Direct Determination of Mechanical Mode Profile in Optomechanical Photonic Crystals

Théo MARTEL[a*], Rémy BRAIVE[a,b,c]

a. Centre de Nanosciences et de Nanotechnologies, Palaiseau, France
b. Université Paris Cité, Paris, France
c. Institut Universitaire de France, Paris, France

* theo.martel@c2n.upsaclay.fr

Purely optical photonic crystals have been intensively studied with SNOM (Scanning Near-field Optical Microscopy) techniques [1, 2] giving important information about losses channels and confinement of photons at the nanoscale. But, given the rising importance of photonic crystals for optomechanics, a similar approach for mechanical modes has yet to be done. Indeed, in these crystals, even if experimental observations match results from numerical simulations of mechanical modes, simulations are still the only way to deduce the spatial distribution of phonons, yet. The *in-situ* investigation of the mechanical losses and mode extension would provide interesting hints on the design optimization of optomechanical crystals.

In this work, we study breathing mechanical modes embedded in a suspended one-dimensional GaP photonic crystal (Fig.1(a)). Here, we work with a confined optical mode at 1.55 µm with a measured Q-factor around 3.5 10^5, and a breathing mode at 2.8 GHz with a Q-factor of a few hundred at room temperature and atmospheric pressure (Fig.1(b) and 1(c)). The optomechanical coupling between these 2 modes is $g_0 \approx 2\pi \times 300\ kHz$.

In order to study the extension of the mechanical mode, a nanotip scans in its close environment the optomechanical crystal (Fig.1(d)). During the scan, the optical and mechanical responses are simultaneously recorded (frequencies, Q-factors and g0). Perturbations induced by the tip allow to extract information about the real spatial extension of both modes. According to simulations, the optimal distance between the nanotip and the crystal should be in the order of hundreds of nanometers in order to get the best signal. This represents a challenge, as the current feedback loop control schemes for near-field imaging cannot be used to control these kinds of tip-sample distances. We thus developed a custom procedure allowing the precise calibration in 3D of the nanotip position relative to the crystal.

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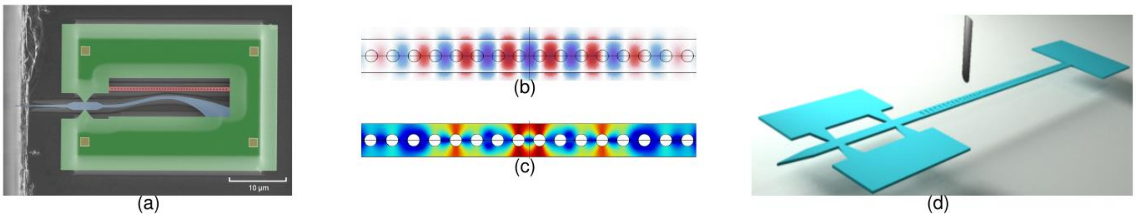

Figure 1 : (a) SEM picture of the studied 1D photonic crystal, a beam with a periodic array of holes. The photonic crystal is in the center of the picture, surrounded by a coupling waveguide and supports bearing the calibration marks. (b-c) Simulated profile of (b) the optical and (c) mechanical mode. (d) 3D view of the experimental configuration, with the nanotip approaching the crystal from above.

Engineering of non-harmonic optical potentials for levitated particles

I. Ben Yedder[a*], D. Raynal[a], J-S. Lauret[a] and L. Rondin[a]

a. Université Paris-Saclay, ENS Paris-Saclay, CNRS, CentraleSupélec, LuMIn, 91405 Orsay Cedex, Francereplace this with the second address

* ines.ben-yedder@universite-paris-saclay.fr

Dynamical control of non-harmonic potentials of a levitated particle is an essential step toward the generation of advanced quantum states, enhanced force sensing, and the study of thermodynamics at the nanoscale.

Here, we demonstrate the generation and control of an optical potential with tunable harmonic, cubic and quartic components. These potentials are generated through the simple superposition of two spatially shifted laser trapping beams using an acousto-optic modulator (AOM) [1]. We proposed a method to characterise these potentials properties and overcome AOM non linearities by studying the particle dynamics in shaped potentials tuned from harmonic to bistable.

Our work opens the way to the study of non-equilibrium dynamics in complex potentials [2] and generating quantum non-Gaussian states for mesoscopic particles [3].

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TWO MOLECULES COUPLED TO A NANO-MECHANICAL OSCILLATOR

G.Bertel[a*], C.Dutreix[a] and F.Pistolesi[a]

a. Univ. Bordeaux, CNRS, LOMA, UMR 5798, Talence, France

* guillaume.bertel@u-bordeaux.fr

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.

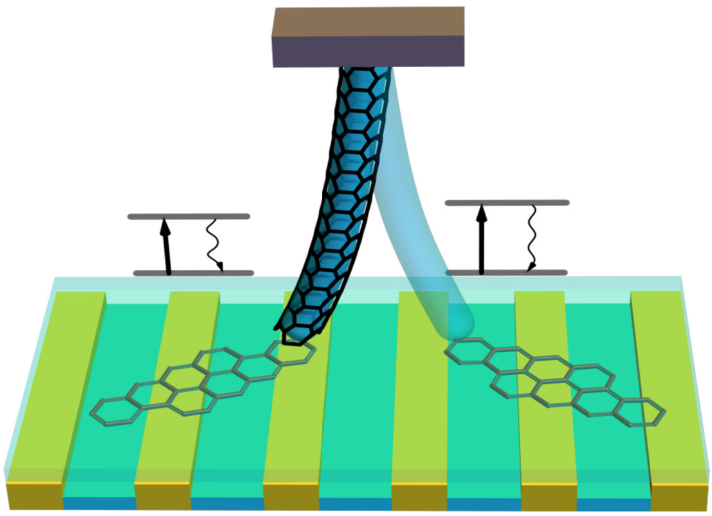

Figure 1: Schema of the system of two molecules coupled to a mechanical oscillator

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Transient nonclassical mechanical states in nonlinear quantum optomechanics

Jonathan L. Wise*, Clement Dutreix, and Fabio Pistolesi

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

* jonathan.wise@u-bordeaux.fr

Introducing a controlled and strong anharmonicity in mechanical systems is a present challenge of nanomechanics, since the anharmonicity may be exploited to generate nonclassical states of motion. Significant theoretical and experimental effort has been invested in this direction in the field of cavity optomechanics, where the intrinsic nonlinear interaction provides an ideal playground for exploring such physics [1].

While most previous works have focused on the steady state solution [2, 3], we propose here a simple method for generating transient nonclassical mechanical states of an oscillator via driving of the optical cavity. In our procedure the cavity and oscillator are both prepared in coherent states; the subsequent system evolution in the presence of the cavity drive leads directly to the formation of a nonclassical state for the oscillator. A perturbative analytical treatment for weak drive captures well the physics of these states, which resemble quantum superpositions of coherent states. The strong nonclassicality of the oscillator state is manifested by negativity in its Wigner function and is shown via numerical simulation to be robust against weak dissipation.

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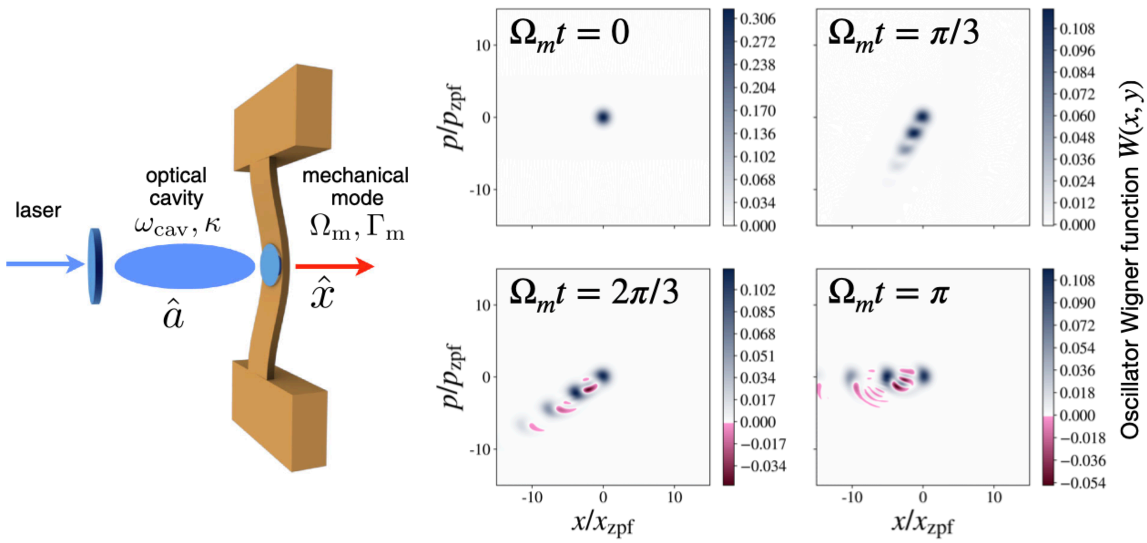


Figure 1 : Left: Schematic of the typical optomechanical system considered, where a mechanical mode interacts with an optical cavity that is driven by a laser [1]. Right: Mechanical oscillator Wigner function for different times where negative areas indicate the formation of a highly nonclassical state. The initial state is assumed to be composed of coherent states for both the oscillator and the cavity.

Injection locking of two integrated opto-mechanical oscillators

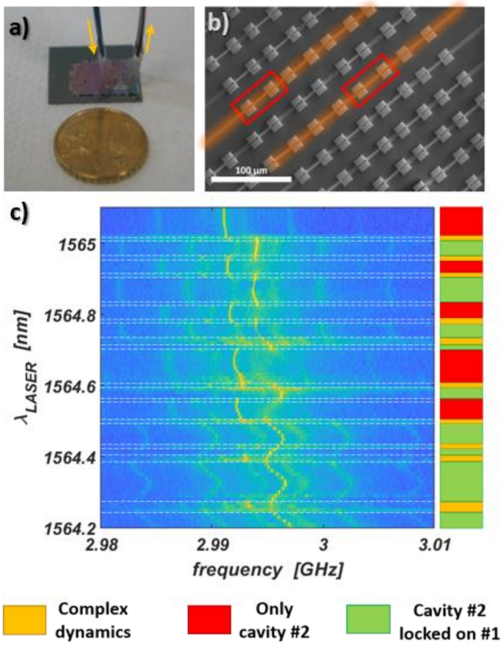
G. Beltramo [1,*], R. Horvath [1], G. Modica [1] R. Braive [2,3]

[1] : C2N, CNRS, Université Paris-Saclay, Palaiseau, France
[2] : C2N, CNRS, Université Paris Cité, Paris, France
[3] : Institut Universitaire de France

* gregorio.beltramo@c2n.upsaclay.fr

Injection locking between independent but similar systems is at the heart of many fields of physics and biology such as synchronization, complex dynamical (comprehending chaotic behavior) but are also a key ingredient for neuron-like devices. Obviously, the field of optomechanics, where a periodical mechanical modulation is imprinted on the optical carrier, is no exception, at the condition of reaching self-sustained oscillation.

We employed a one-dimensional Gallium Phosphide (GaP) photonic crystal (PhC) nanobeam suspended on top of a silicon-on-insulator waveguide, obtained thanks to hybrid adhesive bonding. To ensure an easy and stable in time connection between oscillators, two fiber-block arrays are glued on top of the input and output gratings of the Si waveguides (Fig. 1a-b). Thus, light at telecommunication wavelength modulated at 3 GHz by a first optomechanical oscillator in the self-sustained oscillation regime (mechanical lasing) can be fed as input to a second oscillator, practically establishing a link, a coupling, between them. From there, different coupling topologies will lead to different behaviors of the whole system. It can be one way, where the first oscillator is driving the second one (injection locking) or two ways where the two are mutually affecting each other (mutual synchronization).



