Abstracts of Talks

Groupement de recherche
MecaQ Optomécanique & Nanomécanique Quantiques

Single Mesoscopic Phononic Mode Thermodynamics

Ilya Golokolenov[a*], Arpit Ranadive[a], Luca Planat[a,b], Martina Esposito[a], Nicolas Roch[a], Xin Zhou[c], Andrew Fefferman[a] and Eddy Collin[a]

a. Institut Néel UGA - CNRS, 25 rue des Martyrs, 38042 Grenoble, France
b. Silent Waves, 25 rue Ponsard, 38100 Grenoble, France
c. IEMN, U.Lille - CNRS, av.Henri Poincaré, 59650 Villeneuve d'Ascq, France

* ilya.golokolenov@neel.cnrs.fr

We report on an experimental technique that enables us to track fluctuations in a mesoscopic mechanical object cooled to millikelvin temperatures. It is based on the measurement of a mode's motion by means of a microwave cavity to which it couples. We achieve the extreme sensitivity required for these measurements using two stages of parametric amplification in series with a more conventional measurement chain. In particular, we use a quantum-limited travelling wave parametric amplifier (TWPA) preceded by built-in optomechanical gain induced by blue-sideband pumping.

We present the direct observation of a *single phononic mode* real-time energy fluctuations, from its statistical distribution (PDF) and power spectral density (PSD, see Figure). We demonstrate that we can separate the true thermodynamics contribution from material-dependent effects, presumably linked to TLS defects (two-level systems). The latter produces a strong 1/f contribution visible in the PSD. For the former, we resolve the frequency cutoff at Γ_m in the PSD and the specific exponential distribution of the PDF, which are characteristic of a single mode with energy relaxation rate Γm. These stochastic thermodynamics results realised in the classical limit of the mode will be extended to the quantum regime in the future [1].

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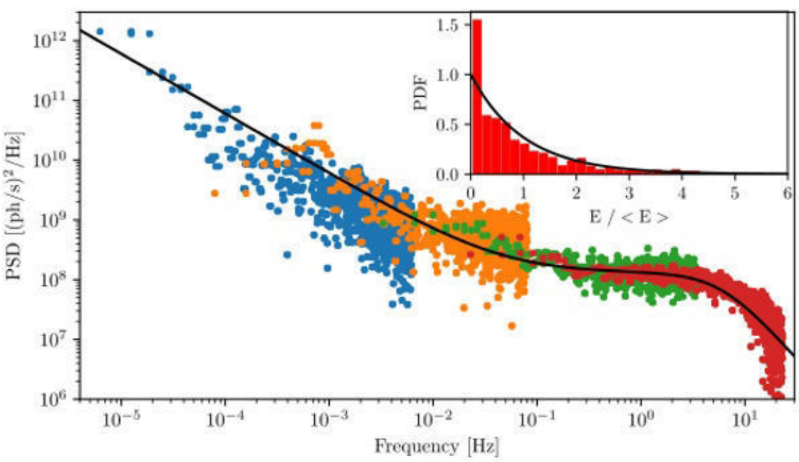

Figure 1 : Power Spectral Density (PSD, main) and normalised Probability Distribution Function (PDF, inset) of measured photon flux at 200 mK. Colours for different acquisition speed; black solid lines are fits.

System for studying optomechanical parametric instability and its active mitigation

M.Turconi[a*], T. Harder[a], R. Soulard[a] and W. Chaibi[a]

a. Université Côte d'Azur, CNRS, OCA, ARTEMIS,
* margherita.turconi at oca.eu'

Parametric instability (PI) is an optomechanical phenomenon that affects the stability of Fabry-Perot cavities and thus it can drastically limit the sensitivity of gravitational wave (GW) detectors. GW detectors based on laser interferometry are indeed very sensitive optomechanical systems composed of km-scale Fabry-Perot cavities with high mechanical quality suspended mirrors and very high circulating power (design value: 800kW). PI consists in the amplification of a mirror's mechanical mode, due to radiation pressure exerted by the resonant optical field which is scattered by the mirror's vibrations themselves. The first PI was observed in the LIGO detectors in 2015 [1], preventing the detector functioning at only 50kW of circulating power. Several PI mitigation techniques were implemented in LIGO [2] that allowed to operate the detectors up to 200kW. We propose an active and flexible PI mitigation strategy based on radiation pressure of a movable laser beam (Fig. 1A) that is potentially very promising for mitigation of PI in third generation of GW detectors that aims at improving 10 times the sensitivity with >1 MW of circulating power. A key part of this technique is a 2D deflection system which needs to be fast and stand high power beams. We will show the results obtained with 2 acousto-optic deflectors. A maximal deflection frequency of 10 MHz is reached with a 3.6W beam which is stable over the whole deflection range (Fig. 1B). This technique will be studied and validated on a table-top cavity.

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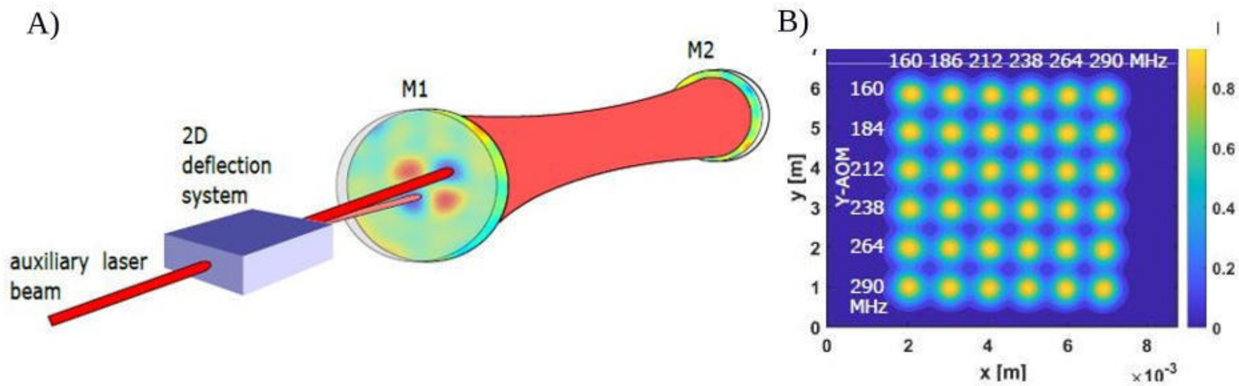
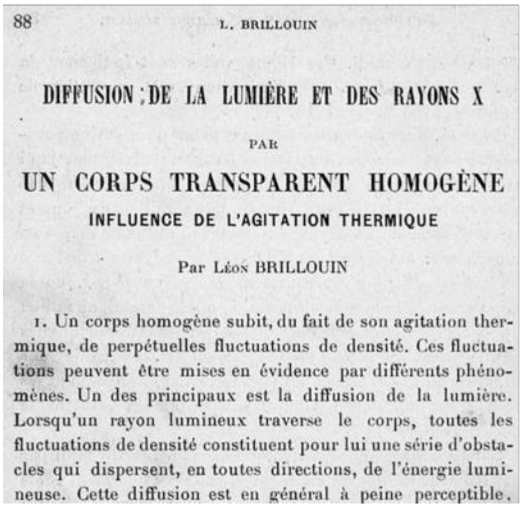


Figure 1 : A) Schematics representing the working principle of the PI attenuation strategy based on radiation pressure. An auxiliary laser impinges and is reflected on a movable mirror of a FP cavity affected by PI, the 2D deflection system allows to apply a damping force with a good spatial overlap with the PI. B) Demonstration of the 2D beam deflection. The image is obtained with a long exposure time while the beam is moved row by row from top to bottom every 3µs. The maximal angular amplitude is 34 mrad in 1D, the beam size impinging on the mirror depends on the propagation length after the 2D deflection system.

Centenary of Brillouin scattering : from fundamentals to applications

BEUGNOT Jean-Charles

In 1922, Léon Brillouin published an article in the "Comptes Rendus de Physique" on the scattering of light by acoustic waves originates form thermal fluctuations. He theoretically demonstrates, for the first time, that these acoustic waves induce a frequency shift of the scattered light. The invention of lasers made this scattering very efficient and open many technological and industrial developments in materials spectroscopy, medical microscopy, lasers and distributed fiber optic sensors.



88 L. BRILLOUIN

DIFFUSION DE LA LUMIÈRE ET DES RAYONS X

PAR

UN CORPS TRANSPARENT HOMOGÈNE

INFLUENCE DE L'AGITATION THERMIQUE

Par Léon BRILLOUIN

1. Un corps homogène subit, du fait de son agitation thermique, de perpétuelles fluctuations de densité. Ces fluctuations peuvent être mises en évidence par différents phénomènes. Un des principaux est la diffusion de la lumière. Lorsqu'un rayon lumineux traverse le corps, toutes les fluctuations de densité constituent pour lui une série d'obstacles qui dispersent, en toutes directions, de l'énergie lumineuse. Cette diffusion est en général à peine perceptible.

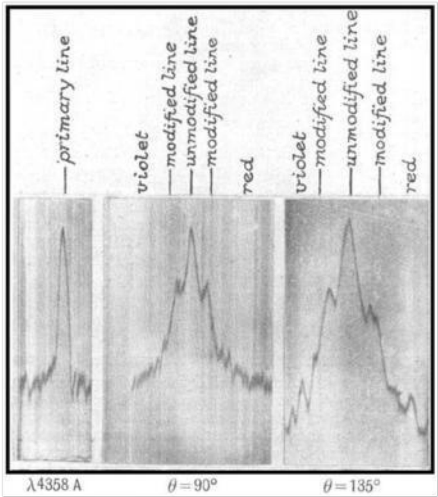


Figure 1 : Left, copy of the first page of the paper published by Léon Brillouin in 1922. Right, Experimental verification of Brillouin scattering in benzene By E. Gross in 1930.

Current Affiliation:
Institut FEMTO-ST
CNRS UMR 6174 / Université de Franche Comté
15b, Avenue des Montboucons,
25030 Besançon

Dynamical and Quantum Backaction Electro-Optics

Presenter: J. M. Fink
Institution: Institute of Science and Technology Austria (ISTA)
Email: jfink@ist.ac.at

We introduce a multi-mode cavity electrooptic system [1, 2] that exhibits the physics known from cavity optomechanics [3] except that the mechanical mode is replaced by a microwave cavity to which we have direct access. We show efficient (15%) and quantum-enabled (Nin < 1) conversion between microwave and telecom wavelength photons [4], as well as dynamical and quantum back-action that gives rise to electromagnetically induced transparency and two-mode squeezing between microwave and optical fields (in preparation).

