uibk.ac.at

Several experimental groups are trying to bring and control the center-of-mass of an optically levitated dielectric nanosphere in the quantum regime. In this talk I will discuss and motivate an alternative approach based on magnetic levitation of nano- and micromagnets. In the first part of the talk we will discuss a recent theoretical proposal for an all-magnetic on-chip quantum interferometer scheme capable to prepare large quantum superpositions of a superconducting microsphere with a mass of 10^13 amu's. As a figure of merit, we show that at such mass and superposition size scales, the faint gravitationally-induced decoherence model proposed by Penrose and Diósi in the 80's could be unambiguously falsified. In the second part of the talk, we will discuss the possibility to magnetically levitate a single magnetic domain nanoparticle. We will show that at such small scales the Einstein-De Haas effect plays a crucial role in the stability of the trap. We will further discuss some on-going work on the possibility to bring the degrees of freedom of the nanomagnet in the quantum regime, namely the center-of-mass, the orientation, and the macrospin degree's of freedom.

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Nonreciprocity and magnetic-field free isolation based on optomechanical interactions

Freek Ruesink[a], Mohammad-Ali Miri[b], Andrea Alù[b], and Ewold Verhagen[a]

[a]*FOM Institute AMOLF, Center for Nanophotonics, Science Park 104, 1098 XG Amsterdam, The Netherlands; e-mail: ruesink@amolf.nl*

[b]*University of Texas at Austin, Department of Electrical and Computer Engineering, 1616 Guadalupe St., UTA 7.215, Austian, TX 78701, USA*

Photonic elements that break Lorentz reciprocity allow to control the flow of light in unusual ways, and provide functionality such as isolation and circulation that would be particularly useful in compact, on-chip systems. A possible route towards violating reciprocity without a magnetic field relies on a spatiotemporal modulation of the refractive index, which is straightforwardly achieved in optomechanical systems. We derive the minimal requirements to create nonreciprocity in a wide class of optomechanical systems that involve a pair of optical modes coupled to a mechanical mode. These conditions highlight the importance of an appropriately tailored phase difference between the intra-cavity bias photons of the two optical modes. We utilize these principles to demonstrate up to 10 dB optical isolation telecom wavelengths in a silica microtoroid optomechanical system. In line with our theoretical model, nonreciprocal transmission is preserved in the case of non-degenerate modes and also yields nonreciprocal parametric amplification. Our results open a route to creating a broad variety of nonreciprocal effects in optomechanical systems in any electromagnetic and mechanical frequency regime, including optomechanical metameterials with new topologically properties.

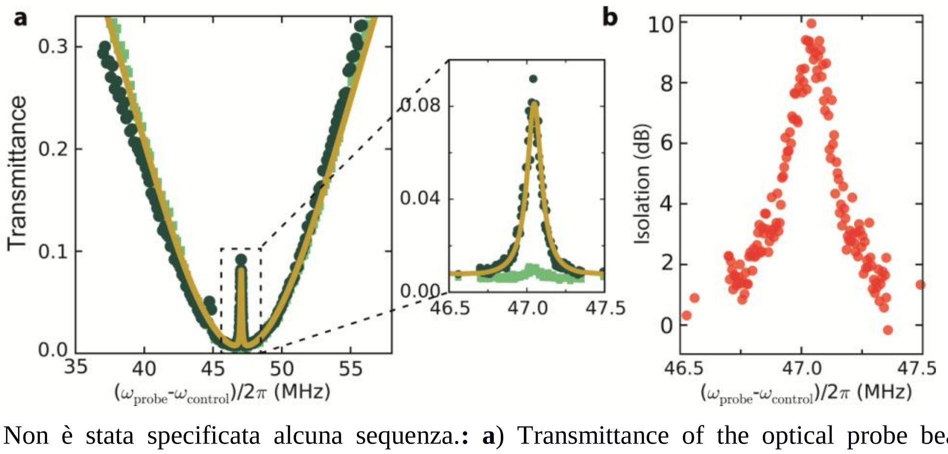

Figure Errore. Non è stata specificata alcuna sequenza.**: a**) Transmittance of the optical probe beam as a function of probe-control detuning with the control frequency tuned to the red mechanical sideband. When the probe beam co-propagates (dark-green circles) with the control beam, an Optomechanically Induced Transmission (OMIT), which is absent when the control and probe counter-propagate (light-green squares) thus resulting in non-reciprocal optical transmission. The solid yellow line is a fit of the non-reciprocal transparency window to the dark-green circles. b) The resulting isolation, quantified as the ratio of the measured transmittance of the probe beam in both directions.