Here, we focus on injection locking configuration where, an isolator, placed in between the oscillators prevents light from the second oscillator to act on the first one. Two optomechanical crystals with closed enough optical and mechanical resonances, namely $\lambda_{res1,2}$ ~ 1564.5 nm, Ω_{m1} = 2.996 GHz and Ω_{m2} = 2.993 GHz, have been found (Fig 1.c). By driving them to the self-sustained regime and scanning the optical wavelength, regions where locking of the second oscillator frequency on the first oscillator one can be retrieved (green region – only Ω_{m1} visible). On the opposite, the red area highlights the wavelength range where no locking is observed (only Ω_{m2} is visible) because the oscillation of first one is not strong enough to drive it. Between these two well identified domains, more complex dynamics appears (yellow regions). By changing the driving amplitude, we study the evolution of these domains and investigate locking and complex dynamics range extensions.

For mutual synchronization experiments, two approaches will be followed; either with a purely optical coupling where only the modulated light is shared or an opto-mechanical one where the optical and mechanical degree of freedom are simultaneously hybridized. Both coupling configurations find practical applications in telecommunications, either for clock distribution among different chips or for more stable signal generators, working directly in the few GHz regime.

Nano-optomechanical exploration of charge waves in suspended nanowire

Hugo Weltz[a], Philip Heringlake[a], Cattleya Dousset[a], Benjamin Pigeau[a] and Olivier Arcizet[a]

a. CNRS – Institut Néel UPR2940 et Université Grenoble Alpes, Grenoble, France

A suspended Silicon Carbide nanowire forms a very interesting mechanical resonator for near-field force measurements. It is capable of measuring forces in the atto-Newton range (10^{-18} N) at room temperature. This high sensitivity enables us to detect the interaction between a single electron at the free end of the nanowire and an electrostatic field of 10 V/m.

We have developed an atomic force microscope, based on the optical readout of these nanowires vibrations, capable of measuring near-surface two-dimensional force fields. Its operation has been tested by measuring local electrostatic fields on a nanostructured sample [1] and by mapping the radiation pressure force of light confined in an optical cavity [2].

The interaction between the readout laser and the nanowire induces electron-hole pairs in the semiconductor. These pairs can dissociate, under the action of diffusion and electric fields, which generates charge waves propagating in the nanowire. These free charges can interact with a transverse electric field and generate a measurable force on the nanowire.

We have measured and investigated the spatio-temporal dynamics of these charge waves using a pump-probe experiment. We then use this force to non-invasively probe the electronic transport properties of the nanowire, giving results consistent with the literature.

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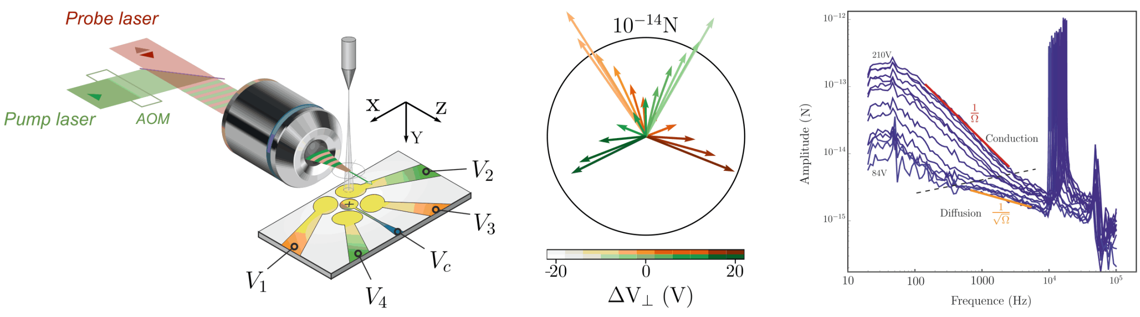

Figure 1 : Schematic diagram of the measurement where a sample composed of independent electrodes generates electric fields below the nanowire illuminated by a probe laser and a pump laser modulated in amplitude. In the middle is a vectorial representation of the free charges induced forces measured at different transverse electric fields. At the right the large band response of the nanowire for different longitudinal electric fields.

Highly coherent and strongy coupled nanomechanical drums at temperatures near 1 mK

Richard Pedurand[1], Amir Youssefi[2,3], Eddy Collin[1], Tobias Kippenberg[2,3], Andrew Fefferman[1]
1. Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel
2. Laboratory of Photonics and Quantum Measurement (LPQM), Swiss Federal Institute of Technology Lausanne (EPFL)
3. Center for Quantum Science and Engineering, EPFL.

Resonators with very low mechanical damping rates have recently been demonstrated [1,2]. In the absence of significant dephasing, the resulting mechanical coherence times could enable memories in hybrid systems for quantum communication and computation. They could also be used for testing fundamental aspects of quantum mechanics. At the same time, nuclear demagnetization refrigeration (NDR), producing microkelvin cryostat temperatures, has been applied to microwave optomechanics, yielding passive ground state cooling of 15 MHz mechanical modes [3]. Until now, researchers in these two fields have not combined NDR with low-dissipation mechanical resonators. Doing so could yield mechanical relaxation times $1/(\Gamma_m \bar{n}_{\mathrm{th}})$ beyond the state-of-the-art because both the damping rate Γ_m and the thermal phonon occupation $\bar{n}_{\mathrm{th}}$ are expected to decrease as the cryostat is cooled toward 1 mK. We have cooled devices of the type described in [2] down to T_{cryo}=1.5 mK. The resonance frequency of the mechanical modes remained temperature dependent even at 1.5 mK (see Fig.), demonstrating that the devices remain thermally coupled to the cryostat. Using the measured damping rate $\Gamma_m/2\pi$ =60 mHz at 1.5 mK and assuming perfect thermal equilibrium between the mechanical mode and the cryostat we find $1/(\Gamma_m \bar{n}_{\mathrm{th}})$ =150 msec, which is comparable to the 140 msec mechanical relaxation time measured at T_{cryo}=30 mK and T_{mode}=80 mK in [1]. Furthermore, devices of our type were shown in [2] to have $g_0/2\pi$ =10 Hz (compared with $g_0/2\pi$=0.9 Hz in [1]) and negligible pure dephasing 0.09 Hz.

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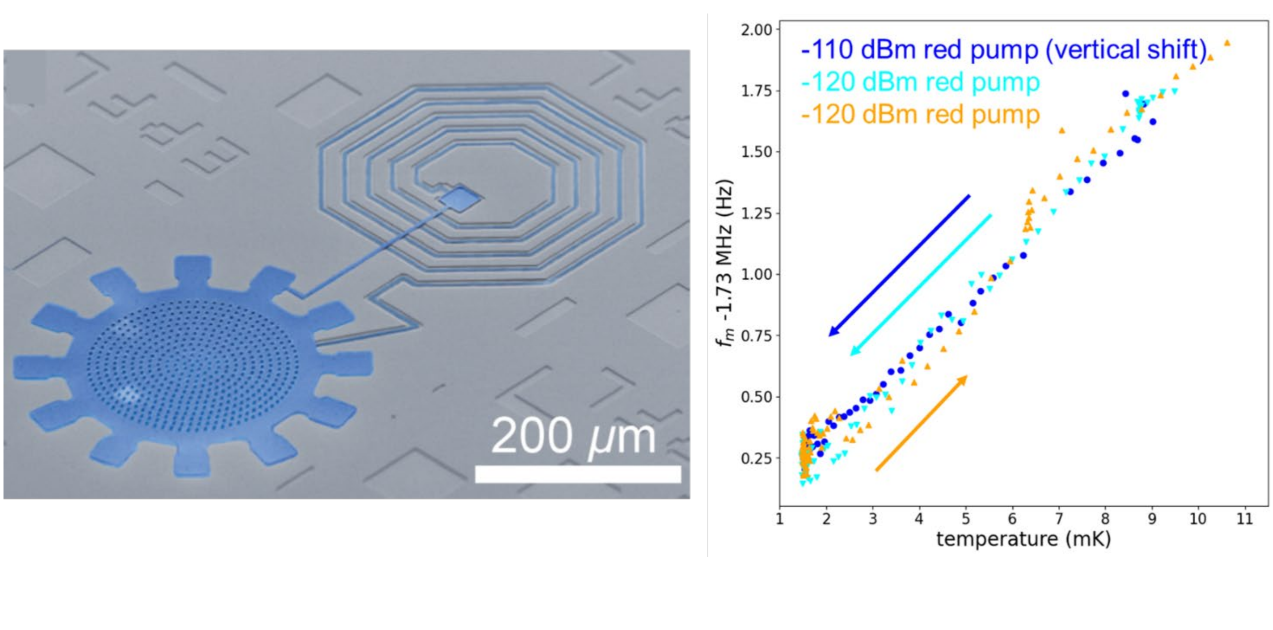
Figure : (left) Device of the type measured in the present work. The flat drum is suspended over a fixed electrode in a trench, forming a capacitor that is coupled to the spiral inductor. See [2] for device details. (right) Temperature dependence of the resonance frequency of the drum down to 1.5 mK. The arrows indicate the direction of the temperature sweep corresponding to each data point color.



Optimizations of reservoir computing in a nonlinear nanomechanical resonator

Toky Harrison RABENIMANANA[a*], Xin ZHOU[a]

a. Univ. Lille, CNRS, Centrale Lille, Univ. Polytechnique Hauts-de-France, UMR 8520 - IEMN, F-59000 Lille, France

* toky-harrison.rabenimanana@univ-lille.fr

Reservoir computing is a branch of artificial intelligence derived from recurrent neuron network theory. It has the advantage of being efficient in many applications like speech recognition, image classification and time series prediction [1].

Recently, studies aimed at using new physical systems for reservoir computing have emerged, and microelectromechanical systems (MEMS) have often been considered [2]. This new kind of reservoir computer consists in creating a network of virtual nodes from a single physical node formed by the MEMS device. The input signal is modulated by a temporal mask, each value of which is equal to the weight corresponding to each virtual node of the reservoir. To add memory, a delayed response of each virtual node is reintroduced into the reservoir. A readout trained weight matrix is then used with the response of each virtual node to obtain the output.

In this study, we consider a reservoir computer based on nanoelectromechanical system (NEMS). The device is composed of a circular silicon nitride membrane which is electrostatically actuated [3]. When performing the computation, several parameters are involved in the experimental setup, and our work consists in optimizing them in order to improve the performance of the reservoir computer. We first develop a model of the considered device, which is numerically solved with Matlab ordinary differential equation solver. The parameters, used for modeling, are obtained from fitting the experimental results. Once we have these parameters, we launch simulation of the reservoir computer. To evaluate its performance, the NARMA benchmark has been chosen [4]. It consists in predicting a series of number from a given input. After training the reservoir computer, we see in Figure 1 a comparison between the target and the predicted values. This result shows how effective reservoir computing can be in time series prediction.