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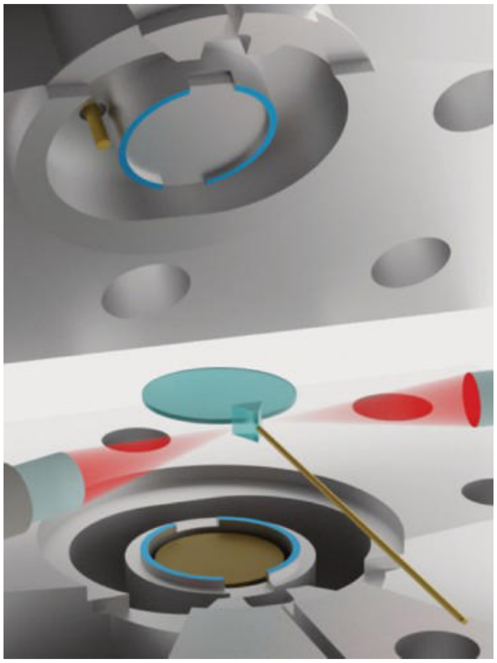
This image shows an exploded view rendering of the electro-optic device consisting of a lithium niobate whispering gallery mode optical resonator sandwiched between two halves of a tunable 3D superconducting microwave cavity.



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Sub-Hz closed loop electro-optomechanical oscillator with gallium phosphide photonic crystal integrated on SoI circuitry

Róbert Horváth[a,*], Giuseppe Modica[a], Inès Ghorbel[b], Grégoire Beaudoin[a], Konstantinos Pantzas[a], Isabelle Sagnes[a], Aude Martin[b], Alfredo de Rossi[b], Sylvain Combrié[b], Rémy Braive[a,c,d]

a. C2N – CNRS/Université Paris-Saclay, Palaiseau, France
b. Thales Research & Technologies, Palaiseau, France
c. Université Paris Cité, Paris, France
d. Institut Universitaire de France (IUF)

* robert.horvath@c2n.upsaclay.fr

Optomechanical resonators combine mechanical and optical resonators coupled by a nonlinear interaction, resulting in self-sustained oscillations. Optomechanical crystals are their nanoscale counterpart, whereby the operating optical power scales down with size dramatically. This has opened prospects for a wide range of applications in microwave photonics, from sensing to quantum computing.

Within this frame, we demonstrate a Gallium-phosphide one-dimensional optomechanical crystal (OMC), heterogeneously integrated on top of a silicon on insulator circuitry. Mechanical self-oscillation, characterized with a sharp decrease of the signal linewidth, is observed for certain wavelength detuning. In order to improve the signal stability an electro-optomechanical feedback loop is constructed, using integrated electrodes fabricated next to the OMC (seen in yellow on Fig 1a). The electric field between the electrodes is directly actuating the OMC by taking advantage of the piezoelectric properties of the material. A low phase noise of -111 dBc/Hz at 100 kHz offset frequency (illustrated on Fig 1b) is achieved thanks to the stabilization feedback.

This approach provides a system which bridges the gap between size and performance and makes optomechanical oscillators competitive with current microwave signal generators. Such coherent oscillation directly in the optical domain on a nanoscale device integrated with silicon circuits opens new avenues in microwave photonic circuits and even in photonic reservoir computing.

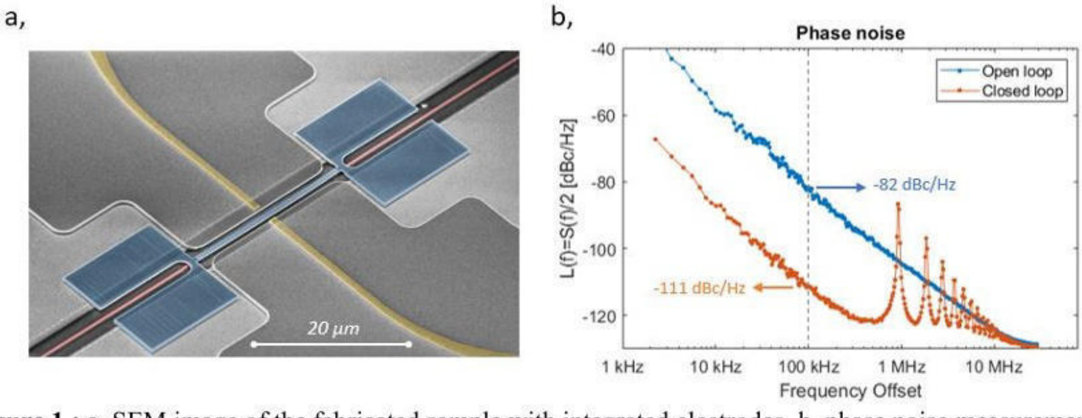

Figure 1 : a, SEM image of the fabricated sample with integrated electrodes. b, phase noise measurement of the open and closed loop optomechanical oscillator

Enhanced Cavity Optomechanics with Quantum-Well Exciton Polaritons

N. Carlon Zambon [a,c*], Z. Denis [b], R. De Oliveira [b], S. Ravets [a], C. Ciuti [b], I. Favero [b], and J. Bloch [a]

a. Centre de Nanosciences et de Nanotechnologies (C2N), CNRS-Université Paris-Saclay, 91120 Palaiseau.
b. Université Paris Cité, CNRS, Matériaux et Phénomènes Quantiques, F-75013 Paris, France
c. Current address: Photonics Laboratory, ETH Zürich, CH-8093 Switzerland.
* carlonn@ethz.ch

A key figure of merit in optomechanics is the single-photon quantum cooperativity (C_q). Recent works achieved a large cooperativity by engineering resonators with ultra-low mechanical and optical losses [1]. A complementary approach is to enhance optomechanical interactions while working with modest optical and mechanical quality factors. Less stringent bandwidth limitations in optomechanical conversion are thereby imposed [2], while suppressing optical heating and added noise [1].

In this context, GaAs- based resonators engineered to simultaneously confine photons, phonons and QW excitons offer an intriguing opportunity [3]: in the strong exciton-photon coupling regime the system hosts hybrid quasi-particles, or polaritons. These modes are both spectrally separated from the exciton-induced absorption peak, enabling large optical quality factors, while their excitonic component is extremely sensitive to strain fields owing to the large GaAs deformation potential, thus prospecting strong optomechanical interactions. We analytically model the tripartite interaction of light, QW excitons, and sound in three semiconductor microresonators architectures: when considering parameters complying with current GaAs technologies, we show that a near-unity C_q can be obtained for a single polariton excitation. Furthermore, we investigate how polariton nonlinearities modify dynamical back-action via squeezing [4].

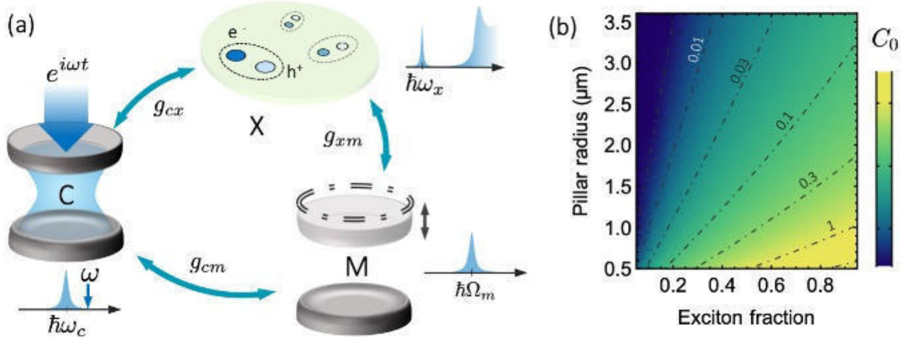

Figure 1 : (a) Sketch of the system: a resonator supports optical and mechanical modes with respective frequencies ω_c and Ω_m and embeds a quantum well supporting an excitonic resonance at ω_x. The modes present tripartite couplings (g_{ij}) and the cavity mode is coherently driven. (b) Single-polariton optomechanical cooperativity in a micropillar resonator as a function of the exciton fraction and of its radius.

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Design of opto-phononic sensing devices based on mesoporous materials

Edson R. Cardozo de Oliveira[a*], Chushuang Xiang[a], Priscila Vensaus[b], Martin Esmann[a], Nicolas L. Abdala[b], Maria C. Fuertes[c], Paula C. Angelomé[c], Omar Ortiz[a], Axel Bruchhausen[d], Hernan Pastoriza[d], Bernard Perrin[e], Galo J. A. A. Soler-Illia[b], and Daniel Lanzillotti-Kimura[a]

a. Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies, 91120 Palaiseau, France
b. Instituto de NanoSistemas – Universidad Nacional de San Martín-CONICET, 1650 Buenos Aires, Argentina
c. Gerencia Química & Instituto de Nanociencia y Nanotecnología, Centro Atómico Constituyentes, CNEA-CONICET, 1650 Buenos Aires, Argentina
d. Centro Atómico Bariloche & Instituto de Nanociencia y Nanotecnología, CNEA-CONICET, R8402AGP Rio Negro, Argentina
e. Sorbonne Université, CNRS, Institut des NanoSciences de Paris, INSP, F-75005 Paris, France

*edson.cardozo@c2n.upsaclay.fr

The manipulation of coherent acoustic waves at the nanoscale usually requires multilayers with thicknesses and interface roughness defined down to the atomic monolayer, [1] resulting in expensive devices with predetermined functionality. Mesoporous materials (Fig. 1(a)) can be good candidates to overcome these limitations. Due to the high surface-to-volume ratio and tailorable mesopores, the incorporation of chemical functionalization to nanoacoustics is possible. Here, we present multilayered resonators based on mesoporous SiO_2 and TiO_2 (Fig 1(b)) with acoustic resonances in the 5-100 GHz range. [2] We characterize the acoustic response using coherent phonon generation and detection experiments. [3] Fig. 1(c) show experimental results of phononic modes in structures with different mesoporous layer thicknesses. Modes up to 30 GHz are confined within the mesoporous layer.

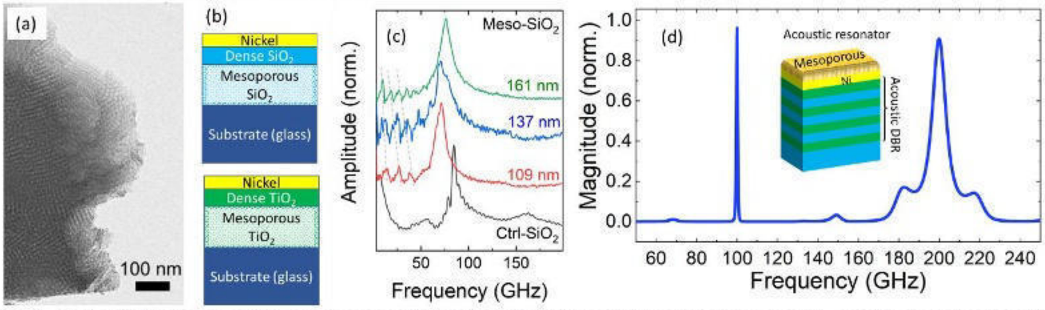

Figure 1 : (a) TEM image of mesoporous thin film. (b) Schematic of the samples. (c) Phononic spectra of samples with different mesoporous layer thicknesses. (d) Simulations of the pump-probe spectra for the proposed structure. Inset shows the layer configuration of the device.

