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P01 - ABDELLAOUI Mohammed

Metrology and Nano-Mechanical Testing for Nano-Manufacturing and Nano-Bio Interfaces: Challenges and Future Outlook

P02 - ABOUELKHIR Nour Eddine

Quantum Information Processing with Nanomechanical Resonators: High-Fidelity Qubit Operations and Entanglement via Optical Cavities

P03 - ALONSO TOMAS David

Enhancing the performance of photonic integrated circuits: Remote and Cascaded Synchronization of Optomechanical Crystal Oscillators

P04 - AMGHAR M'Bark

Tunable phonon-photon coupling induces double MMIT and enhances slow light in an atom-opto-magnomechanics

P05 - ARFINI Matteo

Development of a recipe for a high coherence planar geometry superconducting drumhead resonator

P06 - ARORA Nishta

Nanomechanical logic with atomically thin resonators

P07 - BAGHERI HAROUNI Malek

Interaction between magnons and mechanical modes of a levitated Yttrium Iron Garnet (YIG) sphere

P08 - GIL GOUVEIA MAIA BARBOSA Alexandre

Bell Correlations and Optical Quantum Memory in Noble-Gas Nuclear Spins

P09 - BERMEJILLO SECO Alvaro

Dissipation in 2D magnet nanomechanical resonators across the phase transition

P10 - BERNAZZANI Lorenzo

Fluctuating drive of coupled classical oscillators can simulate dissipative qubits

P11 - BHATTACHARJEE Paromita

Acousto-optoelectric effect in organic-inorganic semiconductor systems

P12 - CHAFATINOS Dimitri Lisandro

Optical control of the time-crystalline phases in a polariton condensate with a mechanical clock

P13 - CHEN Chen

Traveling Surface Acoustic Wave Induced Removal of NSB Proteins from the Acoustic Biosensor

P14 - CHEN Tuoyu

Photonic crystal cavity design and characterization for pulsed optomechanical quantum measurement

P15 - DAKIR Yassine

Quantum teleportation and dynamics of quantum correlation for two qubits open systems

P16 - DATTA Shaoni

Deterministic Fock states in Brillouin optomechanics

P17 - DE ALBUQUERQUE BATISTA Adriano

Amplification and squeezing in parametrically-driven resonators near instability based on Floquet theory and Green's functions

P18 - DE PEDRO EMBID Ismael

Coherent Modulation of Microcavity Polaritons at Liquid Nitrogen Temperatures

P19 - DHIMAN Shivangi

Self induced oscillations in non-linearly coupled magnetomechanical systems

P20 - DICKSON Sarah Elizabeth

Low optical noise for single-photon detection in a mechanically-mediated electro-optic transducer

P21 - DOLZ Moira Ines

MEMs for magnetic characterization of micro-nano structures

P22 - EDMONDS Matthew James

SWIFT : Standing Wave Fibre Interference Trap

P23 - ESHAQI SANI Najmeh

Time-reversal symmetry and adiabatic processes

P24 - FERHAT Hiba El Batoul

Brillouin Scattering in Subwavelength Silicon Waveguides

P25 - GAIDI Safae

Exploring Quantum Speed Limit: Impact of Detuning and Initial Coherence in Optomechanical Systems

P26 - GARCIA BELLES Raquel

Investigating classical and quantum losses in HBARs

P27 - GASPARI Andrea

Optomechanical oscillator network for neuromorphic computation

P28 - GHOSH Bristi

Parametric feedback cooling of levitated optomechanics: A perturbative path integral approach

P29 - HONG Seongi

Entanglement dynamics of levitated nanoparticle in coupled cavities in PT-symmetric regime

P30 - IKKEN Nada

Quantum Teleportation Using Nanomechanical Oscillators

P31 - JEONG Mungyeong

Optomechanical Microwave Isolator in Room Temperature

P32 - KERN Max-Emanuel Richard

Quantum squeezing in a nonlinear mechanical oscillator

P33 - KLADARIC Igor

A mechanical qubit

P34 - KOKOVIN Artem

Attenuation of flexural phonons in crystalline two-dimensional materials

P35 - KUMAR Mohit

Inverse design of nanomechanical resonators for quantum optomechanics

P36 - KUMAR Soumya Sanjay

Exploring Multi-Tone Driven Duffing Resonators: Towards a New Paradigm in Nonlinear System Analysis