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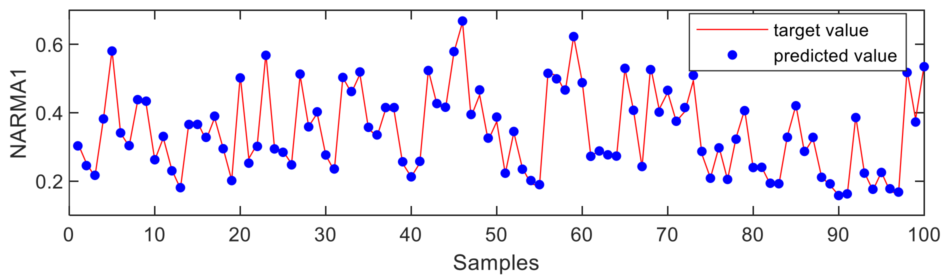

Figure 1 : NARMA1 benchmark, comparison between the target and predicted values

High-order topological states using band inversion

Konstantinos Papatryfonos[a*], Anne Rodriguez[a], Edson Cardozo de Oliveira[a], Daniel Lanzillotti-Kimura[a]

a. Centre for Nanosciences and Nanotechnologies, C2N, Palaiseau, France
*konstantinos.papatryfonos@c2n.upsaclay.fr

Topological interface states have been demonstrated for a wide range of excitations including photons, phonons, vibrations, polaritons, and more. In particular, acoustic interface states have been evidenced in superlattices with frequencies at tens to hundreds of GHz [1,2]. A recently demonstrated scheme to generate interface states in one-dimensional superlattices is based on the principle of band inversion, obtained by concatenating two periodic lattices with inverted spatial mode symmetries around the bandgap [3,4]. Most of the realizations exploit a given bandgap for which there is one symmetry inversion. In this work, we present high-order topological nanophononic interface states in multilayered structures based on GaAs/AlAs. We achieve and control the band inversion by modifying the unit cells of the two lattices. We then extend the principle of band inversion to create an interface state at higher order bandgaps (Fig.1). By carefully choosing the appropriate material thickness ratio in the two concatenated superlattices, we show that we can engineer interface states at the n^{th} bandgap. We showcase designs for versatile topological devices where interface states are simultaneously created across a wide frequency range. Additionally, we designed hybrid structures formed with two concatenated superlattices with different order bandgaps centered around the same frequency that support interface states. The topological modes can be experimentally accessed in Brillouin or pump-probe experiments. The ability to explore higher bandgap order acoustic interface states in the GHz range is unique in nanophononic superlattices due to the linear dispersion relation of acoustic phonons. The demonstrated systems can be exploited investigate regions that are difficult or impossible to study in electronics or optics, due to their non-linear dispersion relations.

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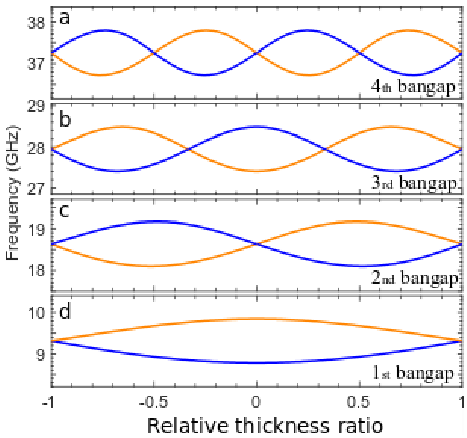

Figure 1 : Band inversion of the acoustic bandgap. The mode symmetries are indicated with orange (symmetric) and blue (anti-symmetric) lines.

Operating ultrasensitive nanowire force field sensors at cryogenic temperature.

C. Gouriou[a*], F. Fogliano[a], P. Heringlake[a], A. Fontana[a], A. Reigue[a], B. Besga[a], B. Pigeau[a] and O. Arcizet[a]

a. Institut Néel, CNRS and Université Grenoble Alpes, F-38042, Grenoble, France 1

∗ clement.gouriou@neel.cnrs.fr

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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. Those thermal waves couple to several mechanisms which include in particular temperature induced nanowire reflectivity changes, thermomechanical lateral deformation, photothermal modulation of the optical forces. We present several techniques and tools that we used to probe the thermal properties of our nanowire.

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

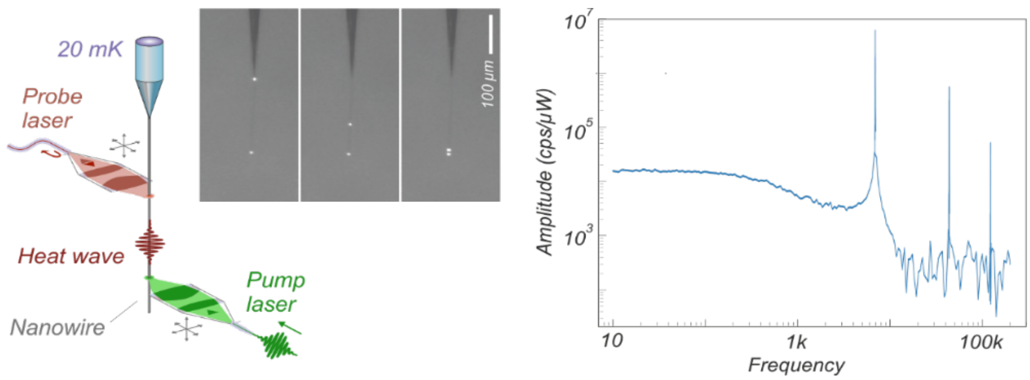

Figure 1: 2 movable pump and probe laser spots can be positioned at different positions along the nanowire. Intensity modulating the pump laser intensity allows generating thermal waves propagating along the nanowire. The right plot represents the amplitude of the modulated probe light reflected flux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

Topological interface modes in hyperuniform pillared metabeam

Runcheng Cai[a,b*], Laurent Carpentier[a], Yabin Jin[c], Xiaoying Zhuang[b,d], Yan Pennec[a*] and Bahram Djafari-Rouhani[a*]

a. Institut d'Electronique, de Microélectonique et de Nanotechnologie, UMR CNRS 8520, Département de Physique, Université de Lille, 59650 Villeneuve d'Ascq, France
b. Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, 200092 Shanghai, China
c. School of Aerospace Engineering and Applied Mechanics, Tongji University, 200092 Shanghai, China
d. Institute of Photonics, Department of Mathematics and Physics, Leibniz University Hannover, Germany

* runcheng.cai@univ-lille.fr; yan.pennec@univ-lille.fr; bahram.djafari-rouhani@univ-lille.fr

Hyperuniform structures cover the intermediate regime between random and periodic structures and provide new ways for wave control[1]. In this work, we present the topological interface modes in hyperuniform pillared metabeam with mirror symmetry. We calculate the band structures of hyperuniform metabeam via the supercell method and find that the hyperuniform metabeam can create some new low-frequency bandgaps compared to the periodic one. Moreover, the Zak phases of the hyperuniform metabeam and its SSH-like counterpart are obtained by checking the band-edge state symmetries[2]. It is found that Zak phases of some bandgaps for two configurations are different, namely, these bandgaps are non-trivial. We demonstrate the multiple topological interface modes occurring between two SSH-like hyperuniform configurations. Our study offers a reliable platform for studying topological properties and designing wave control devices.

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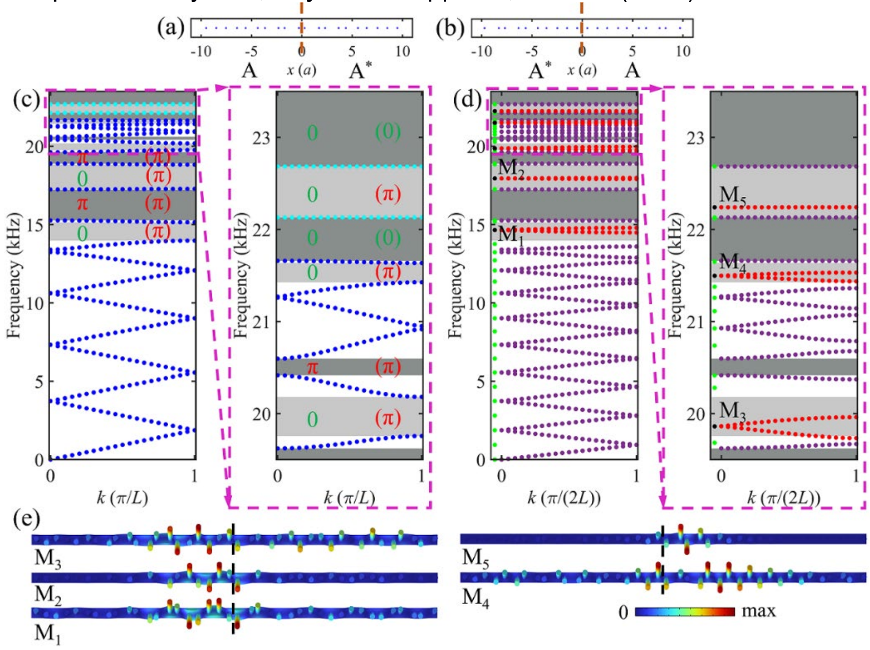

Figure 1 : Hyperuniform pillar distribution AA* (a) and A*A (b) with mirror symmetry. (c) Band structures of AA* and A*A metabeams, the Zak phases of bandgaps for AA* and A*A metabeams are respectively shown on the left and right. (d) Band structures of topological pillared metabeam AA*A*A. Topological interface modes are indicated by red dots. (e) Fields associated with the interface modes M_1-M_5 in (d). The black bars indicate the interfaces.

Optomechanical Coupling between a Waveguide and a high Q factor Cavity

Abdellatif Gueddida, Ricardo Alcorta Galvan, Yan Pennec*, Marco Miniaci, Charles Croenne, Gaëtan Lévêque, and Bahram Djafari Rouhani

Institut d'Electronique, Microélectronique et Nanotechnologie, UMR CNRS 8520, Department of Physics, University of Lille, 59652 Villeneuve d'Ascq.

* yan.pennec@univ-lille.fr

The excitation and the detection of the optical and mechanical properties of an optomechanical (OM) cavity are often carried out by means of a tapered fiber coupled to a tunable laser. The tapered fiber is configured in a loop shape near the central part of the OM cavity, where the position of the fiber must be adjusted to enhance the coupling with the OM cavity [1]. However, previous research has indicated that even with a reduced distance between the cavity and the tapered fiber, only a limited amount of light can be effectively introduced into the cavity [2]. To tackle this issue, an integrated waveguide with defined geometrical parameters could offer efficient coupling with the OM cavity.

This work aims at improving the optical coupling between a waveguide and an OM crystal through a parametric study of the optical properties of the system. The OM crystal is constituted by a silicon nanobeam with periodic holes in the middle and periodic stubs on its sides. Then, a tapered OM cavity is created inside the phoxonic nanobeam by a parabolic change of the geometrical parameters of both the holes and the stubs. The integrated waveguide used as a pathway for the incident light is deposited parallel to the nanobeam. This waveguide is terminated by a tapered Bragg mirror constituted by holes in order to stop the progression of light and keep it in the vicinity of the OM cavity. In this study, the efficiency of the optical excitation of the OM cavity is investigated as a function of two geometrical parameters D and L0, where D is the distance between the waveguide and the nanobeam and L0 defines the position of the first hole in the waveguide with respect to the center of the OM cavity (Fig. 1). The OM cavity exhibits optical modes with a notably high Q-factor, where the associated OM coupling rate g based on the overlap between the elastic and optical fields of the OM cavity modes reaches values of about $g/2\pi=320$ kHz [3].

