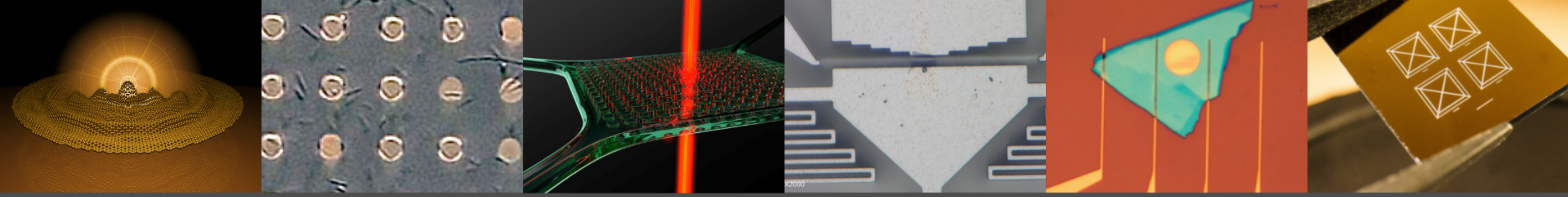


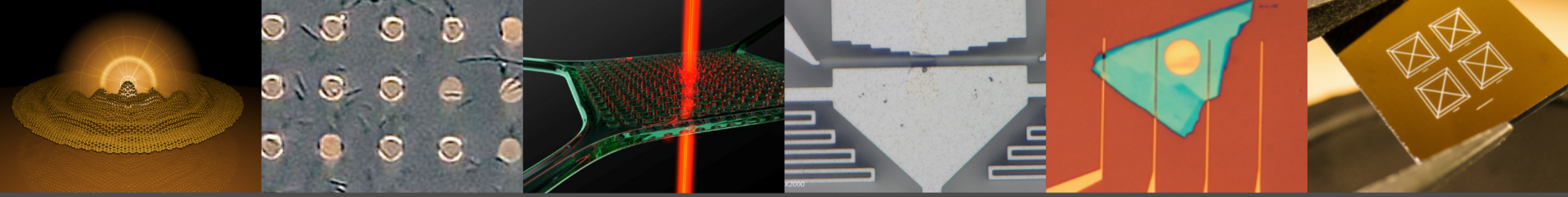
FNS / 2023
Frontiers of Nanomechanical Systems

TU Delft
6 - 9 June 2023

Book of Abstracts

Frontiers of Nanomechanical Systems (FNS)

June 6-9, 2023



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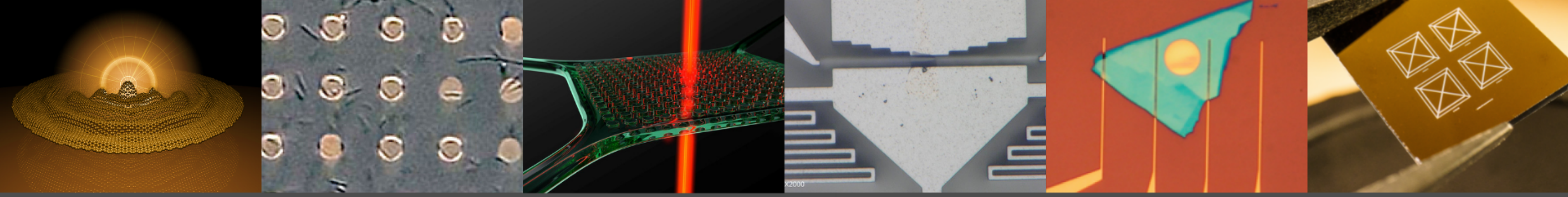


Message from conference chairs

Frontiers of Nanomechanical Systems (FNS) is a workshop series with the purpose to bring together the international community engaged in fundamental research on micro- and nano-electromechanical systems (MEMS & NEMS). The workshop intends to promote the cross-fertilization of ideas and stimulate international interactions in this rapidly growing area.

Nano and micromechanical resonators are unique platforms for fundamental science and fill in the gap between the microscopic world of molecular vibrations and the world of macroscopic vibrational systems. The research frontiers they open lie at the interface between quantum & classical nonlinear dynamics and extend from condensed matter physics to statistical physics, many-body physics far from thermal equilibrium, and nanotechnology. At the same time, owing to their small size and ultra-low mass, they offer new opportunities in terms of functionality and sensitivity, and thus are expected to enable new breakthroughs in sensing, communications, and computing both in classical and quantum regimes.

After three successful FNS series in 2017 in the Italian Alps, 2019 in Palm Springs California, and the 2021 online event organised by ICFO, FNS2023 will be held at the Art Centre Delft, close to TU Delft campus, in the Netherlands, from June 6-9, 2023. TU Delft is one of the leading technical universities in Europe with several groups active in different areas of nanomechanical systems including optomechanics, bio-nanoscience, 2D materials, novel sensing methodologies, nonlinear dynamics, and quantum technologies.

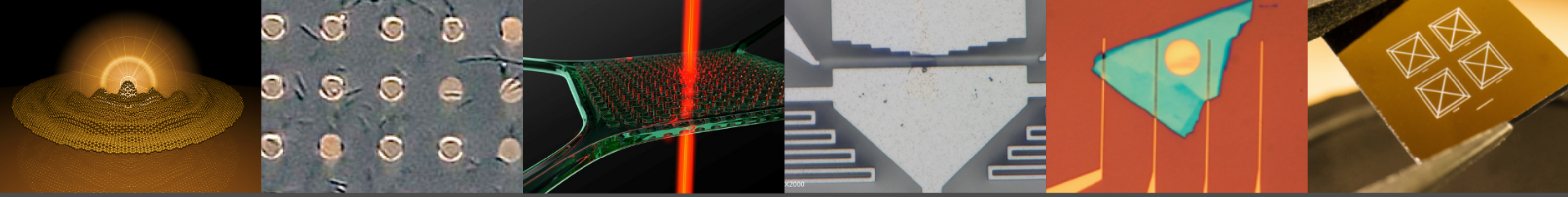
In FNS2023 we aim at putting together an exciting scientific program by inviting renowned scientists working in the cross-fields of nanomechanics to communicate their recent findings and exchange experience. The 4-day program of FNS2023 will include invited talks, contributed talks, poster sessions, and discussions on the recent advancements in nanomechanical systems.

We wish everyone a successful meeting, full of exchange and improvement of ideas and knowledge in diverse fields of nanomechanics.

Farbod Alijani

Peter Steeneken

Herre van der Zant



Organizing Committee

Hans Goosen (Treasurer)

Lucienne Dado

Annemieke van Ast

Nick Wansink

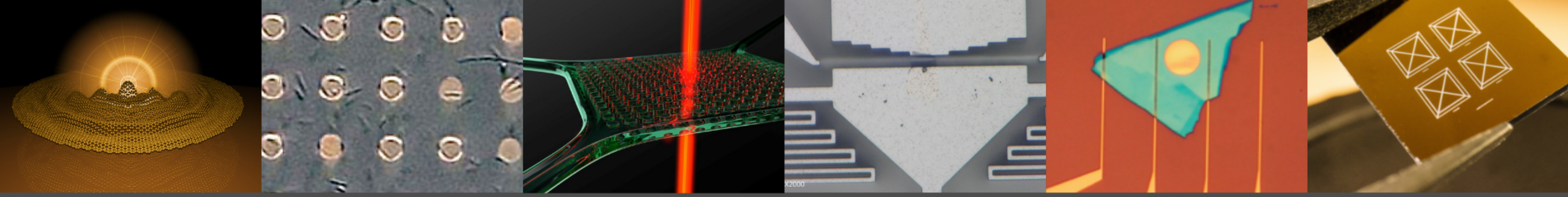
Santiago Mendoza Silva

Hendrik Jaap Algra

FNS Committee

Adrian BACHTOLD
Ho Bun CHAN
Mark DYKMAN
Fabio PISOLESI
Michael ROUKES
Eva WEIG
Hiroshi YAMAGUCHI

- **Adrian Bachtold**, Professor, ***ICFO Barcelona***
- **Ho Bun Chan**, Professor of Physics, ***HKUST China***
- **Mark Dykman**, Professor of Theoretical Physics, ***Michigan State University***
- **Fabio Pistolesi**, Professor of Physics / CNRS Research Director, ***Université de Bordeaux***
- **Michael Roukes**, Frank J. Roshek Professor of Physics, Applied Physics, & Bioengineering, ***California Institute of Technology***
- **Eva Weig**, Professor of Nano and Quantum sensors, ***Technical University of Munich***
- **Hiroshi Yamaguchi**, Senior Distinguished Researcher / Group Leader, Physical Sciences Laboratory, ***NTT Basic Research Laboratories, Kanagawa***



Invited Speakers

FNS2023 has the pleasure to host renowned scientists in the fields of micro/nanomechanical systems and related areas to present their recent results. Our invited speakers are (in alphabetical order):

Natalia Ares
(Oxford)

Motoki Asano
(NTT)

Adrian Bachtold
(ICFO)

Kirill Bolotin
(Freie University)

Aashish Clerk
(Chicago)

Ho Bun Chan
(HKUST)

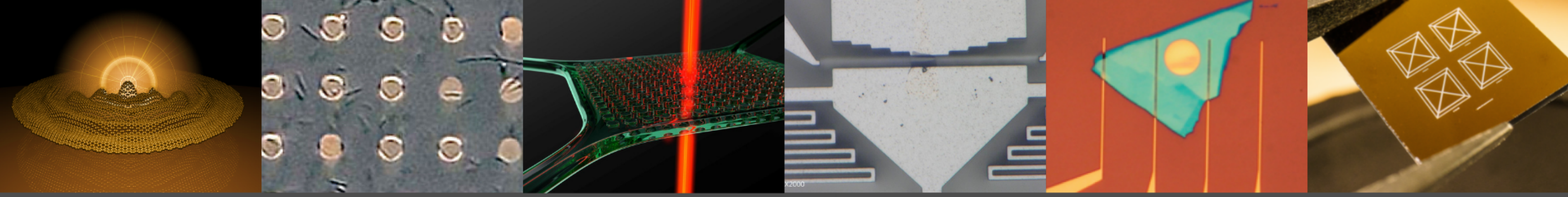
Eddy Collin
(CNRS)

Mark Dykman
(Michigan State)

Alex Eichler
(ETH)

Ivan Favero
(CNRS)

Pertti Hakonen
(Aalto)



Richard Norte
(TU Delft)

Oskar Painter
(Caltech)

Fabio Pistolesi
(Université de Bordeaux)

Menno Poot
(TUM)

Romain Quidant
(ETH)

Gianluca Rastelli
(Trento)

Amir Safavi-Naeini
(Stanford)

Elke Scheer
(Konstanz)

Albert Schliesser
(Copenhagen)

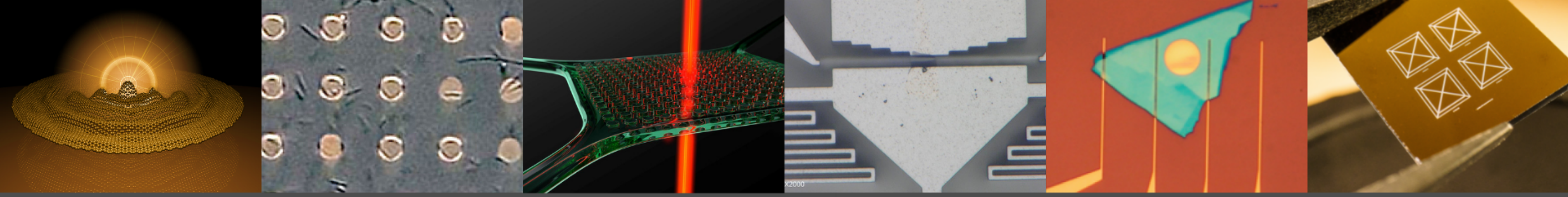
Gary Steele
(TU Delft)

Gerard Verbiest
(TU Delft)

Ewold Verhagen
(AMOLF)

Eva Weig
(TUM)

Hiroshi Yamaguchi
(NTT)



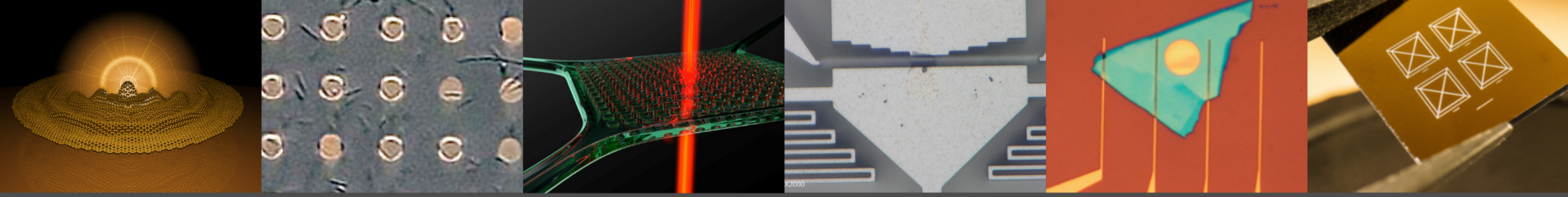
Conference Venue

FNS2023 will be held at the Art Centre Delft, close to TU Delft campus.

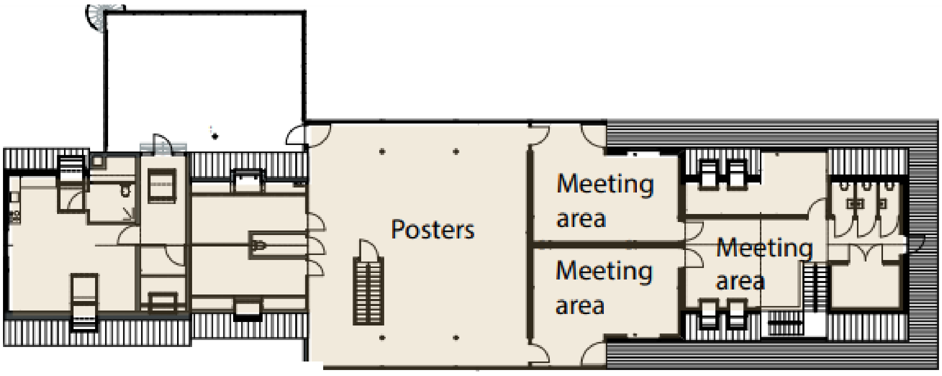
Art Centre Delft is a former farm from the nineteenth century, partly renovated, partly expanded with bright, spacious rooms. Glass parts from floor to ceiling give the feeling of staying in a glass house and a huge wooden terrace offers a fantastic view of the most beautiful piece of nature in Midden-Delfland in all seasons. What started as a Gallery for the arts has evolved over the years into an event location.

The Gallery hosts about six different exhibitions per year, all made possible by the Land Art Delft Foundation. In the garden, sometimes hidden among the greenery, you can also see all kinds of works of art. During a meeting, or during lunch/drinks, a walk through the sculpture park of the Land Art Delft Foundation is really worthwhile.

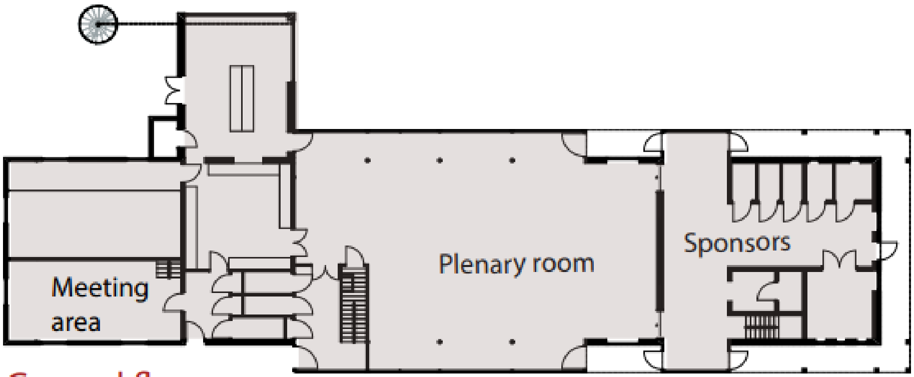
Wifi Art Centre: ACD guests



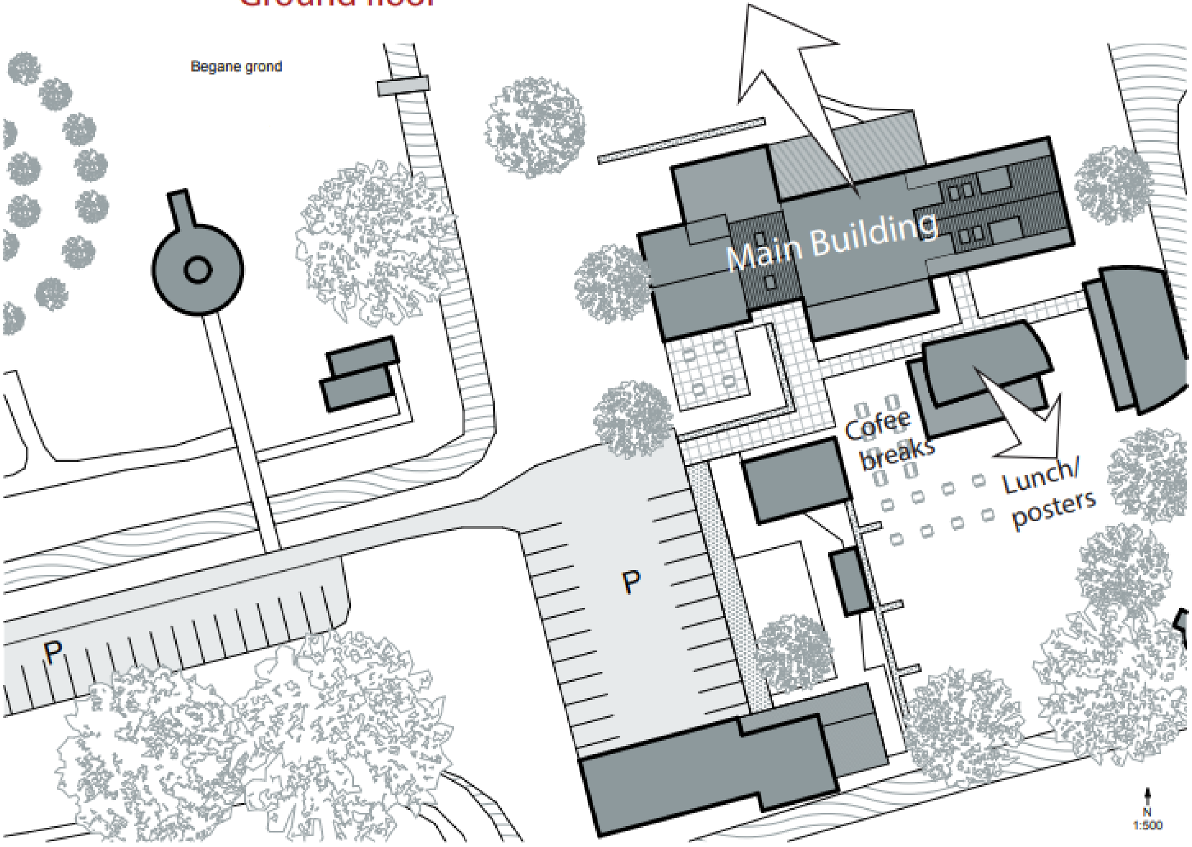
Venue Map

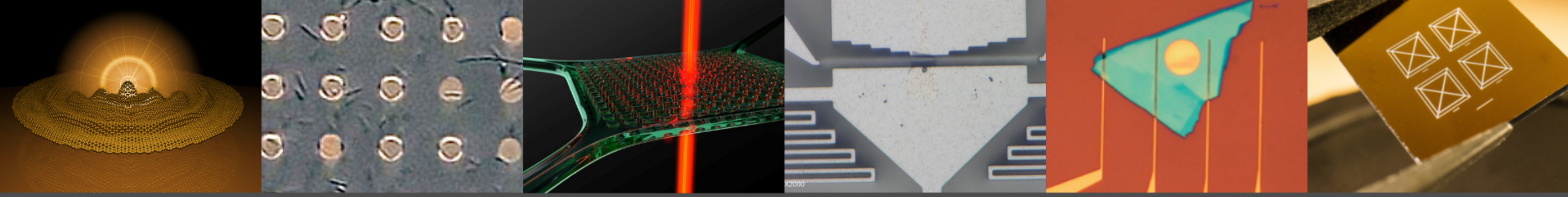


First floor



Ground floor



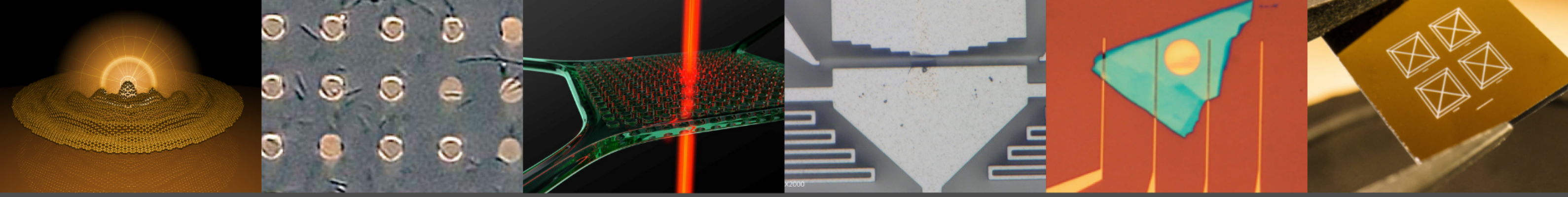


Bus Transport

Here you find the schedule of the arranged coaches (BAB VIOS TOURINGCAR) from designated places in Delft to bring participants in the morning to the conference venue and in the evening back to the centre of Delft.

	June 6th, 2023	June 7th, 2023	June 8th, 2023	June 9th, 2023
Morning transport	**07.45h** **Bus 1**: Shanghai hotel, Westcord hotel, Hampshire Hotel, Art Centre Delft	**07.45h** **Bus 1**: Shanghai hotel, Westcord hotel, Hampshire Hotel, Art Centre Delft	**07.45h** **Bus 1**: Shanghai hotel, Westcord hotel, Hampshire Hotel, Art Centre Delft	**08.00h** **Bus 1**: Shanghai hotel, Westcord hotel, Hampshire Hotel, Art Centre Delft
	07.45h **Bus 2**: Delft Central station, Art Centre Delft	**07.45h** **Bus 2**: Delft Central station, Art Centre Delft	**07.45h** **Bus 2**: Delft Central station, Art Centre Delft	**08.00h** **Bus 2**: Delft Central station, Art Centre Delft
Evening transport	**19:00h** **Bus 1**: Art Centre Delft, Hampshire Hotel, Westcord hotel, Shanghai hotel	**19:00h** **Bus 1**: Art Centre Delft, Hampshire Hotel, Westcord hotel, Shanghai hotel	**17:00h** **Bus 1**: Art Centre Delft, Madurodam	**17:00h** **Bus 1**: Art Centre Delft, Hampshire Hotel, Westcord hotel, Shanghai hotel
	19.00h **Bus 2**: Art Centre Delft, Delft Central station	**19.00h** **Bus 2**: Art Centre Delft, Delft Central station	**21.00h** **Bus 2**: Madurodam, Delft Central station	**17.00h** **Bus 2**: Art Centre Delft, Delft Central station

The bus stop Delft Central station (grey icon) is in front of restaurant Pavarotti (green icon), which is on the other side of the bus station and taxi spot (yellow icon).



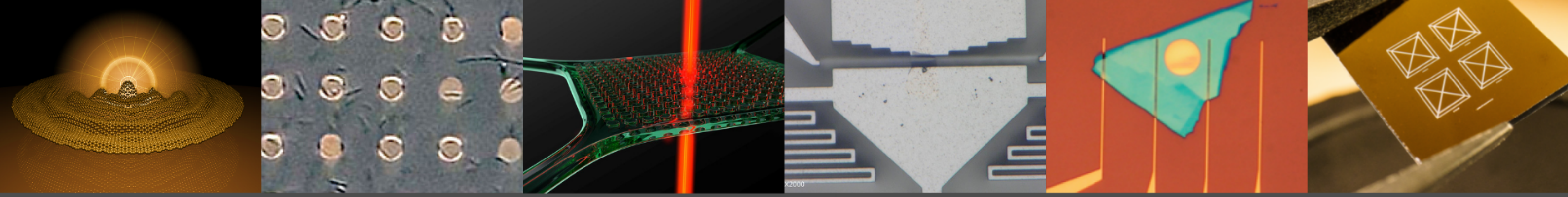
Conference Dinner

The conference dinner will take place on 08.06.2023 in Madurodam.

What makes the small country of the Netherlands so great? When we arrive at Madurodam you will first have the time to discover this and more at Madurodam, a small city full of beautiful miniatures, playful activities and the best attractions.

There is so much to see, discover and do at Madurodam. You become acquainted with the stories of the Netherlands in a surprising way. The models are exact replicas of special buildings and objects, on a scale of 1:25. Through intensive daily care, the greenery, especially small-leaved trees and bushes, are kept to a maximum of 60 centimetres high.

We will arrange the transport with coaches on Thursday evening 08.06.2023 from the Conference Venue Art Centre and one stop in the city centre of Delft to [Madurodam The Hague](#) (approximately 30 minutes).



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General Information

Delft

Delft is one of the oldest cities in The Netherlands, which was already established as early as 1246. Delft is nicknamed ‘de Prinsenstad’ (the Prince’s City), because William of Orange, the first in the Dutch royal line, held court in Delft in the 16th century. Other famous historical figures who once lived and worked in Delft are the painter Johannes Vermeer, the inventor of the microscope Anthonie van Leeuwenhoek, and lawyer Hugo Grotius, who laid the foundations for international law.

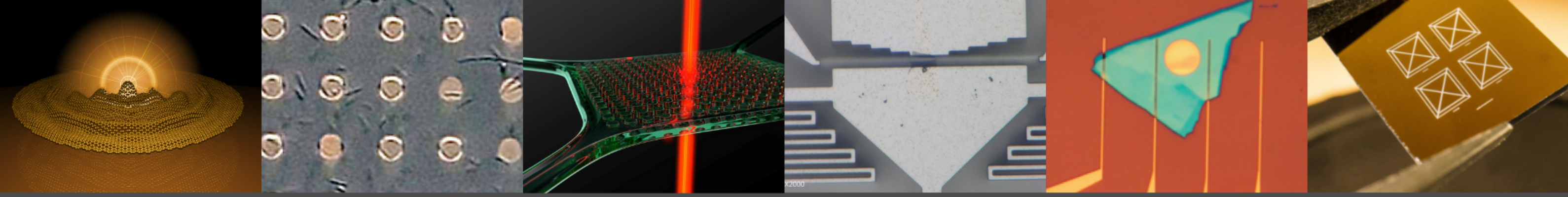
The city has a beautiful, well-preserved, lively historical centre, with characteristic canals, ancient merchant houses, old churches and the splendid city hall, making it valued by tourists throughout the year. Visitors can choose from a variety of good-quality accommodations.

Delft is situated in the province of South Holland between the cities of Rotterdam and The Hague, in the central (western) part of the Netherlands.

Tourist Information

On the following website all the information you need for a visit to Delft: Tourist information

This website contains, among others, recommended restaurants, good places to have a drink and the hotspots you must see when staying in Delft.



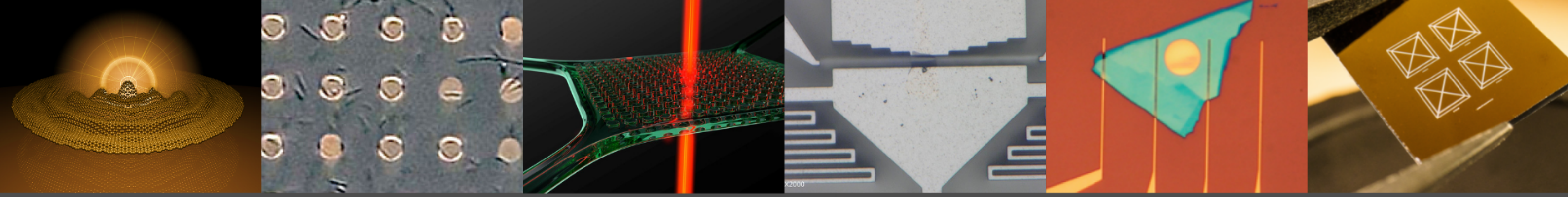
Abstracts for invited and contributed talks

FNS2023 will include 6 themes each hosting a number of invited and/or contributed talks.
The topics can be found below

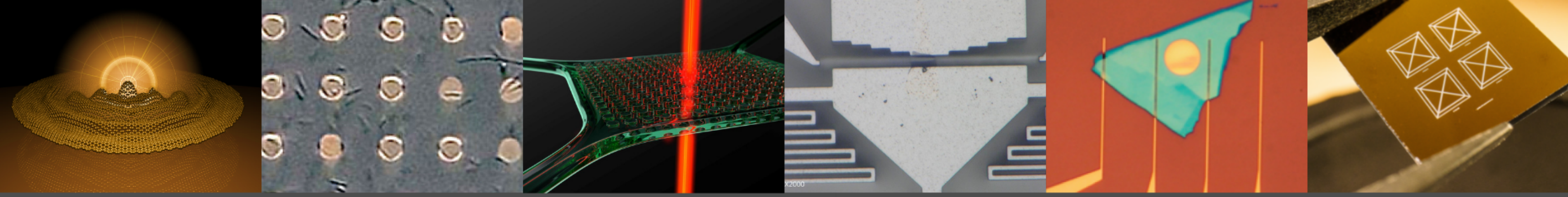
Quantum Resonators (9 talks)	Phase, Symmetry, Topology (5 talks)	Nonlinear Dynamics (6 talks)	Fluctuations and dissipation (4 talks)	Sensing and Control (6 talks)	Phonons, Solutions, Excitons (8 talks)

Tuesday June 6, 2023

8:15-9:00	Registration & coffee	
9:00-9:15	Welcome words	Local organisers
9:15-9:50	*Topological solitons in the arrays of nanomechanical parametric resonators* Hiroshi Yamaguchi (NTT, Japan)	Chair: Herre van der Zant
9:55-10:30	*In-equilibrium thermodynamics of a mesoscopic mechanical object towards the quantum ground-state* Eddy Collin (Grenoble, France)	
10:30-11:00	Coffee break	
11:00-11:25	*Boosting the nonlinearity of mechanical resonators approaching the quantum regime* Adrian Bachtold (ICFO, Spain)	Chair: Eva Weig
11:30-11:55	*Emergent phenomena in driven nonlinear quantum resonators* Gary Steele (TUD, Netherlands)	
12:00-12:15	Sponsor pitch	
12:20-13:20	Lunch	
13:20-13:55	*Quantum state preparation and tomography of entangled mechanical resonators* Amir Safavi-Naeini (Stanford, USA)	Chair: Simon Gröblacher

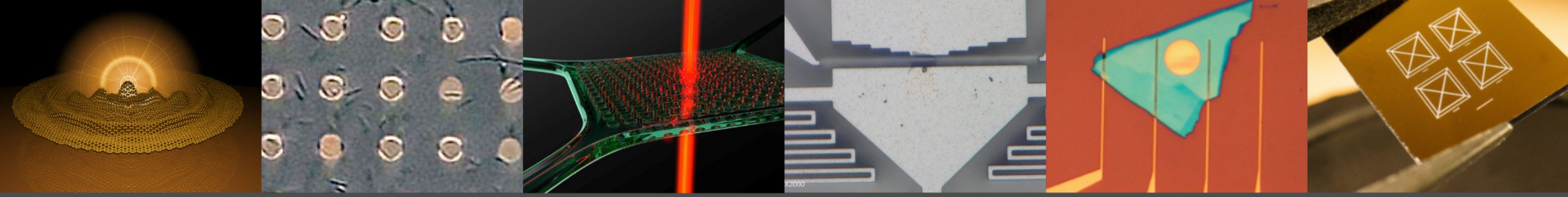


14:00-14:35	*Topologically-imposed vacancies and mobile solid 3He on carbon nanotube nanomechanical resonator* Pertti Hakonen (Aalto, Finland)	
14:40-15:15	*Optomechanical meta-matter: Nonreciprocity and topology in synthetic nanomechanical networks* Ewold Verhagen (AMOLF, Netherlands)	
15:15-15:45	Coffee break	
15:45-16:10	*Nonlinear dynamics and fluctuations in micronscale membrane resonators* Elke Scheer (University of Konstanz, Germany)	Chair: Daniel Lopez
16:15-16:40	*Cavity acousto-mechanics: A platform for linear and nonlinear dynamics* Samer Houri (IMEC, Belgium)	
17:00-19:00	Poster presentations & welcome reception	
19:00	Bus transport	

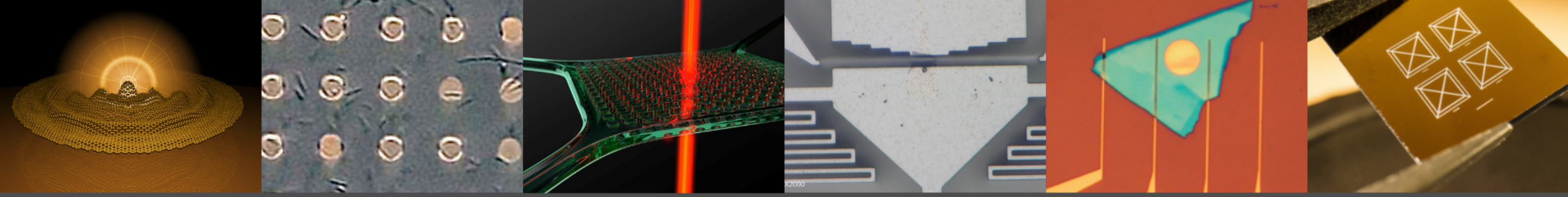


Wednesday June 7, 2023

8:15- 8:30	Welcome coffee	
8:30-8:55	*Ultralow dissipation mechanical resonators for quantum optomechanics* Amirali Arabmoheghi(EPFL, Switzerland)	Chair: Yaroslav Blanter
9:00-9:25	*Nanomechanical qubit and non-linearities* Fabio Pistolesi (Université de Bordeaux, France)	
9:30-9:55	*Coherent feedback cooling of a nanomechanical membrane with atomic spins* Gianluca Schmid (Basel, Switzerland)	
9:55-10:25	Coffee break	
10:25-11:00	*Phonon engineering of TLS defects in superconducting quantum circuits* Oskar Painter (Caltech, USA)	Chair: Albert Schliesser
11:05-11:30	*Optomechanical interactions enriched by excited carriers* Ivan Favero (Université de Paris, France)	
11:35-12:00	*Surface acoustic wave transduction of nanomechanical pillar resonators* Silvan Schmid (TU Wien, Austria)	
12:05-12:25	Sponsor pitches	
12:30- 13:30	Lunch	
13:30-14:05	*Transient time symmetry breaking in driven oscillators* Mark Dykman (Michigan State University, USA)	Chair: Fabio Pistolesi
14:10-14:45	*Phase transitions & exotic states in an array of driven nonlinear quantum oscillators:insights from an exact solution* Aash Clerk (University of Chicago, USA)	
14:45-15:15	Coffee break	
15:15-15:50	*Optomechanical scanning force microscopy with high-Q resonators* Alex Eichler (ETH, Switzerland)	Chair: Ho Bun Chan

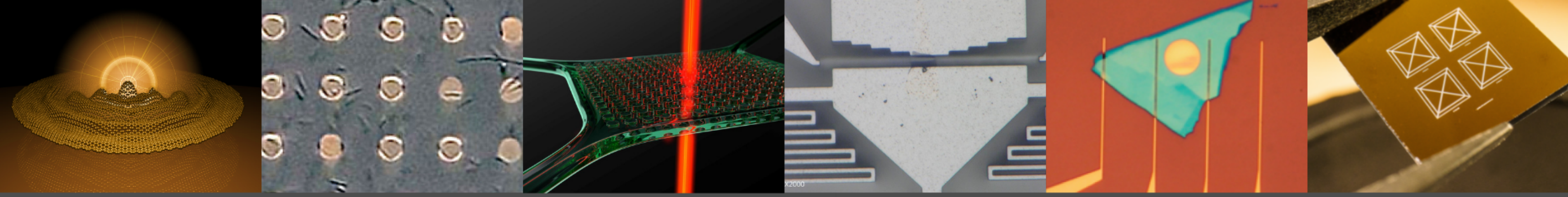


15:55-16:20	*Measuring radiation torque shot noise and full potential control of a levitated nano-dumbbell* Fons van der Laan (AMOLF, Netherlands)	
16:25-16:50	*Nanomechanical resonator frequency measurement and fundamental lower limits of frequency uncertainty* Vladimir Aksyuk (NIST, USA)	
17:00-19:00	Poster presentations & drinks	
19:00	Bus transport	

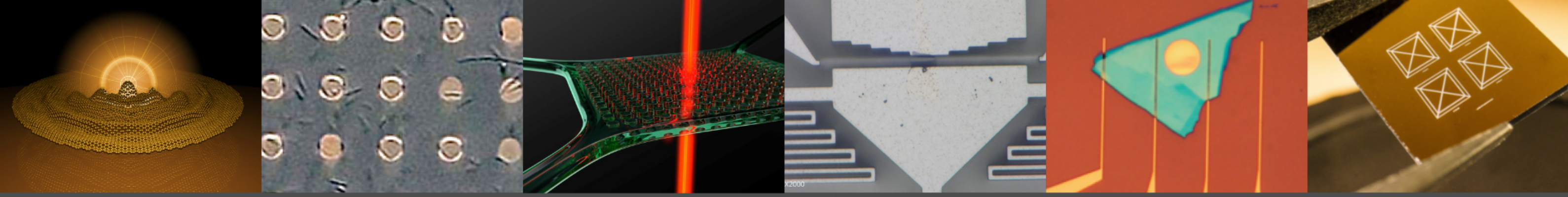


Thursday June 8, 2023

8:15-8:30	Welcome coffee	
8:30-8:55	*Phononic waveguides as coherent phonon sources* Clivia Sotomayor Torres (ICN2, Spain)	Chair: Peter Steeneken
9:00-9:25	*Controlling excitons in strained 2D semiconductors* Kiril Bolotin (Freie University Berlin, Germany)	
9:30-9:55	*Tension tuning of sound and heat transport in graphene* Gerard Verbiest (TUD, Netherlands)	
9:55-10:25	Coffee break	
10:25-11:00	*Controlled dynamics of a levitated nanoparticle in a hybrid optical/RF integrated trapping platform* Romain Quidant (ETH, Switzerland)	Chair: Kamil Ekinci
11:05-11:30	*Kinetic-inductive mechano-electric coupling* David Haviland (KTH, Sweden)	
11:35-12:00	*Cavity optomechanical liquid prober using a twin-microbottle resonator* Motoki Asano (NTT, Japan)	
12:05-12:25	Sponsor pitches	
12:30- 13:30	Lunch	
13:30-14:05	*Period-tripled oscillations in electromechanical resonators* Ho Bun Chan (HKUST, China)	Chair: Adrian Bachtold
14:10-14:45	*Magneto-mechanics and nonlinear dynamics of 2D antiferromagnetic membranes* Makar Šiškins (NUS, Singapore)	
14:45-15:15	Coffee break	
15:15-15:50	*Building nanoscale engines with fully suspended carbon nanotubes* Natalia Ares (University of Oxford, UK)	Chair: Raphael St-Gelais

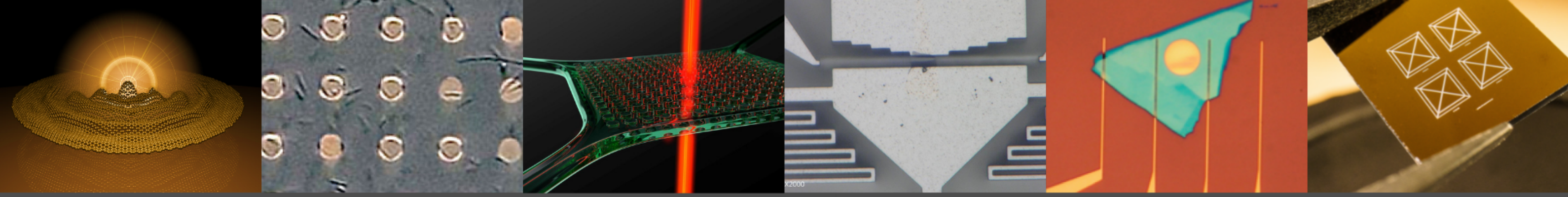


15:55-16:20	*Detection of Brownian motion via a quantum dot coupled to a highly miniaturized mechanical resonator* Clemens Spinnler (Basel, Switzerland)	
17:00	Bus transport from Art Centre to Madurodam	
18-19:30	Madurodam park visit & welcome drinks	
19:30- 21:30	Dinner	
21:30	Bus transport	



Friday June 9, 2023

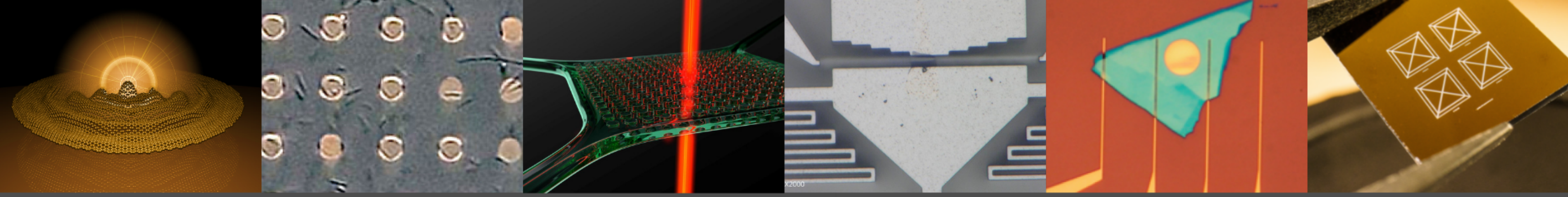
8:45-9:00	Welcome coffee	
9:00-9:25	*Engineering the speedup of quantum tunneling via dissipation* Gianluca Rastelli (University of Trento, Italy)	Chair: Clivia Sotomayor Torres
9:30-9:55	*Thermal fluctuations of a nanomechanical beam resonator in a viscous fluid* Kamil Ekinci (Boston University, USA)	
10-10:30	Coffee break	
10:35-11:00	*Inducing micromechanical motion by optical excitation of a single quantum dot* Pierre Verlot (Université Paris-Saclay, France)	Chair: Hiroshi Yamaguchi
11:05-11:40	*Quantum control of phononic membrane resonators: from milikelvin to room temperature* Albert Schliesser (Copenhagen University, Denmark)	
11:45-12:10	Sponsor pitches	
12:15-13:15	Lunch	
13:15-13:50	*High-Q spiderweb nanomechanics inspired by machine learning* Richard Norte (TUD, Netherlands)	Chair: Robert Blick
13:55-14:20	*Relaxation and dynamics of predisplaced silicon nitride strings* Menno Poot (TUM, Germany)	
14:20-14:50	Coffee break	
14:50-15:15	*Spontaneous parametric down-conversion in MEMS micro mirrors* Peter Degenfeld-Schonburg (Bosch GmbH, Germany)	Chair: Silvan Schmid
15:20-15:55	*Can a single nanomechanical mode generate a frequency comb?* Eva Weig (TUM, Germany)	
16:00-16:30	Closing words & poster awards	Local organisers & FNS committee
17:00	Bus transport	



Invited and contributed talks

Listed in alphabetical order of the presenter’s surname

(*Links available under “Abstracts for invited and contributed talks*”)



Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

NANOMECHANICAL RESONATOR FREQUENCY MEASUREMENT AND FUNDAMENTAL LOWER LIMITS OF FREQUENCY UNCERTAINTY

Mingkang Wang[1,2], Rui Zhang[3], Robert Ilic[1], Yuxiang Liu[3] and Vladimir A. Aksyuk[1*]
[1]Microsystems and Nanotechnology Division, National Institute of Standards and Technology
[2]Institute for Research in Electronics and Applied Physics, University of Maryland
[3]Department of Mechanical Engineering, Worchester Polytechnic Institute

*contact: vladimir.aksyuk@nist.gov

In this work [1], we derive the Cramer-Rao lower bound (CRLB) thermodynamic limit for resonance frequency measurement precision for a classical harmonic oscillator subject to dissipation, thermodynamic noise, detection uncertainty and with or without external excitation. We propose and implement a general statistically efficient frequency estimator and experimentally show frequency uncertainty reaching the CRLB on the cavity-optomechanically detected ≈ 1 pg, ≈ 28 MHz stress-engineered nanomechanical resonator for up to ≈ 0.1 s averaging, both with and without external excitation. We obtain a relative frequency uncertainty below 10^{-6} in a continuous measurement without any external excitation using only the resonator's thermodynamic fluctuations at room temperature, and 10^{-7} uncertainty for a resonator driven open loop without any feedback or stabilization. The stress-engineered nanomechanical resonator with high frequency-Quality factor product ($fQ \approx 10^{12}$) could be used for frequency-readout displacement sensors.

The derived CRLB not only gives the exact prefactor in the Allan deviation at long τ, but exactly describes the small τ behavior, including the transition between the thermodynamically limited $\tau^{-1/2}$ and the instrumental-uncertainty limited $\tau^{-3/2}$ scaling. CRLB is also derived in the continuous quantum regime, accounting for measurement uncertainty and backaction, as well as the arbitrary finite temperature.

Experimental measurement of frequency Allan deviation at room temperature using the optimal estimator agrees with the CRLB without adjustable parameters.

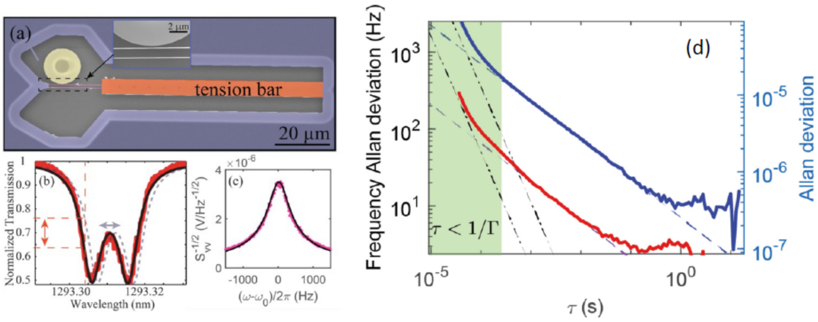
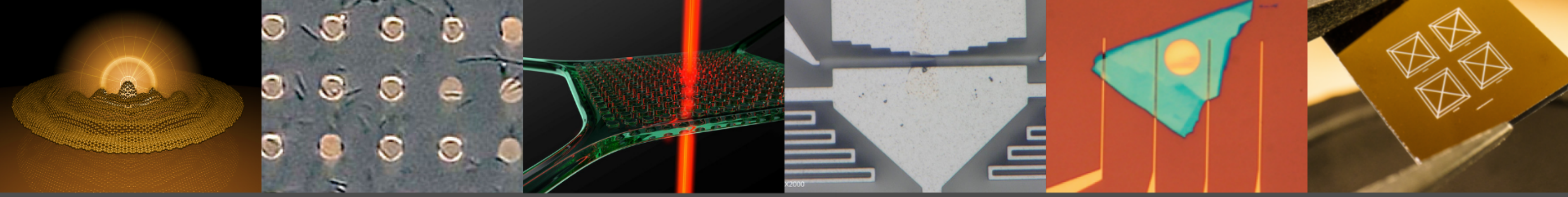


Figure 1: (a) colorized scanning electron micrograph of the tuning fork with tension bar and microdisk optomechanical cavity readout. Inset shows a magnified view. (b) optical resonance seen in the transmission spectrum. (c) mechanical resonance seen in the output signal power spectral density. (d) Measured frequency Allan deviation with (red) and without (blue) application of an external electrostatic drive.

References

[1] Wang, M., Zhang, R., Ilic, R. et al. Fundamental limits and optimal estimation of the resonance frequency of a linear harmonic oscillator. Commun Phys 4, 207 (2021).



Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Ultralow Dissipation Mechanical Resonators for Quantum Optomechanics

Amirali Arabmoheghi[*1,2], **Mohammad J. Bereyhi**[1,2], **Alberto Beccari**[1,2],
Alessio Zicoschi[1,2], **Guanhao Huang**[1,2], **Yi Xia**[1,2], **Tobias J. Kippenberg**[1,2], **Nils J. Engelsen**[*1,2]

[1]Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland
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It has been shown that the flexural modes of high aspect ratio strained structures exhibit enhanced quality factors compared to the loss angle of the material. This phenomenan, dissipation dilution, has been exploited in strings and membranes by reducing the mode curvature at the clamping points (ie. soft-clamping [1]), enabling quality factors approaching 1 billion [2]. In recent works, we have demonstrated novel approaches to soft-clamping in nanomechanical strings. We have shown that fundamental modes of binary-tree-like resonators (Fig. 1A) exhibit quality factors as high as 7.8×10^8 at room temperature due to cascaded branching [3]. We have also shown that in polygon-shaped resonators that are suspended at their vertices (Fig. 1B), a mode localized in their perimeter exhibits soft-clamping while having a compact geometry. The 'perimeter modes' in our best devices reach record Q of 3.6 billion at room temperature - a four times improvement in ten folds smaller devices compared to the state of the art [4]. With a modified polygon resonator, with increased segment width (Fig. 1H), we have measured the thermal force sensitivity of a polygon resonator via efficient optical measurement of thermal motion of its perimeter mode (Fig. 1J). The achieved low value of $1.3\,\mathrm{aN}/\sqrt{\mathrm{Hz}}$ at room temperature shows the great potential of these devices for force sensing and quantum optomechanics applications.

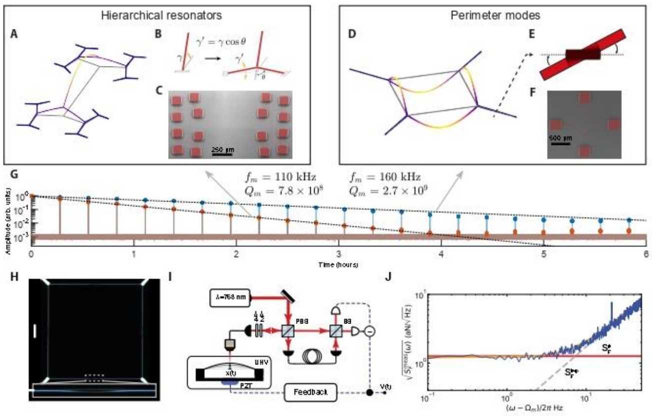

Figure 1: Ultralow dissipation mechanical resonators. A: Mode shape of fundamental mode of a binary tree mechanical resonator. B: Mode gradient transformation over a branch. C: Scanning electron micrograph (SEM) of a binary tree structure. D: Mode shape of a perimeter mode. E: Cross-section of a polygon resonator tether. F: SEM of a polygon resonator. G: Ringdown measurement of mechanical quality factor of a binary tree device (red) and perimeter mode (blue). H: Optical microscope image of a polygon resonator. White scale bar: 100 μm. I: Optical homodyne interferometer used for measurement. J: Measurement of force sensitivity.

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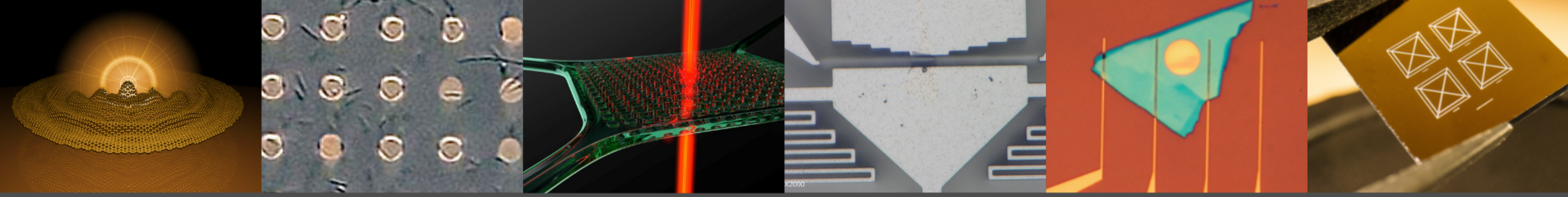

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Building nanoscale engines with fully suspended carbon nanotubes

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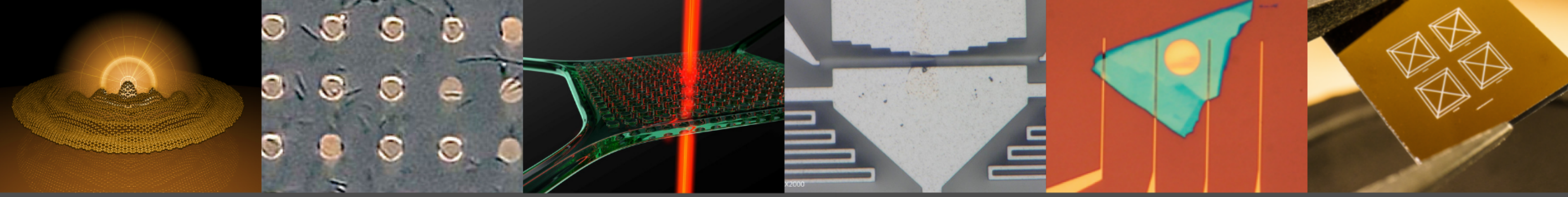
The development of quantum devices that can be controlled with great speed and precision has presented us with the opportunity to probe thermodynamics processes at the nanoscale. Coupling charge or spin states to mechanical motion might allow us to measure the thermodynamic cost of quantum information processing. With fully-suspended carbon nanotube devices, we find that the coupling of electron transport to the nanotube displacement is ultra-strong. We also find that spin orbit interaction couples single spin states to the nanotube's motion. These coupling mechanisms are allowing us to study engines in which the effects of fluctuations and quantum effects play a significant role. I will show an information engine based on charge to motion coupling and I will discuss prospects for realizing single spin engines.



Frontiers of Nanomechanical Systems (FNS) workshop
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Cavity optomechanical liquid prober using a twin-microbottle resonator

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Cavity optomechanics in liquid environment has attracted interests for developing ultrasensitive sensors in biology and rheology [1]. Pioneering works enabled us to operate cavity optomechanical devices with a microdroplet [2] and microfluid [3]. Although these fixed-by-design architectures are suitable to passively interact with liquid portions, it is challenging to actively approach to arbitrary positions in liquid like the scanning probe mechanical cantilever [4]. Here we demonstrate the free-access cavity optomechanical liquid probes using a twin-microbottle resonator (TMBR). The TMBR consists of two microbottle resonators, where high-Q optical whispering gallery modes (WGMs) are individually confined in each bottle, and the mechanical radial breathing modes (RBMs) are mutually coupled between the two bottles [Fig. 1(a)]. By immersing a bottle into liquid with keeping another bottle in air, we observed frequency shift and linewidth broadening in thermal fluctuations of the mechanical RBMs, which originates in the viscoelastic property of liquid [Fig. 1(b)]. Furthermore, tracing frequency fluctuation (i.e., Allan deviation) with phase-locked loop allows us to estimate mass resolution of this prober to be on the order of several pico-gram, comparable to a single bacterium [5] [Fig.1(c)]. This cavity optomechanical liquid prober can be applicable to ultrasensitive *in-situ* metrology as biochips and rheometers. This work was partly supported by JSPS KAKENHI (21H01023).

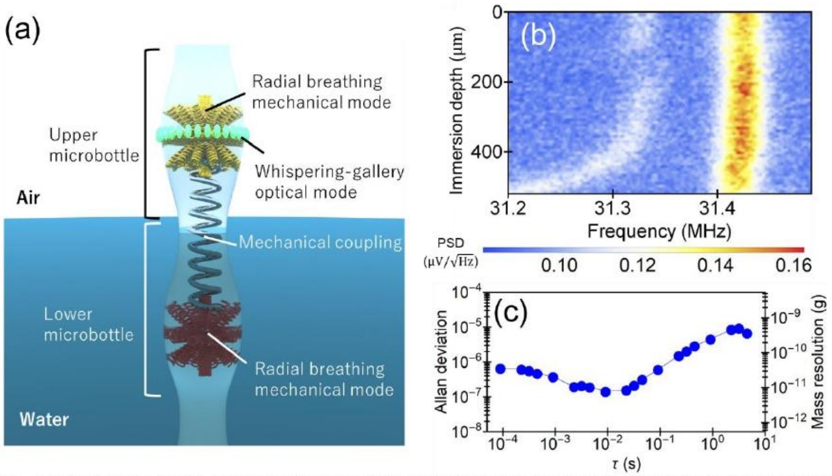

Figure: (a) A schematic of TMBR. (b) Power spectral density (PSD) in thermal fluctuation of coupled mechanical modes with respect to the immersion depth from the initial position of the liquid surface close to the bottom neck of device. (c) Allan deviation and mass resolution with respect to the integration time.

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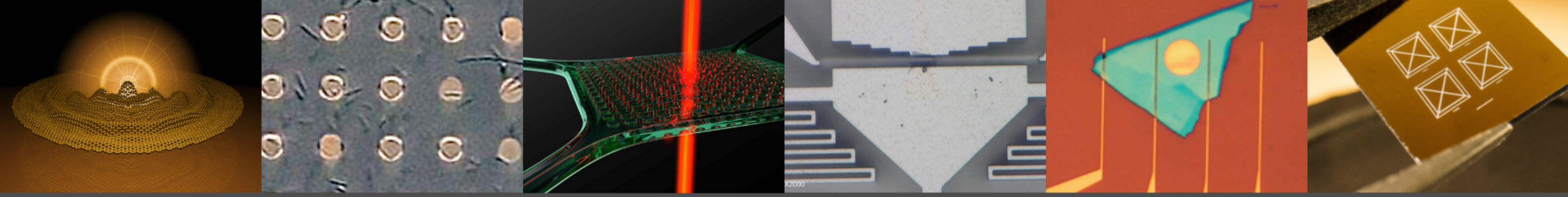

Controlling excitons in strained 2D semiconductors

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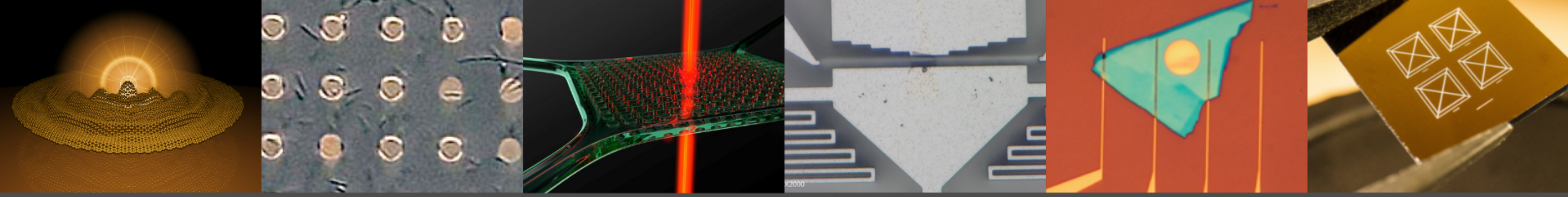
In this talk, I will show that transport, valley properties, lifetimes, and couplings between different types of excitons in 2D semiconductors from the group of transition metal dichalcogenides (TMDs) can be tuned by strain engineering. First, I will discuss strain engineering approaches to control the strain tensor in TMDs in situ at cryogenic temperatures. I will discuss the induction of controlled uniaxial, biaxial, and spatially non-uniform strain distributions. We will use spatially non-uniform strain to transport excitons around and study their interconversion. Next, we will use uniform mechanical strain engineering to demonstrate a new type of excitonic state with unique properties that does not exist in unstrained material. That state results from the hybridization between two ordinarily distinct classes of excitons – "dark" free excitons characterized by very long lifetimes but low oscillator strength and localized excitons featuring high oscillator strength but low density. We use experimental and theoretical tools to prove that the hybridized state combines the advantages of the underlying species making it uniquely suitable, e.g., for storing quantum information. Finally, I will discuss changes in valley lifetime and valley coherence vs. strain in strained TMDs. We will see that coupling between free and localized excitons – which can be controlled via strain – plays a prominent role in defining these properties.



Frontiers of Nanomechanical Systems (FNS) workshop
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Boosting the nonlinearity of mechanical resonators approaching the quantum regime

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An open question in mechanics is whether mechanical resonators can be made nonlinear with vibrations approaching the quantum ground state. This requires engineering a mechanical nonlinearity far beyond what has been realized thus far. In this talk, I will present a mechanism to boost the Duffing nonlinearity by coupling the vibrations of a nanotube resonator to single-electron tunneling and by operating the system in the ultrastrong coupling regime [1]. Remarkably, thermal vibrations become highly nonlinear when lowering the temperature. The average vibration amplitude at the lowest temperature is 13 times the zero-point motion, with approximately 42% of the thermal energy stored in the anharmonic part of the potential. Our work paves the way for realizing mechanical qubits [2] and quantum simulators emulating the electron-phonon coupling [3,4].

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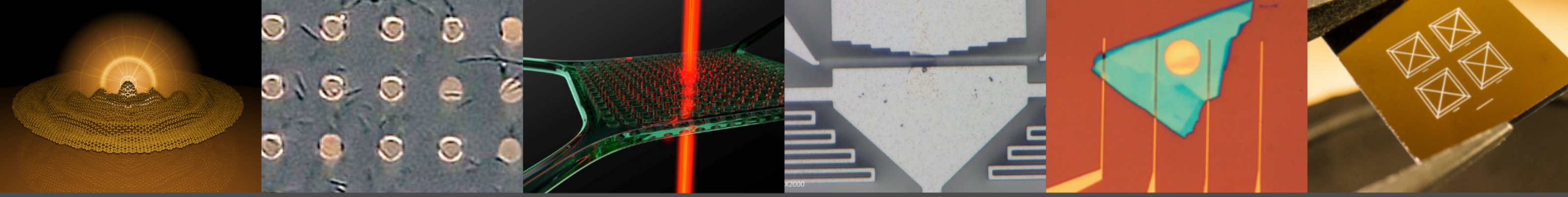

Frontiers of Nanomechanical Systems (FNS) workshop
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Period-tripled oscillations in electromechanical resonators

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We present measurements of the dynamics of an electromechanical resonator with two modes designed to be near 1:3 internal resonance, with periodic driving applied to the upper mode close to its eigenfrequency. With efficient energy transfer between the modes, the lower mode can undergo stable vibrations with period tripled that of the drive [1]. Such oscillations break the time-translation symmetry imposed by the periodic drive. The system settles into one of three stable vibration states with identical amplitudes but phases differing by 2π/3. We show that the zero-amplitude state remains dynamically stable for all driving strengths and frequencies. Excitation of the period-tripled vibrations requires an initial perturbation. We choose to apply the activation using a secondary drive on the lower mode that is subsequently removed.

The system can be induced to controllably switch among the three period-tripled states and the zero amplitude state using secondary drive pulses of different phases. Furthermore, when the higher mode itself becomes bistable due to strong resonant drive or parametric modulations, an additional set of period-triple states emerges in the lower mode. For parametric drive on the higher mode, the vibrations in the lower mode are period-sextupled with respect to the drive. There are 6 coexisting vibration states with identical amplitudes, but phases differing by π/3. Our demonstration of period-tripled vibrations in a resonator at internal resonance open new opportunities in using mechanical resonators in ternary memory and logic as well as in simulations of spin-1 systems.

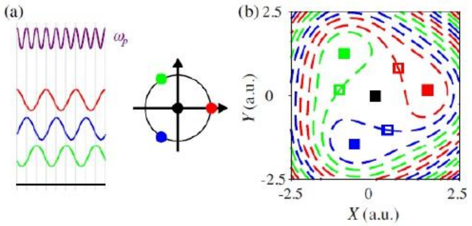

Figure 1. (a) Period tripled oscillations breaks the time translation symmetry imposed by the periodic drive. (b) Separatrices between the basins of attractions. From [1].

This work is supported by the Research Grants Council of Hong Kong SAR (Project No. 16305117).