In sensing applications, the mesoporous layer has to have access to the environment and thus be the outermost layer in a structure. [4] We designed new structures based on surface mesoporous spacer cavity on top of an acoustic distributed Bragg reflector to confine phonons at 100 GHz (inset of Fig. 1(d)). Simulations show strong coherent-phonon signals at the designed frequency (Fig. 1(d)). Our findings unveil a promising platform for nanoacoustic sensing and reconfigurable optoacoustic nanodevices based on soft, inexpensive fabrication methods.

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Thermodynamics of information processing, material science, gravitational waves and out-of-equilibrium statistical physics: all-purpose silicon µ-cantilevers

Ludovic Bellon

In this presentation, I will show how thermal noise, far from being just a limitation, can be a precision tool to explore material science as well as a door to puzzling statistical physics phenomena. This serendipity driven random walk though the physics of atomic force microscopy cantilevers [1] will turn out having applications in:
- measurement of the internal dissipation of coatings [2,3]
- gravitational wave detectors [4]
- effective temperature of out of equilibrium systems [5-7]
- cantilever based optical switches [8]
- thermodynamics of information processing [9,10]

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Quantum Thermometry using an optomechanical crystal

Emile Ferreux[a,b*], Ferhat Loubar[a,b], Olga Kozlova[c], , Rémy Braive[d], Tristan Briant[a], Stéphan Briaudeau[b]

a. Laboratoire Kastler Brossel, Sorbonne Université
b. Laboratoire Commun de Métrologie, Conservatoire National des Arts et Métiers
c. Laboratoire National de métrologie et d'Essai
d. Centre de Nanosciences et de Nanotechnologies

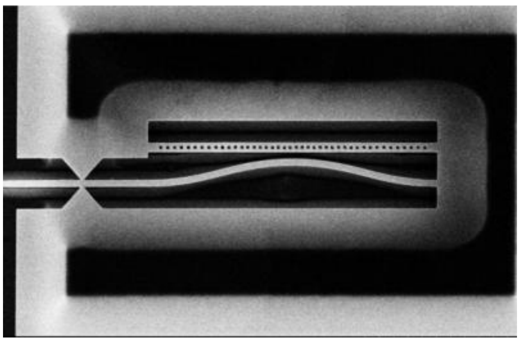
* emile.ferreux@lkb.upmc.fr

In the international system of units, the kelvin was redefined in 2019 by fixing the value of the Boltzmann constant. This project aims to create a quantum thermometer based on this new definition by measuring the Brownian motion of a mechanical resonator.

The sensor used is an optomechanical device that acts as a photonic and phononic crystal, behaving both as a 3 GHz mechanical resonator and a high finesse optical cavity at 1.5 μm.

The measurement is based on noise-thermometry with an optical phase readout in which the thermal noise of the mechanical oscillator is used to measure temperature using the equipartition theorem relating the mean squared displacement of a mechanical resonator to its temperature. Calibrating the effective mass of the resonator and the measure's sensitivity yields a direct temperature measurement.

In term, we wish to get rid of any measurement artifact, thus create a primary thermometer. Making a primary sensor requires making a measurement independent of the effective mass of the resonator. The goal is to use a laser's quantum radiation pressure noise as a reference to calibrate the resonator's thermal noise using the correlations between the quadratures of the field within the resonator.



Studying the thermal properties of silicon carbide nanowires between room and cryogenic temperature

Alex Fontana [1,@] , Clement Goriou, Francesco Fogliano [2] , Olivier Arcizet [3] , Benjamin Pigeau [3]
1 : Institut Néel
Institut polytechnique de Grenoble - Grenoble Institute of Technology, Université Grenoble Alpes, Centre National de la Recherche Scientifique : UPR2940
2 : Department of Physics and Astronomy [Basel]
Klingelbergstrasse 82, CH-4056 Basel - Switzerland
3 : Institut Néel (NEEL) - Website
CNRS : UPR2940, Université Grenoble Alpes
25 rue des Martyrs - BP 166 38042 GRENOBLE CEDEX 9 - France

A common strategy to improve the sensitivity of nano-mechanical force probes such as silicon carbide nanowires (NWs) is to bring these systems at low temperature. Alongside the desired reduction of the damping and the thermal noise, a drawback is that the heat conduction becomes less efficient and the thermal properties of the probes are less understood, hence granting the thermalization of the NW is not trivial.

In order to shed light on the thermal properties of the NWs, we make use of a pump- probe setup [1] (see figure) which can be operated from room temperature down to 32.2 mK. Modulating the laser pump intensity generates heat waves which propagate along the NW, generating a displacement captured by the probe laser. The analysis of the response curves for different parameters, i.e. temperature, pump position, allows us to distinguish the different mechanisms at play, which include temperature-induced reflectivity changes in the NW, photothermal effects, and radiation pressure.

Mid-IR to Visible Optomechanical Transduction with Molecules in a Nanocavity

Christophe Galland

Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

E-mail: chris.galland@epfl.ch

The internal vibrational modes of molecules embedded in plasmonic nanogap can be used as ultrahigh frequency (1 – 50 THz) mechanical oscillators and constitute a new form of optomechanical nanocavities [1]. I will first briefly review recent experiments evidencing quantum correlations that are generated between light and collective molecular vibrations in the process of spontaneous off-resonant Raman scattering [2-5], in the absence of any cavity. Then, I will introduce our work on plasmonic gap modes [6,7] and show that coupling molecular vibrations to properly designed dual-resonant plasmonic cavities [8] allows for the observation of coherent optomechanical transduction between mid-infrared (~32 THz) and visible (~450 THz) electromagnetic fields [9].

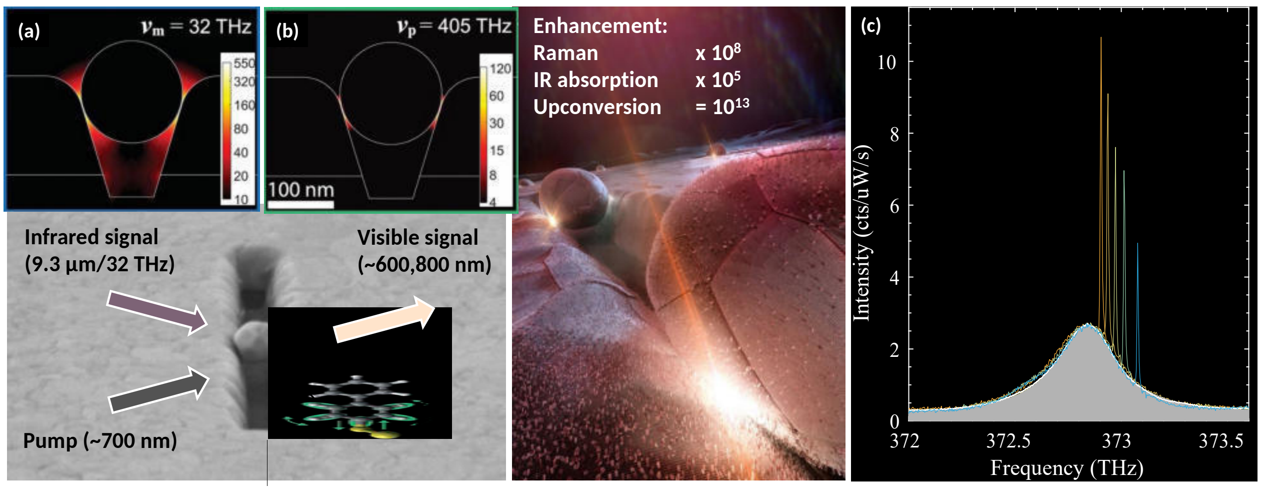


Fig. 1 Coherent frequency conversion with a molecular optomechanical cavity. (a,b) Simulated field enhancement factors for mid-IR and visible illumination. The lower panel shows an SEM picture of the nanoparticle-in-groove cavity, while the right panel is an artistic rendering of the device. Estimated enhancement factors result in 13 orders of magnitude improvement in per-molecule upconversion efficiency. (c) Example of high-resolution Raman spectrum (Stokes sideband, laser at 405 THz) with the upconverted signal (colored lines) riding on the spontaneous emission line (grey shade) as the mid-IR laser frequency is tuned around 32.4 THz (or 1080 cm^{-1}).

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Optimal Cooling of Multiple Levitated Particles: Theory of Far-Field Wavefront-Shaping

Jacob Hüpfl [1] , Nicolas Bachelard [1, 2] , Markus Kaczvinszki [1] , Michael Horodynski [1] , Mathias Kuhmayer [1] , Stefan Rotter [3]
1 : Institute for Theoretical Physics [Vienna]
2 : Laboratoire Ondes et Matière dÁquitaine
Centre National de la Recherche Scientifique : UMR5798, Université de Bordeaux : UMR5798
3 : Technische Universität Wien

The opportunity to manipulate small-scale objects pushes us to the limits of our understanding of physics. Particularly promising in this regard is the interdisciplinary field of levitation, in which light fields can be harnessed to isolate nano-particles from their environment by levitating them optically. When cooled down towards their motional quantum ground state, levitated systems offer the tantalizing prospect of displaying mesoscopic quantum properties. Currently restricted to single objects with simple shapes, the interest in levitation is currently moving towards the manipulation of more complex structures, such as those featuring multiple particles or different degrees of freedom. Unfortunately, current cooling techniques are mostly designed for single objects and thus cannot easily be multiplexed to address such coupled many-body systems. Here, we present an approach based on the spatial modulation of light in the far-field to cool down multiple nano-objects in parallel. Our procedure is based on the experimentally measurable scattering matrix and on its changes with time. We demonstrate how to compose from these ingredients a linear energy-shift operator, whose eigenstates are identified as the incoming wavefronts that implement the most efficient cooling of complex moving ensembles of levitated particles. Submitted in parallel with arxiv:2103.12592, this article provides a theoretical and numerical study of the expected cooling performance as well as of the robustness of the method against environmental parameters.

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GHz acoustic phonon transport in optophononic waveguides

C. Xiang[a*], E. Cardozo de Oliveira[a], O. Ortiz[a], P. Priya[a], A. Rodriguez[a], L. LeGratiet[a], I. Sagnes[a], A. Lemaitre[a], M. Morassi[a], M. Esmann[a], N. D. Lanzillotti-Kimura[a]

a. Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies (C2N), Palaiseau

* email: chushuang.xiang@c2n.upsaclay.fr

During the past decade, confinement of ultrahigh-frequency acoustic phonons in planar structures and micropillars has been achieved [1]. However, coherent manipulation of propagation and dynamics of phonons remains challenging [2][3]. Here, we aim at characterizing the transport of 20 GHz phonons in acoustic waveguides based on GaAs/AlAs multilayers.