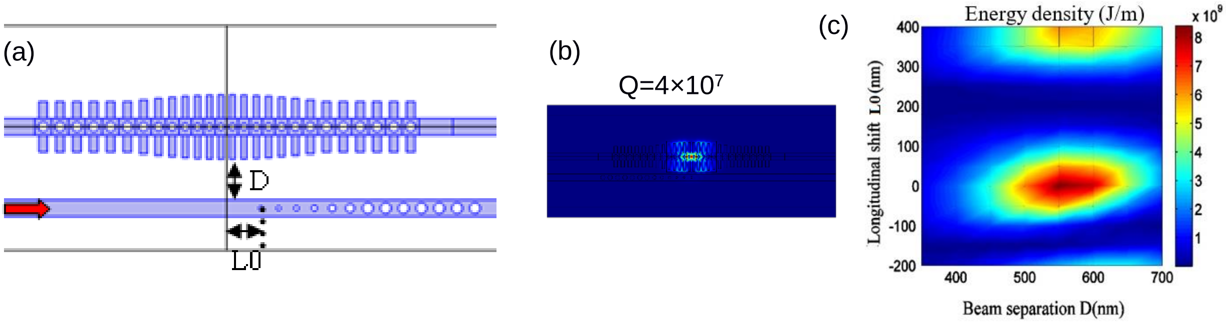

Figure 1: (a) Scheme of the OM circuit. The red arrow shows the incident light beam. (b) Electric field distribution of one of the optical cavity modes located at λ=1550 nm. (c) The energy density corresponding to the previous mode calculated as a function of D and L0.

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Anomalous nonlinear features in the self-oscilation regime of microwave optomechanical devices

Alexandre Delattre[*1], **Ilya Golokolenov**[1], **Xin Zhou**[2], **Andrew Fefferman**[1], **Eddy Collin**[1]

[1]Institut Néel, CNRS Grenoble, France
[2]IEMN, CNRS Lille, France

*contact: alexandre.delattre@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 string of width and thickness about 100 nm. While the mechanical and microwave parameters are rather similar to our previous device, the typical behaviour 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. A large meta-stable region is visible on the negative-detuning side of the graphs, while the self-oscillation is lost when the power is increased beyond a new instability line (top diagonal limit of the graphs). Above this limit, the parametric instability cannot be re-established unless the power is completely switched off.

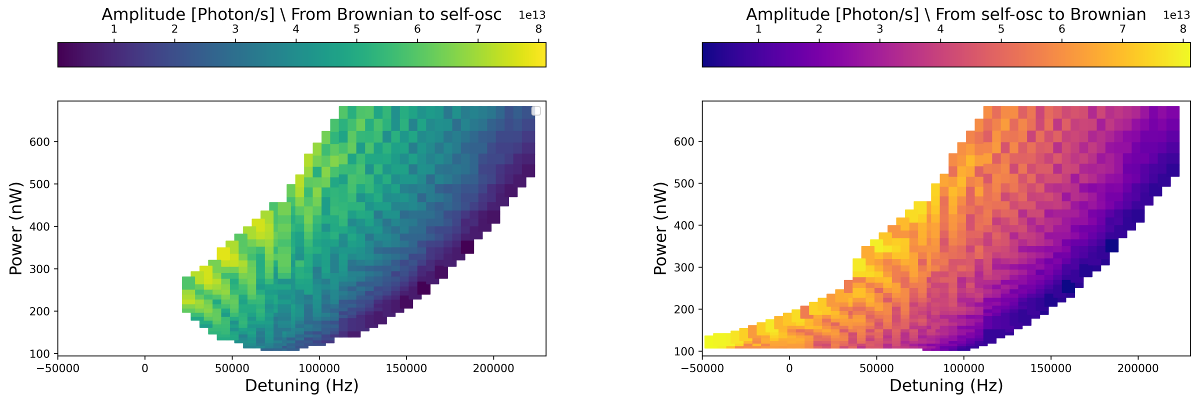

Figure 1: Self-oscillation amplitude (photons/s, T = 600 mK) measured when entering from the Brownian state (left), or leaving self-oscillation (right), as a function of pump power (nW) and detuning ($\Delta = \omega_{pump} - (\omega_{cavity} + \omega_{mechanics})$, Hz).

We propose a theoretical model to understand these unique features, based on the introduction of the microwave cavity Kerr nonlinearity. As for the other nonlinear features of opto-mechanical systems, the self-oscillating state appears to be a unique tool to quantify the cavity intrinsic non-linear Hamiltonian. The key experimental ingredients are thus a very large applied microwave power and a very high-Q cavity.

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Scanning microwave microscopy for investigations of mode coupling, between the AFM-tip mode and the silicon nitride membrane mode

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

Scanning microwave microscopy (SMM), because of the flexible AFM-tip operations in the nanoscale, has attracted more and more interest in imaging aF/fF scale capacitance [1]. It has recently been used for the investigation of MEMS/NEMS mechanical mode coupling in a suspended membrane [2]. In this work, we will present the investigations of mode coupling by using SMM tool to excite and detect two nanoelectromechanical resonators. The system consists of a metallic AFM-tip capacitively coupled to a silicon nitride membrane covered with a thin aluminium layer. The AFM-tip has a fundamental vibration mode around ~15.4 KHz and the resonance frequency of the silicon nitride membrane is around ~8.4 MHz. In order to investigate the mode coupling between the AFM-tip and the membrane, we exploit the concept of phonon-cavity by pumping the membrane resonator at its sideband and using the second signal to probe at either the tip or the membrane at the same time. This technique allows us to study the electromechanically induced transparency and amplification [3].

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Effects of surface roughness and top layer thickness on the performance of Fabry-Perot cavities and open resonators based on distributed Bragg reflectors

Edson Rafael Cardozo de Oliveira[a*], Konstantinos Papatryfonos[a] and Daniel Lanzillotti-Kimura[a]

a. Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies, 91120 Palaiseau, France
* edson.cardozo@c2n.upsaclay.fr

Optical and acoustic resonators based on distributed Bragg reflectors (DBRs) hold significant potential in both applied and fundamental research. [1,2] Their applications span over diverse domains, including lasers, optomechanics, and quantum technologies. In the presence of perfectly flat material interfaces and surfaces, the DBR resonator quality factor primarily depends on the number of DBR pairs and can be arbitrarily increased by adding more pairs. However, the reality of material growth and fabrication always entails some surface roughness, even in samples produced using cutting-edge techniques. [3] Here, we present a comprehensive analysis of the impact of surface roughness on the performance of both Fabry-Perot and open-cavity resonators based on DBRs. Our findings illustrate that even a small, nanometer-scale surface roughness can reduce the quality factor of a given cavity, as shown in Figure 1. Moreover, it imposes a limitation on the maximum achievable quality factor, regardless of the number of DBR pairs. These effects hold direct relevance for practical applications. Our investigation underscores the importance of accounting for surface roughness in the design of both acoustic and optical DBR-based cavities, while also quantifying the critical significance of minimizing roughness during material growth and device fabrication processes.

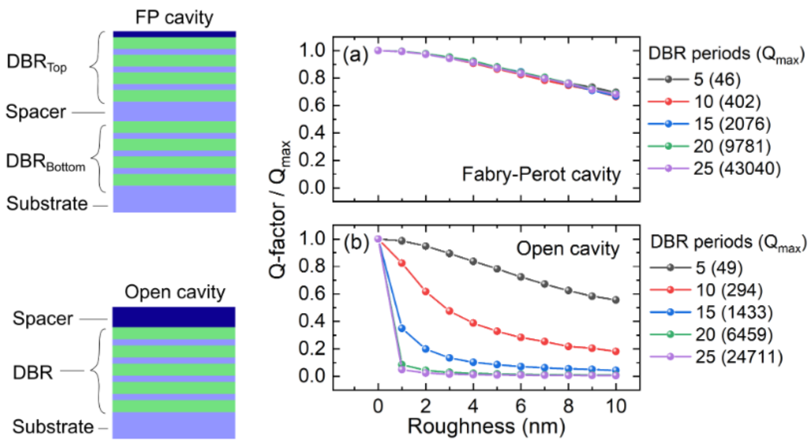

Figure 1: Normalized acoustic quality factor dependence on the last layer roughness for different combination of number of DBR pairs, for (a) Fabry-Perot cavity and (b) open resonator. The insets on the left represent the schematics of the simulated structures.

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Topological pillared phononic crystals

B. Djafari Rouhani*

Institut d'Electronique, de Microélectonique et de Nanotechnologie, UMR CNRS 8520, Département de Physique, Université de Lille, 59650 Villeneuve d'Ascq, France

* bahram.djafari-rouhani@univ-lille.fr

Pillared phononic crystals are constituted by an array of pillars deposited on a plate or on a beam. We review our recent works on topological properties of these structures, based on our collaborations with several groups [1-8].
The pillared structures exhibit both Bragg bandgaps due to the periodicity and hybridization gaps, associated with local resonances of the pillars, that make them useful both as phononic crystals and as sub-wavelength metamaterials. After a brief introduction to their band structure, we study theoretically their topological properties by considering a honeycomb lattice where we break the space inversion symmetry. We show different topological phases emulating the analogs of quantum valley and spin Hall effects (QVHE and QSHE) [1,2]. We demonstrate robust edge states with one-way propagation as well as the realization of a T-junction splitter where the control of wave propagation takes advantage of both pseudo-spin and valley degrees of freedom. The waves leaving the edge waveguides show a rich variety of refraction phenomena at the outlets, including positive and negative refractions as well as evanescent waves at the boundary of the crystal with the surrounding plate [1,3]. Beside edge modes, the above topological structures can also display corner modes and tailoring the interaction of both types of modes can give rise to a sharp Fano resonance [4]. Finally, a high quality zero-dimensional topological vortex mode has been designed by a Kekulé distorsion of the pillars' positions [5].

We have also studied pillared beam structures where the pairing of the pillars along the beam provides the analog of the Su-Schrieffer-Heeger (SSH) model and allows the realization of interface modes between two topologically different phases. In particular, a robust topological Fano mechanical resonance is achieved in a pillared beam from the superposition of a dark and a bright edge mode associated to two different types of waves exhibiting a common gap [6]. These investigations are currently extended in two directions. One is dealing with disordered structures with a hyperuniform distribution of the pillars where the existence of new low-frequency bandgaps allows multiple interface modes between two SSH-like configurations [7]. The other is dealing with optomechanic nanobeams constituted by an array of holes and stubs (the analog of pillars) that we have studied during the last years [8]. The aim is the design of simultaneous phononic and photonic topological interface states in SSH-like structures.

