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MecaQ Optomécanique & Nanomécanique Quantiques

6th Annual Meeting

15th & 16th November 2021

Book of Abstracts

GDR Groupement de recherche

MecaQ Optomécanique & Nanomécanique Quantiques

Session 15-01

15-11-2021

9.30 – 10.30

Yiwen Chu (invited)

Circuit quantum acousto-dynamics with bulk acoustic wave resonators

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Keywords: quantum acoustics, acousto-dynamics, superconducting circuits, quantum electronics

Bulk acoustic wave (BAW) resonators are mechanical oscillators that confine sound waves in a solid-state material. Due to their use in a wide range of classical devices, they have been engineered to exhibit high quality factors, and their interactions with electromagnetic fields have been extensively studied. Recently, BAW resonators have also rapidly developed into a promising platform for new quantum devices. In this talk, I will give an overview of our work on interfacing them with microwave frequency superconducting circuits. I will then focus on our recent work on measuring quantum states of phonons using a circuit quantum acousto-dynamics device operating in the strong dispersive regime.

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MecaQ Optomécanique & Nanomécanique Quantiques

Session 15-02

15-11-2021

11.00 – 12.30

Xin Zhou

Gernot Gruber

Christian Degen (invited)

Silicon nitride drum electromechanical resonator at room temperature and in the mK temperature range

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Silicon nitride (SiN) mechanical resonators are attractive for sensing and signal processing because of their nanogram effective mass and high-quality factor with typical resonance frequency in the MHz range [1]. However, the insulation feature of SiN greatly limits the implementations of SiN mechanical resonators in electrical systems with large coupling effect.

Here, we will present our recent achievements in a novel SiN microelectromechanical system (MEMS), in which a SiN drum resonator coated with a thin aluminum layer is capacitively coupled to an aluminum drum resonator serving as a top gate [2]. The ultra-clean fabrication process allows to have SiN drum resonators with typical resonator frequencies in ~ 10 MHz range and high-quality factor (Q) ~10^4 at the room temperature, reaching current state of art. With this unique device structure, we investigated the coupling effect between two parallel-coupled mechanical resonators (the SiN drum and the Al drum) by taking the SiN drum as a phonon cavity to perform double-tone operations, through an analog of microwave opto-mechanical system, as shown in Fig.1. The measurement results are in good agreement with our analytical calculations based on capacitive coupling model. Besides, we also characterized this device in mK temperature range by using a travelling wave microwave optomechanical interferometer. With its high sensitivity measurement scheme, we could measure this device at the linear region in mK temperature and the Q reaches ~10^4 for Al drum and ~10^5 for SiN drum.

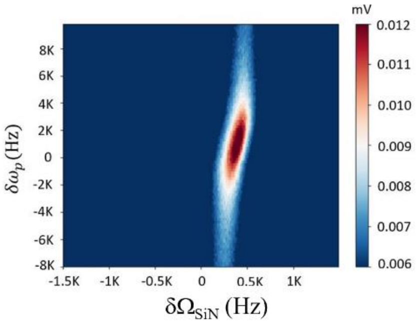

Figure 1: amplitudes of the probe signal as function of the pump frequency and probe frequency. Here, we use double-tone operation by pumping SiN drum resonator at the frequency $\omega_{\mathrm{p}} = \Omega_{SiN} + \Omega_{Al} + \delta\omega_p$ and probing SiN drum around $\omega_{\mathrm{probe}} = \delta\Omega_{SiN} + \Omega_{SiN}$, where Ω_{SiN} and Ω_{Al} are resonance frequency of SiN drum and Al drum. This measurement was performed at room temperature.

[1] Scott S. Verbridge, Harold G. Craighead, Jeevak M. Parpia.,"A megahertz nanomechanical resonator with room temperature quality factor over a million,'' Appl. Phys. Lett. 92, 013112 (2008).

[2] X.Zhou, S.Venkatachalam, R. Zhou, H.Xu, A.Pokharel, A.Fefferman, M. Zaknoune, E.Collin, "High-Q and high-Coupling gated silicon nitride drum resonators,'' vol.21, 5738–5744 (2021).

Interrelation of elasticity and thermal bath in nanotube cantilevers

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We report the first study on the thermal behavior of the stiffness of individual carbon nanotubes [1]. We observe a reduction of the Young's modulus over a temperature range 10-300 K with a slope −(173±65) ppm/K in its relative shift. These findings are reproduced by two different theoretical models based on the thermal dynamics of the lattice. These results reveal how the measured fundamental bending modes depend on the phonons in the nanotube via the Young's modulus.

The samples consist of singly clamped nanotube cantilevers, which are functionalized by a small Pt particle deposited at the free end using an advanced mass-controlled deposition process [2]. The Pt particle scatters back the light coming from a strongly focused HeNe laser beam [3]. The backscattered light is used to measure the temperature dependence of the mechanical resonance frequency $\boldsymbol{f(T)}$ of the fundamental flexural mode. This enables us to directly infer the relative change in Young's modulus Y at different temperatures: $\frac{\boldsymbol{Y(T)-Y(0)}}{\boldsymbol{Y(0)}} = \frac{\boldsymbol{f^2(T)-f^2(0)}}{\boldsymbol{f^2(0)}}$. The experimental results agree with the temperature dependence of the resonance frequency predicted by molecular dynamics simulations, which take into account the lattice dynamics of the nanotube. Our measurements are also consistent with the Young's modulus directly computed from a quasiharmonic approximation of the free energy of the phonon modes.

This work not only shows how the stiffness of an individual nanotube is related to its phonons, but it also highlights the role of the phonon thermal bath in nanotube cantilevers, which is a topic of importance in the field of nanomechanical resonators.

[1] S. Tepsic et al., Physical Review Letters **126**, 175502 (2021)
[2] G. Gruber et al., Nano Letters **19**, 6987-6992 (2019)
[3] A. Tavernarakis et al., Nature Communications **9**, 662 (2018)

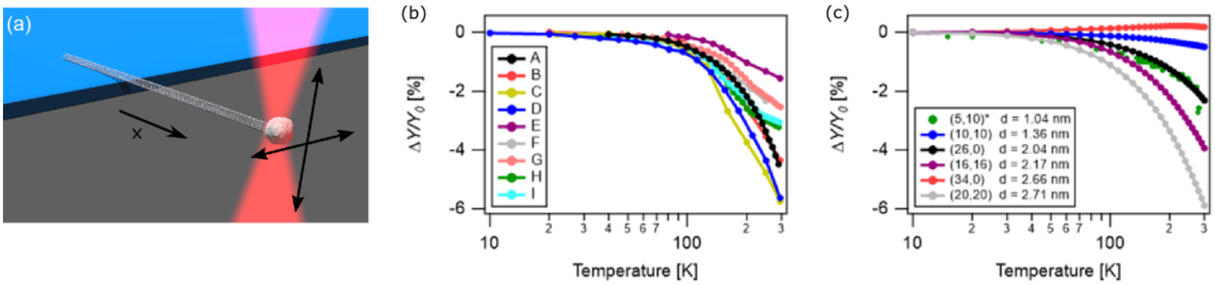

Figure 1: (a) Schematic of a nanotube cantilever with a Pt particle at the free end. (b) Experimental and (c) theoretical temperature dependence of the Young's modulus for different nanotubes.

From Nanomechanics to Spins

Christian Degen[a*]

Nanomechanical resonators are exquisite sensors for weak magnetic forces, with exciting prospects in nanoscale detection and imaging of nuclear and electronic spins. In this talk, I will give an overview of our laboratory's activities in this field, including force detection with optomechanical membranes, nuclear spin imaging with the technique of magnetic resonance force microscopy, and use of mechanical oscillators for improved NV center magnetometry.

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MecaQ Optomécanique & Nanomécanique Quantiques

Session 15-03

15-11-2021

14.00 – 16.05

Anne Louchet-Chauvet (invited)

Anne Rodriguez

Jiawen Liu

Mélanie Lebental

Zürich Instruments

Rohde & Schwarz

Hybrid optomechanical processes in bulk rare-earth ion-doped crystals

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Initially considered for solid-state laser materials, rare-earth ion-doped crystals (REIC) have now become a prominent system in many topics including quantum memories, optical metrology, wideband signal processing and imaging, due to their extraordinary coherence properties at cryogenic temperature.

The inherent coupling to strain of the ions' optical lines, owing to the monolithic nature of the REIC, has long been exploited for spectroscopic studies [1]. More recently, the emergence of quantum optomechanics shed new light on REIC, exposing them as interesting strain-coupled hybrid mechanical systems [2].

In this tutorial, I will explore optomechanical processes from the viewpoint of a REIC spectroscopist. I will describe how the spectral holeburning mechanism enables remarkably sensitive vibration detection in a cryogenic environment [3]. Then I will present our recent experimental demonstration of an excitation-induced optomechanical backaction in a room-temperature bulk REIC [4]. I will show that these systems offer an unprecedented degree of sensitivity and control, confirming their significance in the active field of hybrid optomechanics.

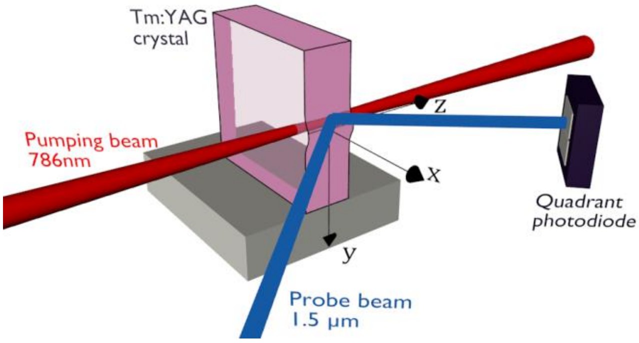

Figure 1: Schematic experimental setup for the observation of an excitation-induced motion in a bulk rare-earth ion-doped crystal.

[1] Keating, K. B., & Drickamer, H. G., Effect of pressure on the spectra of rare earth ions in crystals. *The Journal of Chemical Physics*, 34(1), 143-151 (1961).

[2] Mølmer, K., Le Coq, Y., & Seidelin, S., Dispersive coupling between light and a rare-earth-ion–doped mechanical resonator. *Physical Review A*, 94(5), 053804 (2016).

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[4] Louchet-Chauvet, A., Verlot, P., Poizat, J. P., & Chanelière, T., Optomechanical backaction processes in a bulk rare-earth doped crystal. *arXiv preprint* arXiv:2109.06577 (2021).

Polarized Brillouin spectroscopy in optophononic micropillar cavity operating at 18 GHz

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Inelastic scattering of light by acoustic phonons has potential for the tailored generation of frequency combs, laser-line narrowing, and all-optical data storage. These applications require strong optical fields and a large overlap between the optical and acoustic modes to be efficient. The main obstacle in Brillouin scattering measurements on objects of a few µm size is stray-light rejection. This limits the accessible acoustic phonons to few tens of GHz. In this work, we present a novel strategy based on polarization filtering to maximize the signal to noise ratio in a free-space Brillouin scattering measurement.

We designed an optophononic elliptical micropillar resonator based on AlAs/GaAs superlattices to simultaneously confine light and sound with an acoustic mode at 18 GHz (Fig. 1a). This results in enhanced optomechanical interactions [1,2]. Due to the pillar ellipticity, the degeneracy of horizontally (H) and vertically (V) polarized cavity mode is lifted (Fig. 1b), leading to polarization-dependent reflection coefficient r_H and r_V. The filtering technique is based on the rotation of polarization induced by the elliptical micropillar. By resonantly exciting the pillar with a mode matched beam of polarization projected on both H and V (Fig. 1c), the reflected laser and the Brillouin signal undergo a different rotation of polarization. We measured elliptical pillar with diameters of few µm presenting an optical mode with a Q-factor of 6000 and an optical mode splitting of ~0.1nm, as shown in Fig. 1b.

The optophononic micropillars could be integrated into fibered and on-chip [3], can be engineered to reach the stimulated Brillouin scattering regime, and are compatible with quantum dots, making them relevant for quantum communication.

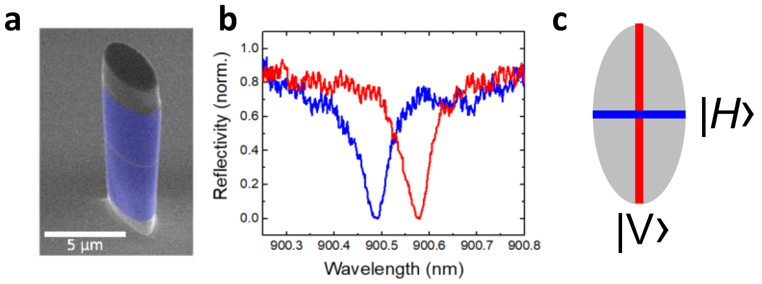

Figure 1 : a SEM image of an elliptical micropillar **b** Measured cavity reflectivity for horizontally polarized (blue) and vertically polarized (red) incident light as a function of the laser-cavity detuning energy for a micropillar with major and minor axis respectively equal to 4 and 2 µm as shown in **c**.