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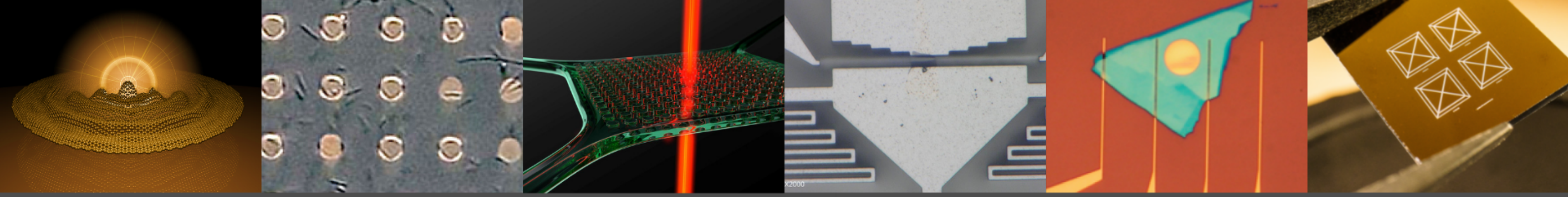

Frontiers of Nanomechanical Systems (FNS) workshop
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Phase transitions & exotic states in an array of driven nonlinear quantum oscillators: insights from an exact solution

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The interplay of parametric driving, interactions and dissipation is of widespread interest in both classical and quantum systems, including recent connections to bosonic quantum information processing. The behaviour of such systems becomes even richer in truly many-body, multi-mode settings. I will describe recent theoretical work [1] studying such a multi-mode system, where an exact analytic description of the quantum problem is possible using a variant of quantum detailed balance (so-called "hidden time reversal symmetry" [2]). The exact solution reveals a wealth of surprising phenomena, from the emergence of dissipative phase transitions, new kinds of symmetry breaking, and the emergence of quantum states with surprisingly strong pairing correlations. The class of systems we study could be realized in nanomechanical resonator platforms, superconducting quantum circuits, and more general quantum optical setups.

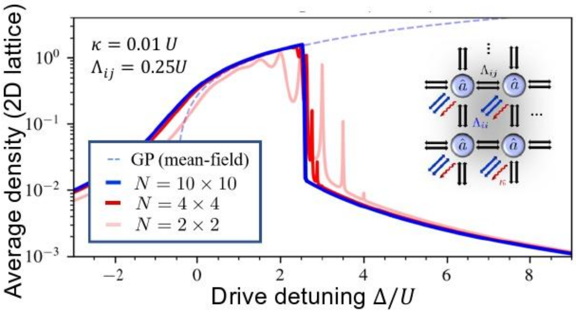

Fig. 1: Emergence of phase transitions from a clustering of discrete resonances in a 2D array of driven oscillators as system size is increased

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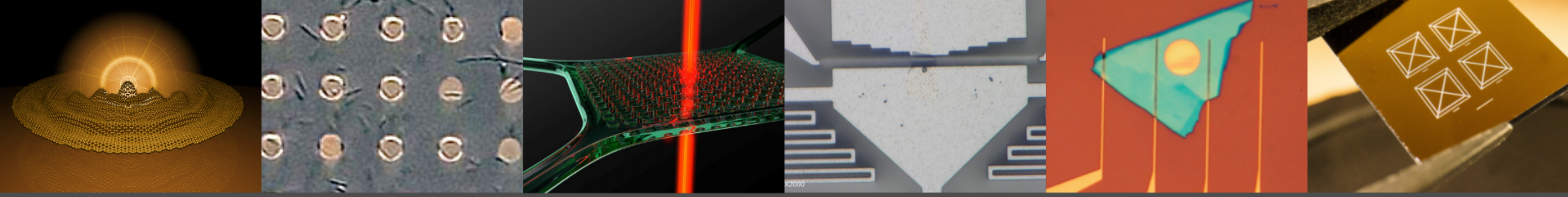

Frontiers of Nanomechanical Systems (FNS) workshop
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In-equilibrium thermodynamics of a mesoscopic mechanical object: towards the quantum ground-state

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Laure Mercier de Lépinay[3], **Mika Sillanpää**[3], **Andrew D. Armour**[4], **Luca Planat**[5], **Martina Esposito**[1],
Arpit Ranadive[1], **Nicolas Roch**[1], **Olivier Bourgeois**[1], **Andrew Fefferman**[1], **Eddy Collin**[*1]

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Today, physicists are able to control mechanical modes within mesoscopic objects down to the quantum level: it is now possible to create mechanical Fock states, to entangle mechanical modes from distinct objects, store quantum information or transfer it. Indeed mechanics *is* quantum, very much like anything else in Nature. All of this is in particular referred to as a new engineering resource for quantum technologies. But there is much more beyond this utilitarian aspect: invoking the original discussions of Braginsky and Caves where a quantum oscillator is thought of as a quantum detector for a classical field (a gravitational wave), it is also a unique sensing capability for quantum fields. The subject of study is then *the baths* to which the mechanical mode is coupled to, tackling topical questions linked e.g. to Material Science or Quantum Gravity [1].

Studying in-equilibrium properties of a quantum mesoscopic mechanical mode is obviously extremely challenging: for objects of reasonable sizes, the fundamental mode resonance frequency lies in the MHz range, which requires sub-milliKelvin brute-force cooling to achieve a thermal population $n_{th} < 1$. We created a microwave optomechanical platform implemented on a nuclear demagnetisation cryostat for this purpose [2]. Recently, we indeed demonstrated that a drumhead aluminum device of about 15 μm diameter can be cooled to its quantum ground state, meaning that *all its mechanical modes* shall satisfy $n_{th} < 1$ [3].

But this result was based on the measurement of mean quantities; much more can be learned from *fluctuations*. We developed a new approach to optomechanics, based on a Traveling Wave Parametric Amplifier (TWPA) that enables to resolve in real-time the energy fluctuations of a mechanical mode. At high temperature (in the classical limit), we obtained both the Power Spectral Density (PSD) and the Probability Distribution Function (PDF) for the first flexure of a beam device. The former is characteristic of an Ornstein-Uhlenbeck process, while the latter is nothing but the Boltzmann exponential law [4].

From these results, we learn that it is in principle possible to reach *single phonon resolution* near the quantum ground state of motion, provided the optomechanical coupling is large enough. This would open up unique new capabilities; experiments are ongoing. Besides, beyond textbook behaviors we also resolved *unexpected signatures* that deserve to be commented. These demonstrate how rich micromechanics, and microwave optomechanics is; the complete description of these quantum platforms is still to be produced.

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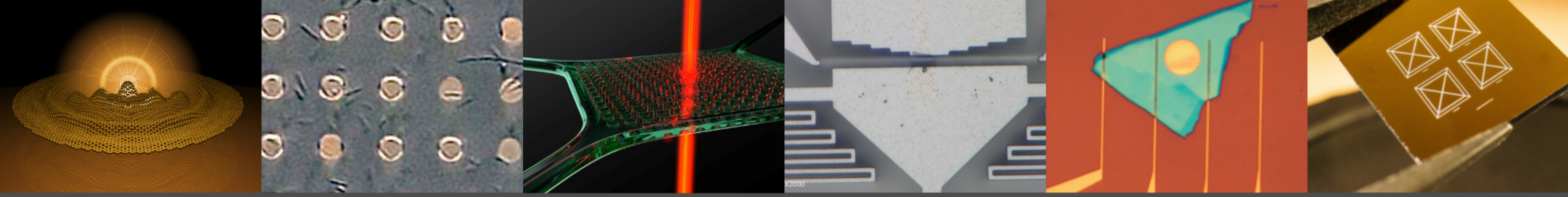

Frontiers of Nanomechanical Systems (FNS) workshop
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Spontaneous parametric down-conversion in MEMS micro mirrors

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The performance requirements for MEMS sensors and actuators, such as scanning micro mirrors, are increasing as emerging applications in the fields of highly automated driving or augmented reality are in increasing demand. During final testing, a device is rejected as soon as it does not fulfill the performance specifications which decreases yield and thus increases the overall cost. In many cases, unexpected device failure or performance issues can be traced back to nonlinear system behavior [1]. This entails the need for system models which take nonlinear sensor dynamics into account and a fundamental understanding of the underlying nonlinear physics is often essential for an improved MEMS design. Here, we present a comprehensive analysis of nonlinear dynamics in scanning MEMS micro mirrors ranging from careful measurements and modeling of nonlinear system behavior on the level of individual chips [2] up to wafer-level testing of several hundred devices [3]. The underlying nonlinear mode-coupling phenomenon, known as spontaneous parametric down-conversion (SPDC) exhibits a sudden transition from mostly linear to nonlinear system behavior. The threshold amplitude or rather critical point only lies within the operational amplitude of a device when a specific frequency resonance condition (a 1:1:1 internal resonance) for the mechanical modes of the device is closely matched. Due to fabrication imperfections of MEMS process technologies small deviations in the geometry between several devices of the same design occur which consequently influences the frequency spectrum of each individual device and therefore decides about the fulfillment of the resonance condition. We demonstrate the benefits that can be achieved by employing the insights gained from single-chip measurements and models to the analysis of a large number of devices on wafer level and suggest a possible path towards successful design iterations. Moreover, above the threshold we show that the micro mirror displays fundamental nonlinear behavior ranging from stationary state bifurcations to limit cycles.

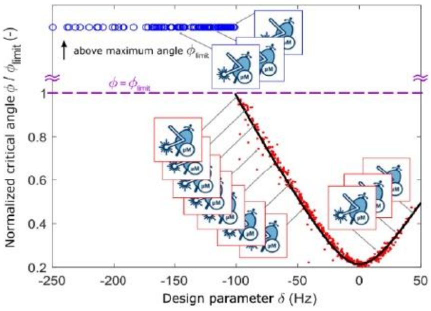

Figure 1: Over 600 measured micro mirror devices matched with the predicted behavior for the critical point of spontaneous parametric

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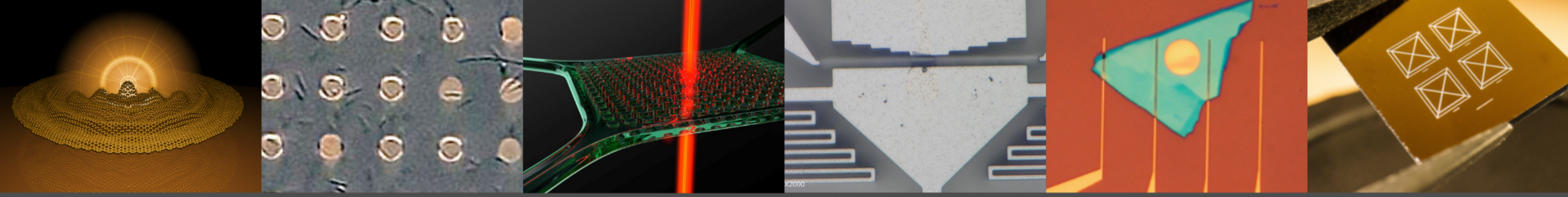

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TRANSIENT TIME SYMMETRY BREAKING IN DRIVEN OSCILLATORS

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A periodically driven system generally is symmetric with respect to translation in time by the drive period. Such discrete time-translation symmetry can be spontaneously broken. We will discuss two different types of the symmetry breaking. One of them is transient. It occurs in a resonantly driven nanoresonator where the state of forced vibrations at the drive frequency loses stability and the resonator starts vibrating in the rotating frame at a frequency, which is generally much smaller than the drive frequency. These vibrations are superposed on the vibrations at the drive frequency leading to a frequency comb, in the laboratory frame, and thus, to the time-symmetry breaking, an effect recently observed in the experiment [1]. We will discuss a mechanism that can lead to such vibrations as well as the broadening of the lines of the frequency comb. This broadening comes from phase diffusion, which ultimately restores the discrete time-translation symmetry. The other example is a system of coupled parametrically driven oscillators. The coupling is weak, it does not lead to new states other than the states of period-2 vibrations of individual oscillators. However, it can affect the rates at which the oscillators switch between these states due to classical or quantum fluctuations. The system maps onto an Ising system. The Ising transition corresponds to a transition into a state with broken time-translation symmetry. The ordered system vibrates at twice the period of the parametric drive. In a finite-size system such broken-symmetry state survives for a finite time. We will concentrate on the situation where the oscillators have slightly different eigenfrequencies. Such disorder breaks the mapping on the conventional Ising model in a nontrivial way that has no analogs in spin systems. The system provides a physical implementation of the so-called asymmetric Ising model. We will consider the dynamics of a disordered system of parametric oscillators, including the onset of a stationary current in the configuration space and the properties of diffusion waves in a one-dimensional oscillator chain.

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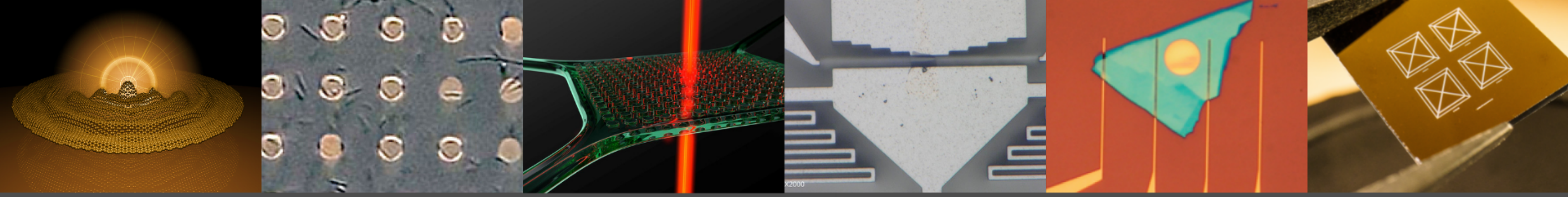

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Optomechanical scanning force microscopy with high-Q resonators

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In this talk, I will review our recent work towards building an ultrasensitive scanning force microscope using an optomechanics silicon nitride membrane [1–6]. We are motivated by the far-future goal of obtaining atomically resolved nanoscale magnetic resonance imaging (NanoMRI) of complex molecules. An instrument that can achieve this goal must combine exceptional sensitivity to magnetic moments, sub-nanometer scanning resolution, and precise control of nuclear spins through nuclear magnetic resonance (NMR) pulses. I will highlight several technical challenges and how we intend to overcome them.

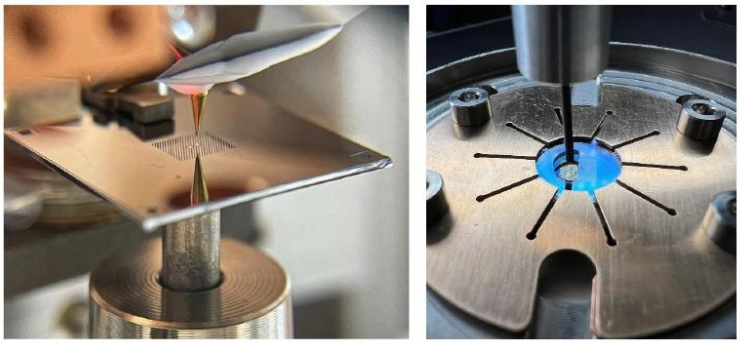

Figure 1: Membrane-based scanning force microscope. Photos by D. Hälg, T. Gisler and S. Misra. .

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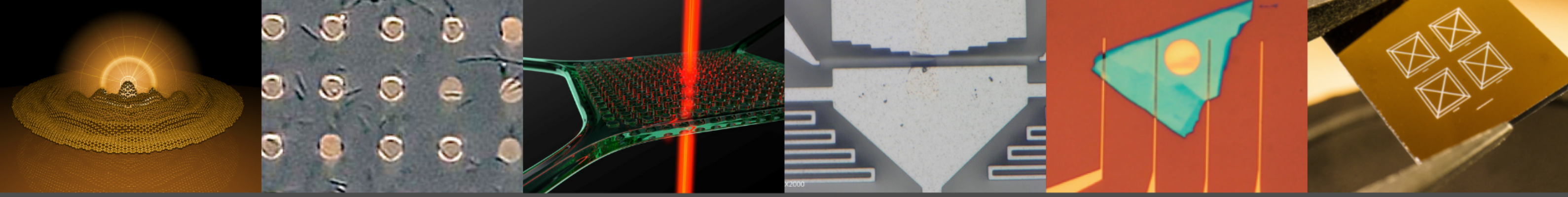

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Thermal Fluctuations of a Nanomechanical Beam Resonator in a Viscous Fluid

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At the turn of the 20^{th} century, electrometers [1] and galvanometers [2], which featured proof masses attached to linear springs, displayed irregular movements around their equilibrium points despite all "precautions and shields." These experiments eventually led to the realization that fundamental physics, namely thermal fluctuations, was responsible for the observations. It also became clear that thermal motion limited the overall precision of a measurement using a mechanical mass-spring system. More than a century later, thermal fluctuations still remains at the center of precision metrology—especially, using nanoelectromechanical systems (NEMS) [3] and AFM microcantilevers. These state-of-the-art miniaturized mechanical systems are even more susceptible to thermal noise than their macroscopic counterparts since they tend to be extremely compliant to forces. Here, we study the thermal Brownian fluctuations of a quintessential nanomechanical system, a doubly-clamped nanomechanical beam, in a viscous fluid. In particular, we rely on experiments and theory to understand the the spatial and spectral distribution of the fluctuations.

On the theoretical side, we first obtain the equation of motion and the mechanical susceptibility of the beam. To this end, we combine Stokes' oscillating cylinder theory [4] with the Euler-Bernoulli beam equation with tension [3]. We then employ the fluctuation-dissipation theorem to determine the position-dependent *power spectral density (PSD)* of the displacement fluctuations of the beam [5]. The end result is a formula for the PSD, expressible as a sum of the PSDs of the individual eigenmodes of the beam.

We compare this theory with experiments on silicon nitride nanomechancial beams with tension. We use optical interferometry to measure the displacement fluctuations of beams with different linear dimensions in air and water. The PSD of the thermal noise in air shows distinct peaks at the eigenfrequencies; integration of the PSD over frequency for each individual peak provides the modal spring constant for each mode. We then use these experimentally-determined spring constants and eigenfrequencies in our analytical expression to predict the PSD of beam fluctuations in water. Using solely experimental parameters, we obtain excellent agreement between the experimental data and the theory. This agreement, up to the twelfth eigenmode in air and seventh eigenmode in water, validates our overarching assumptions: the Brownian force has a colored PSD due to the "memory" of the fluid but is delta-function correlated and mode-independent in space.

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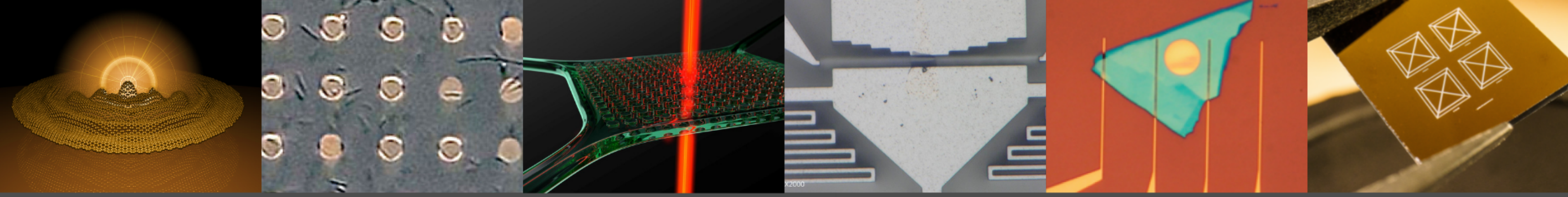

OPTOMECHANICAL INTERACTIONS ENRICHED BY EXCITED CARRIERS

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At optical wavelength far from electronic resonances, vibrating matter possesses an optical refractive index that reflects the dispersive action of bound electrons. This is the picture that prevails for canonical optomechanical interactions in the solid-state.

I will discuss new optomechanical phenomena arising when carriers are in contrast excited in unbound states. Grounded on both experiments and theory, the discussion will address two phenomena:

a) The generation of a mechanical frequency comb stabilized under high optical pumping within a semiconductor resonator [1]
b) The enhancement of optomechanical interactions and nonlinearities when polaritons are formed between a quantum well exciton and whispering gallery modes of a semiconductor disk [2]

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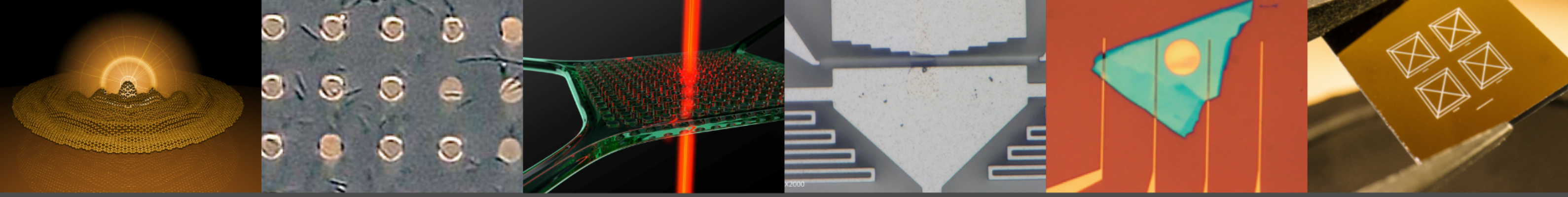

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

TOPOLOGICALLY-IMPOSED VACANCIES AND MOBILE SOLID ^{3}HE ON CARBON NANOTUBE NANOMECHANICAL RESONATOR

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Low dimensional fermionic quantum systems are exceptionally interesting because they reveal distinctive physical phenomena, including among others, topologically protected excitations, edge states, frustration, and fractionalization. Two-dimensional ^{3}He has indeed shown a remarkable variety of phases on top of graphite/graphene lattice. Our aim was to lower the dimension of the ^{3}He system even more by confining it on a suspended carbon nanotube.

In our measurements the mechanical resonance of the nanotube with adsorbed sub-monolayer of ^{3}He was measured as a function of coverage and temperature down to 10 mK. At lowest temperatures and low coverages we have observed a liquid-gas coexistence which transforms to the famous 1/3 commensurate solid phase at intermediate densities. However, at larger monolayer densities we have observed a quantum phase transition from 1/3 solid to a completely new, soft and mobile solid phase, see Fig.1. We interpret this mobile solid phase as 2/5 bosonic commensurate crystal consisting of helium dimers with topologically protected zero-point vacancies which are delocalized at low temperatures. The mobility of the new solid phase at $T < 0.1$ K was attributed to the effect of quantum delocalization of vacancies which can transfer mass. We thus demonstrate that ^{3}He on a nanotube merges both fermionic and bosonic phenomena, with a quantum phase transition between fermionic solid 1/3 phase and a newly observed bosonic dimer solid. On the basis of our results, we infer a possibility of Bose-Einstein condensation of vacancies and supersolidity in the new phase below $T \sim 10$ mK.

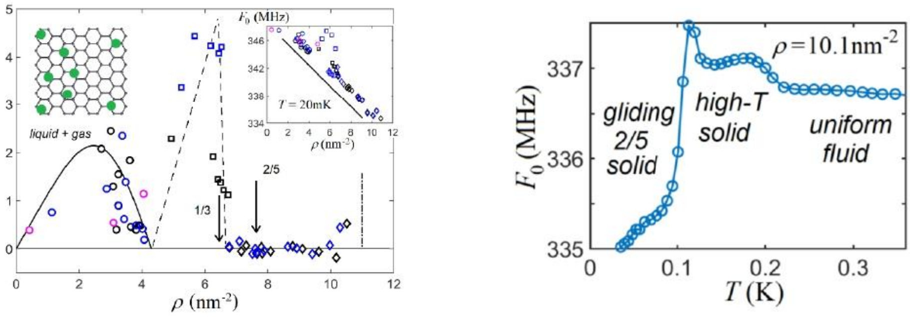

Figure 1: Frequency shift δF_0 of the resonant frequency in the low temperature phases compared to the liquid. Circles: transition from clustered liquid + gas coexistence to a uniform fluid; Squares: melting of the 1/3 solid; Diamonds: difference between gliding solid and fluid. The insert on the right at $T = 20$ mK shows quantum phase transitions from fluid to the 1/3 solid and from the 1/3 solid to the soft gliding solid. (Right) Transition from the gliding solid to the rigid high-T solid manifested by an abrupt increase of the stiffness of the oscillating tube. The second transition from high-T solid to liquid is seen as a drop in the stiffness.

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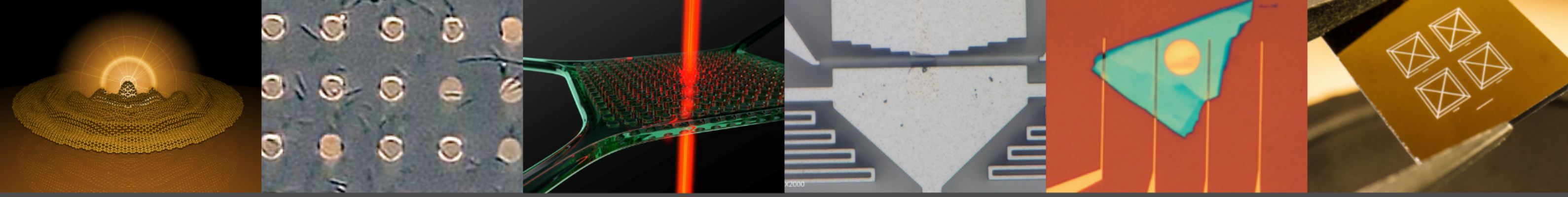

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Kinetic-inductive mechano-electric coupling

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We use the principles of cavity opto-mechanics [1] to realise a resonant mechanical force sensor suitable for low-temperature atomic force microscopy. The sensor is based on a new type of electro-mechanical coupling, dual to electrostatic or capacitive coupling traditionally used in microwave electro-mechanics [2]. Cantilever motion induces surface strain, causing a change in the kinetic inductance of a superconducting nanowire and shifting the resonance frequency of a compact microwave plasma mode with high quality factor. The device is fully co-planar and relatively easy to fabricate, requiring no crossing wires. We show how to transform the cavity impedance for optimal coupling to a transmission line and readout circuit. For the device shown below we estimate the bare Kinetic Inductive Mechano-Electric Coupling (KIMEC) rate $g_0/2\pi \sim$ 3–10 Hz. We also demonstrate phase-sensitive detection of cantilever motion using a multifrequency pumping and measurement scheme.

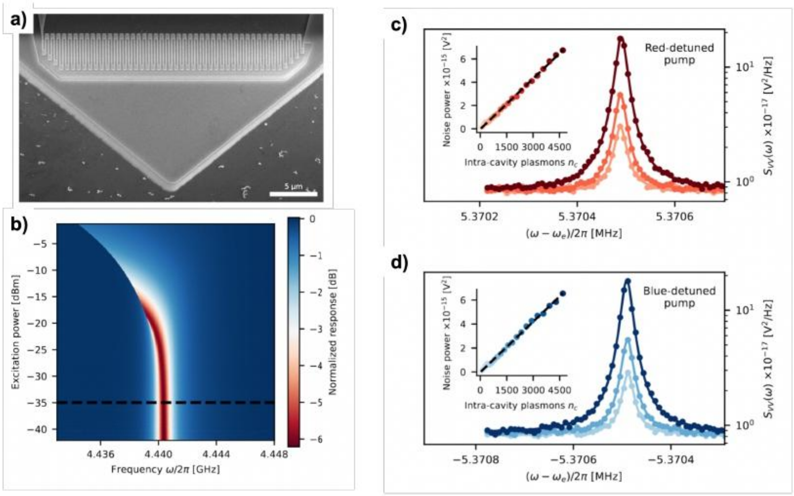

Figure 1: a) Scanning Electron Micrograph of a nanowire of NbTiN, meandering along the clamping line of a triangular cantilever. b) The microwave plasma mode is over-coupled to a transmission line and measured in reflection, showing a small dip in amplitude (see panel b) and full 2π phase flip (not shown). The sharp resonance at $\omega_0/2\pi = 4.4403$ GHz (linewidth $\kappa/2\pi = 1.2193$ MHz) bends toward lower frequency and bifurcates with increasing power, due to nonlinear kinetic inductance caused by current-induced breaking of Cooper pairs. c) and d) The mechanical resonance is excited by a residual white noise force and the motion noise is detected by measuring close to ω_0 while pumping with a detuned pump at $\omega_e = \omega_0 \pm \omega_m$, where $\omega_m/2\pi = 5.3705$ MHz is the resonance frequency of the lowest flexural mode of the cantilever. The measurement reveals the mechanical linewidth $\gamma_m/2\pi = 25$ Hz. The sample in the resolved-sideband regime with $\omega_m > \kappa$.

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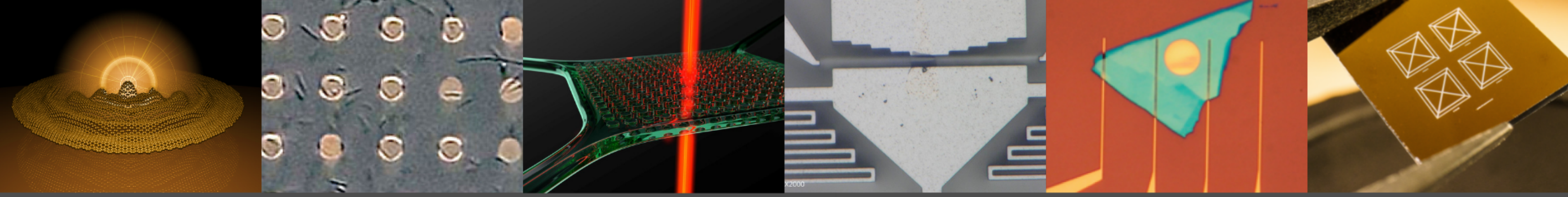

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Cavity acousto-mechanics: A platform for linear and nonlinear dynamics

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This work introduces cavity acousto-mechanical systems whereby a Piezoelectric Micromachined Ultrasonic Transducer (PMUT) generates acoustic waves in a 1-dimensional fluid filled cavity, and the acoustic pressures thus generated exert a backaction on the PMUT membrane, hence coupling the mechanical and acoustic domains. This system exhibits some analogy with the well-known cavity opto-mechanical systems [1] with the main distinction being that the fluid-filled cavity supports acoustic modes rather than optical ones. Further distinctions between the two include the fact that coupling in cavity acousto-mechanical systems can be attributed to both dispersive (acoustic pressure), and dissipative (acoustic radiation) interactions [2].

Unlike bulk acoustic transducers [3], PMUTs enable significant acoustic backaction due to them being mechanically thin and flexible, a schematic of which is shown in Figure 1(a). Consequently, in liquid the resonance peak of the PMUT, as measured via a laser Doppler vibrometer (LDV), is imprinted with the acoustic cavity modes, as shown in Figure 1(b). Cavity acousto-mechanical interactions can then be expressed as:

$$\begin{gathered}\ddot{x}+(\gamma_{Mech})\dot{x}+\omega_M^2(1-\varepsilon V(t))x+\alpha x^3=\sum_j \eta_j p_j+f(t)\\ \ddot{p}_j+(\gamma_{cav,j})\dot{p}+\omega_{cav,j}^2(1-\epsilon x)p_j=\beta\ddot{x}\end{gathered} \tag{1}$$

In air, upon exciting the PMUT with a ~2ω signal, degenerate parametric oscillations are observed, Figure 1(c). However, in liquid, due to the acousto-mechanical interactions and the presence of multiple acoustic cavity peaks, both degenerate and non-degenerate parametric oscillations are observed upon excitation with a ~2ω pump, as shown in Figure 1(c). Thus, cavity acousto-mechanics makes it possible to generate acoustic frequency combs.

In summary, this work introduced the concept of cavity-acousto mechanics whereby PMUTs and acoustic cavities are coupled. Both linear (resonance) and nonlinear (parametric oscillations) responses of the cavity acousto-mechanical system are observed, thus providing a means to generate controllable acoustic frequency combs and acoustic pulses upon the application of a continuous, single frequency, excitation signal.

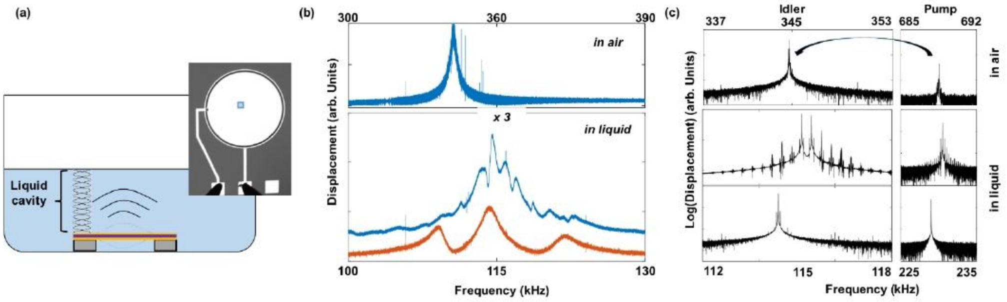

Figure 1: (a) Schematic of fluid filled cavity and acoustic standing wave. A micrograph of the PMUT (inset). (b) Resonance in air (top), and in liquid (bottom) for low (red) and high (blue) liquid levels. (c) Parametric oscillations in air (top) and liquid (center, and bottom). In liquid degenerate (bottom panels) and non-degenerate (middle panels) parametric down-conversion is seen.

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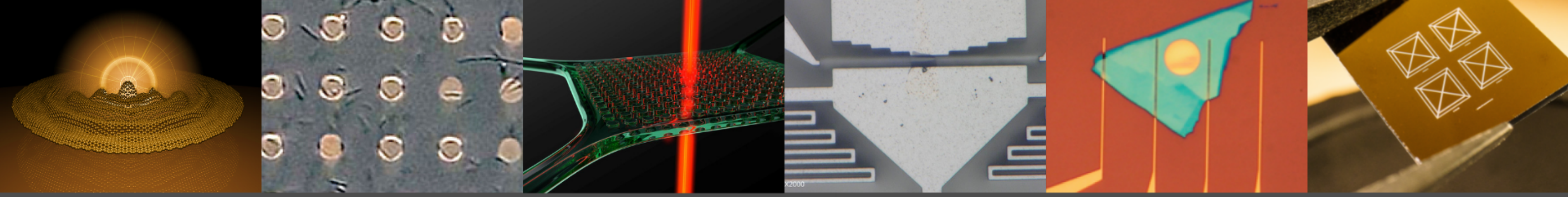

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High-Q Spiderweb Nanomechanics Inspired by Machine Learning

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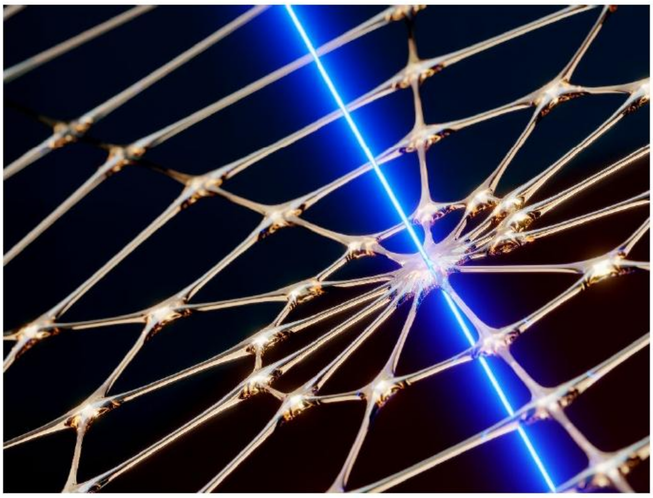
From ultra-sensitive detectors of fundamental forces to quantum sensors and networks, mechanical resonators are enabling next-generation microchip technologies to operate in room temperature environments. Nanoresonators under tensile stress stand as a leading microchip platform in these advances by allowing for mechanical resonators whose motion is remarkably isolated from ambient thermal noise. However, to date, human intuition has dominated as the main driving force behind design processes. Recently machine learning algorithms have begun to challenge traditional forms of creativity from art to writing in ways that would have seemed out of reach a few years ago. Here we experimentally show that these capabilities extend into the realm of microchip designs. Inspired by nature and guided by machine learning, a spiderweb nanomechanical resonator is developed that exhibits vibration modes which are isolated from ambient thermal environments via a novel "torsional soft-clamping" mechanism discovered by the data-driven optimization algorithm. This bio-inspired resonator is then fabricated; experimentally confirming a new paradigm in mechanics with quality factors above a billion in room temperature environments. In contrast to other state-of-the-art resonators, this milestone is achieved with a compact design which does not require sub-micron lithographic features or complex phononic bandgaps, making it significantly easier and cheaper to manufacture at large scales. Here we demonstrate the ability of machine learning to work in tandem with human intuition to augment creative possibilities and uncover new strategies in computing and nanotechnology.



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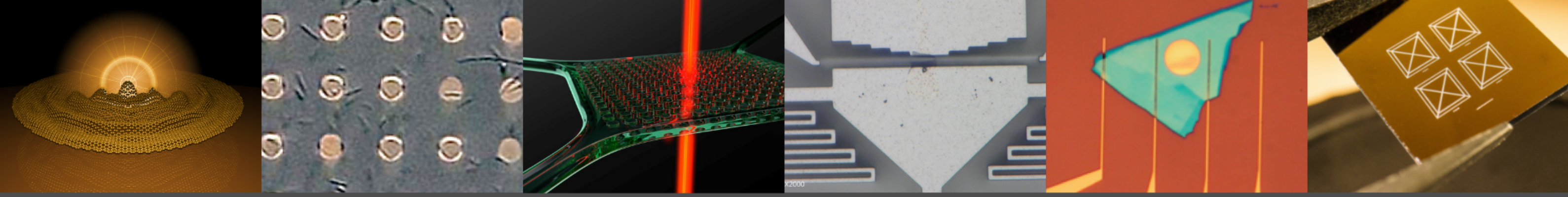

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Phonon engineering of TLS defects in superconducting quantum circuits

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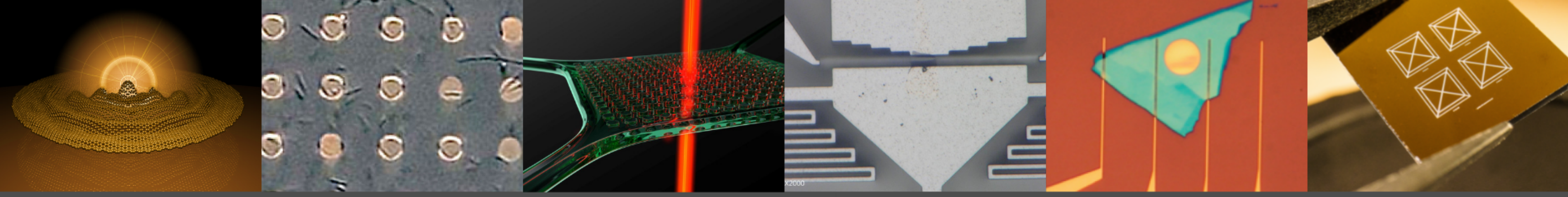
Material defects are ubiquitous. Seven decades ago, defects challenged the new-born semiconductor industry, and today they are one of the major roadblocks for quantum technologies. Solid-state quantum devices, in particular, superconducting qubits, stand out as one of the leading platforms for fault-tolerant quantum computing. However, the performance of superconducting qubits is limited by the presence of various microscopic forms of two-level state (TLS) defects in the amorphous surfaces of the materials that make up the qubits. Previous attempts to address this issue mostly focused on circuit designs that reduced the negative impact of TLS. In this talk, I will introduce an orthogonal approach that engineers the primary phonon bath of the TLS, and in doing so, turns the TLS into a coherent, useful quantum resource in the toolbox of superconducting quantum circuits. First, I will introduce a hybrid platform which utilizes acoustic bandgap metamaterials to structure the phonon modes in the vicinity of the Josephson junction of a transmon qubit, and show experimental results on significantly enhanced TLS lifetime for those TLS within the junction and resonant within the acoustic bandgap of the metamaterial. Next, I will discuss quantum sensing of individual low-frequency TLS fluctuators in this hybrid platform, using the long-lived TLS as a probe to gain further insights into the defect physics.



Frontiers of Nanomechanical Systems (FNS) workshop
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Nanomechanical qubit and non-linearities

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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. 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 describling the recent observation of this phenomenon [3].

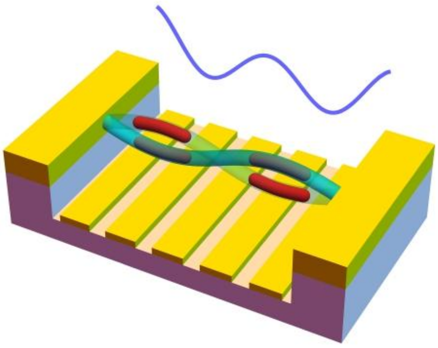

Figure 1: A schematic of the system considered, a suspended carbon nanotube with embedded two quantum dots. In the background it is shown the electrostatic potential generated by the five electrodes and localizing the electrons on the two dots.

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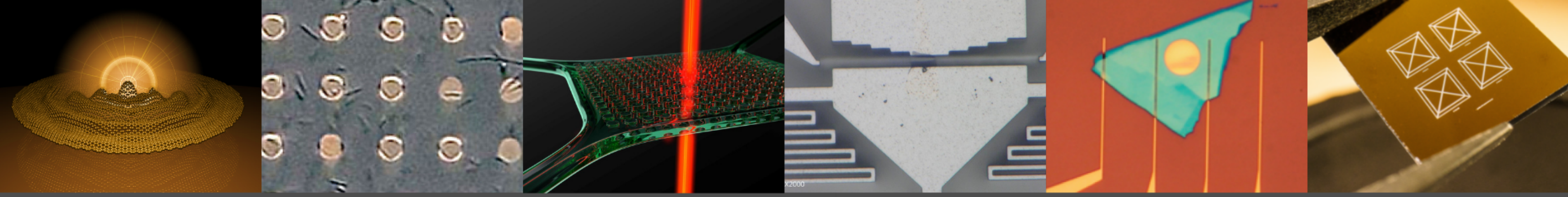

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Relaxation and dynamics of predisplaced silicon nitride strings

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Silicon nitride (SiN) is an ideal material for optomechanics, as its high stress enables mechanical resonators with very high quality factors. Typically, the film stress can only be changed via the deposition process, making a systematic study of the stress dependence of e.g. the damping very challenging. We show that we can control the stress in micromechanical SiN strings geometrically [1]. Our "S-beams" are designed with a predisplacement in a double S-shape and thus initially longer than the distance between the two clamping points. Upon release, they straighten and partially relax their stress; how much depends on the design. This relaxation is studied by performing electron microscopy before and after release (b) and we find that the straightening matches well with finite-element simulations. However, for a deeper understanding of the statics and dynamics of predisplaced resonators, an analytical model is developed [2]. Expressions for the bending and tension energy are derived, which are functionals of the displacement profile $u(x)$. From these, a modified version of the Euler-Bernoulli equation is obtained. After projection onto a cosine modeshape, the mechanics is described by two variables only. This way, the energy can be visualized as a potential landscape (a); its shape determines e.g. the final relaxed displacement and the resonance frequencies. A number of experimental findings can be explained with our analytical model. For example, it is found that, although no out-of-plane displacements are involved, many of these are intimately related to buckling.

Experimentally, the driven responses of a large number of resonators are sensed with on-chip Mach-Zehnder interferometers. This way, the stress dependence of the eigenfrequencies (c) and quality factors (d) are obtained. A strong shift of the resonance frequency on the initial displacement and length is observed. Still, for a large range of parameters, the predisplaced resonators act as strings with a - now geometrically tunable - tension (c). The quality factors change strongly with tension and it is found that the damping rate is a better metric. Its stress dependence is captured by a semi-analytical model, that builds on previous work where the curvature sets the dissipation. Initial measurements hint that the internal damping is different for the in- and out-of-plane modes (d), providing important clues for the understanding of dissipation in SiN. Finally, the influence of different predisplacement shapes (c) and further applications of the geometric tuning method are discussed. Thus, our devices not only provide valuable insight in the role of stress in the damping of SiN resonators, but also add geometrically-tunable stress as a new degree of freedom for optomechanics and beyond.

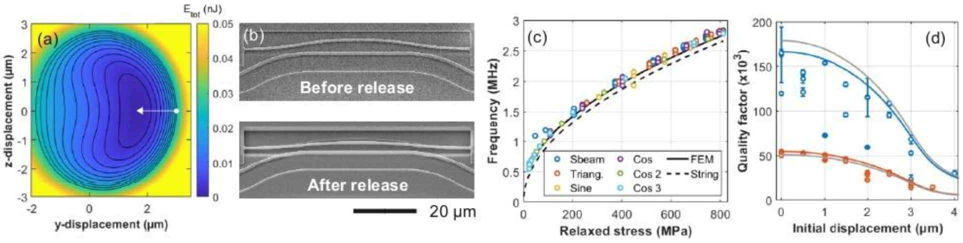

Figure 1: (a) Calculated energy landscape (b) SEM micrographs (c) resonance frequencies and (d) quality factor of predisplaced SiN strings. The colored lines fit the data better than the gray ones, indicating that the in- (orange) and out-of-plane modes (blue) require different internal quality factors.

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CONTROLLED DYNAMICS OF A LEVITATED NANOPARTICLE IN A HYBRID OPTICAL / RF INTEGRATED TRAPPING PLATFORM

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The study and control of levitated nano- and micro-objects has gained considerable attention over the last decade owing to its potential to advance both fundamental science and technology. While early levitation experiments made use of optical potentials and weakly absorbing dielectric polarizable particles, the toolbox expanded in recent years to include techniques borrowed from the atom-trapping community. The development of electrostatic and magnetic levitation made it possible to overcome excessive photoheating of the trapped specimen and extended levitation to a broader range of particles, including particles with internal degrees of freedom. Furthermore, on-chip integration has been identified as key to interface levitodynamics with other existing technologies, to increase platform robustness, and to devise autonomous and portable sensors.

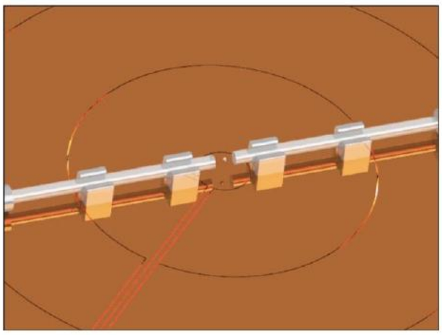

Figure 1: Artistic representation of an integrated levitation platform interfacing plan RF electrodes with optical trapping and readout.

In this presentation we discuss our most recent advances in the development of integrated hybrid levitation platforms combining RF planar electrodes with integrated photonics. We focus on two different experiments. The first one explores the potential of levitated microparticles for inertial sensing. The second experiment focuses on free-fall dynamics in a dark double-well potential.

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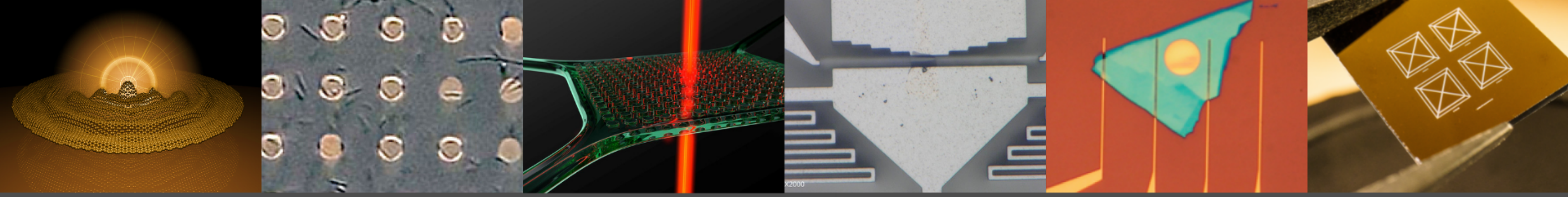

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Engineering the speedup of quantum tunneling via dissipation

Dominik Maile[1], **Joachim Ankerhold**[1], **Sabine Andergassen**[2], **Wolfgang Belzig**[3], **Gianluca Rastelli***[4]

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It is common sense that when a quantum coherent system is not perfectly isolated from the environment, quantum effects are destroyed and the system fundamentally follows the classical mechanics' rules. This is not always the case. Indeed, the dissipative interaction, namely the interaction between a quantum system and its external bath, can lead to an *enhancement* of quantum effects.

We show that such a situation can occur when a particle in a metastable potential, see Fig. 1a, is coupled to a dissipative bath via its momentum. We find that the escape rate is exponentially enhanced [1]. Remarkably, even in the presence of "standard" position dissipation, momentum dissipation can enhance exponentially the escape rate in a large range of the parameter space. When both dissipative interactions are present, the rate exhibits a nonmonotonic behavior as a function of the dissipative coupling strengths, see Fig. 1b.

This theoretical model can be realized in a superconducting Josephson circuit with an extremely simple scheme to achieve the suitable dissipation that plays the desired game, see Fig. 1c. In our proposal [2], we show that the engineered electromagnetic environment formed by the external impedances and coupled to a current bias Josephson junction can enhance the quantum tunneling of the superconducting phase from a metastable state. This environmentally assisted quantum tunneling can therefore speed up the relaxation dynamics of the phase towards the absolute energy minimum.

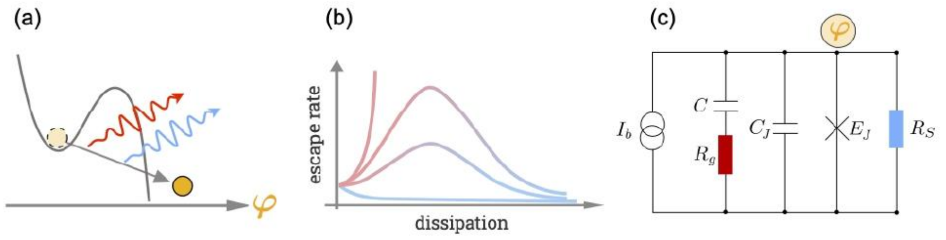

Figure 1

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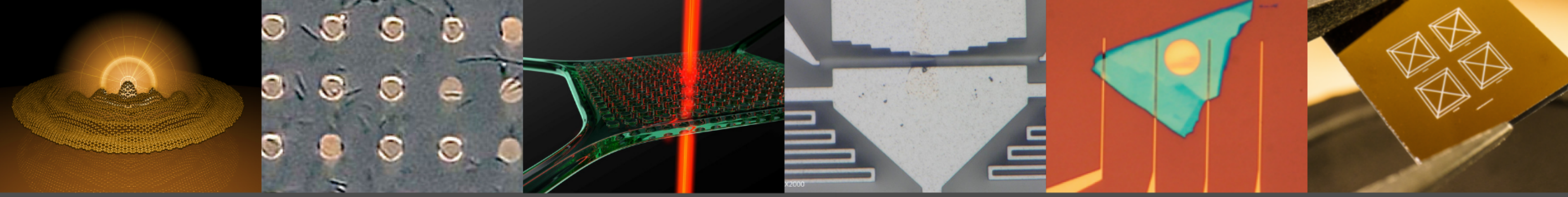

Frontiers of Nanomechanical Systems (FNS) workshop
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Nonlinear dynamics and fluctuations in micronscale membrane resonators

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Micronscale siliconnitride membane resonators operated in the nonlinear regime, far beyond the Duffng regime, exhibit unusual dynamic behavior, including localized overtones of spatial modulation [1], parametric flexural mode coupling and persistent response [2]. Membrane resonators are ideal model systems to investigate these nonlinear dynamics, since information detected in the time domain as well as spatial information can be obtained optically or using an inductive method [3].

In this talk we will also report about a novel method based on low-frequency modulation to characterize the noise squeezing arising from the nonlinearity. We demonstrate an antiresonance effect between the “quasi modes” of the nonlinear mechanical system in the sideband spectra and show that the antiresonance frequency is directly connected to the noise squeezing factor of the system, establishing hence a simple and robust method for its determination [3].

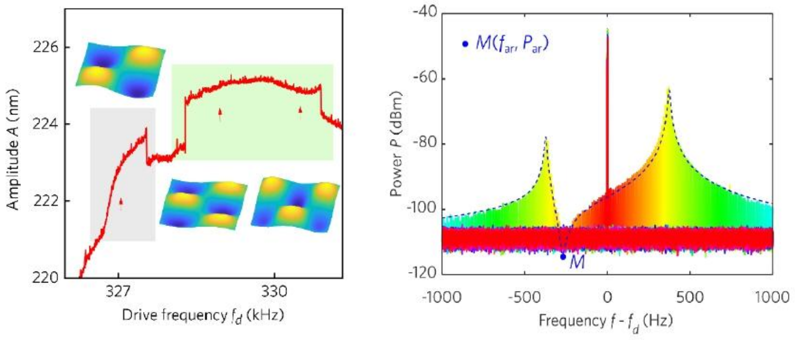

Figure 1: Left: Averaged amplitude of a rectangular membrane (thickness ~ 340 nm) obtained from imaging optical profilometry in the persistent response regime, where several flexural modes are superimposed to the ground mode (here: linear eigenfrequency f_0 = 322 kHz). The insets show examples of mode patterns captured at the frequencies indicated by arrows (adapted from [2]). Right: Power spectrum of sidebands when using very low frequency modulation as a function of the detuning, showing an antiresonance at *M*. From [3].

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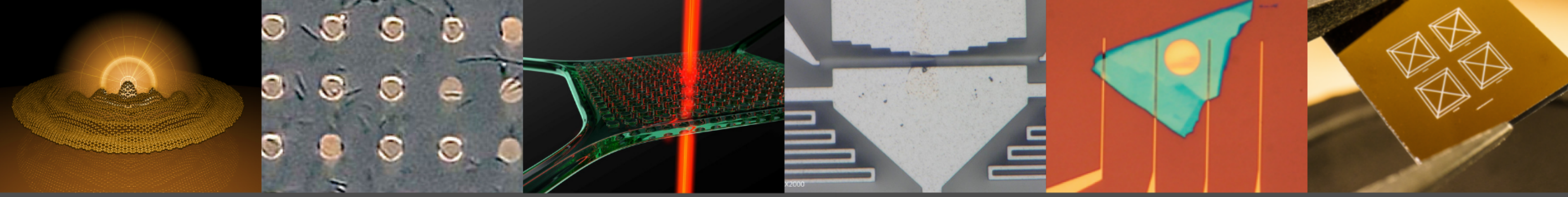

Frontiers of Nanomechanical Systems (FNS) workshop
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QUANTUM CONTROL OF PHONONIC MEMBRANE RESONATORS: FROM MILLIKELVIN TO ROOM TEMPERATURE

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Nanomechanical membrane resonators under high tensile stress realize very high quality (Q-)factors due to dissipation dilution. Soft-clamping techniques can boost this effect beyond $Q>10^9$, e.g. through phononic crystal patterns which minimize resonator bending under oscillation [1]. We plan deploy such resonators in a range of quantum sensing and transduction applications [2]. This requires the ability to control the quantum state of such a resonator mode.

In a first approach, termed coherent control, we couple the motion of the membrane to another quantum degree of freedom, specifically a supercurrent in a microwave resonator. The excitations of the microwave resonator are frozen out at the milliKelvin operation temperature. Driving the system with a coherent microwave tone then allows the mechanical system to effectively dissipate into a low-entropy microwave bath. Such electromechanical sideband cooling allows us reach the quantum ground state of motion [3]. This is enabled, not least, by the remarkable coherence of the mechanical system, with heating rates below 10 phonons/sec.

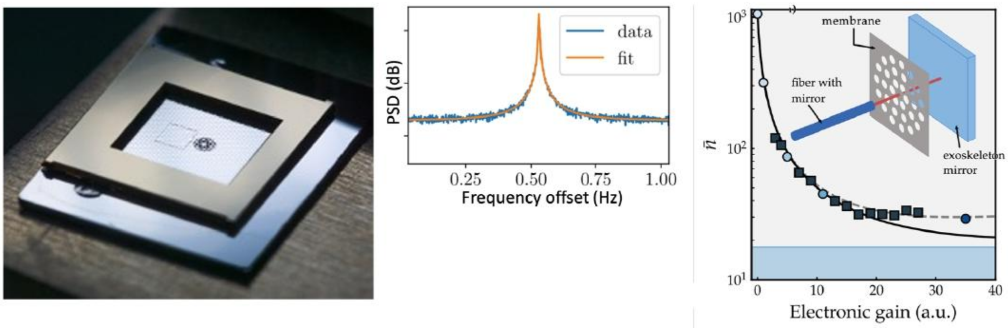

Figure 1: Left: phononic membrane inside a its silicon frame, atop a second chip with a superconducting loop.
Middle: Measured resonance peak around 1.49 MHz, of mHz-level width at mK-temperatures.
Right: Mechanical phonon occupation under feedback cooling from room temperature (inset shows the setup)

In a second approach, known as measurement-based quantum control, we take a continuous measurement of the mechanical position, which is both strong (yields high precision in short time) and efficient (no excess backaction). Then we feed back a force conditioned on the measurement record to force the system into its quantum ground state [4]. Recently, we have applied the same techniques to a mechanical resonator held at room temperature [5].

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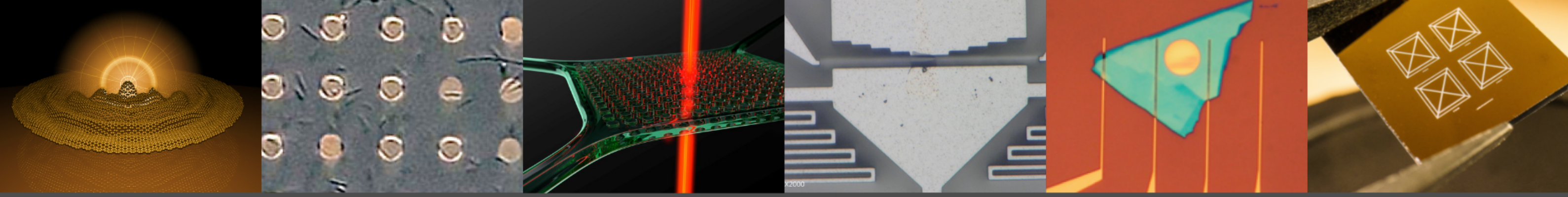

Frontiers of Nanomechanical Systems (FNS) workshop
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Surface acoustic wave transduction of nanomechanical pillar resonators

Hendrik Kähler[1], **Holger Arthaber**[2], **Robert Winkler**[3], **Robert G. West**[1], **Ioan Ignat**[1], **Harald Plank**[3], **Silvan Schmid**[*1]

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One of the challenges of nanoelectromechanical systems (NEMS) is the effective transduction of the tiny resonators. Vertical structures, such as nanomechanical pillar resonators, which are exploited in a wide range of fields, such as optomechanics, acoustic metamaterials, and nanomechanical sensing, are particularly challenging to transduce. Existing electromechanical transduction methods are ill-suited as they complicate the pillars' fabrication process, put constraints on the pillars' material, and do not enable a transduction of freestanding pillars. Here, we present an electromechanical transduction method for nanomechanical pillar resonators based on Rayleigh scattering of surface acoustic waves (SAWs), see Fig. 1 [1]. We demonstrate the transduction of freestanding nanomechanical platinum-carbon pillars in the first-order bending and compression mode (Fig. 2). Since the principle of the transduction method is based on resonant scattering of a SAW by a nanomechanical resonator, our transduction method is independent of the pillar's material and not limited to pillar-shaped geometries. It represents a general method to transduce vertical mechanical resonators with nanoscale lateral dimensions.

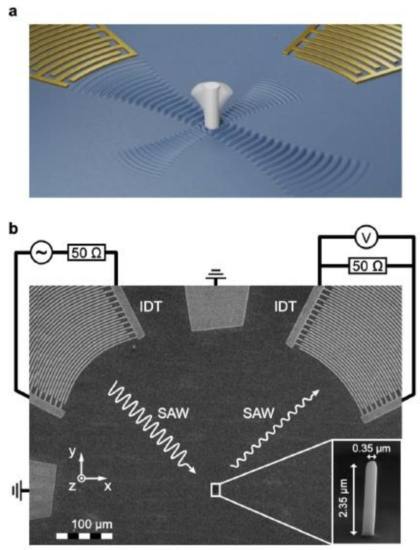

Figure 1: Surface acoustic wave (SAW) transduction scheme. **a** One interdigital transducers (IDT) emits a SAW to drive the pillar resonator in the center. The other IDT detects the motion of the pillar by measuring the SAW scattered by the pillar resonator at resonance. **b** Scanning electron microscope image of a device.

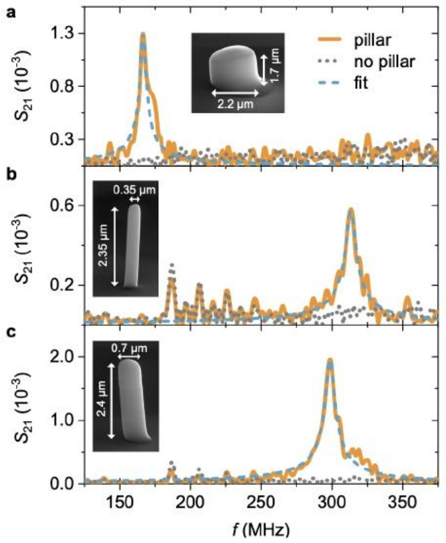

Figure 2: Frequency response of pillar resonators transduced by surface acoustic waves (SAW). The pillars emit SAWs themselves around their resonances which result in an increased scattering parameter S_{21}. The widest pillar (**a**) vibrates in the first-order bending mode and the thinner pillars (**b**,**c**) in the first-order compression mode.

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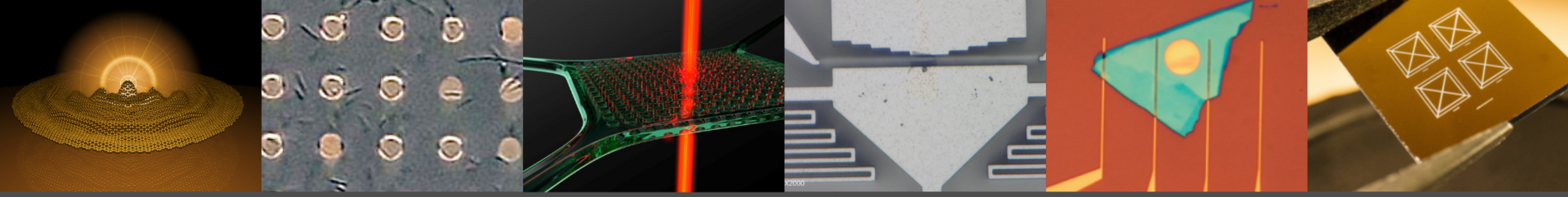

Frontiers of Nanomechanical Systems (FNS) workshop
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Coherent Feedback Cooling of a Nanomechanical Membrane with Atomic Spins

Gian-Luca Schmid[*1,2], **Chun Tat Ngai**[1], **Maryse Ernzer**[1], **Manel Bosch Aguilera**[1], **Thomas M. Karg**[1,2], **Philipp Treutlein**[1,2]
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Coherent feedback stabilises a system towards a target state without the need of a measurement, thus avoiding the quantum backaction inherent to measurements. In certain tasks such as cooling of resonators, coherent feedback can outperform measurement-based feedback. In our experiment, we employ coherent feedback (see Fig. 1) to remotely cool a nanomechanical membrane oscillator using the collective spin of an atomic ensemble as controller [1]. The interaction between the two system is mediated by light [2]. To enhance the cooling performance, we make use of the versatile quantum toolbox which exists for ground state cooling and quantum control of atomic spins. Direct manipulation of the spins allows us to tune the spin-membrane interaction from strong coupling to an overdamped regime (Fig. 2). We perform spin-membrane state swaps combined with stroboscopic spin pumping to cool the membrane in a room-temperature environment to 216 mK in 200 µs. We observe and study the effect of feedback delay, inherent to the macroscopic distance between system and controller, on the cooling performance.

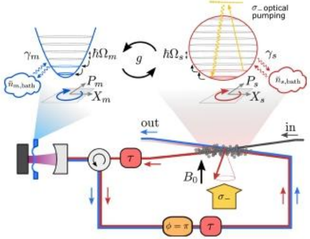

Figure 1: Sketch of the feedback loop: The light passes first the spin, then the membrane then the spin again. On the path back to the spin, the phase of the light is shifted, such that the second interaction with the spin is the time-reverse of the first one.