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Pathway to tunable nanophononics with mesoporous materials

Edson Rafael Cardozo de Oliveira [a*], Chushuang Xiang[a], Priscila Vensaus[b], Martin Esmann[a,c], Nicolas L. Abdala[b], Maria C. Fuertes[d], Paula C. Angelomé[d], Axel Bruchhausen[e], Hernan Pastoriza[e], Bernard Perrin[f], 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, Escuela de Bio y Nanotecnologías, Universidad Nacional de San Martín-CONICET, Buenos Aires, Argentina
c. Institute for Physics, Carl von Ossietzky University of Oldenburg, 26129 Oldenburg, Germany
d. Gerencia Química, Instituto de Nanociencia y Nanotecnología, CNEA-CONICET, 1650 Buenos Aires, Argentina
e. Centro Atómico Bariloche & Instituto de Nanociencia y Nanotecnología, CNEA-CONICET, R8402AGP Rio Negro, Argentina
f. Sorbonne Université, CNRS, Institut des NanoSciences de Paris, INSP, F-75005 Paris, France
* edson.cardozo@c2n.upsaclay.fr

Ultrahigh-frequency acoustic-phonon resonators usually require atomically flat interfaces to avoid phonon scattering and dephasing, [1] leading to expensive fabrication processes, and are bound to fixed frequency operations. Mesoporous materials, with pores at the nanoscale, are good candidates to overcome such limitations. The tailorable mesopores allow the incorporation of chemical functionalization to nanoacoustics. Here, we present multilayered resonators based on mesoporous SiO_2 and TiO_2 (Fig. 1(a)) with acoustic resonances in the 5-100 GHz range. [2,3] We characterize the acoustic response using pump-probe experiments. [4] Fig. 1(b) show experimental results of acoustic modes in structures with different mesoporous configurations. Modes up to 60 GHz are confined within the mesoporous layer, as shown in Fig 1(c). Under liquid infiltration the mesoporous materials present changes in the mechanical properties, and therefore, in the acoustic response. [5] 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)) and be sensitive to environmental changes, such as relative humidity. Simulations show strong coherent-phonon signals at the designed frequency (Fig. 1(d)). Our findings unveil a promising platform for reconfigurable and tunable optoacoustic nanodevices based on soft, inexpensive fabrication methods.

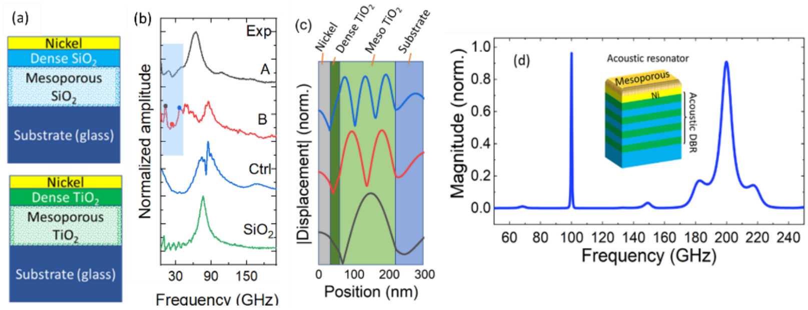

Figure 1: (a) Schematic of the samples. (b) Measured spectra of the surface displacement of TiO_2-based samples A, B and Control, and SiO_2-based. The low-frequency-shaded areas (up to 50 GHz) indicate the first confined modes in the mesoporous layer. (c) Displacement field of the modes at 13, 25.5 and 38 GHz on TiO_2 sample B. (d) Simulations of the pump-probe spectra for the proposed structure. Inset shows the layer configuration of the device.

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Frequency control and nonlinearity in a small array of electro-optomechanical resonators

Gladys Jara-Schulz[a*], Sylvain Barbay[a], Rémy Braive[a,b,c]

a. Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, C2N, 91767, Palaiseau, France
b. Université Paris Cité, Rue Thomas Maan, Paris France
c. Institut Universitaire de France (IUF)
* gladys.jara-schulz@c2n.upsaclay.fr'

During the last decade, in many fields of physics, the study of coupled identical sub-systems and their collective behaviour has brought lots of attention due to their potential applications in complex networks, neuromorphic computing, etc. in different fields or, more explicitly, e.g., synchronization related phenomena for ultra-sensitive sensing or remote control. Meanwhile, many different individual on-chip micro and nano technologies devices have been developed and have attracted significant attention due to their scalability [1,2]. However, many detrimental effects could prevent efficient interaction between sub-systems and its surrounding. Thus, controlling these interactions is a crucial element in implementing potential applications.

Here, the sub-system under study is a micro electro-optomechanical system consisting of a suspended photonic crystal resonator [3] with electrically driven MHz mechanical modes. The use of three degrees of freedom (optics, mechanics, electronic) allows us the investigation of a complete picture of this system and different means of controlling their behaviours. In this work, three of these sub-systems are mechanically coupled to each other in a “all-to-all” configuration (See Fig. 1a). Thus, we studied the impact of external parameters, such as light injection, the electric forcing, as well as the impact of internal parameters, such as coupling scheme of these resonators.

We have shown it is possible to overcome the frequency mismatch induced by nano-fabrication, allowing us to achieve an ideal system. Furthermore, our system displays, at low voltage, linear or nonlinear behaviour thanks to the electrical control (see Fig.1 c-d). The linear and bistable regime had been, experimentally and numerically.

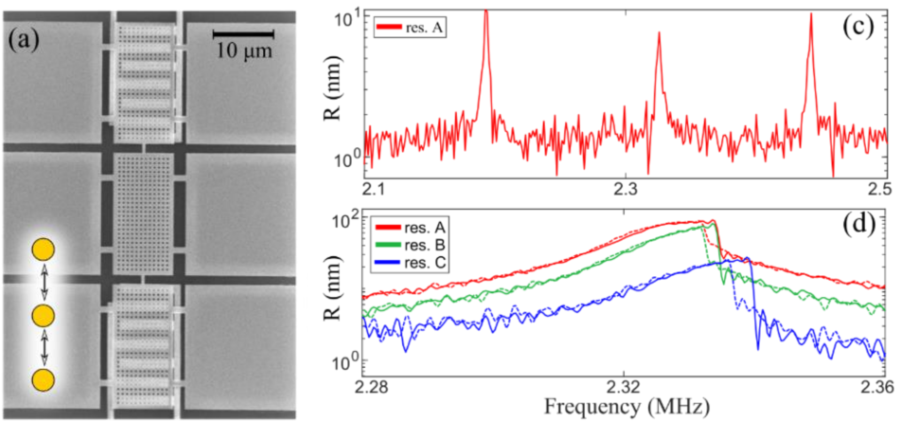

Fig. 1 SEM images of three photonic crystal resonators for “next-neighbour” (a) coupling scheme. Experimental measurements of the mechanical response in frequency domain for resonator A, at V = 1.2 V (c) and, nonlinear regime for resonators A, B and C at V = 3.0 V (d).

Finally, numerical simulations of our system have shown synchronization among the resonators, which opens avenues for the demonstration of chimera states in a small network of nanoscale optomechanical resonators.

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Optimal generation and detection of GHz acoustic phonon using elliptical micropillars

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

a. Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies (C2N), 10 Boulevard Thomas Gobert, 91120 Palaiseau, France

* chushuang.xiang@c2n.upsaclay.fr

Micropillar structures based on GaAs/AlAs multilayers can confine photons and phonons at ultrahigh frequencies [1][2]. The investigation of phonons in these structures can be performed in the time domain with the pump-probe technique. For the circular micropillars, efficient generation and detection of acoustic phonons occur at the center and the slope of the optical cavity, respectively, leading to challenges in simultaneous optimization of these two processes [3][4]. Here, we overcome this issue by designing micropillars with elliptical cross-section [5][6]. The elliptical cross-section lifts the degeneracy of the optical cavity modes, splitting into two modes with orthogonal polarization (H and V). By aligning the polarization of the pump and the probe beams with H and V modes in a cross-polarization scheme, we experimentally achieve the optimization of phonon generation and detection. Figure 1 (a) top panel illustrates the measured H (blue) and V (red) modes in three pillars. The bottom panel displays the cross-polarized laser pulses coupled with the respective optical modes. The pump is tuned in resonance with the V mode to excite the structure while the probe, coupled with the H mode, detects phonon dynamics via photoelastic effect. Figure 1 (b) presents the measured phonon amplitudes in five pillars with different ellipticities. Two extreme cases (circular and 4x2 µm) exhibit near-zero measured phonon amplitudes, as the probe is positioned at the center or outside the cavity mode. We achieve the optimization of generation and detection in the 4x2.4 µm pillar. This simultaneous and efficient excitation and detection are promising for future developments in constructing a phononic network.

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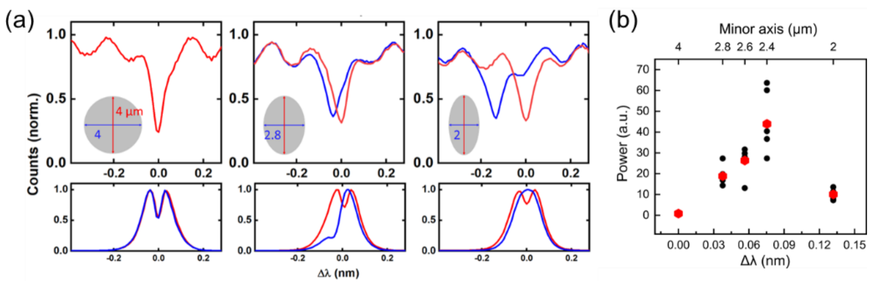

Figure 1 : (a) Top panel: experimental reflectivity spectra of three micropillars with different ellipticities. Bottom panel: laser pulse is tuned at the centre of the V mode. Pump (red) and probe (blue) are coupled with V and H modes, respectively. (b) Phonon power as a function of the mode splitting Δλ between the two optical modes and the minor axes of elliptical micropillars.

GHz acoustic phonon transport in optophononic waveguides

C. Xiang[a*], E. R. 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), 10 Boulevard Thomas Gobert, 91120 Palaiseau, France

* chushuang.xiang@c2n.upsaclay.fr

During the past decade, confinement of ultrahigh-frequency acoustic phonons in planar structures and micropillars has been achieved [1][2][3]. However, coherent manipulation of propagation and dynamics of phonons remains challenging [4][5]. Here, we aim at characterizing the transport of 20 GHz phonons in acoustic waveguides based on GaAs/AlAs multilayers. We used a reflection-type pump-probe technique to generate and detect acoustic phonons. In order to evaluate the phonon transport, we performed the pump-probe measurements in two configurations: local, when both pump and probe are overlapped, and remote, by physically separating both beams. In the later configuration we analyse the direct time-of-flight of phonons generated in the pump position reaching the probe. Time-dependent reflectivity variations for local and remote measurements are shown at the top and bottom panels in figure 1(a), respectively. In order to analyse 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 at ~20 GHz has an exponential decay in time, as observed in standard resonators. When the probe beam is separated 8 μm from the pump beam, we observe a delayed signal at ~20 GHz reaching 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 promising for revealing the fundamental properties of phonon dynamics and manipulating phonon propagation in more complex structures.

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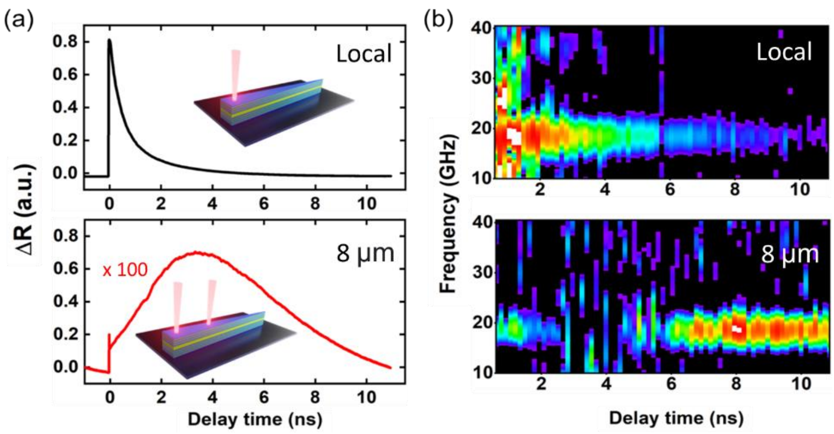

Figure 1 : Time-dependent reflectivity for local measurement (top), where pump and probe beams are focused on the same position, and remote measurement, where the probe is separated 8 μm from the pump. (b) Windowed Fourier transform results corresponding to the time traces shown in (a).