[1] F. R. Lamberti, et al, Opt. Express **25**, 24437 (2017)
[2] S. Anguiano, et al, Phys. Rev. Lett. **118**, 263901 (2017)
[3] O. Ortiz, et al, Appl. Phys. Lett. **117**, 183102 (2020)

Fast miniaturized THz detector based on bi-material optomechanical resonator

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We fabricated and characterized “dog-bone” resonators (Fig. 1a) with a suspended beam that acts as an optomechanical device converting THz signals into mechanical oscillations at MHz frequency. Thanks to the bi-material structure (Au/GaAs), our resonators respond very strongly to the incident THz light (Fig. 1b) and thus can be employed as a sensitive THz detector operating at room temperature [1]. On our device, a responsivity of ~280fm/nW is obtained, which is 5-10 times better with respect to a previous realization described in ref.1. Here, we further implement phase lock loop (PLL) measurements which show that the device can respond at high speed, >1 MHz, when operated on the fundamental out-of-plane flexural mode, and is only limited by the cut-off frequency of PLL. By probing our system with a THz square wave signal, we show that the temporal shape of the signal can be well recovered at a frequency higher than 10 kHz (Fig. 1c).

In addition to the terahertz detection, our system can also serve as a great platform for fundamental research when the mechanical oscillation is forced into a strong non-linear regime by an external drive. In particular, we showed, for the first time, a Duffing response from our device driven by THz radiation (Fig. 1d). This effect can also be exploited to build reconfigurable logic gates for THz signal processing [2], which is studied in our ongoing work.

[1] Belacel, Cherif, et al. Nature communications 8.1 (2017): 1-8.
[2] Manjappa,M. et al. Nature Communications 9, 4056 (2018).

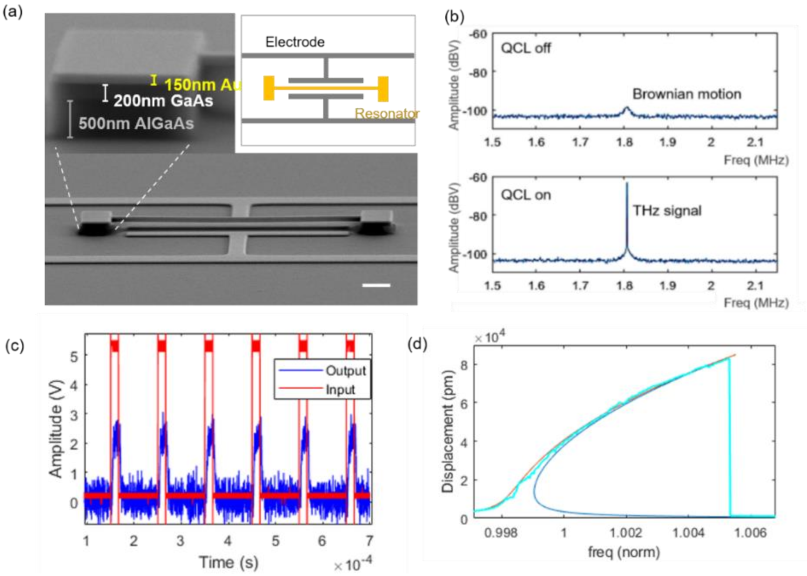

Figure 1 : (a) SEM images of a dog-bone resonator; (b) THz detection; (c) Recovering 10 kHz pulse signal; (d) Duffing response in the nonlinear regime driven by THz light.

Quantum chaos and non Euclidean photonics

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Quantum chaos is a research field dedicated to semiclassical physics [1], i.e. the relationship between a quantum system and its classical counterpart. The predictions are investigated in any wave system, namely quantum, acoustic, microwaves, optics,…

One of the major hypothesis is the localization of eigenmodes on classical periodic trajectories, which was evidenced with quasi two-dimensionnal microlasers some times ago [2]. Recently it became possible to fabricate three-dimensionnal (3D) microlasers with high optical quality by direct laser writing, in particular surface-like microlasers. We investigated Möbius strip microlasers and demonstrated by experiments and FDTD simulations that the modes were located on periodic geodesics [3], a geodesic being the shortest path between two points on a surface. A typical wavefunction and its corresponding periodic geodesic are presented in Figure 1, which evidences the connections between waves and particles in a non-Euclidean photonic device.

[1] H.-J. Stöckmann, *Quantum chaos, an introduction*, Cambridge University Press (1999).
[2] E. Bogomolny et al. *Trace formula for dielectric cavities II: regular, pseudo-integrable, and chaotic example*s, Physical Review E, vol. 83, 036208 (2011).
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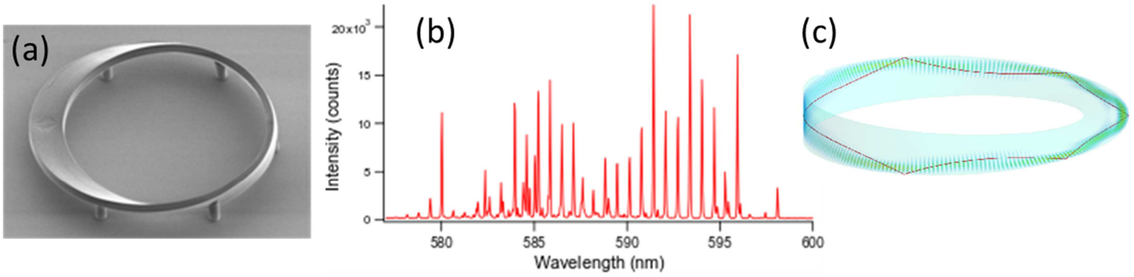

Figure 1: (a) Scanning Electronic Microscope (SEM) image of a Möbius strip microlaser with diameter 100 µm. (b) Typical experimental laser spectrum from a Möbius strip microlaser. (c) High-Q wavefunction of a Möbius strip resonator calculated by 3D FDTD simulation, which is located on the periodic geodesic in red line.

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MecaQ Optomécanique & Nanomécanique Quantiques

Prix D. Cattiaux

15-11-2021

17.45 – 18.15

Société Française de Physique

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A macroscopic object passively cooled to its quantum ground state of motion

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Recent advances in observing and exploiting macroscopic mechanical motion at the quantum limit brought opto-mechanical experiments down to always lower temperatures and smaller sizes, boosting a new research area were (more compatible) low energy photons are employed: microwave opto-mechanics.

Superconducting microwave circuits are in use and bridge opto-mechanics with quantum electronics, which positions the former as a new resource for quantum information processing. But microwave opto-mechanical platforms provide also unique capabilities for testing quantum mechanics at the most basic level: if one thinks about these devices in terms of quantum-limited detectors, the focus is on the *thermodynamic baths* that continuously interact with the mechanical degree of freedom. The fundamental questions that are addressed are then quantum thermodynamics, the boundary between classical and quantum mechanics defined by wavefunction collapse, and ultra-low temperature materials properties.

In order to perform such experiments at the frontier of modern physics, we created a unique micro-wave/micro-Kelvin opto-mechanical platform. We demonstrate for the first time the passive cooling of a 15 MHz aluminium drumhead mechanical device down to 500 micro-K, reaching a population for the fundamental mode of 0.3 quanta on average [1]; all higher modes being empty to a very high probability. Using microwave opto-mechanics as a non-invasive detector, we report on the *in-equilibrium* thermal properties of this lowest frequency mode, in particular the *fluctuations of the population number*.

[1] D. Cattiaux et *al.*, arXiv:2104.09541 (2021)

Session 16-01

16-11-2021

9.30 – 10.30

Ilaria Zardo (invited)

Towards phonon engineering at the nanoscale: material design and innovative experimental techniques

Ilaria Zardo[1]

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Keywords: phonons, thermal transport, phonon engineering, crystal phase, twinning superlattice, Raman spectroscopy

The recently growing research field called *"Nanophononics"* deals with the investigation and control of vibrations in solids at the nanoscale. Phonon engineering leads to a controlled modification of phonon dispersion, phonon interactions, and transport.[1,2] However, engineering and probing phonons and phonon transport at the nanoscale is a non-trivial problem.

In this talk, we discuss how phononic properties can be engineered in nanowires [3-5] and the challenges and progresses in the measurement of the thermal conductivity of nanostructures and low dimensional systems.[6,7]

References

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[2] S. Voltz *et al.*, *Eur. Phys. J. B* **89**, 15 (2016)
[3] M. De Luca *et al. Nano Lett.* **19**, 4702 (2019)
[4] D. de Matteis *et al. ACS Nano* **14**, 6845-6856 (2020)
[5] E. M. T. Fadaly *et al. Nano Letters* **21**, 3619-3625 (2021)
[6] D. Vakulov *et al. Nano Lett.* **20**, 2703-2709 (2020)
[7] M. Y. Swikels *et al. Phys. Rev. Appl.* **14**, 024045 (2020)

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MecaQ Optomécanique & Nanomécanique Quantiques

Session 16-02

16-11-2021

11.00 – 12.30

Yann Louyer (invited)

Damien Raynal

Attocube Systems

Nonequilibrium statistical physics in optomechanical levitation platforms

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Keywords: statistical physics, optical trapping, optomechanical tweezer, optomechanics

Optical trapping of dielectric nanoparticles immersed in a rarefied gas is part of the levitating optomechanical platforms. This subfield of optomechanics, first appeared in 1976 via Ashkin and then revisited in 2010 by Raizen & others, is an exciting research area that continues to grow. One of its major goals has been achieved very recently, namely, the cooling of the center-of-mass motion of the levitating particle to its quantum ground state.

One of the benefits of vacuum optical tweezers is the ability to tune dissipation and study non-equilibrium physics in the underdamped regime. The common thread of my talk is related to nonequilibrium statistical physics that intrinsically emerge in vacuum optical tweezers. I will present two such examples.

In the first, we study the effect of nonconservative scattering forces on the underdamped nonlinear dynamics of trapped nanoparticles at various air pressures. These forces induce significant low-frequency position fluctuations along the optical axis and the emergence of toroidal currents in both position and velocity variables.

In the second, we trap a nanodimer and present a realization of the tilted rotational periodic potential in the inertial regime. In a finite dissipation range, the bistability between the locked (torsional) and running (rotational) states is induced by an elliptical polarization tilting the washboard potential. This two-state coexistence is further accompanied by a giant acceleration of the effective rotational diffusion coefficient, which is corroborated by Langevin simulations and a two-state model.

Shortcut to equilibrium with a levitated particle

D. Raynal[a], T. de Guillebon[a], J.-S. Lauret[a], E. Trizac[b], and L. Rondin[a]

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Due to its importance in nano-physical and biological systems, understanding and mastering out-of-equilibrium physics is crucial. A notable example is the opportunity to realize transformations between equilibrium states faster than the natural relaxation time of the system [1]. In this context, *shortcut to equilibrium* protocols have been theoretically devised and demonstrated in the overdamped regime [2]. However, the extension of these protocols to arbitrary damping regimes is essential to understand how general they fundamentally are, and since natural relaxation time can hinder the operation of nanomechanical systems.

By providing a sensitive measurement and control on a single particle dynamics [3] and allowing to tune the damping of the systems [4], optical levitation offers a unique testbed to address this question. Thus, we use a single particle trapped in an optical harmonic potential of controlled stiffness to study its relaxation under transformation. We demonstrate the first shortcut to equilibration for such transformations in the underdamped regime and discuss potential limitations enforced by the experimental implementation of these protocols.

Our work paves the way for developing general optimal protocols for state-to-state transformations, with a natural application to the realization of efficient nano-heat engines in the classical or quantum regime [5].

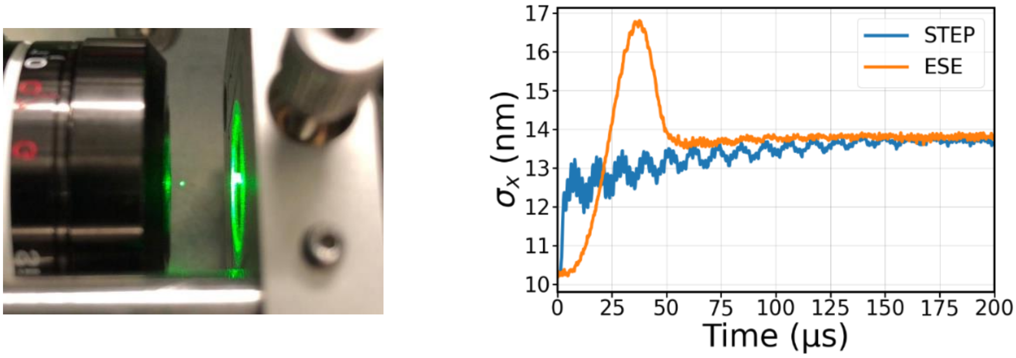

Figure 1: (Left) Picture of a levitated particle (bright green spot). (Right) Particle mean square displacement under a shortcut protocol for decompression in the underdamped regime (orange, ESE), compared with the equivalent abrupt decompression (blue, STEP).