P37 - KUMAR Vishnu

Electrostatically transduced 1D Silicon Phononic Crystals and Cavity Interactions

P38 - LEE Changjoo

Microwave Frequency Comb Generation in High Kinetic Inductance Superconducting Coplanar Waveguide

P39 - MARKAS Georgios

Membrane Resonators: a Promising Platform for Sensing Applications

P40 - MARX Tobias

MEMS oscillators at Bosch Research

P41 - MARZIONI Francesco

Two-membrane etalon

P42 - MEILOF Sarah

Optomechanical Strong-Coupling between a Planar Microwave Cavity and a High-Stress Silicon Nitride Membrane in a Flip-Chip Device

P43 - MOSAAD Ahmed Abdelmonem Barakat

TLS coupling strength estimation using parametric normal mode splitting

P44 - NAYA HERNANDEZ Javier

Towards Quantum Transduction with an Integrated Gallium Phosphide Platform

P45 - NGAI Tsz Ue

Measurement of Casimir Force between Gold Sphere and Graphene using a Silicon Cantilever

P46 - PAVLOVICH Margaret Bailey

Optomechanical resource for fault-tolerant quantum computing

P47 - PENG Zhenyang

Graphene Josephson Junctions for Quantum Metrology

P48 - QIU Run Fa Jonny

Microwave to optical transduction based on opto-electro-magneto-mechanics

P49 - RASPONI Francesco

Amplitude and phase noise in two-membrane cavity optomechanics

P50 - ROBIN Paul Joseph

Release-Free Subwavelength Optomechanical Resonators for Quantum Transduction between Microwave Phonons and Optical Photons

P51 - ROMAN RODRIGUEZ Victor

Double-Quantum-Dot qubit ultrastrongly coupled to mechanical vibrations in a suspended carbon nanotube

P52 - SCHWARZ Mirco Stephan

Fabrication and mechanical characterisation of hBN/Si3N4 resonator

P53 - SEN GUPTA Surangana

Josephson Optomechanics

P54 - SPITZNER Noah Lion Friedrich

Bullseye Cavities for Integrated Nonlinear Phononic Circuits

P55 - TENBRAKE Lukas

Cavity optomechanics with polymer-based multi-membrane structures

P56 - VAN EVERDINGEN Laurens Rudolf

Towards coherent detection of a single electron spin using Magnetic Resonance Force Microscopy

P57 - VAZQUEZ RODRIGUEZ Elsa

Towards large quantum delocalization over a CNT resonator coupled to a qubit.

P58 - VOLZ Matthias

Design of lithium niobate on silicon (LNoSi) surface acoustic waveguide for hybrid integrated phononiccircuits

P59 - ZICOSCHI Alessio

Denstity-Modulated Phononic-Engineered Membranes for Room-Temperature Quantum Optomechanics

P60 - ZINTH Agnes Maria

Optimizing an Integrated Photonic Racetrack Resonator for Optomechanical Synchronization

P01

Metrology and Nano-Mechanical Testing for Nano-Manufacturing and Nano-Bio Interfaces: Challenges and Future Outlook

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Nanometrology refers to measurement techniques that assess materials' properties at the nanoscale. Laboratory-based characterization of nanomaterials has been a key enabler in the growth of nanotechnology and nano-enabled products. Due to the small sizes involved, dimensional measurements have dominated such characterization, supported by significant advancements in stand-alone electron/ion microscopes and scanning probe microscopes.

However, the scope of nanometrology extends far beyond off-site, laboratory-based dimensional measurements and is expected to have a significant impact on the design of nano-enabled materials and devices. In this works, we discuss some of the available techniques for laboratory-based characterization of mechanical and interfacial properties in nanometrology. We also provide a deep insight into emerging techniques for measuring these properties, considering the needs in advanced manufacturing and nanobio-interactions to develop multifunctional instrumentation, traceable and standardized methods, and modeling tools for unambiguous data interpretation. We also discuss the evaluation of nanomechanical properties and surface/interface responses of materials, within the context of manufacturing processes and standardization. Finally, we address the scientific and technological challenges required to move towards real-time nano-characterization for rapid, reliable, repeatable, and predictive metrology to support the scaling up of nanomaterials and nano-enabled products from research to industry and market.