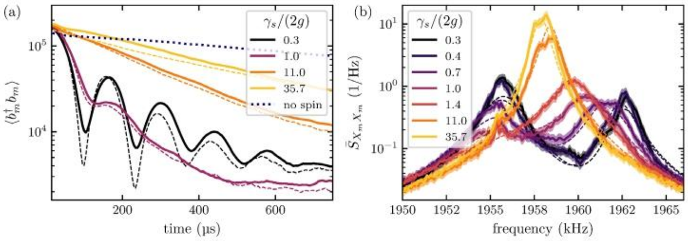

Figure 2: Membrane photon occupation (a) and spectrum of the membrane coupled to the spin (b). The different curves show the state of the membrane for different spin linewidth. For spin linewidth smaller than the coupling *g* between spin and membrane, we see energy exchange oscillations (a) and a normal mode splitting (b). If the linewidth of the spin is increased, the energy exchange oscillations are dampened and we reach the limit of Fermi's golden rule where the spin acts as broad reservoir.

Starting from a cryogenically pre-cooled membrane, this method would enable cooling of the mechanical oscillator close to its quantum mechanical ground state. Furthermore, our approach to engineer coherent long-distance interactions with light [2] makes it possible to couple physically very different systems in a modular way, opening a range of new opportunities for quantum feedback control in hybrid quantum networks [3]. The coherent feedback on the macroscopic membrane paves the way towards more elaborate quantum protocols such as the generation of non-classical states via state swaps [4] as well as further studies of coherent feedback in the quantum regime.

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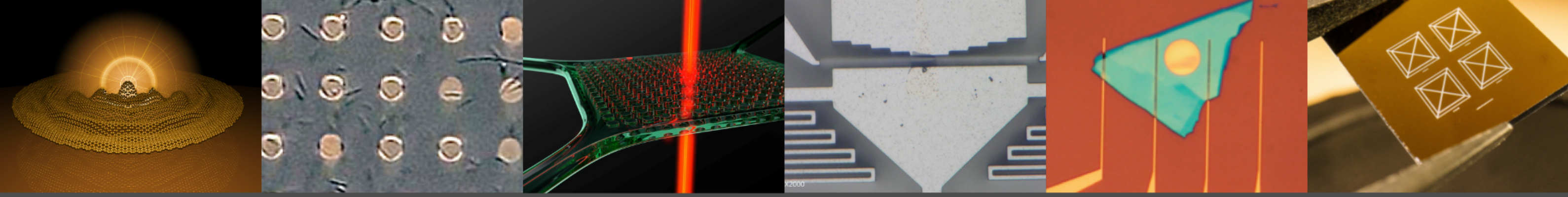

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Magneto-mechanics and nonlinear dynamics of 2D antiferromagnetic membranes

Makars Šiškins,[1]* **Ata Keşkekler**,[2] **Maurits J. A. Houmes**,[3] **Timofey M. Savilov**,[1] **Gabriele Baglioni**,[3] **Samuel Mañas-Valero**,[4] **Eugenio Coronado**,[4] **Konstantin S. Novoselov**,[1] **Yaroslav M. Blanter**,[3] **Herre S. J. van der Zant**,[3] **Peter G. Steeneken**,[2, 3] **and Farbod Alijani**[2]

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Nanomechanical systems made of two-dimensional (2D) crystals are promising to address challenges in creating better sensors, smaller electronic and mechanical devices due to their atomic thickness [1][2]. In many of these devices, 2D materials that undergo a phase change, like 2D magnets, are of interest. However, coupling of magnetic effects in 2D materials to mechanical degrees of freedom, for instance via magnetostriction, remains elusive.

Here, we investigate 2D material membranes with magnetic phase transitions using their nanomechanical motion. We explain the fabrication of ultrathin 2D material membranes and techniques used to probe their motion. We then discuss their notable mechanical properties and show that magnetic phases can be studied by looking at the resonant motion of these membranes [3]. Finally, we theoretically substantiate the correlation between the motion of these membranes and the magnetic ordering at the phase transition temperature, and experimentally verify it for 2D layered antiferromagnets and their heterostructures. This magneto-mechanical coupling allows to modify magnetic properties of these membranes through strain, and vice versa - to affect dynamics of their motion with a change of magnetization. We then look at more complex effects in their nanomechanical motion by driving the 2D material membranes from linear to nonlinear regimes, observing anomalies in both linear and nonlinear stiffness experimentally near the phase transition.

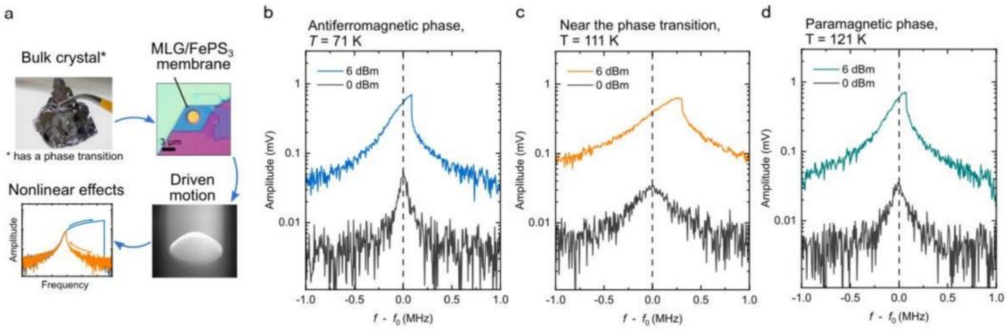

Figure 1: Right panel: (a) Schematic diagram of the experimental workflow. Left panel: Linear and nonlinear resonance peaks of the magnetic membrane at a temperature T, corresponding to (b) antiferromagnetic phase, (c) the phase transition and (d) paramagnetic phase.

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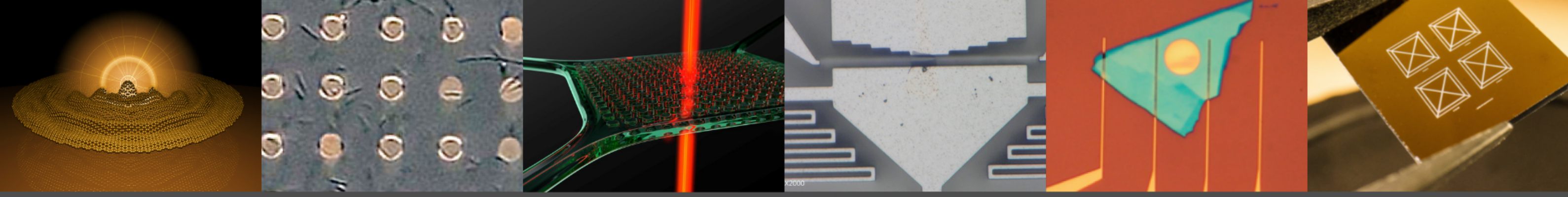

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PHONONIC WAVEGUIDES AS COHERENT PHONON SOURCES

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In the quest for phononic circuits for possible information processing [1], the phonon source plays a key role. Several sources of phonon sources have been investigated and here we explore the generation of phonons by means of a 2D SOI phononic crystal membrane cavity with a guided mode around 6.8 GHz. By incorporating an air-slot flanked by phononic crystal mirrors, we turn the phononic waveguide into an optomechanical platform that exploits photonic modes localised by inherent fabrication variations [2] for the transduction of mechanical modes. Such a platform exhibits fine control of phonons using light, and is capable of coherent self-sustained phonon generation via mechanical lasing around 6.8 GHz [3]. The platform operates at room temperature and is compatible with CMOS technology.

(a)

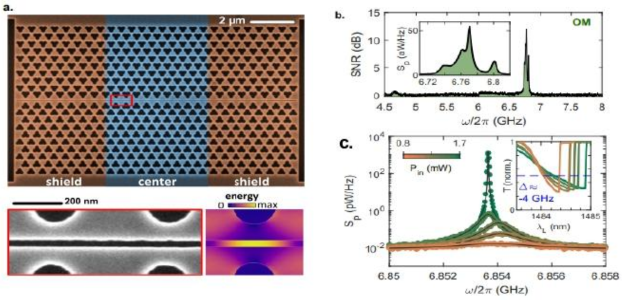

Figure 1. (a-top) SEM image of the optomechanical cavity waveguide and the central air-slot region. (a-bottom left) Magnified SEM image of the center slot highlighted above in red. (a-bottom right) The electromagnetic energy density. (b) Mechanical mode probed with a tapered fiber loop. Inset: magnified spectrum of the same mode. (c) Radio-frequency spectrum of transmitted light showing the mechanical mode. Dynamical back-action is observed leading to mechanical lasing. Colour scale indicates laser power in mW. Inset: driven optical mode exhibits a thermo-optic shift with increasing power.

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Detection of Brownian-motion via a quantum dot coupled to a highly miniaturised mechanical resonator

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Coupling a single-photon emitter to a mechanical resonator is a promising route toward operations involving a single photon and a single phonon. The underlying dynamics in such systems are determined by the non-linear nature of the quantum emitter, differentiating them from those of cavity optomechanical systems. Semiconductor quantum dots (QDs) can be coupled to mechanical motion via deformation potential coupling. So far, QD-mechanical coupling in the GHz-regime has been shown several times. [1][2] However, the coupling between the two systems could only be measured by external driving of the mechanical motion.

Here, we approach this issue by coupling self-assembled InAs QDs to mechanical membrane resonators. We present three mechanical resonator designs, see Fig. 1(a-c): a cantilever, a freely suspended beam, and a phononic crystal beam. Furthermore, our membrane design hosts a heterostructure diode to control and stabilise the QD's charge state. This results in narrow optical linewidths (≈450 MHz) and an increased mechanical sensitivity.

We probe the Brownian motion at low temperature, 4 K, of the mechanical resonator via the resonance fluorescence from a single quantum dot. [3] The mechanical noise imprinted on the QD's photons is extracted via an autocorrelation ($g^{(2)}$) measurement and subsequent Fourier analysis, see Fig. 1(d-f).

The highest mechanical frequency that we report is several times higher than the emitter's excited-state decay rate $\Omega_\mathrm{m} \approx 10\Gamma_\mathrm{r}$. Significantly, the mechanical quality remains at a high level, 2×10^3, due to the implementation of a phononic bandgap structure and low intrinsic losses. We estimate a vacuum coupling rate from our simulations of up to $g_\mathrm{ep}/2\pi$ =3 MHz. Together with the high mechanical frequency, this puts the system into the resolved sideband regime.

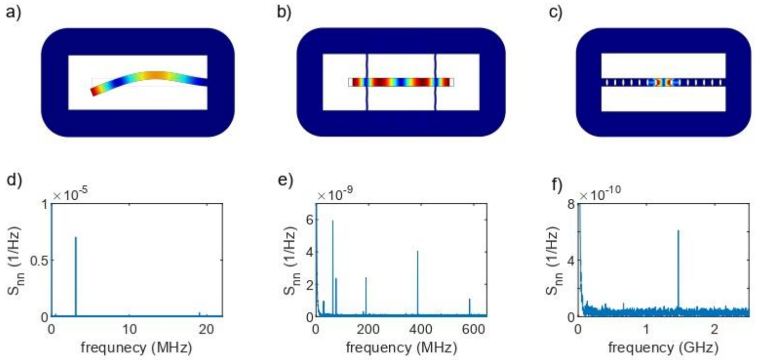

Figure 1: Normalised displacement profile of the mechanical membrane resonators simulated using COMSOL Multiphysics: (a) cantilever, (b) freely suspended beam, and (c) phononic crystal beam. For each resonator, the highest mechanical mode that we observe is displayed. (d-f) Brownian-motion measurements of the resonators shown in (a-c).

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Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Emergent Phenomena in Driven Nonlinear Quantum Resonators

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Strongly driven nonlinear quantum resonators built from microwave-frequency superconducting Josephson circuits have recently been developed in our group for quantum sensing of DC currents [1], nanomechanical resonators [2], and radio frequency photons [3], and have been demonstrated to be capable of reaching the quantum regime [4].

While the nonlinearity of these microwave devices can be considered a limitation of their sensing capabilities due to a reduced dynamic range, we have found that driving these systems into the nonlinear regime can enable unanticipated techniques based on parametric interactions, including cavity stabilisation and improved cooling using four-wave mixing processes [5] and parametrically-mediated non-reciprocal heat flow [6].

In addition to these new applications, strong driving of these cavities also leads to new emergent phenomena. In this talk, I present experiments and physical insight into some of those which we have recently observed, including the emergence of a negative-mass Bogoluibov “ghost” mode of a driven Duffing oscillator near an exceptional point [7, 8], and the emergence of an apparent nonlinear damping from a purely conservative nonlinearity through quantum fluctuations [9], highlighting strongly-driven nonlinear quantum cavities as a rich breeding ground for exploring new quantum physics and sensing techniques.

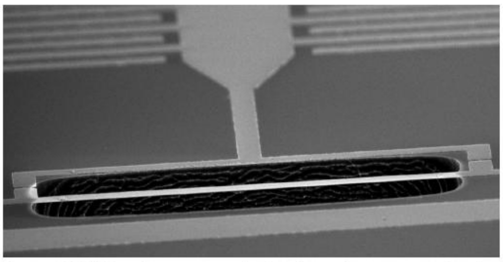

Figure 1: A nonlineary SQUID microwave cavity for detecting nanomechanical displacements

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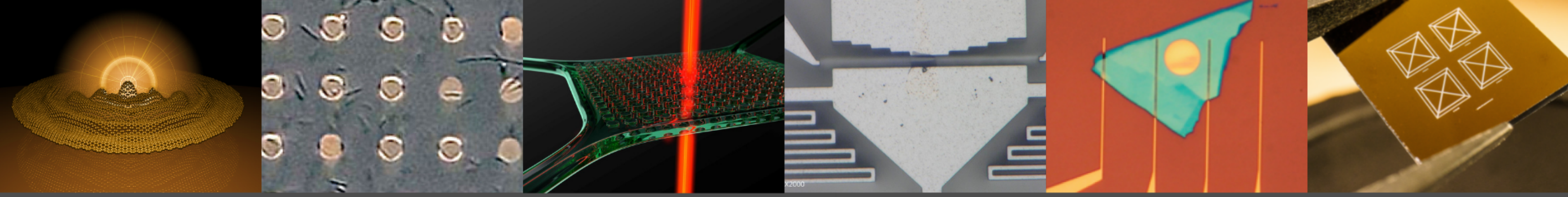

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Measuring Radiation Torque Shot Noise and Full Potential Control of a Levitated Nano-dumbbell

F. van der Laan[1,2], **J.A. Zielinska**[1], **F. Tebbenjohanns**[1], **R. Reimann**[1], **J. Vijayan**[1], **A. Norrman**[1], **L. Novotny**[1], **M. Frimmer**[1]

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The main goal of optomechanics is to optically measure and optimally control mechanical motion. Optically levitated nanoparticles are a particularly interesting optomechanical platform, because the mechanical potential arised through the interaction with light and due to their inherent decoupling from the environment. Besides their center-of-mass (translational) motion, dumbbells (or dimers) allow for the measurement and control of rotational degrees of freedom. When trapped in linearly polarized light, the dumbbell aligns to the polarization axis due to a restoring torque, resulting in so-called librational motion. In contrast, the dumbbell is driven to rotate when trapped in circularly polarized light.

Here, we demonstrate our control over the librational motion in two ways.
Firstly, we feedback cool the libration motion to sub-Kelving temperature and perform reheating experiments to quantify the contributions of different heating source. We show that we can reach a regime wherein the heating of the libration is dominated by radiation torque shot noise, i.e., measurement backaction [1].
Secondly, we set the libration potential by controlling the degree of polarization of the trapping beam. Since the degree of polarization sets the libration potential, we can tune the libration frequency from maximum (around 300 kHz) to approach zero, while keeping the center-of-mass motion of the particle trapped. Thus, we establish a rotation free fall in which one rotational angle can freely evolve [2].

These results constitute important steps towards gaining quantum control over rotational motion and harnessing levitating particle as torque sensors. Operating in the backaction limited regime is a prerequisite for feedback cooling the libration into its motional groundstate. Additionally, the potential control benifits using the levitated dumbbell as a torque sensor since it greatly increases the integration time of the sensor.

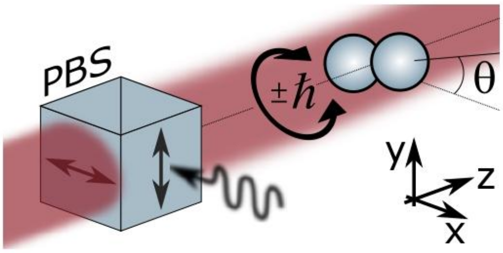

Figure 1: Pictorial representation of radiation torque shot noise. An anisotropic scatterer in a linearly polarized light field experiences a fluctuating torque which arises from the vacuum fluctuations, illustrated as entering the unused port of the polarizing beamsplitter (PBS).

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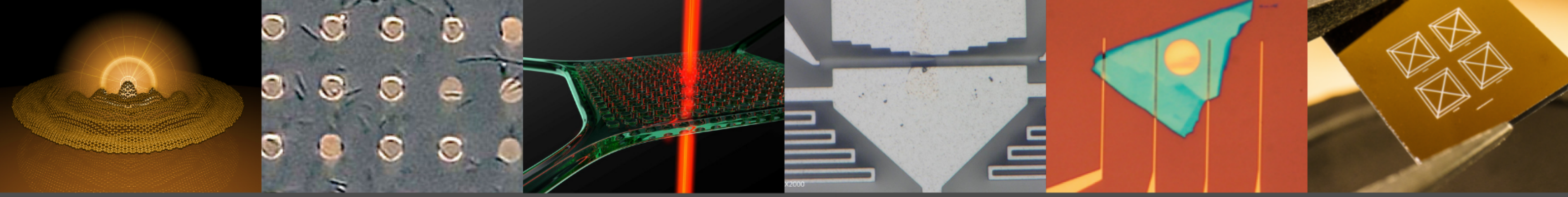

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Tension Tuning of Sound and Heat Transport in Graphene

G. J. Verbiest[1], H. Liu[1], M. Lee[2], M. Siskins[1,2], H. S. J. van der Zant[2], and P. G. Steeneken[1,2]

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Heat transport by acoustic phonons in 2D materials is fundamentally different from that in 3D crystals [1] because the out-of-plane phonons propagate in a unique way that strongly depends on tension and bending rigidity. Since in-plane and out-of-plane phonon baths are decoupled, initial studies suggested they provide independent pathways for heat transport and storage in 2D materials [2,3]. Here, we induce tension in freestanding graphene membranes (Fig.1a) by electrostatic force, and use optomechanical techniques (Fig.1b) to demonstrate that it can change the rate of heat transport by as much as 33% at an electrostatically induced tension of 0.07 N/m (Fig.1c-e) [4]. Using phonon scattering and Debye models, we explain these observations and found that heat is carried by a distribution of acoustic phonons with frequencies that range far into the GHz regime, and it appears that the heat transport rate is not only tuned by the effect of tension on the phonon velocities, but that also the effect of tension on the scattering rates at the boundaries of the suspended membranes plays a dominant role. Thus, we not only elucidate phononic heat transport mechanisms in suspended 2D materials, but also provide a promising route for controlling nanoscale heat transport by tension, which enables pathways for optimized thermal management in 2D-based phononic, thermoelectric, electronic and quantum devices.

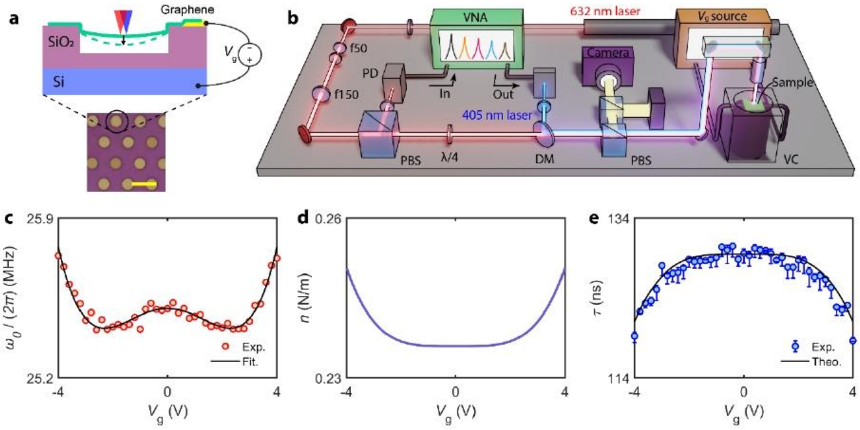

Figure 1. (a) Schematic of graphene resonator suspended on SiO_2/Si substrate. Top, cross-section view; bottom, optical image. (b) Interferometric setup. The graphene resonator is placed inside a vacuum chamber (VC). The blue (405nm) laser is intensity modulated by a vector network analyser (VNA) to actuate the resonator. Intensity variations of the reflected red (633nm) laser caused by resonator motion, are measured by photodiode (PD) and recorded with the VNA. PBS: polarized beam splitter; DM: dichroic mirror. (c) Points, resonance frequency $\omega_0/(2\pi)$ versus gate voltage V_g measured in one graphene device; line, fitting to extract the electrostatically induced tension n on the membrane. (d) n versus V_g. (e) Points, thermal time constant τ versus V_g for the same device; line, fitting to data using the Debye-scattering model.

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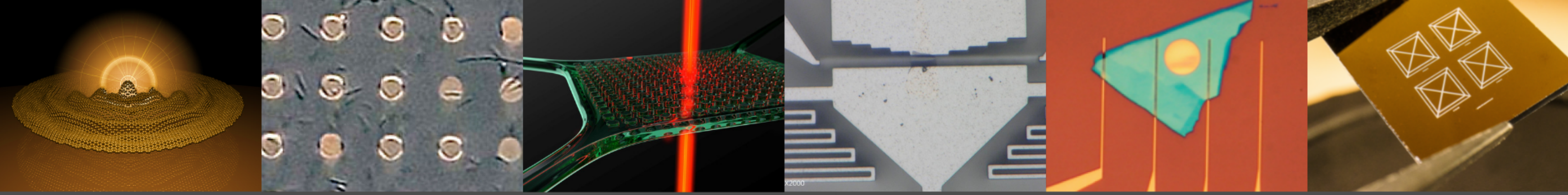

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Optomechanical meta-matter: Nonreciprocity and topology in synthetic nanomechanical networks

Jesse Slim[1], **Javier del Pino**[1,2], **Clara Wanjura**[3,4], **Matteo Brunelli**[5], **Andreas Nunnenkamp**[6], **Ewold Verhagen**[*1]
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Unidirectional wave propagation is useful in the efficient routing of information, and a hallmark feature of various topological phases. For bosons, like photons or phonons, nonreciprocity can be achieved through judicious forms of spatiotemporal modulation. We study the states and transmission characteristics of small networks of nanomechanical resonators that are formed and controlled with laser light. In the nano-optomechanical systems we develop, multiple MHz-frequency flexural mechanical resonator modes are parametrically coupled to a nano-confined optical cavity field with high strength.

Using the dynamics of the radiation pressure interaction in the nanocavity driven by temporally modulated laser fields allows to couple the mechanical modes into effective small resonator networks, inducing arbitrary quadratic bosonic Hamiltonians for nanomechanical motion [1]. The induced interactions simultaneously break time-reversal symmetry and control non-Hermitian dynamics through squeezing interactions. As a result, the phononic networks feature synthetic magnetism and both Hermitian and non-Hermitian topological phases. We report the various types of light-induced geometric phases that are responsible for unidirectional transmission, chiral amplification, and the active control of exceptional point physics and phonon lasing instabilities. By resolving thermal fluctuations in the network, we reveal that the breaking of time-reversal symmetry can enhance the efficiency with which a 'hot' resonator is cooled by colder reservoirs. Finally, we experimentally demonstrate quadrature nonreciprocity [2] - a form of unidirectional propagation without breaking time-reversal symmetry that establishes a mechanism for non-Hermitian topological phases, with interesting potential for signal processing and sensing applications

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Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Inducing micromechanical motion by optical excitation of a single quantum dot

J. Kettler[1,2], **N. Vaish**[1,2], **L. M. de Lépinay**[1,2], **B. Besga**[1], **P.-L.de Assis**[1,2], **O. Bourgeois**[1], **A. Auffèves**[1,2], **M. Richard**[1,2], **J. Claudon**[2], **J.-M. Gérard**[2], **B. Pigeau**[1], **O. Arcizet**[1], **P. Verlot***[3,4] and **J.-P. Poizat**[1,2]

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Hybrid quantum optomechanical systems[1] interface a macroscopic mechanical degree of freedom with a single two-level system such as a single spin[2], a superconducting qubit[3] or a single optical emitter[4]. Recently, hybrid systems operating in the microwave domain have witnessed impressive progress[5]. Concurrently, only a few experimental approaches have successfully addressed hybrid systems in the optical domain, demonstrating that macroscopic motion can modulate the two-level system transition energy[6]. However, the reciprocal effect, corresponding to the backaction of a single quantum system on a macroscopic mechanical resonator, has remained elusive. In contrast to an optical cavity, a two-level system operates with no more than a single energy quantum. Hence, it requires a much stronger hybrid coupling rate compared to cavity optomechanical systems. Here, we build on the large strain coupling between an oscillating microwire and a single embedded quantum dot[6] (QD). We resonantly drive the quantum dot's exciton using a laser modulated at the mechanical frequency. State-dependent strain then results in a time-dependent mechanical force that actuates microwire motion. This force is almost three orders of magnitude larger than the radiation pressure produced by the photon flux interacting with the quantum dot. In principle, the state-dependent force could constitute a strategy to coherently encode the quantum dot quantum state onto a mechanical degree of freedom.

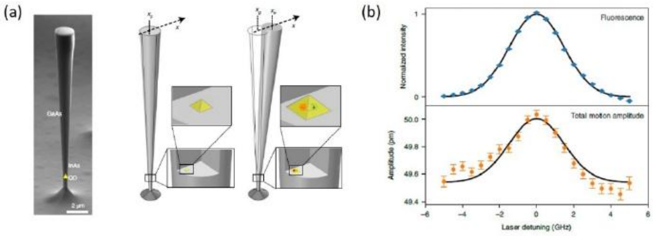

Figure 1: (a) Left: Scanning electron micrograph of the 18 μm long GaAs 'trumpet' hybrid mechanical system, including an implanted InAs QD close to its basis. Middle-right: Principle of the excitonic hybrid mechanical actuation: the effective volume of the QD depends on its state (ground state, middle and excited state, right), associated with a strain which results in motion actuation for an off-axis QD. (b) Resonant hybrid optomechanical response (bottom) as a function of the average number of photon inside the QD (top).

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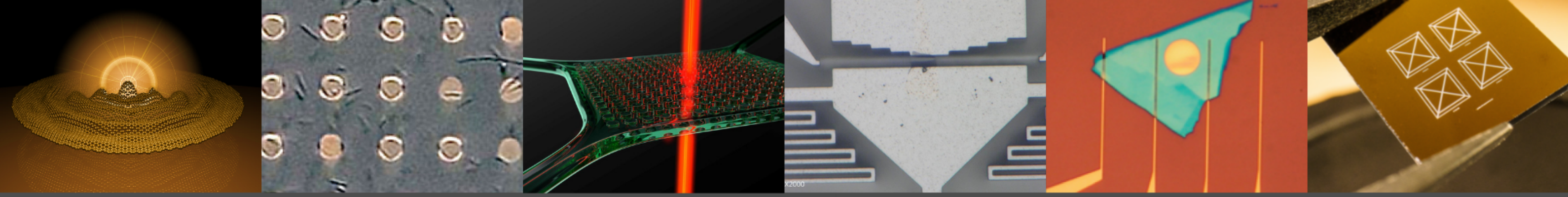

Frontiers of Nanomechanical Systems (FNS) workshop
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Can a single nanomechanical mode generate a frequency comb?

Eva Weig*[1,2,3]
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Doubly-clamped nanostring resonators excel as high Q nanomechanical systems enabling room temperature quality factors of several 100,000 in the 10 MHz eigenfrequency range. Dielectric transduction via electrically induced gradient fields provides an integrated control scheme while retaining the large mechanical quality factor [1]. Dielectrically controlled nanostrings are an ideal testbed to explore a variety of dynamical phenomena ranging from multimode coupling to coherent control [2].

Here I will focus on the nonlinear dynamics of a single, resonantly driven mode. The broken time reversal symmetry gives rise to the squeezing of the string's fluctuations. As a result of the high mechanical Q factor, the squeezing ratio is directly accessible from a spectral measurement [3]. It is encoded in the intensities of the two spectral peaks arising from the slow dynamics of the system in the rotating frame. For stronger driving, an onset of self-sustained oscillation is observed which leads to the generation of a nanomechanical frequency comb. The effect is a consequence of a resonantly induced negative effective friction force induced by the drive. This is the first observation of a frequency comb arising solely from a single mode and a single, resonant drive tone [4].

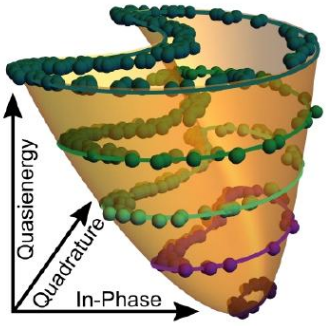

Figure 1: Nonsinusoidal limit cycles in the rotating frame, superimposed with the associated quasienergy surface. The limit cycles originate from the resonantly induced friction force, and give rise to a nanomechanical freuqency comb.

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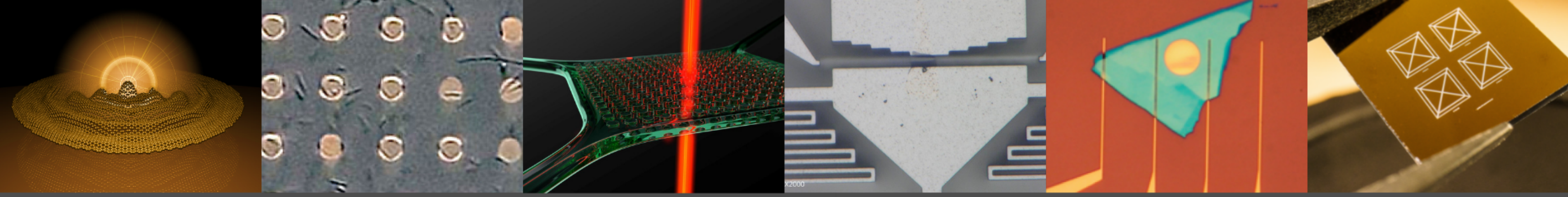

Frontiers of Nanomechanical Systems (FNS) workshop
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Topological Solitons in the Arrays of Nanomechanical Parametric Resonators

Hiroshi Yamaguchi[*], **Daiki Hatanaka, Motoki Asano, and Samer Houri**
NTT Basic Research Laboratories
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Topological soliton is the fundamental excitation observed in various nonlinear systems. In the simplest one-dimensional system, for example that described by Sine-Gordon equation [1], the topological soliton is the phase boundary between two identical but topologically distinguished domains created by the spontaneous breaking of translational symmetry. Its annihilation requires an energy to overcome the phase rotation and the existence is energetically protected by the topological properties. As has been widely demonstrated in the system of topological insulators, importing the concept of topology into artificial 2D lattice systems, such as photonics, microwave, and acoustics structures, is promising to open up new directions in device and material technologies based on the topologically robust properties. In this talk, we present our theoretical and numerical works that demonstrate 1D and 2D topological solitons using the arrays of parametric resonators. The key idea is to use quadrature variables, i.e. the sine and cosine oscillation amplitudes, in parametric oscillation to define the phase of dynamical variables. In 1D system, the boundary between 0-phase and π-phase parametric oscillation shows the feature of topological solitons and the motion can be driven by the electromechanical harmonic actuation of resonators [2]. In 2D system, four quadrature components in the square array of doubly degenerate circular membrane resonators play as the similar role as magnetic moments in ferromagnetic systems and the numerical simulation shows that the texture of skyrmion, which is one of the most important 2D topological solitons, can be generated by the parametric excitation. We performed a FEM calculation to prove the feasibility using a realistic device designs [3]. In both 1D and 2D cases, we also discuss the robustness against the frequency fluctuation of resonator arrays.

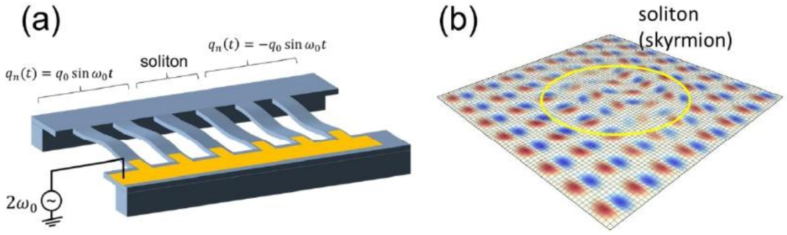

Figure: Schematic drawings showing the displacement distribution of (a) 1D and (b) 2D topological solitons.

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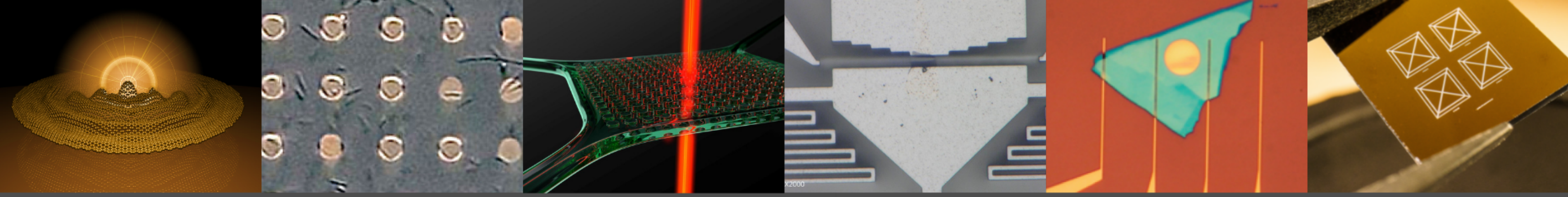
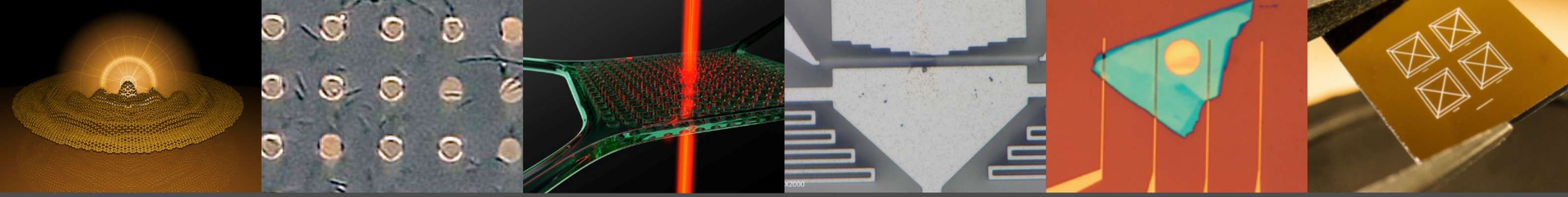


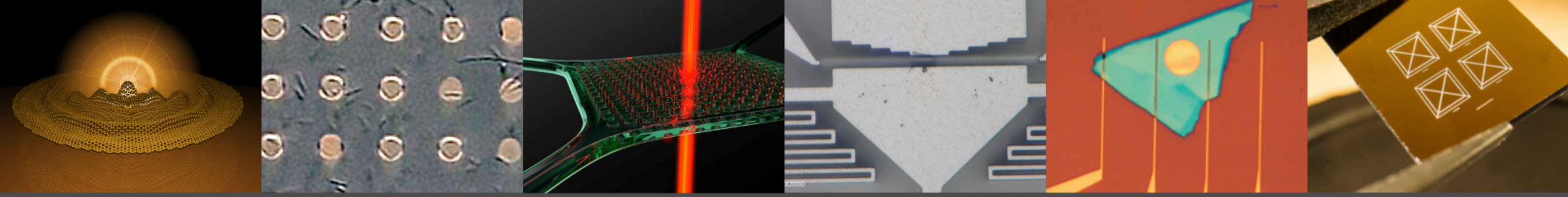
Conference Posters

Tuesday, June 6th, 17:00h

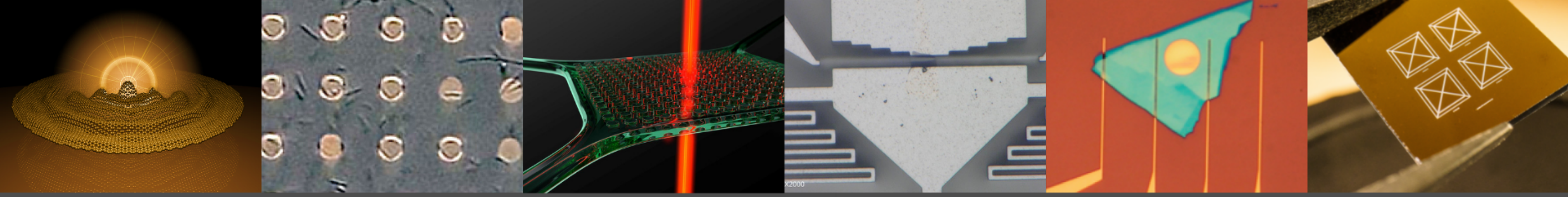
Poster title	Institution, Country	Presenter
Symmetry breaking in a parametrically modulated quantum oscillator	University of Konstanz, Germany	Daniel Boneß
Nonlinear coupled parametrically driven Duffing resonators	University of Konstanz, Germany	Wolfgang Belzig
Ultra-strong coupling between two harmonic oscillators	IISC, India	Soumya Ranjan Das
Flux coupled hybrid electromechanical system with a transmon qubit	IISC, India	Tanmoy Bera
Anomalous parametric amplification of degenerate first mode in micromechanical coupled beam systems	IISC, India	Vishnu Kumar
Anomalous nonlinear features in the self-oscilation regime of microwave optomechanical devices	CNRS, France	Alexandre Delattre
Investigation of the location of tunneling two level systems and the role of normal-state electrons in nanoelectromechanical resonators	CNRS, France	Baptiste Alperin
Exploiting the spin-mechanical coupling between an oscillating membrane and a nitrogen-vacancy center	NBI, Denmark	Evangelia Aspropotamiti
Towards spin-optomechanics with nitrogen-vacancy centers in diamond	NBI, Denmark	Felix Hahne
Comparative study of multi-object acoustic levitation trapping algorithms	TU Delft, Netherlands	Frederike Wörtche
Magnetic force microscopy with nanowire resonators	University of Basel, Switzerland	Hinrich Mattiat
Frequency noise in lithium niobate nano-acoustic resonators	Stanford, USA	Matthew Maksymowych



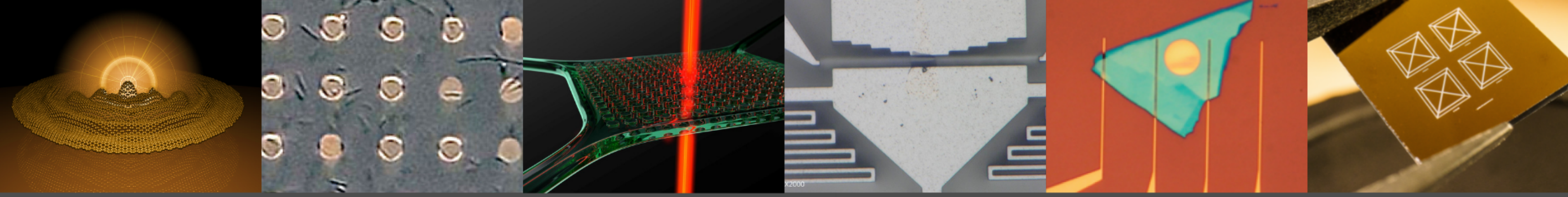
Energy dissipation in 3D-printed polymer micro-resonators	TU Delft, Netherlands	Jikke de Winter
Noems as a platform for non-hermitian phenomena	IISC, India	Sudipta Nayak
Optoacoustic active cooling in waveguides	Max Planck Institue, Germany	Laura Blazquez
Direct determination of optomechanical photonic crystal mechanical mode profile via quasi near-field perturbation	Université Paris-Saclay, France	Théo Martel
Metamaterials of fluids of light and sound	Instituto Balseiro and Centro Atómico Bariloche , Argentina	Alex Fainstein
On-chip distribution of quantum information using traveling phonons	TU Delft, Netherlands	Amirparsa Zivari
Centimeter-scale nanomechanical resonators with ultralow dissipation	TU Delft, Netherlands	Andrea Cupertino
Modeling the multi-mode nonlinear dynamics of nanomechanical resonators	TU Delft, Netherlands	Ata Keskekler
Fabrication of SiC optomechanical crystals	TUM, Germany	Berke Demiralp
Frequency stabilization of self-sustained oscillations in sideband-driven electromechanical resonator	HKUST, China	Boqi Zhang
Disordered coupled parametric oscillators and asymmetric Ising models	HKUST, China	Chengxiao Han
Acoustic spin pumping and the back-action in a phononic crystal cavity	NTT, Japan	Daiki Hatanaka
Transmission line electromechanics	ISTA, Austria	Denise Puglia
Membrane-based nanoMRI	ETH, Switzerland	Diego Visani
Coherent multifrequency microwave measurement for phase-sensitive detection of nanomechanical motion	KTH, Sweden	Ermes Scarano



Dry processing of high Q 3C-silicon carbide nanostring resonators	TUM, Germany	Felix David
Two molecules coupled to a nano-mechanical oscillator	Université de Bordeaux, France	Guillaume Bertel
Strange nonlinearity of nanobeam and generated frequency combs in mechanical modes and harmonics	KAIST, South Korea	Hyunjin Choi
Resonance frequency tracking schemes for micro- and nanomechanical resonators	TU Wien, Austria	Hajrudin Besic
Optomechanical rheology of liquids at gigahertz frequencies	Université de Paris, France	Hamidreza Neshasteh
Fabrication of nanomechanical diamond devices via a scalable smart-cut method	UC Sanata Barbara, USAS	Hyunseok Oh
Probing nanomotion of single bacteria with graphene drums	TU Delft, Netherlands	Irek Roslon
Vacuum gap electromechanical devices with integrated piezoelectric actuator	TU Wien, Austria	Ioan Ignat
Optomechanical coupling of a microwave cavity to a large membrane	TU Delft, Netherlands	Jean-Paul van Soest
Optomechanics of suspended magnetic van der waals materials	Université de Strasbourg, France	Joanna Wolff
Spin detection using ultra-coherent silicon nitride string resonators	ETH, Switzerland	Bhavesh Kharbanda
Nanomechanical absorption spectromicroscopy of individual Au nanorods	TU Wien, Austria	Kostas Kanellopulos
Fluctuations driven coupled oscillators as a quantum simulator	University of Konstanz, Germany	Lorenzo Bernazzani
Towards strain coupling of nanomechanical motion to quantum dots in GaAs zipper cavities	TU Eindhoven, Netherlands	Matteo Lodde

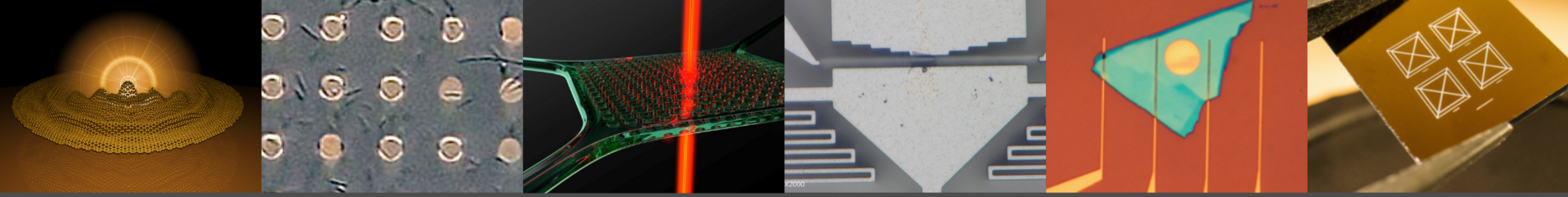


Dynamical backaction cooling of sideband-unresolved mechanical modes using multimode optomechanical interactions	Amolf, Netherlands	Menno Jansen
Collective dynamics in circuit optomechanical systems	EPFL, Switzerland	Mahdi Chegnizadeh
A phononic frequency comb from a single driven nonlinear nanomechanical mode	TUM, Germany	Maria Kallergi
Real-time measurements of a carbon nanotube electromechanical system hosting a double-quantum dot	ICFO, Spain	Marta Cagetti
Coherent feedback towards light-mediated mechanical self-interactions	University of Basel, Switzerland	Maryse Ernzer
Effect of helium ion implantation on nanomechanical resonators in 3C-SiC	Helmholtz-Zentrum Dresden-Rossendorf , Germany	Nagesh S. Jagtap
Advances in 3D magnetic resonance force microscopy	ETH, Switzerland	Nils Prumbaum
Fluctuating states and non-monotonic nonlinear friction in nanotube oscillators	Università Politecnica delle Marche, Italy	Pierpaolo Belardinelli
Development of continuous sub-mk refrigeration for ground-state cooling of mechanical resonators	CNRS, France	Andrew Fefferman

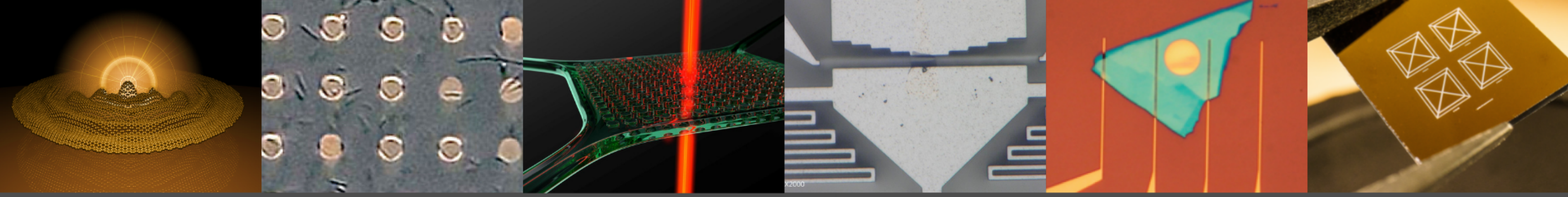


Wednesday, June 7th, 17:00

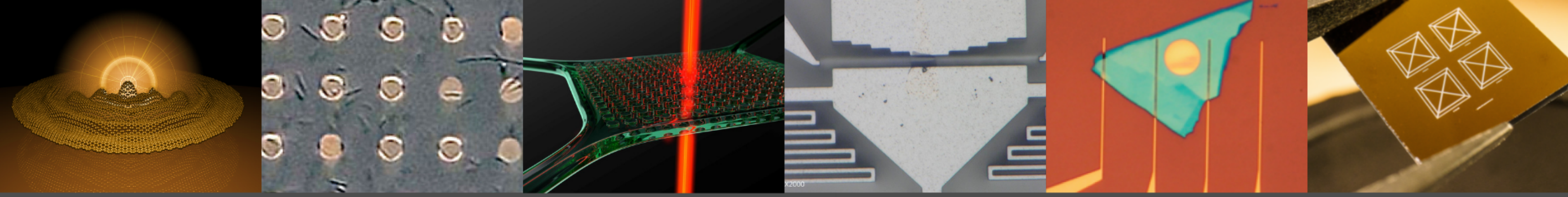
Poster title	Institution, Country	Presenter
Novel nanotube multiquantum dot devices	ICFO, Spain	Roger Tormo Queralt
Thin film device characterization using picosecond ultrasonics	TU Delft, Netherlands	Ruben Guis
Graphene mechanical resonator; electro-mechanical properties and radio application	Ewha Womans University, South Korea	Yugyeong Je
Gallium phosphide 2D optomechanical crystals for deterministic single-photon quantum memories	NBI, Denmark	Sho Tamaki
A voltage-controllable magnetic tip for membrane-based scanning force microscopy	ETH, Switzerland	Shobhna Misra
Mechanical frequency control in inductively coupled electromechanical systems	Walther-Meißner-Institut, Germany	Thomas Luschmann
Tuning nonlinear dynamics of nanomechanical resonators via soft-clamping	TU Delft, Netherlands	Zichao Li
Dynamical backaction evading magnomechanics	TU Delft, Netherlands	Clinton Potts
Dandelion-class phononic membrane resonators	NBI, Denmark	Eric Langman
Mechanical mode imaging of a high-Q hybrid hBN/Si3N4 resonator	University of Basel, Switzerland	Francesco Fogliano
Resolution limits of sensors based on Duffing resonators	TU Delft, Netherlands	Tomás Manzaneque
Toward room-temperature observation of quantum radiation force noise driving a trampoline's motion	ETH, Switzerland	Vincent Dumont
Nanomechanical resonator based on twisted bilayer graphene	ICFO, Spain	Parmeshwar Prasad
Intermodal coupling in two-mode nanostrings	TUM, Germany	Ahmed A. Barakat
Towards nanomechanical detection of fT bio-magnetic fields	University of Hamburg, Germany	Alexander Schwarz



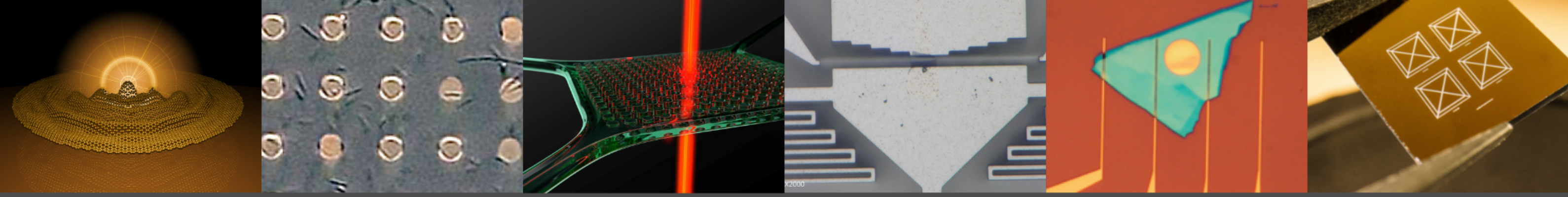
Enhancing the sensitivity of silicon photonic ultrasound sensors by optimizing the stiffness of polymer cladding	TU Delft, Netherlands	Tufan Erdogan
Nonlinear nanomechanical resonators approaching the quantum ground state	ICFO, Spain	Chandan Samanta
Quantum coherent control in pulsed waveguide optomechanics for photon-phonon entanglement via brillouin scattering	Max Planck Institute, Germany	Laura Blazquez
Towards a mechanical qubit in a carbon nanotube	ICFO, Spain	Christoffer Møller
Period tripling states and non-monotonic energy dissipation in MEMS with internal resonance	Penn State University, USA	Daniel Lopez
Tunable frequency comb in flexural-mode-coupling regime in nonlinear mechanical membrane resonators	University of Konstanz, Germany	Fan Yang
Strongly driven spin-mechanical systems for enhanced mechanical sensing	University of Oregan, USA	Hailin Wang
Prospects for a microshell optomechanical resonator	Yale, USA	Jinuk Kim
Linear and nonlinear cavity optomechanics with Niobium-based superconducting nanoelectromechanical systems	Korea Research Institute of Standards and Science,	Jinwoong Cha
Purely quartic nonlinearity in cavity optomechanics	Université de Bordeaux, France	Jonathan L. Wise
Toward nanomechanical probe for Majorana zero modes	Korea Research Institute of Standards and Science,	Junho Suh
A hybrid superconductor/nanomechanical magnetic field detector for biomagnetism	CNR, Italy	Luca Pellegrino
Quantum well exciton polaritons in an disk optomechanical microcavity	Université de Paris, France	M.F. Colombano Sosa
Optical coherent feedback control of a mechanical oscillator	University of Basel, Switzerland	Manel Bosch Aguilera
Study of heat transport in Silicon Nitride nanomechanical resonators for high precision sensing and energy conversion applications	University of Ottawa, Canada	Raphael St-Gelais



135 days of aging measurement on a silicon nitride nanomechanical resonator	University of Ottawa, Canada	Michel Stephan
Mechanical overtone frequency combs	Aalto, Finland	Matthijs de Jong
Electrothermally tunable metal-graphene-silicon nitride membrane mechanical device	University of Konstanz, Germany	Mengqi Fu
High-Q factor complex oxides MEMS resonators from epitaxial thin films	CNR, Italy	Nicola Manca
Har.py: Automatic nano-harp characterization	TUM, Germany	Philipp Bredol
Position-dependent noise characteristics in optomechanical transduction of InP nanowires	TU Wien, Austria	Robert G. West
Conceptually new meters of noise intensity or temperature: exploiting noise-induced transitions in micro/nano-resonators at short time scales and providing a huge range	Lashkaryov Institute of Semiconductor Physics, Ukraine	Stanislav Soskin
A nano-electromechanical quantum simulator	ICFO, Spain	Stefan Forstner
Theory behind the realization of a mechanical qubit	ICFO, Spain	Victor Roman-Rodriguez
High-Q trampoline mechanical resonators in crystalline InGaP with engineered reflectivity	Chalmers, Sweden	Witlef Wieczorek
Scanning microwave microscopy for investigations of mechanical vibrations and mode coupling	IEMN, France	Xin Zhou
Optomechanics with magnetically levitated drops of liquid He-3 and He-4	Yale, USA	Yogesh S. S. Patil
Design and fabrication of kinetic-inductive electro-mechanical force sensors	KTH, Sweden	August K. Roos
Clamped and sideband-resolved silicon optomechanical crystals	Chalmers, Sweden	Johan Kolvik
Tunable graphene phononic crystals	Freie Universität Berlin, Germany	Yuefeng Yu
Magnetic order in 2D antiferromagnets disclosed by spontaneous anisotropic magnetostriction	TU Delft, Netherlands	Maurits Houmes



Ultra-strong amorphous silicon carbide for nanomechanics	TU Delft, Netherlands	Minxing Xu
Surface-acoustic-wave induction of a giant synthetic hall effect in graphene	University of Hamburg, Germany	Robert H. Blick
Non-magnetic portable probe for characterising mechanic resonators in vacuum at low temperatures	Università degli studi G. d'Annunzio, Italy	Enrico Ragucci
Analysis and interpretation of force volume data acquired with a tuning fork AFM at cryogenic temperatures by using intermodulation products	University of Basel, Switzerland	Marco Zutter
Tension mediated intermodal coupling among mechanical modes of a silicon nitride membrane	IISC, India	Nishta Arora



Abstracts of Posters

Listed in alphabetical order of the presenter’s surname

(Links available under “Conference Posters”)

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Investigation of the location of tunneling two level systems and the role of normal-state electrons in nanoelectromechanical resonators.

Baptiste Alperin[*1], **Gwénaëlle Julie**[1], **Eddy Collin**[1], **Andrew Fefferman**[1]

[1]Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France

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At low temperatures, in amorphous matter, tunneling two level systems (TTLS) affect the damping and the noises in nanoelectromechanical resonators, optomechanical systems and qubits.
Lulla *et al.* [1] showed that in silicon "goalpost" nanoelectromechanical resonators covered with 30 nm of aluminium, the mechanical dissipation in the normal state of aluminium is higher than in the superconducting state. This showed the importance of normal-state electrons in the damping mechanisms.
Kamppinen *et al.* [2] studied pure aluminium goalposts of 150 to 200 nm thickness. By applying a magnetic field to their resonator, they could choose the state of the electrons in the aluminium, whether they were superconducting or normal. They found that the electrons do not contribute significantly to the damping in their devices.

In order to find the reason for the different behavior observed in these two works, we are fabricating goalpost shaped resonators made of bare aluminium of the same lateral dimension as one of the devices studied in [2] but with different thickness ranging from 30 to 400 nm. A 60 nm thick goalpost is shown in Fig. 1. We will look for a thickness dependence of the damping by normal-state electrons with the expectation that it will elucidate the discrepancy between the previous works.

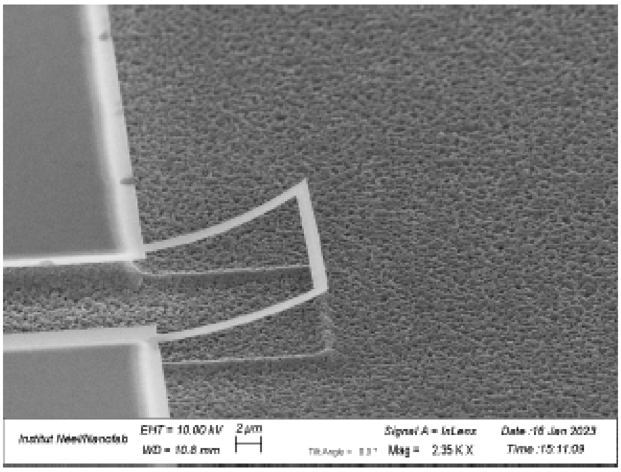
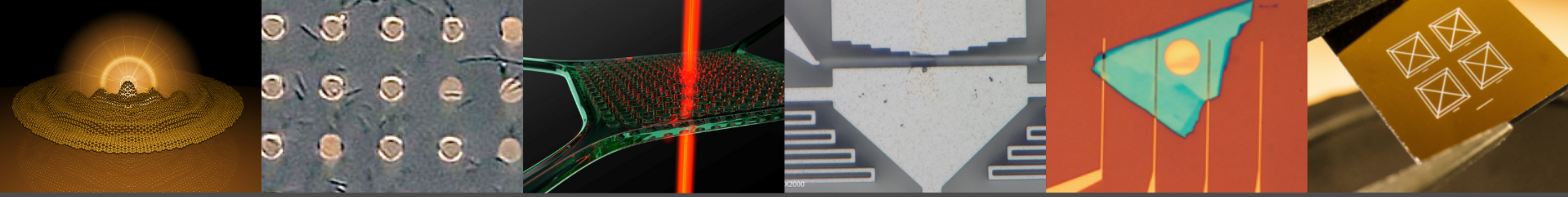


Figure 1: SEM picture of the suspended goalpost shaped resonator made of 60nm Aluminium.

References

[1] K. Lulla, M. Defoort, C. Blanc, O. Bourgeois, and E. Collin. Evidence for the role of normal-state electrons in nanoelectromechanical damping mechanisms at very low temperatures. *Physical review letters*, 110(17):177206, 2013.

[2] T. Kamppinen, J. Makinen, and V. Eltsov. Dimensional control of tunneling two-level systems in nanoelectromechanical resonators. *Physical Review B*, 105(3):035409, 2022.



Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Tension Mediated Intermodal Coupling among Mechanical Modes of a Silicon Nitride Membrane

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Understanding complex coupling mechanisms between mechanical modes is essential for many applications such as timing circuits and to improve the precision of nanomechanical sensors [1]. We study intermodal coupling among flexural mechanical modes of a square silicon nitride membrane. The suspended membrane is 100nm thick and 500um x 500um in area, as shown in figure 1(a). We actuate the device using a piezo shaker and detect multiple mechanical modes using a laser doppler vibrometer. Figure 1(b) shows mode shapes of fundamental (1,1) and higher coupled mode (2,2) with resonant frequency of ~ 813KHz and 1630KHz respectively. In the nonlinear regime, the modes couple due to the tension induced by the large oscillation amplitude. This can be monitored by tracking the undriven response of the fundamental mode while providing actuation force near the higher mode. Figure 1(d) and (e) show the effect of driving higher mode (2,2) on the frequency response of the fundamental mode (1,1). At lower drives, the resonant frequency of the fundamental mode is nominally unaffected. On increasing the drive strength, as the drive frequency increases, the resonance frequency of the fundamental mode gradually increases and then abruptly decreases to its original value beyond a critical frequency as shown in figure 1(e). We explore the form of this nonlinear coupling and further study its impact on the quality factor of the coupled mechanical mode.

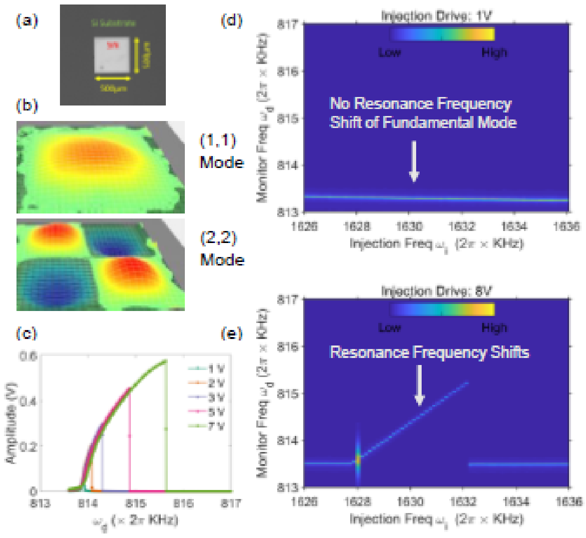

Figure 1: (a) Optical micrograph of suspended 100nm thick square silicon nitride membrane of area 500μm x 500μm. (b) Mode shape of fundamental (1,1) mode and coupled higher mode (2,2). (c) The frequency response of the fundamental mode shows hardening nonlinearity with increasing actuation drive. Response of fundamental mode on varying the injection frequency around the higher coupled mode with actuation drive strength of (d) 1V and (e) 8V.

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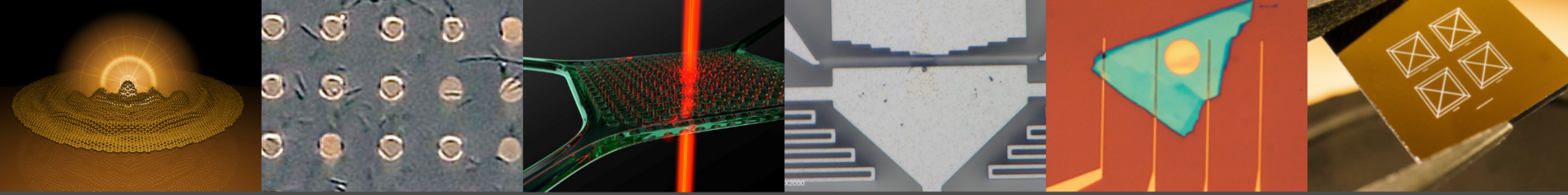

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

INTERMODAL COUPLING IN TWO-MODE NANOSTRINGS

Ahmed A. Barakat[*1], **Anh Tuan Le**[1], **Avishek Chowdhury**[1], **Eva M. Weig**[1]

[1]Chair of Nano and Quantum Sensors, Technical University of Munich

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Two-level systems are known in various fields of science to exhibit interesting dynamical phenomena using different ways of interaction. In nanostrings, the fundamental in-plane (IP) and out-of-plane (OOP) modes exhibit analogous phenomena under linear, nonlinear and parametric coupling, providing a baseline for other analogous phenomena celebrated in quantum two-level systems [1]. In this work, through a dielectric actuation of nanostrings [2] and using micro-cavity-assisted detection scheme, the linear and nonlinear dynamics of the string can be controlled under forced and parametric excitation. Under forced excitation, a characterization of the nanostrings is carried out providing an overall picture of the system's dynamics by varying a bias voltage and recording the eigenfrequencies corresponding to the IP and OOP modes of each string, see Fig. 1.

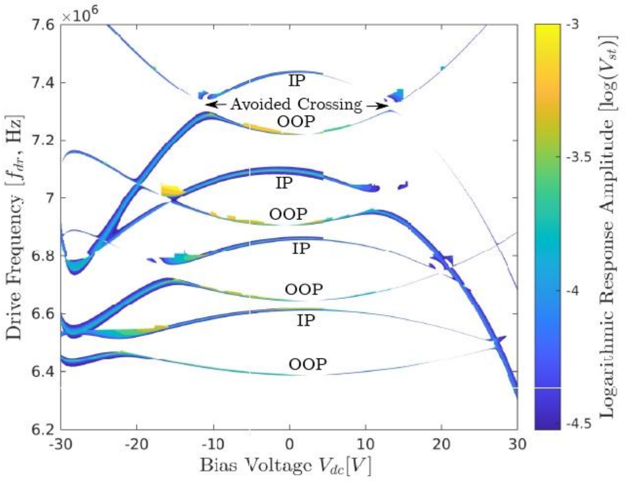

Figure 1: Resonance chart showing resonance frequencies and amplitudes of the in-plane (IP) and out-of-plane (OOP) modes of four nanostrings driven together at a Drive Frequency and a Bias Voltage.