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MecaQ Optomécanique & Nanomécanique Quantiques

Session 16-03

16-11-2021

14.00 – 15.00

Laure Mercier de Lépinay (invited)

Quantum mechanics-free subsystem with mechanical oscillators

Laure Mercier[a*]

Quantum mechanics sets a limit on the precision of the continuous measurement of an oscillator's position. However, with an adequate coupling configuration of two oscillators, it is possible to build an oscillator-like subsystem of quadratures isolated from quantum and classical backaction which therefore does not suffer from this limit. We realize such a “quantum mechanics-free” subsystem using two micromechanical drumheads coupled to microwave cavities. Multitone phase-stable microwave pumping of the system allows to implement the necessary effective coupling configuration. We first demonstrate the measurement of two collective quadratures, evading backaction simultaneously on both of them, obtaining a total noise within a factor of 2 of the full quantum limit. Secondly, this measurement technique is directly adapted to the detection of continuous variable entanglement which is based, according to the Duan criterion, on variance estimates of two collective quadratures. We therefore verify the stabilized quantum entanglement of the two oscillators deeper than had been possible before for macroscopic mechanical oscillators.

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MecaQ Optomécanique & Nanomécanique Quantiques

Session 16-04

16-11-2021

16.30 – 17.00

Samantha Sbarra

Antoine Reigue

Multimode weighting of individual nanoparticles with a semiconductor optomechanical resonator

Samantha Sbarra [a*], Louis Waquier [a], Stephan Suffit [a], Aristide Lemaître [b], and Ivan Favero [a]

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Due to their small size, nanomechanical systems exhibit a strong response to external perturbations, which has led to remarkable progress in mass spectroscopy over the last decade [1,2]. The combination with optomechanical concepts should lead to further advances, thanks to the unprecedented sensitivity and bandwidth of optomechanical techniques [3]. Here, we use the intense optomechanical coupling at work in gallium arsenide disk resonators to perform continuous and parallel optical tracking of multiple optical and mechanical modes of the resonator. The vibration modes are optically excited by sinusoidal modulation of the input laser, and their ultra-high frequency amplitude and phase signal are demodulated. A new multiphysics model describes the optomechanical experiments under these conditions, including photothermal interactions and (non)linear absorption in the device, allowing a quantitative interpretation of the output signal [4]. Detection of solid nanoparticles of femto-gram mass, about the size of a single virus, landing on the disk resonator is demonstrated in real-time. By modeling these multimode signals with analytical and numerical tools, the mass and volume of the particle are assessed, demonstrating the effectiveness of optomechanical devices for the dual mechanical and optical analysis of nanometric objects. These are the first steps towards a rapid and quantitative method for identifying individual biological particles.

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2. M. S. Hanay, S. Kelber, A. K. Naik, D. Chi, S. Hentz, E. C. Bullard, E. Colinet, L. Duraffourg, and M. L. Roukes, "Single-protein nanomechanical mass spectrometry in real time," Nat. Nanotechnol. **7**, 602 (2012).
3. M. Sansa, M. Defoort, A. Brenac, M. Hermouet, L. Banniard, A. Fafin, M. Gely, C. Masselon, I. Favero, G. Jourdan, and S. Hentz, "Optomechanical mass spectrometry," Nat. Commun. **11**, 3781 (2020).
4. S. Sbarra, P. E. Allain, A. Lemaître, and I. Favero, "A multiphysics model for high frequency optomechanical sensors optically actuated and detected in the oscillating mode," Appl. Phys. Lett. Photonics **086111**, 1–6 (2021).

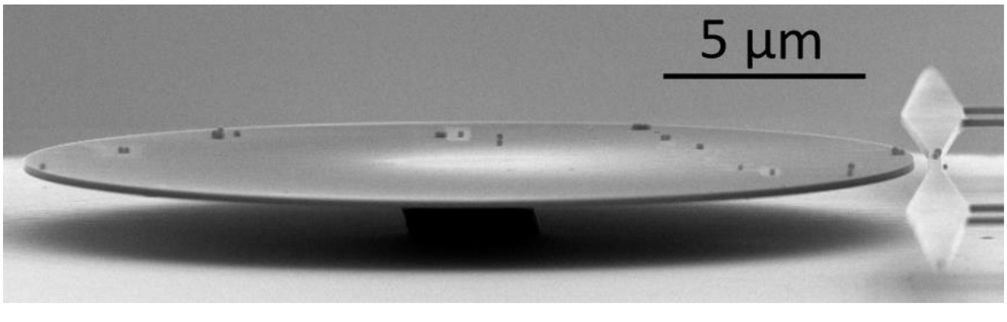

Figure: SEM image of the optomechanical resonator employed for weighting nanoparticles in real-time.

Cavity nano-optomechanics with suspended nanowires

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We report on the modelization and experimental realization of a cavity nano-optomechanical system made of a SiC nanowire inserted in a high finesse fibred micro-cavity. The ultra-high sensitivity of the nanowires, their sub-wavelength dimensions and their strong interaction with light, associated to the small mode volume of the cavity, provides important coupling strength and an ideal configuration to finely study the two facets of the optomechanical interaction.

In this talk we will present how we evaluate the large optomechanical coupling strength of our system as well as the optical force applied on the nanowire using a response measurement setup. In particular, we will stress the high force sensitivity down to a single photon modulation. Additionally, we will show how the combination of the Mie theory used to describe the scattering of the light by the nanowire and a transfer matrix formalism lead to a mean field numerical model giving access to the outgoing and intra cavity field depending on the nanowire properties and position. We will present results in quantitative agreement with the experimental measurements realized in our group [1] for both aspects of the optomechanical coupling, in a situation where only few photons are present in the cavity.

Additionally, our work [2] highlights the existence of configurations where the insertion of the nanowire in the cavity leads to an increase of the resonant cavity length, a surprising effect since the insertion of a dielectric is supposed to increase the optical path which should result in a decrease of the resonant cavity length. We will present recent experimental results confirming the prediction of the model and discuss the origin of this effect.

Finally, this work opens the road for future investigations of the nanowire in the middle system at the single photon level. Indeed, preliminary work shows the possibility to observe a static bistability close to the single intra-cavity photon opening the road to broadband squeezing of the outgoing cavity field.

[1] F. Fogliano et al, Mapping the cavity optomechanical interaction with sub-wavelength-sized ultrasensitive nanomechanical force sensors, **PRX** 11, 021009 (2021)
[2] A. Reigue et al, Cavity nano-optomechanics with suspended subwavelength-sized nanowires: modelization and novel phenomenology, **in preparation**.

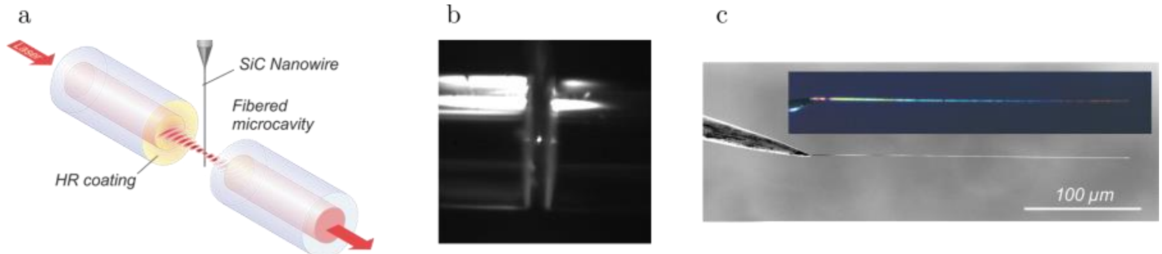

Figure 1: (a) Scheme of the optomechanical system made of a nanowire inserted in a fibred micro-cavity. (b) Picture of the optical cavity, one can observe the light scattered out of the cavity by the nanowire. (c) Image of a typical nanowire

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Plasmonic magnification of optomechanical coupling

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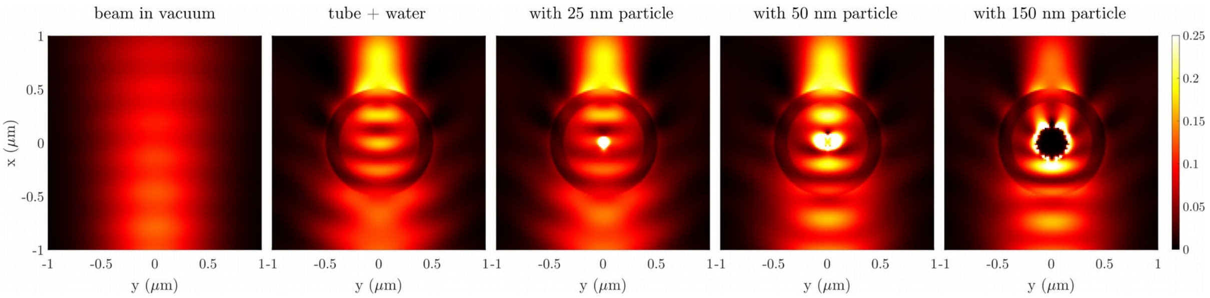
The possibility to remotely detect individual nano-objects in situ still is a physical challenge that restrains the development of promising applications especially to biology where particles evolve in a microfluidic environment. In this work we numerically investigate the case where a metallic nano-particle is transported in a microtube channel and propose a high precision method based on the coupling of the optical field supported by the particle and the mechanical vibration of the channel. We quantified the change in the optomechanical force experienced by the microtube as the particle circulates. We show that this effect holds for any size of particle even when scattering is negligible.

We considered a borosilicate glass tube of outer diameter 0.5 µm and inner radius 0.375 µm where spherical gold nanoparticles (NPs) travel in water. The system is illuminated by laser beam focused closely from the tube. It is well known that, because of plasmon resonance, the optical behavior of nanosize metallic particles can be either diffusive or absorbent strongly depending on their dimension. For this reason we considered three different radii: 150 nm, 50 nm or 25 nm travel. Indeed, it can ben computed [1] that for the largest of these value scattering dominates when absorption does for the smallest at the considered wavelength. This system combines numerous and in addition coupled electromagnetic phenomena: diffraction from the tube, lensing due to water, surface plasmon, absorption and diffusion of the NP that prevent any derivation of an analytical model. Hence, we opt for a numerical approach, to be able to catch the dynamic of the system we chose a finite-difference time-domain (FDTD) method using the open-source software package MEEP [2] (Figure 1).

From that we have been able that with an incident power of 1 W the motion of the particle in the tube generated a mechanical force shift on the order of 1 nN.

[1] K. Metwally, S. Mensah, and G. Baffou. The Journal of Physical Chemistry C, **119**(51):28586–28596, 2015.
[2] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J.D. Joannopoulos, and S. G. Johnson. Computer Physics Communications, **181**(3):687 – 702, 2010.



beam in vacuum | tube + water | with 25 nm particle | with 50 nm particle | with 150 nm particle

Figure 1 : Cross-section of optical intensity distribution in the z=0 plane averaged on half a period. The source is y-polarized. Note that the oscillations - particularly visible on the left panel - are a numerical artifact due to temporal discretization.

Quantum well exciton polaritons in a whispering gallery mode semiconductor microcavity

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Exciton-polaritons are half-light, half-matter particles, broadly used in many-body physics and quantum technologies. We report on the observation of the strong coupling regime between the excitonic transition of InGaAs/GaAs multiple quantum wells and a discrete series of Whispering Gallery Modes (WGM) of a disk microcavity. Optical modes and excitonic resonance are tuned by varying the temperature and the cavity size. 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 3 and 6 meV, function of the concerned optical mode. They are in accordance with a new theoretical model, which describes analytically polaritons that are formed in a WGM box. The regime of polariton lasing is also observed, with strong evidences of polaritonic non-linearities. The control of polaritons in such disk resonator establishes the platform for polaritonic optomechanical experiments.