Squeezing and amplification in microwave optomechanics

C. Ockeloen-Korppi[a], E. Damskägg[a], J.-M. Pirkkalainen[a], T. T. Heikkilä[b], F. Massel[b], and M. A. Sillanpää[a]

[a] *Department of Physics, Aalto University, P.O. Box 15100, FI-00076 AALTO, Finland.*
[b] *Department of Physics and Nanoscience Center, University of Jyväskylä, P.O. Box 35 (YFL), FI-40014 University of Jyväskylä, Finland.*

According to the principles of quantum mechanics, it is not possible to construct an amplified perfect copy of an oscillatory signal. A process which leads to strong amplification of both the quadrature amplitudes, thus yielding information about the amplitude and phase of the oscillations, necessarily adds noise at least an amount equal to the zero point fluctuations of the meter. This fundamental limit, known as the standard quantum limit (SQL), has been reached in microwave frequency experiments taking advantage of nonlinearities of Josephson junctions. Alternatively, if the information in one quadrature is lost in a phase-sensitive amplification process, it is in principle possible to make an amplified complete reconstruction of the other quadrature. Here we introduce such a nearly perfect phase-sensitive measurement based on mechanical oscillations, characterized by an immeasurably small noise less than 0.2 quanta at gigahertz frequencies. We use a cavity optomechanical scheme involving a micromechanical aluminum drum, coupled to a superconducting microwave cavity. A reservoir engineering approach using two microwave pump tones enables designing a system that has the mechanical oscillator acting as a dissipative reservoir, which drives the cavity into a nonclassical steady state. Phase-sensitivity also allows us to create strongly squeezed itinerant microwave radiation where the vacuum fluctuations are suppressed by 4 decibels below SQL over a broad band. A source of bright squeezed microwaves opens up applications in manipulations of quantum systems, and noiseless amplification allows for sensitive detection when operated at modest cryogenic temperatures.

Microwave optomechanics in a 3D superconducting cavity with an (ultra) high-Q silicon nitride membrane

Mingyun Yuan, Vibhor Singh, Yaroslav M. Blanter, Gary A. Steele

Kavli Institute of NanoScience, Delft University of Technology, PO Box 5046, 2600 GA, Delft, The Netherlands email: g.a.steele@tudelft.nl

In this talk, I will present recent results from our group implementing microwave optomechanics in a 3-dimensional superconducting microwave cavity. In comparison to conventional planar cavities, the 3D architecture offers the possibility of scaling to quality factors exceeding 10^8, enabling microwave cavity linewidths down to the range of a few Hz. Here, we couple the motion of a mm-sized silicon nitride membrane to 30 mm microwave photons in the superconducting cavity using an antenna configuration inspired by recent 3D superconducting qubit experiments. With a cavity Q of 10^5 and a mechanical Q up to 128 million, we achieve a large cooperativity of up to 10^5 and demonstrate cooling of the membrane motion to 35 microkelvin, 5.2 thermal quanta. Future experiments optimizing the 3D cavity quality factor and incorporating trampoline resonators, we expect to be able to cool deep into the quantum ground state, push deep into the radiation pressure shot noise limit, and ultimately approach the limit of single-photon strong coupling.

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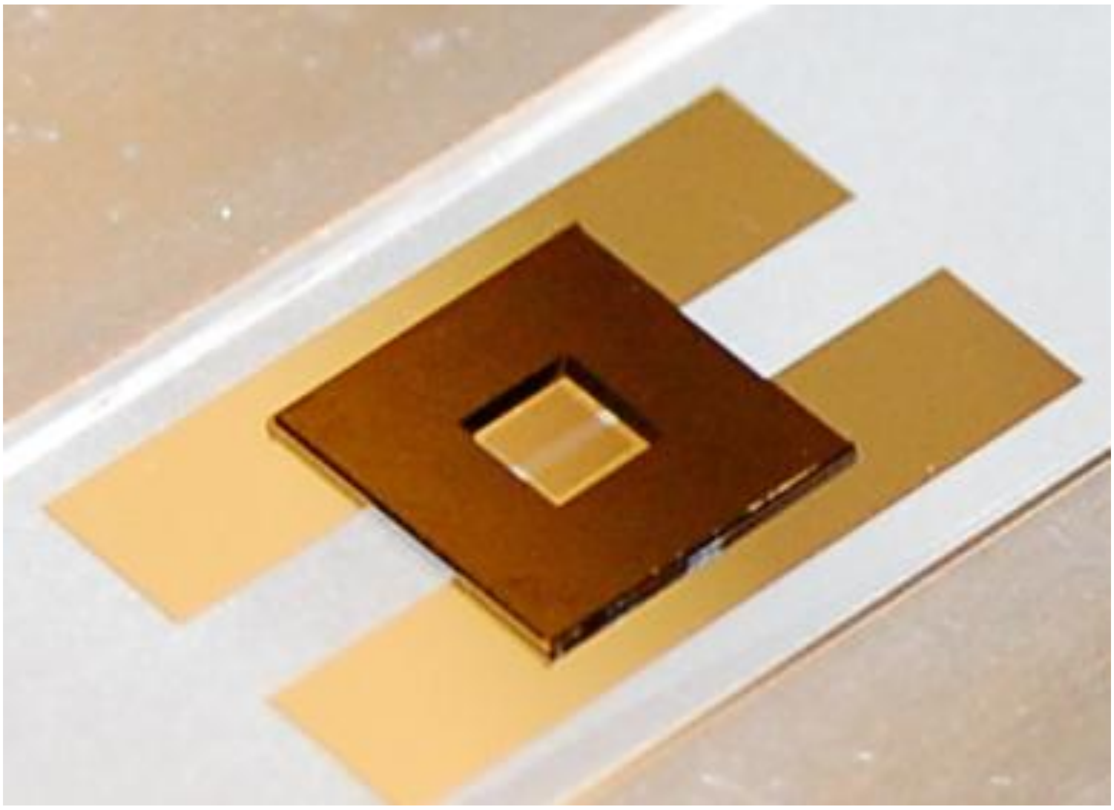