In this picture, when both eigenfrequencies of each string are tuned near to each other, they diverge instead of crossing each other, in a phenomenon called *avoided crossing* indicating at least a linear coupling between both modes [3]. The coupling strength between both modes in each spring is therefore investigated and found to be varying according to the strength of the applied electrostatic field. In addition, a strong nonlinear behavior is witnessed in the vicinity of the avoided crossing indicating the existence of a stronger dynamical coupling . In summary, this work aims at giving a more comprehensive understanding of the dynamics of coupled two-mode nanostring systems under dielectric actuation.

References

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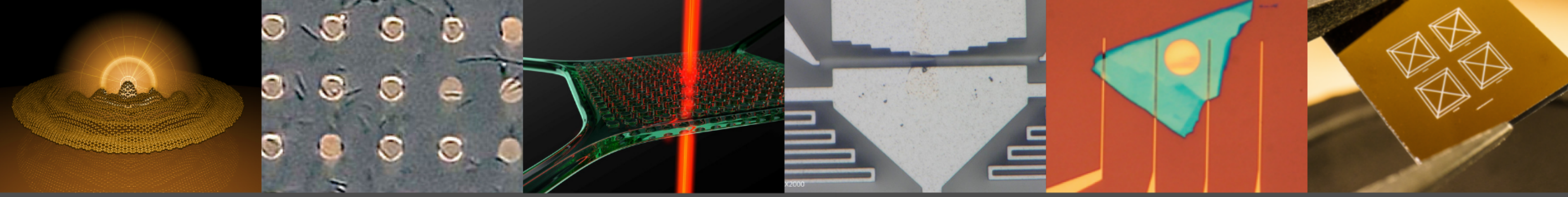

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

FLUCTUATING STATES AND NON-MONOTONIC NONLINEAR FRICTION IN NANOTUBE OSCILLATORS

Pierpaolo Belardinelli[1*], **Wei Yang**[2], **Adrian Bachtold**[2], **Mark Dykman**[3], **Farbod Alijani**[4]

[1]Department of Construction, Civil Engineering and Architecture, Polytechnic University of Marche, Ancona, Italy
[2]ICFO, The Barcelona Institute of Science and Technology, Castelldefels, Barcelona, Spain
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Carbon nanotube (CNT) electromechanical resonators are devices of choice for investigating the interplay of electronic transport and nonlinear dynamics at the nanoscale (Fig. 1A). Owing to their high-frequency and quality-factors, they have also been used for mass and force detection with extreme sensitivities [1].

In these systems, the coupling between mechanical and electrical degrees-of-freedom is strong and can lead to bi-stability and self-oscillations (see Fig. 1B). At the same time, owing to their small size, they are extremely susceptible to different noise sources, thus making them an interesting platform for investigating new phenomena that can emerge from the interplay of noise and nonlinear dynamics [2].

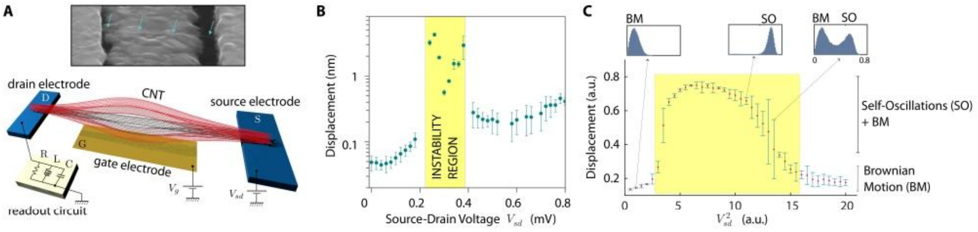

Figure 1: **A**. Schematic of the suspended carbon nanotube electromechanical resonator. Voltages are applied to source/drain (blue) and gate (gold) electrodes. The inset shows the scanning electron microscopy image with a tilted nanotube. The trench width is $1.1\,\mu$m. **B**. Experiments showing the displacement variance as a function of the source-drain voltage V_{sd} for gate voltage $V_g = -616$ mV (Fig. 3c of [3]). **C**. Numerical simulation of the fluctuating states of the nanotube oscillator. Within the instability region, thermally excited vibrations co-exist with self-sustained vibrations on an isolated branch.

In this work, we report self-sustained oscillations in a carbon nanotube originating from the combination of electron tunneling and thermal effects [3]. The electro-mechanical cross-talk leads to a non-monotonic evolution of the nonlinear friction force, resulting in co-existence of large-amplitude self-sustained oscillations and thermal vibrations (Fig. 1C).

We show that the stable self-sustained oscillations lie on an isolated branch in the space of the parameters. They can be unveiled via stochastic switching from the branch that corresponds to thermal vibrations. Such a dynamical scenario is often hidden, it is qualitatively different from the more conventional scenario where self-oscillations are activated via a Hopf bifurcation of an equilibrium state. The noise-induced population of an isolated self-oscillation state showcased here represents a novel bistable configuration for nanomechanical systems that can be of interest for coherent and stochastic resonant devices.

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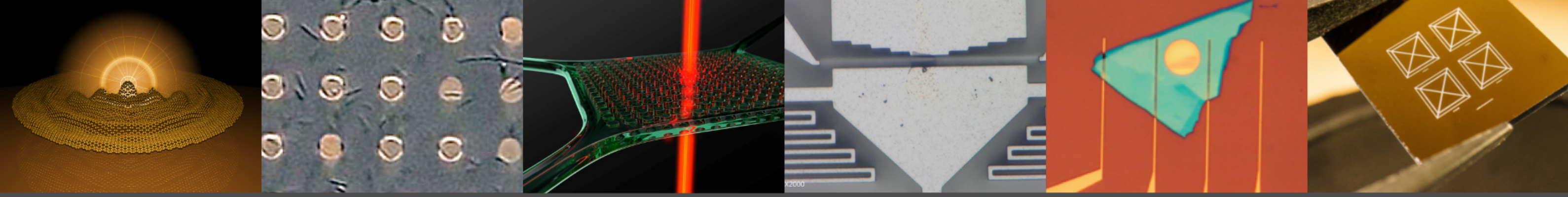

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Nonlinear Coupled Parametrically Driven Duffing Resonators

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[1] Department of Physics, University of Konstanz, Germany
[2] INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, 38123 Povo, Italy
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Resonators driven by a parametric excitation can result in chaos, bifurcation, and synchronization. Nonlinear coupling between resonators can also lead to complex dynamics, including multi-stability or frequency locking. Therefore nonlinear coupled parametrically driven Duffing resonators are a type of oscillators that exhibit rich nonlinear dynamic behavior. The study of these systems has important implications for the design and control of mechanical systems and is a rapidly growing area of research.

We consider two Duffing resonators that are slightly detuned. Both are driven independently by a parametric force close to twice of the eigenfrequency. The resonators are coupled in a nonlinear way. We derive and solve the nonlinear coupled equations of motion in the classical regime, obtaining steady-state amplitudes of both parametric Duffing resonators. Investigating different parameter regimes, we find the most interesting case: when a stable bifurcation occurs. An increasing coupling strength or asymmetric Duffing nonlinearities of the resonators reduce the arms of the bifurcation. Increasing the parametric driving force overcomes these effects and produces a well pronounced bifurcation. For equal driving forces we can find perfectly connected branches while they detach in different ways for unequal driving strengths.

With the ideal parameter setup, we move from the classical to the quantum regime and derive the effective Hamiltonian for the quantum fluctuations. A first analysis of a part of the Hamiltonian indicates the occurrence of squeezed states which can be related to entangled states.

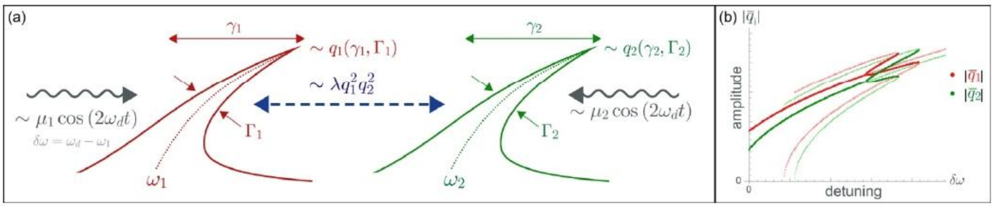

Figure 1: (a) Sketch of two Duffing resonators (i = 1,2) with eigenfrequencies ω_i, Duffing nonlinearities γ_i, and damping Γ_i. Both Duffing resonators are driven independently by a parametric force with amplitude μ_i close to twice of the eigenfrequency. The resonators are coupled nonlinear by a coupling strength λ. The eigenfrequencies are assumed to be close to each other and the driving frequency ω_d. (b) Steady state solutions of the two nonlinear coupled resonators for equal driving forces $\mu_1 = \mu_2$ showing a stable bifurcation in a symmetric setup, i.e. equal damping $\Gamma_1 = \Gamma_2$ and equal Duffing nonlinearities $\gamma_1 = \gamma_2$. The driving force is of the order $\mu_i \sim \omega_d \Gamma_i$ and the coupling is defined in terms of the Duffing nonlinearity, i.e. $\lambda = \frac{33}{80}\gamma$. The bold lines correspond to stable steady state solutions while the others are unstable.

Fluctuations driven coupled oscillators as a quantum simulator

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We investigate a system composed of two coupled oscillators subject to stochastic fluctuations in its internal parameters. The goal would be to further extend the well-known classical analogy of the quantum dynamics of two level systems (TLS) described by Schrödinger's equation, provided by coupled oscillators [1-2]. This analogy has been already tested in multiple experimental setups. Examples of systems exploited on the experimental test-beds are given by coupled nanomechanical string resonators or optically levitated particles [3-5]. Notwithstanding, a result of this classical analogy is that the Bloch's vector (BV) dynamics, arising from the classical coupled oscillators problem, leads to the same relaxation time for all the components of the BV $T_1 = T_2$, which is in contrast with the general case of quantum TLS. Our aim is to show that this fundamentally quantum feature, i.e. $T_1 \neq T_2$, can be implemented as well in the aforementioned classical systems by adding stochastic fluctuations in their internal parameters. Moreover, these stochastic contributions might be easily engineered in the control apparatus of those systems. A better understanding of such fundamental features of the quantum-classical analogy in these kinds of systems could lead to further proposals for hybrid mechanical systems as simulators of quantum systems made of coupled spins.

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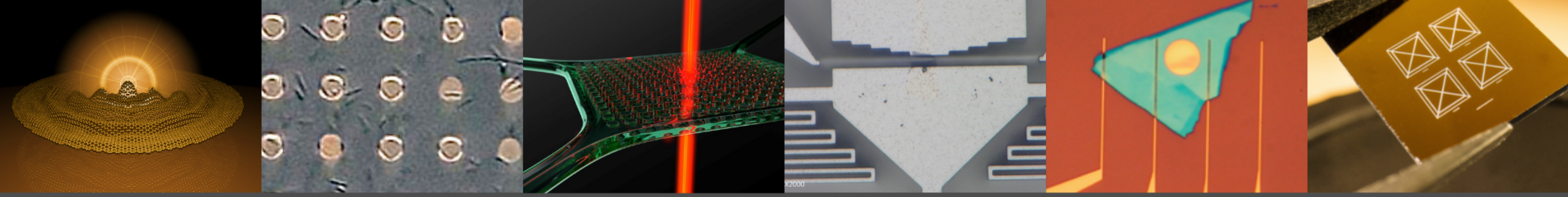

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

TWO MOLECULES COUPLED TO A NANO-MECHANICAL OSCILLATOR

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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.

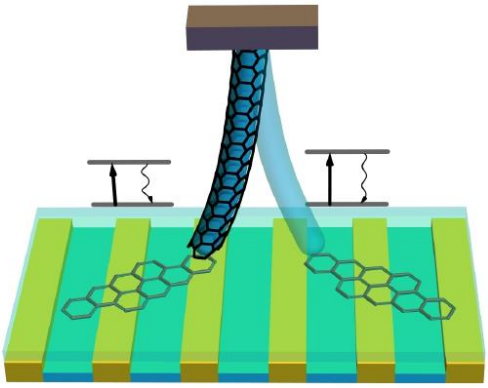

Figure 1: Schema of the system of two molecules coupled to a mechanical oscillator.

References

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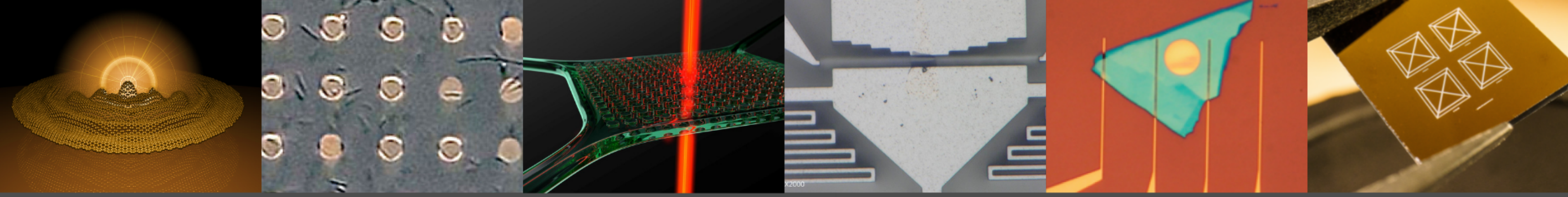

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Resonance frequency tracking schemes for micro- and nanomechanical resonators

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Most nanomechanical sensing applications rely on detecting changes of resonance frequency. In commonly used frequency tracking schemes, the resonator is driven at or close to its resonance frequency. Closed-loop systems can continually check whether the resonator is at resonance and accordingly adjust the frequency of the driving signal [1]. In this work, we study three resonance frequency tracking schemes, a feedback-free (FF), see Fig. 1, a self-sustaining oscillator (SSO), and a phase-locked loop oscillator (PLLO) scheme. We improve and extend the theoretical models for the FF and the SSO tracking schemes, and test the models experimentally with a nanoelectromechanical system (NEMS) resonator. We employ a SSO architecture with a pulsed positive feedback topology and compare it to the commonly used PLLO and FF schemes. We show that all tracking schemes are theoretically equivalent and that they all are subject to the same speed versus accuracy trade-off characteristics. In order to verify the theoretical models, we present experimental steady-state measurements for all tracking schemes (Fig. 2). Frequency stability is characterized by computing the Allan deviation. We obtain almost perfect correspondence between the theoretical models and the experimental measurements. These results show that the choice of the tracking scheme is dictated by cost, robustness and usability in practice as opposed to fundamental theoretical differences in performance.

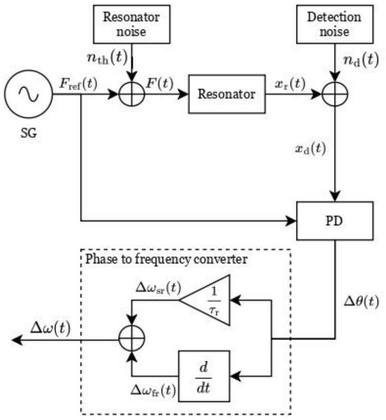

Figure 1: Block diagram of the feedback-free (FF) frequency tracking scheme. We show that when the FF tracking scheme is operated in the combined/sum mode proposed in this work, it offers an equivalent speed versus accuracy trade-off characteristics as the closed-loop SSO and PLLO schemes. This is achieved by combining (adding) the slow and fast frequency responses that can be obtained by simple processing of the phase output from the demodulator.

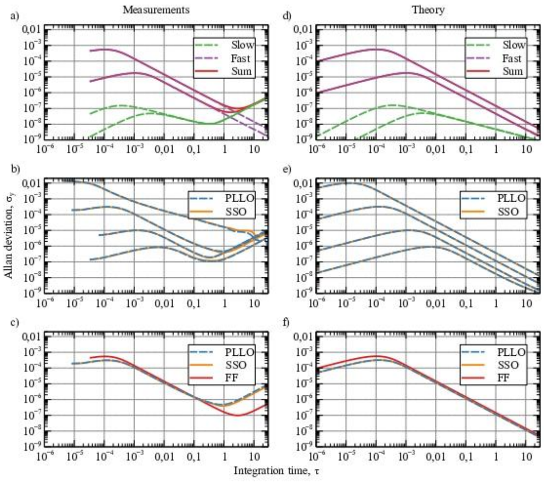

Figure 2: Comparison of experimental Allan deviations with theory. (a) Allan deviations for three FF tracking modes with second order demodulation filters of bandwidth $f_{\rm L} = \{100\,{\rm Hz}, 1\,{\rm kHz}\}$ (b) Comparison of PLLO and SSO tracking schemes for $f_{\rm PLL} = \{10\,{\rm Hz}, 50\,{\rm Hz}, 500\,{\rm Hz}, 5\,{\rm kHz}\}$. c) Comparison of PLLO and SSO with $f_{\rm PLL} = 500\,{\rm Hz}$ and FF scheme (combined/sum mode) with $f_{\rm L} = 1\,{\rm kHz}$ d)-f) Theoretical model based computations for the same settings as in the measurements a)-c).

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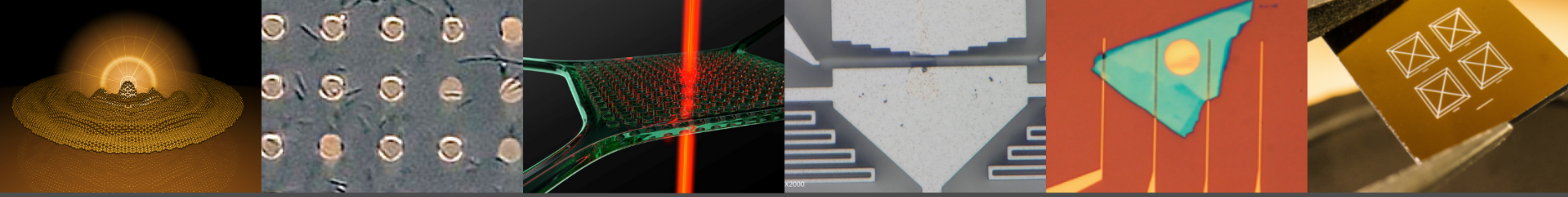

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

OPTOACOUSTIC ACTIVE COOLING IN WAVEGUIDES

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Brillouin-Mandelstam scattering describes the nonlinear interaction of two photons mediated by an acoustic phonon. In optical fibers, the acoustic phonons addressed in backward Brillouin-Mandelstam scattering are different for Stokes and anti-Stokes processes. Therefore, in order to achieve phonon cooling, there is no need to work in the resolved sideband regime, unlike with optomechanical cavities [1]. Here, we experimentally demonstrate active optomechanical cooling of acoustic phonons using Brillouin-Mandelstam scattering in a chalcogenide glass photonic crystal fiber (PCF). We study the behavior of both Stokes and anti-Stokes Brillouin-Mandelstam resonances as a function of pump power. As we work in weak coupling, we can use the relation $\frac{\bar{n}_{ss}}{\bar{n}_0} = \frac{\Gamma_m}{\Gamma_{\text{eff}}}$, where $\bar{n}_{ss}$ $(\bar{n}_0)$ is the mean phonon number in the steady-state (initial state) and $\Gamma_{\text{eff}} = \Gamma_{\text{opt}} + \Gamma_m$ is the effective dissipation rate of the acoustic mode. Γ_m is the acoustic dissipation rate and Γ_{opt} the optically-induced acoustic loss. The effective dissipation rate Γ_{eff} is given by the half-width at half-maximum (HWHM) of the resonance. Using the Bose-Einstein equation $\bar{n} = 1/(e^{\hbar\Omega/k_B T} - 1)$, the effective temperature of the resonant phonons (Ω) can be calculated. In Fig. 1 a) the change in effective temperature for the anti-Stokes phonons is shown, being reduced from 293 K at room temperature to 74 K. The asymmetry between Stokes and anti-Stokes peaks is another footprint of phonon cooling, shown in Fig. 1 b).

An effective temperature decrease by 219 K has been measured, which is an improvement of factor 4 to 8 to previously reported experiments [2, 3].

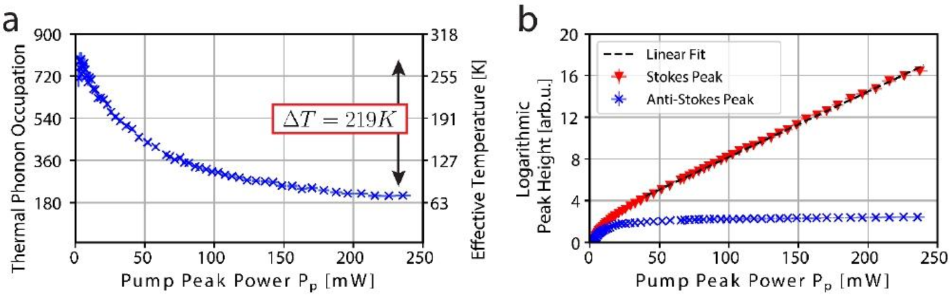

Fig. 1 **a** Decrease of acoustic phonon population and effective temperature of the resonant anti-Stokes phonons with frequency $\Omega = 7.35\ GHz$ as a function of pump power. **b** Peak height in logarithmic scale of Stokes (red) and anti-Stokes (blue) Brillouin resonances as a function of pump power.

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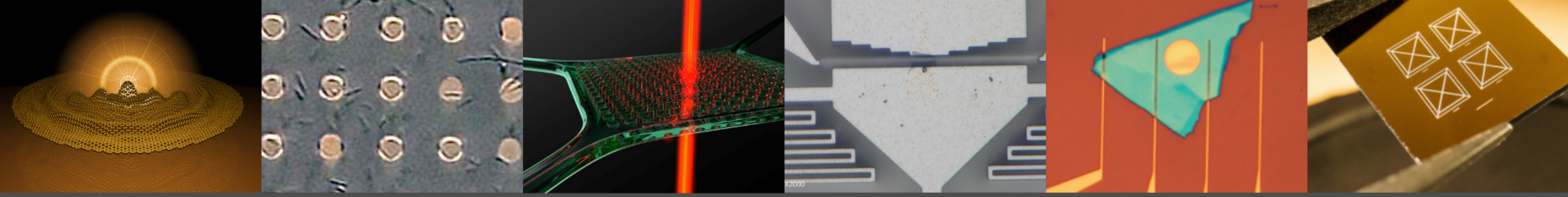

Frontiers of Nanomechanical Systems (FNS) workshop
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Surface-acoustic-wave induction of a giant synthetic Hall effect in graphene

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Any departure from graphene's flatness leads to the emergence of artificial gauge fields that act on the motion of the Dirac fermions through an associated pseudomagnetic field.[1] Here, we demonstrate the tunability of strong gauge fields in nonlocal experiments using a large planar graphene sheet that conforms to the deformation of a piezoelectric layer by a surface acoustic wave. The acoustic wave induces a longitudinal and a giant synthetic Hall voltage in the absence of external magnetic fields. The superposition of a synthetic Hall potential and a conventional Hall voltage can annihilate the sample's transverse potential at large external magnetic fields. Surface acoustic waves thus provide a promising and facile avenue for the exploitation of gauge fields in large planar graphene systems.[2]

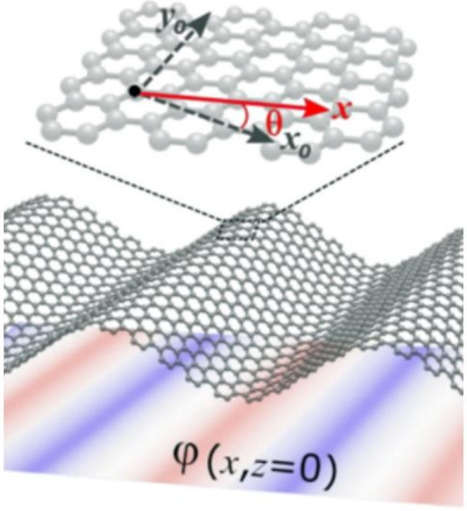

Figure 1: Acoustically driven graphene inducing a synthetic Hall voltage.

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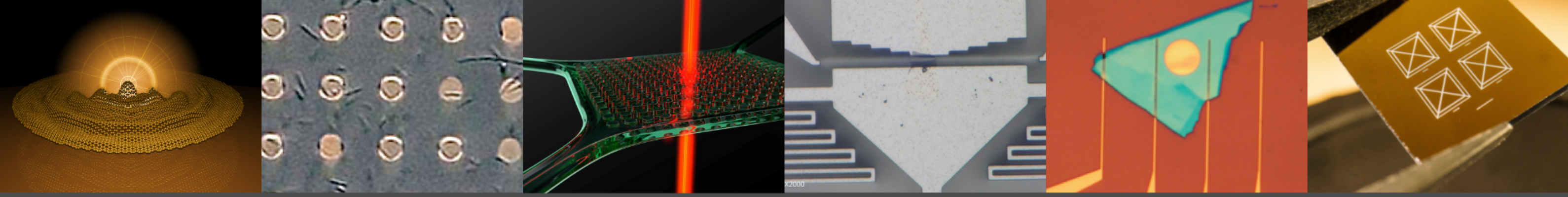

Frontiers of Nanomechanical Systems (FNS) workshop
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Symmetry breaking in a parametrically modulated quantum oscillator

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A weakly damped nonlinear oscillator modulated close to twice its eigenfrequency can have two stable states with the same vibration amplitudes but opposite phases. The states are equally populated due to classical or quantum fluctuations. In the absence of coupling to a thermal bath, the dynamics in the rotating frame is determined by the Hamiltonian $g(Q,P)$ that has two symmetric wells as a function of the coordinate Q (Fig. 1).

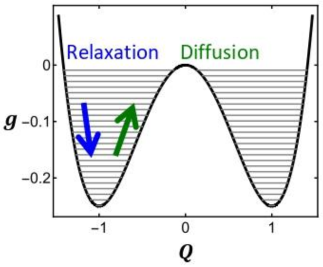

Fig. 1: *Relaxation and Diffusion over the rotating wave energy states.*

Coupling to a thermal reservoir leads to transitions between the Fock states of the oscillator. For zero temperature, the energy of the oscillator in the lab frame decreases in each transition. At the same time, the value of g can decrease or increase as a result of a transition, albeit with unequal probabilities. Relaxation results from transitions toward smaller g, which are more likely than transitions where g increases. However, due to a finite probability of transitions toward larger g, the relaxation is accompanied by diffusion over the oscillator states in the rotating frame. Ultimately, this diffusion results in overbarrier transitions between the wells [1, 2].

An extra force at half the modulation lifts the symmetry of the wells and therefore the symmetry of the states (Fig. 2). This leads to a change of the rates of interwell transitions. In the classical regime this change was studied in [3,4].

Here we study how a force at half the modulation frequency affects the oscillator dynamics in the quantum regime. As we show, a significant change of the state populations can take place already where the force is comparatively weak. The mechanism is the force-induced change of the rates of interstate switching. The change is exponential in the ratio of the force amplitude to the appropriately scaled quantum length. It is large even where the effect of the force on the mean-field oscillator dynamics is small. This provides a mechanism for a transition to the time-crystal phase in coupled quantum oscillators.

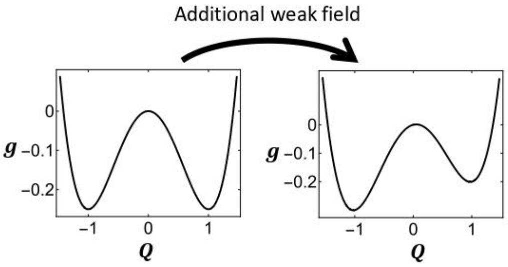

Fig. 2: *Symmetry breaking of the rotating wave energy g due to an extra force at half the modulation frequency.*

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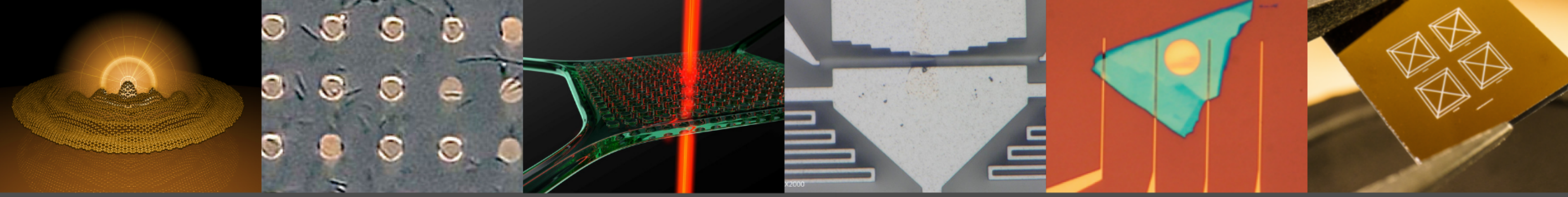

Frontiers of Nanomechanical Systems (FNS) workshop
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OPTICAL COHERENT FEEDBACK CONTROL OF A MECHANICAL OSCILLATOR

Maryse Ernzer[1], **Manel Bosch Aguilera***, **Matteo Brunelli**[1], **Gian-Luca Schmid**[1], **Thomas Karg**[1],
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Quantum feedback is a powerful technique for cooling and controlling quantum systems. The conventional strategy relies on quantum-limited measurements followed by classical processing and feedback actuation onto the system. However, quantum mechanics also allows for coherent feedback of quantum signals, without destroying coherence in the process. Such coherent feedback may exploit the information stored in non-commuting observables, while circumventing the decoherence and back-action noise associated with a measurement. Coherent feedback has thus the potential to improve quantum control and provide new capabilities in a broad range of physical systems [1–3].

We have implemented a coherent feedback platform in an optomechanical system and used it to control and cool the vibrations of a nanomechanical membrane [4]. In our coherent feedback setup [see Fig. 1] a beam of light feeds back signals on a nanomechanical membrane placed inside an optical cavity, by making the beam interact with the membrane multiple times in a closed-loop geometry mediating self-interactions. The originality of the proposed feedback platform is that feedback is directly applied onto the mechanical mode, which interacts twice with the same light field, but on different cavity modes. This allows to independently tune each interaction by manipulating the light field in between, introducing quadrature rotations and phase shifts, time delays, and in principle even nonlinear optical operations.

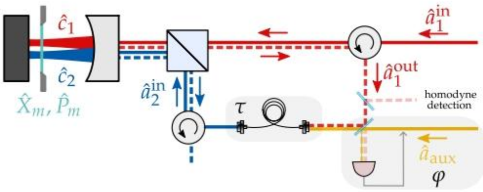

Figure 1: An incoming light beam $\hat{a}_1^{\text{in}}$ is injected into an optomechanical cavity, where it drives the cavity field $\hat{c}_1$ that interacts with a mechanical oscillator with quadratures $\hat{X}_m, \hat{P}_m$. The back-reflected beam $\hat{a}_1^{\text{out}}$ is combined with an auxiliary local oscillator mode $\hat{a}_{\text{aux}}$ to control the phase of the feedback loop φ. The combined field is delayed by τ with the help of an optical fiber, before being sent back as input $\hat{a}_2^{\text{in}}$ for a second interaction with the mechanical oscillator in an orthogonal polarization cavity mode $\hat{c}_2$. The outgoing light after the second interaction leaves the loop. A small fraction of $\hat{a}_1^{\text{out}}$ is picked up for detection and phase locking of the loop.

Tuning the optical phase and delay of the feedback loop allowed us to control the motional state of the mechanical oscillator, its resonance frequency and damping rate, the latter of which we used to cool the membrane close to the quantum ground state. Our theoretical analysis provides the optimal cooling conditions, showing that this new technique enables ground-state cooling. Experimentally, we showed that we can cool the membrane to a state with $\bar{n}_m = 4.89 \pm 0.14$ phonons (480 µK) in a 20 K environment. This lies below the theoretical limit of cavity dynamical backaction cooling in the unresolved sideband regime. Our feedback scheme is very versatile, offering new opportunities for quantum control in a variety of optomechanical systems.

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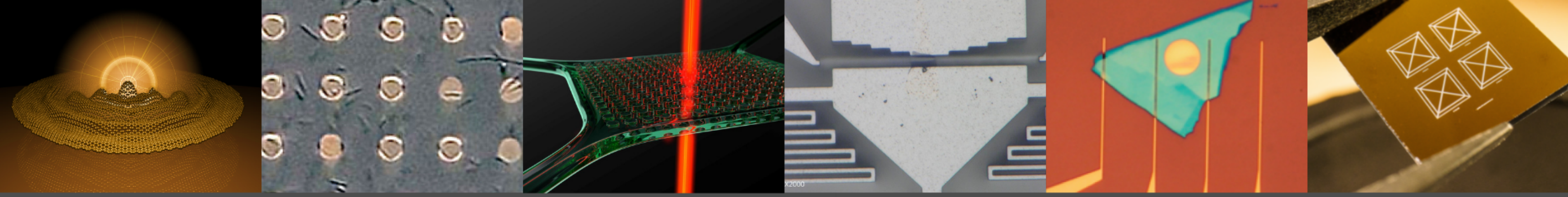

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`har.py`: Automatic Nano-Harp Characterization

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Nanostring resonators present a promising platform for sensing applications, signal processing and quantum information technology. Often only one or a few mechanical modes are directly relevant for the application. The remaining mechanical spectrum usually does not receive much attention, because its characterization is a time consuming task. However, the full mechanical spectrum of a string resonator is a sensitive probe for various mechanical and material parameters [1, 2]. The spectra of a "nano-harp", i.e. a series of string resonators with varied geometries, encode valuable information for process optimization. Nevertheless, full characterization of such a nano-harp is a tedious task and therefore often unfeasible.

To overcome this, we present a method to automatically record all visible flexural modes for such harps of string resonators. The method works for any setup that allows recording local mechanical response spectra and that allows scanning the measurement position across the sample. Steppers without absolute position feedback suffice and no additional imaging is required. We apply this method to harps of highly stressed SiC nanostring resonators and demonstrate how this helps to speed up the process and sample design development. The source code of our python implementation of this method is available upon request.

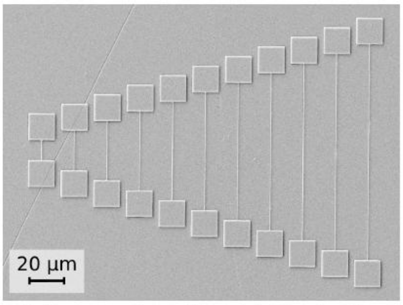

Figure 1: SEM micrograph of a series of string resonators with varied string lengths: a "nano-harp". Reprinted from [2], with the permission of AIP Publishing.

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Frontiers of Nanomechanical Systems (FNS) workshop
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Real-time measurements of a carbon nanotube electromechanical system hosting a double-quantum dot

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Mechanical resonators are systems that present high-quality factors and can easily couple to a wide range of forces rendering them excellent candidates for sensing and quantum information. In particular, carbon nanotubes (CNTs) have been exploited in many fields such as mechanical oscillators due to interesting proprieties [1]. Quantum dots (QDs) have been defined in nanotubes to read out and control the mechanical motion electrically [2]. One of the main difficulties in quantum dots defined in a carbon nanotube is measuring the system's dynamics when the electrons are bounded in the quantum dot, where common techniques based on conductance measurements are not applicable. This state is however interesting for the realization of electro-mechanical qubits, ultraprecise sensors, and quantum simulators [3]. The target is to employ CNT-based sensing dots to carry out real-time measurements of a carbon nanotube electromechanical system hosting a double quantum dot at a timescale faster than the mechanical period.

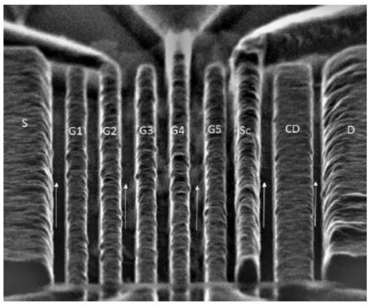

Figure 1 G1-G5 to full control the DQD and CD control the charge sensor QD. Arrows points the suspended CNT

In order to achieve the target we have fabricated a CNT suspended over 5 gates (needed to fully control double quantum dots (DQD)) and in addition to this, a contacted side segment of the system (SC,CD, and D in the figure1) to create a QD, also defined in the same CNT suspended over the 5 gates, that serves as a charge sensor (CS). CS monitors the DQD without interfering with the system, solving the previously mentioned problem.

Looking ahead, the next step will be measuring the device at low temperature in order to do Real-time measurements in the Coulomb blockade state and to detect the mechanical motion of the CNT down to the level of its zero-point motion. This system is also the first step for engineering a model system in which electronic degrees of freedom are defined within four quantum dots and coupled to the vibrational modes of the CNT. If successful, the project will enable the first experimental platform for the quantum simulation of electron-phonon coupling. [4]

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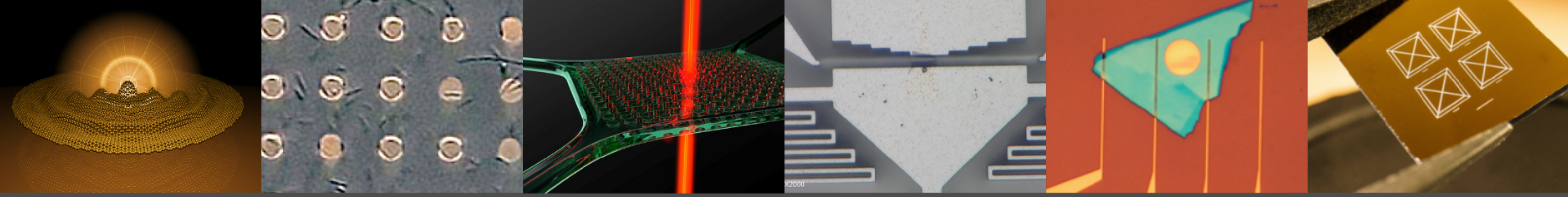

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Collective dynamics in circuit optomechanical systems

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Optomechanical systems are polyvalent platforms suited for controlling an extremely long-lived mechanical degree of freedom, realizing high-precision sensors, and benchmarking quantum mechanics at a macroscopic scale. Nevertheless, most of their implementation fails to harvest the advantages of multimode systems, mainly due to challenges in realizing reproducible mechanical, optical, and microwave resonances. Here, we investigate multiple nearly degenerate mechanical oscillators optomechanically coupled to a shared microwave resonator, implemented by superconducting mechanically compliant vacuum gap capacitors shunted by spiral inductors. We show that the mechanical oscillators undergo a transition from individual to collective dynamics as their optomechanical interactions are enhanced. Theoretical studies and numerical simulations show that observing the collective behavior strongly depends on the disorder of the mechanical frequencies. We finally study the sideband cooling of multimode mechanical systems, where one collective mechanical mode is efficiently cooled down while the individual modes retain the large phonon occupations. Our design allows us to measure the occupation of individual mechanical oscillators by coupling each of them to an auxiliary microwave resonator.

By optimizing our circuit optomechanical platform [1], we achieved extremely low disorders among mechanical oscillator frequencies, less than 0.1%, and observed the transition from the individual ones to the collective mechanical mode, and, even further, the strong coupling of the collective mechanical mode and the microwave resonator. With high quality factor of the mechanical oscillators, each above 10 million, we could cool the collective mode close to the ground state. In the near future, we can use the same system to study the entanglement among multiple macroscopic mechanical oscillators.

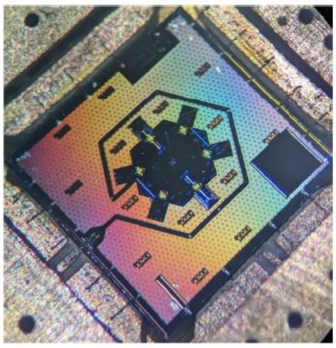

Figure 1: 6 coupled optomechanical systems with degenerate mechanical oscillators and auxiliary microwave resonators.

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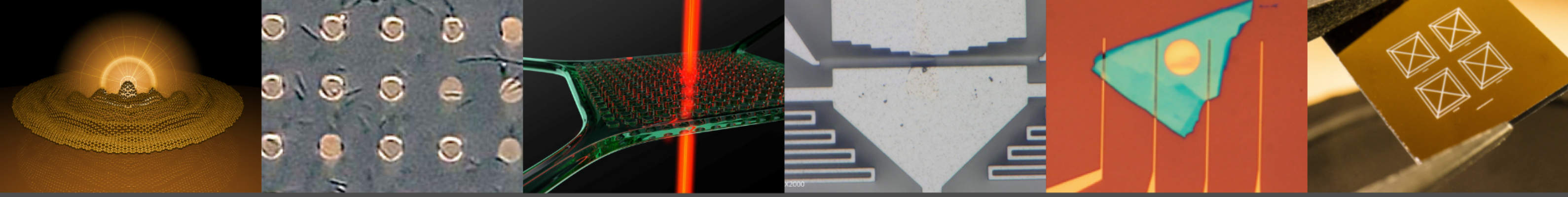

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Frequency combs generated from strong nonlinear modes in a doubly clamped nanomechanical beam

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Nonlinearity is a fascinating phenomenon that offers rich physics not present in the linear domain and potential for a range of applications [1-3]. This nonlinearity is easily visible in nanomechanical systems, especially those with high sensitivity due to their small device sizes. We investigated the nonlinearity of a doubly-clamped nanobeam at low temperature by strongly driving it. Surprisingly, we were able to observe dips appearing in certain parts of the frequency-amplitude curves despite being far from coupling with higher mechanical modes, and frequency combs were detected at those points simultaneously in mechanical modes and higher harmonics signals [4].

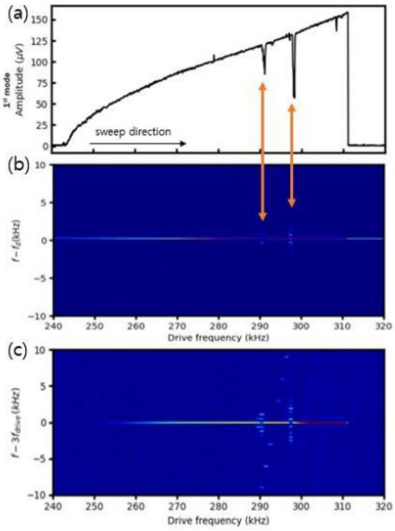

Figure 1. (a) Amplitude response curve of the 1st mode of the resonator as a function of drive frequency f_d. Specific frequencies exhibited dips in amplitude during the frequency sweep. (orange double-headed arrows) (b) Spectra of 1st mode for increasing drive frequency. (c) Spectra of 3 times harmonics generated by 1st mode for increasing drive frequency.

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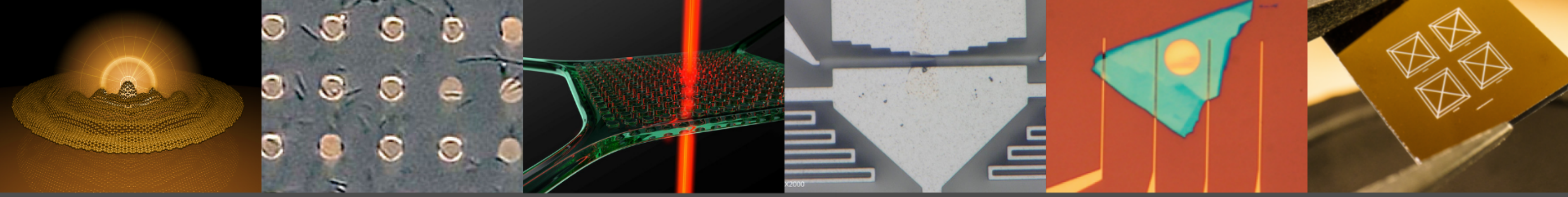

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Quantum well exciton polaritons in an disk optomechanical microcavity

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Maximizing optomechanical cooperativity is a key task in the field of optomechanics, as it allows for more precise control and manipulation of mechanical systems using light. One strategy for achieving this is to use exciton polaritons, which are hybrid particles formed by the superposition of confined photons and excitons in a semiconductor microcavity [1]. Exciton polaritons have an ultra-small effective mass due to the IR photonics component, which allows them to form Bose Einstein Condensates at relatively elevated temperatures. Additionally, their strong nonlinearity inherited from the exciton part makes them sensitive to strain fields, making them suitable for obtaining strong optomechanical interactions [2]. This approach has the potential to increase the optomechanical coupling g0, relaxing the need for small optical linewidth and low mechanical dissipation rates. Our work explore the potential of polaritons in micro-disk optomechanical resonators.

Our hybrid optomechanical systems consist of a Gallium Arsenide (GaAs) resonator with an embedded InGaAs quantum well (QW) (Fig 1). These resonators form a three-partite system combining high frequency ($\sim$0.7-1 GHz) mechanical modes, high-quality ($Q_o \sim 10^5$) optical whispering gallery modes (WGMs), and QW excitonic modes. The confinement of the optical and excitonic modes in a sub-micron volume results in strong exciton-photon coupling, leading to the formation of polaritons.

We present experimental results demonstrating the generation of polaritons in our disk structure. Using confocal microscopy at low temperature and near-field experiments with a nanophotonic waveguide integrated on the chip and coupled to the disk, we observe the strong coupling signatures of polaritons, such as anti-crossing, and measure Rabi splitting values between 6 and 10 meV. These results agree with a Hopfield model that includes analytical expressions for Rabi coupling in gallery mode resonators. In addition, we present the first optomechanical experiments performed on our hybrid platform, showing the potential for using these systems for exploring a range of phenomena, including polariton lasing and exploring quantum fluids properties on heavy objects.

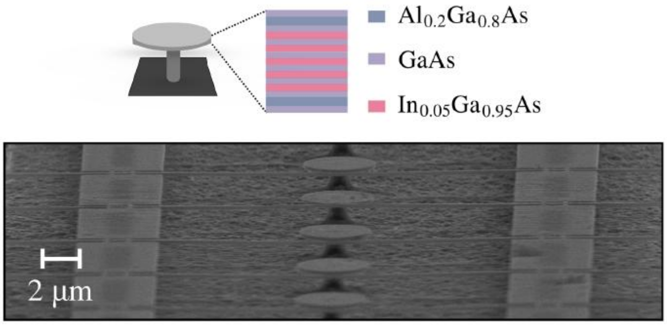

Figure 1: Multiple quantum well InGas/GaAs heterostructure

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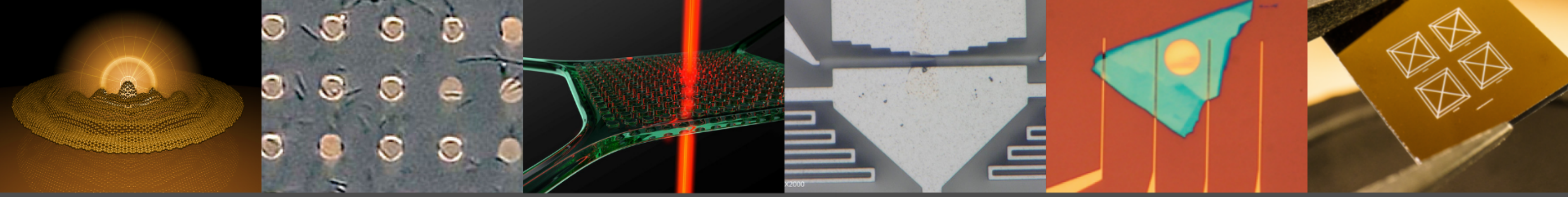

Frontiers of Nanomechanical Systems (FNS) workshop
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Centimeter-scale nanomechanical resonators with ultralow dissipation

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Strained mechanical resonators with high aspect ratio are extensively used in precision sensing over a wide length-scale range, from centimeter-long resonators employed as mirror suspensions in gravitational-wave detectors [1], to on-chip nonomechanical resonators enabling ultra-sensitive force sensing and quantum optomechanics [2]. Their widespread use owes to their exceptionally low mechanical dissipation, as the combination of high aspect ratio and high tensile stress allows extremely high quality factors.

The perspective of increasing even further the aspect ratio would lead to resonators with centimeter-scale length and nanometer thickness, unlocking new regimes unexplored with on-chip devices thus far. Yet, the extreme aspect ratio comes with new and unprecedented challenges in terms of high computational cost of the design process and fabrication limitations to successfully suspend the structures.

Here we combine multi fidelity Bayesian optimization with novel fabrication processes to develop and fabricate silicon nitride mechanical resonators with centimeter-length and nanometer thickness. The fabricated devices are then experimentally measured, showing a quality factor approaching 10 billion at room temperature, value only shown at cryogenic temperature with crystalline materials until now. This results in manifold advantages as larger coherence time, higher spectral purity, enhanced force sensitivity and large frequency stability, opening new doors for both fundamental physics and sensing applications [3].

Figure 1: (LEFT) Multi fidelity Bayesian optimization iterations. (CENTER) microscope pictures of the fabricated devices. (RIGHT) Ringdown measurement.

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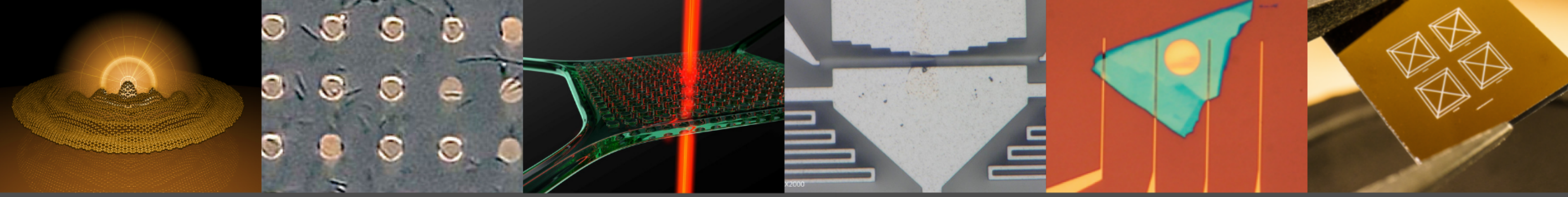

Frontiers of Nanomechanical Systems (FNS) workshop
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Ultra-strong coupling between two harmonic oscillators

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Cavity-optomechanical systems provide means to control and manipulate the state of massive mechanical oscillators. Using such devices, quantum ground state cooling of the mechanical resonator[1], coherent state transfer between optical and mechanical mode[2], quantum entanglement between two mechanical oscillators[3], and storage of quantum information in the mechanical domain has been demonstrated. We developed an optomechanical device based on a 3D superconducting waveguide cavity and a nanomechanical resonator. By driving the system parametrically, the two oscillators can be brought into resonance. By tuning the strength of the parametric pump, we achieve the ultra-strong coupling, a regime where the coupling strength becomes comparable to the frequency of the mechanical resonator itself, exceeding all the system's dissipation rates. The maximum coupling strength we were able to achieve is 37% of the frequency of the mechanical resonator. With further increase in the pump strength, we reach a domain were the cavity-optomechanical system becomes unstable leading to some interesting behaviours and a deeper insight into the system. Below is the image of the mechanical oscillator that is coupled to a 3D waveguide cavity.

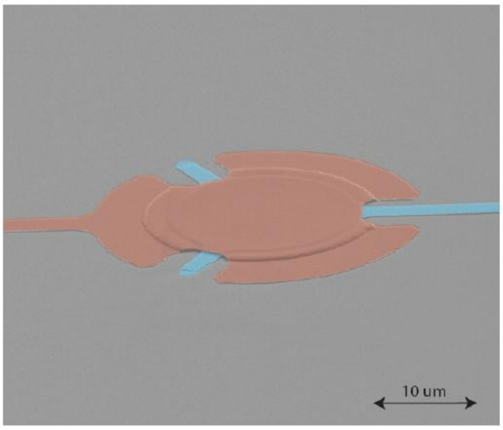

Figure 1: Mechanical oscillator

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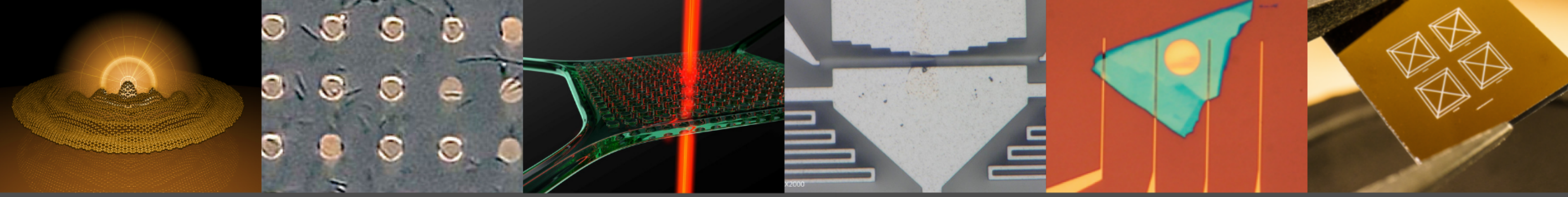

Frontiers of Nanomechanical Systems (FNS) workshop
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Dry processing of high Q 3C-silicon carbide nanostring resonators

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We fabricate string resonators from strongly stressed 3C-silicon carbide (SiC) grown on a silicon substrate. In the conventional fabrication process, we do electron-beam lithography with PMMA to define a metallic hard mask for the subsequent dry-etching step via a liftoff process. This requires some wet-chemical process steps, which can destroy our samples. Here we describe an alternative process, which avoids all wet-chemical process steps to enable superior quality. It involves the use of a negative electron-beam resist as an etch mask, as well as the completely reactive-ion etching-based release of the nanostrings. The dry-processed nanostrings can be fabricated with a high yield and exhibit high mechanical quality factors at room temperature for various string lengths.

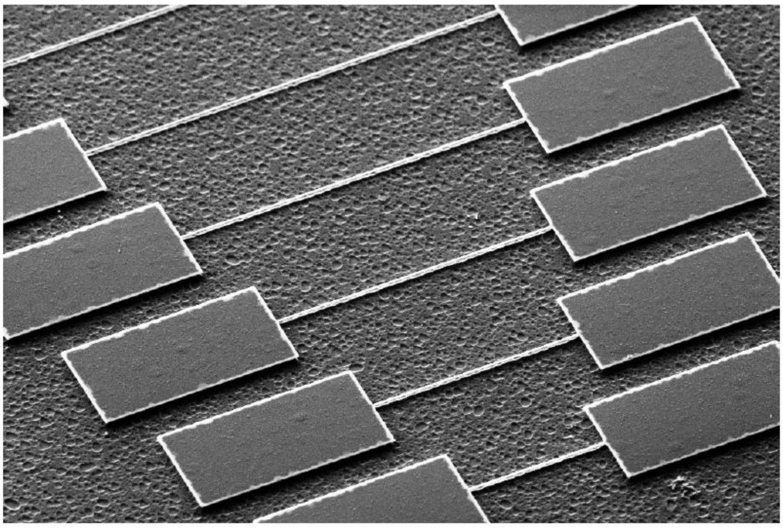
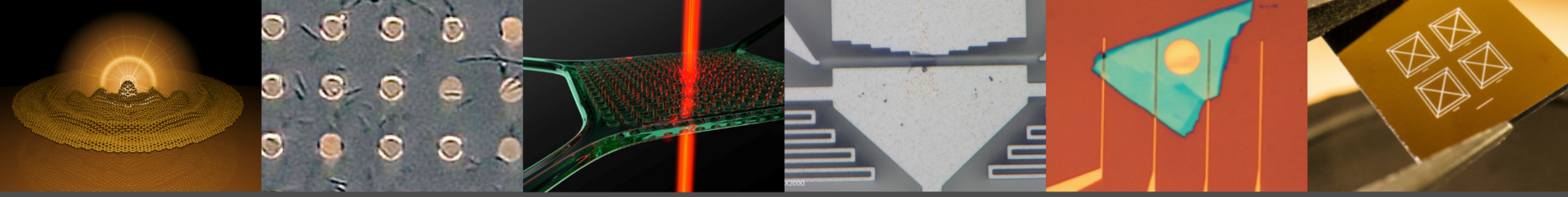


Figure 1: Dry-processed string resonator array with variation in string length.



Frontiers of Nanomechanical Systems (FNS) workshop
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Mechanical overtone frequency combs

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Mechanical frequency combs have recently seen a growth of interest. On one side, there is increasing attention for the quasi-periodic behavior of nano- and micromechanical systems from the field of nonlinear dynamics[1]. On the other side, the fixed frequency relation and long coherence time of mechanical frequency combs form appealing properties for applications in sensing[2] and quantum acoustics[3]. So far, the main challenge of these combs has been the strict requirements on drive frequencies and power. We recently demonstrated[4] a mechanism by which the modes of a suspended micromechanical (trampoline) resonator can be made into a frequency comb, without any external drive frequency. This is based on the dielectrophoretic force that this resonator experiences from an incident laser that is reflected by the substrate surface below the resonator. The same optical field is also responsible for an optothermal parametric drive that is enhanced by the photonic crystal structure patterned on the suspended resonator. Together, these effects greatly simplify the creation and operation of mechanical frequency combs, which provides a path forward for future applications.

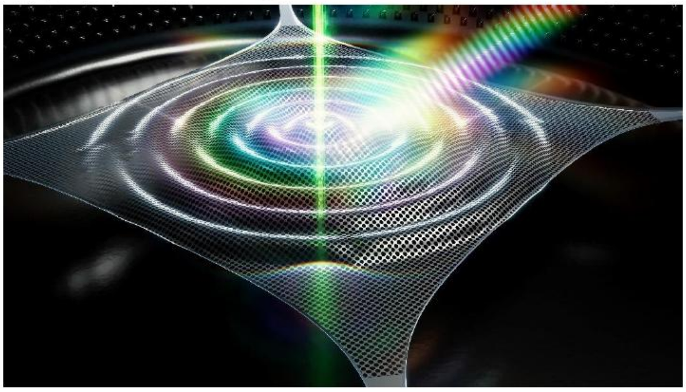

Figure 1: Artist's impression of mechanical overtone frequency comb

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Frontiers of Nanomechanical Systems (FNS) workshop
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Anomalous nonlinear features in the self-oscillation regime of microwave optomechanical devices

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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.

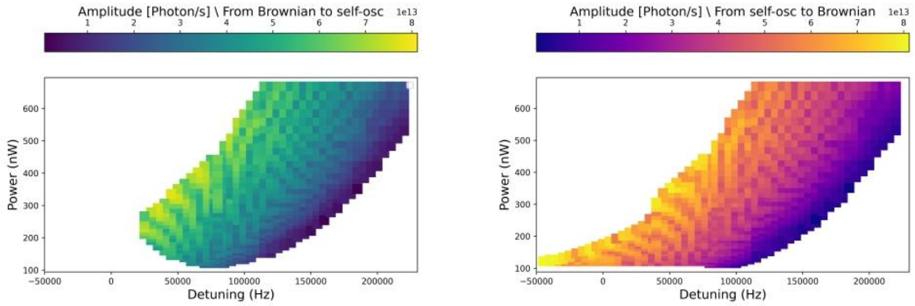

Figure 1: Self-oscillation amplitude (photons/s, T = 600 mK) measured when entering from the Brownian state (left), or leaving self-oscillation (right), as a function of pump power (nW) and detuning ($\Delta = \omega_{pump} - (\omega_{cavity} + \omega_{mechanics})$, Hz).

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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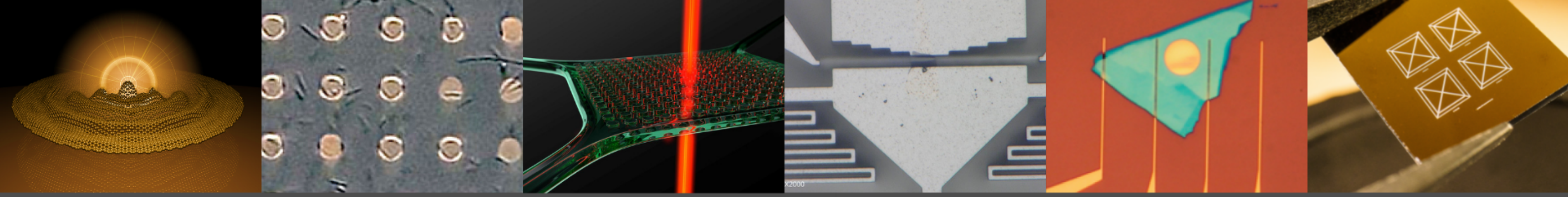

Frontiers of Nanomechanical Systems (FNS) workshop
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FABRICATION OF SIC OPTOMECHANICAL CRYSTALS

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Optomechanical crystals, which were introduced with the silicon material base, have proven to precisely control the mechanical vibrations with the means of optical fields by radiation pressure interaction. [1]. Similar platforms are also used in the diamond material base with having a potential to achieve spin-phonon interactions. [2].

Here we focus on optomechanical crystals in silicon carbide (SiC). SiC is a relatively new material in the fields of optomechanics and nanomechanics which possesses spin defects. It is significantly easier to process than diamond, and chemically more stable than silicon.

We demonstrate the fabrication steps of optomechanical crystals made from thin film SiC grown on silicon wafers oriented along the 100 and 111 crystal directions.

We will also discuss the impact of 4 different mask materials on the dry anisotropic etching of SiC and isotropic dry/wet etching of silicon.

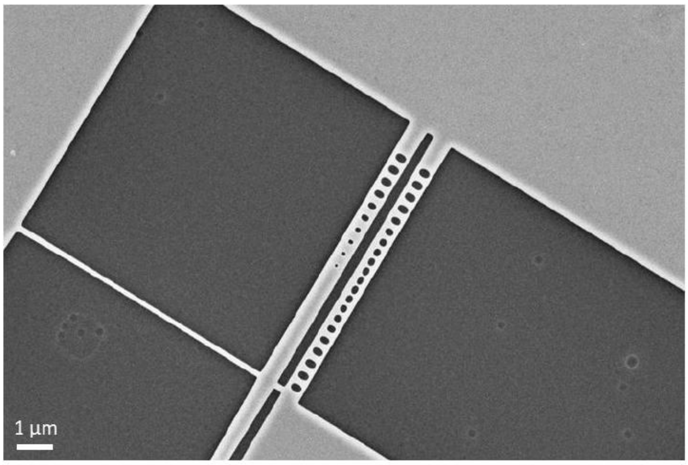

Figure 1: SiC (grown on 100 Si) optomechanical crystal with a coupling waveguide.

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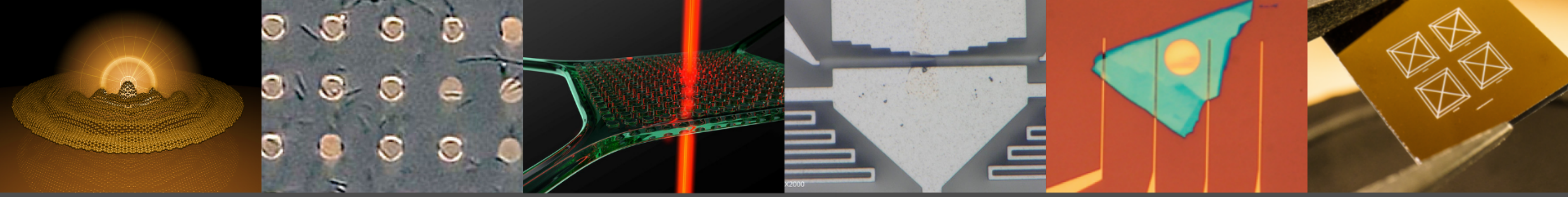

Frontiers of Nanomechanical Systems (FNS) workshop
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Energy dissipation in 3D-printed polymer micro-resonators

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Biosensors measuring properties like mass, density and stiffness on a single cell level can help diagnose diseases [1]. Mass sensing of cells, bacteria and viruses is typically performed with resonant microstructures. Polymer micro devices are attractive for their ease of fabrication and low cost [2]. Recently such microstructures were fabricated using an emerging 3D printing technique called two-photon polymerization (2PP), as an alternative to conventional lithography-based fabrication [3]. In this work, we printed microcantilevers and microbridges from IP-S polymer (elastic modulus ~ 4MPa), annealed and analyzed their dissipation characteristics. The printed cantilevers/bridges had a quality factor up to 1000. Tensile-stressed narrow bridges (Fig 1A) achieved a record quality factor of 1819 (Fig 1B). After analyzing various damping mechanisms in our devices, we concluded that energy dissipation in our polymer devices was mainly dominated by bulk friction damping. Our next step is to print suspended microchannel resonators to analyze particles of biological interest suspended in their native liquids.