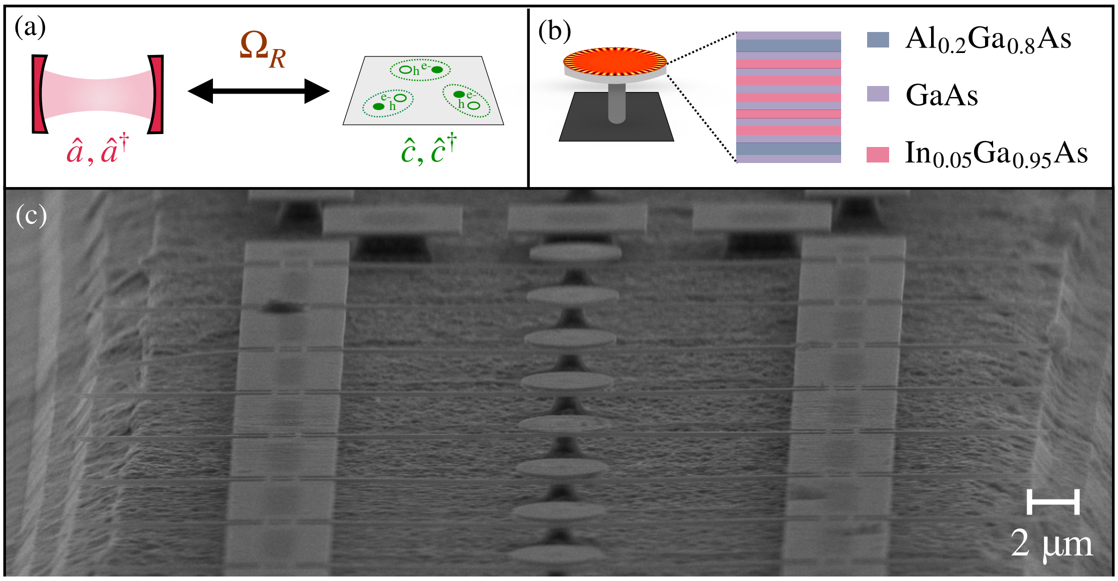

Figure 1 : (a) Sketch illustrating the strong coupling between the cavity modes and the MQW excitons (b) Side view layout of the disk with the MQW structure present in the disk layer, and the spatial profile of a WGM. (c) SEM micrograph of a sample containing a distribution of different disk and waveguides

Electro-Optomechanical Modulation Instability in a Semiconductor Resonator

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In semiconductor nano-optomechanical resonators, several forms of light-matter interaction can enrich the canonical radiation pressure coupling of light and mechanical motion and give rise to new dynamical regimes. Here, we observe an electro-optomechanical modulation instability in a gallium arsenide disk resonator. The regime is evidenced by the concomitant formation of regular and dense combs in the radiofrequency and optical spectrums of the resonator associated with a permanent pulsatory dynamics of the mechanical motion and optical intensity. The mutual coupling between light, mechanical oscillations,carriers, and heat, notably through photothermal interactions, stabilizes an extended mechanical comb inthe ultrahigh frequency range that can be controlled optically.

[1] Pierre Etienne Allain, et al. Physical Review Letters **126**, 243901 (2021)

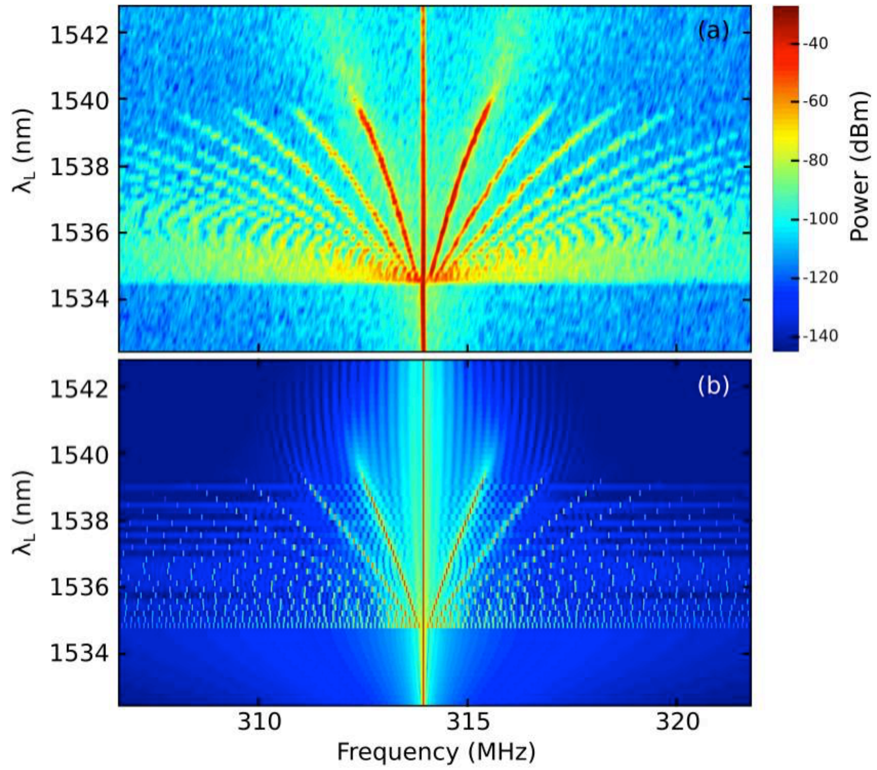

Figure 1: Radio-frequency spectrum of the optical output of a gallium arsenide disk resonator in the electro-optomechanical modulation instability regime. Starting from the self-oscillation regime at small input laser wavelength, a radio-frequency mechanical comb is suddenly developing as the wavelength is increased beyond a threshold. The comb teeth are then progressively separating. A pulsed mechanical motion appears in the time domain. (a) Experiments. (b) Theory.

Coherent Perfect Absorption in coupled Nano-Opto-ElectroMechanical Systems

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Coupled nano-opto-electromechanical systems (NOEMS) are ideal platform to test physical concepts applied to mechanics. Large amount of various photonic structures able to couple to external fields were used to exhibit coherent perfect absorption (CPA) [1-3].

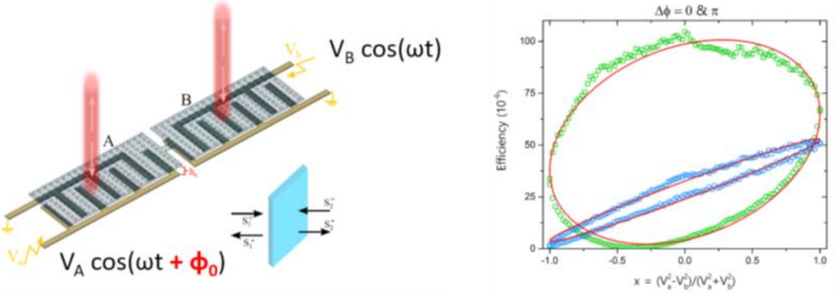

Figure 1: (left) Schematic view of the experimental set-up. (Right) Coherent absorption control in a linear two-port system (experiment and fit).

We hereby introduce our recent results on mechanical-like coherent perfect absorption (and transmission) phenomenon in a coupled nano-opto-electromechanical system. It consists in two mechanically coupled optomechanical cavities (Fig. 1), each cavity consisting of a membrane suspended over a pair of integrated interdigitated electrodes. On one hand, electromechanical transduction allows us to convert electrical energy injected into the system into mechanical displacements. On the other hand, optomechanical transduction enables to detect the system's displacements in the form of mechanical eigenmodes of the coupled NOEMS. When coherently exciting both cavities with two identical excitations whose phase difference and amplitudes are controllably varied (Fig. 1), it is possible to observe a modulation of the mechanical response which is found to be enhanced or lowered. This is completely analogous to how absorption (or transmission) behaves in a photonic structure [4]. This variation is well understood and modelled by analytic forms or via the mechanical dynamics equations of our system. Applications in optics pave the way for the NOEMS scheme that can for now deal with astonishing physics e.g. realization of optical switches, logical gates or polariton states to name a few.

[1] N. Gutman et al., Optics Letters, vol. 38, no. 23, pp. 4970-4973 (2013).
[2] Papaioannou et al., Light: Science and Applications, 5, e16070 (2016).
[3] Baranov et al, Nature Reviews Materials, 2, 17064 (2017).
[4] Baldacci et al, Life, New Materials and Plasmonics, 26, pp. 219-230 (2015).

Proposal for a nanomechanical qubit

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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. For more details see [1].

[1] *Proposal for a nanomechanical qubit,* F. Pistolesi, A.N. Cleland, and A. Bachtold, Phys. Rev. X **11**, 031027 (2021).

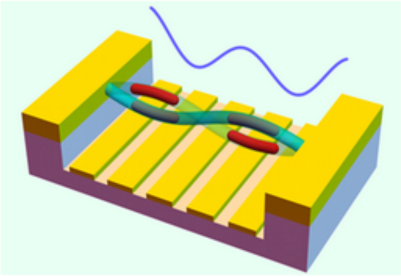

Figure 1: Artist view of the device: a suspended carbon nanotube where a double quantum dot is coupled to the second flexural mode. The five gate pads are used to form the binding potential for the electrons (back-ground plot) and to manipulate the mechanical and electronic degrees of freedom.

Magnon-exciton proximity coupling at a van der Waals heterointerface

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Spin and photonic systems are at the heart of modern information devices and emerging quantum technologies. An interplay between electron-hole pairs (excitons) in semiconductors and collective spin excitations (magnons) in magnetic crystals would bridge these heterogeneous systems, leveraging their individual assets in novel interconnected devices. We report the magnon-exciton coupling at the interface between a magnetic thin film and an atomically-thin semiconductor [1]. Our approach allies the long-lived magnons hosted in a film of yttrium iron garnet (YIG) to strongly-bound excitons in a flake of a transition metal dichalcogenide, $MoSe_2$. The magnons induce on the excitons a dynamical valley Zeeman effect ruled by interfacial exchange interactions. This nascent class of hybrid system suggests new opportunities for information transduction between microwave and optical regions.

[1] A. Gloppe et al., Magnon-exciton proximity coupling at a van der Waals heterointerface, arXiv:2006.142571 (2021)

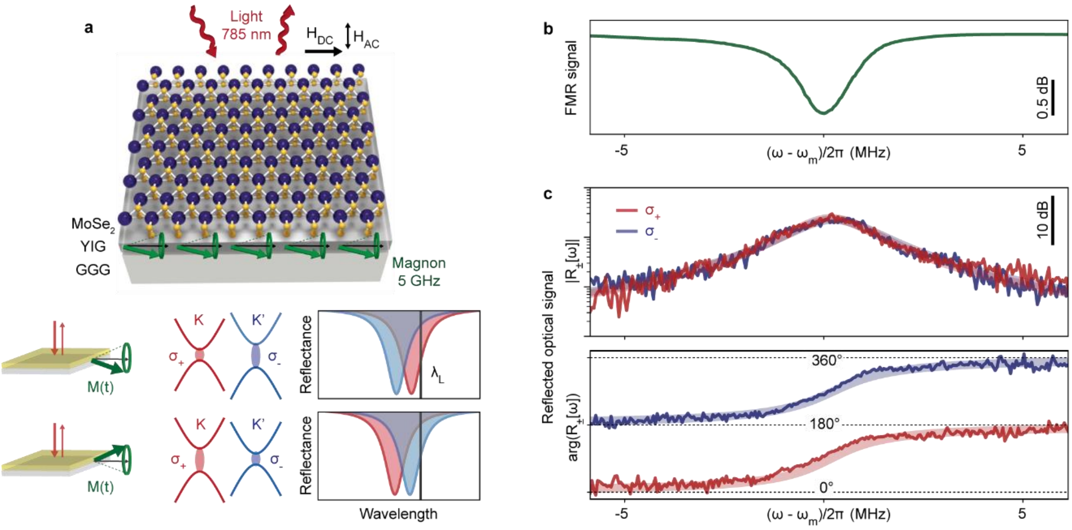

Figure 1: a) Atomically-thin flakes of $MoSe_2$ are stacked on a magnetic YIG film grown on gadolinium gallium garnet. A microwave antenna excites magnons of the fundamental magnetostatic mode of frequency $\omega_m/2\pi$. The magnons support a coherent oscillation of the magnetization vector, responsible for an effective magnetic field modulating the excitonic resonances of the $MoSe_2$ flakes through a dynamical valley Zeeman effect. b) Microwave absorption signal revealing the ferromagnetic resonance (FMR) at $\omega_m/2\pi = 5.64$ GHz. c) Magnitude and relative phase of the optically-probed FMR spectra $R_\pm[\omega]$ with left-handed σ_+ and right-handed σ_- circularly polarized light to address respectively the K and K' valleys of the $MoSe_2$ flake.