Towards testing quantum gravity by quantum-enhanced interferometry

P. Traina

Istituto Nazionale di Ricerca Metrologica (INRiM), Strada delle Cacce 91, 10135 Torino, Italy
email: p.traina@inrim.it

The dream of building a theory unifying general relativity and quantum mechanics, the so-called quantum gravity (QG), has pushed theoretical physics research for decades, even if for many years no testable prediction emerged from these studies. Some QG theories predict the non-commutativity of position variables at Planck scale inducing a slight random wandering of transverse position (called "holographic noise"). This noise could be in principle experimentally detected, but is expected to be extremely faint, requiring non-standard techniques for its revelation. Recently, to measure the possible existence of the "holographic noise", the FermiLab "Holometer", a system of two coupled 40-m-long Michelson interferometers with unprecedented sensitivity to cross-correlated signals in a broad frequency band, was built. On the other hand, a sub-shot-noise phase measurement in a single interferometer (e.g. gravitational wave detector) exploiting squeezed light was suggested [1,2] and recently realized [3]. Here we discuss the enhancement in sensitivity [4] that can be obtained by introducing the use of quantum light in a holometer-like experiment, and prompted by these considerations we present the efforts at INRIM to realize an analogous system on a table-top scale with the aim of reaching, in a foreseeable future, a phase sensitivity almost comparable with the one obtained at FermiLab.

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Advanced Virgo: status and gravitational waves detections

F. Travasso [a,b]

[a] *Department of Physics and Geology, University of Perugia, via Pascoli, 06123 Perugia;*
[b] *INFN - Perugia, via Pascoli, 06123 Perugia*
e-mail: flavio.travasso@pg.infn.it

On 11 February 2016, the LIGO - Virgo collaboration has announced the detection of gravitational waves from a coalescing black hole binary system during the first observational run with the Advanced LIGO detectors(1).

This presentation describes the Advanced Virgo experiment, its status, the mechanical solutions and optical scheme used to reduce the noises in the system and to increase its sensitivity till 10^{-21}m @100Hz(2).

The observed signals of two events and one candidate event are also presented and their impact on current black hole population models is discussed.

Furthermore, we stress the importance of a strong collaboration between LIGO, Virgo and the future GW detectors in order to increase the detection significance and to improve the sky localization of the GW sources.

Finally, we highlight the necessity to extend this strong collaborative attitude to all concerned astrophysical communities, in order to start the era of GW astrophysics.

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Classical Stückelberg interferometry with a nanomechanical two-mode system

Eva Weig[1]

[1]*Department of Physics, University of Konstanz, 78457 Konstanz, Germany*

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].

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Topological Energy Transfer in an Optomechanical System with Exceptional Points

H. Xu[a], D. Mason[a], L. Jiang[a], J. G. E. Harris[a,b]

[a]*Department of Physics, Yale University, New Haven, Connecticut 06511, USA.*
[b]*Department of Applied Physics, Yale University, New Haven, Connecticut 06511, USA.*

Exceptional points are topological singularities in the spectrum of an open system where complex eigenvalues of the underlying non-Hermitian Hamiltonian coalesce. It was predicted that topological operations can be used to transfer energy between normal modes provided the system possesses an exceptional point[1-3]. We show the existence of an exceptional point in a cryogenic optomechanical system, and demonstrate the transfer of energy between two vibrational modes using topological operations[4]. We also show that the topological energy transfer is non-reciprocal[5-7].