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P02

Quantum Information Processing with Nanomechanical Resonators: High-Fidelity Qubit Operations and Entanglement via Optical Cavities

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We propose a method for quantum information processing that utilizes the motional degrees of freedom in nanomechanical devices to store information. Our qubits are based on the two lowest energy states of mechanical resonators, which are made strongly anharmonic through the application of appropriate electrostatic fields. Single qubit rotations are performed using radio-frequency voltage pulses applied to each resonator individually. For two-qubit entangling gates, we couple the qubits to a shared optical resonance within a high-finesse cavity. Our analysis shows that gate fidelities above 99% are achievable under practical experimental conditions.

P03

Enhancing the performance of photonic integrated circuits: Remote and Cascaded Synchronization of Optomechanical Crystal Oscillators

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Despite nature's inherent tendency toward disorder, systems that adjust their rhythms to oscillate in harmony—referred to as synchronization—are found everywhere. Synchronization can be observed in various contexts, from planetary orbits and cardiac rhythms to chemical reactions, wherever oscillating systems and weak interactions among them exist. Advances in the electronics industry have harnessed this phenomenon to improve the performance of digital processing elements. As integrated photonic technology now aims to process optical signals on a chip, the need for reference signals to synchronize actions becomes crucial to prevent errors in optical systems and communication interfaces. Here, optomechanics, the branch of physics that explores interactions between light and mechanical excitations, can provide a solution. Optomechanical oscillators (OMOs) can generate high-amplitude, self-sustained mechanical motion driven and controlled by optical fields, making them ideal for serving as clock reference signals in photonic integrated circuits.

Among the various optomechanical devices [2], silicon optomechanical crystal cavities (OMCs) stand out as promising candidates for this task. They are compatible with routing microwave phonons [3], allowing for the extension of this approach to phonon-photon hybrid circuits, where multiple OMOs can interact with each other. However, the large optical resonant frequency dispersion between nominally equivalent OMCs due to fabrication disorders complicates all-optical synchronized operation of these devices.

In this work, we present two different approaches for achieving the synchronization of the dynamics of two chip-integrated OMCs acting as OMOs. In our platform, the cavities support separated optical resonances, enabling the independent driving and monitoring of each resonator. The two configurations are distinguished by their interaction mechanisms. In one approach, oscillators communicate through an external optical feedback where the output modulation generated by one of the OMOs modulates the laser light driving the other. In the other approach, the geometries interact through a weak mechanical link that enables the spontaneous synchronization of their dynamics over a certain range of detuning between their natural mechanical frequencies. Additionally, we demonstrate the cascaded locking of the dynamics of both oscillators to an external reference signal injected into one of the OMOs.

The results, which are supported by a numerical model, lay the ground work for the distribution of reference signals among large networks of OMOs in photonic integrated circuits.

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P04

Tunable phonon-photon coupling induces double MMIT and enhances slow light in an atom-opto-magnomechanics

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In this paper we theoretically investigate the magnomechanically induced transparency phenomenon and the slow/fast light effect in the situation where an atomic ensemble is placed inside the hybrid cavity of an optomagnomechanical system. The system is driven by dual optical and phononic drives. We show double magnomechanically induced transparency (MMIT) in the probe output spectrum by exploiting the phonon-photon coupling strength. In addition, the fast and slow light effects in the system are explored. Besides, we show that the slow light profile is enhanced by adjusting phonon-photon coupling strength. This result may have potential applications in quantum information processing and communication.

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P05

Development of a recipe for a high coherence planar geometry superconducting drumhead resonator

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The field of cavity optomechanics, which explores the radiation pressure force-induced interaction between a mechanical oscillator and a driven electromagnetic cavity, holds promises for major applications in various fields. These range from quantum sensing and metrology [1], to quantum information processing [2] and fundamental tests of quantum mechanics and gravity [3]. In the microwave regime, where mechanical resonators are embedded as free-hanging capacitor plates in a planar superconducting cavity, remarkable experimental results such as ground state cooling of the mechanical motion[4] , squeezing [5] and quantum entanglement [6] have been achieved. Despite this outstanding progress, conventional micro-fabrication techniques [7] pose a practical limit for the possibility of overcoming two of the main challenges in superconducting electromechanical devices. On the one hand, the mechanical vibrations of the drumhead resonator should be well separated from the environment in order for the oscillator to preserve its quantum coherence. On the other hand, however, it is crucial that the optomechanical coupling is engineered to be higher than the dissipation rate of both resonators.