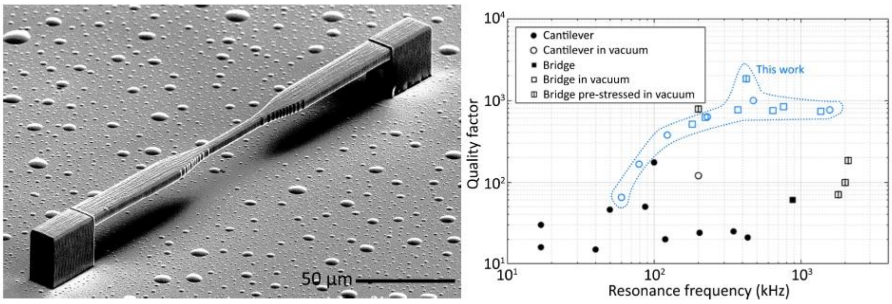

Figure 1: Energy dissipation in 3D-printed polymer bridge. A) A two-photon polymerized thin narrow bridge IP-S polymer bridge. B) Experimentally measured record-breaking quality factors in polymer resonators.

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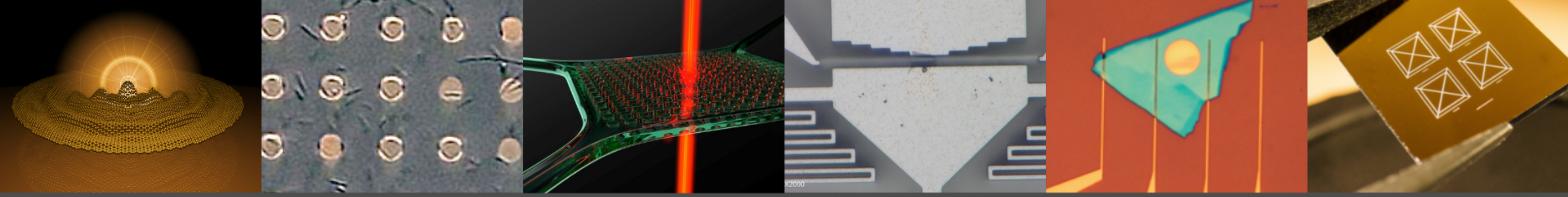

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Toward Room-Temperature Observation of Quantum Radiation Force Noise Driving a Trampoline's Motion

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When coherent light reflects from a mechanical element, the momentum "kicks" from randomly arriving photons produces a white force noise – the shot noise or quantum noise of light. We aim to create a sufficiently sensitive mechanical "microphone" capable of hearing the "hiss" of the photons landing on it.

We present our progress toward realizing such system, illustrated in Fig. 1(a). The motion of a high mechanical-Q silicon nitride trampoline mechanical element is predicted to be dominated by this quantum laser noise over a broad range of frequencies – kHz to MHz – *and* at room temperature, as shown in Fig. 1(b). Thus far, we have mounted a $Q > 10^7$ trampoline within a $\sim$ 50-micron-long, finesse $\sim 10^4$ fiber-cavity (an optical resonator) inside a 10^{-8} torr vacuum chamber. We locked a 1550 nm continuous-wave laser to the cavity resonance using a combination of mechanical [1] and radiation pressure feedback [2]. We are currently limited by the non-linear readout of the trampoline's motion due to its large thermal motion – thermal intermodulation noise [3] – and are working on optically cooling while stiffening the trampoline using two lasers [4].

We predict that systems like these should be able to produce squeezed light over similar frequency ranges (kHz to MHz), and measure motion near the "standard quantum limit" (SQL) at room temperature. Furthermore, they could be used to produce room temperature entanglement between laser beams or two mechanical elements.

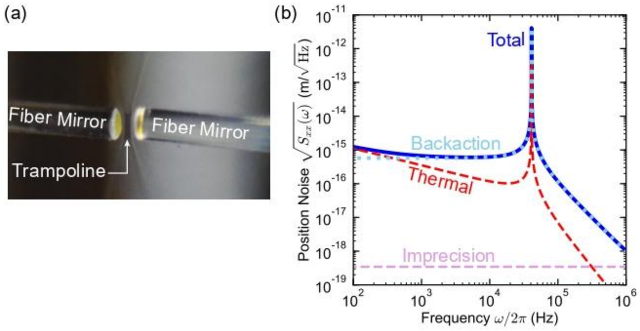

Figure 1: Toward observation of broadboad room temperature quantum radiation pressure force noise. (a) Photograph of our optical cavity formed by two fiber mirrors, with a trampoline at its center. (b) Predicted equivalent position noise amplitude spectral density of a trampoline at room temperature for readily achievable experimental parameters (trampoline of frequency $\Omega_m/2\pi = 41$ kHz, quality factor $Q = 40 \times 10^6$ placed in a cavity of finesse $\mathcal{F} = 10^4$ and length $L = 100$ µm and circulating power $\bar{P}_{\mathrm{circ}} = 1$ W). Dashed pink is imprecision noise (due to laser shot noise), dashed red is thermal noise, dotted light blue is quantum radiation force noise, and dark blue curve is the quadrature sum of these contributions. From ~1 kHz to 1 MHz the quantum noise of a laser is predicted to dominate the motion of a trampoline such as the system shown in (a).

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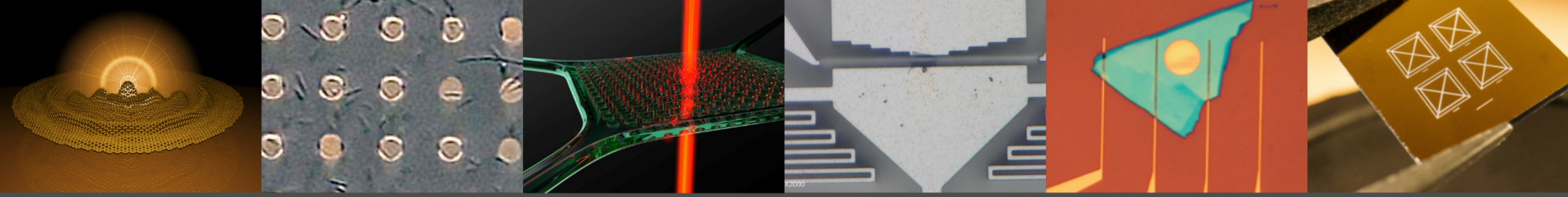

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

ENHANCING THE SENSITIVITY OF SILICON PHOTONIC ULTRASOUND SENSORS BY OPTIMIZING THE STIFFNESS OF POLYMER CLADDING

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Ultrasound is widely used for medical imaging, and photo-acoustic imaging is an emerging modality for the diagnosis of diseases. Currently, photo-acoustic imaging systems still use piezo-electric materials to detect ultrasound waves. These materials have limited sensitivity and bandwidth. Future applications of this modality require a large matrix of broadband, high-resolution, highly-sensitive, and scalable ultrasound sensors. To meet these requirements, silicon photonic circuits have been utilized as ultrasound sensors [1]. Namely, a silicon photonic waveguide deforms when the ultrasound pressure waves impinge on it, leading to a change in effective refractive index, n_e, due to geometrical and photo-elastic effects. However, these effects are weak, which limit the intrinsic sensitivity of silicon photonic ultrasound detectors. Moreover, recent demonstrations of polymer-coated waveguides also enhanced the sensitivity of silicon photonic ultrasound sensors significantly, yet insufficient to reach acousto-mechanical-noise-limited sensing [2]. In this study, we investigate the effect of mechanical and optomechanical properties of polymer claddings on the sensitivity of silicon photonic ultrasound sensors. First, we model the refractive index sensitivity of silicon photonic waveguides to impinged pressure i.e. the change in n_e, due to change in incident pressure P and we find:

$$\frac{\partial n_e}{\partial P} = \frac{\partial n_e}{\partial n_c} \cdot \frac{\partial n_c}{\partial P} = -\frac{\partial n_e}{\partial n_c} \cdot \frac{1}{2} n_c^3 p_{12} \cdot \frac{(1-2v)(1+v)}{1-v} \frac{1}{E} \tag{1}$$

where n_c, p_{12}, E, and v are refractive index, elasto-optic coefficient, Young's modulus (stiffness), and Poisson's ratio of the cladding material, respectively. Second, we experimentally investigate the sensor sensitivity as a function of cladding stiffness. As a simple addition to the CMOS fabrication, PDMS with distinct curing-agent-to-base ratios were mixed and spin-coated on the silicon photonic ring resonators to prepare claddings with different stiffness(Fig. 1a-c). To characterize these sensors, ultrasound pulses were fired in water and the sensor response was recorded (Fig. 1d). Then the resonance shift sensitivity $(\partial\lambda_r/\partial P)$ was computed by normalizing the sensor sensitivity $(\partial I/\partial P = \partial I/\partial\lambda_r \cdot \partial\lambda_r/\partial P)$ to the photonic sensitivity $(\partial I/\partial\lambda_r)$. Young's modulus of the cladding was measured using nanoindentation and ultrasound sensitivities were compared to different cladding stiffnesses (Fig. 1e). The observed dependence is not inversely proportional (see Eq. (1) and Fig.1e, dashed line), which may be caused by several effects and requires further investigation. We demonstrated ultrasound sensing with enhanced sensitivity by optimizing cladding stiffness. Our aim is to enable silicon photonic ultrasound detectors for challenging photoacoustic imaging applications such as intra-vascular imaging or living mouse brain imaging.

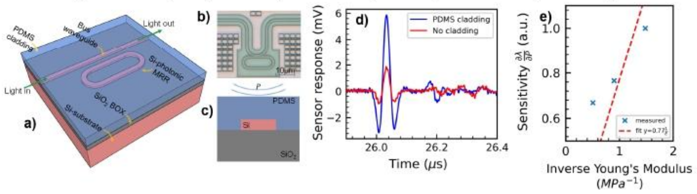

Figure 1: a) 3D sketch, b) microscope image, and c) cross-sectional sketch of the PDMS-coated silicon photonic ring-resonator. d) Recorded response of the silicon photonic ultrasound sensor to the incident ultrasound pulse with and without PDMS cladding (averaged 3000x). e) Resonance shift sensitivity for different stiffness of the cladding.

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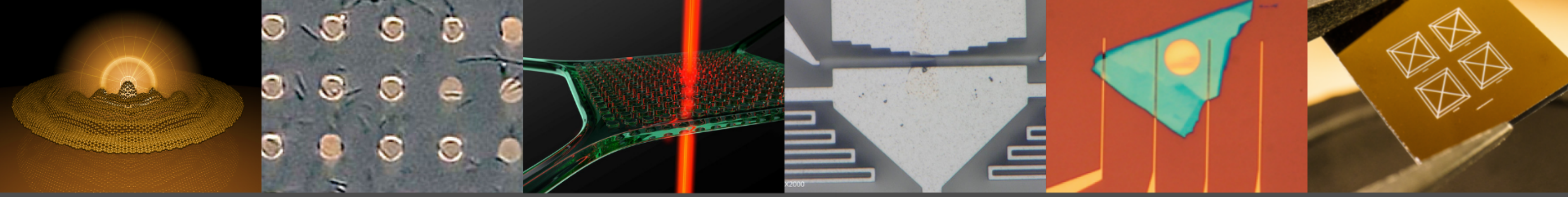

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Coherent feedback towards light-mediated mechanical self-interactions

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Coherent feedback has been proposed as a technique for quantum control of a physical system without introducing unnecessary noise due to a measurement process, an with the potential to use the simultaneous processing of two non-commuting quadratures [1, 2]. As such, coherent feedback has been put forward to allow for a multitude of interesting protocols, such as noise-cancellation, enhancement of entanglement, state swaps, generation of nonlinearities and improvement of the cooling performance [3].

The coherent feedback scheme that we have implemented consists in passing light through a membrane-in-the-middle optomechanical cavity setup in the unresolved sideband regime, and recycling the light after its first interaction to redirect it to the cavity in an orthogonal polarization. Before the second interaction with the light the loop phase can be adjusted such that the feedback signal is transduced onto the desired light quadrature. Moreover the delay of the feedback loop determines the specific mechanical quadrature that is fed back to the mechanical oscillator. [4]

Combining both high quality factor mechanical oscillators and a coherent feedback scheme, it becomes possible to realize quantum noise backaction cancellation and mechanical squeezing. By upgrading the mechanical oscillator to a high quality factor soft clamped membrane $Q > 10^7$, we are reducing the coupling to the thermal environment reservoir and thus easing the way to bring the mechanical motion into the quantum backaction dominated regime. Furthermore, as the coherent feedback scheme allows to tune the phase of the feedback loop, it can realize a destructive interference between the quantum backaction terms deriving from both the first and the second optomechanical interaction. Depending on the loop phase φ and up to the measurement efficiency η we can cancel the backaction at a rate that scales with the optomechanical coupling strength g following $\propto g(1+\eta\cos\varphi)$ [5]. The feedback loop does not only enable noise cancellation, but also the generation self-interactions. In fact the light beam that enters the cavity for the second time already contains a mechanical signal related to the position imprinted onto the light meter during the first interaction. When interacting with the mechanical motion for a second time, an interaction term $\propto \hat{X}_{\mathrm{m}}^2$ appears. This corresponds to a one-axis twisting interaction leading to mechanical squeezing at a squeezing rate $\eta g \sin\varphi$ [5].

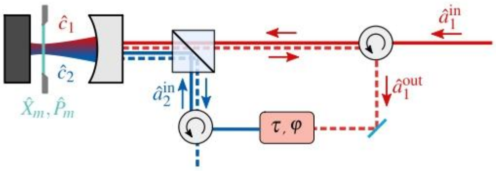

Figure 1: Coherent feedback scheme, where an ingoing light beam couples into a cavity, interacting with a mechanical oscillator. The back-reflected light is collected, and after experiencing a loop phase φ and a delay τ, redirected towards the cavity for a second interaction.

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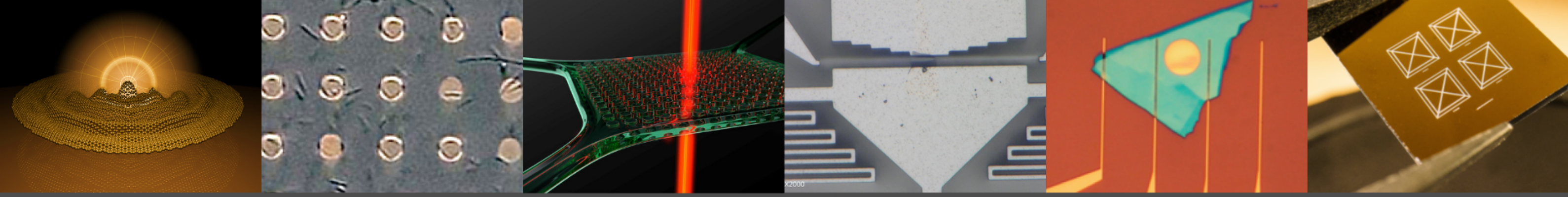

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METAMATERIALS OF FLUIDS OF LIGHT AND SOUND

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Lattices of exciton polariton condensates represent a rich platform for the study and implementation of non-Hermitian non-linear bosonic quantum systems. Actuation with a time dependent drive provides the means, for example, to perform Floquet engineering, Landau-Zenner-Stückelberg state preparation, and to induce resonant inter-level transitions. With this perspective we introduce polaromechanical metamaterials (Figs. 1a-b), two-dimensional arrays of μm-size zero-dimensional traps confining light-matter polariton fluids and GHz phonons.

A strong exciton-mediated polariton-phonon interaction [1] can be exploited in these metamaterials, both using electrically injected bulk-acoustic waves [2] or self-induced coherent mechanical oscillations [3], to induce a time-dependence in the level energies and/or in the inter-site polariton coupling J(t). This has remarkable consequences for the dynamics. For example, as shown in Fig.1c, when locally perturbed by continuous wave optical excitation, polaritons respond by locking the energy detuning between neighbor sites at multiples of the phonon energy [4]. We theoretically describe these observations in terms of synchronization phenomena involving the polariton and phonon fields. We study lattices of closely connected traps (defined by a linear optomechanical coupling), and also well separated traps (characterized by a quadratic optomechanical coupling), and discuss the role of dissipation and non-linearities in the stability of the observed asynchronous locking. The described metamaterials open the path for the coherent control of dissipative quantum light fluids with hypersound in a scalable platform.

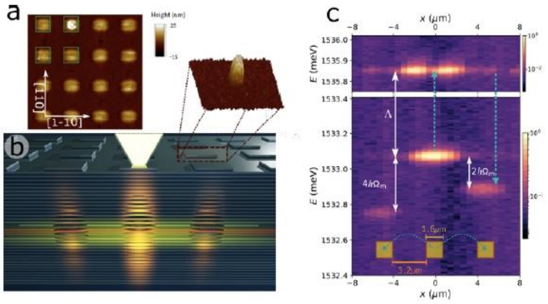

Figure 1: (a): AFM image of an array of 1 μm square intra-cavity traps. A scheme of the microcavity patterned with square-shape traps is presented in (b). Panel (c) shows the spatially resolved emission spectra obtained for focused non-resonant excitation with powers above the polariton condensation threshold. The central trap (x=0) and the two closest neighbors can be identified. Both s-like symmetry ground and p-like excited states of polaritons in the traps are observed. Note that the neighbor trap ground state energies asynchronously lock at relative detunings corresponding to 2 and 4 times the phonon frequency $\Omega_m/2\pi \sim 20$GHz.

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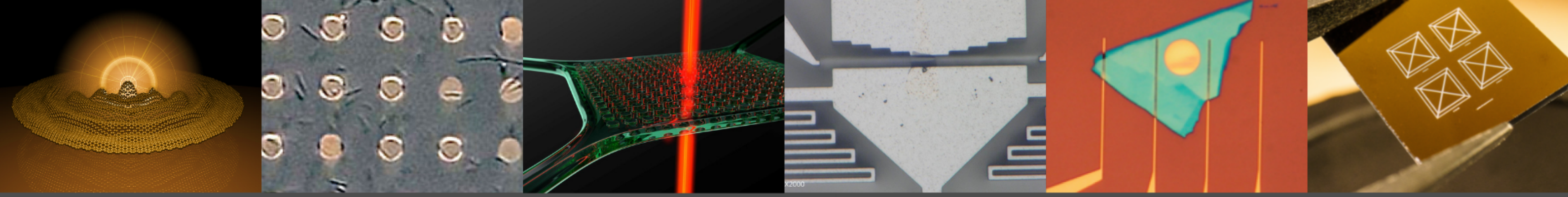

Frontiers of Nanomechanical Systems (FNS) workshop
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Development of continuous sub-mK refrigeration for ground-state cooling of mechanical resonators

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

Figure 1: The extremely low contact resistance between the aluminum and copper of this heat switch was achieved by plasma etching the Al and Cu and then depositing Au without breaking vacuum [2].

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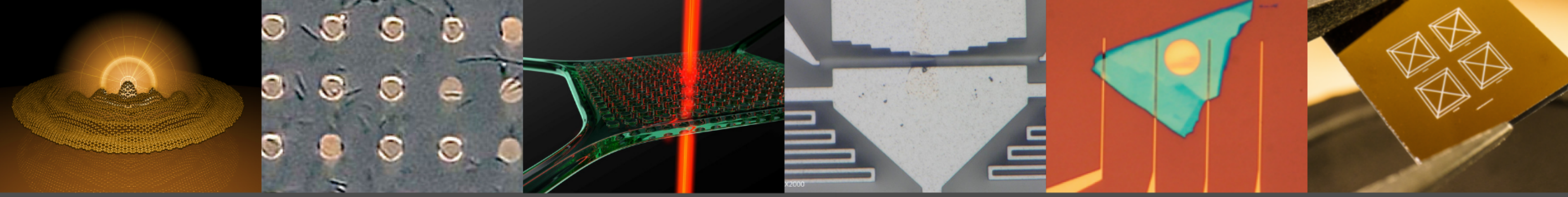

Frontiers of Nanomechanical Systems (FNS) workshop
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Mechanical mode imaging of a high-Q hybrid hBN/Si$_3$N$_4$ resonator

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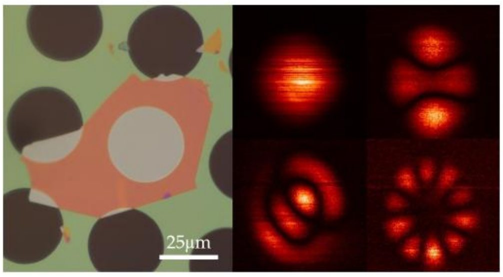
2D materials enable the fabrication of nanomechanical resonators with high aspect ratios, very low mass, and high resonance frequencies[1, 2]. They have remarkable mechanical properties, such as extremely high fracture strength and Young's Modulus[3]. A wide variety of 2D materials are now subject of large research efforts, due to their unique electronic, magnetic and optical features, as well as the potential to combine these materials in layered heterostructures[4]. Hexagonal boron-nitride (hBN)[5] is known to have comparable mechanical properties to graphene, but in contrast to graphene and other 2D materials it has a large bandgap making it a transparent insulator with low absorption. hBN has also been shown to host bright and stable quantum emitters, which are strain-coupled to the motion of the crystal lattice. These properties make hBN a prime candidate for optomechanical devices and integration into high-finesse optical cavities.



In this work [6] we imaged and characterized the mechanical modes of a 2D drum resonator made of hBN suspended over a high-stress Si3N4 membrane. Our measurements demonstrate hybridization between various modes of the hBN resonator and those of the Si$_3$N$_4$ membrane. The measured resonance frequencies and spatial profiles of the modes are consistent with finite-element simulations based on an idealized geometry. Spectra of the thermal motion reveal that, depending on the degree of hybridization with modes of the heavier and higher-quality-factor Si$_3$N$_4$ membrane, the quality factors and the motional mass of the hBN drum modes can be shifted by orders of magnitude. This effect could be exploited to engineer hybrid drum/membrane modes that combine the low motional mass of 2D materials with the high quality factor of Si$_3$N$_4$ membranes for optomechanical or sensing applications.

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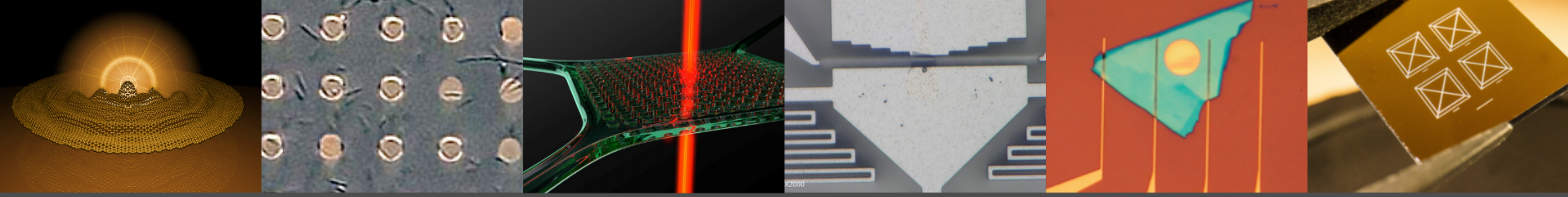

Frontiers of Nanomechanical Systems (FNS) workshop
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A nano-electromechanical quantum simulator

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Electron-phonon interactions lead to a plethora of phenomena in strongly correlated solid-state systems such as superconductivity and charge-density waves. However, the complex dynamics manifesting these phases can be beyond the reach of computational modelling, especially when taking into account electron-electron interaction. Therefore, one of the outstanding challenges in the field of correlated-electron physics is a widely tuneable model system that can mutually couple several electronic and phononic degrees of freedom. To date, no such system has been experimentally realized. While previous efforts have mostly focused on cold-atom configurations, nano-electromechanical systems are naturally suited to address this challenge. One of the most challenging requirements to engineering such a system is the achievement of ultrastrong electromechanical coupling, which has been recently demonstrated by our research group in a capacitively coupled carbon nanotube [1]. Leveraging this capability, we work to engineer a model system in which electronic degrees of freedom are defined within four quantum dots and coupled to vibrational modes of a carbon nanotube [2]. If successful, the project will enable the first experimental platform for quantum simulation of electron-phonon coupling.

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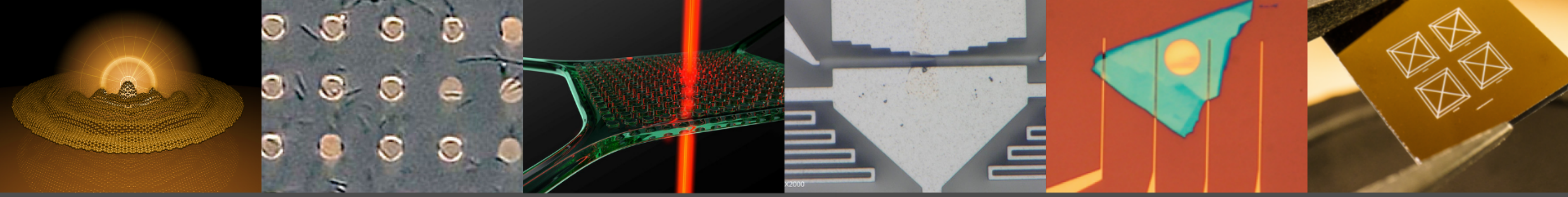

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Electrothermally tunable metal-graphene-siliconnitride membrane mechanical device

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Controlling the properties of mechanical devices over a large range is interesting for many applications such as filters and sensors as well as for fundamental research such as nonlinear dynamics, optomechanics and quantum readout. In this work, we demonstrate a novel on-chip tunable structure composed of a suspended siliconnitride (SiN) membrane with a graphene layer on top which is connected to metal electrodes. Benefiting from the high electrical and thermal conductivity and great flexibility of graphene, the developed tuning structure only requires a simple device structure in which graphene acts as conductive channel to heat the suspended membrane locally. The force induced by the thermal expansion difference between the metallic electrode and the SiN membrane first tunes the residual stress in the SiN membrane and then spatially deflect (as shown in Figure 1) or even breaks the metal-graphene-SiN membrane when the loading power overcomes a threshold. Through the developed structure, we realize an extreme large eigenfrequency tuning (more than 50 %) of the vibration mode and the breaking of the symmetry of the membrane. An analytical model taking into account the difference in thermal expansion of the components of the has been built and quantitatively describes the threshold loading power needed to induce spatial deflection and the curvature of the spatial deflection.

In addition, by injecting an alternating voltage to the device and thus applying a periodic force to the membrane through thermal expansion, we achieve an on-chip excitation of the membrane resonator as well as nonlinear parameter manipulation which paves the way to investigate the nonlinear dynamics of multidimensional and composite nanomechanical resonators.

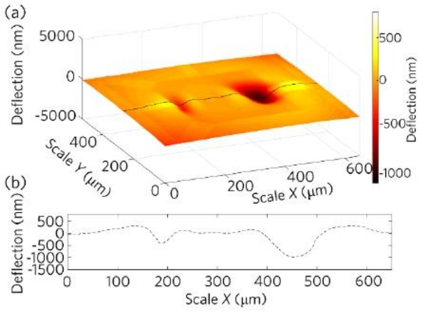
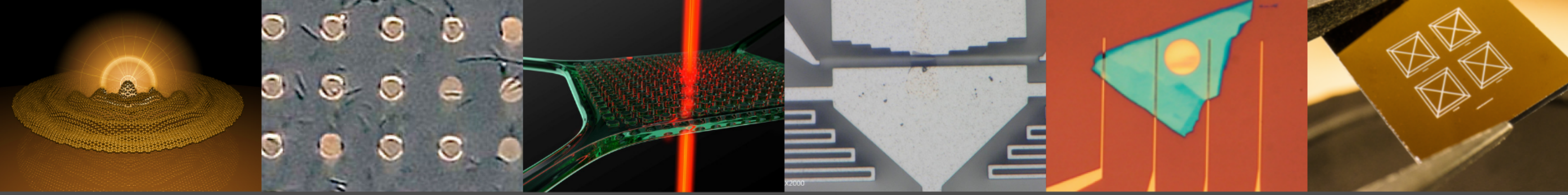


Figure 1: (a) Imaging white-light interferometry-captured image of the spatial deflection of the metal-graphene-SiN membrane with V_{DC} = 2.9 V. (b) Line cut through the deflection profile, at the position indicated by the black-line in (a).



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Thin Film Device Characterization using Picosecond Ultrasonics

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The excellent electronic, mechanical and optical properties of 2D materials make them a hot research topic, for example for applications in electronics and in sensors. Gaining insights into these nanomaterials in the time domain can be done using acoustic reflections, since soundwaves will propagate through any material, and the speed of sound is much slower than the speed of light. However short wavelengths are required. Using femtosecond laser pulses, we can generate ultra-high frequency acoustic pulses using the photoacoustic effect [1] . With this, it is possible to measure the acoustic modes in such thin films.

To make the high-frequency filters for the 5G band, free-standing thin film bulk acoustic resonators (FBARs) have been widely used. They consist of a thin film of a piezoelectric material sandwiched between two electrodes, suspended over a cavity. We have used the 2D piezoelectric material BTO, and used picosecond ultrasonics measurements to verify the predicted FBAR mode at 233GHz [2].

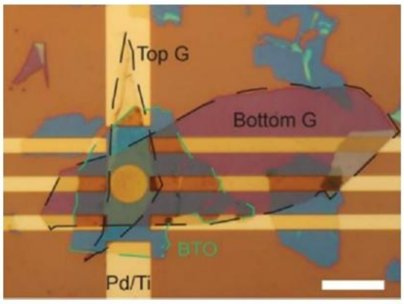

Figure 1: BTO flake between graphene electrodes, used as an FBAR resonator at 233GHz.

Also, one can look into the adhesion between different materials, by studying the reflections from such an interface. If the adhesion between the film and substrate is perfect, there will be some transmission based on the acoustic impedances. However, if the adhesion is bad, there is a layer of air in between and all acoustic energy will be reflected back. From the decay in the measured standing wave amplitude, the acoustic reflection coefficient can be calculated. This reflection coefficient can then be used to determine the interfacial stiffness, which characterizes the adhesion. We have used this to prove that the adhesion in an SiO2-SrTiO3 interface can be improved by 70% after annealing. This can be used to make better-sealed pressure sensors [3].

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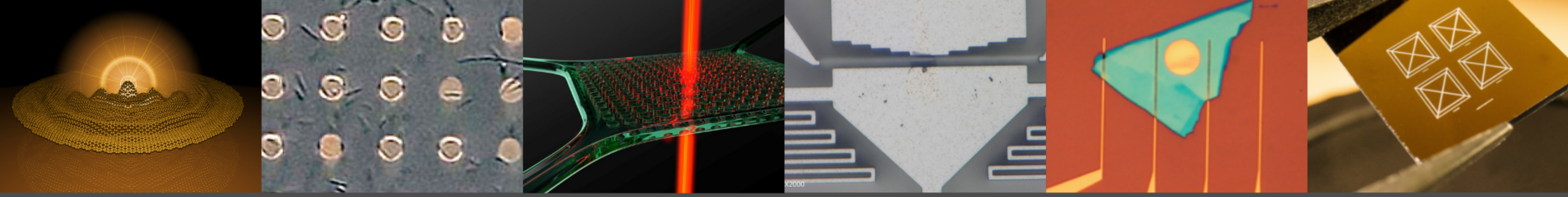

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Towards spin-optomechanics with nitrogen-vacancy centers in diamond

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Coupling massive mechanical systems to a quantum nonlinearity - a spin, for example - would allow to access a new range of phenomena, enabling the generation of non-classical states of motion and potentially tests of quantum mechanics for macroscopic objects. In order to study such hybrid system at the quantum level, the spin-mechanical coupling rate needs to be larger than the decoherence rates of both the mechanical resonator and the spin. Our spin degree of freedom is provided by a nitrogen-vacancy (NV) colour center in diamond, which can display coherence times beyond 100 microseconds at cryogenic temperatures. While there has been work reported on spin-mechanical coupling with different types of mechanical resonators such as nanowires [1], levitated micromagnets [2] and membrane trampolines [3], our mechanical resonator is embedded in a silicon nitride membrane patterned with a phononic crystal [4] and can reach hundred milliseconds long quantum coherence time at millikelvin temperatures [5]. The spin-mechanical interaction is mediated by magnetic field gradients, which are generated by nanomagnets deposited on the resonator surface. By taking advantage of the high quantum coherence of both systems, and by carefully engineering the nanomagnets to reach large magnetic field gradients, we expect that this platform will eventually enable quantum-coherent spin-mechanical coupling. Here we present our implementation strategy, results of scanning NV microscopy of on-chip deposited hundred nanometer sized soft magnets and fast spin control pulses.

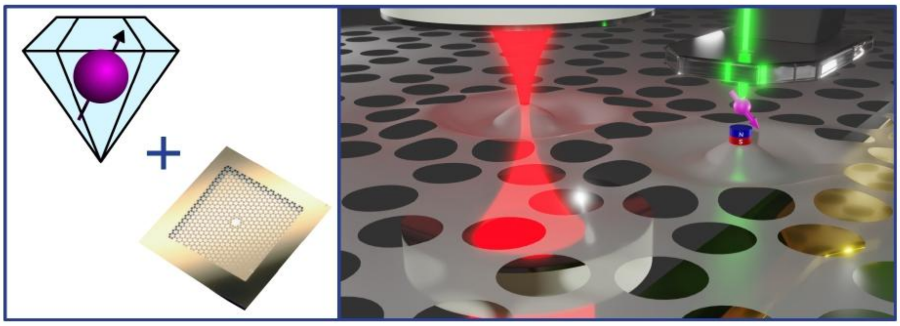

Figure 1: Conceptual image of the spin-mechanical interface between a silicon nitride membrane and a NV diamond tip using a nanomagnet as the force mediator.

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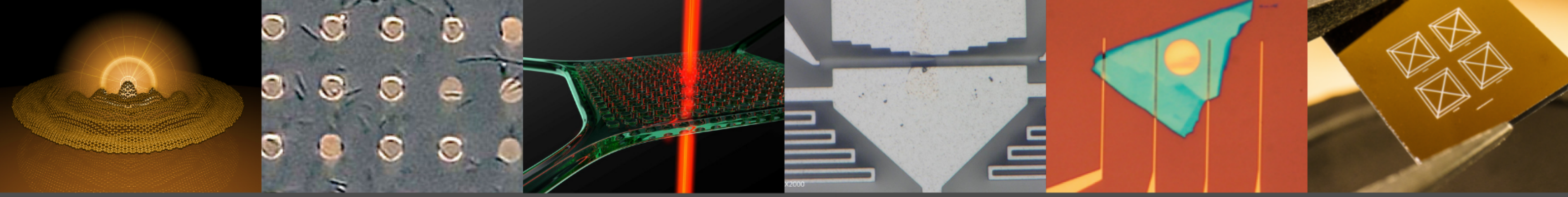

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DISORDERED COUPLED PARAMETRIC OSCILLATORS AND ASYMMETRIC ISING MODELS

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A parametric oscillator with two coexisting states of identical amplitude but opposite phases can be used to represent a classical bit or an Ising spin for logic or computation applications. Introduction of coupling among multiple parametric oscillators enables mapping onto the Ising model of interacting spins. Coupled parametric oscillators have been used to build Ising machines that are considered in the context of inferring the ground state of these systems. So far, Ising machines are analyzed using symmetric Ising models where the energy of the system is invariant to interchanging two spins. Here, we show that in the presence of weak disorder, coupled parametric oscillators map instead onto asymmetric Ising models in which the symmetry of interchanging two spins is broken. Specifically, two coupled parametric oscillators do not affect each other in a symmetric fashion.

Our system consists of two micromechanical torsional resonators fabricated side-by-side. Under parametric modulation, each resonator develops two coexisting vibrational states with phase difference of π. Noise induces random switching between the states (Fig. 1). In the absence of coupling, the transition rates out of the two states are identical in each resonator, independent of the phase of the other resonator. We then introduce weak coupling that favors vibrations of opposite phases in the two resonators, in analogy to two Ising spins that are antiferromagnetically coupled. The transition rate of one resonator depends on whether the phase of the other resonator is identical or opposite. When the two resonators have near identical eigenfrequencies, the transition rates of the two units are modified due to the coupling by almost the same factor, in a manner similar to Ising spins in equilibrium. Detailed balance is maintained. On the other hand, when the eigenfrequencies are tuned to be mismatched, the transition rates change by different amounts due to the coupling. The system resembles two Ising spins with asymmetric interactions. We show that detailed balance is broken. A probability current in the discrete state space is generated. The probability current depends linearly on the eigenfrequency mismatch.

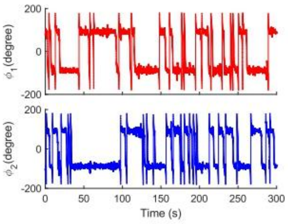

Figure 1: Switching of the phase of resonator 1 (red) and 2 (blue) as a function of time.

The asymmetric coupling between Ising spins play an essential role in neural networks. Despite the large amount of theoretical works, these models have not yet been implemented in experiments. Apart from opening new opportunities of using parametric oscillators for asymmetric Ising models in neural networks and biological systems, the findings also provide a platform to investigate novel physical phenomena that arises due to the asymmetric interactions.

This work is supported by the Research Grants Council of Hong Kong SAR (Project No. 16304620).

Frontiers of Nanomechanical Systems (FNS) workshop
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Acoustic spin pumping and the back-action in a phononic crystal cavity

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Collective spin wave excitation, called magnons, interacts to acoustic phonons via magnetoelastic effect, which enables magnetic controls of the phonon dynamics and demonstration of the nontrivial transports such as nonreciprocal propagations [1,2]. Previous magnomechanical systems have been realized by exploiting surface acoustic wave (SAW) devices as a platform because of the well-developed fabrication and measurement technologies. However, the millimeter-scale cavity footprint prevents its scalability and has limited development of integrated circuits. Here, we utilize a phononic crystal (PnC) cavity and waveguide architecture to construct a wavelength-scale magnomechanical hybrid system (Fig. 1a). We demonstrate acoustic pumping of magnons in a ferromagnetic Ni film with a cavity resonance (Fig. 1b) and phononic cavity modulation in frequency and damping via the back-action effect (Fig. 1c). Furthermore, strain-engineered acoustic resonances reveal mode-dependent magnetoelastic interaction. The phononic circuit platform, enabling complete spatial and mode-selective controls of magnomechanical elements, extends capability of the hybrid technology in microwave signal processing for wireless communications devices and quantum acoustic systems.

This work was supported by JSPS KAKENHI Grant Number 21H05020.

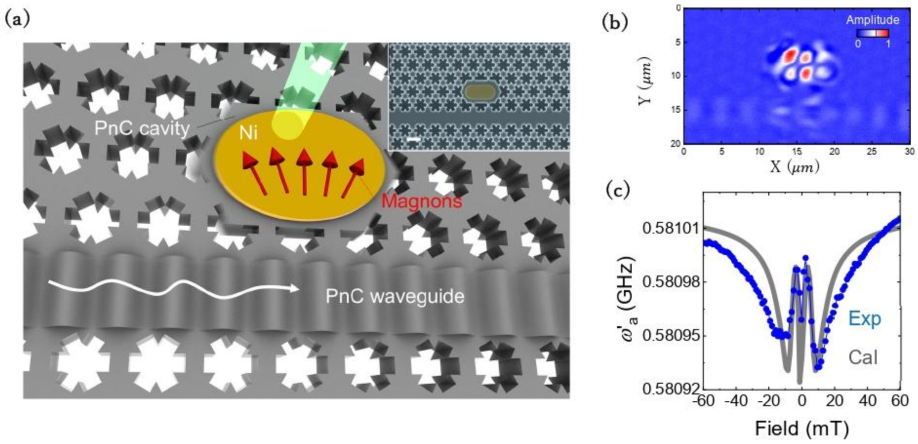

Figure 1: (a) A schematic of PnC cavity magnomechanical system. Propagating vibrations (phonons) in the waveguide excite acoustic cavity resonances which drive magnons in the Ni film and are modulated due to the back-action. The inset shows an SEM image of the device and the scale bar is 4 μm. (b) Experimental mode profile of the cavity resonance. (c) Cavity resonant frequency (ω_a) dependent on an external magnetic field.

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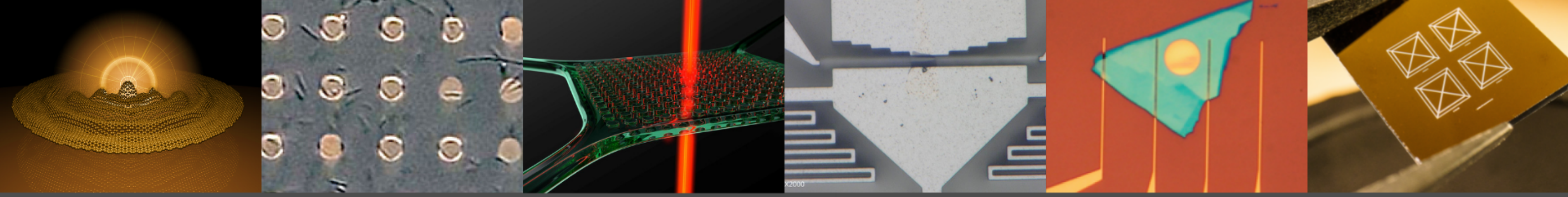

Frontiers of Nanomechanical Systems (FNS) workshop
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Magnetic order in 2D antiferromagnets disclosed by spontaneous anisotropic magnetostriction

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Layered two-dimensional (2D) magnetic materials offer an emerging platform for fundamental studies of magnetism in the 2D limit. Their stackability into van der Waals heterostructures opens pathways to non-trivial magnetic phases and technological applications, including sensors, memories and spintronic logic devices [1]. However conventional techniques to study the magnetsim in these materials, such as neutron scattering, magnetization measurement by a superconducting quantum interference device (SQUID) are challenging, due to the small volumes of exfoliated 2D materials. Other methods, suited to 2D materials, require electrical conductance, the presence of specific optical modes or ferromagnetic order; they are therefore difficult to apply [1].

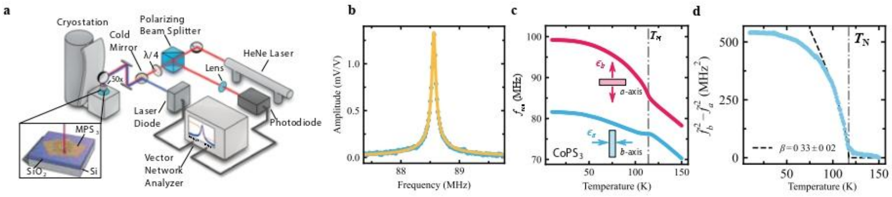

Figure 1: **a,** Schematic illustration of the laser interferometry setup and sample with rectangular cavity array. **b,** Measured amplitude of the fundamental resonance peak in a CoPS$_3$ drum at $T = 10$ K and and the fitted Lorentzian. **c,** Temperature dependence of f_0 of a CoPS$_3$ rectangular membrane with different crystalline orientations. The dashed line indicates the transition temperature T_N extracted from the data.**d,** Difference of the corrected frequency squared $\tilde{f}_\mathrm{b}^2 - \tilde{f}_\mathrm{a}^2$ proportional to the order parameter. The dashed-dotted line indicates the measured transition temperature T_N. The dashed black line is a powerlaw fit through the data close to T_N from which β is extracted.

Here we show a general opto-mechanical method that, by using the direct coupling between magnetization, strain, and resonance frequency of suspended 2D magnets, allows us to study the phase transitions in insulating 2D magnetic materials [2–4]. We transfer a thin flake of MPS$_3$ (M = Fe, Co, Ni) on to a substrate with rectangular cavities arranged in a star like pattern to create drums of a single crystal with different cavity orientations. We opto-mechanicaly actuate these drums and extract their resonance frequency as a function of temperature. By studying the difference between different orientation we are able to extract the magnetic order parameter. From the temperature dependence of the order parameter we are able to determine the critical exponents characterizing the magnetism. By comparing these between different flakes their thickness dependence is investigated.

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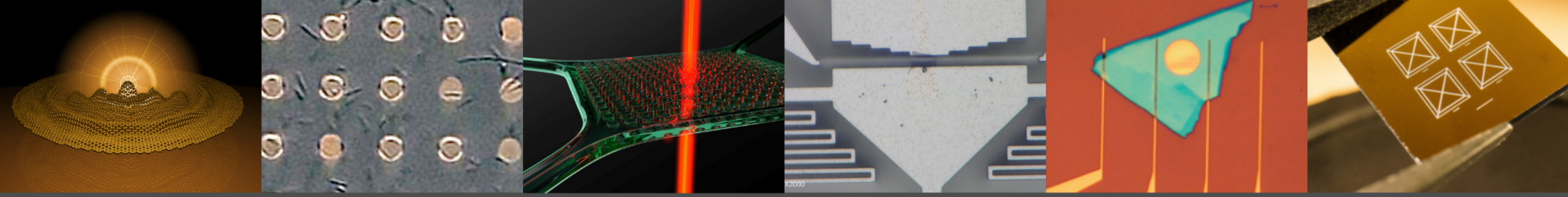

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Strongly Driven Spin-Mechanical Systems for Enhanced Mechanical Sensing

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The sensitivity of mechanical-oscillator-based sensing is in part limited by the spectral linewidth of the mechanical oscillator. In this paper, we show that a strongly driven spin-mechanical system features a mechanical response with a linewidth, which can be a few orders of magnitude smaller than the intrinsic linewidth of the mechanical oscillator, providing a promising mechanism for enhanced mechanical sensing.

For our experimental studies, a nitrogen vacancy (NV) center in a diamond cantilever couples to out-of-plane vibrations of the cantilever through the excited-state deformation potential. The cantilever used, which is embedded in a phononic crystal square lattice as shown in Fig. 1a [1], features a fundamental mode with Q=1.3x10^6 and f=28 MHz (see Fig. 1b). Photoluminescence excitation (PLE) studies were carried out in a NV near the middle of the cantilever as shown in the confocal optical image (see the inset in Fig. 1c). Strong and resonant mechanical driving induces a large splitting in the optical transition shown in the PLE spectrum in Fig. 1c. A comparison between experiment and theory shows that this splitting can be attributed to the strain-induced shift of the NV optical transition generated by the maximal displacement of the oscillating cantilever.

In the limit that the splitting is large compared with the zero-phonon linewidth, NV fluorescence at a given optical excitation frequency becomes sensitive to minute detuning between the mechanical mode and the external driving force, even when the detuning is far smaller than the intrinsic linewidth of the mechanical mode. The resulting mechanical response is characterized by resonances with a linewidth much smaller than the intrinsic mechanical linewidth. For the mechanical response shown in Fig. 1d, the linewidth observed (0.3 Hz) is about 70 times smaller than the intrinsic mechanical linewidth (22 Hz). A greater reduction in the linewidth can be achieved with a stronger external mechanical drive. The greatly enhanced sensitivity to mechanical detuning can provide an effective mechanism for mechanical sensing, for example, by monitoring frequency shift of the mechanical oscillator through the sharp mechanical response.

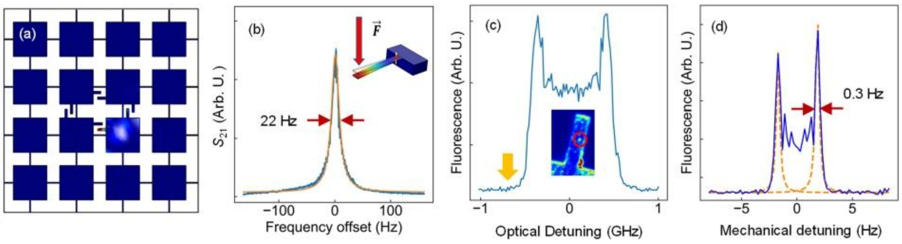

Figure 1: (a) Schematic of the sample structure, with a lattice period of 76 μm. The width and length of the bridge is 1.3 and 20 μm, respectively. (b) Spectral response of the cantilever used in the experiment, with a length near 15 μm. Radiation pressure is used to drive the mechanical mode. (c) PLE spectrum of the E_y transition from a NV center highlighted by the red circle in the confocal optical image in the inset, obtained under resonant driving of the mechanical mode. (d) Fluorescence from the NV center vs mechanical detuning with the optical excitation field fixed at the frequency indicated by the arrow in (c) and with stronger mechanical drive than that used for (c). All experiments were carried out at T=8 K.

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Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Vacuum gap electromechanical devices with integrated piezoelectric actuator

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The implementation of nanometer vacuum gap capacitors in cryogenic electromecanical devices has opened long shut doors for exploring the boarders between quantum and classical mechanics [1]. Building upon this work, these quantum NEMS (QNEMS) have been included in more intricate measurement schemes [2, 3] inspiring new transducer applications like directional amplifiers [4]. Despite these new research paths, the design of vacuum gap capacitor QNEMS did not evolve significantly since the first experiments in 2011. Most prominently, the diameter of devices rarely exceed more than $14\,\mu\text{m}$ and capacitor gaps larger than $50\,\text{nm}$.

Here, we report on the fabrication of nanometer gapsized QNEMS that overcome theses long-standing geometry limitations. Fig. 1a shows a false color SEM image of a typical device with an capacitor diameter of $40\,\mu\text{m}$. We integrate an additional piezoelectric actuator for bridging the gap to sensor applications and exciting membranes modes with amplitudes of several nanometers. In all our devices, several mechanical modes can be excited (Fig. 1b). We demonstrate electromechanical coupling at cryogenic temperatures and determine a capacitor gap of $32\,\text{nm}$. The presented devices show that current geometry limitations of vacuum gap QNEMS can be overcome and we anticipate that the relaxed design restrictions will be vital for the development of novel applications based on vacuum gap QNEMS.

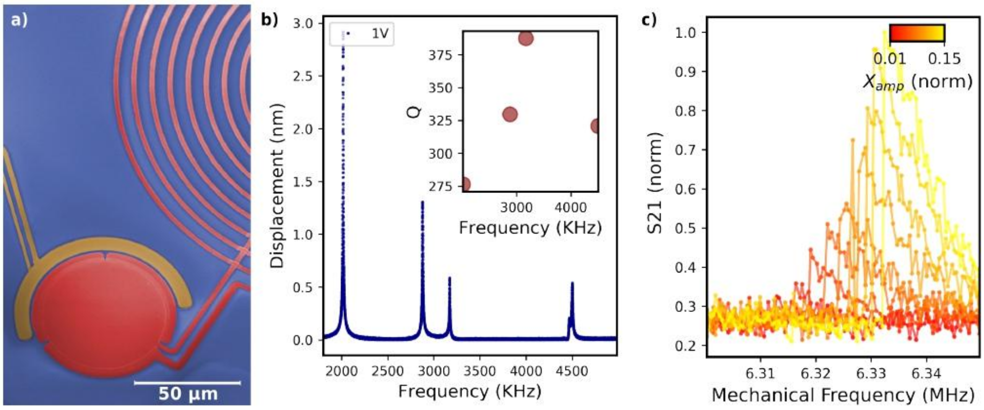

Figure 1: **a)** False-colored SEM image of the device. Red represents both sides of the capacitor, as well as the spiral inductor. Yellow is used for the intergated piezoelectric actuator. **b)** Laser Doppler vibrometer measurements of a membrane with radius of $24\,\mu\text{m}$ at room temperature under vacuum. **Inset:** Q factors of the modes observed. **c)** Lower sideband of electrical cavity transmission measurement while coherently driving a membrane of diameter $12\,\mu\text{m}$ at cryogenic temperatures.

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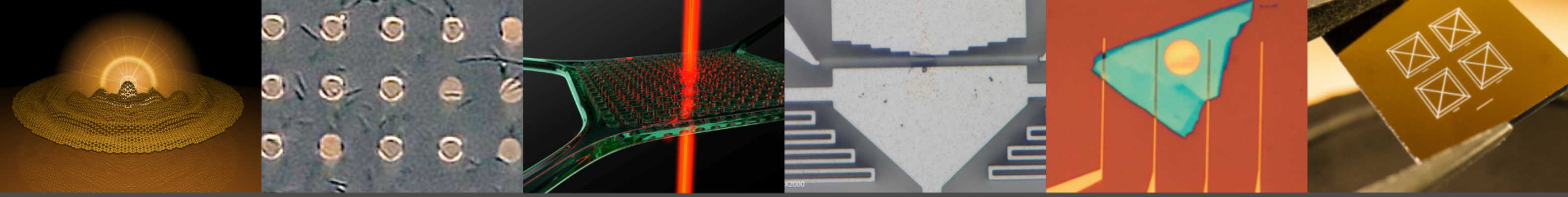

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Effect of helium ion implantation on nanomechanical resonators in 3C-SiC

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Silicon carbide (SiC) is a suitable candidate for nanoelectromechanical systems due to its superior mechanical properties. It is also an interesting material platform to study the coupling of mechanical modes with localized spins associated with irradiation-induced defects. Such a spin-mechanical system can be used for quantum sensing applications [1].

The nanomechanical resonators in 3C-SiC are fabricated by standard semiconductor processing techniques such as electron beam lithography and reactive ion etching. They are characterized using Fabry-Pérot interferometer. In the preliminary experiments, we focus on the material modification by helium ion broad beam implantation on strained 3C-SiC resonators. The effect of varying fluence on resonance frequencies and quality factors is studied. With the fluence of 1 X 10^{14} /cm^2 we observe decrease in resonant frequencies (~ 15%) and quality factors.

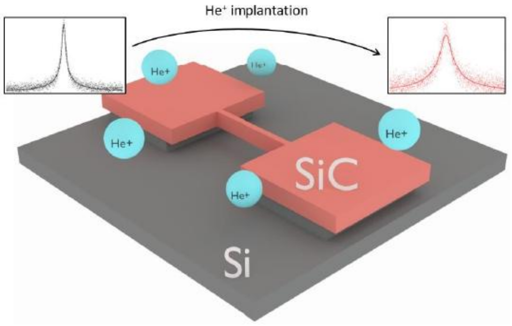

Figure 1: He$^+$ implantation scheme on resonators in 3C-SiC [Insets show change in the resonance spectrum]

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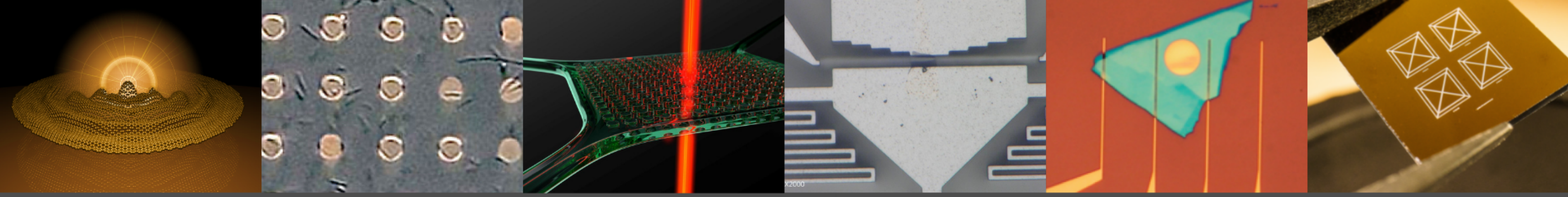

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Dynamical backaction cooling of sideband-unresolved mechanical modes using multimode optomechanical interactions

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Optomechanical systems hold great promise for applications in quantum information transduction and sensing. To be able to operate in this regime, their optical and mechanical modes need to be in their respective ground states to avoid destroying the quantum information passing through them. In some systems this can be achieved by operating them at cryogenic temperatures. For mechanical modes in the MHz range this is however not sufficient, as they will still have significant thermal occupancy.

Optomechanics can be used to cool beyond this thermal occupancy by coupling to a driven optical cavity. To do this efficiently, the optical linewidth needs to be smaller than the mechanical frequency (the so-called resolved sideband condition), such that Stokes scattering is suppressed.

Ojanen and Børkje [1] proposed a cooling scheme which bypasses this requirement by using an auxiliary mechanical mode to induce optomechanically induced transparency at the frequency corresponding to Stokes scattering of the primary mechanical mode. This will suppress the Stokes scattering, allowing the mode to be cooled by anti-Stokes scattering, even when the optical linewidth is larger than the mechanical frequency.

We have designed an optomechanical device possessing mechanical modes in both the MHz and GHz range, coupled to the same optical mode. In this device, the sideband-resolved GHz modes can be used to suppress the Stokes scattering into the sideband-unresolved MHz mode. We report on our activities to fabricate, characterize, and employ this device to cool down a sideband-unresolved mechanical mode below the limit set by quantum backaction.

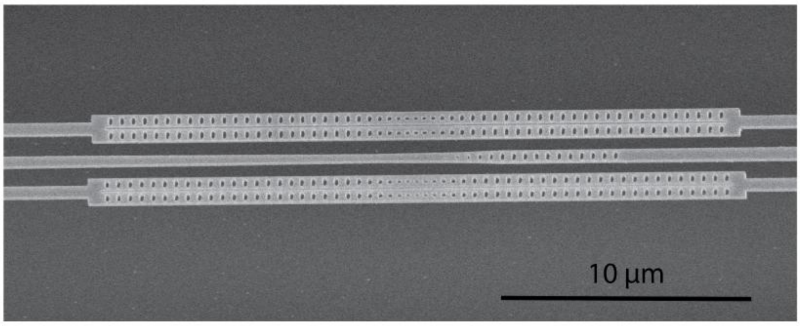

Figure 1: SEM micrograph of a fabricated device, which consists of two zipper cavities and a waveguide for optical access. Each zipper cavity consists of two optomechanical nanobeams, possessing a confined optical mode and a GHz mechanical breathing mode. The two beams together have a MHz differential flexural mode.

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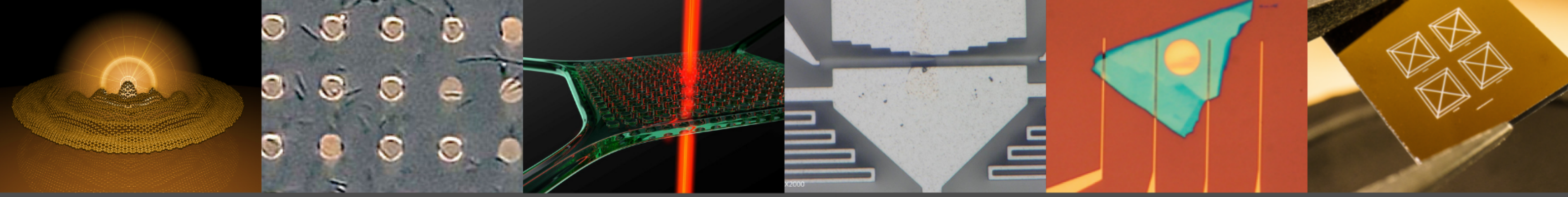

Linear and Nonlinear Cavity Optomechanics with Niobium-Based Superconducting Nanoelectromechanical Systems

Jinwoong Cha

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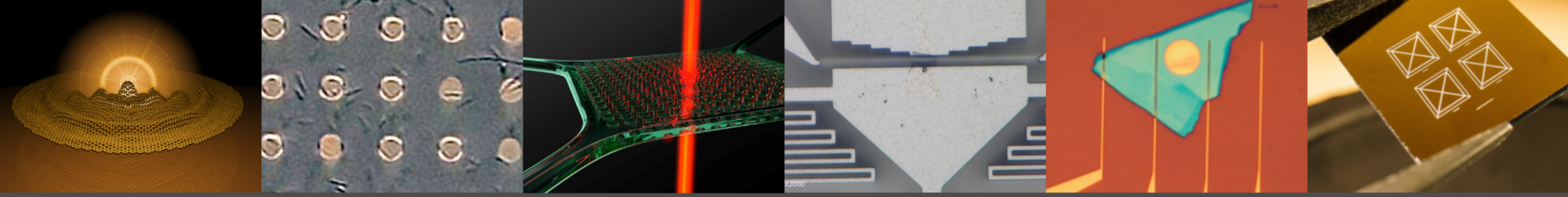
Nanoscale mechanical vibrations can strongly interact with various quantum states such as microwave fields, optical photons, superconducting qubits, spins and electrons. Engineering and utilizing their mutual interactions are thus crucial for a wide range of applications including quantum sensing and transduction.

Superconducting nanoelectromechanical system that integrates microwave cavities and nanomechanical resonators is of great scientific and technological importance as this on-chip system can support strong optomechanical coupling of microwave fields and mechanical vibrations.

In this talk, I will describe a niobium-based superconducting nanoelectromechanical system we have been developing at KRISS and discuss cavity optomechanical phenomena demonstrated in our device. We employ niobium as a base superconducting material due to its superior superconducting properties compared to those of aluminum, which make niobium suitable for quantum transducers. Our device demonstrates fundamental optomechanical back-action effects including motional cooling and amplification, and optomechanically induced reflection at 4.2 K and in strong magnetic fields up to 0.8 T. We further explore optomechanical effects beyond the linear regime with a strong microwave drive and realize the generation of microwave frequency combs via nonlinear wave-mixing processes. I will then discuss our on-going efforts towards the development of quantum transducers at KRISS.



Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Toward nanomechanical probe for Majorana zero modes

Junghyun Shin[1], **Jinhong Park**[2], **Kunwoo Kim**[3], **<u>Junho Suh</u>**[*1]
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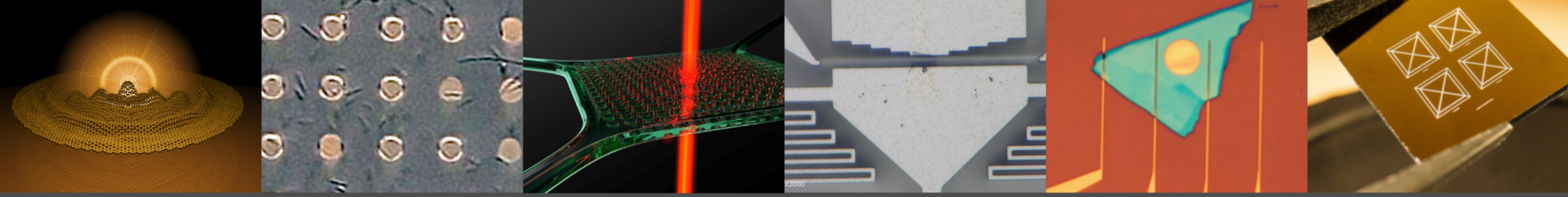
Majorana zero modes (MZM) at the boundary of a topological superconductor could provide a platform for topological quantum computation utilizing its non-abelian exchange statistics. This motivated numerous experiments to generate and observe MZMs in nanowire-based devices, mostly via quantum transports. Here, we propose a distinct approach that employs superconducting nanoelectromechanical resonators to detect and control MZMs. Thin aluminum film deposited on InAs two dimensional electron gas (2DEG) induces topological superconductivity to the 2DEG. When a narrow stripe of aluminum film is removed, a pair of MZM is expected to appear at the ends of the exposed area. We position a nanomechanical resonator in a way that the change in local density of states from MZMs affects the nanomechanical resonant frequency. Subsequently the nanomechanical frequency shift probes the evolution of MZMs under magnetic field and chemical potentials that could reveal the topologically distinct states. The current status and recent results from the proposed experiments are discussed.



Frontiers of Nanomechanical Systems (FNS) workshop
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A phononic frequency comb from a single driven nonlinear nanomechanical mode

J. Ochs[1], D. Boneß[1], G. Rastelli[2], M. Seitner[1], M. Kallergi[4], W. Belzig[1], M. Dykman[3], E. M. Weig[1,4]
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Doubly-clamped nanostring resonators excel as high Q nanomechanical systems enabling room temperature quality factors of several 100,000 in the 10 MHz eigenfrequency range. Dielectric transduction via electrically induced gradient fields provides an integrated control scheme while retaining the large mechanical quality factor [1]. Dielectrically controlled nanostrings are an ideal testbed to explore a variety of dynamical phenomena ranging from multimode coupling to coherent control [2]. Here I will focus on the nonlinear dynamics of a single, resonantly driven mode.

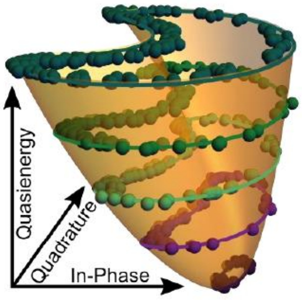

Figure 1**:** Nonsinusoidal limit cycles in the rotating frame of the resonantly driven nonlinear nanomechanical resonator induced by RIFF superimposed with the associated quasienergy surface. Each trajectory maps out a constant-quasienergy contour. With increasing drive power, the contour moves up in quasienergy, allowing to sample its entire surface.