Probing the magnetic phase transition of a few-layer FePS$_3$ suspended membrane

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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 like graphene or 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,b**). For this first study, we probed the phase transition of FePS$_3$, an Ising zigzag antiferromagnet, combining two complementary methods on the same experimental setup: Raman spectroscopy and nano-optomechanics [2,3]. The magnetic phase transition of the membrane was attested by a modification of its Raman signature arising from the vibrational modes of the iron atom in the crystal (Fig.1**c**), concomitant with changes in the drumhead mechanical resonance frequencies around its Néel temperature, monitored through the spectra of their Brownian and laser-actuated motions (Fig. 1**d**). These first measurements open to the exploration of magnetic van der Waals heterostructures phase transitions and to their control by strain.

[1] B. Huang *et al.* Emergent phenomena and proximity effects in two-dimensional magnets and heterostructures, *Nature Materials*, **19**, (2020).
[2] J.-U. Lee *et al.* Ising-type magnetic ordering in atomically thin FePS$_3$, *Nano Letters*, **16**, (2016).
[3] M. Šiškins *et al.* Magnetic and electronic phase transitions probed by nanomechanical resonators, *Nature Communications*, **11**, (2020).

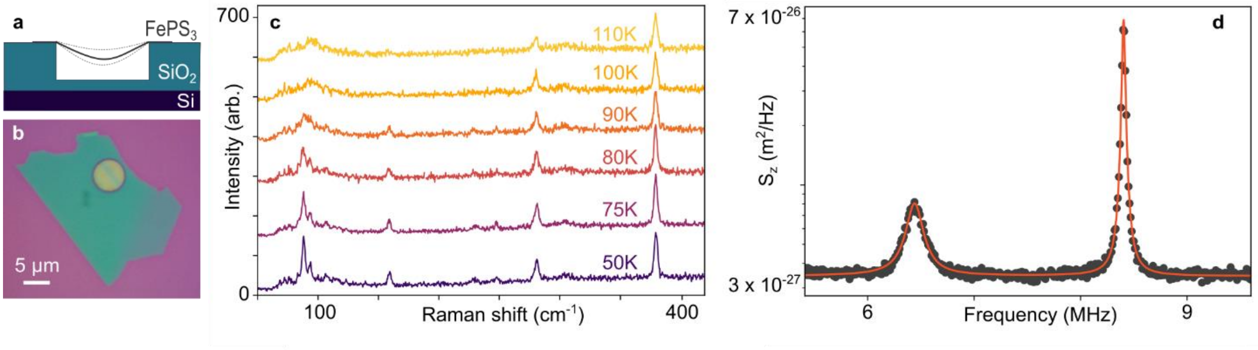

Figure 1: **a**. Schematic representation of a nanoresonator made of few-layer FePS$_3$ suspended over a hole etched in a Si/SiO$_2$ substrate. **b**. Optical picture of the studied sample constituted of a FePS$_3$ suspended membrane with an estimated thickness of 10 nm (appearing in yellow) over a hole of 6 µm in diameter and 400 nm in depth. **c**. Raman spectra recorded around the Néel temperature of our sample. The spectra are vertically offset for clarity. **d**. Displacement spectral density of noise of the FePS$_3$ membrane at room temperature (black dots: data, orange line: Lorentzian fits).

Optomechanical discrete-variable quantum teleportation scheme

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We propose an experimental protocol to realize discrete-variable quantum teleportation [1] using optomechanical devices. The photonic polarization superposition state of a single photon is teleported to a phononic superposition of two micromechanical oscillators by means of photon-phonon entanglement generation and optical Bell state measurement using two-photon interference. Verification of the protocol is performed by coherent state transfer between the mechanical devices and light. Simulations show the feasibility of the proposed scheme at millikelvin temperatures using state-of-the-art gigahertz optomechanical devices [2,3].

[1] C.H.Bennett,G.Brassard,C.Crépeau,R.Jozsa,A.Peres,and W. K. Wootters, Phys. Rev. Lett. 70, 1895 (1993).
[2] Pautrel, S., Denis, Z., Bon, J., Borne, A. & Favero, I. An optomechanical discrete variable quantum teleportation scheme. *Phys. Rev. A* **101**, 063820 (2020)
[3] Fiaschi, N., Hensen, B., Wallucks, A. *et al.* Optomechanical quantum teleportation. *Nat. Photon.* (2021)

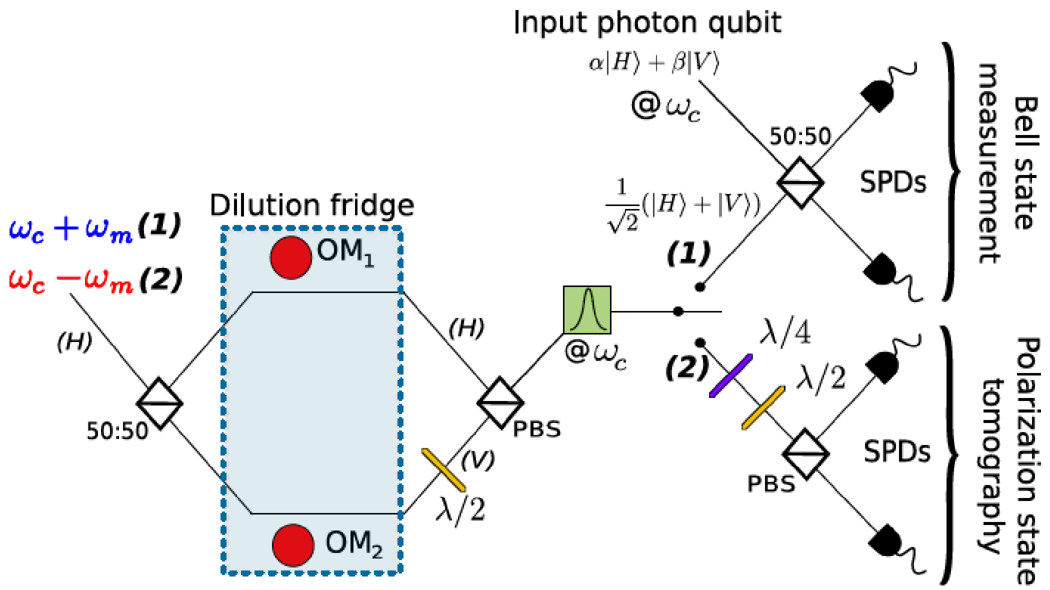

Figure 1 : Schematics of the protocol setup with its two steps.

Towards a mechanical qubit in a double quantum dot in a carbon nanotube-based device

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D. Czaplewski[c] , A. N. Cleland[d] , F. Pistolesi[e], A. Bachtold[a]

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Mechanical resonators are systems which present high quality factors and can easily couple to a wide range of forces. For this reason, they are excellent candidates for sensing and quantum information. While their qualities as sensors have been exploited for many years, it is only recently that their potential use as quantum bits (qubits) have been proposed.

To enable a mechanical qubit, the resonator may be coupled to an external force which induces anharmonicity in the energy dispersion curve of the harmonic oscillator. While they exist some theoretical proposals [1][2], inducing non-linearities on the energy spacing of a mechanical resonator has not yet been achieved experimentally.

In this context, the force exerted by single electron tunnelling on the mechanical vibration of quantum dots embedded in carbon nanotubes has been shown to induce such anharmonicity [2]. In practice this effect necessitates operation in the so-called strong coupling regime. In this regime, the mechanical motion of the carbon nanotube couples to the single electron tunnelling on the quantum dot leading to a ladder of charge-mechanical energy states.

In our work, we present data that evidences the ultra-strong coupling for the single quantum dot case and preliminary data for a double quantum dot system (DQD). In the latter, an electronic two-level system (eTLS), based on the delocalisation of an electron over the two quantum dots, can efficiently couple to the second flexural mode of the carbon nanotube. In the above mentioned ultra-strong coupling regime, the system presents an energy difference between its ground and first excited states significant enough to be used as a basis for a qubit.

The qubit decoherence of the charge-mechanical hybrid system is expected to display a sizeable improvement with respect to current state-of-the-art charge qubits [2]. In our project, we aim to show how to implement such a system experimentally including: our novel nanofabrication techniques for high quality DQDs and cavity read-out of the qubit states.

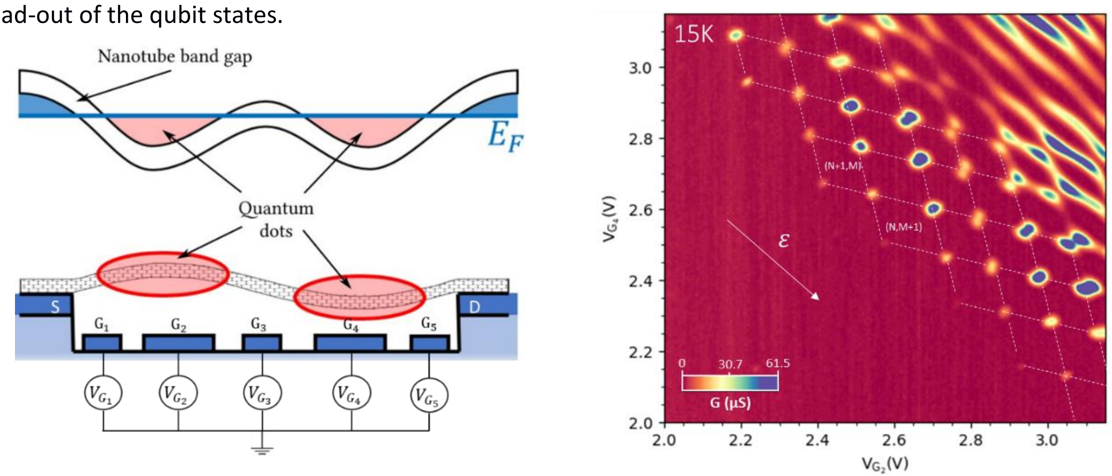

Figure 1 : (Left) Scheme of a double quantum dot system defined on a suspended carbon nanotube over five gate electrodes. (Right) Double quantum dot charge stability diagram of one of our devices at 15K.

[1] F. Pistolesi, A. N. Cleland, and A. Bachtold. Proposal for a nanomechanical qubit. Phys. Rev. X 11, 031027, 2021.
[2] S. Rips and M. J. Hartmann. Quantum information processing with nanomechanical qubits.Physical Review Letters, 110, 3 201

Dynamical chaos in nonlinear micromechanical resonators

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Chaos is a nonlinear phenomenon at the boundary between harmonic oscillators and stochastic systems, as it is both deterministic and non-periodic. Present in nature, from the precession of moons to the evolution of the weather, chaos can also be tailored for specific applications using electronics or optical systems. In mechanics, chaotic dynamics has mostly been demonstrated in buckled structures through strong electrostatic coupling or involved, specific geometries.

Recently, a few studies [1-3] demonstrated that any vibrating mechanical structures, driven in a strong nonlinear regime, may be placed in a chaotic regime. This generic way of generating chaos in micro/nano-mechanical systems (M/NEMS) opens new perspectives, combining the high sensitivity of these structures with the unique properties of chaos.

In this talk, I will present chaos generation from an off-the-shelf MEMS using either frequency or amplitude modulation schemes [2] (Fig. 1). Its complex dynamics, mainly characterized by non-periodicity through Poincaré sections and non-reproducibility through Lyapunov exponents, quantitatively agrees with numerical simulations. In a last part I will present some applications combining MEMS' original purpose and chaos' singular properties [4], and discuss possible fields of exploration in both applied and fundamental research.

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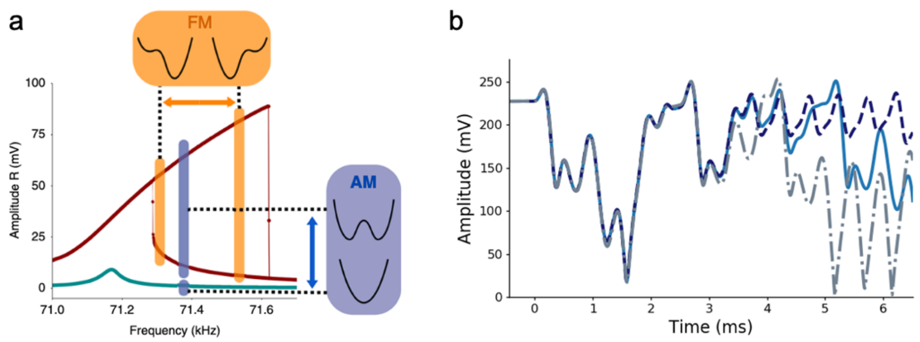

Figure 1: a Driving a resonator from the linear (blue curve) to the nonlinear regime (red curve) creates a hysteresis. By applying a modulation in amplitude (AM, blue box) or in frequency (FM, orange box) within this hysteresis enables to switch between the different dynamical states of the system. **b** Using specific modulation parameters, the resonator enters the chaotic regime. Similar initial conditions lead to different results, highlighting the non-reproducibility arising from the intrinsic noise of the system.