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Optimizing electro-optomechanical transduction using equivalent circuits

E. Zeuthen[a,b], A. Schließer[a], J. M. Taylor[c,d], and A. S. Sørensen[a]

[a] *Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark*
[b] *Institute for Theoretical Physics & Institute for Gravitational Physics (Albert Einstein Institute), Leibniz Universität Hannover, Callinstraße 38, 30167 Hannover, Germany;*
e-mail: emil.zeuthen@itp.uni-hannover.de
[c] *Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, Gaithersburg, Maryland 20899 USA*
[d] *Joint Center for Quantum Information and Computer Science, National Institute of Standards and Technology and the University of Maryland, College Park, Maryland 20742 USA*

A mechanical oscillator can serve as an efficient link between electromagnetic modes of different frequencies. We find that such a transducer can be characterized by two key parameters, the signal transfer efficiency and added noise temperature. In terms of these, we evaluate its performance in various tasks ranging from classical signal detection to quantum state conversion between, e.g., superconducting circuitry and traveling optical signals.

Having established the requirements for efficient performance, we turn to the question of optimization. We address this by developing a unifying equivalent-circuit formalism for electro-optomechanical transducers. This approach accommodates arbitrary linear circuits and integrates the novel optomechanical transduction functionality into the well-established framework of electrical engineering, thereby facilitating its implementation in potential applications such as nuclear magnetic resonance imaging and radio astronomy. We consider such optomechanical sensing of weak electrical signals and discuss how the equivalent circuit formalism can be used to optimize the electrical circuit design. We also discuss the parameter requirements for transducing microwave photons in the quantum regime.

Participants

Surname, Name	Institution	e-mail
Bassi, Angelo	Università di Trieste	bassi@ts.infn.it
Bigongiari, Alessandra	Università di Pisa	alessandra.bigongiari@df.unipi.it
Buchheit, Andreas	Universitat des Saarlandes	andreas.buchheit@gmail.com
Cantatore, Giovanni	Università di Trieste	giovanni.cantatore@ts.infn.it
Cernotik, Ondrej	Universitat Hannover	ondrej.cernotik@itp.uni-hannover.de
Cohadon, Pierre-Francois	Laboratoire Kastler Brossel, ENS	cohadon@lkb.upmc.fr
Fink, Johannes	Institute of Science and Technology Austria	jfink@ist.ac.at
Gil-Santos, Eduardo	Université Paris Diderot	eduardo.gil-santos@paris7.jussieu.fr
Giovannetti, Vittorio	Scuola Normale Superiore Pisa	v.giovannetti@sns.it
Groblacher, Simon	Delft University of Technology	s.groeblacher@tudelft.nl
Higgonbotham, Andrew	JILA, University of Colorado, Boulder	andrew.higginbotham@colorado.edu
Kaikkonen, Jukka-Pekka	Aalto University	jukka-pekka.kaikkonen@aalto.fi
Feofanov Alexey	Ecole Politechnique Lausanne	alexey.feofanov@epfl.ch
Kralj, Nenad	Università di Camerino	nenad.kralj@unicam.it
Malossi, Nicola	Università di Camerino	nicola.malossi@unicam.it
Marchesoni Fabio	Università di Camerino	fabio.marchesoni@pg.infn.it
Marin, Francesco	Università di Firenze	marin@fi.infn.it
Marquardt, Florian	Universitat Erlangen-Nurnberg	florian.marquardt@physik.uni-erlangen.
Moadel Haghighi, Iman	Università di Camerino	imanmoaddel.haghighi@unicam.it
Muhonen, Juha	AMOLF Amsterdam	J.Muhonen@amolf.nl
Naticchioni, Luca	Università di Roma La Sapienza	luca.naticchioni@roma1.infn.it
Noury, Adrien	ICFO Barcelona	adrien.noury@icfo.es
Palma, Massimo	Università di Palermo	massimo.palma@unipa.it
Paternostro, Mauro	Queen's University, Belfast	m.paternostro@qub.ac.uk
Pontin, Antonio	Università di Firenze	pontin@fi.infn.it
Poot, Menno	Delft University of Technology	mennopoot@gmail.com
Riedinger, Ralf	Universitat Wien	ralf.riedinger@univie.ac.at
Romero-Isart, Oriol	Universitat Innsbruck	oriol.romero-isart@uibk.ac.at
Ruesink, Freek	AMOLF Amsterdam	F.Ruesink@amolf.nl
Sillanpaa, Mika	Aalto University	mika.sillanpaa@aalto.fi
Steele, Gary	Delft University of Technology	g.a.steele@tudelft.nl
Traina, Paolo	INRIM Torino	p.traina@inrim.it
Travasso, Flavio	Università di Perugia	flavio.travasso@pg.infn.it
Vitali, David	Università di Camerino	david.vitali@unicam.it
Weig, Eva	Universitat Konstanz	eva.weig@uni-konstanz.de
Xu, Haitan	Yale University	haitan.xu@yale.edu
Zeuthen, Emil	Universitat Hannover	emil.zeuthen@itp.uni-hannover.de