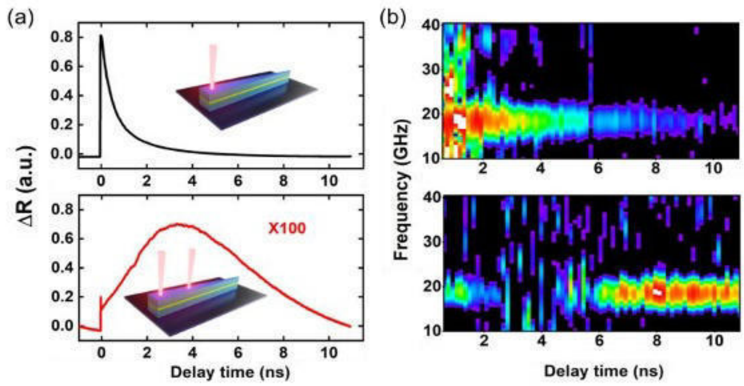

Figure 1 : (a) Time-dependent reflectivity for local measurement (top), where pump and probe beams are focused on the same position, and remote measurement, where probe is separated 8 um from the pump. (b) Short-time Fourier transform results corresponding to the time traces shown in (a).

We used a reflection-type pump-probe technique to generate and detect acoustic phonons. In order to evaluate their transport properties, we performed two kinds of measurements: local and remote pump-probe. We tested the phonon exchange between two positions by spatially separating the phonon generation and detection processes. Time-dependent reflectivity variations for local and remote measurements are shown at the top and bottom panels in figure1(a), respectively. In order to analyze the evolution of acoustic phonons in time, we performed a windowed Fourier transform. For the local experiment (figure 1(b), top panel), the acoustic mode has an exponential decay in time, as observed in standard resonators. When the probe beam is focused at 8 um distance from the pump beam, a delayed 20 GHz wave packet shows up and reaches the maximum amplitude at around 8 ns (figure 1(b), bottom panel). This delayed signal is the first indication of phonon transport in optophononic waveguides. This result is also promising for revealing the fundamental properties of phonon dynamics and manipulating phonon propagation in more complex structures.

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Optomechanical rheology of liquids at gigahertz frequencies

Hamidreza Neshasteh [1,@] , Marco Ravaro [1] , Sébastien Hentz [2] , Guillaume Jourdan [2] , Ivan Favero [1]
1 : Laboratoire Matériaux et Phénomènes Quantiques
Centre National de la Recherche Scientifique : UMR_7162, Université Paris Cité : UMR_7162
2 : CEA, LETI
Université Grenoble Alpes, CEA, LETI, 38000, Grenoble

Investigation of the rheological properties of liquids is of interest for fundamental research and critical for a variety of industrial applications. In the last two decades, microscale rheometers have addressed some intrinsic limitations of conventional measurement techniques, unable to detect phenomena occurring at very small stress or at high rate in complex liquids [1]. In this respect, micro- and nano-optomechanical resonators have recently demonstrated a new potential for mechanical sensing, included of liquids, thanks to their extreme sensitivity to external perturbations [2]. Due to the reduced dimension, their frequency response further extends the range of present state of the art micro-electromechanical fluidic probes, limited to 100MHz. This enables the investigation of the ultra-high frequency fluidic behavior, included the signature of the viscoelastic transition of non-Newtonian liquids [3].

In this contribution we present the use of a semiconductor optomechanical disk resonator for probing the fluidic response at nanoscale and at frequencies exceeding 1 GHz. For a Newtonian liquid, our analytical modeling shows the existence of different dissipation regimes for the radial breathing modes of the resonator immersed in a compressible viscous liquid. While at low frequency the shear viscosity is the main source of dissipation, above 500MHz the mechanical mode energy mainly drives propagating acoustic waves. In the case of complex liquids, the disk mechanical mode is capable of probing the deviation from a Newtonian behavior. These predictions have been confirmed by a set of measurements on water and complex viscous liquids.

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Abstracts of Posters

Two molecules coupled to a nano-mechanical oscillator

Guillaume Bertel*[1] and Fabio Pistolesi[1]

[1]Laboratoire Ondes et Matière d'Aquitaine – LOMA, Université de Bordeaux, CNRS, UMR 5798, Talence, F-33405, France. – France

Abstract

It has been predicted that the flexural mode of a carbon nanotube can couple strongly to an electronic two-level system present in single molecules (1,2). Detection and manipulation of the oscillator is possible by exciting the two-level system with a laser and measuring the fluorescence photons (3). The coupling is based on the (static) Stark effect, and the displacement dependence of the two-level system energy splitting. In this work we investigate how two two-level systems can be coupled by a single mechanical oscillator. We find that the effective interaction can entangle the two molecules. We also find that the effect of the electromagnetic and mechanical environment has to be reconsidered, in view of the strong coupling of the two-level system to the oscillator. Our preliminary results show that spectroscopic measurements could be used to observe the entanglement generated by the oscillator.

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*Speaker

ps optical delay line with centimetre long nanofiber for optical fiber quantum processing

Alexandre Matic, Adrien Godet, Jacques Chrétien, Kien Phan-Huy, and Jean-Charles Beugnot*

Institut FEMTO-ST, UMR 6174, UBFC, Besançon, France

* jc.beugnot@femto-st.fr

We purpose an optical delay line based on optical nanofibers. Silica high elasticity and the low pulling force required to stretch a nanofiber allow to get optical delays up to 20 picoseconds with a 10 centimeter-long optical nanofiber at telecommunications wavelength. Nanofibers (1µm diameter) requires only a fraction of the force as compared to classical 125 µm-diameter optical fibers.
Optical delay induced by stretching a nanofiber is measured with a high-resolution reflectometer Luna OBR 4600. This tool uses Rayleigh Reflectometry in Frequency Domain (OFDR) to achieve up to 10 µm resolution in spatial domain (i.e. 0.05 ps in time domain).
A 120 mm-long nanofiber with 1.0 µm diameter has been characterized with this tool.
Results given on figure 1 (right) are in agreement with our theoretical model. We were able to produce a 18.8 ps optical delay by stretching up to 4\% a 120 mm-long nanofiber.
A short optical fiber delay line can be a useful tool for quantum fiber interference

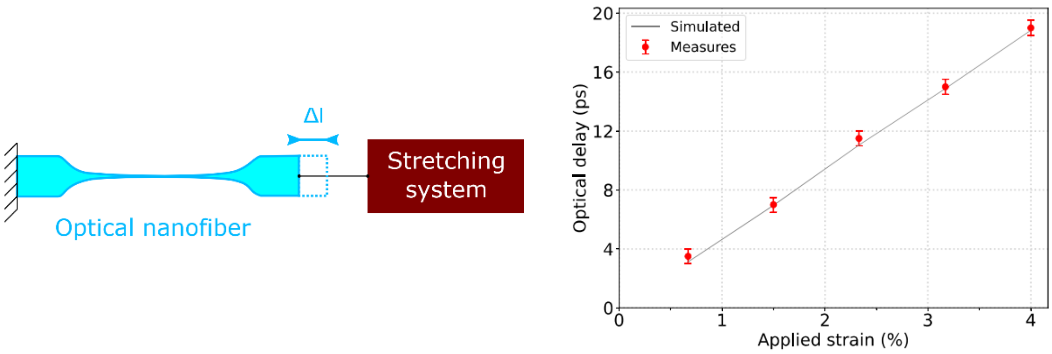

Figure 1 : (left) (optical fiber stretcher principle. The stretching system can be a piezoelectric actuator, a manual translation stage or a step by step motor. (right) Measured and theoretical optical delays at 1550nm for different applied strains on a 12cm long optical nanofiber with a diameter of 1 micrometer .

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[2] A. Godet *et al.*, Optica 4, 1232 (2017)
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Large evanescently-induced Brillouin scattering at the surrounding of a nanofibre

Fan Yang[a], Flavien Gyger[a], Li Zhang[a], Meng Pang[a], Luc Thévenaz[a], Adrien Godet[b], Jacques Chrétien[b], Jean-Charles Beugnot[b*]

a. Group for Fibre Optics, EPFL, Lausanne, Switzerland
b. Institut FEMTO-ST, UMR 6174, UBFC, Besançon, France

* jc.beugnot@femto-st.fr

Brillouin scattering has been widely exploited for advanced photonics functionalities such as microwave photonics, signal processing, sensing, lasing, and more recently in micro- and nano-photonic waveguides [1]. Due to the small transverse dimension, the tapered optical fiber have a number of optical and mechanical properties that make them very attractive for both fundamental physics and technological applications. Contrary to standard telecom fiber where the Brillouin scattering effect is characterized by a single Lorentzian resonance centred at 10.86 GHz (@ 1550nm) [2], in tapered silica fiber, we identified several Brillouin resonances at different frequencies from 5 GHz to 10 GHz coming from surface, shear and compression elastic waves (fig 1). And for a large evanescent optical field surrounding the nanofiber, we observe an efficient Brillouin scattering in gas [3]. We show drastic Brillouin scattering enhancement by increasing the gas pressure with a maximum Brillouin which is 79 times larger than in a single mode fibre (fig1.e).