Rotational dynamics of a levitating diamond in a Paul trap

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Levitation of large objects is promising for testing the limit between the quantum and the macroscopic world. It can also enable development of ultra-sensitive mechanical force sensors as well as to test stochastic thermodynamic models at the nanoscale [1]. Moreover, being able to fully control the rotational dynamic of a levitating particle opens bright prospects towards the detection of intrinsic angular properties such as the Einstein-de Haas and the Barnett effects [2].

Our platform consists in a micron-sized diamond embedded with NV centers levitating in an electrodynamic trap also called Paul trap. The angular stability of the diamond offered by the Paul trap makes this platform ideal to couple the NV centers spin to the librational modes. It has led to the first observation of mechanical cooling using the NV centers spin inside the diamond [3]. More recently, a full control of the diamond orientation has been achieved using NV centers diamagnetism due to a spin level anticrossing [4].

Aside from NV coupling to the motion, the ponderomotive nature of the Paul trap features regime where the diamond fully rotates stably at half of the trap frequency. Furthermore, photophoretic forces due to the heating of the laser directly affect the diamond angular motion which can lead to a full rotation of the diamond. We will present our latest results towards understanding these aspects and their influences on the spin-mechanical coupling.

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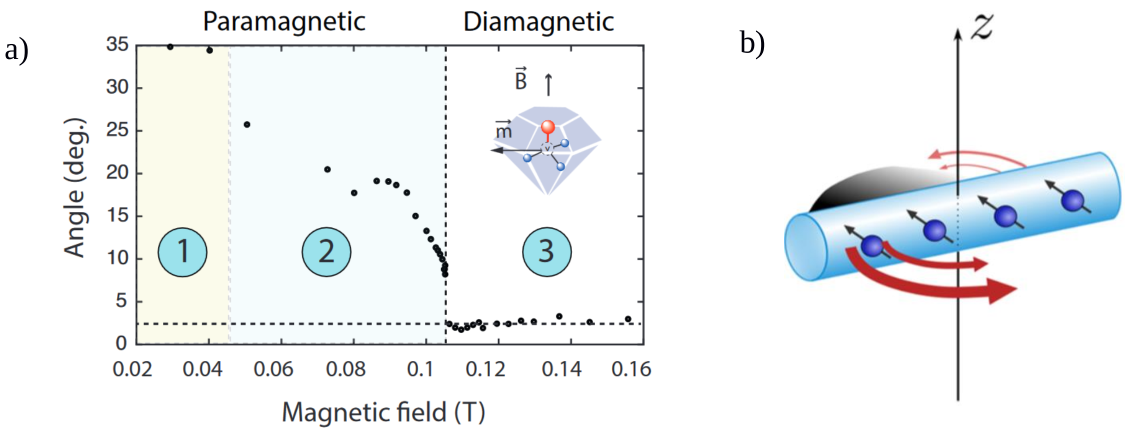

Figure 1 : a) Angle between a NV center class and the magnetic field direction for a levitating diamond as a function of the magnetic field amplitude. b) Schematic view of a cylindrical rotating diamond.

Phonon localization in 1D quasi-periodic structures

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Acoustic heterostructures operating at GHz-THz range [1] involving shorter wavelengths (~10 nm) and longer mean free paths constitute a suitable platform to study localization phenomena in quasi-periodic structures. The localized acoustic phonons and its dynamical interactions can be experimentally accessed in ultrafast pump-probe spectroscopy. The one-dimensional (1D) quasiperiodic structures based on the Aubry-André (AA) model and the Fibonacci sequence have been studied in multiple physical platforms to address many-body localization. A smooth localization/delocalization transition was recently demonstrated in quasiperiodic structures ruled by the interpolating Aubry-André-Fibonacci (IAAF) model [2]. We theoretically address the 1D tight-binding IAAF model to study this localization transition for phonons in the 20-200 GHz frequency range in 1D AlGaAs/GaAs superlattices.

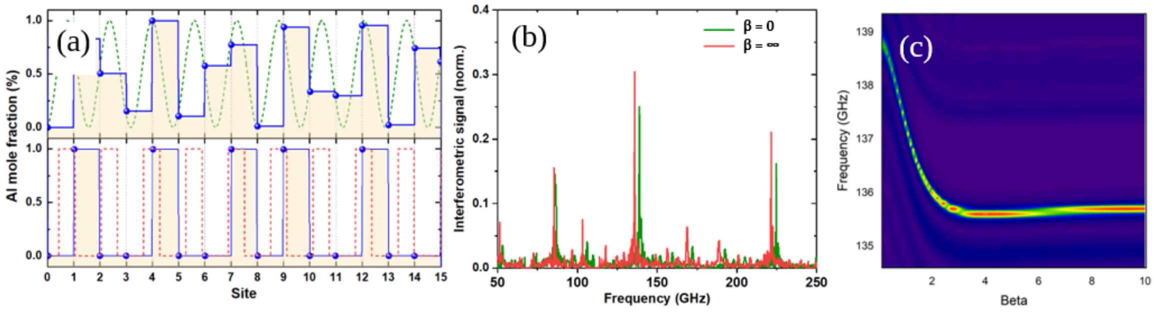

Figure 1: (a) Spatial variation of Al mole fraction in the lattice structure for two limiting cases i.e. $\beta = 0$ (top) and $\beta = \infty$ (bottom). (b) Simulated pump-probe interferometric spectrum for the two cases. (c) Evolution of localized acoustic mode at 136 GHz for the structures at different values of β.

Figure 1(a) shows the spatial variation of the Al mole fraction across the structure. The structure develops as pure AA and Fibonacci sequence model as a function of tunable parameter β [2] which allows to interpolate between limiting cases of β = 0 and ∞, respectively. The simulated pump-probe interferometric spectrum based on photoelastic interactions for the two structures are shown in Fig.1(b). The pump-probe spectrum reveals the presence of three localized modes at 85, 136, and 221 GHz, as the AA model transforms into Fibonacci sequence. Fig.1(c) shows the evolution of the second localized acoustic mode in the pump-probe spectrum is studied as a function of β. The calculated localized phonon mode spectrum highlights the potential of using acoustic superlattices to study localization phenomena at nanoscale.

We have theoretically studied the localized acoustic modes generated due to on-site potential modulation in complex 1D quasi-periodic structures based on IAAF model. We demonstrate the use of nearly linear dispersion of acoustics phonons that allows direct modelling of the complex array structure dynamics.

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Towards hybrid OM with hBN in a fiber-based Fabry-Perot cavity

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Hybrid quantum systems which combine cavity optomechanics (OM) and cavity quantum electrodynamics have recently emerged as promising devices. Here we report on our implementation of an experimental platform for studying such systems. The platform is built around a fiber-based open-access Fabry-Perot optical cavity (FFPC) [1], within which different interchangeable samples can be precisely positioned, forming a membrane/nanowire-in-the-middle (MIM/NIM) OM system [2] (Fig. 1 (a)).

We used CO2 laser ablation to fabricate mirror templates with optimized geometry on the tip of optical fibers [3]. Such fibers are placed in a titanium cage designed to allow a MIM system to be operated in high vacuum within a ^{4}He bath cryostat. The length of the resulting FFPC is widely tunable and can be locked to the laser frequency using the Pound-Drever-Hall stabilization scheme, both a room temperature and at 4K. We deposited a flake of hexagonal boron nitride (hBN) on a Norcada holey membrane to realize a suspended drum micromechanical resonator (Fig. 1 (b)), which we inserted inside the FFPC to realize a MIM system (Fig. 1 (c)). We then measured the dispersive effect of the membrane on the cavity resonance frequency.

Our forthcoming study of dynamical OM effects in this MIM system should provide valuable data on the mechanical properties of hBN. We then aim to observe the impact of a quantum emitter positioned within the hBN drum [4] on its OM interaction with the cavity field [5].

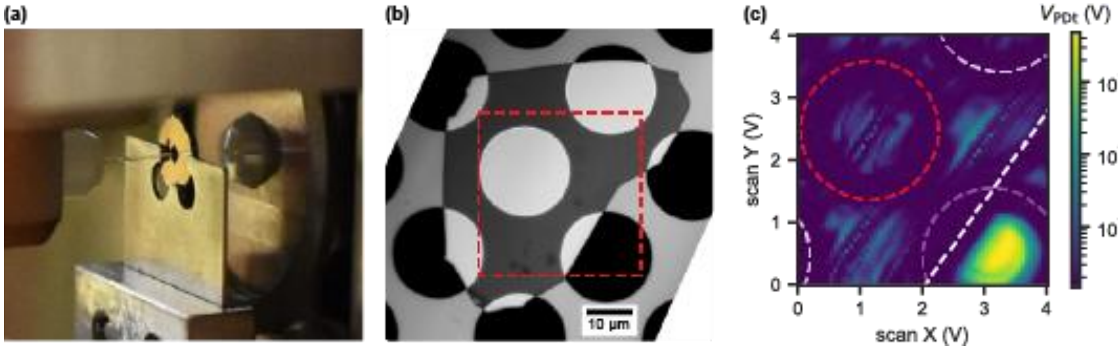

Figure 1 : (a) Picture of a Norcada holey membrane held between two fiber mirrors, defining a fiber-based MIM system. (b) Microscope image of an hBN flake on the holey membrane, defining a suspended drum. (c) Peak transmission of the MIM system as the membrane is scanned laterally, with the edges of the membrane holes and of the hBN flakes outlined. The scan area corresponds to the red outline in (b).

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[5] Aporvari et al., *Strong Coupling Optomechanics Mediated by a Qubit in the Dispersive Regime*, Entropy **23**, 8 (2021)

Topologically robust interface modes by band inversion for colocalization of light and sound

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The concept of band inversion is explained as inverted spatial mode symmetries in periodic lattices and is a key feature in the creation of topologically robust interface modes. When two periodic lattices with inverted mode symmetries are concatenated together, it leads to the generation of an interface mode inside the band gap [1]. The robustness of these modes against chirality preserving perturbations has been exploited for a wide range of excitations (photons, plasmons, phonons, vibrations, polaritons). Most of these realizations explored a single kind of excitation. Despite its potential in the manipulation and control of interactions, the simultaneous topological confinement of multiple excitations remains an open challenge.

In this work, we have studied multilayered GaAs/AlAs structure which supports simultaneously inverted band structures for light and sound. This gives rise to a colocalized interface mode for both 1.34 eV photons and 18 GHz phonons. Fig.1a shows simulation of the colocalized optical and acoustic fields in the structure. We experimentally validate the concept by optical reflectivity (Fig.1b) and coherent phonon generation and detection through picosecond optical pump-probe spectroscopy (Fig.1c) [2-3]. We theoretically predict a robust photoelastic interaction between optical and acoustic interface mode which manifests a stable Brillouin cross-section when the structure is subjected to chirality-preserving fluctuations. Potential future applications include engineering of robust optomechanical resonators compatible with active media such as quantum wells and quantum dots.

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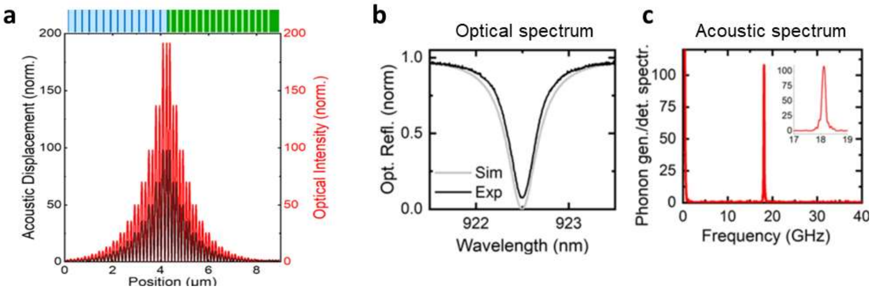

Figure 1 : a Simulation of colocalized topological interface mode for light and acoustic phonons. **b** Optical reflectivity spectrum. **c** Pump-probe phonon generation-detection spectrum

Efficient generation of coherent acoustic phonons with fiber-integrated microcavities

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Coherent phonon generation by picosecond optical pump-probe spectroscopy [1] is an important experimental tool for studying acoustic properties at the nanoscale. In this work, we integrate semiconductor micropillar cavities confining near-infrared light and 18 GHz acoustic phonons with single-mode fibers. This approach solves three major challenges of existing pump-probe experiments using mechanical delay lines: (1) stability of the optical mode overlap, (2) reproducibility of the excitation conditions, and (3) high power densities limiting the range of compatible samples. These shortcomings have so far been a roadblock in establishing pump-probe spectroscopy as a quantitative tool for nanoacoustics.