Strain sensors based on FR in strongly-coupled nanoparticles

Najat Ahmidayi[a*], William d'Orsonnens[b], Thomas Maurer[b], and Gaëtan Lévêque[a]

a. Institut d'Electronique, Microélectronique et Nanotechnologie, UMR CNRS 8520, Université de Lille, 59652 Villeneuve d'Ascq, France.
b. UTT-Université de Technologie de Troyes, 12 rue Marie Curie-Cs 42060-10004 TROES CEDEX, France.
* najat.ahmidayi@univ-lille.fr

The capability of metallic nanoparticles to generate localized surface resonances (LSPR) have made them choice candidates in many applications, from biosensing to solar energies. In nanostructure assemblies consisting of two nanoparticles (NPs) or more, the LSPR depends strongly on the interparticle spacing due to the coupling via their near-fields(*1*). The possibility of exploiting this property in the realization of strain sensors has led to the birth of a new field in nanophotonics called plasmomechanics(*2*). The realization of strain sensors with high performance requires plasmonic resonances with high quality factor such as Fano resonances (FR). In this respect, we have carried out an optomechanical study of a plasmomechanical system supporting FR, a gold disk and a rod, deposited on polydimethylsiloxane (PDMS) membrane under stretching (from 0% to 20%).

When the NPs are close enough to each other, the first excited dark mode of the rod can hybridize with the bright dipole mode of the disk, leading to the formation of a bonding and an antibonding modes whose interference is at the origin of a FR profile. Figure 1(a) represents the evolution of the resonance maxima as a function of the applied displacements, the inset showing the FR at ε=0%. When the displacement percentage passes from 0% to 20%, the bonding mode exhibits a strong blueshift of 67.1 nm while the antibonding mode shows a smaller shift in the opposite direction, of 14 nm. Indeed, when the PDMS is under stretching NPs move away from each other and the gap undergoes a dramatic amplification with a percentage higher than that of the applied strain, which causes a decoupling and a transition to weak interaction between the two modes accompanied with a strong decrease of the electric field amplitude in the gap region (see Figure1(d) and (e)). Moreover, our system provides the best sensitivity (3.35nm/% for the bonding mode) compared to a similar system of isolated NPs (1.9nm/%)(*3*).

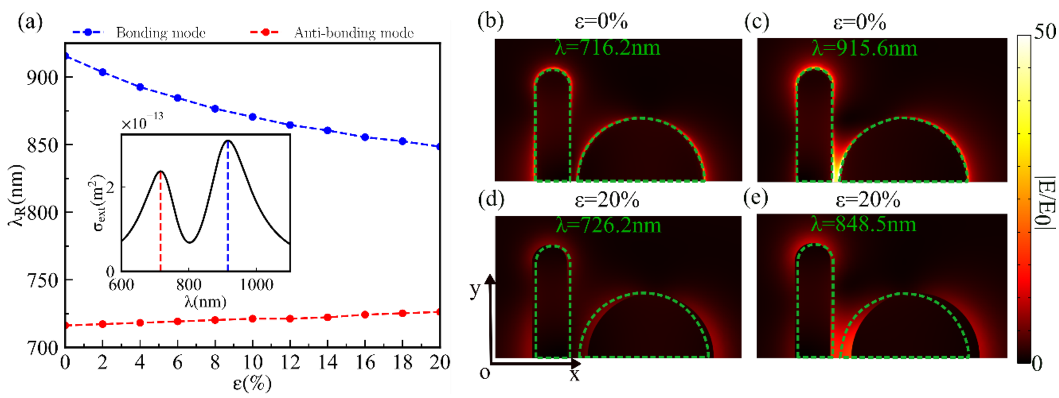

Figure 1 : Calculated evolution of the resonance wavelength as a function of the applied displacements ranging from 0% to 20% (a); electric field distribution of the structure at rest and under 20% of deformation respectively: for the antibonding mode [(b) and (d)] and for the bonding mode [(c) and (e)].

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Optomechanical clocks - towards the GHz range

Thomas Furcatte[a], Joan Barceló[a,b], Wioletta Trzpil[a], Sébastien Regord[a], Marc Gely[a], Munique Kazar Mendes[a], Guillaume Jourdan[a], Sébastien Hentz[a], Marc Sansa[a*]

a. CEA-Leti, Université Grenoble Alpes, F-38000 Grenoble, France
b. Present address: Electronic Systems Group, Universitat de les Illes Balears, 07122 Palma, Spain

* email: marc.sansaperna@cea.fr

Clocks based on MEMS technologies have made great strides in the past few years, but high-performance at the GHz frequency remains elusive due to the limits of electrical transduction. We propose a new approach to clocks, mixing optomechanical transduction and electromechanical actuation, thus coupling elements from MEMS field and integrated photonics technology. The oscillators are built around a microdisk resonator, mechanically operating in a radial breathing mode, which beneficiates from the optomechanical back-action to upgrade their $f\text{x}Q$ factors up to $1\text{x}10^{13}$. Although they have the potential to scale to the high-GHz in frequency while attaining high performance thanks to their excellent transduction, we demonstrate the concept with two optomechanical MEMS-based oscillators operating at 315 MHz and 630 MHz, built with a 200 mm VLSI technology. The oscillators show performances at the state of the art, with a measured phase noise of (respectively) -98 dBc/Hz and -90 dBc/Hz at 10 kHz offset, and a floor of -120 dBc/Hz in both cases. Interestingly, contrary to purely electromechanical MEMS technologies, the performance does not degrade with frequency: this opens the way to frequency multiplication by improved MEMS design as opposed to complex electronics.

This work also elucidates the noise dynamics in the system. In standard optomechanical resonators, the transduction sensitivity allows reaching the limit of detection imposed by the resolution of the thermomechanical noise, resulting in a phase random walk growth within the mechanical bandwidth. At countercurrent from the trend, optomechanical based clocks should rely on efficient electromechanical actuation coupling, and degraded transduction sensitivity. Additionally, as the displacement spectral density associated to the thermomechanical noise scales with the inverse cubic of the frequency, one would expect an improvement of the signal-to-noise ratio while increasing the operating frequency. Finally, we also demonstrate the capability of the devices to operate as optomechanical self-oscillators, resulting in a stable clock with no feedback circuit. This first demonstration shows that integrated clocks based on optomechanics are a unique alternative for high frequency and high-performance applications, solving many of the limitations of classical MEMS technologies.

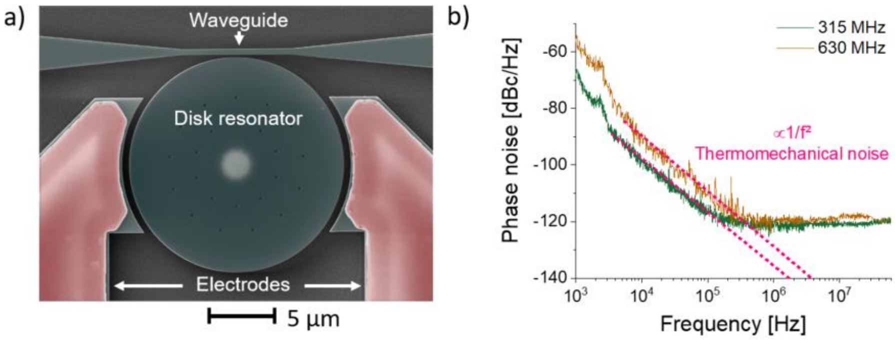

Figure 1 : a) Colored scanning electron microscope (SEM) picture of the resonator. b) Phase noise spectrum of the oscillators at 315 MHz and 630 MHz

Efficient optical coupling to gallium arsenide nano-waveguides and resonators with etched conical fibers

S. Pautrel[a], F. Malabat[a*], L. Waquier[a], M.F. Colombano Sosa[a], M. Morassi[b], A. Lemaitre[b], I. Favero[a]

a. Laboratoire Matériaux et Phénomènes Quantiques (MPQ), CNRS, Paris, France
b. Université Paris-Saclay, CNRS, C2N, Palaiseau, France

*florent.malabat@u-paris.fr

We explore new versatile methods for efficient optical coupling to on-chip gallium arsenide nanophotonic structures using etched conical optical fibers. With a single-sided conical fiber taper, we demonstrate efficient coupling to an on-chip photonic bus waveguide in a liquid environment. We then show that it is possible to replace such bus waveguide by two joined conical fibers to directly couple light into a target whispering gallery disk resonator. This approach proves compliant with demanding environments, such as a vibrating pulse tube and is demonstrated both in the telecom band and in the near infrared. The versatility and high coupling efficiency of this method are promising for quantum optics and sensing experiments in constrained environments where obtaining high signal-to-noise ratio remains a challenge.

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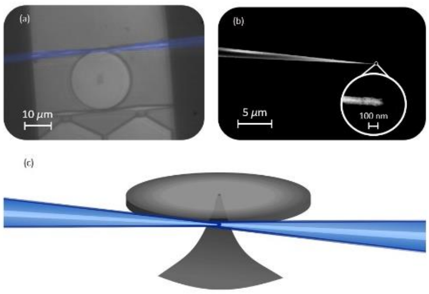

Figure 1: (a) Experimental situation with a 11 μm radius, 200 nm thick GaAs disk resonator. The homemade conical optical fibers are false colored in blue. (b) SEM micrograph of a conical fiber fabricated by us. Some surface roughness is visible, and always present with the current fabrication procedure. However, it is experimentally not detrimental to the optical coupling efficiency. (c) Sketch of the coupling principle.

Millikelvin photon-counting quantum optomechanics with gallium arsenide disk resonators

Samuel Pautrel[a*], Adrien Borne and Ivan Favero

a. Laboratoire Matériaux et Phénomènes Quantiques (MPQ), CNRS-UMR7162, Université Paris Cité, 75013 Paris, France

* samuel.pautrel@u-paris.fr

During the last decade, there has been several demonstrations of mechanical oscillators put close to their ground state, which is the state of minimal energy dictated by quantum mechanics. Starting from the mechanical ground state, it has been showed both theoretically and experimentally that the physics of optomechanics allow manipulating the quantum state of a mechanical mode at the single phonon level.
We will discuss the feasibility of single-phonon heralding schemes for real-world applications such as quantum teleportation [1], as well as the potential of gallium arsenide disk resonators for this type of experiments. We designed and built a cryogenic experimental setup that allows measurements at mK temperatures and will show our experimental results on cooling the fundamental GHz breathing mode of a 1.3 um radius disk close to its ground state.