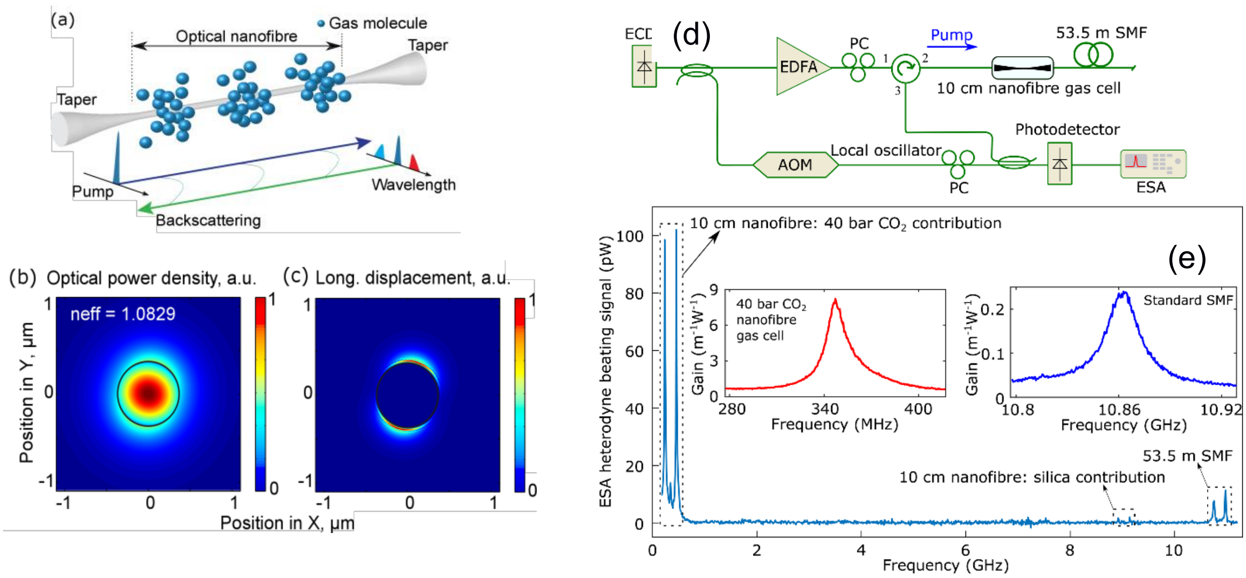

Figure 1 : (a) Conceptual view of the Brillouin scattering in a nanofibre gas cell. (b) Computed spatial optical power distribution @1550nm for a 740 nm diameter nanofiber surrounded with 40 bar CO2 gas. (c) Computed longitudinal displacement @ 350 MHz (d) Heterodyne experimental set-up and (e) beating spectra of the 10 cm nanofibre gas cell and the appended 53.5 m SMF. The red and blue line correspond to the backward Stokes Brillouin gain spectra for the 40 bar CO2 nanofibre gas cell and for the SMF.

[1] B. J. Eggleton, *et al.,* Nature Photonics 13, 664 (2019).
[2] M. Nicklès *et al*., J. of Light. Tech. 15, 1842 (1997).
[3] F. Yang *et* al., Nat. Comm 13:1432, (2022).

Vibrational Resonance Amplification in a Thermo-Optic Optomechanical Nanocavity

Guilhem Madiot[a], Sylvain Barbay[a], Rémy Braive[a,b,c]

a. C2N – CNRS, 10 Blvd Thomas Gobert 91120 Palaiseau, France
b. Université Paris Cité, Rue Thomas Mann 75013 Paris, France
c. Institut Universitaire de France (IUF)

* remy.braive@c2n.upsaclay.fr

The enhancement mechanism of a weak (undetectable) signal, known as vibrational resonance, is activated by modulating an input field at high frequency and submitting it to a bistable system. Such general and wide spread concept has been theoretically investigated on various type of systems e.g. neural networks, excitable systems and even biological networks. Meanwhile, few experimental works have also been published but with devices whose works of principle rely on different physics (electronic circuits, VCSELS, electromechanical resonators…). In all these demonstrations, there are as many nonlinearities involved as there are systems. However, up to now, no demonstration of vibrational resonance has been performed using an integrated optical nanocavity with the well-known and largely used thermo-optical nonlinearity. Such nonlinearity manifests itself and strongly impacts optical and nanophotonic devices to the point of allowing tunability and elementary computational all-optical components.

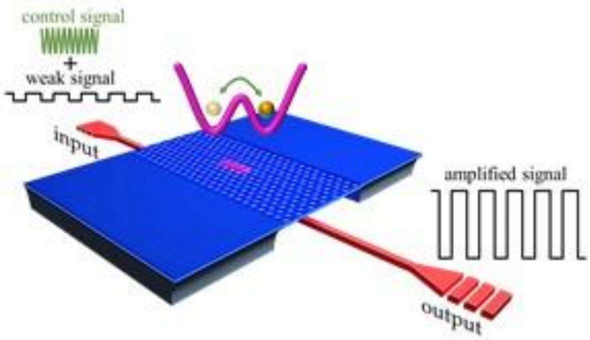

Figure 1: Schematic diagram of vibrational resonance with an optomechanical resonator exhibiting thermo-optic non-linearity. A weak signal as well as a control signal are sent to the system allowing the amplification of the first mentioned signal.

In this context, we present a first experimental demonstration of weak optical signal amplification in a thermo-optically bistable optomechanical nanocavity, a fortiori operating in the telecom domain. We make use of a fully integrated hybrid platform including a suspended InP photonic crystal whose mechanical vibrations can interestingly be exploited to access the thermal properties of the system. Using thermo-optical nonlinearity, amplification of a weak optical signal of up to 16 dB have been achieved [1].

Yet, the study of weak signal enhancement is of immediate interest for current nanophotonic technologies, in which the amplification of low-power signal remains a necessity. Beyond the optical domain, interaction between optical and mechanical degree of freedom, present in suspended photonic crystal, could open avenues of amplification of optical signal thanks to mechanics or vice versa. Furthermore, the optomechanical dimension of this system makes it also particularly well suited for sensing application like e.g. thermometry.

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Probing local thermodynamical properties of resonators through electromechanical coupling in a SEM

Clément Chardin[a*], Sébastien Pairis[b, c], Fabrice Donatini[b, c], Moïra Hocevar[c], Jean-Philippe Poizat[b, c], Julien Claudon[d], Alex Fontana[b, e], Ludovic Bellon[e], Pierre Verlot[f]

a. School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK
b. Institut Néel, Université Grenoble Alpes, F-38042 Grenoble, France
c. CNRS, Institut Néel, F-38042 Grenoble, France
d. Univ. Grenoble Alpes, CEA, INAC, PHELIQS, -38000 Grenoble, France
e. Univ Lyon, ENS de Lyon, CNRS, Laboratoire de Physique, F-69342 Lyon, France
f. IUF, 1 rue Descartes, 75231 Paris Cedex 05
* clement.chardin@nottingham.ac.uk

The interest for ultra-sensitive nanomechanics has grown tremendously over recent years, opening new areas of interest for both technological and fundamental research. A number of detection methods have been studied, for various types of resonators of always smaller dimensions and masses. However, one of the limitations in the use of recent ultra-coherent nanostructures for quantum opto- and electro-mechanics is the thermal transport in such systems.

In this work, we present a novel electro-mechanical measurement scheme which was proposed recently [1] and relies on the coupling of the displacements of a nano-resonator with a strongly focused electron beam in a Scanning Electron microscope (SEM). The resulting secondary electrons (SE) current is then modulated by the motion of the resonator, allowing the resolution of its high-frequency fluctuations. We discuss how the measurement of these fluctuations can be used to probe local thermodynamical properties of InAs nanowires, which is an important step in the understanding of thermal effects at the nanoscale.

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[2] C. Chardin et al., In prep.

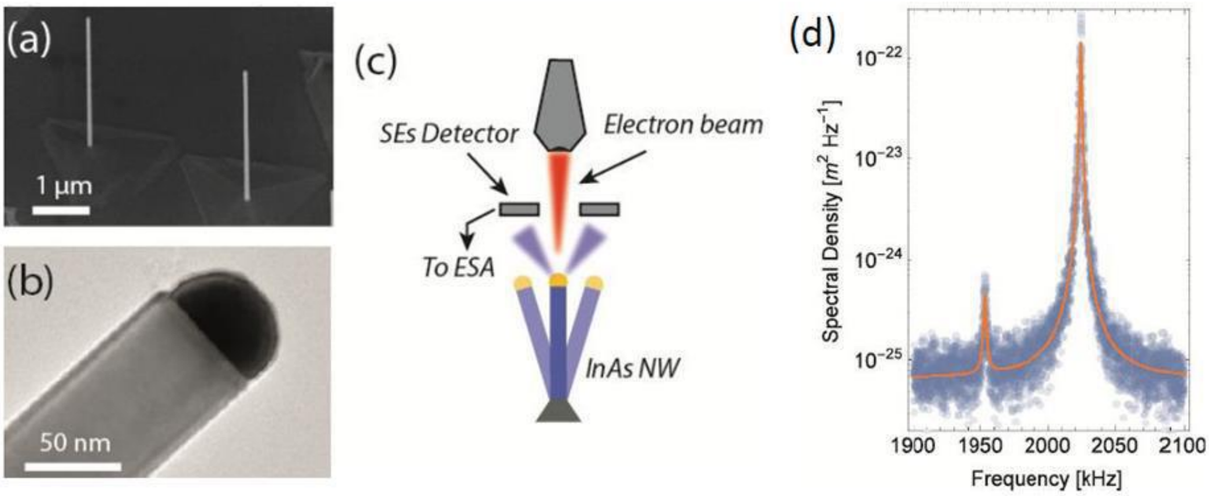

Figure 1 : (a) SEM micrograph showing two of the typical InAs nanowires used in the reported work. (b) TEM micrograph showing a magnified view of such InAs nanowire. (c) Schematic principle of the detection scheme. The fluctuations of the emitted secondary electrons are monitored as to reveal the nanomechanical motion fluctuations. (d) Typical motion spectrum obtained from the spectral analysis of the secondary electrons fluctuations

Self-oscillation regime of nano-beam based opto-mechanical systems

A. Delattre[a], I. Golokolenov[a], E. Collin[a*]

a. UGA Institut Néel - CNRS, 25 rue des Martyrs, 38042 Grenoble cedex 9

∗ ≪eddy.collin@neel.cnrs.fr≫

Microwave-based opto-mechanical systems present a parametric instability when driven by a so-called "blue-detuned" pump, at a large enough power. In this regime, a very large motion amplitude state is triggered, which imprints a comb in the measured microwave signal. This regime has been studied by our group for 2D "drum-head" mechanical devices, demonstrating unique features among which the ability to fit nonlinear effects (coupling non-linearity, Duffing non-linearity) [1].

Here we report on measurements performed on a 1D "beam-based" structure: a 50 μm long SiN beam of width and thickness about 100 nm. While the mechanical and microwave parameters are rather similar to our previous device, the typical behaviour measured is very different. We show as an example in Fig. 1 the measured signal amplitude at the Stokes sideband, as a function of microwave pump power and detuning (temperature 400 mK). Strikingly, the meta-stable regions are different, and non-linear contributions seem to be of a different kind. Further theoretical developments are required to understand these features in detail.

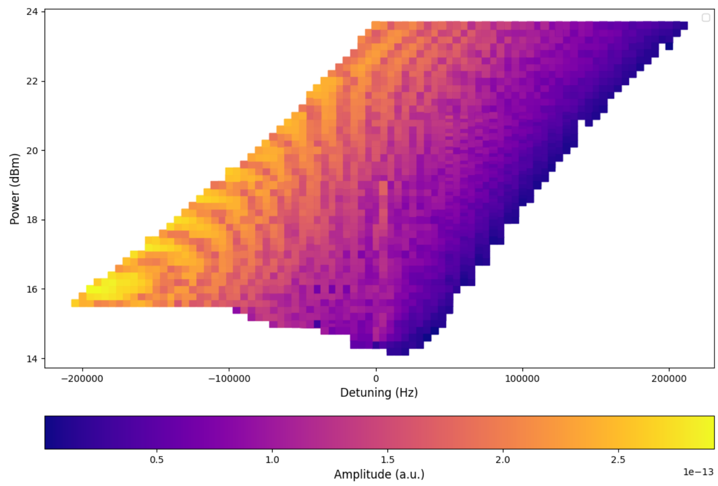

Figure 1: Amplitude of the Stokes peak in the self-oscillating regime of a 4 MHz nanomechanical beam device embedded in a 6 GHz microwave cavity. Data taken at 400 mK, as a function of pump frequency detuning and power.