Our approach allows us to observe stable coherent phonon signals over at least a full day and at extremely low excitation powers down to 1µW. We performed detailed power dependence studies revealing a mutual coherence between the optical and the phononic modes [4].

The monolithic sample structure is transportable and provides a means to perform reproducible plug-and-play experiments. The integration with fibers might also establish the missing link between high frequency acoustic phonon engineering and stimulated Brillouin scattering in structured optical fibers [5].

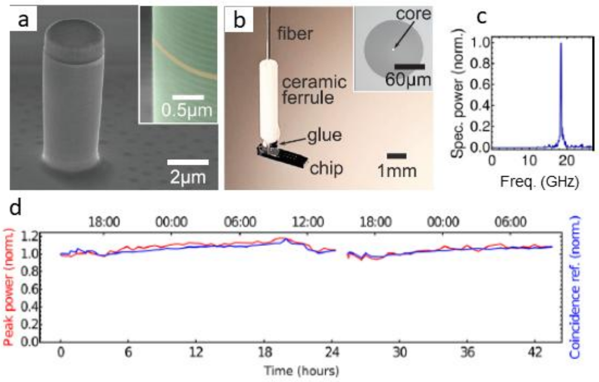

Figure 1: a Optophononic micropillar cavity. **b** Device integrated into a single mode fiber. **c** Nanophononic response of the device measured by pump-probe spectroscopy. **d** Stability of the response over 42h. Figure adapted from Ref. [2].

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Vectorial force field sensing at the nanoscale and in quasi realtime using suspended nanowires

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We demonstrate a nanowire-based vectorial force field sensor operating in quasi real-time. This is achieved by optical readout of the driven motion of a singly clamped nanowire. The nanowire is free to oscillate in the horizontal transverse plane and presents two fundamental eigenmodes with quasi similar frequencies oscillating along perpendicular orientations. When inserted in an external force field, the quasi degenerated mechanical eigenmodes will be dressed by the force field's local gradients. By tracking the dressed frequencies and eigenmode orientations we can reconstruct the structure of the force field gradient matrix and the force field itself.

The measurement principles were validated during previous experiments based on a spectro-angular analysis of the nanowire thermal noise in 2D. The electrostatic force fields around a metallic tip was imaged in [2], while the case of a rotational force field was analyzed in [1,3]. Here, we developed advanced protocols based on coherently driven trajectories, using phase locked loops and demodulators to track both eigenmodes perturbations. With a 100 times faster measurement rate, a quasi real-time measurement rate is demonstrated, which allows to approach nanostructured surfaces at closer distances. We will present our first observations of force fields above metallic nanostructures, and in particular how one can discriminate and analyze electrostatic forces arising from the sample topology and from the residual electrostatic fields and discuss the Casimir forces in those novel geometries.

The strong electrostatic forces close to a surface can easily cause measurement instabilities. Using a FPGA-based real-time feedback in 2D, we generated artificial force fields that can serve to compensate and balance the action of external force fields on the nanowire. The feedback architecture is based on the processing in real time of the nanowire motion, projected along an adjustable measurement vector, whose fluctuations are transformed into force fluctuations via a voltage biased electrode positioned along an adjustable direction. This tunable approach allows to emulate any class of uniaxial 2D force field gradient. In particular, if both feedback vectors are non-collinear, one can generate a rotational force field of non-conservative nature, which allows to rotate and adjust the nanowire eigenvectors.

This artificial force field leads to a squeezing of the noise trajectory in the 2D position and velocity spaces, while generating an oriented circulation in the nanowire trajectories.

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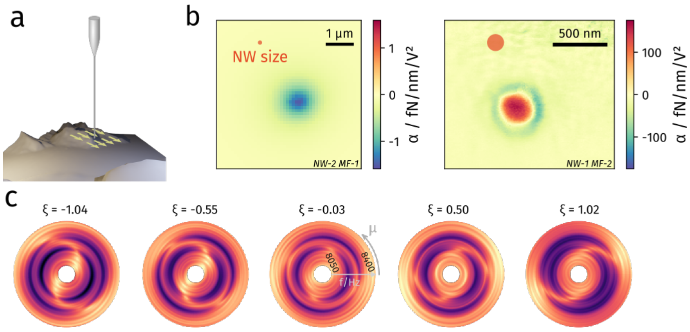

Figure : a) Nanowire scanning a structured surface b) Electrostatic quadratic force on an elevation (left) and a hole (right) in a metallic surface. c) Rotation of one nanowire eigenmode (outer ring), caused by active realtime feedback.

Thermometry of a single levitated nanodiamond

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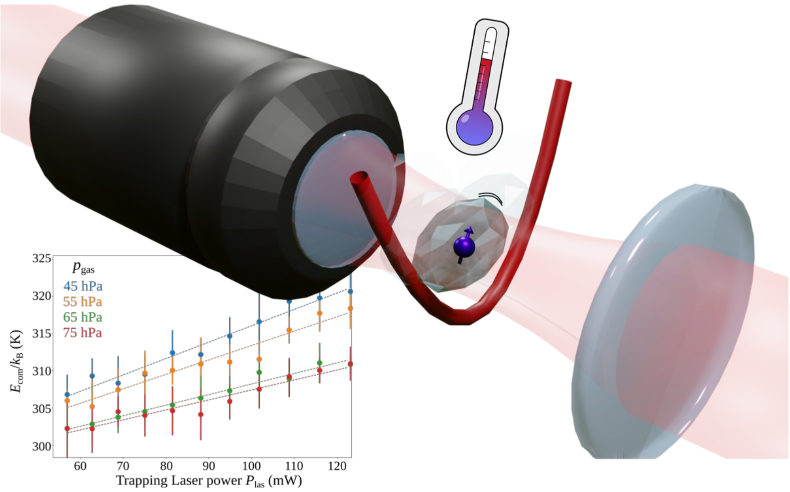
Levitodynamics, the science of levitated particles in vacuum, is foreseen as a unique platform for ultrasensitive force detection, studies of macroscopic quantum mechanics, and nanothermodynamics [1]. These exciting prospects could even be boosted up using a hybrid spin-mechanical system. For instance, one can levitate a diamond hosting NV color centers that act as ancillary quantum systems coupled with the diamond dynamics [2].

However, optically levitated diamonds have shown poor stability and significant internal heating while trapped in a moderate vacuum. These drawbacks jeopardize the benefit from the spin-mechanical coupling.

To understand and overcome these limitations, we study here the thermometry of single levitated nanodiamonds. Taking advantage of the temperature sensing properties of NV centers, we measure the internal temperature of levitated nanodiamonds. We then study the parameters impacting nanodiamonds heating and discuss its causes. Also, we quantify the coupling between nanodiamond internal temperature and its dynamics in the optical trap.

Using levitated nanodiamonds hosting NV centers as excellent nanoscale temperature probes, our work shines a light on nanoscale thermal effects in these systems. Besides, it provides essential elements to improve the stability and to limit the heating of levitated nanodiamonds, toward their use in quantum spin-mechanical experiments.



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Operating ultrasensitive nanowire force field sensors at cryogenic temperature.

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Cooling down nanomechanical force probes is a generic strategy to enhance their sensitivities through the concomitant reduction of their thermal noise and mechanical damping rates. However, heat conduction mechanisms become less efficient at low temperatures, which renders difficult to ensure and verify their proper thermalization.

To operate with minimally perturbing measurements, we implement optomechanical readout techniques operating in the photon counting regime to probe the dynamics of suspended silicon carbide nanowires in a dilution refrigerator. We demonstrate their thermalization down to 32.2 mK and report on record sensitivities for scanning probe force sensors, at the 40 zN/Hz^0.5 level, with a sensitivity to lateral force field gradients in the fN/m range.

To understand the non-trivial light induced static heating curves observed on the nanowire motional noise temperature, we implemented dynamical photo-thermal response measurements based on a pump-probe scheme making use of 2 lasers, which can be piezo-positioned at different positions along the nanowire. The intensity-modulated pump laser generates thermal waves which propagate along the nanowire, while their impact on the nanowire mechanical, optical and photothermal properties is investigated with the second probe laser. We discuss the different mechanisms at play which include in particular temperature induced nanowire reflectivity changes, photothermal response and radiation pressure forces.

This work opens the road toward nanomechanical vectorial imaging of faint forces at dilution temperatures, at minimal excitation levels.

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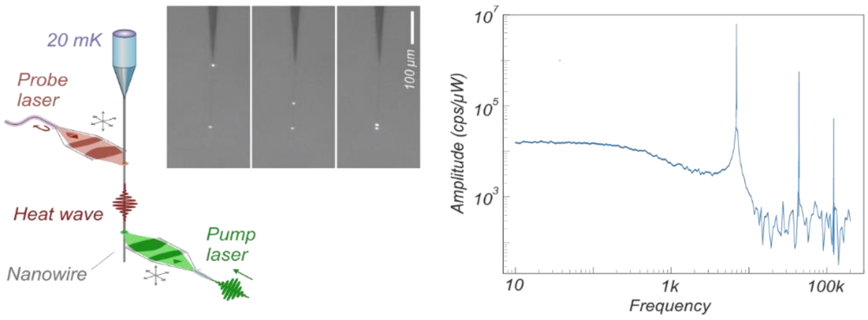

Figure 1 : 2 movable pump and probe laser spots can be positioned at different positions along the nanowire. Intensity modulating the pump laser intensity allows to generate thermal waves propagating along the nanowire. The right plot represents the amplitude of the modulated probe light reflected flux measured for increasing modulation frequencies. The resonant mechanical responses are visible as well as the low frequency photo-thermal response of the nanowire.s

Slow acoustical waves in the GHz for integration of nano-optomechanical oscillators

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Oscillators in the ultra high frequency (UHF) regime are present in almost every domains, from industry to daily applications. However, the price to pay for their great phase noise performances is the limited integrability due to the bulky architecture needed for the oscillations stabilization. Optomechanical crystals with working frequency in the GHz have shown great compactness and integrability in the last few years [1]. Combining them with acoustic waves could lead to a new generation of ultra-stable optomechanical oscillators (OMOs) working directly at the frequency of interest with potentially low phase noise. In the envisioned device, the resonator part is made by a 1D photonic crystal suspended over a silicon waveguide, sustaining optical modes around 1.55µm and mechanical modes around a few GHz [2]. A key-element in such a scenario is the possible introduction of the needed delay for oscillations stabilization thanks to phononic waveguides. In particular, exploiting the properties of a slow propagating acoustical mode, it will be possible to introduce the needed hundreds of ns delay in a fully-integrable manner. Design, fabrication and experimental results of a slow acoustic mode in the GHz propagating through a III-V semiconductor phononic waveguide will be shown with an experimentally measured time delay introduction in the order of ns/µm [3]. Moreover, a first prototype of an integrated OMO with an on-chip acoustic feedback control will be additionally discussed.

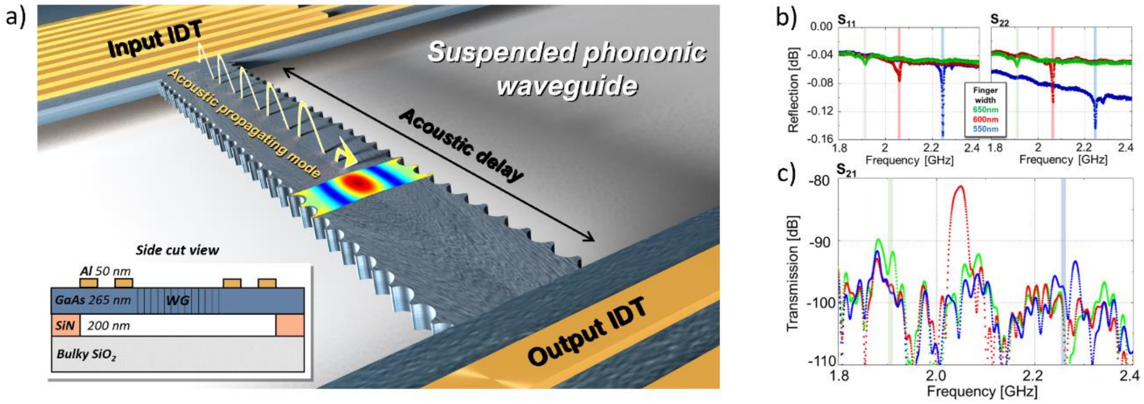

Figure 1 : a) Schematic of the phononic waveguide under investigation. B) Reflection coefficients of integrated transducers. c) Measured transmitted mechanical propagating mode.