Under strong driving conditions, we observe an onset of self-sustained oscillation in the rotating frame. This phenomenon can be attributed to a resonantly induced negative effective friction force (RIFF) induced by the drive. The high anharmonicity of the limit cycles manifests as the generation of a nanomechanical frequency comb in the power spectrum. Previous work has shown that the theory of RIFF shows better agreement with the experimental data when a conventional nonlinear damping term is added to the model [3]. Here we focus on the experimental investigation of this nonlinear dissipation term, which has not been studied in dielectrically controlled string resonators to date, and which could lead to a deeper understanding of the RIFF.

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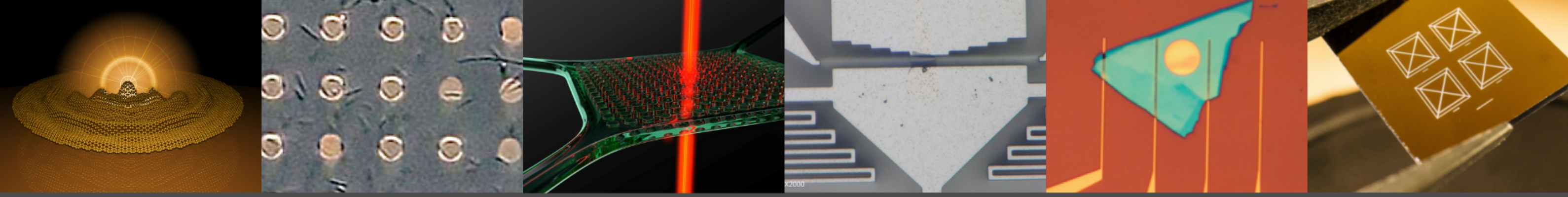

Frontiers of Nanomechanical Systems (FNS) workshop
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Nanomechanical Absorption Spectromicroscopy of Individual Au Nanorods

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Optical techniques for detection and spectral characterization of single molecules became an indispensable tool in a huge variety of fields in the last three decades [1]. The rationale behind their development is the overall ability to reveal the heterogeneity of each molecule due to the local environment. Among them, optical absorption-based analysis by nanomechanical photothermal sensing has already shown its capabilities in the visible spectral range with astonishing sensitivity at the single-molecule level [2]. This approach has the advantage to detect in principle any kind of non-fluorescent molecule, since it measures the absorption due to the photothermal heating of the system under study rather than its fluorescence. Here, we push further the capabilities of our approach in the NIR-IR spectral range with full absorption spectral characterization of single gold nanorods (Au-NR) (Fig.1), simultaneously unravelling their plasmonic and polarization properties (Fig.2). Upon illumination of a wavelength-tunable laser in raster-scanning mode, the Au-NR absorbes part of its energy, releasing it to the environment as heat. The corresponding temperature increase is detected via resonance frequency detuning of our nanomechanical resonator, here silicon nitride drumhead structures, due to mechanical stress reduction. In this way, the characteristic plasmon-driven absorption spectra of Au-NRs can be analyzed, their polarization properties unravelled, and their interaction with the local environment clarified in synergy with FEM, paving the way for single-molecule spectroscopy in the NIR-IR range by nanomechanical photothermal sensing.

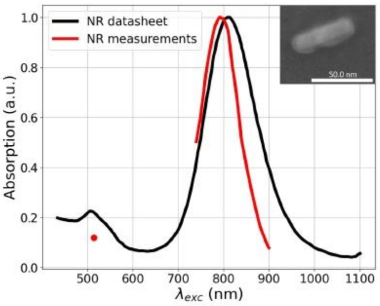

Figure 1: Red curve: absorption cross-section spectrum of single Au-NRs measured by nanomechanical photothermal sensing. Black curve: Ensemble average absorption spectrum given by the datasheet. Inset: SEM micrograph of a single silica-coated Au-NR.

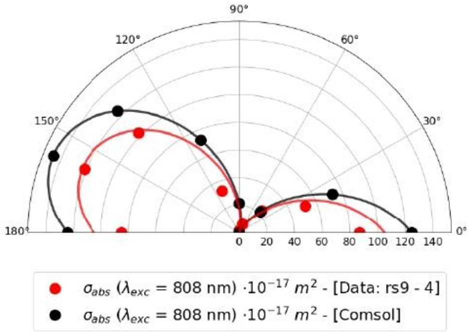

Figure 2: Polar plot of the absorption cross-section of a single Au-NR measured at $\lambda = 808\ nm$ as a function of the laser polarization angle (red dots), compared with the FEM simulations (black dots). The solid curves represent the $cos^2(\theta_{pol})$ fitting, both for the experimental (red) and FEM data (black).

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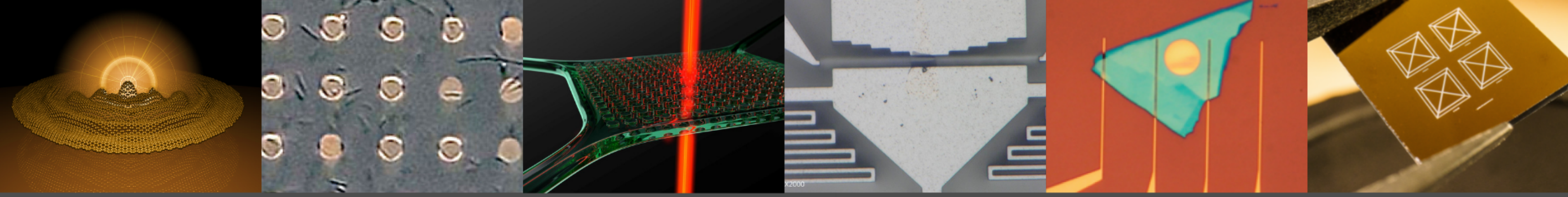

Frontiers of Nanomechanical Systems (FNS) workshop
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Modeling the multi-mode nonlinear dynamics of nanomechanical resonators

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The extreme sensitivity, efficiency and high resonance frequencies of nanomechanical resonators are properties sought by many next generation technologies. Thanks to their atomically thin size, unique structural properties and large aspect ratios, these devices can respond to minuscule forces and can reach large oscillation amplitudes providing enhanced signal-to-noise ratios. However, in this large oscillation regime, the oscillator response becomes nonlinear, where linear assumptions breakdown. Many studies of nonlinear dynamics of nanoresonators have been reported, however in most cases the nonlinear coefficients in the equations of motion were treated as fit parameters, which in reality are functions of geometric and material properties [6]. It was also shown that the single mode response can be influenced by a higher mode of vibration via nonlinear coupling between these two modes [2], yet deeper into the nonlinear regime, even the assumption of two modes coupling to each other can quickly fail, as more modes start to interact, directly and indirectly where they start to dramatically influence the effective stiffness and dissipation of the resonator.

In this study, we develop and execute a physics-based method to characterize the strong nonlinear dynamics of nanomechanical resonators in a wide frequency range to study global multi-modal interactions. To do this, we perform experiments on a graphene nanodrum that are driven opto-thermally which then we construct its multi-mode nonlinear reduced-order model using Finite Element Method (FEM) simulations based on physical parameters, without using any empirical fit parameters. We then use numerical continuation techniques to obtain steady-state oscillations of the reduced order model to compare the simulated response to experimental response. We obtain very good agreement between experiments and simulations, revealing the global effects of multi-modal interactions and internal energy dissipation pathways.

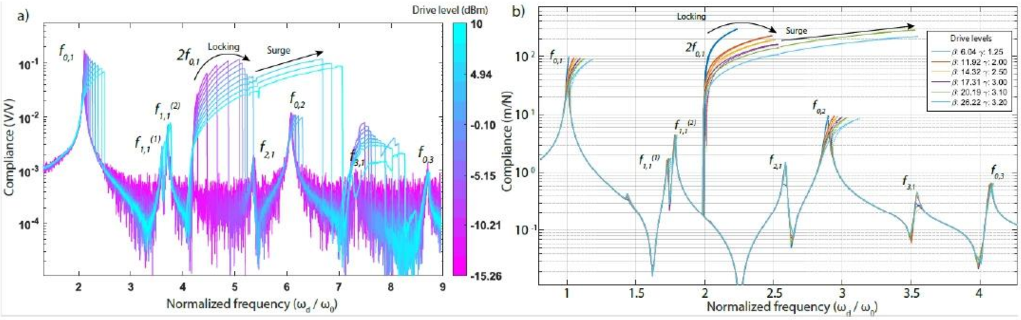

Figure 1: a) Experimental complex multi-mode frequency response of a graphene drum. b) Simulated multi-mode ROM frequency response of graphene drum, successfully capturing the global nonlinear dynamics.

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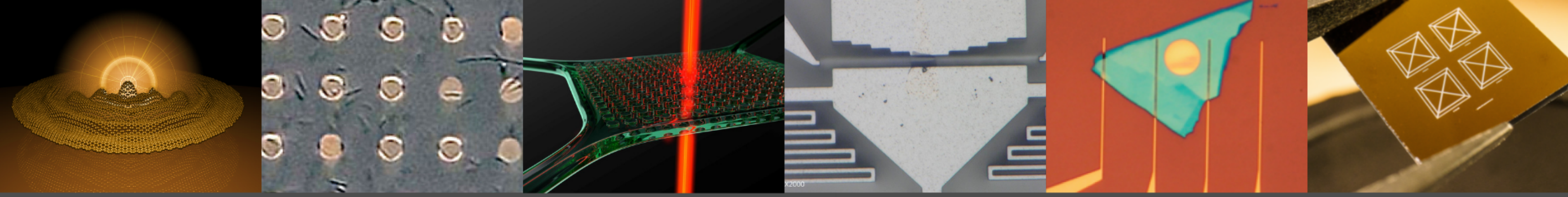

Frontiers of Nanomechanical Systems (FNS) workshop
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SPIN DETECTION USING ULTRA-COHERENT SILICON NITRIDE STRING RESONATORS

B. Kharbanda[*1], **L. Catalini**[1], **M. Bereyhi**[2], **A. Arabmoheghi**[2], **N. J. Engelsen**[2], **T. J. Kippenberg**[2], **C. L. Degen**[1], **A. Eichler**[1]

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In recent decades, significant advancements in engineering nanomechanical resonators have resulted in several high aspect-ratio resonator devices, such as strings and membranes, with higher and higher quality factors. The characteristic long coherence time combined with small effective mass makes these devices a promising platform for force sensing experiments, enabling room-temperature force sensitivity $\approx 1\,\mathrm{aN}/\sqrt{\mathrm{Hz}}$.

Here we report on the implementation of quasi-1D soft-clamped silicon nitride resonators for cavity-based optomechanical sensing. These resonators feature Q-factors up to $> 10^9$ at room temperature [1] and effective mass on the order of pg. They are arranged as strings in a polygon configuration and integrated with photonic cavities on a chip, which allow compact and high-precision read-out of the mechanical motion through a tapered optical fibre.

Thanks to the record-breaking mechanical properties featured by these devices and the compact optomechanical read-out, we envisage such resonators as a new tool with higher force sensitivity than higher dimensional force sensors [2] to detect individual spins and to map out the positions of spins in a complex sample [3]. These devices could hence behave as a nanoscale variant of magnetic resonance microscopy (MRI). For this application, it will be necessary to cool the resonators to very low temperatures (<100 mK) in order to suppress thermomechanical fluctuations.

The first step involves cooling the device to <100 mK. While an increment in the quality factor in this temperature regime is expected [4], the optomechanical properties of these integrated-systems remain unexplored.

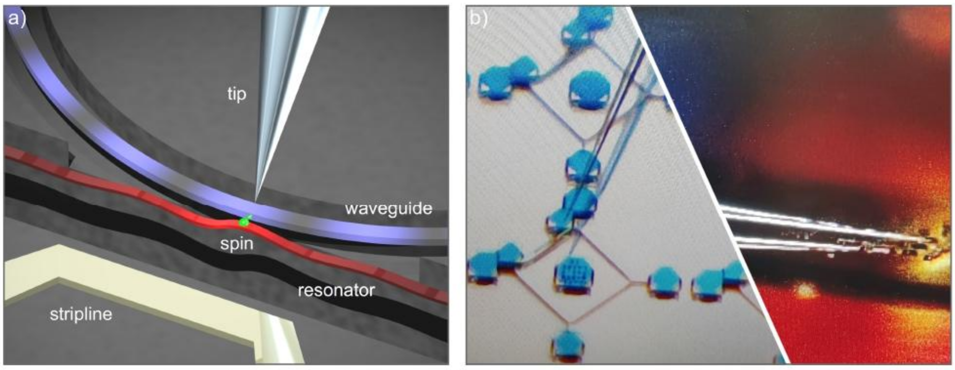

Figure 1: a) A schematic for the envisioned Magnetic Resonance Force Microscopy implementation. b) Addressing the polygon mechanical resonator with integrated photonics using a tapered fibre.

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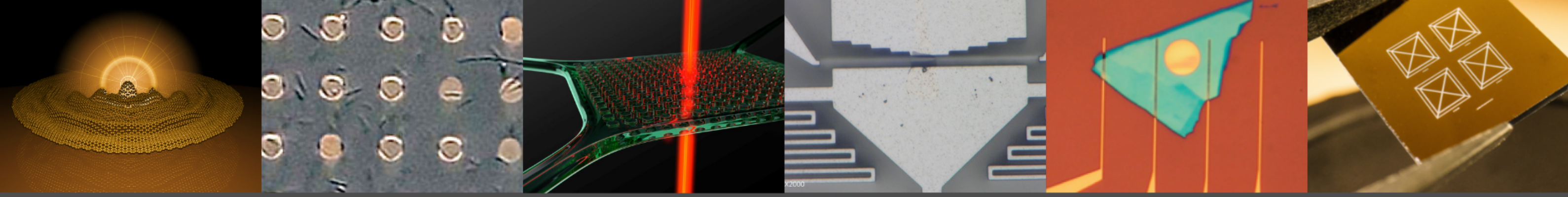

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Prospects for a microshell optomechanical resonator

Jinuk Kim[1], **Akshai Jayakumar Pillai**[2], **Yilin Li**[1], **Jiaxin Yu**[2], **Yiqi Wang**[2], **Yogesh S.S. Patil**[1], **Jack G.E. Harris**[*1,2,3]
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Cavity optomechanics, a branch of physics studying the interaction between optical waves and mechanics, has attracted much attention in relation to various applications, including high-precision sensors and tests of fundamental physics. For an optomechanical device to work effectively, it must be able to effectively confine optical waves and mechanical vibrations and enable them to interact with each other.

Whispering gallery mode(WGM) resonators employs total internal reflection for confining optical and mechanical waves. For optical waves, a resonator made from a transparent solid with a smooth surface has been shown to have a Q-factor of greater than 10^{10}[1]. Meanwhile, superfluid helium based mechanical resonators have been reported to have a Q-factor of up to 10^8 due to extremely low mechanical losses of superfluid helium[2].

Here, we propose an optomechanical resonator made of a micron-thick glass shell filled with superfluid helium. This resonator simultaneously hosts two kinds of WGMs: acoustic WGMs inside the shell and optical WGMs on the shell. Since the shell is sufficiently thin, the evanescent tails of each mode overlap, thus permitting interaction through electrostriction. Microscale thickness glass shell has been experimentally demonstrated recently by applying the glassblowing technique to Si/glass wafers[3]. To achieve high-Q acoustic modes and strong interaction by optimizing shell thickness has been investigated.

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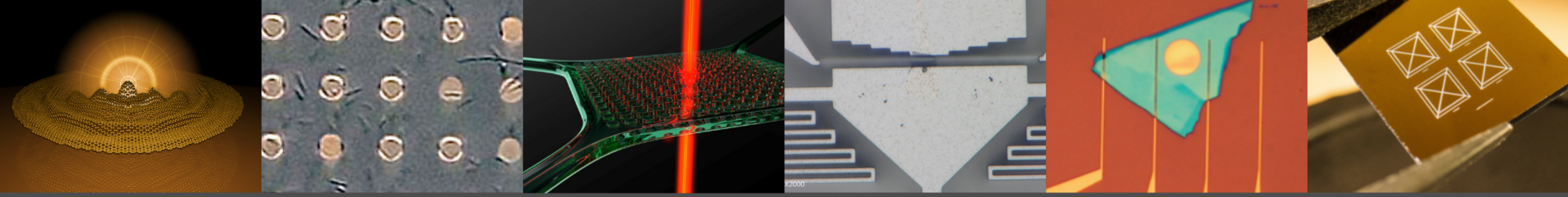

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Clamped and sideband-resolved silicon optomechanical crystals

Johan Kolvik[1,†], **Paul Burger**[1,†], **Joey Frey**[1], **Nils Ciroth**[1], **Raphaël Van Laer**[*1]

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Optomechanical systems currently receives sustained research interest in context of both classical and quantum information processing. Wavelength-scale structures such as silicon optomechanical crystals (OMCs) are among the leading devices thanks to their high optomechanical coupling rates [1, 2]. These devices are typically suspended to prevent mechanical leakage. This dramatically reduces their thermal contact area – leading to excess noise [2, 3] – and creates barriers in scaling up phononic circuits. Previous efforts to address this via unsuspended OMCs have operated outside the resolved-sideband regime [4, 5]. Here, we design and measure the first *clamped* silicon OMCs with sizeable zero-point optomechanical coupling rates in the resolved-sideband regime. The design features a strongly confined mechanical mode with frequencies $\omega_m/(2\pi) \approx 5.5$ GHz co-localized with an optical mode at $\omega_o/(2\pi) \approx 195$ THz (Fig.1**a**&**b**). The OMCs are fabricated on a silicon-on-insulator platform *without* etching the underlying silicon dioxide. By exploiting X-point mechanical modes, we achieve strong acousto-optic overlap while keeping the guided mode separated from the acoustic continuum.

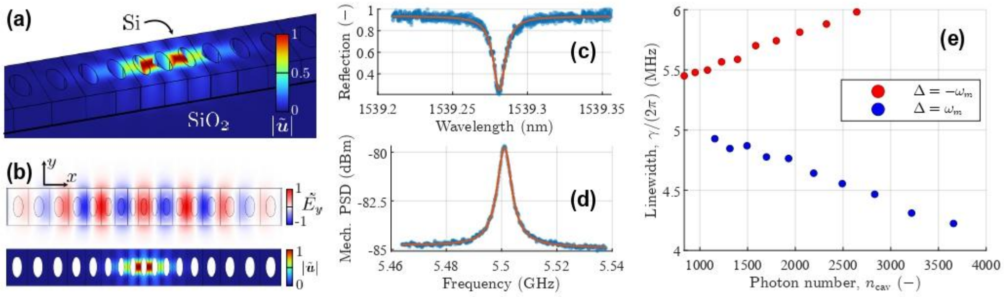

Figure 1: *Clamped silicon OMCs*. **(a)** Simulated mechanical mode profile. The color map depicts $|\tilde{\boldsymbol{u}}| = |\boldsymbol{u}|/|\max(\boldsymbol{u})|$, where $\boldsymbol{u}$ is mechanical displacement. **(b)** Top-down view of co-localized mechanical and optical modes. Optical mode plotted with normalized transverse electrical field $\tilde{E}_y$. **(c)** Normalized optical reflection spectrum with Lorentzian fit. **(d)** Optically measured mechanical power spectral density (PSD) with Lorentzian fit. **(e)** Measurement of the mechanical linewidth γ as function of average intracavity photon number n_{cav} for pump detuning $\Delta = \pm\omega_m$.

The optical field within the cavity interacts with the high-wavevector mechanical mode through radiation pressure. This enables optical read-out of the mechanical mode (Fig.1**d**) for which we observe mechanical quality factors of $Q_m \approx 1000$ at room temperature. We measure optical linewidths $\kappa/(2\pi) \approx 1.4$ GHz (Fig.1**c**) such that we are in the resolved-sideband regime with $\omega_m/\kappa \approx 3.9$. Blue- and red-detuned thermal spectroscopy yields the zero-point optomechanical coupling $g_0/(2\pi) \approx 350 \pm 50$ kHz (Fig.1**e**). In summary, we demonstrate the first clamped OMCs in the resolved-sideband regime. The approach provides a new path toward optomechanical circuits for both classical and quantum technology.

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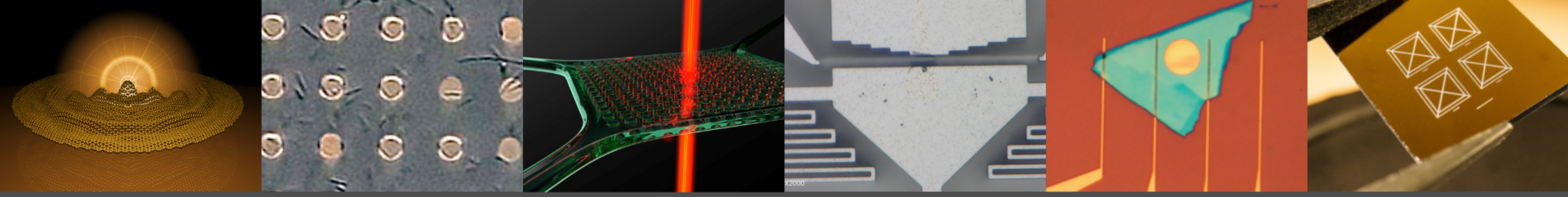

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Anomalous Parametric Amplification of Degenerate First Mode in Micromechanical Coupled Beam Systems

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Parametric amplification has been studied extensively in micro/nano-systems to enhance the small signal response [1]. Here, we demonstrate an interesting phenomenon whereby we observe selective parametric excitation of one of the degenerate modes in a coupled system while the other mode stays unaffected. The coupled system is a double ended tuning fork device that consists of two beams in fixed-fixed configuration coupled via a coupling bar on either end. Corresponding to first mode of the beams, two modes are observed one of which involves the two beams moving together in the same direction (in phase mode) while in the other mode, the two beams move in opposite direction (out of phase mode) as shown in figure 1a. During a bidirectional frequency sweep at 2ω, we observe that amplification occurs in the out of phase mode *only* during a reverse sweep while the other mode shows no excitation at all as shown in figure 1b (Response amplitude at different ac voltages is shown in the inset). Assuming a coupled spring mass system, this behavior can be explained by excitation of the spring constant of the coupling block at 2ω which only affects the out of phase mode (See Eq 1). Furthermore, we also observe that a parametric pump at 2ω combined with excitation at ω at different relative phases shows markedly different gain responses for the two degenerate modes as shown in figure 1c. The out of plane mode exhibits an oscillation of amplitude when plotted against phase as per expectations but also shows two features that are different from normally reported results: 1) The frequency response becomes flat at high amplitudes followed by a jump nonlinear behavior 2) This response only occurs in reverse sweeps and no significant effect is observed in forward sweep as shown in figure 1d. Current simple models (as shown in figure 1e) do explain some of the observed behavior but further refinements are necessary to explain the observed measurements in totality.

$$\begin{gathered} m\ddot{u} + c\dot{u} + (k + k_c + \delta k_c \sin(2\omega t))u = 0 \\ m\ddot{v} + c\dot{v} + k\,v = 0 \end{gathered} \tag{1}$$

where, m, k and c are the mass, spring constant and damping coefficient of each of the coupled resonators, k_c is coupling spring, δk_c is the perturbation amplitude of the coupling spring induced by capacitive actuation at frequency 2ω, $u = x_1 + x_2$ and $v = x_1 - x_2$ are the coordinates for the out of phase and in phase modes.

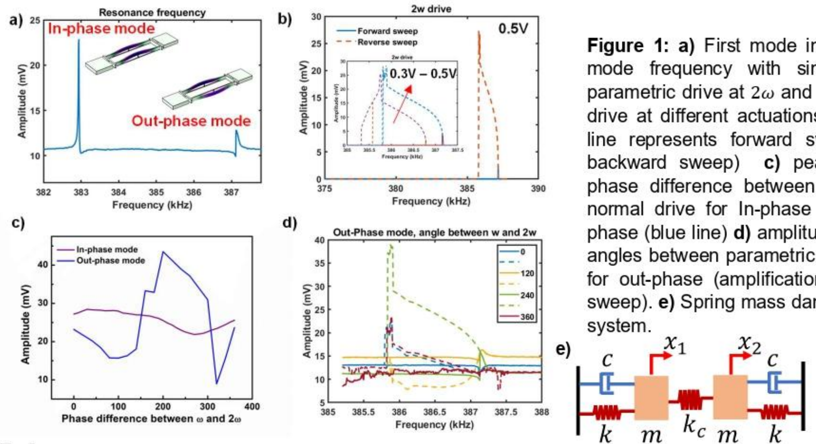

Figure 1: a) First mode in-phase and out-phase mode frequency with simulated illustration **b)** parametric drive at 2ω and sense at ω, parametric drive at different actuations shown in inset (solid line represents forward sweep and dotted line backward sweep) **c)** peak amplitude variation phase difference between parametric drive and normal drive for In-phase (purple line) and out-phase (blue line) **d)** amplitude variation at different angles between parametric drive and normal drive for out-phase (amplification observed in reverse sweep). **e)** Spring mass damper model for coupled system.

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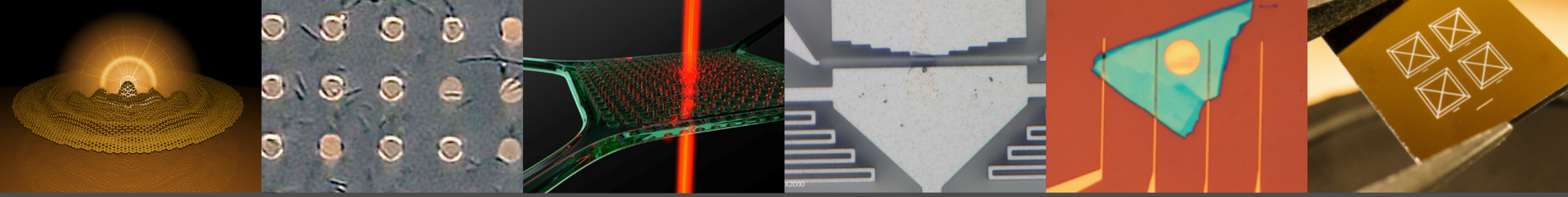

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Dandelion-Class Phononic Membrane Resonators

Eric C. Langman[*1], **Mads Kristensen**[1], **Ilia Chernobrovkin**[1], **Albert Schliesser**[1]
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Phononic membrane resonators are a robust concept which provide high-quality mechanical resonators intrinsically isolated from their environment by a phononic shield [1]. In our lab, we utilize 4 main defect designs, depending on application and tolerances. Here, we examine so-called Dandelion-class resonators, which are optimized for force-sensitivity applications [2], as well as ideal when optomechanical coupling or cooperativity [3].

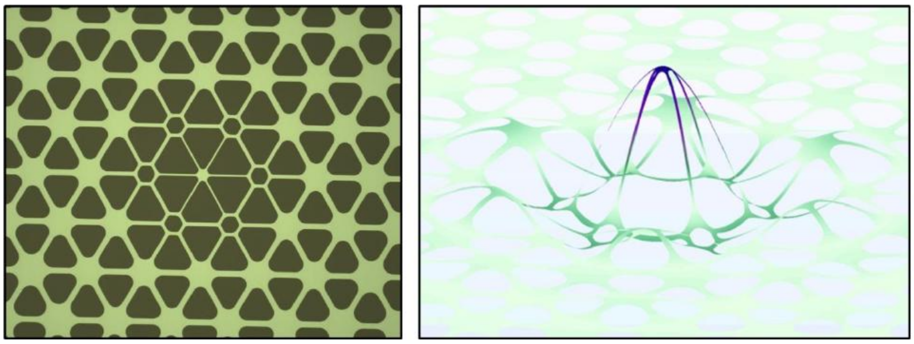

Figure 1: Micrograph and mode shape of typical Dandelion-class phononic membrane resonator, exhibiting a trampoline-like design at the center of a defect within a phonic crystal.

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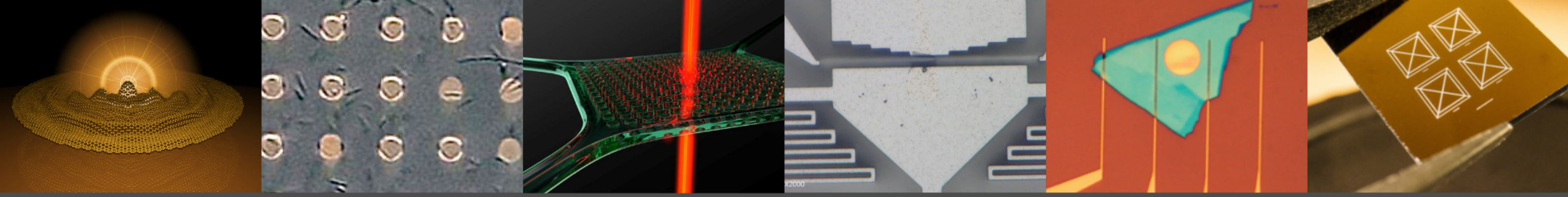

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Tuning Nonlinear Dynamics of Nanomechanical Resonators via Soft-Clamping

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Micro and nanomechanical resonators are ubiquitous in a variety of applications in modern technology. Owing to their small size, forces in the nN range can already trigger large-amplitude oscillations in these devices and lead to a wealth of nonlinear phenomena including bi-stability, parametric resonance, self-oscillations, and mode-coupling. The observation of these nonlinear phenomena has been conventionally achieved by tuning the nonlinear stiffness of resonators either by electrostatic [1] or opto-thermal forces [2].

Here, we introduce a new strategy to engineer nonlinear dynamics of nanomechanical resonators by manipulating their geometry. By design optimization of the supports using torsion beams in a high-Q Si_3N_4 string resonator, we control in-plane to out-of-plane mechanical couplings to re-scale the geometric nonlinearity in a wide range, from softening to hardening. We show that these supports enable stress engineering of the devices from buckled configurations to 0.8 GPa, allowing us to tune the Q-factor [3] and geometric nonlinearity, simultaneously. The method presented here can thus be used to find the optimum geometries that enhance the linear dynamic range of nanomechanical resonators, and paves the way towards utilization of geometric design and soft-clamping methods for controlled manipulation of nonlinear dynamics at the nanoscale.

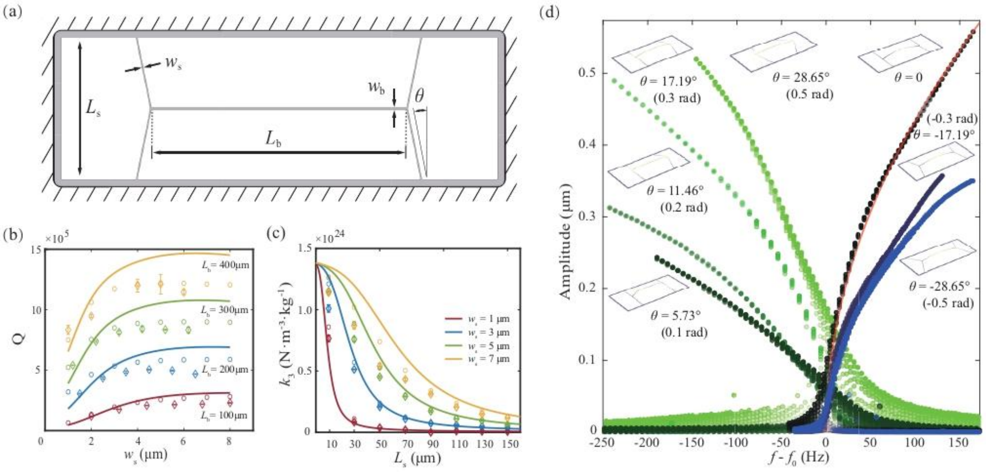

Figure 1: (a) Schematic of the designed nanomechanical resonator. Parameters θ, L_s , w_s are the design parameters that are varied to re-scale the geometric nonlinearity and tune the Q-factor. (b) Analytical (lines), FEM (circles) and measured (diamonds) Q-factor of resonators with $\theta = 0$, $w_b = 2$μm when varying w_s and L_b. (c) Analytical (lines), FEM (circles) and measured (diamonds) Duffing constant k_3 of resonators with $\theta = 0$, $w_b = 2$μm when varying L_s and w_s. (d) Measured Duffing response of the resonators with $L_b = 200$μm, $w_b = 2$μm, $L_s = 150$μm, $w_s = 1$μm and varying θ.

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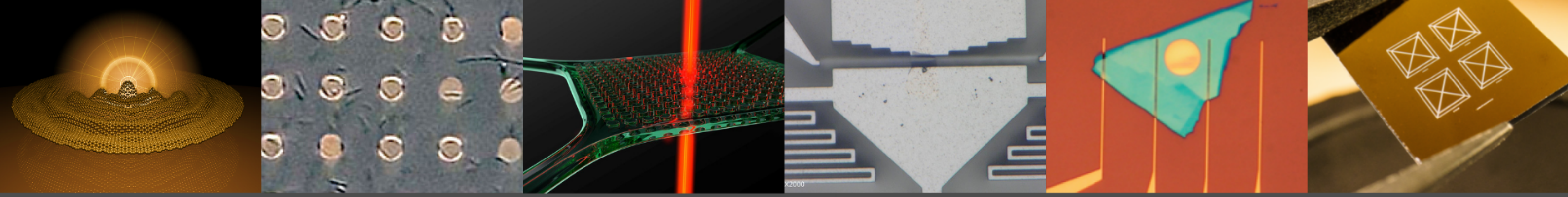

Frontiers of Nanomechanical Systems (FNS) workshop
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TOWARDS STRAIN COUPLING OF NANOMECHANICAL MOTION TO QUANTUM DOTS IN GaAs ZIPPER CAVITIES

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Coherent interactions between different quantum systems are essential for quantum information processing, which typically involves controlling individual quantum systems and transferring quantum information between different types of quantum bits. A good candidate as intermediate bus between quantum systems is represented by acoustic phonons, as they can couple to virtually all other excitations in the solid state, can easily be integrated in a chip and confined using phononic crystals, leading to long coherence times.

A promising platform for the realization of photon-phonon interactions are zipper cavities [1] with an optomechanical cavity consisting of 1D photonic crystal which confines both a mechanical and an optical mode. Embedding semiconductor quantum dots (QDs) into this nano-optomechanical system (depicted in Fig. 1) creates a tripartite interaction between light, acoustic waves and excitons, that could be exploited to create single phonons or entangled mechanical states, creating a versatile platform for quantum information processing [2,3].

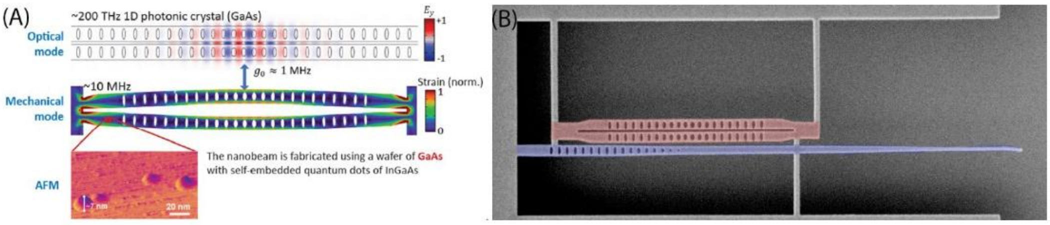

Figure 1. **A**. Simulations of the optical and mechanical modes of the device. **B.** False colored SEM image of a fabricated device. In red: zipper cavity with tapered clamping points to enhance the strain. In blue: side-coupled waveguide.

In our device the optomechanical cavity allows optical driving of the in-plane flexural mode which then couples to the energy levels of the QDs via the strain. To prove this tripartite interaction we aim to measure how the photoluminescence of the QDs is affected by the optically driven mechanical mode, and compare the exciton-phonon coupling with results obtained in different implementations such as surface acoustic waves [4] and nanopillars [5].

Preliminary measurements of the optomechanical response of the device have shown that by resonantly driving the resonator we can enhance the phonon population up to 10^7. By increasing the mechanical Q – by reducing the clamping losses of the cavity – a phonon population as high as 10^{11} can be achieved, allowing a strain coupling of tens of GHz. We report our experimental progress towards observing the effect of that coupling on the emission of QDs, which feature linewidths of similar magnitude.

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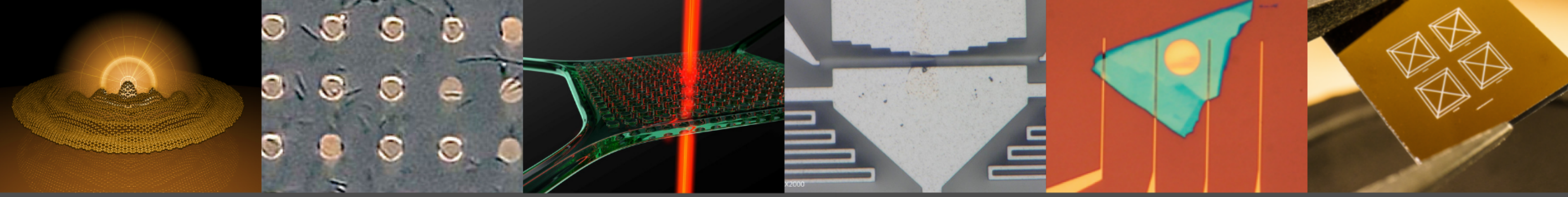

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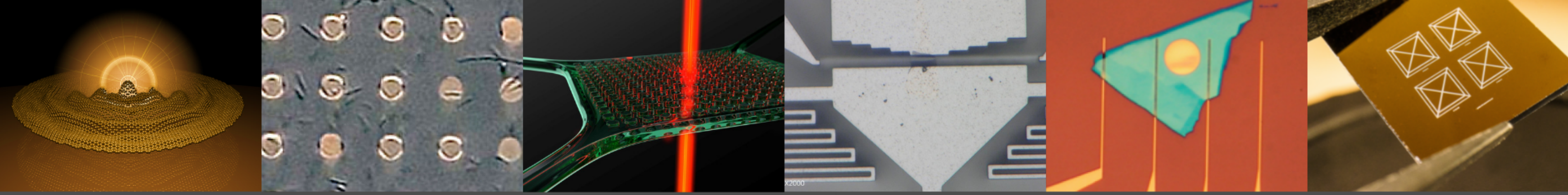

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PERIOD TRIPLING STATES AND NON-MONOTONIC ENERGY DISSIPATION IN MEMS WITH INTERNAL RESONANCE

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In this work [1] we study free ringdown dynamics of a MEMS system with two modes near a 1:3 internal resonance. By separately preparing initial states and measuring the motion of both modes, we demonstrate that dependent on the initial relative phase the modes can either bypass or enter a phase-locked state, which can persist several times longer than the dissipation timescales. The sustained energy transfer between modes in the phase-locked state leads to non-monotonic energy dependence for one of the modes and overall lower dissipation rate for the system. The observations are accurately modeled by the coupled equations of motion, and can be understood by considering the low frequency mode as entering or bypassing a period tripling state under the influence of the periodic force from the high-frequency mode.

We study the nonlinear dynamics of two coupled MEMS resonators during free ringdown. The two resonators are designed with commensurate 1:3 eigenfrequencies to facilitate fast energy transfer at internal resonance (IR). Remarkably, the two modes are observed to phase-lock during ringdown and persist in this state for much longer than their intrinsic dissipation timescales. During relaxation, the low-frequency mode exhibits striking non-monotonic energy dissipation and negative modal energy dissipation rate (transient energy gain). Out transient dynamics observations are complementary to the recent steady state results [2], both of which have been independently explained by an intuitive model that regards the low-frequency mode at period-tripling states (PTS) created by the high-frequency mode, similar to the period-two states in parametric oscillators. The observation and the model pave the way to engineering efficient energy flow between coupled nonlinear MEMS, which can be used for frequency stabilization and dissipation engineering.

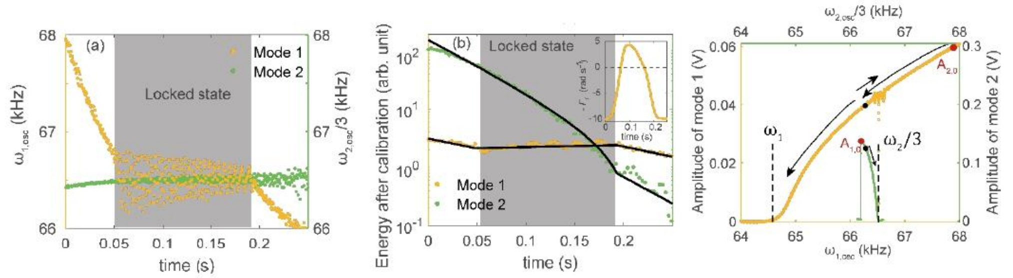

Figure 1: Measured (a) oscillating frequencies and (b) energy of mode1 (yellow) and mode2 (green). During locking mode1 shows a non-monotonic and negative dissipation rate ($-\Gamma_1$ above 0 in (b), inset). (c) shows driven spectra of the two modes indicating evolution of frequencies and amplitudes (black arrows) starting from initial unlocked states (red dots in (c), left white zone in (a,b)) and proceeding through the locked state (black dot and rightward arrow in (c), gray shaded area in (a,b)) before unlocking and relaxing independently (right white zone in (a,b)). In (b) energy flows from mode 2 to mode 1, enabling energy calibration to a common scale by using known individual mode dissipation rates,

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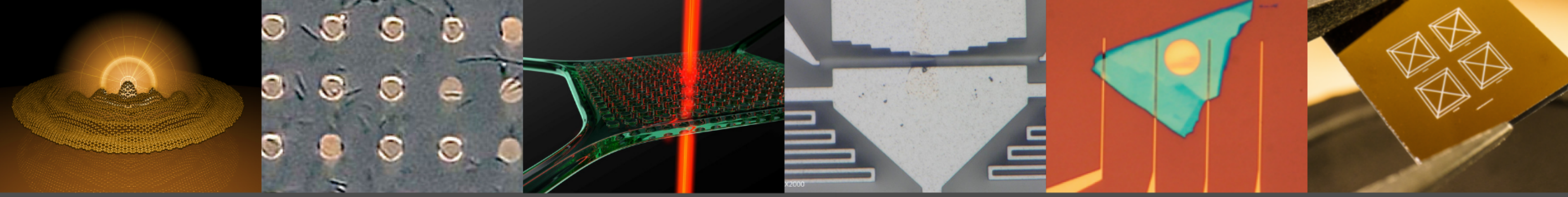

Frontiers of Nanomechanical Systems (FNS) workshop
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Mechanical frequency control in inductively coupled electromechanical systems

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Nano-electromechanical systems couple the center of mass motion of a mechanical element to superconducting quantum circuits at microwave frequencies. While traditional, capacitive coupling strategies operate in the weak opto-mechanical vacuum coupling regime, inductive coupling schemes based on partially suspended superconducting interference devices (SQUID) have demonstrated significantly improved coupling rates [1-4]. It is even expected that these devices have the potential to reach the strong vacuum coupling regime, which will allow to explore phenomena beyond the linearized opto-mechanical interaction.

Here, we present an investigation of a superconducting circuit implementing the inductively mediated nano-electromechanical interaction, reaching a vacuum coupling strength of 50kHz. In addition, the SQUID enabling the control of the coupling strength also results in the possibility to control the mechanical resonance frequency.

We present experimental data demonstrating this in-situ frequency control mechanism, which is quantitatively corroborated by theoretical models based on the Lorentz force induced by the circulating current in the SQUID. In addition, we observe discontinuities in the magnetic field dependent tuning mechanism, which we attribute to the formation of individual flux vortices interacting with the atomic lattice in the superconducting material.

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Frontiers of Nanomechanical Systems (FNS) workshop
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Frequency Noise in Lithium Niobate Nano-Acoustic Resonators

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Nanomechanical resonators show considerable promise for applications in classical and quantum sensing. Microwave frequency lithium niobate devices, comprised of a defect resonator surrounded by a phononic radiation shield, are particularly appealing as they achieve high internal quality factors and can be transduced in parallel via a single RF channel [1]. One of the current limitations to the performance of these devices is frequency noise. Recent studies have suggested that the dominant mechanism of loss is due to coupling of the electric and acoustic fields to two-level systems (TLS) in the lithium niobate. In this work, we report measurements of the frequency noise of lithium niobate nanomechanical resonators of varying geometry, eigenfrequency and metallization. We observe increased dephasing at dilution refrigerator temperatures. Using this information, we characterize the sources of frequency noise (particularly, TLS) and attempt to mitigate dephasing at cryogenic temperatures.

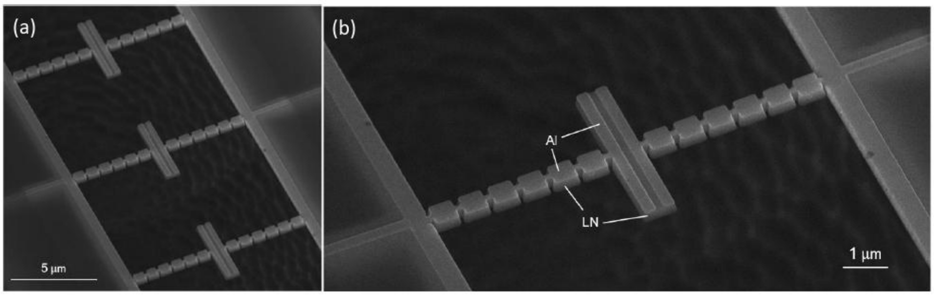

Figure 1: (a) An angled scanning electron micrograph (SEM) of suspended lithium niobate (LN) nanomechanical resonators. (b) SEM image of one LN phononic crystal defect resonator metallized with aluminum (Al) electrodes for piezoelectric transduction.

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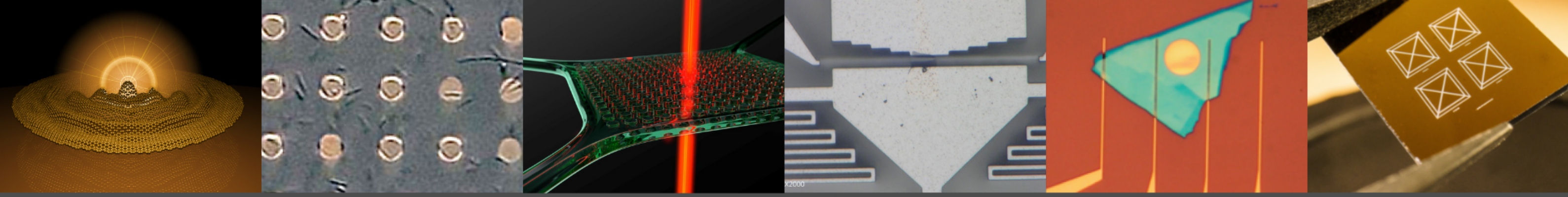

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High-Q Factor Complex Oxides MEMS Resonators from Epitaxial Thin Films

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Different materials are emerging beyond silicon for the realization of micro-electro-mechanical systems (MEMS). Complex oxides are functional materials having strong interplay between structural, electronic, and magnetic properties. Because of that they may open possibilities for developing new mechanical transduction schemes and for further enhancement of device performances. Besides the current integration of oxides, such as PZT with silicon, a full-oxides approach guarantees best material characteristics and allows for the fine tuning of physical properties thanks to the epitaxial growth of thin film and the control built-in strain. Nevertheless, the integration of these materials into micro-mechanical transducers is still at its very beginning and critical basic aspects related to the fabrication process, stress state, and the quality factors of micro-/nano-resonators made from epitaxial oxide thin films need to be investigated.

We will discuss the fabrication protocols and the mechanical characteristics of resonators made of single-crystal oxide thin films. In particular, we will consider ($La_{0.7}, Sr_{0.3})MnO_3$ (LSMO), a prototypical complex oxide showing ferromagnetic ground state at room temperature. The interplay between anisotropic etching, device geometry, and substrate lattice orientation allows for controlling the release process and the clamping conditions of the final devices [1]. These mechanical resonators result to be highly stressed, with strong temperature dependence of the resonance frequency around the magnetic transition. Their Q-factor reach few tens of thousands at room temperature, with indications for a further improvement by optimizing the fabrication protocols [2]. Our results demonstrate that complex oxides can be employed to realize high Q-factor mechanical resonators, paving the way towards the development of full-oxide MEMS/NEMS sensors.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 828784 [3].

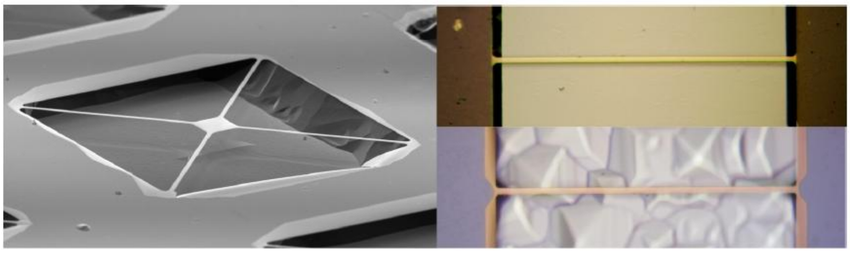

Figure 1: (left) SEM image of a LSMO trampoline having square size of 20 µm and 150 µm-long arms. (right) Comparison between two 250 µm-long LSMO micro-bridges fabricated from thin films grown on top of $SrTiO_3(110)$ (top) and $SrTiO_3(100)$ (bottom) substrates.

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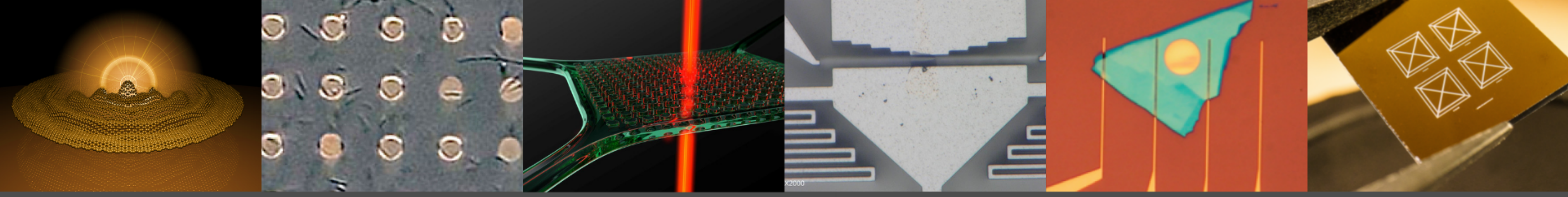

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Resolution Limits of Sensors based on Duffing Resonators

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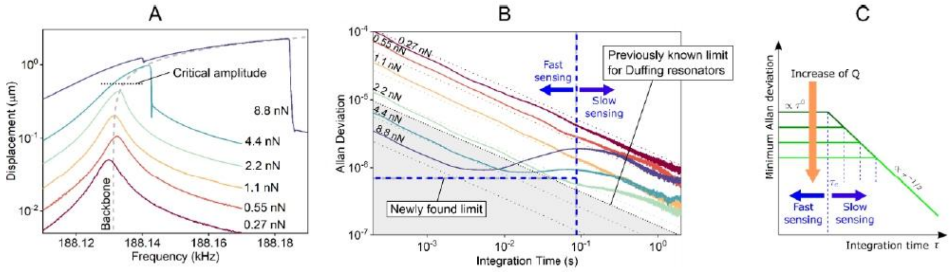
Sensors relying on the frequency shift of a mechanical resonance are ultimately limited by the presence of thermomechanical noise, due to the energy dissipation in the resonator. For linear resonators, the ultimate sensing resolution can always be improved by increasing the integration time in the recording, or the signal to noise ratio through higher driving power. This leaves the non-linear-effects appearing at high driving power as the only limiting factor to define the ultimate resolution. Recently, several works have studied this limit for Duffing resonators, setting the critical amplitude (or onset of non-linearity) as the limit at which the conversion of amplitude noise into phase noise becomes dominant, from which increasing power does not improve resolution [1-3]. Setting this limit leads to the counterintuitive conclusion that increasing the quality factor of a resonator does not improve its ultimate sensing resolution.

With measurements on a thin Si_3N_4 membrane (2 mm x 2 mm x 92 nm) in a phase-locked loop, we present experimental evidence that Duffing resonators surpass the previously proposed limit of Allan deviation (frequency resolution), by increasing driving power beyond the critical amplitude (Figs. A, B). To elucidate this result, we model the amplitude-phase space of a Duffing resonator using perturbation theory. The analysis agrees with the experimental result and yields an ultimate resolution that follows two distinct regimes, fast sensing and slow sensing, corresponding to integration times respectively shorter and longer than the resonator's decay time. In the fast sensing regime, the Allan deviation is minimized at a driving level above the critical amplitude. Importantly, this finding implies that, contrary to the previous knowledge, the ultimate Allan deviation at fast sensing is inversely proportional to the quality factor and independent of the integration time (Fig. C). For slow sensing, the minimum Allan deviation is reached near the critical amplitude, and is independent of the quality factor as previously thought. This understanding of the resolution limits is expected to impact sensing applications requiring high resolution and speed, such as the mass characterization of bio-molecules with high throughput.



A: Frequency sweep measurements of the displacement of the membrane for different amplitudes of the force applied. B: Allan deviation measured at the thermomechanical limit for the same force values as in A. Measurements at 4.4 nN and 8.8 nN surpass the previously known limit. C: Minimum Allan deviation of a Duffing resonator with varying quality factor (Q), derived from our model.

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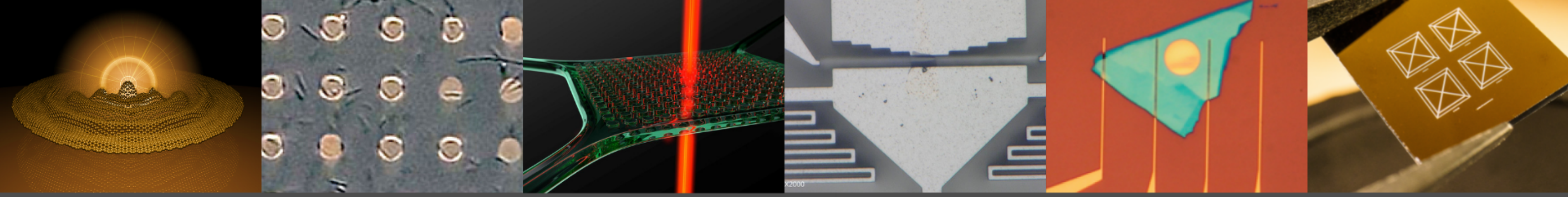

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Direct Determination of Optomechanical Photonic Crystal Mechanical Mode Profile via Quasi Near-Field Perturbation

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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 $1.55\ \mu m$ with a measured Q-factor around 2.10^5, and a breathing mode at $2.8\ GHz$ with a Q-factor of a few thousands 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 g_0). 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. At this distance, a 5-10% change is expected in the optomechanical coupling. This represents a challenge, as the current feedback loop control schemes for near-field imaging cannot be used to control the these kind of distances. We thus developed a custom procedure allowing the precise calibration in 3D of the nanotip position relative to the crystal.

Moreover, at closer distances, the presence of the nanotip introduces a parametric coupling with the cavity opening the path towards ultra-strong coupling between mechanical modes of the tip and the optical mode [3].

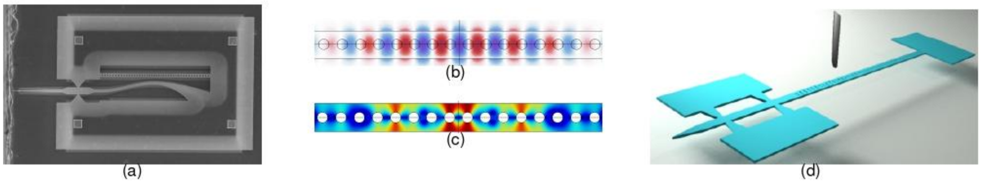
(a) (b) (c) (d)

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.

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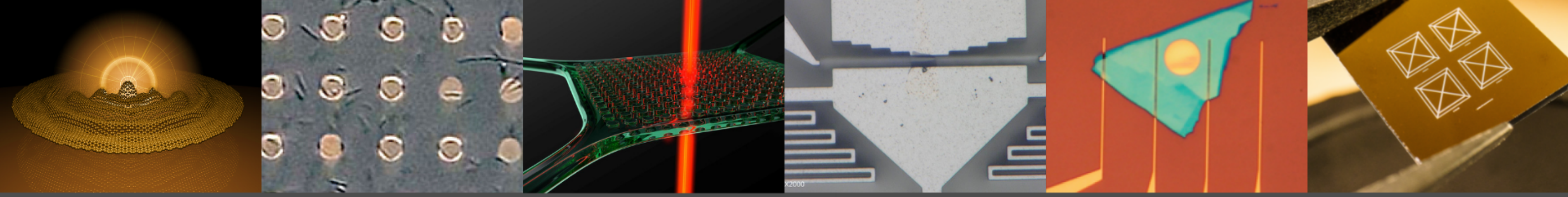

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Purely quartic nonlinearity in cavity optomechanics

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Introducing a controlled and strong anharmonicity in mechanical systems is a present challenge of nanomechanics. The anharmonicity allows one to generate non-classical states of the mechanical oscillator and, if the anharmonicity is sufficiently large, to address individually the mechanical excited states [1].

It is well known that for sufficiently large laser power an optomechanical cavity exhibits a classical static instability. We investigate under which conditions the instability could be tuned in such a way that a smooth crossover could be observed from a harmonic potential to a purely quartic potential [see Fig. (a)]. This behavioural crossover is manifested via correlations in system observables – we calculate, for example, the oscillator displacement spectrum shown in Fig. (b). Unlike the previously studied optomechanical dynamical instability that comes about for large amplitude mechanical oscillations [2], the quartic nonlinearity appears to survive - and is perhaps even enhanced - for low laser power.

One may wonder whether in certain cases the oscillator not only retains its nonlinear behaviour, but also displays purely quantum features – i.e. a quantum nonlinearity. Applying existing results [3] to our parameter regime of interest we observe non-Gaussianity in the oscillator state. The quadratic-quartic crossover could be exploited to tailor an anharmonicity in a precise way, in order to manipulate the state of the mechanical oscillator and, under certain conditions, fabricate non-classical quantum states.

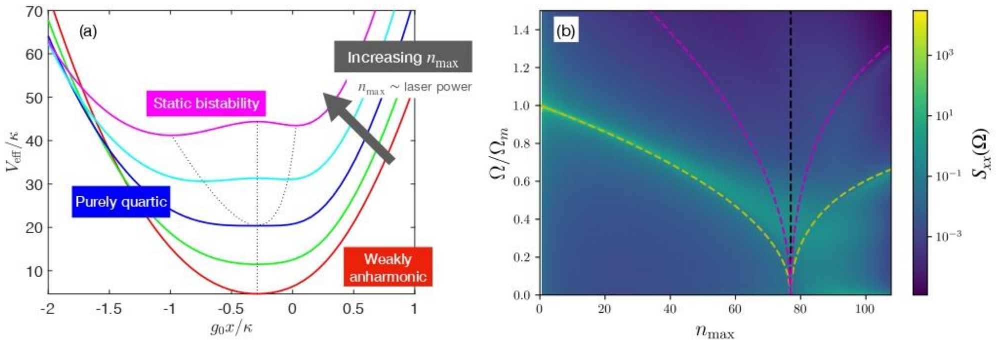

Figure 1: (a) Optomechanical effective potential V_{eff} as a function of oscillator displacement x, for different values of input laser power. The displacement is rescaled by the cavity linewidth κ and the single photon coupling strength g_0. (b) Heatmap of the oscillator displacement spectrum $S_{xx}(\Omega)$ for different laser power, computed via numerical solution of the Fokker-Planck equation. Transition from quadratic to quartic behaviour is manifested in the renormalisation and broadening of the spectral peak.

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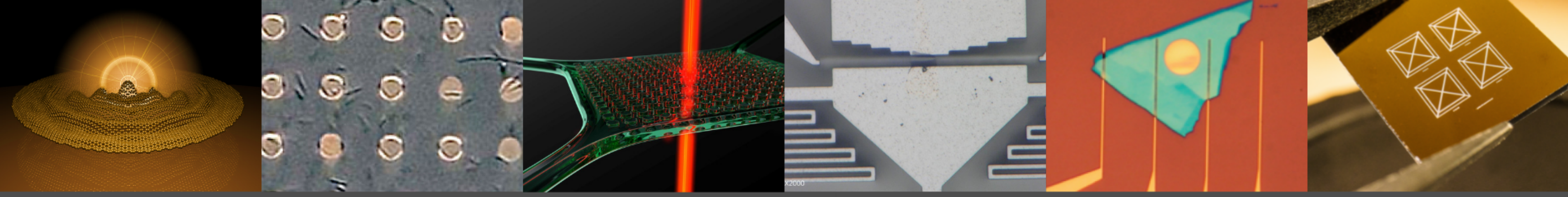

Frontiers of Nanomechanical Systems (FNS) workshop
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Magnetic force microscopy with nanowire resonators

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Free standing nanowires (NWs) naturally present themselves as very sensitive mechanical force sensors. Their high aspect ratio and low mass lead to thermally limited force sensitivities of a few aN $\text{Hz}^{-1/2}$ at cryogenic temperatures.

We use on-chip grown NWs in a pendulum-type geometry as scanning force microscopy probes. Their motion is detected optically with a fiber-based interferometer and the two first order flexural modes are used for force sensing. These resonances are usually split in frequency by many times their linewidth, due to anisotropic clamping and deviations from a perfect circular cross section, and can thus be addressed independently. Reading out the resonance frequencies of both modes, while scanning a sample of interest below the tip of the NW, we simultaneously map the orthogonal in-plane force gradients with a spatial resolution of a few tens of nm [1].

In our recent work, we focus on NWs as magnetic force microscopy (MFM) probes. This requires functionalizing the NWs in a way that they act as mechanical transducers for the magnetic fields originating from the sample of interest.

To achieve this goal state of the art Si NWs were equipped with magnetic cobalt tips using focused electron beam deposition (FEBID).

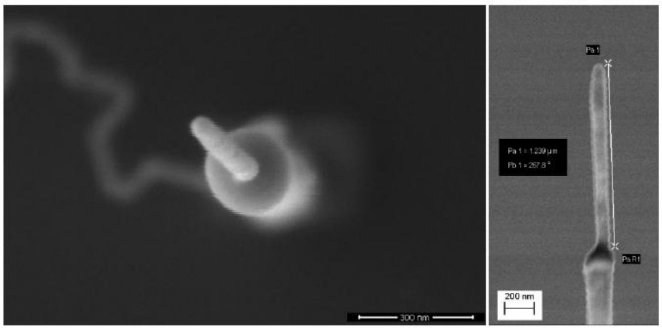

Figure 1: Two different Si NWs with Co FEBID tips.

In comparison to our previous work on fully magnetic Co FEBID NWs [2], we now take advantage of the NW's body serving as a high quality factor mechanical resonator while still maintaining an easy to interpret magnetic tip-sample interaction, described by a simple surface charge model.

Finally we present a NW-MFM experiment conducted on double layer EuGe_2, showing its temperature dependent transition from paramagnetic to ferromagnetic ordering and a tilt of the magnetization out of plane as high perpendicular magnetic fields are applied.

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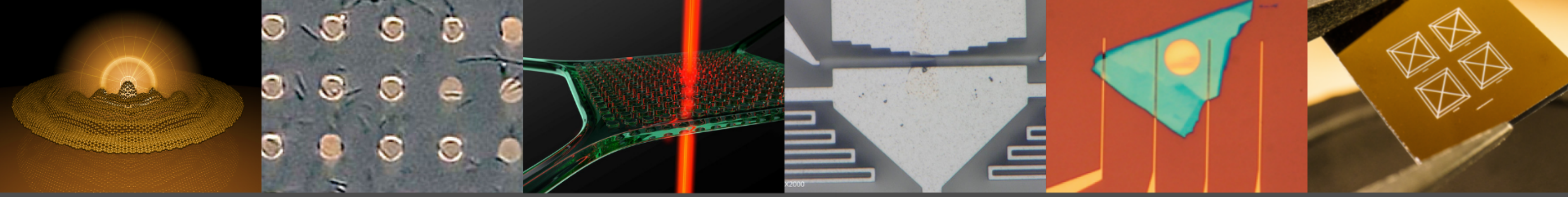

Frontiers of Nanomechanical Systems (FNS) workshop
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Towards a Mechanical Qubit in a Carbon Nanotube

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D. A. Czaplewski[2], **G. Gruber**[1], **A. N. Cleland**[3], **F. Pistolesi**[4], **A. Bachtold**[1]

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We present our efforts towards realizing the first ever mechanical qubit. We employ a suspended carbon nanotube and seek to tailor the energy potential of its mechanical vibrations by strongly coupling its motion to a double quantum dot [1]. Reading out the non-linear vibrations near the quantum ground state requires a sensitive and non-invasive probe which may be acheived using dispersive cavity readout.