[1] D. Cattiaux et al. Phys. Rev. Research **2**, 033480 (2020).

Nanomechanical steady-state squeezing with an optical-frequency two-level system

Clément Dutreix* and Fabio Pistolesi

Université de Bordeaux, CNRS, LOMA, UMR 5798, F-33400 Talence, France

* clement.dutreix@u-bordeaux.fr

Quantum squeezed states are non-classical states for which the noise of one quadrature can be reduced below the zero-point fluctuations. Nanomechanical squeezing has recently been realized in optical cavities through reservoir engineering. This allows the mechanical oscillator to relax into a squeezed steady state surpassing 3dB below the zero-point motion.

Here, we investigate theoretically quantum squeezing in a mechanical oscillator coupling an optical-frequency two-level system through Zeeman/Stark effect. Combining red-sideband cooling and parametric coupling, we show that the oscillator can relax into a squeezed steady-state, more than 3dB below the vacuum fluctuations. This squeezing scheme potentially finds realizations in a broad diversity of nanomechanical systems involving spin qubits, molecular electric dipoles, and quantum dots.

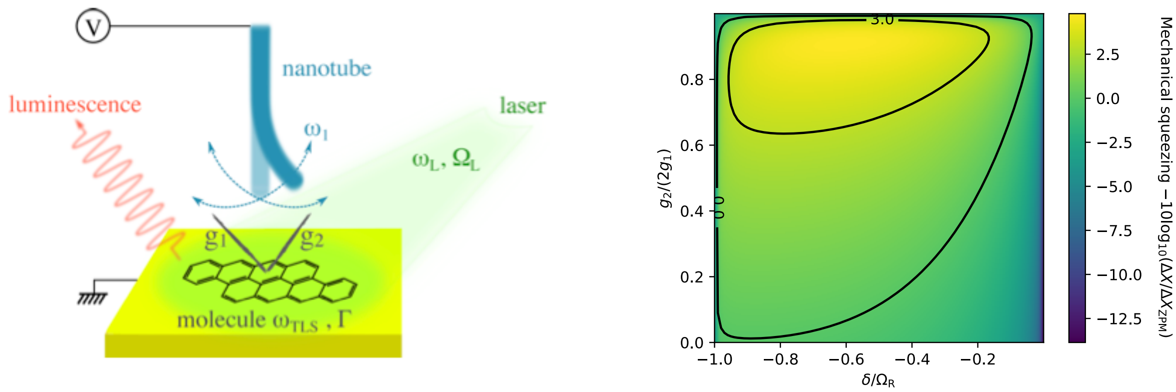

Figure 1 : Nanotube flexural mode of frequency ω_1 coupling the two-level system (TLS) of a laser-driven molecule by Stark effect through DC coupling g_1 and parametric coupling g_2 (*left*). Mechanical squeezing as a function of the coupling ratio $g_2/(2g_1)$ and laser-TLS detuning $\delta = \omega_L - \omega_{TLS}$, which is given in unit of the TLS Rabi frequency $\Omega_R = (\delta^2 + {\Omega_L}^2)^{1/2}$ (*right*).

GDR Groupement de recherche
MecaQ Optomécanique & Nanomécanique Quantiques

Development of continuous sub-mK refrigeration for ground-state cooling of mechanical resonators

James Butterworth,[a] Sébastien Triqueneaux,[b] Matthias Raba,[b] Šimon Midlik,[c] Ilya Golokolenov,[b] David Schmoranzer,[c] Eddy Collin[b] and Andrew Fefferman[b*]

a. Air Liquide Advanced Technologies
b. Institut Néel/CNRS & Univ. Grenoble Alpes, France
c. Charles University, Prague, Czechia

* andrew.fefferman@neel.cnrs.fr

Ground state mechanical systems are usually prepared by passively cooling GHz frequency modes to 10 mK or using optomechanics to actively cool lower frequency modes. In contrasting recent work, a 15 micrometer diameter Al drum was passively cooled below 1 mK, thereby decreasing the average phonon occupation of the 15 MHz fundamental flexural mode below unity [1]. In this approach, the environment of the mechanical mode is cold and the ground-state center-of-mass motion is relatively large. This facilitates studies of foundations of quantum mechanics, quantum thermodynamics and individual tunneling two level systems. We report our development of a continuous nuclear demagnetization refrigerator with a target base temperature of 1 mK. Its design is compatible with cryogen-free dilution refrigerators, so that researchers working at microkelvin temperatures can operate without a helium liquefier and benefit from the large experimental space and automated operation of dry systems. The design relies on our recently demonstrated ultra-high conductance heat switch [2]. We expect this technology to propel several fields on the frontiers of science and technology.

1. D. Cattiaux, I. Golokolenov, S. Kumar, M. Sillanpää, L. Mercier de Lépinay, R. R. Gazizulin, X. Zhou, A. D. Armour, O. Bourgeois, A. Fefferman & E. Collin, *Nature Comm.*, **12**, 6182 (2021).

2. J. Butterworth et al., Superconducting aluminum heat switch with 3 nΩ equivalent resistance, *Rev. Sci. Instrum.* **93**, 034901 (2022).

Suspended nanowires as ultrasensitive force probes for the exploration of proximity forces above surfaces and novel electro-optic forces

Philip Heringlake*[1], Hugo Weltz*[2], Olivier Arcizet[1], and Benjamin Pigeau[1]

[1]Institut Néel (NEEL) – CNRS : UPR2940, Université Grenoble Alpes – 25 rue des Martyrs - BP 166 38042 GRENOBLE CEDEX 9, France

[2]Institut Néel – CNRS : UPR2940, Université Grenoble Alpes – France

Abstract

We present the application of 2D force field imaging based on suspended SiC nanowires. In a first part we discuss the case of quasi realtime force sensing of electrostatic and proximity forces above a nano-structured surface that is approached to the nanowire's vibrating extremity. This technique uses an optical detection of the driven motion of a vertically oriented singly clamped nanowire. The nanowire is free to oscillate in the horizontal plane with two perpendicular eigenmodes with similar frequencies. By tracking these changes of the modes' parameters we reconstruct the force field gradient matrix and the force field itself. With a fast phase-locked loop based measurement a quasi realtime force gradient detection is possible with a sensitivity of fN/nm at 300K. At short distances the nanowire-surface interactions are dominated by electrostatic and proximity Casimir forces whose relative contributions can be tuned by adjusting bias voltages applied to the sample. We present measurements of the electrostatic force landscape together with an experimental method that permits to separate the Casimir from the electrostatic forces. Furthermore we discuss a recently observed electro-optic force caused by optically induced charge separations in the nanowire under the presence of a strong electrical field.

*Speaker

MecaQ Optomécanique & Nanomécanique Quantiques

High frequency vibration sensing in cryostats

Anne Louchet-Chauvet[a*], Thierry Chanelière[b]

a. ESPCI Paris, Université PSL, CNRS, Institut Langevin, 75005 Paris, France

b. Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France

* anne.louchet-chauvet@espci.fr

The recent global effervescence around quantum technologies has led to an increasing need for reliable and efficient cryogenic systems. Continuously-operated closed-cycle cryocoolers are progressively replacing liquid helium cryostats that suffer from heavy logistics and high costs [1]. However, the low running cost and ease of use of dry systems comes at the price of a high level of acoustic vibrations generated by the cycling gas flow. These vibrations are problematic for many cryogenic experiments, including cavity QED, trapped ions spectroscopy, quantum memories and frequency references based on rare-earth ions in crystals, scanning probe microscopy, but also in the field of astronomy with bolometers or gravitational waves detectors.

Relevant diagnosis of the vibrations in a cryostat is a necessity to ensure correct operation of the experiment. The specifications provided by commercial suppliers often prove insufficient to assess the actual impact of vibrations on a given experiment, either because the actual setup mechanical assembly differs from the default configuration, or because the information is incomplete (often limited to low acoustic frequencies of the order or below 1 kHz and/or peak-to-peak values).

In this work we propose an original vibration sensor based on rare-earth ions embedded in a crystal. This vibration sensing method builds upon the piezospectroscopic effect (i.e. the sensitivity of the optical transitions to stress) and benefits from the exceptional coherence properties of rare earth ions in crystals [2] [3]. It combines a high-frequency range (up to 1 MHz) and contactlessness, together with an inertial sensitivity, making it an interesting alternative to accelerometric and interferometric vibration sensing at low temperature.

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CHAOS AND SYNCHRONIZATION IN STRONGLY COUPLED NANO-ELECTROMECHANICAL CAVITIES

Guilhem Madiot[a] Franck Correira[a], Sylvain Barbay[a], Rémy Braive[a,b,c]

a. C2N – CNRS, 10 Blvd Thomas Gobert 91120 Palaiseau, France
b. Université Paris Cité, Rue Thomas Mann 75013 Paris, France
c. Institut Universitaire de France (IUF)

* remy.braive@c2n.upsaclay.fr

Chaos and synchronization are two ubiquitous phenomena in nature. They have triggered a large number of theoretical works in many domains including meteorology, climate change study, neurosciences, spatio-temporal phase transition physics, among others. Signatures of such combination not only lie in the response amplitude but also in its phase. As such, a careful investigation of each quadrature is necessary to unveil the fundamental nature of this phenomenon, with yet experimentally unexplored complex dynamics in nanoscale, optomechanical systems. Beyond its fundamental vivid prospects extending to e.g. quantum chaos, such phenomenon might be now envisioned as potential means for encrypted communications including random number generation or artificial neural networks and atomic clocks to name a few.