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Gallium phosphide optomechanical oscillator on SoI waveguides

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We present a one dimensional photonic crystal, made of Gallium-Phosphide, as an optomechanical oscillator with low phase noise. The photonic wire crystal is heterogeneously integrated on top of a silicon-on insulator circuitry and the light is evanescently coupled from the silicon waveguide. A SEM image shows the fabricated structure on Figure 1. The photonic crystal confines optical modes at telecom wavelengths with high (10^5) quality factors and also mechanical modes in the GHz range. Thanks to the strong interaction between the optical field and mechanical field at 3.35 GHz, a strong optomechanical coupling rate of 160 kHz was measured. The high coupling rate allows the mechanical oscillation to enter the self-oscillation regime characterized by a sharp decrease of linewidth and increased peak power, due to the light coupling this mechanical oscillation is directly imprinted on the optical carrier. In order to further stabilize the oscillation, we built an opto-electronic feedback loop with a time delay, which injects back on the input optical signal the mechanical oscillation. Thanks to this feedback loop, the phase noise at 100 kHz offset frequency has decreased with 25 dB from -84 dBc/Hz in the open-loop case down to -111 dBc/Hz with a sub-Hz linewidth of 0.67 Hz in case with the feedback. The low footprint of the photonic crystal and the potential of on-chip integration with various photonic components opens the way for a compact, low-phase noise opto-mechanical oscillator.

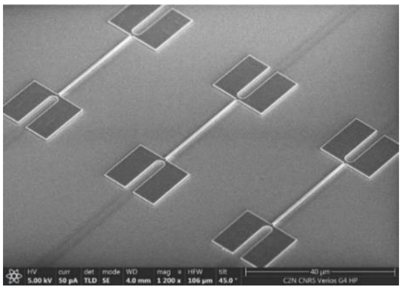

Figure 1 : SEM image of the fabricated photonic wire crystals

Scanning Near-field Optomechanical Crystal

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In this work, we study GHz frequency mechanical modes embedded in suspended one dimensional Gallium Phosphide photonic crystal (Fig. 1 left). The geometry of such system allows to simultaneously control and confine optical and mechanical modes of the investigated crystal within the same volume [1]. Purely optical photonic crystal have been intensively studied with SNOM (Scanning Near-field Optical Microscopy) techniques [2, 3] giving important information about losses channels and confinement of photons at the nanoscale.

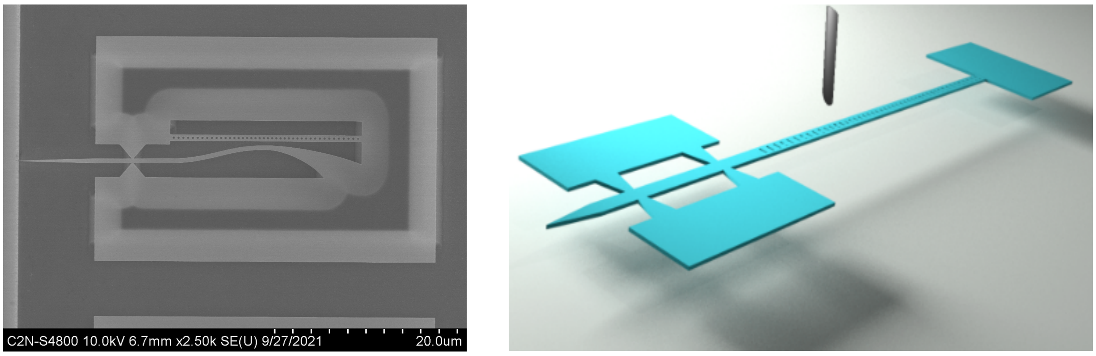

Figure 1: Left: SEM image of one of the used optomechanical cavities. Right: Artist view of the considered setup

In optomechanical crystals, experimental observations match results from numerical simulations of mechanical modes. However, the spatial distribution of phonons is deduced from these simulations without any experimental demonstration, yet. The *in situ* investigation of the mechanical losses and mode extension would provide interesting hints on the design optimization of optomechanical crystal.

In order to perform such study, we record simultaneously the optical and mechanical responses of the cavity while scanning a nanotip in its close environment (Fig. 1 right). Perturbations induced by the tip allow us to extract information about the real spatial extension of both modes. Moreover, the presence of the tip allows to introduce a parametric coupling with the cavity, providing an eventual tuning mechanism.

We will first present the preliminary numerical work on the impact of the tip in the vicinity of the optomechanical cavity. Then, we will introduce the experimental work and the preliminary results of the first attempts at scanning the cavity.

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Optomechanical sensors for noise and quantum thermometry

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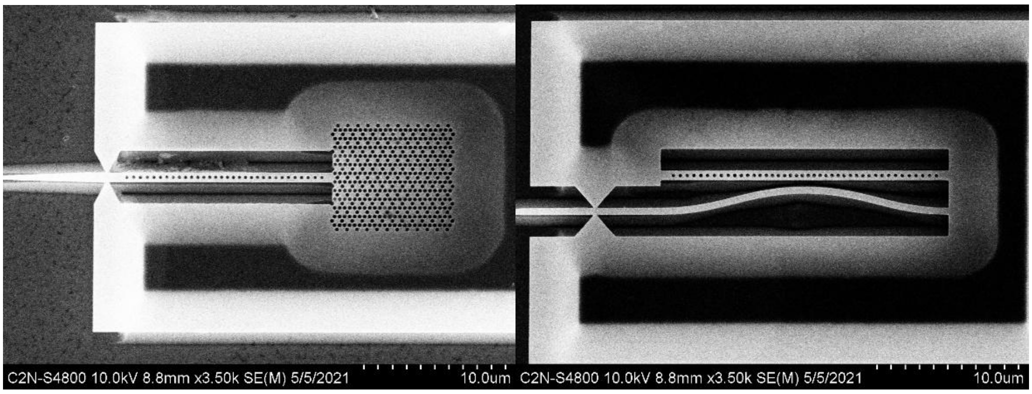
Temperature is probably the most important physical variable of state, influencing a wide range of natural processes. In the redefinition of the International System of Units, the new definition of the kelvin uses energy equivalent and now relies directly on the exact values of the Boltzmann and Planck constants. This opens new opportunities for realizing and disseminating thermodynamic temperature, especially through the development of long-term practical primary thermometry based on quantum mechanism. In this context, we develop an innovative temperature sensor using quantum technologies. The device is based on optomechanical systems combined with quantum measurements techniques that allow one to directly compare thermal fluctuations of a resonator with its quantum noise at low temperature. With the benefit of this quantum calibration the temperature range of the sensor could be further extended up to room temperature using relative noise thermometry.



The device is a 1D optomechanical crystal allowing the co-localization of a 10^4 quality factor optical mode at 1550 nm and ~ 3 GHz frequency mechanical mode with quality factors on the order of 103. The test bench uses a circulating Helium cryostat equipped with metrological resistive thermometer. The relative temperature measurement is achieved by measuring the noise density of the calibrated Brownian motion of the resonator imprinted on the optical probe as phase fluctuations [1]. The temperature is then inferred from the equipartition theorem. The absolute quantum thermometry will rely on the fundamental interaction between the optical field and mechanical motion via the radiation pressure [2]. The resulting quantum correlations, only determined by fundamental constants, will be used to scale the thermally induced mechanical vibrations[3][4].

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Transconductance quantization in a topological Josephson tunnel junction circuit

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Superconducting circuits incorporating Josephson tunnel junctions are widely used for fundamental research as well as for applications in fields such as quantum information and magnetometry. The quantum coherent nature of Josephson junctions makes them especially suitable for metrology applications. Josephson junctions suffice to form two sides of the quantum metrology triangle (cf Fig. 1), relating frequency to either voltage or current, but not its base, which directly links voltage to current.

We propose a five Josephson tunnel junction circuit in which simultaneous pumping of flux and charge results in quantized transconductance in units $4e^2/h=2e/\Phi 0$, the ratio between the Cooper pair charge and the magnetic flux quantum [1]. The Josephson quantized Hall conductance Device (JHD) is explained in terms of intertwined Cooper pair pumps driven by the AC Josephson effect. We describe an experimental implementation of the device and discuss the optimal configuration of external parameters and possible sources of error. The JHD demonstrates that Josephson tunnel junctions are universal, capable of interrelating frequency, voltage, and current via fundamental constants.

We will also present an ongoing experiment performing the spectroscopy of topological Josephson circuits. Using circuit-QED methods, we show that a simple three junction circuit exhibits protected crossings in its energy spectrum. Similar to Dirac cones in solids, the observed degeneracies are the source of the non-trivial topology of Josephson circuits. This is the first step towards the observation and manipulation of more complicated circuits [2-4] in the recently growing field of topological Josephson circuits.

[1] L. Peyruchat et al., Phys. Rev. Research 3, 013289 (2021)
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[3] A. Melo et al., arXiv:2104.11239 (2021)
[4] H. Weisbrich et al., arXiv:2109.03135 (2021)

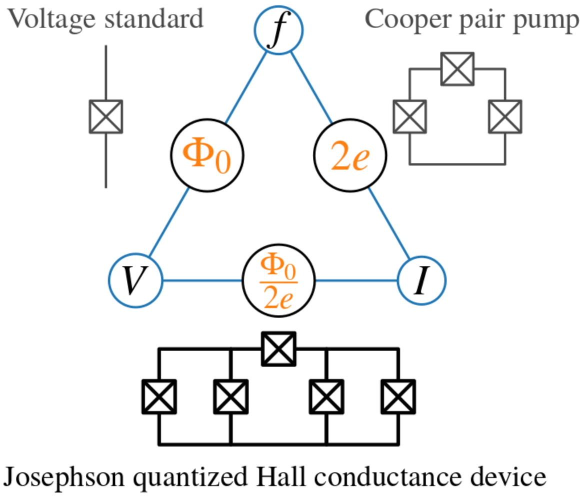

Figure 1: Circuits containing Josephson tunnel junctions can be used to form the metrology triangle. While Josephson junctions have already been used to convert a RF frequency to either a voltage or a current, we propose a new circuit (bottom) that combines both Cooper pair and flux pumping to yield a quantized Hall voltage $V_Y = R_Q I_X$ as in the quantum Hall effect.

Probing local dynamical properties of a nanomechanical resonator with a focused electron beam

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Nanomechanical systems are of increasing interest for both fundamental and practical applications in physics research. Recently, a new detection scheme was proposed, based on a focused electron beam illuminating a nanomechanical resonator, and exploiting the high contrast of the secondary electrons (SE) to measure the high-frequency fluctuations of the resonator. Using this technique, it was notably demonstrated that this process can be so sensitive as to allow a shot-noise – limited detection [1].

Even though the low dimensions and masses of nano-mechanical resonators make them very efficient force sensors, they also make them very sensitive to fluctuation arising from the measurement, be it through optical or electronic processes. Additionally, those measurements will in general create very high temperature gradients inside the resonator due to the much reduced thermal conductivity of nano-objects. This situation will give rise to so-called non-equilibrium states (NES).

In this work we present how the understanding of those NES can enable to determine the dynamical and fluctuational properties of an InAs nanowire by locally probing the fluctuations of such a system through illumination by a focused electron beam. We detail a number of phenomena which take place during this process and stand in the way of a proper local temperature mapping of a nanomechanical resonator [2].

[1] S. Pairis et al., Phys. Rev. Lett. 122, 083603 (2019)
[2] C. Chardin et al., In prep.

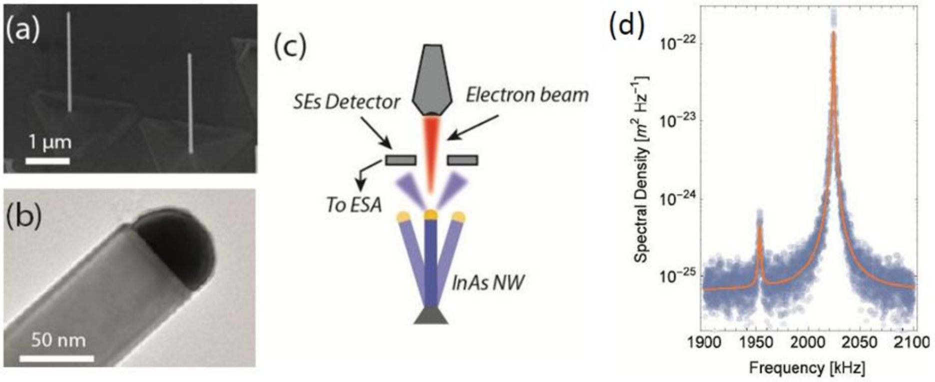

Figure 1 : (a) SEM micrograph showing two of the typical InAs nanowires used in the reported work. (b) TEM micrograph showing a magnified view of such InAs nanowire. (c) Schematic principle of the detection scheme. The fluctuations of the emitted secondary electrons are monitored as to reveal the nanomechanical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

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