Based on a recent work [8], we explore the development of novel micro-fabrication techniques aimed at obtaining a robust and reproducible recipe for planar superconducting electromechanical devices. This latest wafer-scale fabrication process relies on the etching of a trench in the silicon substrate for the deposition of the microwave cavity and on the consequent planarization of the deposited sacrificial layer of oxide through Chemical Mechanical Polishing (CMP). The combination of these two steps allows both for a careful engineering of the vacuum-gap size between the suspended drumhead resonator and the bottom capacitor pad of the LC oscillator, as well as for the possibility of increasing the surface area of the mechanical oscillator and optimizing its strain. As a result, the quantum coherence of superconducting mechanical oscillators could be increased to values comparable to optomechanical platforms implemented with high-stress silicon nitride membranes, while keeping a competitive value of single-photon optomechanical coupling rate. An ultra low quantum decoherence could open up new experimental routes, and place these systems in a suitable parameters regime for exploring the interplay between quantum mechanics and gravity via the generation of massive quantum superposition states.

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P06

Nanomechanical logic with atomically thin resonators

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Nanomechanical computers provide efficient and low-energy information processing capabilities. As electronic computing encounters escalating challenges in sustained scaling and performance improvement, there is a growing interest in mechanical computing. Leveraging the mechanical degrees of freedom and nonlinearities inherent in nanoscale mechanical resonators have the potential to offer alternative solutions for upcoming memory and computing systems. In our work, we utilize the bistability of atomically thin membranes to establish logical states. Additionally, our objective is to showcase parametron based computing by harnessing the substantial tunability of resonance frequency and spring constant modulation in ultrathin resonators. Our CMOS-compatible architecture, coupled with atomic-scale miniaturization, aims to minimize energy consumption, approaching the fundamental Landauer limit. This paves the way for large-scale reconfigurable nanomechanical computers and neuromorphic networks capable of simulating computationally challenging problems and understanding complex interactions.

P07

Interaction between magnons and mechanical modes of a levitated Yttrium Iron Garnet (YIG) sphere

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Magnon excitations, collective excitations of a spin system, have attracted a great deal of attention, recently [1]. Magnons have ability to couple with different quantum excitations such as photons [2], phonons [3] and spin degrees of freedom [4]. Recently, the interaction between magnons of a levitated YIG sphere with its center of mass motion is studied [5]. This interaction describes the coupling between the internal degrees of freedom, magnons, and external ones. Therefore, the external degrees of freedom would be considered as the probe for internal degrees of freedom. The mechanical motion of the levitated YIG sphere provides a platform for new kind of quantum systems. In this contribution, we study the entanglement between the magnons and mechanical motion of a levitated YIG sphere. Moreover, the possibility of occurrence of mechanical induced transparency in this system will be studied.

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P08

Bell Correlations and Quantum Memory in Noble-Gas Nuclear Spins

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A defining feature of quantum theory is the prediction that parts of quantum system can share stronger correlations than allowed by any classical theory. However, the extent and role of these correlations in many-body systems remains largely unknown, as their detection proves experimentally challenging.

Odd isotopes of noble-gas atoms have nuclear spins with extraordinarily long coherence times, exceeding hundreds of hours at room temperature. Although optically inaccessible, they can be interfaced with light, using alkali atoms as mediators. We design an experiment to certify entanglement and nonlocal correlations in a spin-squeezed ensemble of noble-gas atoms, testing the manifestation of genuinely quantum effects in a macroscopic system at room temperature.

Finally, we propose a non-cryogenic optical quantum memory for these noble-gas nuclear spins based on the Atomic Frequency Comb (AFC) protocol. Leveraging this long-lived multimode memory, a ground-based quantum repeater would enable entanglement distribution across distances over 2000 km with only 8 elementary links, and intermittency issues could be alleviated in satellite-based repeaters that promise to span truly global distances

P09

Thermoelastic Damping in 2D magnet nanomechanical resonators across the phase transition

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Understanding and circumventing the energy decay mechanisms in nanoelectromechanical resonators (NEMS) has been paramount in the field over the last two decades. The emergence of two-dimensional (2D) NEMS has provided a new perspective on this challenge, particularly in the case of 2D magnetic materials. Thermoelastic Damping (TED) has been proposed as the primary mechanism behind dissipation in 2D magnetic NEMS, but so far it fails to accurately reproduce the temperature-dependent quality factor.