We present the results of modifying and integrating our fully metallic, double quantum dot design [2] with a superconducting microwave cavity for dispersive readout of the suspended nanotube motion. The superconducting resonator is a Nb spiral inductively coupled to a microstrip [3]. The spiral itself is wired bonded to a NbN gate array which is capacitively coupled to the nanotube and further used to embed a double quantum dot on the nanotube. Our fabrication process yields reliable NbN gates which superconduct after the harsh conditions of our CVD growth. Growing nanotubes in-situ localizes high quality nanotubes [4, 5] above the gate array.

The platform not only enables the readout of a mechanical qubit, but further realizes an high cooperativity optomechanically interface [6] to the mechanical qubit which provides additional control.

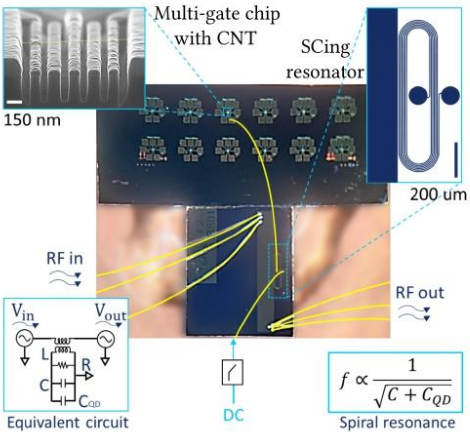

Figure 1: Multi-gate double quantum dot chip wirebonded to a superconductive microwave resonator for dispersive readout.

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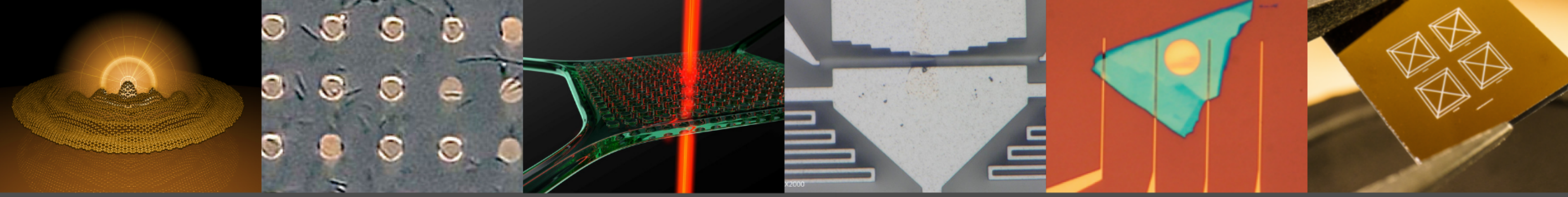

Frontiers of Nanomechanical Systems (FNS) workshop
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NOEMS as a platform for Non-Hermitian Physics

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Non-Hermitian Systems display interesting properties like [1] complex eigenfrequencies, biorthogonality, exceptional points, and nontrivial spectral instability under perturbations. Over the last few years, resolved sideband optomechanical systems have been used to explore this regime for coupled oscillators, demonstrating [2] topological energy transfer, non-reciprocity in energy transfer, and topological structure of adiabatic control loops. We propose a Nano-Opto-electro-mechanical system that can probe similar phenomena and more. The electrical degree of freedom allows exotic and non-trivial couplings as well. The system consists of a silicon racetrack resonator coupled to two mechanical Silicon strings forming an unresolved sideband cavity optomechanical system.

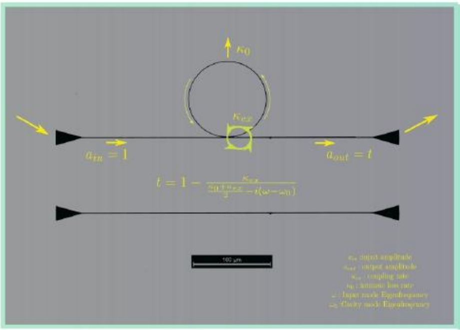

Figure 1: (left) The Optical Cavity

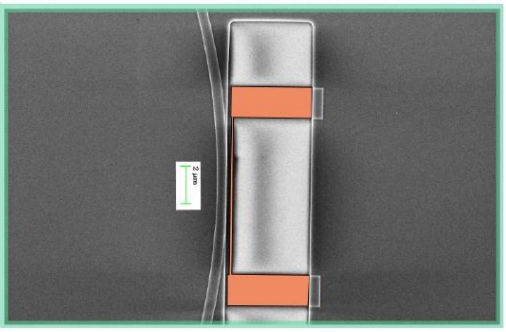

Figure 2: (right) The Defined Mechanical Beam

The Optical field offers a medium for Coupling the various mechanical modes as well as sensing them. Active Electrical and Optical Feedback using pre-programmed Phasor Rotation of mechanical signal allows doing an Adiabatic Closed Loop perturbation around an Exceptional Point. The high electrostatic tunablility[3] of resonant frequency allows achieving PT-symmetric regime.

Hence, we propose to explore Exceptional Point Phenomena and PT-symmetry Phenomena in NOEMS device.

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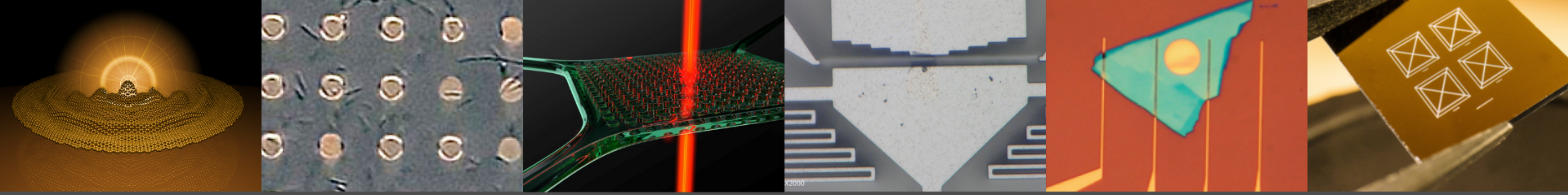

Optomechanical rheology of liquids at gigahertz frequencies

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

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

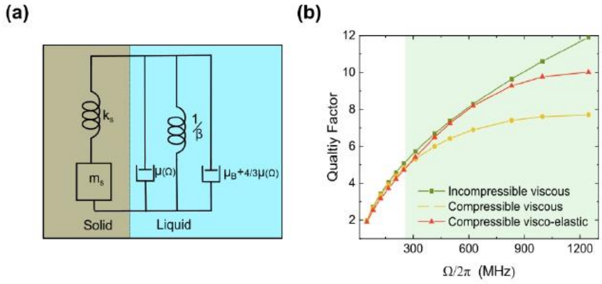

Figure 1: Theoretical study of fundamental radial breathing mode of a microdisk resonator in the presence of a compressible visco-elastic liquid: a) One-dimensional lumped model showing the shear and compressional components of the fluid stress (ks, ms: solid elastic constant and effective mass and; β, μ, μB: liquid compressibility, shear and bulk viscosity); b) Analytical calculation of the quality factor for 3 different liquid models.

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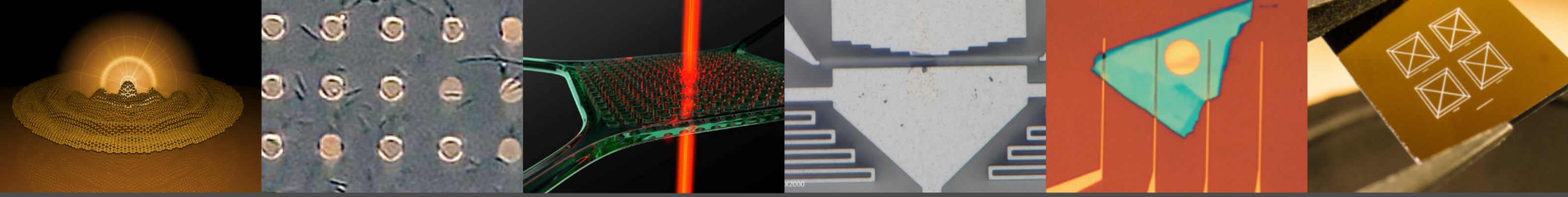

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Fabrication of Nanomechanical Diamond Devices via a Scalable Smart-cut Method

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Diamond is an attractive material for quantum information science and spin-opto-mechanical systems owing to its excellent material characteristics and capability of hosting highly coherent defect-based spins. Diamond mechanical resonators have recently emerged as an interesting system to integrate into quantum devices because they can couple to various quantum systems while maintaining high-quality factors. In particular, diamond optomechanical crystals (OMCs) can host GHz-scale mechanical modes with high mechanical Qs and high strain which enable strong spin-strain coupling [1, 2]. However, fabricating planar diamond nanophotonic and nanophononic device has significant challenges, in large part because of the difficulty of forming high-quality thin films of single-crystal diamond. One approach is the diamond-on-insulator(DOI) method that involves thinning bulk diamond through a combination of laser slicing and plasma etching [3], but this method is time-consuming and results in a wedged membrane with several-micron-scale thickness variations across a 2 x 2 mm sample, greatly limiting the device yield. Here we present results on an alternative smart-cut-like fabrication method [4–6], in which a high dose of implanted ions form a subsurface graphitized layer that can be selectively etched to leave a uniformly thin suspended diamond membrane. This membrane is then bonded to another material, silicon in our case. We use this approach to form and characterize diamond optomechanical structures with embedded defects spins formed during CVD overgrowth.

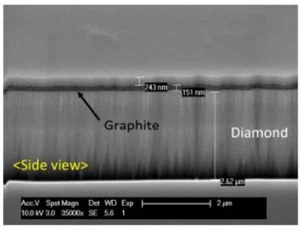

Figure 1: Subsurface graphite and diamond membrane

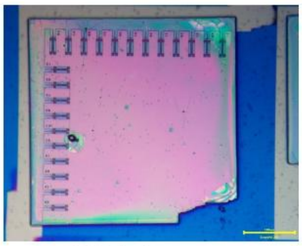

Figure 2: OMC device patterns on a diamond membrane

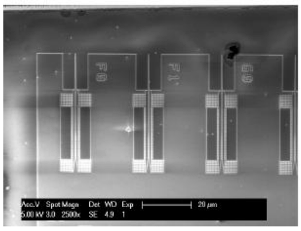

Figure 3: OMC devices with waveguides

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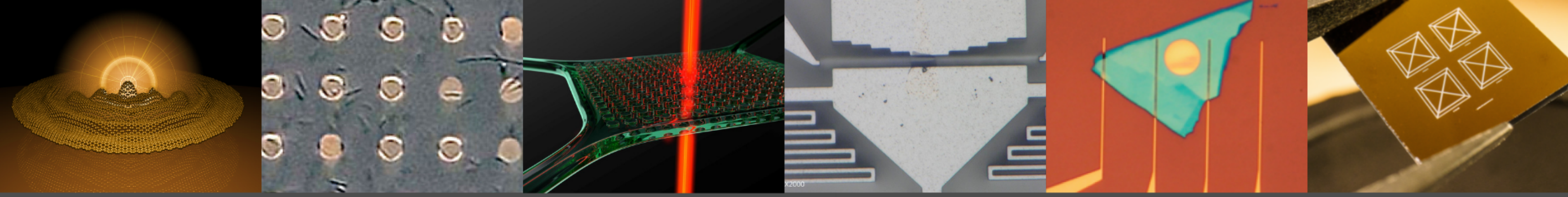

Frontiers of Nanomechanical Systems (FNS) workshop
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Optomechanics with magnetically levitated drops of liquid $^3\mathrm{He}$ and $^4\mathrm{He}$

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Levitated liquid helium drops combine the features of low temperature, isolation, and superfluidity that play an important role in a range of disciplines [1] including optomechanics, wherein the drops' optical whispering gallery modes form an optical cavity, and their surface modes constitute the mechanics. The drops are expected to realize the unexplored regime of the single-photon optomechanical coupling rate $g_0 > \omega_{\mathrm{mech}}$ (the mechanical frequency), approach the single-photon strong-coupling regime $(g_0 > \kappa_{\mathrm{opt}}$, the optical cavity linewidth), and enable access to quantum nondemolition measurements of angular momentum for rotating $^3\mathrm{He}$ drops [2].

Here, we report on recent [1] and ongoing experiments with millimeter-scale drops of pure $^4\mathrm{He}$ and pure $^3\mathrm{He}$ trapped by diamagnetic levitation in high vacuum. We measure the drops' temperature and evaporation rates, and characterize their surface waves, center-of-mass motion, and optical whispering gallery modes. These measurements are all in good agreement with theoretical predictions. We find that superfluid $^4\mathrm{He}$ drops can be trapped indefinitely with a temperature of $\sim 330\ \mathrm{mK}$. Drops of $^3\mathrm{He}$ are expected to reach lower temperatures, but their levitation at temperatures $< 1\ \mathrm{K}$ is complicated by the dynamics of their nuclear spins.

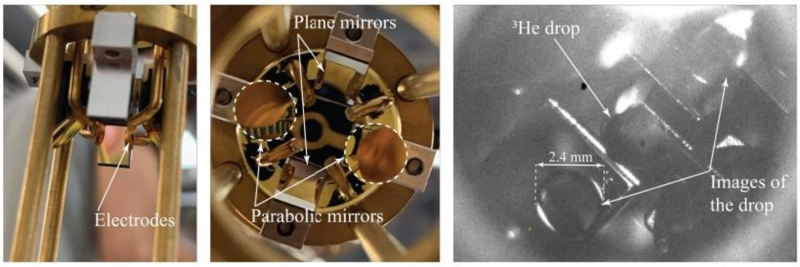

Figure 1: Cryogenic insert with imaging and probe mirrors; Illustrative image of diamagnetically levitated $^3\mathrm{He}$.

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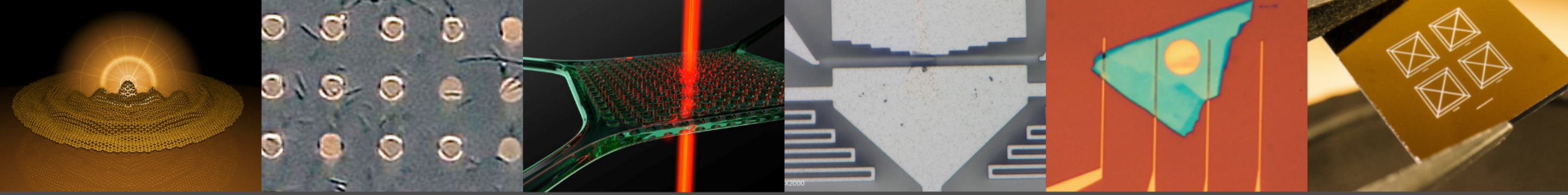

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A Hybrid Superconductor/Nanomechanical Magnetic Field Detector for Biomagnetism

Luca Pellegrino[1,*], **Nicola Manca**[1], **Alejandro Plaza**[1], **Leonélio Cichetto**[1], **Daniele Marré**[2,1]
Federico Maspero[1,3], **Simone Cuccurullo**[3], **Riccardo Bertacco**[3,1]
Eric Wahlberg[4], **Alexei Kalaboukhov**[4], **Floriana Lombardi**[4]
Torben Hänke[5] , **Dhavalkumar Mungpara**[5], **Alexander Schwarz**[5]
Ingo Hilschenz[6], **Enrico Ragucci**[6], **Sara Spadone**[6], **Warner Venstra**[7], **Stefania Della Penna**[6]
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Current commercial setups for magnetoencephalography (MEG) use helmets comprising low Tc SQUIDs. SQUID sensors are barely robust to static and pulsed magnetic fields, such as the ones used in Ultra-Low Field Magnetic Resonance Imaging (MRI) and especially Transcranial Magnetic Stimulation (TMS). For this reason, integration of MEG with these techniques in a unique system at present has not yet been achieved. Our purpose is to develop a magnetic field sensor with sensitivity of the order of 10fT/sqrt(Hz) to measure the magnetic field of the human brain and at the same time quickly recovering in a strong applied field (» 1 T) [1]. This sensor would be suitable for an on-scalp MEG system integrated with multiple imaging modalities to image brain activity and connectivity with high spatial and temporal resolution. We are developing a hybrid device by coupling a high-Q MEMS/NEMS resonator having a magnetic element to a high-Tc superconducting magnetic field focuser in series to a pick-up loop that collects the external magnetic field. The biomagnetic field induces a supercurrent in the loop, which has a geometry designed to generate a strong non-uniform magnetic field in the proximity of the magnetic element of the NEMS resonator (fig.1) [2]. The resonance frequency of the resonator is modified by this magnetic coupling and detected by a fiber-optic interferometer. Optomechanical detection of biomagnetic fields has the advantage of reducing the crosstalk between the channels with respect to electrical detection. This feature requires the development of a cheap, robust and scalable optomechanical platform for a future NEMS-based helmet. We discuss the basic working principle of this hybrid sensor and the advancements made so far for the realization and characterization of the first device prototypes as well for the realization of the optomechanical platform that will host the first magnetometer to be characterized in operative environment.

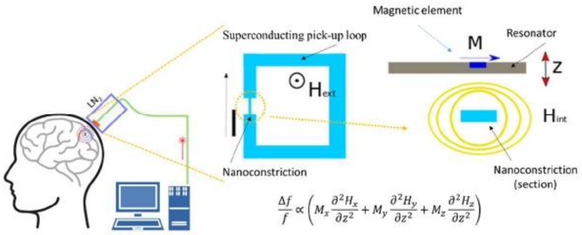

Figure 1: The principle of the OXiNEMS hybrid magnetometer [2].

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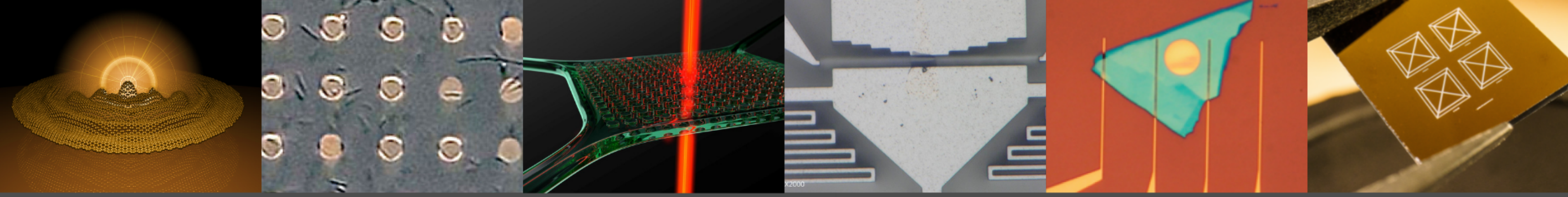

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Dynamical Backaction Evading Magnomechanics

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The interaction between magnons and mechanical vibrations dynamically modify the properties of the mechanical oscillator, such as its frequency and decay rate. Known as dynamical backaction, this effect is the basis for many theoretical protocols, such as entanglement generation or mechanical ground-state cooling. However, dynamical backaction is also detrimental for specific applications. Here, we demonstrate the implementation of a triple-resonance cavity magnomechanical measurement that fully evades dynamical backaction effects. Through careful engineering, the magnomechanical scattering rate into the hybrid magnon-photon modes can be precisely matched, eliminating dynamical backaction damping. Backaction evasion is confirmed via the measurement of a drive-power-independent mechanical linewidth. [1–3]

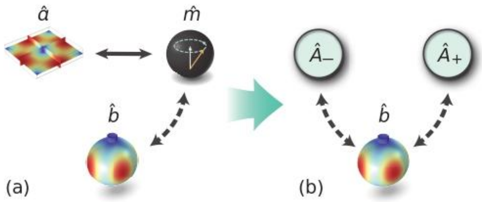

Figure 1: Schematic of the hybrid magnomechanical system. (a) Numerical simulation of the bare magnetic field distribution of the microwave resonance, $\hat{a}$, schematic representation of the uniform Kittel magnon mode, $\hat{m}$, numerical simulation of the mechanical breathing mode of the YIG sphere, $\hat{b}$. (b) Due to strong coupling between the magnon and photon modes this system can be recast, see main text, in terms of a single mechanical mode coupled to two independent bosonic normal modes — the fundamental requirement for the dynamical backaction evasion developed here.

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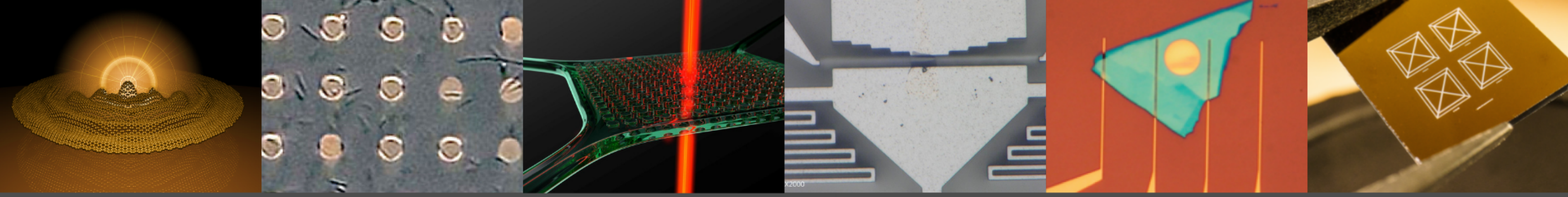

Frontiers of Nanomechanical Systems (FNS) workshop
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Nanomechanical Resonator based on Twisted Bilayer Graphene

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Two graphene layers rotated with respect to each other create Moire pattern. At a twist angle around 1.1° also known as magic angle, the twisted stack exhibits superconductivity and correlated states.[1] The twisted bilayer graphene transits from superconducting to insulating states by tuning the charge carrier density.[2,3] The superconducting behaviour is similar to those of cuprates and other high-temperature superconductors. In this work, we explain our efforts in fabricating nano-mechanical devices based on twisted/Bernel bilayer graphene and probe the exotic states such as superconducting and correlated states.

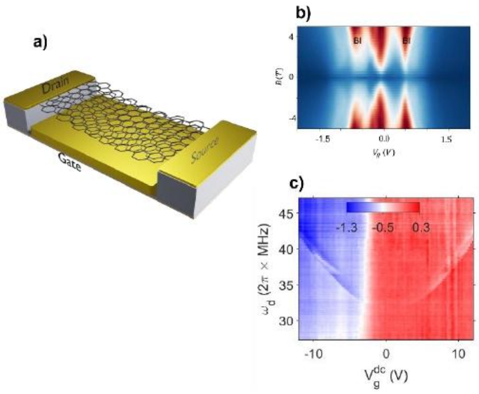

Figure 1: (a) Schematic of the twisted bi-layer graphene NEMS, (b) Magnetic field vs carrier concentration. Single particle band gap (BI) indicates twist angle in suspended twisted bilayer graphene. (c) Resonant frequency dispersion with applied gate voltage in a twisted bilayer graphene nanoresonator.

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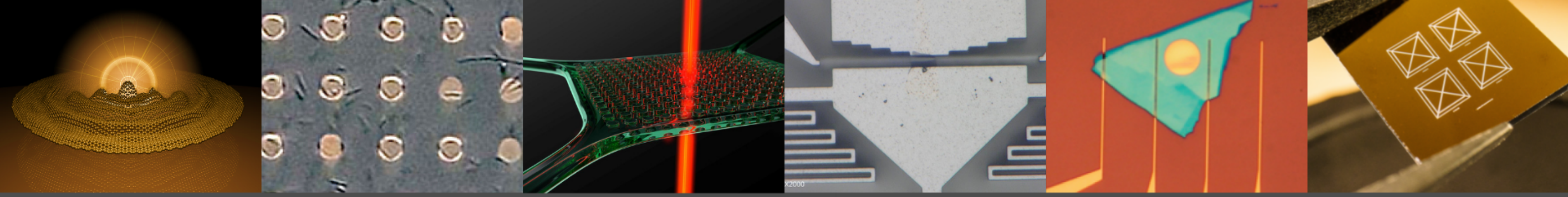

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Advances In 3D Magnetic Resonance Force Microscopy

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Magnetic Resonance Force Microscopy (MRFM) is a promising technique to obtain a 3D visualization of nuclear spin densities inside objects with sub-nanometer spatial resolution [1]. This can be used for the acquisition of three-dimensional nanoscale magnetic resonance images (NanoMRI) of sample structures, which is of great interest in the field of biology. In contrast to other NanoMRI techniques, MRFM is a scanning probe technique measuring the force generated by spatially localized excited spins in a magnetic field gradient [2]. The nanomechanical force sensors used in our work are monocrystalline-silicon cantilevers and are designed to have a very-low spring constants $k_c < 0.1\,\mu\mathrm{N\,m^{-1}}$, therefore achieving force sensitivities in the single digit $\mathrm{aN}/\sqrt{\mathrm{Hz}}$ regime. This allows the detection of the small spin-ensembles required for high-resolution scans.

We will present recent improvements in our measurement setup to increase the speed and reduce the impact of strong static and dynamic cantilever-surface interactions on MRFM measurements [3]. These interactions, caused by the floppiness of the cantilever and surface structures on the RF-microstrip, lead to detrimental static bending effects. By additionally employing novel microstrip designs with embedded nano-magnets this effect is further reduced.

We also present spatial sub-sampling methods, which are introduced into our measurement and reconstruction pipeline to reduce the required data points to be measured during a scan. Through the use of these compressed sensing techniques [4], we can increase the speed and robustness of our measurements.

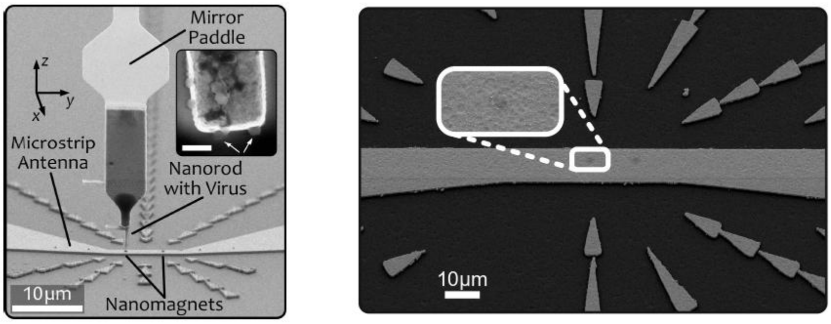

Figure 1: (a): Illustration of the configuration of the MRFM experiment. The samples are attached to a silicon nanorod, which is connected to the silicon cantilever. (b) New microstrip design with embedded FeCo-nanomagnets to reduce non-contact interaction between the cantilever and the microstrip.

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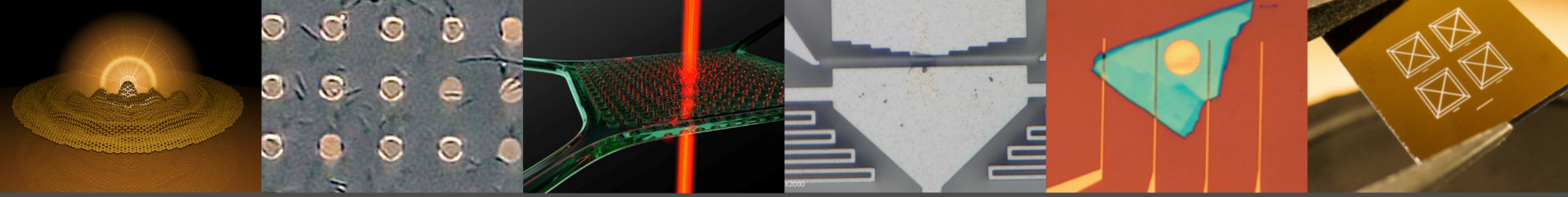

Frontiers of Nanomechanical Systems (FNS) workshop
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TRANSMISSION LINE ELECTROMECHANICS

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Achieving strong interactions between light and mechanical motion is fundamental to science and technology. The dominant approach, cavity optomechanics, embeds a high-quality mechanical system in a resonant cavity to enhance the otherwise feeble light-matter interaction [1]. Here we introduce an alternative approach – transmission line electromechanics – which achieves strong coupling without intermediate resonant elements as employed in previous works [1, 2]. Our method consists of capacitively coupling a metalized Si3N4 membrane to the end of a transmission line. A DC bias (V_{DC}) tunes the system into a strong-coupling regime where the radiative damping from the external transmission line overwhelms the intrinsic mechanical dissipation. Figure 1 (a) shows the transmission (S_{21}) through the circuit and (b) the corresponding cooperativity for different DC bias. Strong coupling is achieved at $V_{DC} > 0.4$ V and $C > 2$ at $V_{DC} \sim 1$ V. We demonstrate a few applications as parametric mechanical driving, mechanical squeezing, and remote cooling and compare the performance from current state-of-the-art devices to our approach. This architecture also has potential applications from sensors and amplifiers to microwave-integrated and hybrid quantum devices.

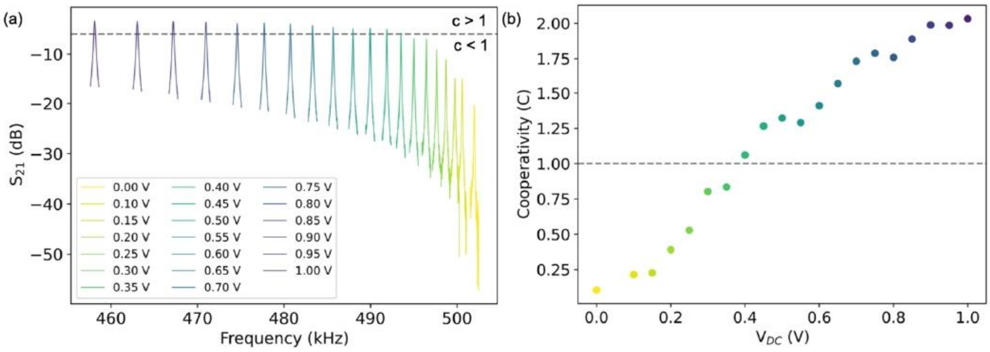

Figure 1: (a) Transmission (S_{21}) for resonances acquired at different voltages. The dashed line indicated the corresponding transmission for a cooperativity of 1. (b) Cooperativity extracted for the resonances showed in figure 1 (a). The dashed line corresponds to a cooperativity of 1.

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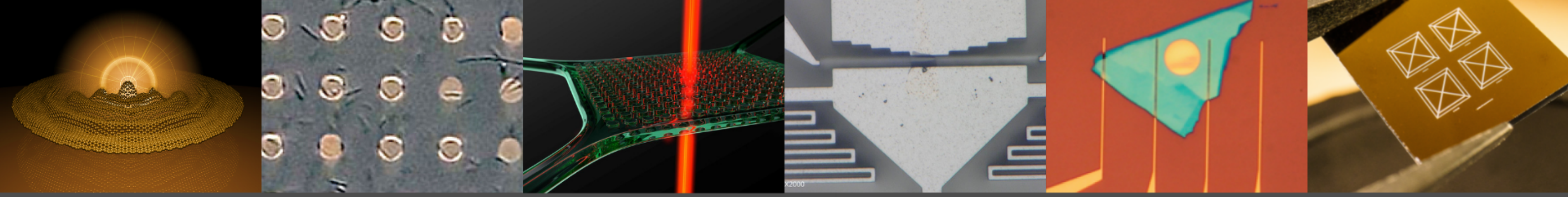

Frontiers of Nanomechanical Systems (FNS) workshop
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Non-magnetic portable probe for characterising mechanic resonators in vacuum at low temperatures

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We present the design and characterisation of an all-ceramic optomechanical probe for (bio-)magnetic field measurements at liquid nitrogen (LN2) temperatures. The probe is developed as part of the OXiNEMS project [1] (www.oxinems.eu) whose goal is to develop a nanoelectromechanical (NEMS) magnetic field sensor based on metal oxides. The probe is intended for basic characterisation of a magnetic field sensor, which is to be be integrated either in a Nuclear Magnetic Resonance or in a Magnetoencephalography system. To detect magnetic fields in the order of 10's of fT, a transducer is proposed [2] which consists of two main components: a micrometer-scale mechanical resonator whose resonance frequency depends on the applied magnetic field, and a high-T_c superconducting flux gradient concentrator (FGC) to enhance the responsivity to the magnetic fields. The resonator displacements are probed using a low-noise fiber interferometer [3], designed to be scalable to facilitate readout of multiple channels. A vacuum space for the sample/sensor guarantees a high Q-factor for the NEMS resonators, which in turn requires vacuum feedthroughs for electrical and optical connections. To avoid interference due to probe magnetization and Eddy currents, the critical parts are implemented using non-magnetic and electrically insulating materials, like Shapal. This material has an excellent thermal conductivity at LN2 temperatures, enabling the cooling of the superconducting FGCs to below their critical temperature (~ 80 K). A motorized distance adjustment between the fiber tip and the resonator allows the fiber to be retracted during cool-down, as well as adjustment to a quadrature point to maximize the optomechanical transduction of biomagnetic signals. The motor design is based on a stick-slip actuator developed previously at the University of Hamburg [4] but implemented here using non-metallic materials and equipped with a spiral spring to minimize the amount of metal near the sensor. For the magnetic characterization we utilize multiple 6 mm PCB pancake coils and a Helmholtz coil set as a reference. The whole probe tip is shielded with a large high T_c superconducting material [5] which can be removed when used in a shielded environment.

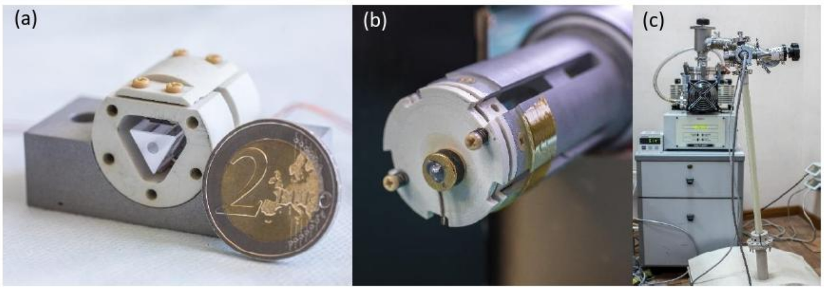

Figure 1: (a) all-ceramic inertial sliding z-motor; the optical fiber for readout is mounted in the center. (b) Non-magnetic portable probe equipped with thermal sensor (c) fully equipped non-magnetic cryo-probe incl. vacuum system and optical- and electrical feedthroughs

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Frontiers of Nanomechanical Systems (FNS) workshop
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Theory behind the realization of a mechanical qubit

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Mechanical oscillators are systems that have been demonstrated with very high-quality factors over a wide range of frequencies and couple to a wide variety of fields and forces, making them ideal as sensors for quantum information. The realization of a mechanically based quantum bit could therefore provide an important new platform for quantum computation and sensing.

Here we explore the coupling of one of the flexural modes with the charge states defined in the double quantum dot defined in the nanotube [1]. We show that the anharmonicity needed to form the mechanical qubit is only possible in the ultrastrong coupling regime. We discuss the condition for the anharmonicity to appear and see that the Hamiltonian defining the electromechanical coupling can be mapped to an anharmonic oscillator, allowing us to work out the energy levels and the inherit decoherence from the mechanical and electronic degrees of freedom.

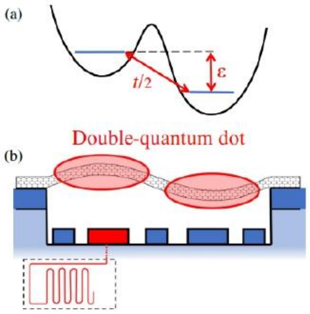
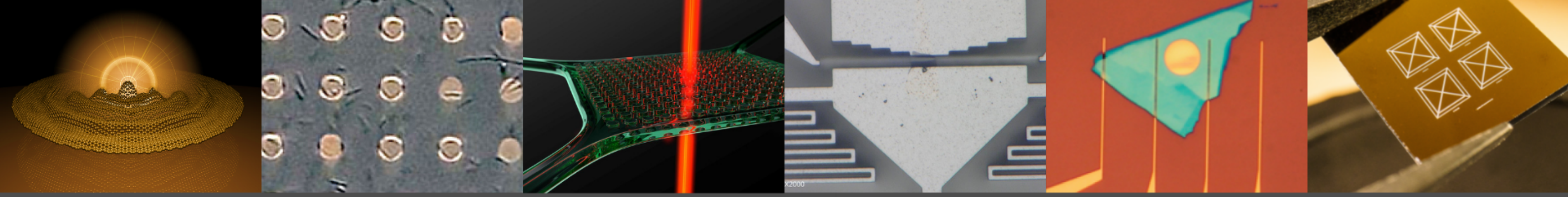


Figure 1 - Schematic setup of the proposed system. a) Double well potential in the double quantum dot leading to the charge states of one excees electron in the nanotube. b) Suspended cabron nanotube in the second flexural mode. One gate is a superconducting cavity for read-out.

Remarkably, the dephasing from the charge states in the double quantum dot is expected to be reduced by several orders of magnitude in the ultrastrong coupling regime. We finally discuss the mechanical qubit manipulation and read-out and propose the realization of a CNOT gate by coupling two mechanical qubits to a superconducting cavity. We also take a master equation approach to numerically solve the system energies in the presence of losses from a circuit Quantum Electrodynamics approach, where we can explore the engineering of the parameter space to the actual experimental implementation of the mechanical qubit.

References



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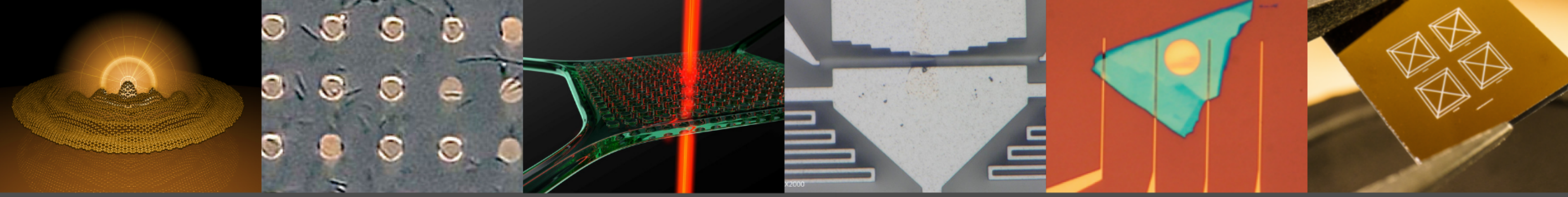

Frontiers of Nanomechanical Systems (FNS) workshop
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Design and fabrication of kinetic-inductive electro-mechanical force sensors

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Nanowires made from thin films of superconducting NbTiN have large kinetic inductance resulting from the inertia (mass) and high velocity of the Cooper pairs. This mechanical energy allows for the realisation of compact lumped-element microwave resonant circuits with high quality factor. We describe the design and fabrication of a device which couples such a microwave resonance to the mechanical resonance of a cantilever, where the cantilever's flexing causes strain in the nanowire, resulting in a change in its kinetic inductance [1].

The cantilever is a triangular plate with one side rigidly clamped to a substrate (Fig. 1a). The flexural eigenmodes are simulated by finite element methods and they show maximum of strain close to the clamped edge (Fig. 1b). A nanowire meandering transverse to the clamping line forms a lumped-element kinetic inductor (Fig. 1c). Quasi-3D electromagnetic simulations with SONNET show that the lowest-frequency self-resonance mode of the meander is about 15 GHz (Fig. 1d). Below this frequency, the meander is a lumped-element "super inductor" which we place in series with an co-planar capacitor (Fig. 1a) to form a compact microwave plasma mode with resonance frequency $\omega_0 \sim 4.5$ GHz.

The nanowire is fabricated by electron-beam lithography and etching a 15 nm layer of NbTiN sputtered on top of a Si wafer with a 600 nm thick layer of ultra-low stress SiN. Photolithography is used to fabricated a co-planar waveguide which forms the input and output port of the device. The SiN cantilever is then released by etching away the Si support, and deep reactive-ion etching releases each device from the wafer. The design is fully co-planar, requiring no crossing wires, with a relatively simple geometry that results in high yield.

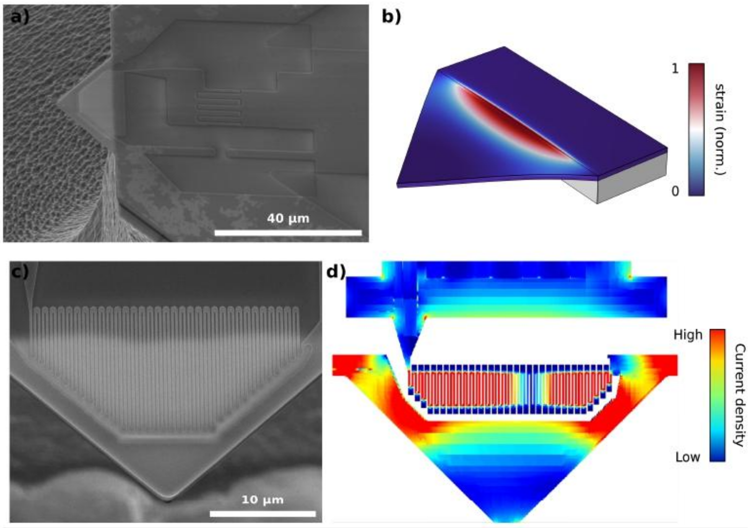

Figure 1: **a)** Scanning electron microscope (SEM) image of the device. **b)** Continuum mechanics simulation of the strain profile with red corresponding to regions of high strain. **c)** SEM image of the meandering nanowire inductor. **d)** Electromagnetic simulation showing the current density at the first self-resonance of the inductor at 15 GHz.

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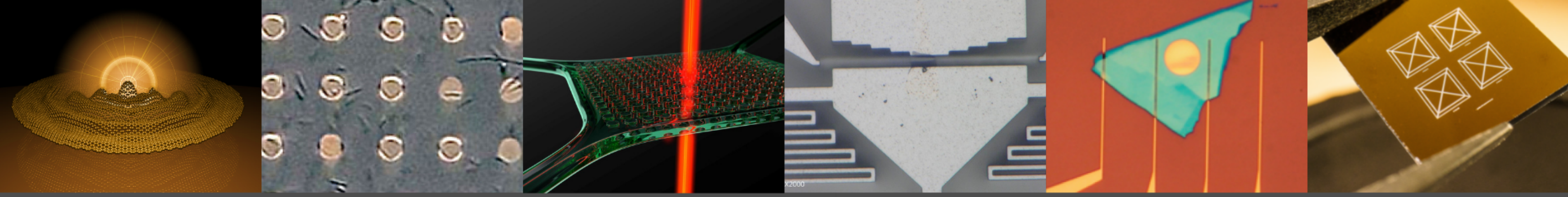

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Probing nanomotion of single bacteria with graphene drums

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Motion is a key characteristic of every form of life. At the molecular scale, motion is a signature of growth and homeostasis of living cells manifesting itself as random-like nanomechanical oscillations with origins that have remained largely unknown. Here, we use the exquisite sensing capabilities of suspended graphene drums to probe bacterial vibrations – at the level of a single bacterial cell [1]. By measuring mutants with varying degree of motility, we can pinpoint flagella as a main constitutor of nanomotion observed in bacteria. We also show the viability of this technique for antimicrobial susceptibility testing, which can become a fast and label-free alternative to current methods.

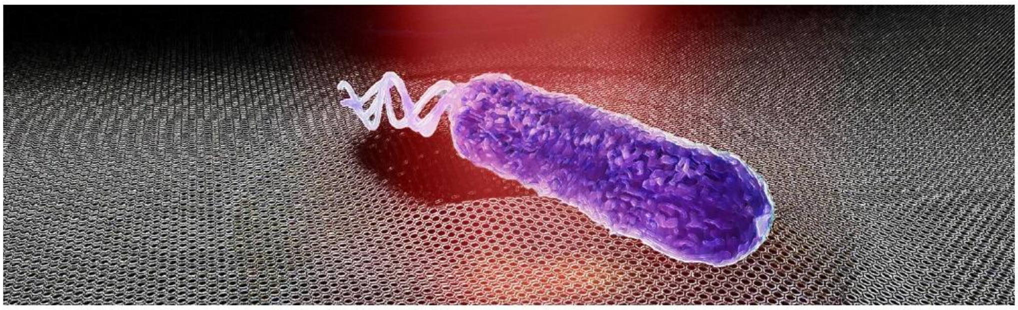

Figure 1: Artist's impression of a single bacterium on a suspended graphene drum probed by a laser.

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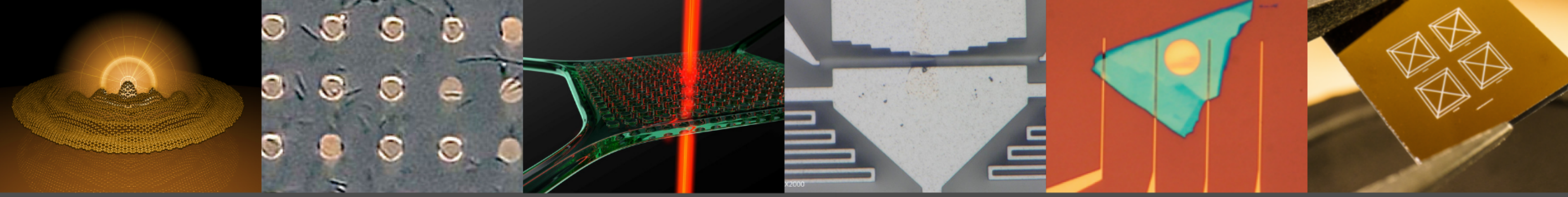

Frontiers of Nanomechanical Systems (FNS) workshop
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Nonlinear nanomechanical resonators approaching the quantum ground state

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An open question in mechanics is whether mechanical resonators can be made nonlinear with vibrations approaching the quantum ground state. This requires engineering a mechanical nonlinearity far beyond what has been realized thus far. Here we discovered a mechanism to boost the Duffing nonlinearity by coupling the vibrations of a nanotube resonator to single-electron tunneling and by operating the system in the ultrastrong coupling regime. Remarkably, thermal vibrations become highly nonlinear when lowering the temperature. The average vibration amplitude at the lowest temperature is 13 times the zero-point motion, with approximately 42% of the thermal energy stored in the anharmonic part of the potential. Our work paves the way for realizing mechanical Schrodinger cat states [1], mechanical qubits [2, 3], and quantum simulators emulating the electron-phonon coupling [4].

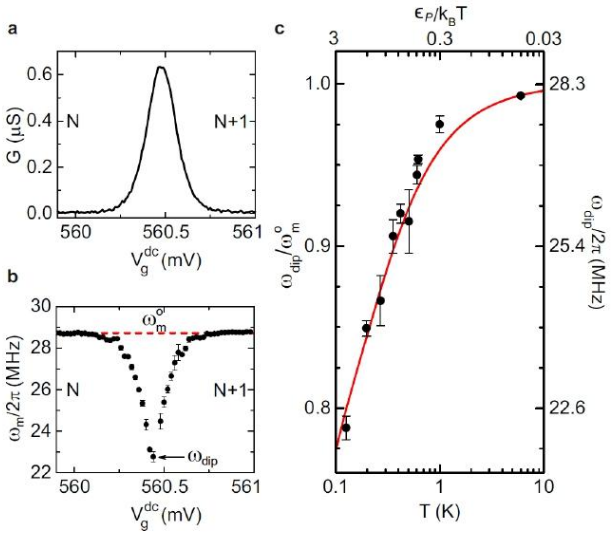

Fig. 1: Enhanced mechanical vibration nonlinearity at low temperature. (a,b) Conductance and mechanical resonance frequency as a function of gate voltage at 300 mK. (c) Temperature dependence of the resonance frequency. The red line is the prediction.

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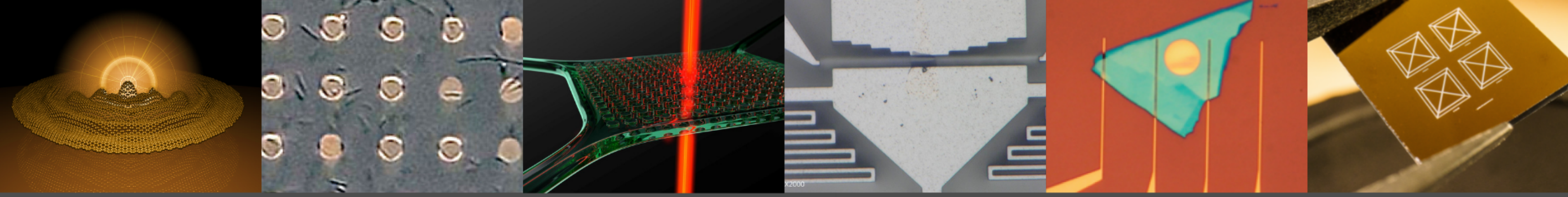

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Coherent multifrequency microwave measurement for phase-sensitive detection of nanomechanical motion

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We propose a multifrequency pump and readout scheme for phase sensitive detection of the mechanical motion of a force sensor designed for use in frequency modulation atomic force microscopy. The principle of transduction is based on cavity electromechanics in the resolved sideband regime. Similar to the so-called 'back-action evasion' scheme [1], we pump the cavity with two tones $\omega_\pm = \omega_0 \pm \omega_d$, symmetrically detuned from the cavity resonance ($\omega_0 \sim 4.5$ GHz) by the mechanical resonant frequency ($\omega_m \sim 5$ MHz). In addition we inertially drive the cantilever close to mechanical resonance $\omega_d \simeq \omega_m$ while listening for response at ω_0 (see Fig. 1a). All drive and measurement signals are created (monitored) with a digital microwave platform [2], with the mechanical drive generated in the base band [0-500 MHz] and the microwave pump tones generated via digital I/Q mixing with a numerically controlled oscillator. The quadrature response at ω_0, resulting from the interference between the motional sidebands produced by the two pumps, is measured via digital down-conversion from the 2nd Nyquist band of a 4 GS/s analog-to-digital converter. This all-digital approach with one common phase reference greatly simplifies the measurement. Our experiment shows the measurement of a single quadrature of the mechanical motion (Figs. 1c-1e), where the control over the mechanical drive phase mimics the effect of the tip surface interaction (Fig. 1b).

We demonstrate the measurement scheme on a cantilever sensor which exploits a new type of electro-mechanical coupling based on the modulation kinetic inductance with strain [3]. Large kinetic inductance is realised in a nanowire 'super inductor' connected in series with a co-planar capacitor to create a high Q microwave plasma mode acting as the cavity. An additional nanowire shunt inductor transforms the cavity impedance to optimally couple the device to a 50Ω transmission line for readout (Figs. 1f, 1g). The responsivity to mechanical phase shift depends on the excitation power and relative phase of the microwave pumps.

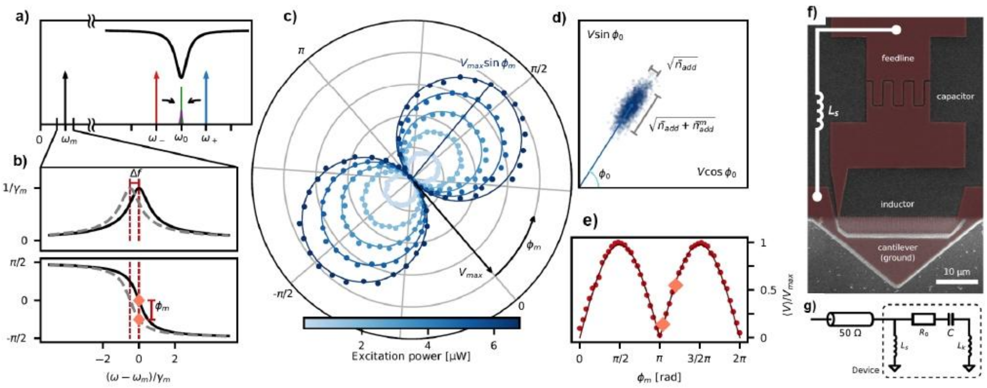

Figure 1: a-b: measurement scheme. c-e: phase and power dependence. f-g sample and equivalent circuit

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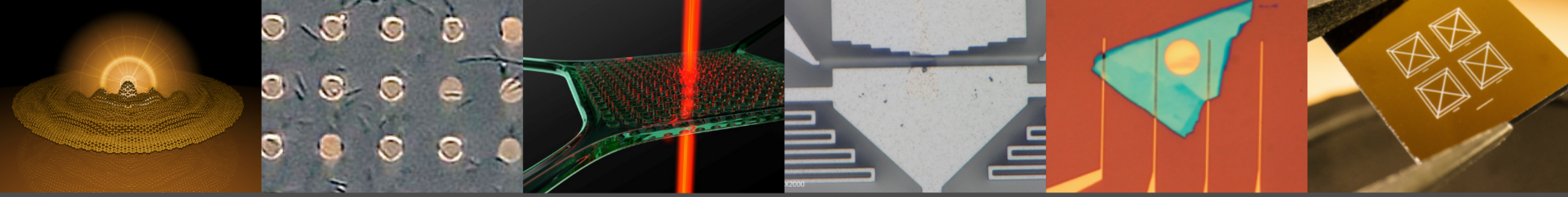

Frontiers of Nanomechanical Systems (FNS) workshop
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Towards nanomechanical detection of fT bio-magnetic fields

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This work has been conducted in the framework of the OXiNEMS [1] project that has two main objectives. Firstly, it aims to establish etching protocols for oxides LSMO, LAO, ETO et., similar to those nowadays available in the vast realm of silicon technology to fabricate NEMS based on these materials. Secondly, these NEMS should be implemented in a novel all-oxide hybrid sensor to detect bio-magnetic fields in the fT-regime as required for magnetoencephalography (MEG). Our envisaged hybrid sensor consists of a superconducting loop made of YBCO with a constriction that acts as field-to-gradient converter and a magnetically sensitive mechanical resonator that detects the Oersted field above the constriction., cf. Fig. 1(a). This set-up is somewhat similar to magnetic force microscopy (MFM) or magnetic exchange force microscopy (MExFM). With the latter, we demonstrated that magnetically sensitive mechanical resonators, i.e., cantilevers in this case, can achieve single spin sensitivity [2].

The work presented here shows finite element-based simulations of different constriction-resonator geometries with the aim to increase the signal above the thermal noise limit. Using a spiral geometry instead of a single constriction we obtain a much larger interaction volume, which increases the signal dramatically. Adjusting the length auf the magnetic element to match the area covered by the spiral further maximizes the signal, because it makes use of a phenomenon that we dubbed edge effect. This optimized geometry, can be fabricated using up-to date technology and is expected reaching a sensitivity of 10 fT/ √Hz at 77 K, cf. Fig. 1(b), which is sufficient for MEG applications. Of course, the achievable sensitivity depends on many more parameters, e.g., the separation between constriction and resonator, which will be discussed as well.

The OXiNEMS project (www.oxinems.eu) has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 828784. The author gratefully acknowledges the fruitful discussions with all members of the consortium, particularly Luca Pellegrino, Stefania Della Penna, Alexei Kalaboukhov, Federico Maspero, Nicola Manca, Simone Cuccurullo, Warner Venstra, Daniele Marré and Riccardo Bertacco.

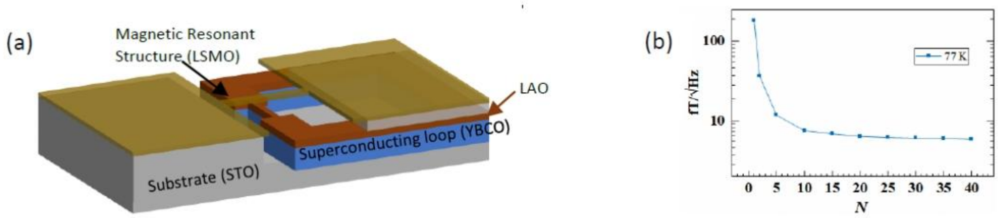

Figure 1: (a) Hybrid sensor composed of a superconducting YBCO pick-up loop with a constriction, above which a magnetically sensitive LSMO resonator is placed. (b) Results for the simulated sensitivity, when the single line constriction is replaced by spiral, which increases the interaction volume dramatically.

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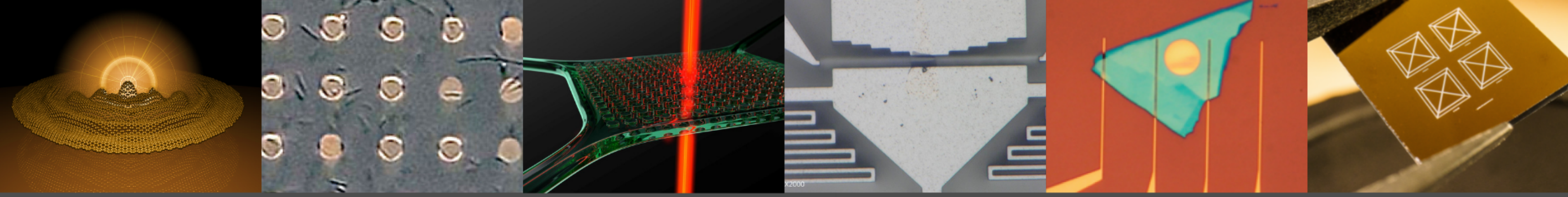

Frontiers of Nanomechanical Systems (FNS) workshop
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A voltage-controllable magnetic tip for membrane-based scanning force microscopy

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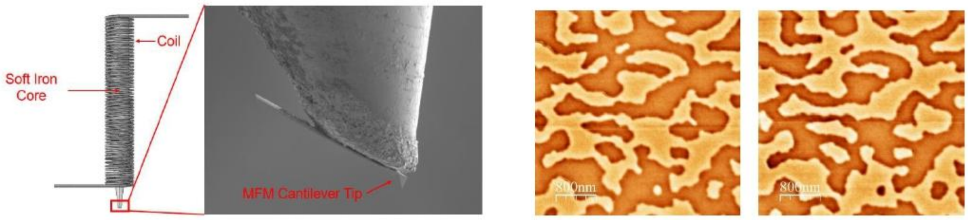
Force Microscopy has become a ubiquitous method for characterization and imaging of microscopic objects. Magnetic force detection, in particular, has found use in methods like Magnetic Force Microscopy (MFM) for 2D imaging of magnetic structures, as well as in Magnetic Resonance Force Microscopy (MRFM) for non-invasive structure determination using 3D imaging. MFM experiments typically use a cantilever with a sharp magnetic tip to measure stray fields. For improved contrast, differential MFM is performed, wherein the magnetization of the tip is inverted between two different scans to separate magnetic from non-magnetic signatures. With our voltage-controllable magnetic tip, we have been able to realize magnetization flipping in situ, applying short current pulses to a local coil wound around the scanning tip. As a benchmarking test, we have performed differential MFM in a conventional setup. Our goal is to integrate the VCMT in our membrane-based scanning force microscope [1] to perform ultrasensitive, differential magnetic force measurements. Ultimately, we hope that it can be used for structure determination of single biomolecules and nanoparticles [2].



(a) (b)

(a) First prototype of the voltage controllable magnetic tip
(b) MFM images using in situ magnetization flipping

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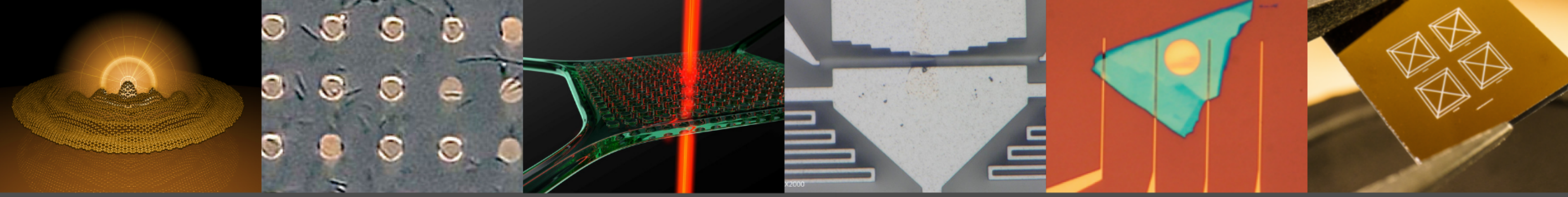

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Conceptually new meters of noise intensity or temperature: exploiting noise-induced transitions in micro/nano-resonators at short time scales and providing a huge range

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A popular method in studies of noise-induced transitions in dynamical systems has been the method of optimal fluctuations, valid when the noise intensity, which can be characterized with a generalized temperature T, is small as compared to a characteristic **activation energy $\boldsymbol{S}_{\mathbf{min}}$**. With an overwhelming probability, the transition path is close to the most probable transition path while the transition flux $J(T) = P(T)\exp(-S_{\min}/T)$, where the exponential (activation) factor depends on T much sharper than the preexponential factor P. Until 2001, only quasi-stationary (or steady) transition fluxes, i.e. those after the formation of quasi-equilibrium (or quasi-steady distribution) in relevant vicinities to metastable states, were studied. Much shorter times have been explored since 2001 [1]. It was found that, generically, $S_{\min}$ grows as time of the transition t decreases. In the context of the present work, it is important that, the weaker dissipation is or, equivalently, the larger the quality factor Q is, the sharper the growth of $S_{\min}$ with the decrease of t is. We illustrate this by the case of an underdamped one-dimensional potential system with a parabolic potential $U(q)$ subjected to a linear friction and white noise while the system escapes from the potential minimum beyond a given coordinate q_b for a given time t lying within the range $1 \ll \omega_0 t \ll Q$, where ω_0 is the eigenfrequency: $\boldsymbol{S}_{\mathbf{min}}/\boldsymbol{\Delta U_p} \approx \boldsymbol{Q}/(\boldsymbol{\omega_0 t}) \gg \mathbf{1}$, i.e. **$\boldsymbol{S}_{\mathbf{min}}$ greatly exceeds the potential barrier $\boldsymbol{\Delta U_p}$ (constituting the activation energy for the quasi-stationary escape)** and **their ratio diverges as $\boldsymbol{Q}$ increases or $\boldsymbol{t}$ decreases**.

There are many classes of systems where the above results are relevant. Micro/nano-mechanical resonators constitute one of them [2]. It is particularly suitable in the present context because of very high values of Q [2].

The recent roadmap for studies of the short-time noise-induced transitions [3] suggested several promising scientific developments and applications. Here, we develop a detailed algorithm for one of the suggested applications.

For most thermometers (or meters of noise intensity), a variation of temperature (or noise intensity) which can be measured is moderate: a ratio R between the upper and lower limits of the measurement range can hardly exceed 10. E.g. the method based on the measurement of the quasi-stationary escape/transition flux can hardly provide the value $4-5$ for R: the upper limit is equal about $\Delta U_p/3$ because the activation factor stops to be sharp for higher T while the lower limit is about $\Delta U_p/13$ because the escape statistics for lower T is too poor. **Measuring the flux on short times, we increase $\boldsymbol{S}_{\mathbf{min}}$, thus lifting the restriction on the upper limit**. We develop a detailed algorithm of the measurements and theory. **In a sense, we replace a measurement of temperature for a measurement of time while time can be measured in a much larger range than temperature can conventionally be measured.**

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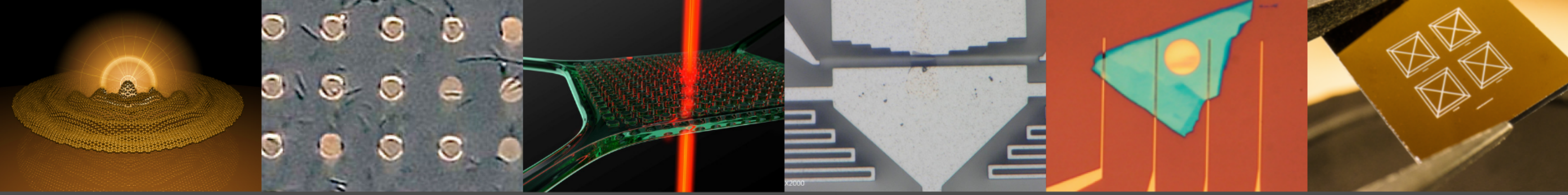

Frontiers of Nanomechanical Systems (FNS) workshop
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135 Days of Aging Measurement on a Silicon Nitride Nanomechanical Resonator

Michel Stephan[1], **Alexandre Bouchard**[1], **Timothy Hodges**[1,2], **Lixue Wu**[2], **Triantafillos Koukoulas**[2], **Richard Green**[2], **Raphael St-Gelais***[1,3,4]
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The eigenfrequency of silicon nitride nanomechanical systems can be measured very precisely due to their high mechanical Q-factor, and associated low thermomechanical fluctuations [1]. While these characteristics promise high-performance sensors of many kinds (e.g., thermal radiation, mass, force), implementation of such sensors will eventually raise questions on longer term stability, notably for calibration purposes. Long term frequency stability and aging in SiN have been far less studied than shorter term fluctuations such as thermomechanical noise. To the best of our knowledge, long term aging of resonators have been studied in the context of crystal clocks [2] and, more recently, in MEMS for timing applications [3] and accelerometry [4], but not in high-Q SiN resonators.