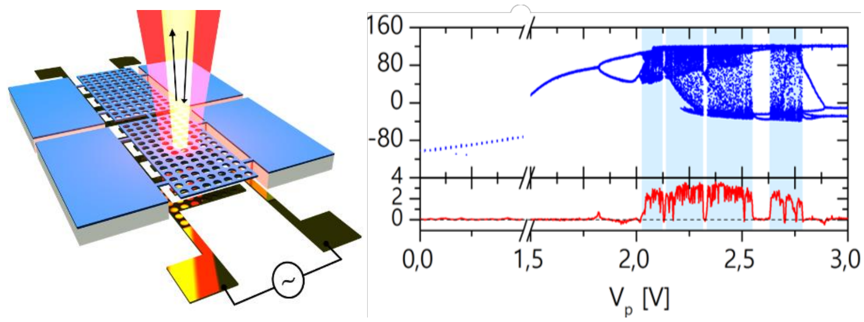

Figure 1: (left) Schematic of the coupled resonators; (right) Bifurcation diagram (blue) and Lyapunov exponent (red) evolution with respect to ng pump voltage

Using two mechanically coupled nano-optomechanical resonators (Fig. 1 left), synchronization on the route to chaos is here achieved by relying on electromechanically induced amplitude modulation of the driving force. Beyond chaos transfer either between two different fields, namely from optics to mechanics or between spatially separated subsystems, we evidence bichromatic chaos at two different carrier tones. Upon simultaneous excitations of the coupled membranes modes, we consistently demonstrate synchronization of their amplitudes thanks to the orthogonality breaking induced by the nonlinearity and on the route to chaos, direct measurements of the quadratures phases reveals a much richer dynamics highlighting desynchronization and intermittent phase synchronization, i.e. phase jumps interrupting the locking of the oscillators' phases while amplitudes are synchronized. Numerical simulations based on a generic model of driven coupled resonators fully support this complex synchronization dynamics [1]. As a perspective, we exploit this concept to generate random number generator [2].

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Quantum well exciton polaritons in a disk optomechanical microcavity

F. Malabat[1], *M.F. Colombano*[1], *R. De Oliveira*[1], *A. Lemaître*[2], *I. Favero*[1]

[1] *Matériaux et Phénomènes Quantiques, Université de Paris, CNRS, 75013, Paris, France*
[2] *Centre de Nanosciences et de Nanotechnologies, Université Paris-Saclay, CNRS, 91460 Marcoussis, France*
florent.malabat@u-paris.fr

Our work is focused on hybrid optomechanical systems formed by GaAs resonator with an embedded InGaAs quantum well (QW). Such resonators form a three-partite system combining high frequency (~0.7- 1 GHz) mechanical modes, high-quality (Qo ~ 105) optical whispering gallery modes (WGMs), and QW excitonic modes. The confinement in a sub-micron volume of the optical and excitonic modes results in a situation of strong exciton-photon coupling. The system then hosts light matter hybrid quasiparticles: polaritons, which share both exciton and photon properties [2].

We present optical experiments demonstrating the generation of polaritons in our disk structure. Optical modes and excitonic resonance are tuned by varying the temperature and the cavity dimensions. The strong coupling signatures, such as anti-crossing, are observed using both confocal microscopy at low temperature, and concomitant near-field experiments using a nanophotonic waveguide integrated on the chip and coupled to the disk. Rabi splitting values evolve between 6 and 10 meV, function of the concerned optical mode. The reported results agree with a Hopfield model including original analytical expressions of Rabi coupling for gallery mode resonators [2]. Finally, we present the first optomechanical experiments performed on the hybrid platform.

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Chiral Discrimination in Helicity-Preserving Fabry-Pérot Cavities

Lorenzo Mauro*[1], Jacopo Fregoni[2], Johannes Feist[2], and Remi Avriller[3]

[1]Laboratoire Ondes et Matière dÁquitaine (LOMA) – Centre National de la Recherche Scientifique : UMR5798, Université de Bordeaux : UMR5798 – Université de Bordeaux, PAC Talence, bât. A4N, 351 Cours de la Libération, 33405 TALENCE CEDEX, France

[2]Universidad Autonoma de Madrid – Spain

[3]Laboratoire Ondes et Matière dÁquitaine – Centre National de la Recherche Scientifique : UMR5798, Université de Bordeaux : UMR5798 – France

Abstract

We theoretically investigate the circular dichroism of a helicity-preserving Fabry-Pérot cavity made of two dielectric metamirrors. The latter are designed to act, in a narrow frequency range, as efficient polarization cross-converters in transmission for one polarization, and almost perfect reflectors for the other polarization. The resulting cavity mode is circularly polarized and decoupled (at resonance) from the outside of the cavity. Despite this decoupling, a Pasteur medium hosted inside the cavity can still couple efficiently to both the outside of the cavity and the helicity-preserving mode, inheriting a partial chiral character. The consequence of this mechanism is twofold: it increases the intrinsic chiroptical response of the molecules by two orders of magnitude and it allows for the formation of chiral polaritons upon entering the regime of strong light-matter coupling.

*Speaker

Photon counting sideband thermometry of an optomechanical GaAs disk resonator

Samuel Pautrel*[1], Adrien Borne[2], Jérémy Bon , and Ivan Favero

[1]Laboratoire Matériaux et Phénomènes
Quantiques – Centre National de la Recherche Scientifique : UMR$_7$162, $Universit\acute{e}deParis : UMR_7162-$
$-Universit\acute{e}ParisDiderot, B\hat{a}t.Condorcet, 10rueAliceDomonetLeonieDuquet, Case7021, 75205Pariscedex13, France$
[2]Laboratoire Matériaux et Phénomènes Quantiques – Université de Paris :
UMR$_7$162, $CentreNationaldelaRechercheScientifique : UMR_7162 - -France$

Abstract

We discuss our progress towards single phonon Brillouin spectroscopy of the GHz radial breathing mode of a GaAs disk resonator. Using cryogenic passive cooling with a dilution refrigerator and single photon counting, we measure and model optomechanical sideband amplitudes. Our work opens an alternative to silicon nanobeams for ultra-high frequency single phonon heralding protocols.

*Speaker

Proposal for a nanomechanical qubit

Fabio Pistolesi*[1], Andrew Cleland[2], and Adrian Bachtold[3]

[1]Laboratoire Ondes et Matière dÁquitaine (LOMA) – Centre National de la Recherche Scientifique : UMR5798, Université de Bordeaux : UMR5798 – Université de Bordeaux, PAC Talence, bât. A4N, 351 Cours de la Libération, 33405 TALENCE CEDEX, France

[2]University of Chicago (University of Chicago) – PME 5640 S Ellis Ave Chicago IL 60615, United States

[3]Institut de Ciencies Fotoniques (ICFO) – Mediterranean Technology Park Av. Carl Friedrich Gauss, 3 08860 Castelldefels (Barcelona), Spain, Spain

Abstract

Mechanical oscillators have been demonstrated with very high quality factors over a wide range of frequencies. They also couple to a wide variety of fields and forces, making them ideal as sensors. The realization of a mechanically based quantum bit could therefore provide an important new platform for quantum computation and sensing. Here, we show that by coupling one of the flexural modes of a suspended carbon nanotube to the charge states of a double quantum dot defined in the nanotube, it is possible to induce sufficient anharmonicity in the mechanical oscillator so that the coupled system can be used as a mechanical quantum bit. However, these results can only be achieved when the device enters the ultrastrong coupling regime. We discuss the conditions for the anharmonicity to appear, and we show that the Hamiltonian can be mapped onto an anharmonic oscillator, allowing us to work out the energy level structure and find how decoherence from the quantum dot and the mechanical oscillator is inherited by the qubit. Remarkably, the dephasing due to the quantum dot is expected to be reduced by several orders of magnitude in the coupled system. We outline qubit control, readout protocols, the realization of a CNOT gate by coupling two qubits to a microwave cavity, and finally how the qubit can be used as a static-force quantum sensor. Reference: PHYSICAL REVIEW X 11, 031027 (2021).

*Speaker

Phonon-Induced Pairing in Quantum Dot Quantum Simulator

Utso Bhattacharya[1], Tobias Grass[1], Adrian Bachtold[2], Lewenstein Maciej[1], and Fabio Pistolesi*[3]

[1]Institut de Ciencies Fotoniques [Castelldefels] – Spain

[2]Institut de Ciencies Fotoniques (ICFO) – Mediterranean Technology Park Av. Carl Friedrich Gauss, 3 08860 Castelldefels (Barcelona), Spain, Spain

[3]Laboratoire Ondes et Matière dÁquitaine (LOMA) – Centre National de la Recherche Scientifique : UMR5798, Université de Bordeaux : UMR5798 – Université de Bordeaux, PAC Talence, bât. A4N, 351 Cours de la Libération, 33405 TALENCE CEDEX, France

Abstract

Quantum simulations can provide new insights into the physics of strongly correlated electronic systems. A well-studied system, but still open in many regards, is the Hubbard–Holstein Hamiltonian, where electronic repulsion is in competition with attraction generated by the electron–phonon coupling. In this context, we study the behavior of four quantum dots in a suspended carbon nanotube and coupled to its flexural degrees of freedom. The system is described by a Hamiltonian of the Hubbard–Holstein class, where electrons on different sites interact with the same phonon. We find that the system presents a transition from the Mott insulating state to a polaronic state, with the appearance of pairing correlations and the breaking of the translational symmetry. These findings will motivate further theoretical and experimental efforts to employ nanoelectromechanical systems to simulate strongly correlated systems with electron–phonon interactions. Reference: Nano Lett. 21, 9661–9667 (2021).

*Speaker

Polarization-controlled Brillouin scattering in elliptical optophononic micropillar resonators

Anne Rodriguez[a]*, Priya[a], Edson Cardozo de Oliveira[a], Isabelle Sagnes[a], Florian Pastier[b], Luc Le Gratiet[a], Martina Morassi[a], Aristide Lemaître[a], Loïc Lanco[c], Martin Esmann[a+], Norberto Daniel Lanzillotti-Kimura[a]

a. Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies, 91120 Palaiseau, France
b. Quandela SAS, 10 Boulevard Thomas Gobert, 91120 Palaiseau, France
c. Université Paris-Cité, CNRS, Centre de Nanosciences et de Nanotechnologies, 91120 Palaiseau, France
+ current affiliation: Institute of Physics, Carl von Ossietzky University, 26129 Oldenburg, Germany
* anne.rodriguez@c2n.upsaclay.fr

Brillouin scattering is extensively used for material characterization, biological imaging, optical and optoelectronic devices [1]. In Brillouin scattering processes, the selection rules formally constrain energy, direction and polarization of the scattered photons for a given input state. Usually, these selection rules in crystalline solids are taken as intrinsic material properties, locking the relative polarization of excitation and signal states [2]. We introduce elliptical optical micropillar resonators to control polarization selection rules. The elliptical shape lifts the degeneracy of optical cavity modes, leading to horizontally (*H*) and vertically (*V*) polarized optical cavity modes. Due to the difference in reflectivity of the *H* and *V* optical modes, the reflected laser polarization is rotated. because of the energy difference, the resonant Brillouin scattering emission undergoes a different rotation of polarization than that of the incident laser. By choosing the polarization and wavelength of the incident laser, we can modify the polarization state of both the Brillouin signal and the reflected laser [3]. In this way, background-free spontaneous Brillouin scattering spectra can be efficiently measured in a cross-polarization scheme. The same working principle applies to any optical system with localized, polarization sensitive modes, such as plasmonic resonators, photonic crystals, and birefringent micro- and nanostructures.