[1] S. Pautrel, Z. Denis, J. Bon, A. Borne, and I. Favero, Optomechanical discrete-variable quantum teleportation scheme, Phys. Rev. A **101**, 063820 (2020)

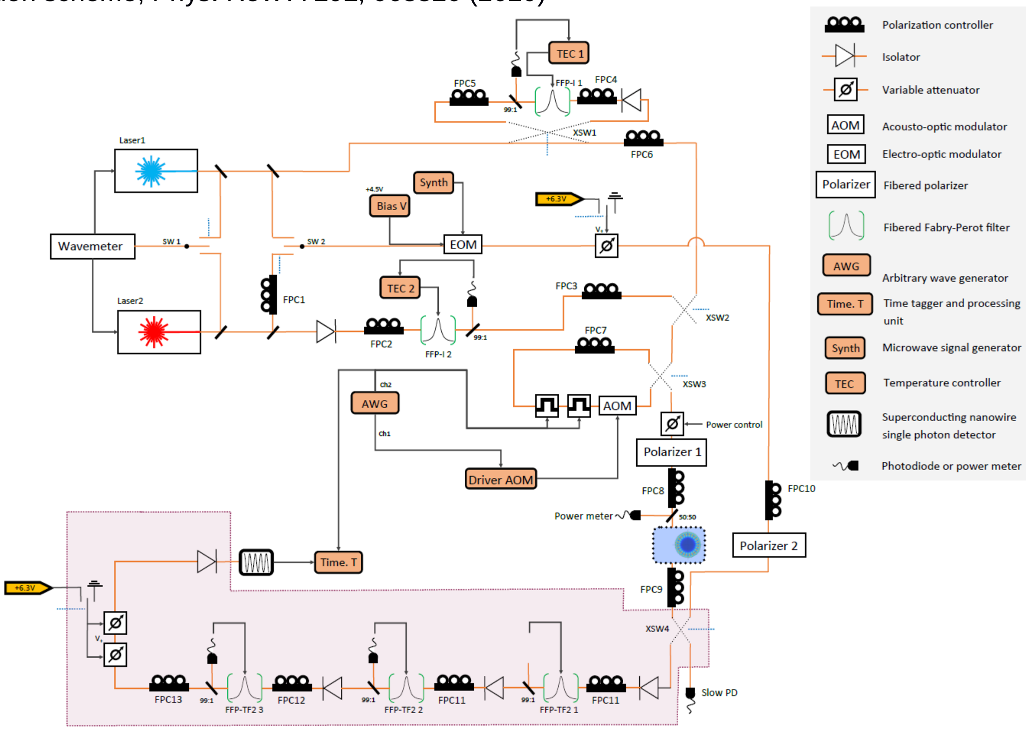

Figure 1 :: Complete optical setup for sideband photon counting measurement with single photon detectors. The small light blue dashed rectangle pictures the dilution fridge.

Microgear: a new optomechanical resonator for enhanced photon-phonon interactions

Andrea Barbero[a*], Samuel Pautrel[a], Adrien Borne[a] and Ivan Favero[a]

a. Université Paris Cité CNRS Laboratoire Matériaux et Phénomènes Quantiques Paris 75013, France

* andrea.barbero@u-paris.fr

Suspended microdisks [1] and optomechanical crystal (OMC) nanobeams [2] are two leading platforms for optomechanical experiments that perform differently: while optomechanical disks couple high quality optical whispering-gallery modes ($Q{\sim}10^6$) with mechanical radial breathing modes with optomechanical vacuum coupling coefficient of the order of $g_0/2\pi \approx$ 200-250 kHz, OMC nanobeams (photonic and phononic crystals designed to confine optical and mechanical modes in a defect) show a higher optomechanical vacuum coupling coefficient of the order of $g_0/2\pi \approx$ 800 kHz, but more modest optical quality factors. Our work aims at combining the best of both worlds.

To that purpose, we designed, fabricated and measured a new GaAs optomechanical resonator that we call microgear. It consists of a rounded photonic crystal that confines in a defect a whispering-gallery like optical mode, maintaining the high optical quality factor typical of whispering-gallery modes and a small mode volume typical of photonic crystals. The simulations show an optical quality factor larger than 10^6, the measurements are around 10^4 because of roughness in our current fabrication process. The defect supports also a high frequency (around 1.8 GHz) mechanical breathing mode well coupled to the optical defect mode thanks to their high colocalization. The simulated optomechanical vacuum coupling coefficient is $g_0 \approx 2\pi{\cdot}370$ kHz, making this device a promising candidate to reach state-of-the-art single photon cooperativity.

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[2] Jasper Chan, T. P. Mayer Alegre, Amir H. Safavi-Naeini, Jeff T. Hill, Alex Krause, Simon Gröblacher, Marcus Aspelmeyer, and Oskar Painter, Laser cooling of a nanomechanical oscillator into its quantum ground state, Nature **478**, 7367 (2011)

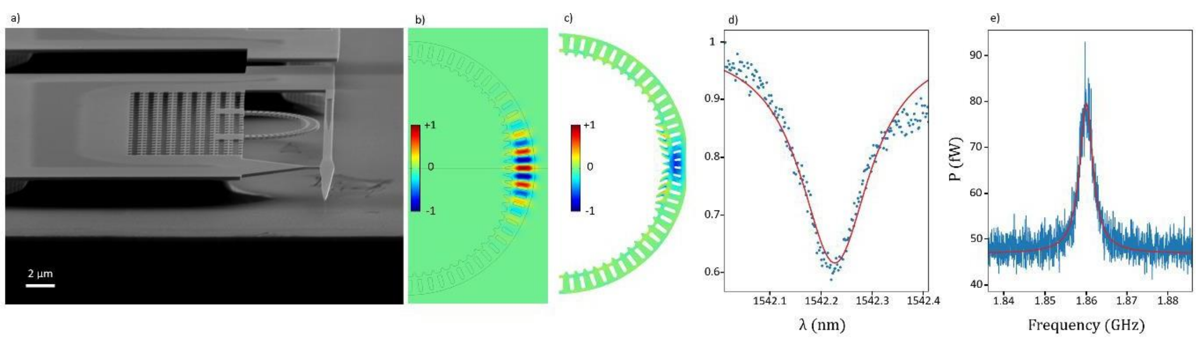

Figure 1: a) SEM image of a fabricated microgear; **b)** top view of the simulated optical mode; **c)** top view of the simulated mechanical mode; **d)** measured optical mode; **e)** measured mechanical mode.

Quantum states of motion of a mechanical resonator

Romain Dezert[a], Samuel Pautrel[a], Ivan Favero[a] and Adrien Borne[a,*]

a. Matériaux et Phénomènes Quantiques, Université Paris Cité / CNRS

* adrien.borne@u-paris.fr

The exploration of optomechanical (OM) systems in the quantum regime is currently attracting interest, ranging from fundamental testing of quantum mechanics in mesoscopic objects to their use in quantum networks, e.g. for transducing or storing quantum information. In this context, this work aims at generating and characterizing arbitrary mechanical quantum states from optomechanical interactions [1] in two-color driven semiconductor microdisks, i.e. mesoscopic massive objects. At the heart of this work is the ability to use OM interactions to add or subtract a single quantum through Raman interactions. This principle has been used very recently in two demonstrations of addition and subtraction of a single phonon from a mechanical thermal state at room temperature [2,3]. Our work targets the creation of low-quanta phonon states, therefore in the low temperature (mK) regime. The state characterization is optical, through homodyne tomography.

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Towards quantum control of an ultracoherent mechanical resonator with a fluxonium qubit

K. Gerashchenko*[(a)], B.-L. Najera-Santos[(a)], R. Rousseau[(a, b)], H. Patange[(a)], A. Riva[(c, d)], M. Villiers[(c, d)], T. Briant[(a)], P.-F. Cohadon[(a)], A. Heidmann (a), H. le Sueur[(e)], A. Sarlette[(c, d)], W. C. Smith [(c, d)], Z. Leghtas[(c, d)], E. Flurin[(e)], T. Jacqmin[(a)] and S. Deléglise[(a)]

a. Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 place Jussieu, 75005 Paris, France
b. Alice & Bob, 53 Bd du Général Martial Valin, 75015 Paris, France
c. Laboratoire de Physique de l' École Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, 75005 Paris, France
d. Centre Automatique et Systèmes, Mines Paris, Inria
e. Quantronics group, Université Paris-Saclay, CEA, CNRS, SPEC, 91191 Gif-sur-Yvette Cedex, France

* kyrylo.gerashchenko@lkb.upmc.fr

Nowadays, the state-of-the-art chip-scale phononic-crystal membrane flexural modes can achieve lifetimes over 100 s and coherence times in the order of seconds in a thermal environment at 10 mK [1]. It can be achieved using softly-clamped silicon-nitride membranes (typically in the MHz frequency range). The strong coupling between these outstanding mechanical resonators and superconducting qubits (typically in GHz frequency range), one of the most promising platform for scalable quantum computers, has been a long-pursued goal, since it could open the door to novel quantum technology applications, like record-beating quantum memories, microwave-optical quantum transducers [2] or even fundamental tests of quantum gravity [3] by placing a membrane mode in a quantum superposition. The main challenge to overcome is reducing the wide frequency difference (typically 10^3) between both quantum devices. Inspired by recent works [4], our group has proposed a novel coupling scheme to finally turn the dream into a reality. We have developed a heavy fluxonium qubit which is highly sensitive to a drive charge at a frequency as low as 1.8 MHz, achieving state-of-the-art coherence times for such a qubit architecture [5]. Additionally, we are capable of producing phononic crystal membranes with a large defect mode that can be capacitively coupled to this qubit.
I would like to present the results of our latest research on the qubit and how it enables us to couple it with the phononic-crystal membrane (an example of such a membrane can be seen in Fig. 1).

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[2] R. W. Andrews, et al. Nat. Phys. 10, 321 (2014)
[3] M. Gely and G. Steele, arXiv:2004.09153 (2021)
[4] J. J. Viennot, X. Ma, and K. W. Lehnert, Phys. Rev. Lett. 121 (2018) 183601
[5] S. Deléglise, et al. arXiv:2307.14329 (2023)

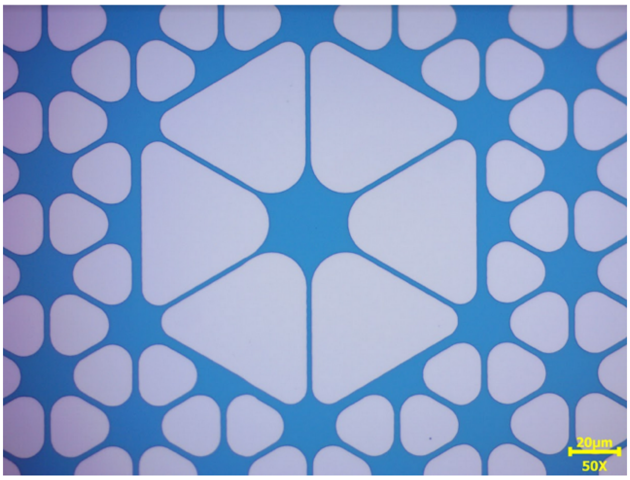

Figure 1 : Example of the membrane used in our group. The defect is placed in the middle.

Brillouin Scattering in Subwavelength Silicon Waveguides

Paula Nuño Ruano[a*], Jianhao Zhang[a,b], Daniele Melati[a], David González-Andrade[a], Xavier Le Roux[a], Eric Cassan[a], Delphine Marris-Morini[a], Laurent Vivien[a], Norberto Daniel Lanzillotti-Kimura[a], and Carlos Alonso-Ramos[a]

a. Centre de Nanosciences et de Nanotechnologies, Université Paris-Saclay, CNRS, France
b. Present address: National Research Council Canada, Canada

* paula.nuno-ruano@c2n.upsaclay.fr

Brillouin scattering, the nonlinear interaction between optical and mechanical fields, has led to remarkable developments in communications, sensing, and quantum technologies in the last decade. Simultaneous confinement of optical and mechanical modes, a requirement for efficient Brillouin interactions, is challenging in silicon-on-insulator (SOI) waveguides due to a strong phonon leakage towards the silica cladding. A successful strategy to overcome this drawback is to isolate the optomechanical silicon waveguide by removing the silica cladding. We exploit subwavelength engineering of the longitudinal and transversal geometries as a promising tool to independently control photonic and phononic modes in suspended silicon waveguides. This is particularly relevant in silicon nanostructures, where forward Brillouin scattering yields the highest gain by relying on longitudinally propagating photons and transversally propagating phonons [1]. Additionally, we could exploit this subwavelength structuration to avoid suspended membranes, allowing for an easier fabrication directly compatible with CMOS technology and opening a new strategy to harness optomechanical interactions [2].