This study explores an extended version of TED, considering anisotropic thermal transport in the in-plane versus the out-of-plane directions. It is found that for van der Waals materials, highly anisotropic in nature, it is critical to account for this difference. In the material of study, FePS3 we find a maximum in the dissipation at the phase transition (118 K), and at a radius of the circular cavity of 0.5um, with the typical Debye peak shape. This points that larger radius drums will have much higher quality factors; surpassing a factor of 100 times higher Q for 10um radius drums.

On the experimental side M. Siskins et al. (2020) [1] first noticed that nanomechanical resonators can be used to detect the phase transition of 2D materials and measure their specific heat. An extended scheme studied the anisotropy of these materials by M. Houmes et al. (2023) [2,3], allowing to measure the magnetic order in absence of a magnetic field. These investigations left open questions about the dissipation, which can be studied in the same setup: a laser interferometer that detects the displacement of the membranes to obtain the resonant frequency and quality factor of its oscillation modes.

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P10

Fluctuating drive of coupled classical oscillators can simulate dissipative qubits

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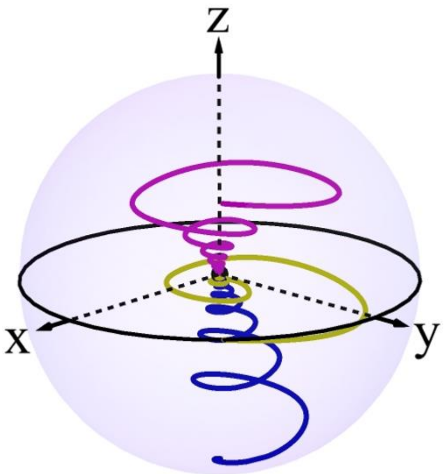
We investigate a system composed of two coupled oscillators subject to stochastic fluctuations in its internal parameters. In particular, we answer the question whether the well-known classical analogy of the quantum dynamics of two-level systems (TLS), i.e. qubits, provided by two coupled oscillators [1] can be extended to simulate the dynamics of dissipative quantum systems. In the context of nanomechanics, the analogy in the dissipation free case has already been tested in multiple experimental setups, e.g., doubly clamped or cantilever string resonators and optically levitated particles [2,3]. A well-known result of this classical analogy is that the relaxation and decoherence times of the analog quantum system must be equal, i.e. $T_1=T_2$, in contrast to the general case of quantum TLS. We 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, we show that these stochastic contributions can be engineered in the control apparatus of those systems, discussing, in particular, the application of this theory to levitated nanoparticles and to nanostring resonators. However, a limit of this improved quantum-classical analogy is that the analog Bloch vector of our system (see figure) always collapses to the center of the sphere, i.e., the state corresponding to an effective infinite temperature. Eventually, we investigate how to extend the present model to simulate finite temperature states.



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P11

Acousto-optoelectric effect in organic-inorganic semiconductor systems

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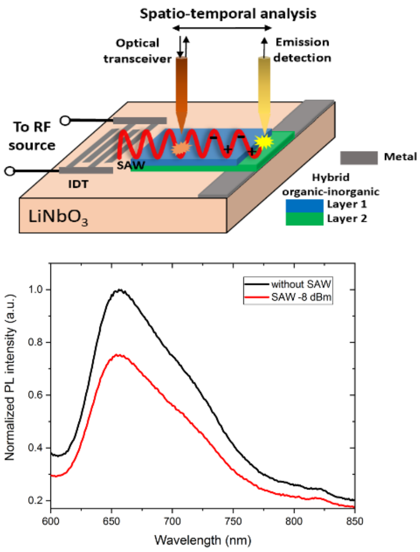