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Optomechanical coupling between a nano oscillator and a single quantum emitter

Mathias Jakob Staunstrup *, Hanna Le Jeannic, and Brahim Lounis

a. Université de Bordeaux, LP2N, Institut d'Optique d'Aquitaine

* mathias.staunstrup@u-bordeaux.fr

Presented on the poster is the optomechanical system of an oscillating carbon nanotube(CNT) coupled to a single molecule quantum emitter through the stark effect. This setup predicts direct readout of nanomechanical motion, cooling, oscillator-dependent photon statistics, and topological actuation of mechanical modes[1][2].

In close correspondence with previously found experimental results [3], we find a zero phonon line width in the 50-70 MHz and GHz range stark shift. Those preliminary results are promising for the development of the proposed optomechanical system.

References:
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[2]: C. Dutreix, R. Avriller, B. Lounis, & F. Pistolesi (2020). Two-level system as topological actuator for nanomechanical modes. Physical Review Research,**2**
[3]: Amin Moradi, Zoran Ristanović, Michel Orrit, Irena Deperasi ska, & Boles aw Kozankiewicz (2019). Matrix-ń ł induced Linear Stark Effect of Single Dibenzoterrylene Molecules in 2,3-Dibromonaphthalene Crystal. ChemPhysChem,**20**, 55-61.

Purely quartic nonlinearity in cavity optomechanics

Jonathan L. Wise*, Clément Dutreix, and Fabio Pistolesi
Univ. Bordeaux, CNRS, LOMA, UMR 5798, F-33405 Talence, France
* jonathan.wise@u-bordeaux.fr

Introducing a controlled and strong anharmonicity in mechanical systems is a present challenge of nanomechanics. The anharmonicity allows one to generate non-classical states of the mechanical oscillator and, if the anharmonicity is sufficiently large, to address individually the mechanical excited states.

It is well known that for sufficiently large laser power an optomechanical cavity exhibits a classical static instability. We investigated under which conditions the instability could be tuned in such a way that a smooth crossover could be observed from a harmonic potential to a purely quartic potential (see Figure 1). Unlike the previously studied optomechanical dynamical instability that comes about for large amplitude mechanical oscillations, the quartic nonlinearity appears to survive — and may even be enhanced — for low laser power. The quadratic—quartic crossover could be exploited to tailor an anharmonicity in a precise way, in order to manipulate the state of the mechanical oscillator and, under certain conditions, fabricate non-classical quantum states.

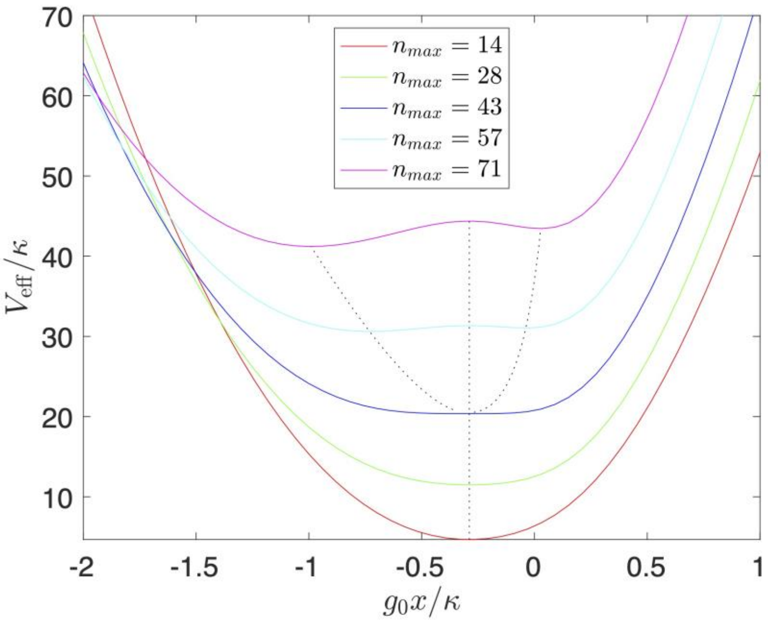

Figure 1 : Effective potential $V_{\rm eff}$ experienced by mechanical oscillator in a cavity as a function of the oscillator displacement coordinate (adimensionalised by its zero point motion) x for different values of the resonant cavity photon number n_{max}. Here, g_0 is the single photon optomechanical coupling strength and κ is the cavity line width. As the laser power is increased, we see a transition from quadratic to quartic and eventually bistable behaviour — the blue curve indicates the case of a purely quartic potential. The dotted lines indicate the potential extrema. Note that the origin of x is shifted for each value of n_{max} for convenience.

Optomechanics of a suspended magnetic van der Waals heterostructure

Joanna Wolff [a*], Loïc Moczko [a], Stéphane Berciaud [a] and Arnaud Gloppe [a]

a. Université de Strasbourg, CNRS, Institut de Physique et Chimie des Matériaux de Strasbourg, UMR 7504, France

* joanna.wolff@ipcms.unistra.fr

The persistence of a magnetic order in a monolayer of van der Waals magnetic material has been established in 2016, offering the perspective to embed a magnetic degree of freedom in heterostructures made of other bidimensional materials such as graphene or light-emitting transition metal dichalcogenides. The physical properties of van der Waals materials can be easily tuned by perturbations like strain or doping, inviting to the exploration of magnetism in two dimensions and its exploitation in novel ultrathin devices [1]. Our approach is to suspend these magnetic materials forming drum-like resonators in order to investigate the influence of the strain on their magnetic order (Fig. 1**a**). We probe the phase transition of a heterostructure encapsulating $FePS_3$, an Ising zigzag antiferromagnet (Fig. 1**b**), combining nano-optomechanics to a complementary method, Raman spectroscopy [2,3]. The magnetic phase transition of the membrane is attested by a change in the drumhead mechanical resonance frequencies around its Néel temperature (Fig. 1**c**) concomitant with a modification of its Raman signature arising from the vibrational modes of the iron atom in the crystal (Fig. 1**d**). This work opens to the study of proximity effects in van der Waals magnetic heterostructures and their control by strain.

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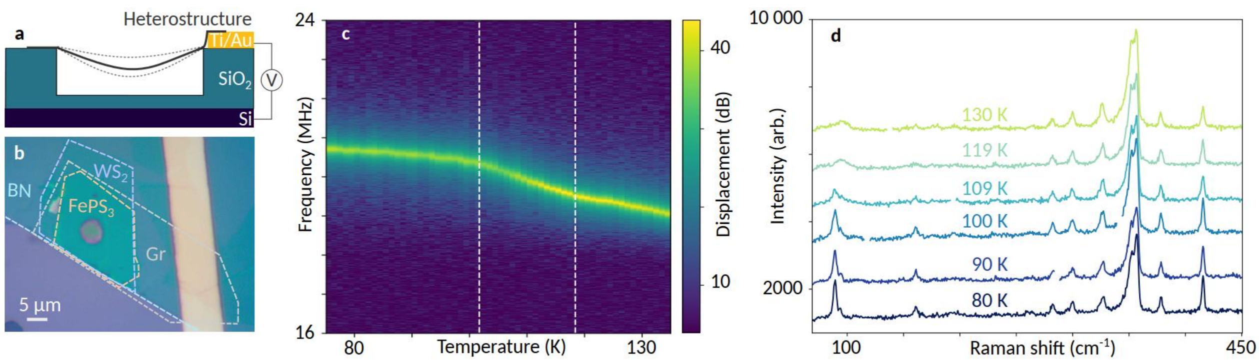

Figure 1: **a**. Schematic representation of a nanoresonator made of a magnetic van der Waals heterostructure suspended over a hole etched in a Si/SiO_2 substrate and connected to an electrode to apply a gate voltage. **b**. Optical picture of the studied sample. **c**. Optically-detected mechanical response to an electrostatic driving for temperatures ranging from 75 K to 135 K. The white dotted lines indicate the change of slope characterising the phase transition around 110 K. **d**. Raman spectra recorded close to the Néel temperature of our sample.

Scanning microwave microscopy for detecting mechanical vibrations of silicon nitride membranes

Hao Xu[a], Didier Theron[a], Sophie Eliet[a], and Xin Zhou[a*]

a. Univ. Lille, CNRS, Centrale Lille, Univ. Polytechnique Hauts-de-France, UMR 8520-IEMN, F-59000 Lille, France
* Correspondence email: xin.zhou@iemn.fr

Highly stressed silicon nitride mechanical resonators, due to nanogram effective mass and high resonance frequency in megahertz, are attractive for various sensing applications [1]. Unlike optical readout schemes, electrical detections of tiny displacements from silicon nitride resonators are more complicated since they require a thin conductive layer covering on the suspended structure to form a capacitive coupling with external circuits [2]. When mechanical resonators are embedded in complex microwave circuits and isolated from passing DC/RF signals, examinations of their mechanical functions become more difficult [2]. It thus becomes essential to develop a detection method that allows in-situ investigations of spatial mechanical vibrations.

Here, we demonstrate our recent progress in using a metallic AFM tip in vacuum (7×10^{-4} mbar) as a suspended gate to measure a silicon nitride drum membrane at room temperature. The membrane is covered with a thin aluminum layer to form a capacitive coupling scheme. In this detection scheme, the tip is fixed but the sample holder can be moved in X-Y-Z directions. In order to drive the membrane by electrostatic forces, both DC and AC signals are added through the tip. For the detection, we implement microwave interferometry on the tip and readout mechanical displacements through frequency down conversion [2]. **Figure 1** shows a 3D spatial map of mechanical responses of the fundamental mode (~8.76 MHz). Based on this platform, we also demonstrate the frequency tunability by DC voltages and mechanical nonlinear dynamics. This platform exhibits potentials in characterizing the spatial dependence of mechanical damping effects and can be extended for investigating other mechanical systems driven by electrostatic forces.

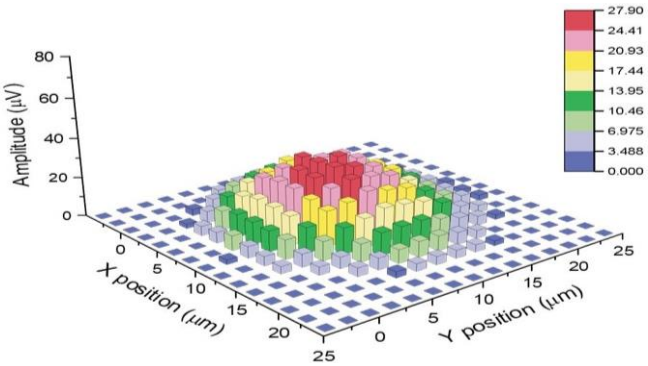

Figure 1 : 3D spatial map of the mechanical responses where the holder's coordinate (X,Y) scans with 28 µm long and 28 µm wide at intervals of 2 µm.

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