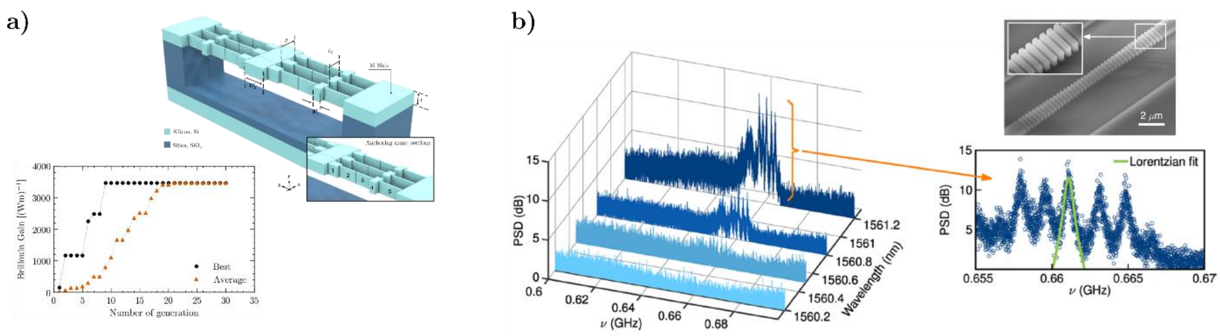

Figure 1: a) Suspended silicon waveguide optimised using a genetic algorithm to provide large Brillouin gain [1]. b) Unreleased SOI nanobeam cavity for strong optomechanical interaction [2].

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Dynamical back-action in room temperature microwave optomechanics

Sumit Kumar[a], Matthew Kenworthy, Henry Ginn and Xavier Rojas[*]

Department of Physics, Royal Holloway University of London,
Egham, Surrey TW20 0EX, United Kingdom

We present advancements in room temperature microwave cavity optomechanics through a 3D architecture. Our setup incorporates a 3D microwave re-entrant cavity coupled to a compliant SiN membrane, enhancing the optomechanical coupling strength. This augmentation allows us to observe dynamical backaction, leading to both amplification and cooling effects. With high pump powers, our system demonstrates self-sustained oscillations, resulting in microwave frequency combs. Notably, we achieve robust optomechanically induced transparency/absorption effects, showcasing the versatile potential of this platform for applications in signal processing.

Modelling and analysis of MEMS inertial sensor wake-up contact switches

Marlon McCarthy[a,b], Sagnik Ghosh[b], Yul Koh[b] and Yoshishige Tsuchiya[a*]

a. School of Electronics and Computer Science, University of Southampton, Highfield Campus, Southampton SO17 1BJ, United Kingdom
b. Institute of Microelectronics, A*STAR, Singapore

* Corresponding author: yt2@ecs.soton.ac.uk

Power management of Internet of Things (IoT) devices that are operated remotely with integrated sensors, batteries and wireless interfaces is crucial to maintain their lifetime longer. An ideal approach is to have a switch to turn on only when necessary, while to turn off to put the devices into sleep with near-zero leakage current. Microelectromechanical systems (MEMS) contact switches can provide improved electrical isolation compared to solid state switches. Recently Ghosh et al. [1] have proposed a MEMS "wake-up" sensor switch, where the MEMS contact switch can work as an inertial sensor and can turn on when acceleration exceeds a threshold that can set by the structural design. Following Ref. [1], detailed numerical analysis has been conducted to understand their operation.

Figure 1 (a) shows a schematic of a MEMS inertial sensor switch with titanium nitride (TiN) contacts. The device consists of a 30-micron-thick rectangular proof mass hinged along one of its long ends. When subjected to an acceleration, the body of the device moves sufficiently to bring a TiN strip on the structure into contact with a TiN counter contact suspended above. A result of static Finite Element Analysis (FEA) via COMSOL is shown in Fig.1(b). The maximum displacement calculated via either static or transient analysis shows linear to the acceleration in Fig. 1(c) and the linear coefficient is altered due to the pulse shape of the acceleration. An experimental result of a MEMS inertial sensor wake-up switch showing the acceleration and voltage output against time is shown in Fig. 1(d), where the MEMS switch is closed at the acceleration of 9.43g. The maximum displacement of the time-based analysis with the acceleration pulse shape closer to the experiment is calculated 0.8 µm, suggesting the actual gap width is narrower than the designed value of 1 µm.

[1] S. Ghosh et al., "Wake-up IoT wireless sensing node based on a low-g threshold MEMS inertial switch with reliable contacts." IEEE MEMS 2023, pp. 491–494.

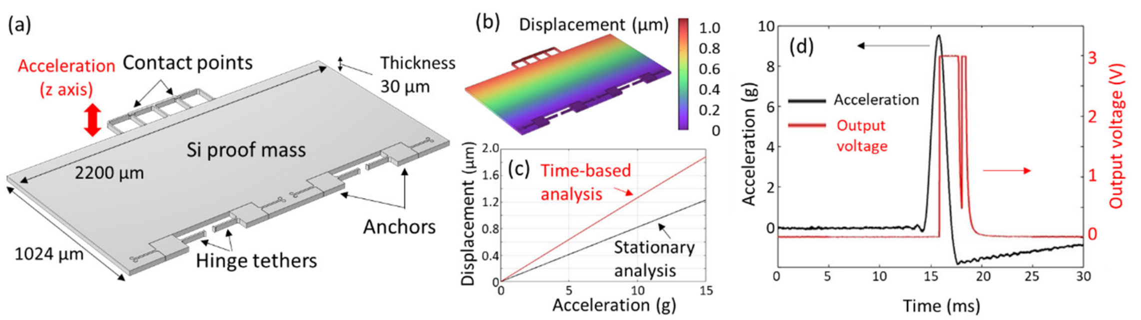

Figure 1: a) A 3D design of a MEMS inertial sensor wake-up contact switch. b) A static simulation result of the displacement distribution in applying 10g. (c) Maximum displacements for the static analysis and the time-based analysis with Gaussian pulse acceleration are plotted with respect to the acceleration. (d) An experimental result of a MEMS inertial sensor wake-up switch showing the acceleration and device voltage output against time.

Finite element analysis of optical displacement detection for silicon Nano-Electro-Mechanical (NEM) resonators

James Fernando[a], Jun-Yu Ou[b], and Yoshishige Tsuchiya[a*]

a. School of Electronics and Computer Science, University of Southampton, Highfield Campus, Southampton SO17 1BJ, United Kingdom
b. School of Physics and Astronomy, University of Southampton, Highfield Campus, Southampton SO17 1BJ, United Kingdom

* Corresponding author: yt2@ecs.soton.ac.uk

Nonlinear mechanical oscillator networks have been proposed to work as neural networks for energy-efficient Artificial Intelligence (AI) hardware [1]. To apply nonlinear silicon Nano-Electro-Mechanical (NEM) resonators [2] for such computing applications, accurate readouts of the full dynamic range of nanobeam motion are required. Optical displacement detection is an option to have better sensitivity and noise tolerance than electrical detection.

This work applies finite element analysis for studying the optical responsivity due to nanobeam motion under the setup of free-space optical detection shown in Fig. 1(a). Figure 1(b) shows a 3D simulation space including a silicon nanobeam and substrate with an input port for calculation of S_{11}, and then the reflectance $R = 100\times|S_{11}|^2$. The reflectance has been simulated for different geometries where the nanobeam is translated from the baseline position with the displacement of Δz. Figure 1(c) shows distribution of the electric field in the simulation space with a translated nanobeam with Δz = 20 nm. For the calculated reflectance of a baseline beam R_{bas} and that of a displaced beam R_{dis}, the change of the reflectance $\Delta R = R_{dis} - R_{bas}$ for varied Δz is plotted with respect to the wavelength λ in Fig. 1(d). The displacement-to-optical-reflectance responsivity defined as $\Delta R/\Delta z$ is estimated for the telecom wavelengths, 0.05%/nm at λ = 1310 nm and 0.006%/nm at λ = 1550 nm.

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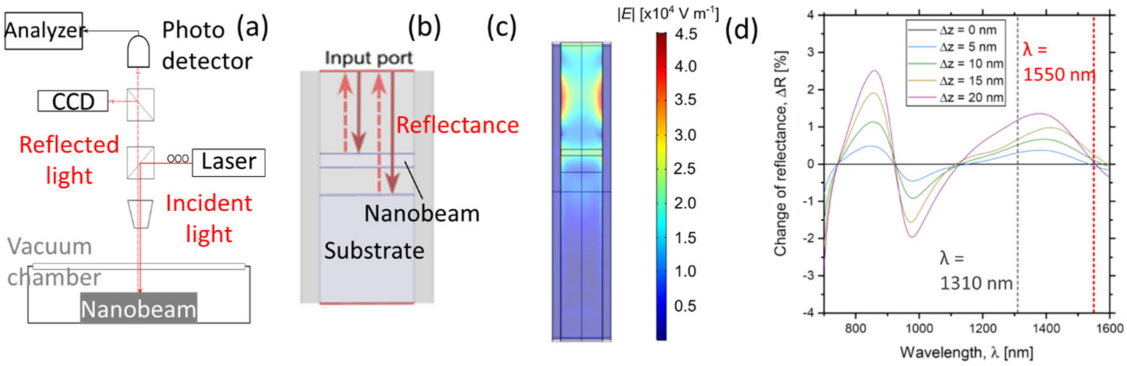

Figure 1: (a) Free space optical detection set-up for NEM resonators. (b) Simulation space for reflectance calculation with a silicon nanobeam and substrate. The beam dimensions are 400 nm (L) x 105 nm (W) x 60 nm (H). (c) A COMSOL calculation result of distribution of the electric field strength, $|E|$, with a translated nanobeam with Δz = 20 nm at λ = 1310 nm (d) Simulated change of reflectance, $\Delta R = R_{dis}$-R_{bas}, as a function of the wavelength λ.

Nanomechanical qubit and non-linearities

F. Pistolesi [a*]

a. Université de Bordeaux & CNRS, LOMA UMR5798, Talence (France)

* Fabio.Pistolesi@u-bordeaux.fr

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. One of the difficulties is to engineer a sufficiently large anarmonicity that allows to manipulate the first levels of the mechnical qubit, independently of the other levels. In Ref. [1] we have shown 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 (cf. the figure), it is possible to induce sufficient anharmonicity in the mechanical oscillator so that the coupled system can be used as a mechanical quantum bit. 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 how the qubit can be used as a static-force quantum sensor. We will discuss how a similar non-linear behaviour is generated when the oscillator is coupled to a single-electron transistor [2] and discuss the theory describing the recent observation of this phenomenon [3].

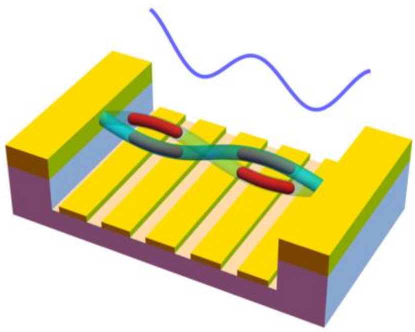

Figure 1: A schematic of the system considered, a suspended carbon nanotube with embedded two quantum dots. In the background it is shown the electrostatic potential generated by the five electrodes and localizing the electrons on the two dots.

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