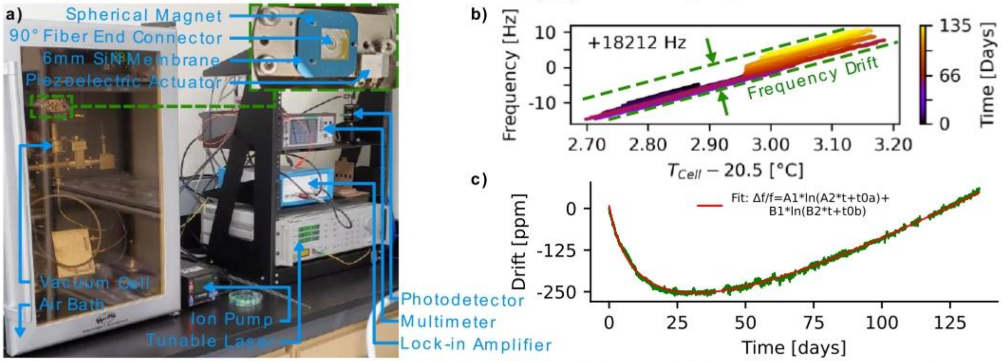

Figure 1: a) Experimental setup b) Frequency VS temperature with time evolution c) Temperature-compensated Frequency drift plot with logarithmic fit

Here we present a temperature-compensated aging measurement of an actuated low-stress, 90 nm thick, SiN membrane (Fig. 1a inset) over 135 days. The resonator is mounted (Fig 1a) in a portable, ion-pump based, high vacuum chamber (10^{-5} Pa vacuum level). The vacuum chamber is placed inside a Measurement International 9300 Air Bath (Fig. 1a) to control its temperature within less than 0.5 K over the measurement period. An optical fiber interferometer (1550 nm wavelength, 240 μW optical power incident on the membrane) paired with a Zurich MFLI lock-in amplifier is used to track, through a phase locked loop (PLL), the resonator fundamental mode eigenfrequency at a rate of 7 times per second. A calibrated Keithley DMM6500 multimeter simultaneously measures the chamber temperature through a Measurement Specialties 55036 Glass NTC calibrated thermistor inside the vacuum chamber.

We measure a maximum frequency drift of 250 ppm of the fundamental mode eigenfrequency. When normalized to the resonator thickness, the drift and its two logarithmic terms (Fig. 1c) are consistent with measurements on thicker crystal resonators [2], pointing towards surface-based aging effect that will be discussed in our presentation.

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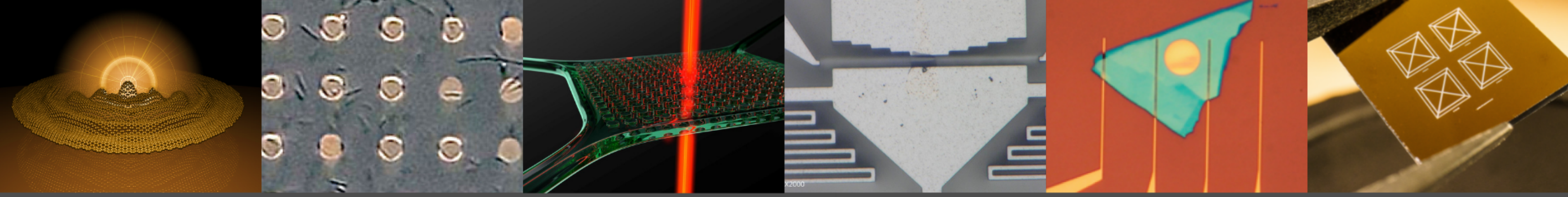

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Study of Heat Transport in Silicon Nitride Nanomechanical Resonators for High Precision Radiation Sensing and Energy Conversion Applications

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We study heat transport in silicon nitride nanomechanical resonators for applications including (1) high resolution detection or infrared and THz radiation, (2) measurements of near-field radiative heat transfer, and (3) passive radiative cooling for energy harvesting. We presents some of our recent findings [1–3] along these three axes.

In [1], we explore the potential of nanomechanical resonators for creating radiation sensors operating at the fundamental detectivity limit of thermal radiation sensing. Reaching this limit requires that the sensor noise is minimized down to fundamental temperature fluctuation noise. In contrast, phase noise in nanomechanical resonators is instead typically dominated by additive noise, such as instrument and thermomechanical fluctuations. Here we experimentally demonstrate optimized low-stress SiN resonators in which additive phase noise is minimized below fundamental temperature fluctuation noise. We also include temperature fluctuation noise with recently proposed models for frequency stability in closed-loop frequency tracking scheme. Our results pave the way towards radiation sensors operating at the fundamental detectivity limit. It also shows that models for frequency stability that include only thermomechanical and detection noise can sometimes be incomplete.

In [2], we explore how passive radiative cooling of silicon nitride membranes could be used for converting ambient heat into electricity. As imposed by the 2nd law of thermodynamics, harnessing ambient heat fundamentally requires a heat sink at a temperature colder than ambient. We achieve such cold sinks by passive radiative coupling of a silicon nitride nanomechanical resonator with outer space, through the atmospheric transparency window. For the first time in the context of passive radiative cooling research, the hot (ambient temperature silicon) and cold (silicon nitride membrane) sides are monolithically integrated on the same chip. This integration paves the way for on-chip heat engines in portable applications that currently rely on non-renewable and finite life-time batteries. The maximum temperature drops achieved experimentally are 9.3 K during daytime, and 7.1 K at night.

Finally, in [3], we study nanomechanical resonators as a tool for near-field radiative heat transfer (NFRHT) research. NFRHT consists of evanescent thermal coupling between bodies at subwavelength distances, increasing the radiative heat transfer beyond the conventional laws of thermal radiation. Due to challenges of non-contact precision alignment at high temperature, theoretical work on NFRHT typically outpaces experimental progress significantly. Approaches reported to mitigate experimental difficulties most often rely on unique custom-fabricated microdevices that have limited reproducibility and flexibility. Here we report measurement of NFRHT in the deep subwavelength regime (down to 180 nm separation) using, as our sensing element, plain silicon nitride membrane resonators—i.e., a commonly available substrate for material research. We notably find that high Q and high temperature sensitivity of SiN mechanical resonances allow a temperature resolution (1.2×10^{-6} K) that is unprecedented in the context of NFRHT research.

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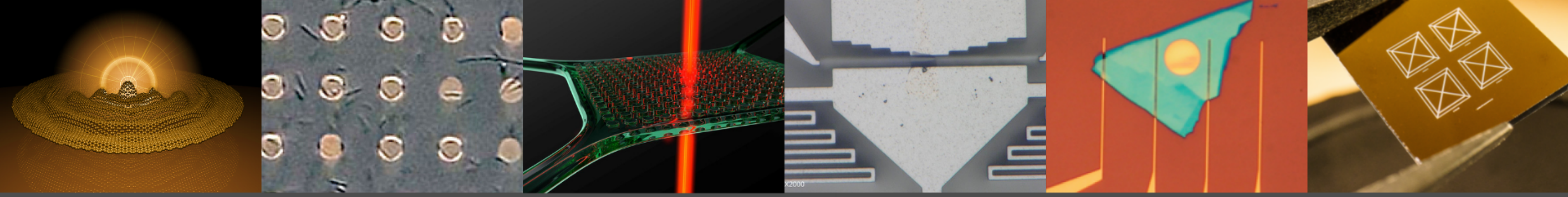

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Gallium phosphide 2D optomechanical crystals for deterministic single-photon quantum memories

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The Quantum nature of nano-mechanical motion attracts researchers and engineers due to its many potential applications from ultra-sensitive force sensing[1,2] to quantum teleportation[3]. Although a quantum optomechanical memory[4] has been achieved recently, deterministic phononic storage is yet to be realised for practical optical quantum communication.

One of the challenges we need to overcome is that the quantum properties of phonons are easily disturbed by thermalisation induced by the optical absorption of laser light, even in cryogenic environments. Another problem is bandwidth mismatch between single photons and phonons which can lead to inefficiency of information conversion.

Here we propose and characterise 2D gallium phosphide (GaP) optomechanical crystals (OMCs) to overcome the above issues. GaP has a large electronic bandgap (2.26 eV) resulting in low two-photon absorption at the telecom-band as well as a large refractive index > 3 enabling a high optical Q-factor[5]. The 2D structures can make thermal phonons dissipate faster, while its high mechanical frequency (typically ~ 2x larger than that of 1D nanobeam[6,7]) can suppress thermal occupation. Below we show characterisation of our device and SEM image. We have measured high optical-Q ~ 112,000 at 1551 nm, and mechanical-Q = 2,236 at 6.47 GHz at room temperature. We also discuss an effective and cryogenic-compatible optical coupling method employing sharply etched tapered fibre.

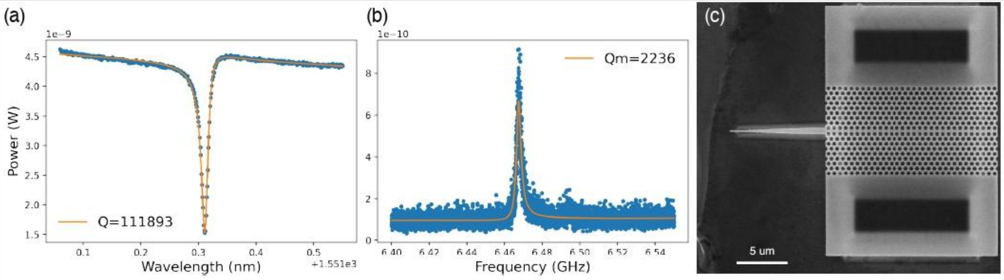

Figure: (a)Optical reflection spectrum and (b)mechanical spectrum at room temperature. (c)SEM image of an OMC.

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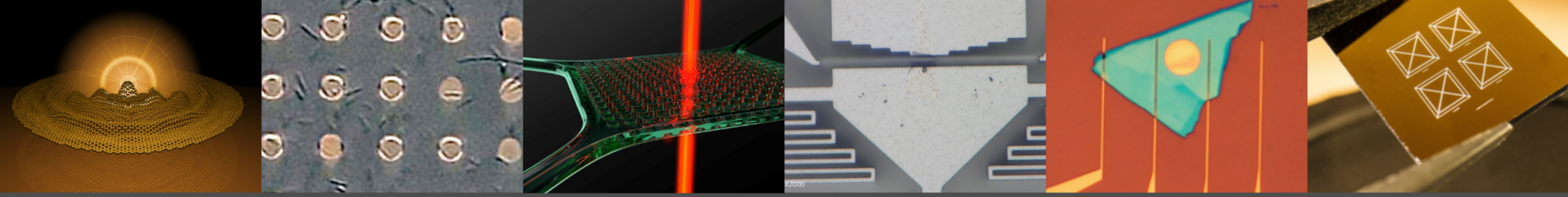

Frontiers of Nanomechanical Systems (FNS) workshop
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Flux coupled hybrid electromechanical system with a transmon qubit

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Recently, magnetic flux-coupled electromechanical devices have shown good potential to control the motional states of massive mechanical oscillators in the quantum regime. We have designed a hybrid electromechanical device where the mechanical resonator is coupled to the electromagnetic mode by embedding it in a SQUID loop[1]. The device consists of a superconducting transmon qubit and a suspended aluminum nanowire. We achieve a vacuum electromechanical coupling rate (g_0) in excess of 50 kHz. With such a high coupling rate and qubit's intrinsic nonlinearity, we achieve a near-ground state cooling of the mechanical resonator, limited only by the sideband resolution parameter. These results make our system a promising platform for reaching the single-photon strong coupling regime.

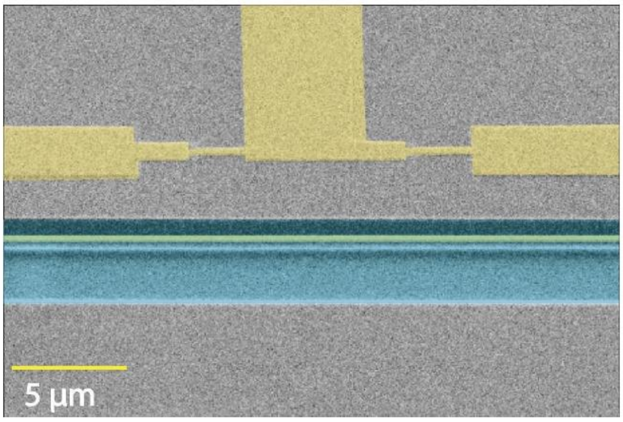

Figure 1: A False color image of the SQUID loop, showing two Josephson junctions and the suspended nanomechanical resonator. The blue region is etched silicon underneath the suspended beam.

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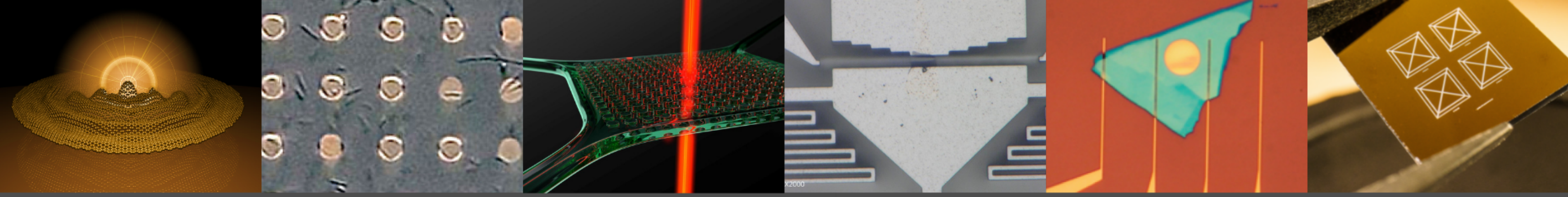

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

NOVEL NANOTUBE MULTIQUANTUM DOT DEVICES

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Addressable quantum states well isolated from the environment are of considerable interest for quantum information science and technology. Carbon nanotubes are an appealing system, since a perfect crystal can be grown without any missing atoms and its cylindrical structure prevents ill-defined atomic arrangement at the surface. In our work, we develop a reliable process to fabricate compact multielectrode circuits that can sustain the harsh conditions of the nanotube growth. Nanotubes are suspended over multiple gate electrodes, which are themselves structured over narrow dielectric ridges to reduce the effect of the charge fluctuators of the substrate. Such devices present two remarkable features. On one hand, the suspended carbon nanotubes present high-quality transport data through multiple quantum dots [1]. On the other hand, the suspended carbon nanotubes generated by our nanofabrication technique are expected to have high quality factors [2]. In addition, an electrostatically defined charge qubit embedded in the nanotube could present remarkable back-action on the mechanical motion of the system and under specific conditions might bring the system to the ultra-strong coupling regime. In that regime, the nanotube acts as an anharmonic oscillator with energy levels that could be used as the basis for a mechanical qubit [3]. Furthermore, the multiple gate electrode structure will allow in the future to define four quantum dots. By coupling these four quantum dots to the mechanical motion of the nanotube, the transition from the Mott insulating state to a polaronic state can be studied [4].

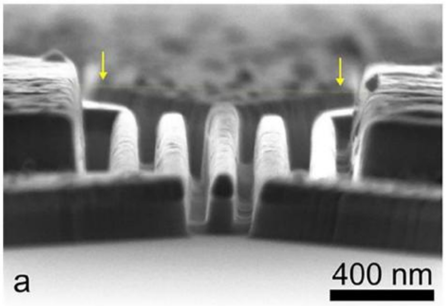

Figure 1: Scanning electron microscope (SEM) image of one of our devices with a carbon nanotube (highlighted by an overlaid yellow line and indicated by two yellow arrows) suspended over five gate electrodes (tilt angle 88° with respect to the chip surface). The nanotube is electrically connected to the source and drain electrodes.

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Frontiers of Nanomechanical Systems (FNS) workshop
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Exploiting the spin-mechanical coupling between an oscillating membrane and a nitrogen-vacancy center

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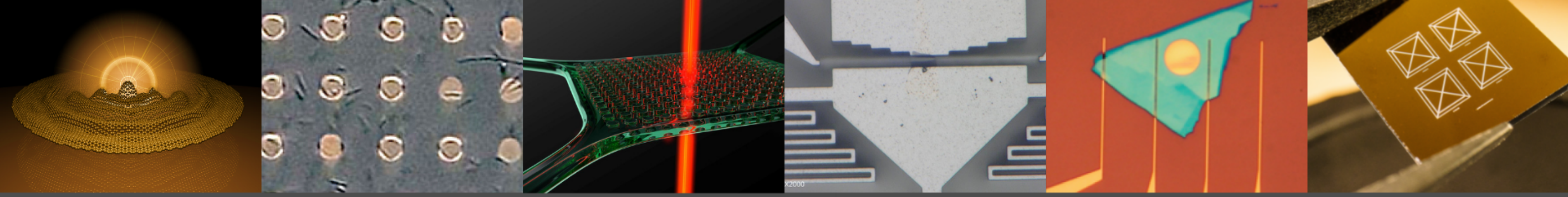
Among the many interesting properties of optomechanical systems, their long coherence time and highly efficient coupling to light makes them particularly interesting as interfaces between light and other systems. This is of particular interest for applications such as communication interfaces to spin systems in quantum information processing. We are theoretically investigating methods to couple spin systems to optomechanical systems and in particular how to exploit the coupling in realistic experimental situations where the coupling between the mechanical oscillator and spin is weak.

In the scheme we are interested in, a magnet is attached to an oscillating membrane. The oscillation of the membrane creates a time-varying magnetic field, which can be coupled to the spin of a nitrogen vacancy (NV) center. NV centers are characterized by their long electron spin coherence, on the order of milliseconds or longer, but have limited photon efficiency due to the strong coupling to the phonon sideband. In the considered scheme the coupling to a membrane can act as an efficient interface between the light and the spin of the NV with applications to quantum communication. Taking into consideration the coupling of the mechanical oscillator to a heat bath and the spin component of the NV, we investigate how we can use the spin-mechanical oscillator coupling to achieve cooling of the membrane, as well as non classical states of the mechanical motion.



Frontiers of Nanomechanical Systems (FNS) workshop
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OPTOMECHANICAL COUPLING OF A MICROWAVE CAVITY TO A LARGE MEMBRANE

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Cavity optomechanics has developed to be a leading platform to study quantum properties of mechanical objects. One common objective is to cool a large mechanical resonator to its ground state and investigate quantum superpositions of these massive objects. Here, a 350 µm size high-stress silicon nitride membrane is placed in an in-substrate phononic shield. This is then capacitively coupled to a microwave cavity in a flip-chip geometry. At a temperature of 10 mK a Q factor of 10^7 has been achieved.[1] Coupling between microwave photons and phonons in the mechanical resonator is obtained in fabricated devices. A single photon-phonon coupling g0 of 2π □ 2 Hz is obtained. Besides this, using a real-time microwave feedback system low frequency noise has been reduced by 30 dB. These steps will enable new optomechanical experiments, such as achieving mode swapping between the large membrane and a qubit, and to measure quantum fluctuations.

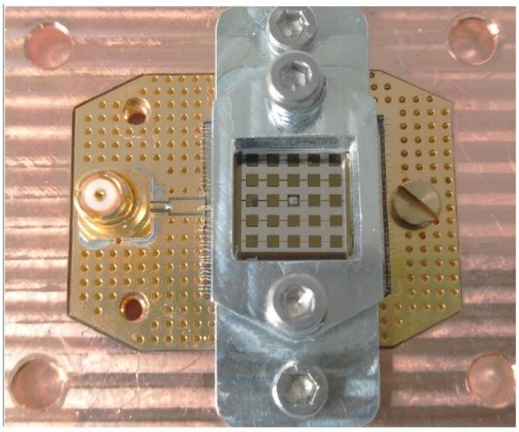

Figure 1: The assembled flip-chip device. The membrane can be seen as a white square in the phononic shield.

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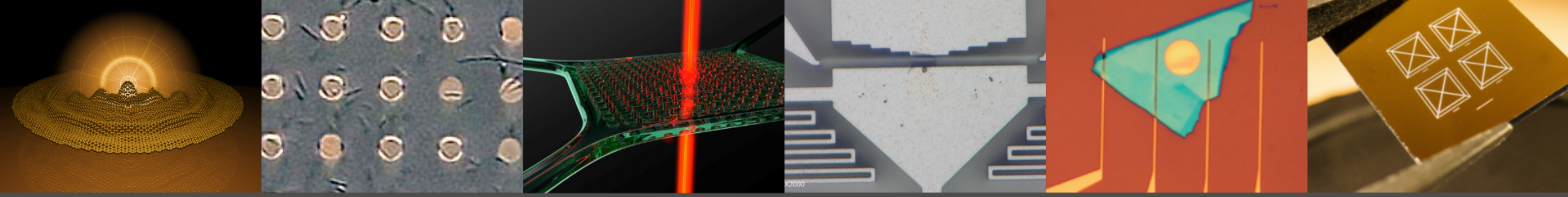

Membrane-based NanoMRI

Diego Visani[1*], **Thomas Gisler**[1], **David Hälg**[1], **Shobhna Misra**[1], **Vincent Dumont**[1], **Javier del Pino**[2],
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Since the invention of the first optical microscope, the ability to image smaller and smaller features has always led to groundbreaking discoveries. From the first images of a cell with optical microscopes to the atomic surface of a material with atomic force microscopes (AFM) [1], the imaging resolution and techniques have constantly evolved. Recently, force-detected nanoscale magnetic resonance imaging (NanoMRI), and in particular magnetic resonance force microscopy (MRFM) showed a spatial resolution down to the nanometer [2, 3]. Single-proton resolution in three dimensions is the ultimate frontier to overcome in order to image nanoscale objects at their fundamental scale. In order to approach this frontier, we are using ultra-high quality factor silicon nitride membranes ($Q \sim 10^8$) as force sensors. These membranes have proven to be a suitable platform to perform inverted scanning force microscopy [4]. Our next step is to apply them for magnetic resonance force microscopy. We aim to demonstrate resonant coupling between the nuclear spins and the membrane. In this regime, the spin Larmor frequency is tuned to match the nanomechanical membrane frequency to maximize the coupling [5, 6]. We analytically and numerically study resonant coupling between a spin ensemble and a membrane resonator to pave the way for future experiments.

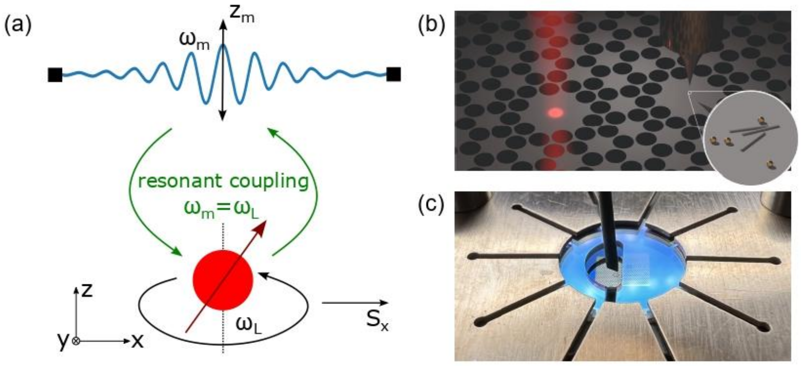

Figure 1: (a): Illustration of the interaction between the spins and the membrane, (b): Schematic of the proposed system, (c): Close-up photograph of the setup.

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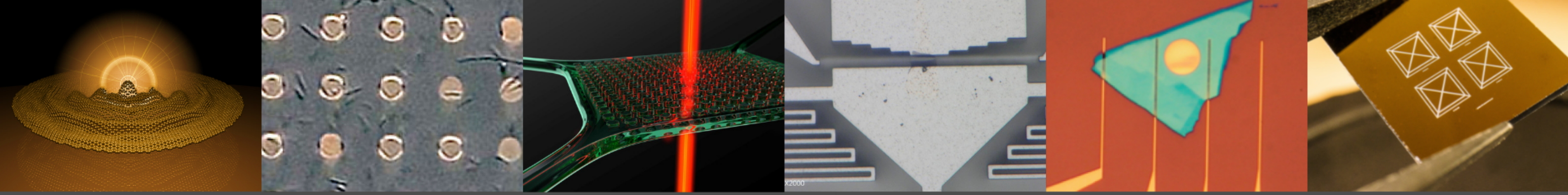

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Position-Dependent Noise Characteristics in Optomechanical Transduction of InP Nanowires

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To reach the full potential of nanowire sensor applications, it is important to understand a nanowire's limiting noise characteristics under optical transduction. Key studies have demonstrated nano-optomechanical transduction of undriven silicon nanowires and their dynamic range as a function of pillar width, cross-sectional geometry, and tapering at the base.[1, 2] In these works, Molina et al. have duly established that high-aspect ratio silicon nanowires can obtain the highest dynamic ranges of any nanomechanical resonator where transduction was chosen to be at the point of highest responsivity: at the maximum of the gradient of the Gaussianbeam. High aspect ratio, gold-tipped indium phosphide nanowires, grown by aerosol-deposited gold nanoparticles,[3] $14\,\mu m$ tall and $107\,nm$ in diameter, were investigated for their spatially-dependent noise properties upon optical transduction according to the principle illustrated in Figure 1a. Though InP nanowires also demonstrate the largest response where the gradient of the Gaussian beam is the maximum (Figure 1b). The wires were measured under a closed-loop scheme with a phase-locked loop in conjunction with an avalanche photodiode. The wires exhibit a nominal plasmonic absorption as observed by the relative frequency shift (Figure 1c). However, an unexplained, outlying noise characteristic in the vicinity is also evident (Figure 1d). For this reason, we explore the noise characteristics of this system by means of a laser position-dependent Allan deviation, to disclose the limiting noise mechanisms and help us understand the behavior of nanowire resonators by this method of transduction. With their extremely high aspect ratio and low effective mass, nanowires have demonstrated impressive sensitivities, which contend and even outperform other nanomechanical systems; an understanding of their noise characteristics under optomechanical read-out gives us the necessary insight toward their ultimate limitations.

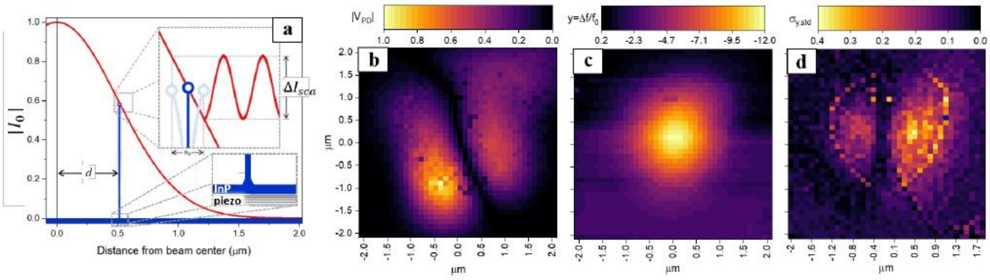

Figure 1: A schematic of the resulting substrate-reflected signal modulated by scattered light off the tip of the pillar, driven by a piezotransducer in a closed-loop scheme, within the gaussian beam intensity profile (**a**). The amplitude of the signal as detected by a photodiode (**b**), relative frequency shift per thousand due to light absorption at the tip (**c**), and basic standard deviation of the relative frequency shift, per thousand, revealing a ring of higher error for a set bandwidth of 10 Hz and integration time of 100 ms (**d**). For each point in these heat maps the mean value for (b & c) and the standard deviation for (d) were determined at the frequency for which the maximum of the amplitude by a adaptive sweeping algorithm.

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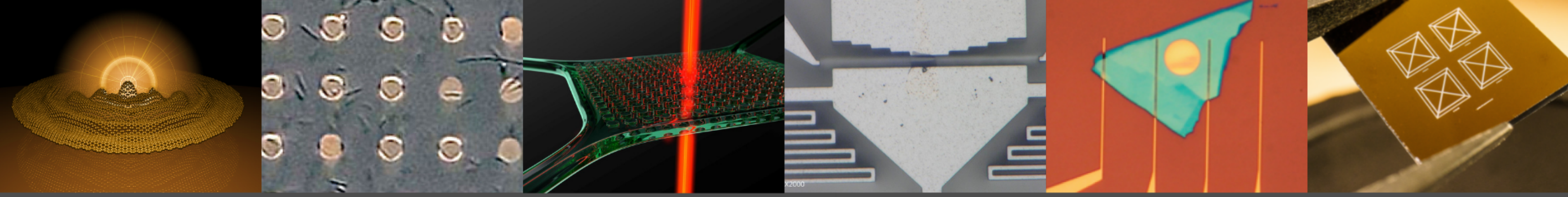

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High-Q trampoline mechanical resonators in crystalline InGaP with engineered reflectivity

Sushanth Kini Manjeshwar[1], **Anastasiia Ciers**[1], **Fia Hellman**[1], **Jürgen Bläsing**[2], **André Strittmatter**[2], **Witlef Wieczorek**[1]

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Tensile-strained materials enable ultra-low dissipation mechanical resonators with frequencies in the range of kHz-MHz [1–4], which are of particular interest for force sensing and quantum optomechanics. Use of strained crystalline materials [5–8] that are compatible with epitaxial growth of heterostructures would allow realizing integrated free-space cavity optomechanical devices, which benefit from stability, ultra-small mode volumes and scalability. We demonstrate micromechanical resonators made from tensile-strained crystalline InGaP that is epitaxially grown on a III-V heterostructure [9]. The strain of the InGaP layer is defined by its Ga content and we realize devices with a stress of up to 470 MPa. We reach mechanical quality factors surpassing 10^7 at room temperature with a $Q \cdot f$-product as high as $7 \cdot 10^{11}$ with trampoline-shaped micromechanical resonators, see Fig. 1. We find that the intrinsic quality factor of InGaP resonators degrades over time. The large area of the central pad of the trampoline allows us to pattern a photonic crystal for engineering its out-of-plane reflectivity. Stabilization of the intrinsic quality factor together with a reduction of mechanical dissipation paves the way for integrated free-space quantum optomechanics at room temperature in a crystalline material platform.

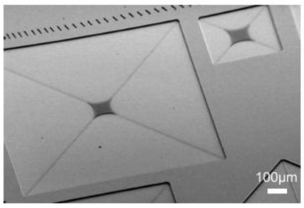

Figure 1: Trampoline-shaped micromechanical resonators fabricated from crystalline InGaP. The resonator reaches a quality factor surpassing 10^7 at room temperature in high vacuum.

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Frontiers of Nanomechanical Systems (FNS) workshop
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OPTOMECHANICS OF SUSPENDED MAGNETIC VAN DER WAALS MATERIALS

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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 such as graphene or light-emitting transition metal dichalcogenides. The physical properties of van der Waals materials can be easily tuned by perturbations like strain or doping, inviting to the exploration of magnetism in two dimensions and its exploitation in novel ultrathin devices [1]. Our approach is to suspend these magnetic materials forming drum-like resonators in order to investigate the influence of the strain on their magnetic order (Fig. 1a). We probe magnetic phase transitions (Fig. 1b,c) in homo- and heterostructures based on $\mathrm{FePS_3}$ and $\mathrm{NiPS_3}$, two materials from the transition metal thiophosphates family displaying a zigzag antiferromagnetic order, combining nano-optomechanics to optical spectroscopies [2, 3]. The tuning by strain of their light emission and magnetic properties is also investigated, in particular the photoluminescence of $\mathrm{NiPS_3}$ [4]. This work opens to the study of proximity effects in van der Waals magnetic heterostructures and their control by strain.

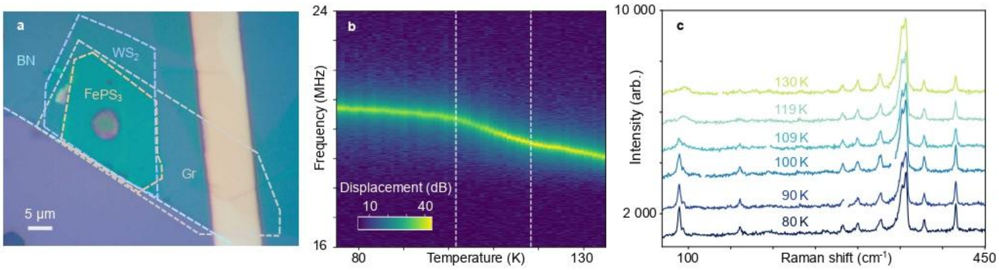

Figure 1: a. Optical picture of a studied sample constituted of a $\mathrm{FePS_3}$-based heterostructure suspended over a hole of 5 µm in diameter and 400 nm in depth. b. Optically-detected mechanical response of the suspended heterostructure to an electrostatic driving for temperatures ranging from 75 K to 135 K. The white dotted lines indicate the change of slope characterizing the phase transition around 110 K. c. Raman spectra of the same heterostructure recorded close to its Néel temperature.

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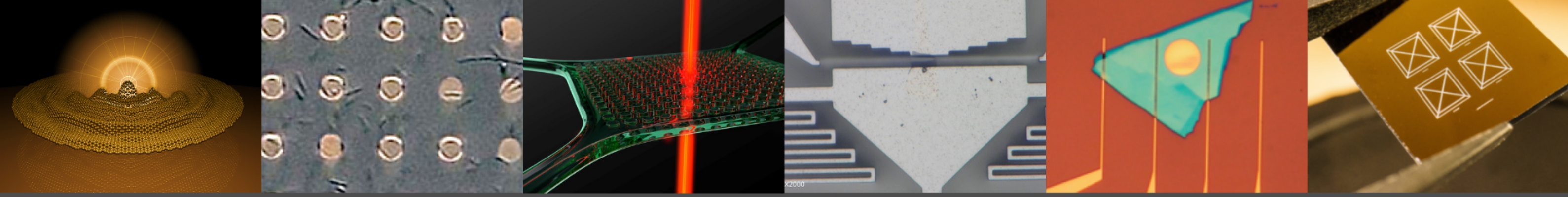

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Comparative Study of Multi-Object Acoustic Levitation Trapping Algorithms

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Mid-air acoustic levitation is a highly versatile method for non-contact manipulation of small objects finding application in, amongst others, pharmaceutical, biological and chemical fields. Imposing an ultrasonic pressure wave-field in between two transducer arrays allows for suspending and manipulating a sub-wavelength sized particle. The governing levitation force stems from the interaction between the incoming pressure field and the scattered field of the suspended object [1]. Opposed to other levitation techniques, acoustic levitation thererore merely sets restrictions on the object size and object density [2]. Furthermore, advances in trapping algorithms permit the levitation of multiple individually controlled objects, elevating the field of acoustic levitation to increasingly complex applications such as improved volumetric holographic displays [3] and assembly processes [4].

Levitation sites in acoustic levitators using two opposing transducer arrays are created by finding an optimal amplitude A_t and/or phase φ_t for each individual transducer such that the superimposed total pressure field has stable traps at desired levitation positions. Two commonly applied (multi-)trap algorithms are the iterative back-propagation and employing an objective function. In the first approach, predefined pressure states at desired trap positions are iteratively propagated to the transducers using a simple transducer model and vice versa to find the optimised transducer states $\{A_t e^{i\varphi_t}\}_{n=1}^{N}$ [5]. For the second class of algorithms, an objective function constructed of a combination of terms related to the levitation force, the corresponding force potential or the pressure at desired trap positions is minimised to determine the transducer states [3, 6]. Here, a comparative study of the different trapping algorithms is presented with specific interest in investigating the quality and homogeneity of multiple traps. A better understanding of the algorithms and their current limitations contributes to multi-object acoustical levitation of micro and nanomechanical systems and structures, allowing the study of their high-frequency dynamics and opening applications for new sensors, multi-particle actuators and manipulators.

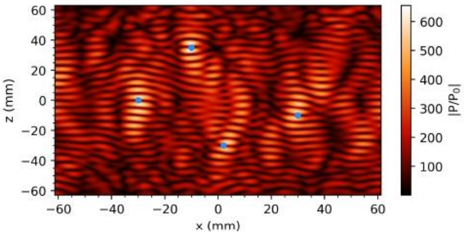

Figure 1: Absolute pressure field normalised with reference pressure P_0. The transducer states are optimised using iterative back propagation to create levitation traps (large pressure gradients) at the positions marked by the blue points.

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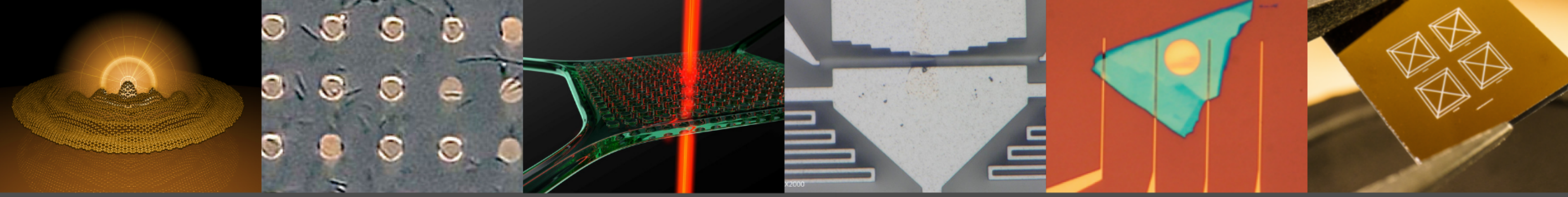

Frontiers of Nanomechanical Systems (FNS) workshop
June 6-9, 2023, Delft, The Netherlands

Ultra-strong Amorphous Silicon Carbide for Nanomechanics

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With dissipation dilution technique, stress distribution on tensile materials is engineered and therefore higher and higher mechanical quality factor (high-Q) are achieved using micro-/nano-mechanical resonators made of various materials, especially a-SiN, c-Si, c-SiC [1]. In order to obtain resonators with even higher mechanical quality factor, thin film materials with higher initial tensile stress, higher yield strength and compatibility of larger aspect ratio, are desired.

In this work, we investigated the mechanical properties of amorphous silicon carbide (a-SiC) grown with LPCVD, and fabricate high-Q mechanical resonators with it. Like the other forms of SiC, LPCVD a-SiC has strong chemical stability, allowing the a-SiC mechanical resonators to suspend over various substrates, including silicon and fuse silica ones. We developed a process flow to characterize the mechanical properties of a-SiC, which in principle can be used to identify the mechanical properties of all tensile thin film materials. Based on the information, dumb-bell shape geometries are used to identify the yield strength of a-SiC, and resulted in an extraordinary value 12 GPa, one of the highest among all amorphous materials. Prior to realizing ultra-high Q factor, we designed and fabricated 1d phononic crystal of different unit cell numbers with a-SiC on both silicon and fuse silica substrates, and fitted out the intrinsic quality factor of a-SiC in a precise way. At the end, 1d taper beam was designed with machine learning algorithm and fabricated, and the expected ultra-high Q factor up to 2×10^8 was measured. This project ensures that LPCVD a-SiC is a strong candidate for developing the next generation ultra-high-Q micro-/nano-mechanical resonators.

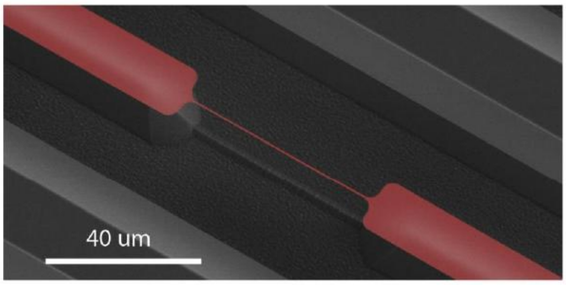

Figure 1: Checking yield strength of amorphous silicon carbide

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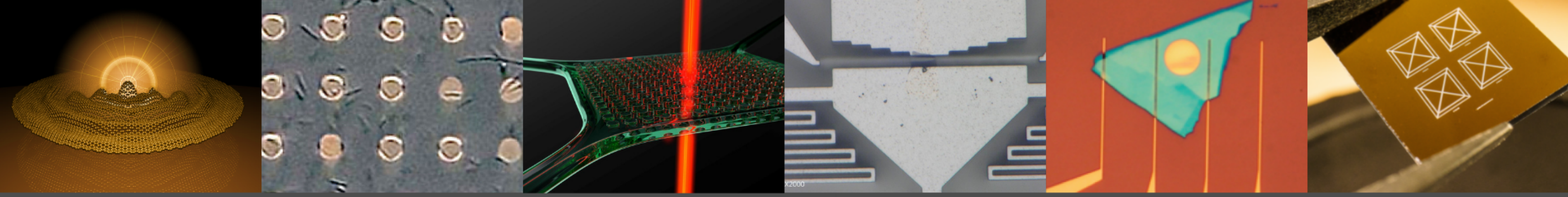

Frontiers of Nanomechanical Systems (FNS) workshop
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Tunable frequency comb in flexural-mode-coupling regime in nonlinear mechanical membrane resonators

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Mode coupling and its spectra response in mechanical systems have attracted broad interest in many realms of physics [1-3]. Meanwhile, fluctuations have also proved its importance in the nonlinear dynamic research as it could lead to many intriguing physics such as squeezing effects [4], anti-resonance sideband [5] and even frequency combs [6]. However, the interplay between fluctuations and mode coupling is still rarely explored.

Here, using a free-standing SiN membrane of a few hundred nanometers thickness, we demonstrate a novel frequency comb when driving the resonator into a nonlinear flexural-mode-coupling regime [2] with a single-tone excitation, and its strength and spacing of combs can be effectively controlled by varying the nonlinear state of the system. We propose that the switching on/off of the frequency comb (i.e., in or out of the limit-cycle regime) results from the interaction between the "quasi-modes" [5] in different harmonics induced by fluctuations of the strongly coupled nonlinear flexural modes. Moreover, the occurrence of the frequency comb also depends on the manner to approach the limit-cycle. Our finding shed lights on the microscopic origin and achieve manipulation of the frequency comb in mechanical resonators.

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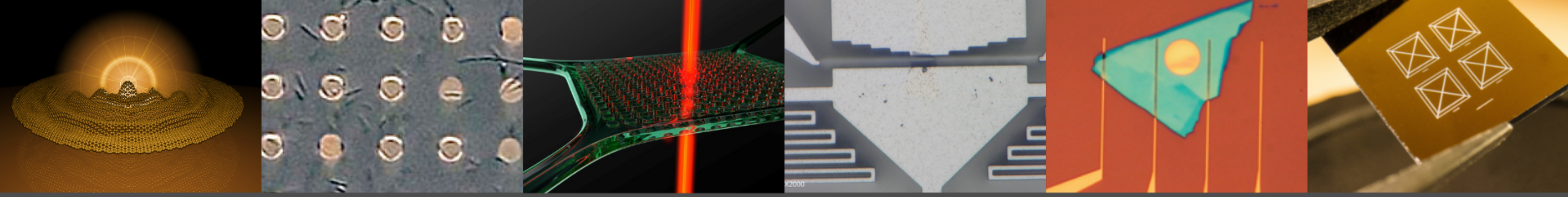

Frontiers of Nanomechanical Systems (FNS) workshop
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Tunable graphene phononic crystals

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Periodic patterning of a material induces a band structure for phonons, in analogy to an electronic band structure in solids created by a periodically varied atomic potential [1]. A phononic band gap is controlled by the patterning design. Such a bandgap may enable applications toward mechanical qubits, efficient waveguides and advanced sensing [2-4]. High-quality phononic crystals have been fabricated using materials such as Si, SiN or hBN [3-5]. However, the tunability of material strain and phononic states limit the progress toward the applications listed above. To address this challenge, we experimentally realized a tunable phononic crystal by graphene, an ultra-thin two-dimensional material with highly out-of-plane flexibility. We experimentally found a band gap from 28 MHz to 32 MHz and showed its strain tunability by ~5 MHz. This suggests a highly tunable mechanical phononic crystal.

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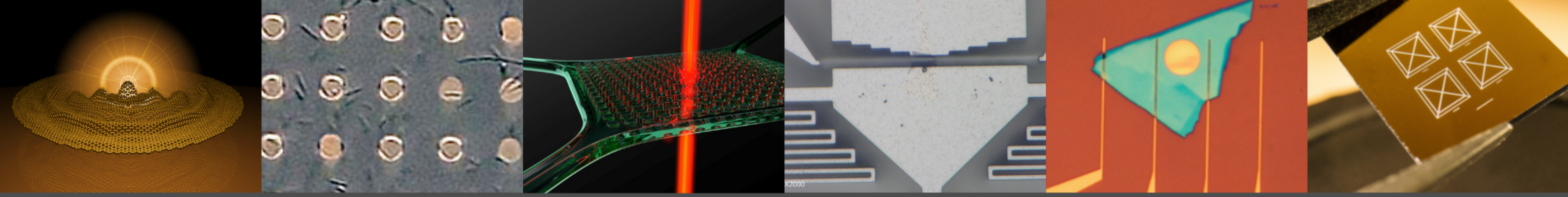

Graphene mechanical resonator; electro-mechanical properties and radio application

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In this work, the electro-mechanical properties and RF (Radio Frequency) applications of graphene nano-electro-mechanical resonators have been studied. The graphene resonators were fabricated in suspended structures on the PMMA (poly(methyl methacrylate)) trench. The resonance frequency of the graphene resonators was measured by an optical measurement method using a laser interferometer. The resonance frequency of the graphene resonators was measured in the megahertz range, which could be tuned by electrostatic actuation. For radio applications, the audio signal was mixed with the input AC frequency by Frequency Modulation (FM). The resonance frequency shift by FM changed the amplitude of mechanical resonance of the graphene resonators. The graphene nano-electro-mechanical radio reproduced the input audio signal audible to the human ear by amplitude demodulation..

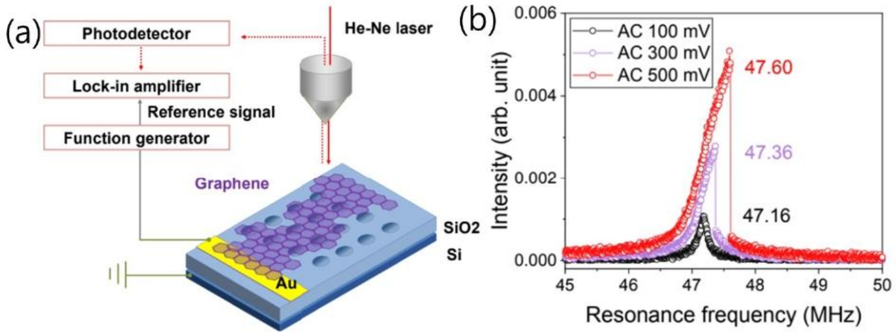
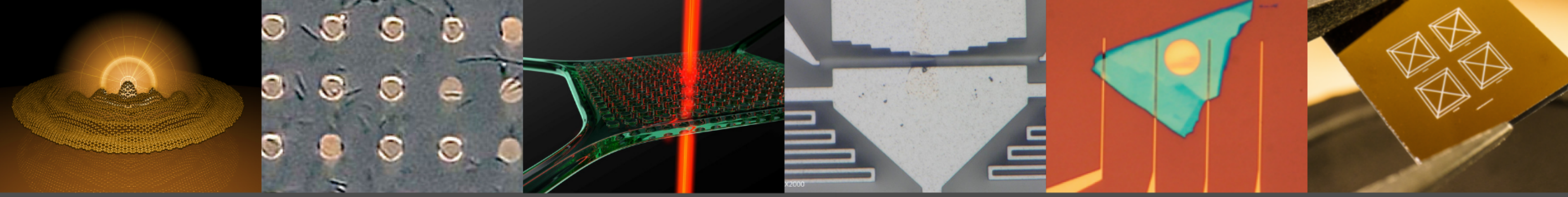


Figure 1: (a) Schematic diagram of measurement of graphene nanomechanical resonator. (b) Non-linear resonance behavior of graphene mechanical resoantor.



Frontiers of Nanomechanical Systems (FNS) workshop
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Frequency stabilization of self-sustained oscillations in sideband-driven electromechanical resonator

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Self-sustained vibrations play an important role in high sensitivity detection and frequency standards using mechanical resonators. For such applications, minimizing the phase noise of vibrations is essential. We present a scheme to stabilize the frequency of an important type of self-sustained vibrations, i.e., the vibrations induced by dynamical backaction in a sideband-driven micromechanical resonator. We study the system that has two vibrational modes [1] with strongly different resonance frequencies and damping constants. The high-frequency mode plays the role of a cavity in an analogy to optomechanical systems. By pumping at the blue detuned primary sideband of the higher mode, the damping of the lower mode is decreased to zero. Parametric instability develops, leading to self-sustained oscillations. They occur not only in the low-frequency mode, but also in the high-frequency one [1].

In the presence of weak noise, the phases of both modes diffuse. The phase changes of the two modes are anti-correlated (Fig. 1a) as a consequence of the discrete time-translation symmetry imposed by the periodic pump. We show that the phase of the upper mode and the phase of the lower mode add up to a constant (within our detection limit) that can be adjusted by the phase of the sideband pump. For a step change of the pump phase, the phases of both modes settle to new values after a transient. By linearizing the equations of motion about a stable vibration state and finding the normal modes, we determine that the time for the transient is determined by the smallest eigenvalue. If the pump change is small, the phase change of each mode is proportional to the pump phase change. The two proportionality constants add up to one. This finding, together with the phase anti-correlation of the two modes, allow us to stabilize the phase of one mode by measuring the phase of the other mode and then compensating for the phase diffusion by adjusting the phase of the pump. We demonstrate that phase fluctuations of either the high or low frequency mode can be significantly reduced, resulting in a much narrower spectral linewidth (Fig. 1b).

Our scheme is distinct from direct feedback that involves stabilizing a particular mode by measuring its phase because a frequency reference near this mode is not required. The results open new opportunities in generating stable mechanical vibrations via parametric downconversion in nonlinear micromechanical resonators, with controlled amplitude and phase. The analysis can be extended to mechanical resonators coupled to optical or microwave cavities. This work is supported by the Research Grants Council of Hong Kong SAR (Project No. 16304219).

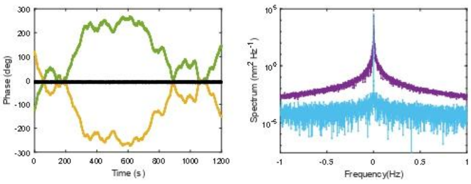

Figure 1 (a) Anti-correlated phase diffusion of the two modes. (b) Reduction of the spectral linewidth.

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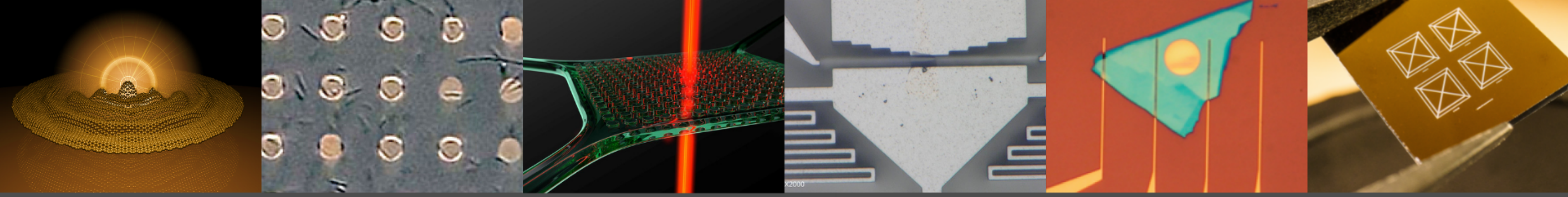

Frontiers of Nanomechanical Systems (FNS) workshop
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Scanning microwave microscopy for investigations of mechanical vibrations and mode coupling

Hao Xu[1], **Didier Theron**[1], **Sophie Eliet**[1], **Christophe Boyaval**[1], **Pascal Tilmant**[1], **Francois Vaurette**[1], **Dmitri Yarekha**[1], **Jeanmarcel Houpin**[1], **Xin Zhou**[*1]

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In recent years, scanning probe microscopy has attracted interests for dielectric property characterization at the nanoscale of a wide range of materials due to its capability to measure aF scale capacitances or variations [1]. For this reason, it can be exploited to manipulate nanomechanical vibrations of NEMS/MEMS [2]. In this work, we present a novel platform of scanning microwave microscopy for manipulating and detecting mechanical vibrations of nanoelectromechanical resonators. In this platform, a metallic AFM (atomic force microscopy) tip is placed on the top of a silicon nitride membrane nanoelectromechanical resonator, acting as a movable top-gate of the coupled membrane resonator. Microwave interferometry is exploited to read out mechanical motions [3]. In this setup, all electrical signals pass through the tip and the membrane is simply connected to the ground.

Based on this platform, we present 3-dimensional spatial maps of the several mechanical modes (see Figure 1 for the fundamental one) and mechanical damping rates by leveraging high resolutions of AFM setup. Besides, we also demonstrate mode coupling between the fundamental mode of the AFM tip (with resonance frequency ~ 15 kHz) and the fundamental mode of the silicon nitride membrane (~ 8 MHz). It allows to manipulate electromechanically induced transparency and amplification of the input signals of both coupled modes through sideband pumping the membrane resonator [4]. This platform facilitates studies of nanoscale mechanical resonators (e.g. carbon nanotube mechanical resonators) and mechanical dissipations, and brings conveniences in manipulating vibration modes located at different positions in suspended structures.

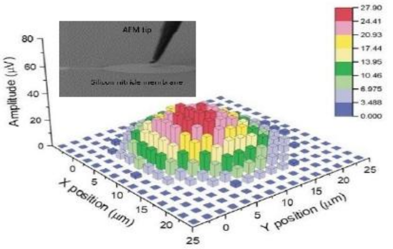

Figure 1: 3D spatial map of the mechanical responses for the fundamental mode, which measured at room temperature. Inset figure is the SEM image of both AFM tip and a silicon nitride membrane resonator.

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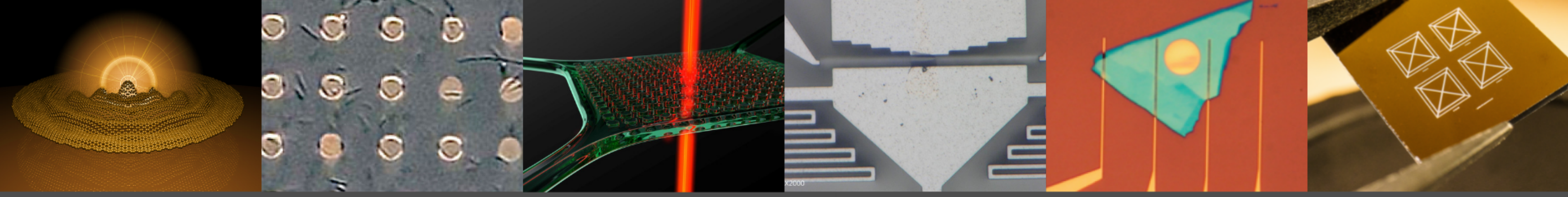

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Quantum coherent control in pulsed waveguide optomechanics for photon-phonon entanglement via Brillouin scattering

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Brillouin scattering can coherently control traveling acoustic excitations in waveguides systems, which enables the manipulation and processing of classical and quantum information. Although it has been investigated in the steady-state regime using continuous waves [1-3], waveguide experiments are often realized by using optical pulses for example for Brillouin-based memory [4,5]. This requires a dynamic framework treatment for the temporal domain including noise dynamics. Here, we present a Hamiltonian formalism to describe the time dynamics of backward Brillouin scattering in a waveguide including quantum Langevin noise [6]. By using this formalism, a closed solution for the coupled-mode equations can be obtained yielding a valuable tool to calculate different scenarios of quantum optoacoustic interactions such as coherent transfer of states between the optical and acoustic domain, cooling based on optoacoustic interactions and entanglement of photons and acoustic phonons. We show for example that the dynamics of Brillouin optomechanics in waveguides can be treated as an array of multiple optomechanical cavities in momentum space (Fig. 1a). We investigate quantum coherent transfer of an optical signal to acoustic phonons, which is for example relevant for storage of quantum states and the process of active phonon cooling through backward Brillouin anti-Stokes scattering. Finally, we discuss entanglement of photon-phonon pairs based on a Brillouin process (Fig. 1b1 – b4). It implies that experiments based on this formalism are realizable by considering current technology and fabrication of optical fibers or integrated waveguides.

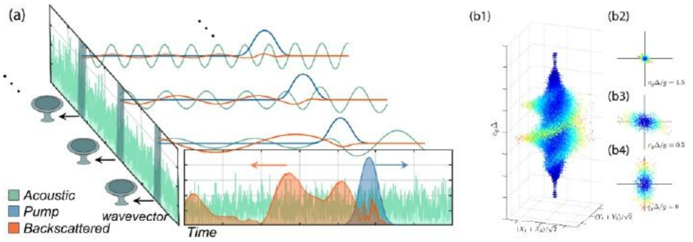

Fig. 1 a Backward Brillouin optomechanics can be formulated in an equivalent way to different separated cavity-like channels. **b1-b4** Brillouin entanglement. The quadrature distribution at different phase mismatch Δ is shown. **b2 – b4** is the transection of **b1** at three points of wavevector |Δ| from larger to smaller.

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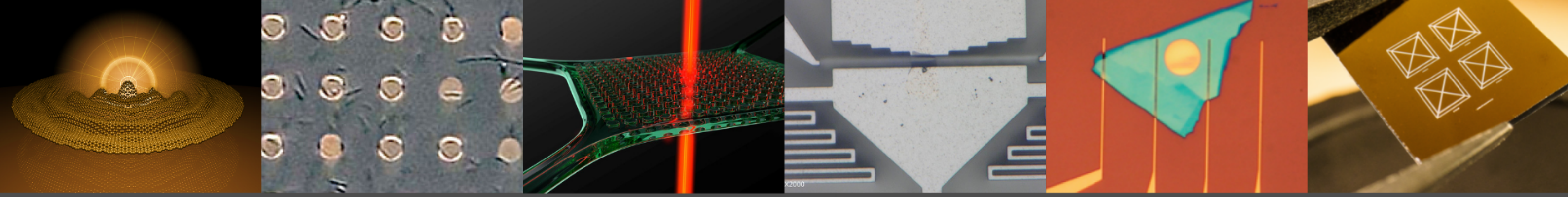

On-chip distribution of quantum information using traveling phonons

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Distributing quantum entanglement on a chip is a crucial step towards realizing scalable quantum processors. Using traveling phonons – quantized guided mechanical wavepackets – as a medium to transmit quantum states is currently gaining significant attention, due to their small size and low propagation speed compared to other carriers, such as electrons or photons. Moreover, phonons are highly promising candidates to connect heterogeneous quantum systems on a chip, such as microwave and optical photons for long-distance transmission of quantum states via optical fibers. Here, we experimentally demonstrate the feasibility of distributing quantum information using phonons, by realizing quantum entanglement between two traveling phonons and creating a time-bin encoded traveling phononic qubit. The mechanical quantum state is generated in an optomechanical cavity and then launched into a phononic waveguide in which it propagates for around two hundred micrometers. We further show how the phononic, together with a photonic qubit, can be used to violate a Bell-type inequality.

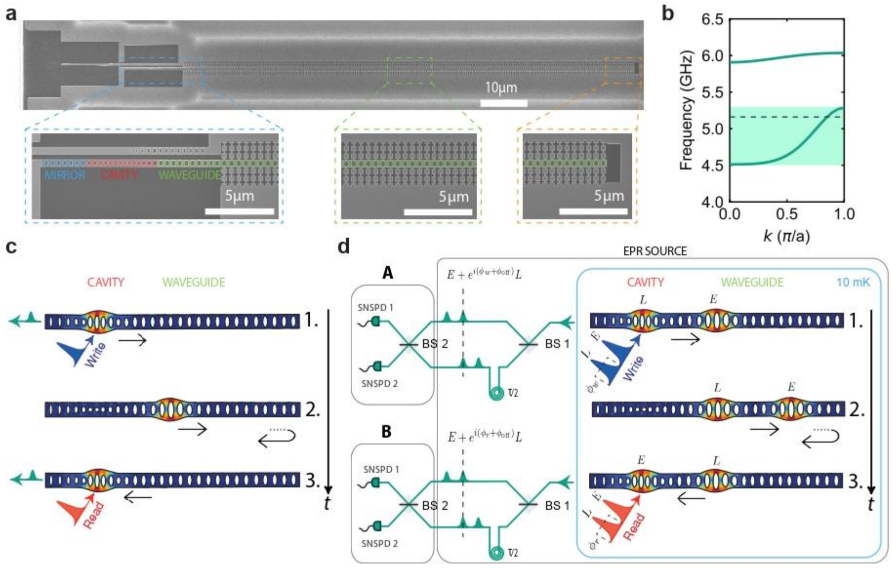

Figure 1: **Device and experimental setup.** a) Scanning electron microscope (SEM) image of the full device. b) Band diagram of a unit cell of the waveguide showing its single mode design for the symmetric mode, with the frequency of interest depicted by the black dashed line. For more information see [1]. c) Sketch of various stages of the protocol for writing and retrieving a mechanical excitation from the structure. The control pulses (write and read) are sent to the cavity to create (1.) and retrieve (3.) the mechanical excitation. In 2. we show the mechanical excitation that travels in the waveguide, with a round-trip time of τ. d) Simplified schematics of the time-bin entangling protocol

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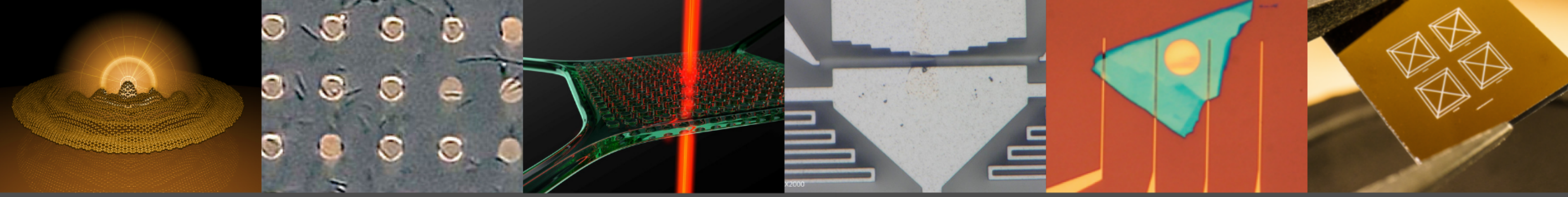

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Analysis and Interpretation of Force Volume Data Acquired with a Tuning Fork AFM at Cryogenic Temperatures by using Intermodulation Products

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In this contribution we present how a four-dimensional dataset acquired with a tuning fork based Atomic Force Microscope (AFM) using mixing products of different drive tones is analysed and interpreted. The method allows to measure force cuboids with reasonable resolution within a single scan taking only about 30 minutes compared to over 10 hours needed by other methods.

The data discussed was measured in a low temperature (4.8 K) tuning fork AFM and made use of advanced measurement methods based on previous work. To summarise, the measurement method used a Multifrequency Lock-In Amplifier (MLA, Intermodulation Products AB) with 32 channels, driving the tuning fork at the free resonance frequency (f_{res}=23.7 kHz) with an amplitude of A_{res} = 100 pm while modulating the tip-sample distance (A_{mod} = 500 pm) with a second drive at a low frequency (f_{mod} = 5 Hz). The resulting tip motion can be described as a beating, this results in mixing products when the tip enters the non-linear interaction regime between tip and sample surface. These mixing signals appear around the resonance frequency of the tuning fork each with a spacing of f_{mod} = 5 Hz.

This presentation focusses on how the force curve can be retrieved from the intermodulation products where amplitudes and phases are separately measured. The resulting force quadratures are compared to traditional z-spectroscopies analysed by the Sader-Jarvis method. The different methods show good agreement and limitations of the new method are discussed. [1-3]

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