Often referred to as "nanoscale earthquakes", surface acoustic waves (SAWs) are elastic waves which can propagate on the surface of a piezoelectric substrate at the speed of sound. A voltage signal applied to comb-like metal electrodes, termed as interdigital transducer (IDT), typically generates SAW in a device. The applications of SAW based systems are wide-ranging spanning electronics, optics, microfluidics and biological based fields used in medical diagnostics to mobile communication and quantum computing [1]. SAWs can transfer energy into its vicinity and control fundamental excitations in surrounding material. When paired with an optically active semiconductor, the photogenerated charge pairs called as excitons can be ionized by SAW into separate electrons and holes, captured in the deformation potential originated by SAW, and swept along with SAW towards an output spot [2]. Utilizing this effect called as acousto-optoelectric (AOE) effect, first of a kind organic polymers, poly(3-hexylthiophene) (P3HT) and poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenvinylen] (MEH-PPV) based charge transport devices [3] and P3HT based excitonic transistor [4] have been demonstrated wherein long-range excitonic transports of 3 to 4.7 mm at room temperature at an applied RF power of −8 dBm have been observed with accompanying quenching of photoluminescence (PL) intensity. This opens up the utilization of AOE effect in emerging low cost and solution processable based semiconductor systems. The basics of such a device [3, 4] with prospects of extending this to heterostructured organic-inorganic semiconductor layered systems for potentially efficient photovoltaic and optoelectronic devices has been discussed here.

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P12

Optical control of the time-crystalline phases in a polariton condensate with a mechanical clock

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Time crystals (TCs) are many-body systems that display spontaneous breaking of time translation symmetry. Microcavity exciton-polaritons are bosonic quasiparticles resulting from the strong coupling between excitons and photons in a driven-dissipative open system and exhibit a transition to a nonequilibrium Bose-Einstein condensate state. The platform for this study is a polaromechanical (Ga,Al)As microcavity, where micrometer traps confine polaritons and $\sim$ 20 GHz mechanical vibrations that are very efficiently coupled. Polaritons exhibit a pseudospin degree of freedom, with its dynamics manifested through the polarization of the emitted light. Recently, under nonresonant continuous wave excitation, a robust time crystal behavior of the polariton condensate was observed: spontaneous and stable oscillation in the spinor dynamics occurs and locks to the rhythm of the GHz-cavity phonons. Different time-crystalline phases were observed as a function of the applied laser excitation power: i) Larmor-like precession of the condensate pseudospins; ii) locking of the precession frequency to self-sustained coherent phonons; and iii) doubling of the TC period by phonons.[1]

In this work, we demonstrate the tuning of the time-crystalline phases in a polariton state of a micrometer trap, through two additional control parameters, that evidence and exploit the critical role of the exciton reservoir that feeds the polariton condensate in the trap. Namely, i) the polarization ellipticity of the continuous wave excitation laser, that is able to induce a spin imbalance in the reservoir and thus induce a synthetic magnetic field affecting the condensate; and (ii) the position of the excitation spot laser respect to the trap, which determines the spatial distribution of the reservoir and is shown to favor a mechanically driven dynamics of the reservoir. These results establish microcavity polaritons affected by mechanics as a platform for the investigation of time-broken symmetry in nonhermitian systems. In addition, it is argued that the mechanically induced time modulation of the coupling between spinor modes could be used to control quantum gates based on polariton fluids proposed for classical and quantum computing.

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P13

Traveling Surface Acoustic Wave Induced Removal of NSB Proteins from the Acoustic Biosensor

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One challenge of current biosensors is to remove non-specifically bound (NSB). Surface acoustic wave (SAW) technology, because of its non-contact and non-marker characteristics, becomes one of the hot research fields and shows great prospects. In this paper, SAW is used to remove NSB. Firstly, the effect of the cut of the piezoelectric material on the removal force is determined based on the dispersion equation of the acoustic wave and the properties of the piezoelectric material. Secondly, the effects of channel height, excitation voltage and fluid medium temperature on the removal process are verified through theoretical calculations. The results show that the SAW force, lift force and drag force induce by the SAW can effectively remove the NSB, among which, SAW force mainly removes the nonspecifically bound from sensor surface, while the lift force and drag force mainly prevent the re-deposition of the removed NSB. Finally, the optimal region where NSB can be removed effectively by SAW is determined by comparing the SAW force and van der Waals force. When the sensing region is located in the optimal region, not only can the NSB be effectively removed, but also the performance of the sensor is guaranteed.

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P14

Photonic crystal cavity design and characterization for pulsed optomechanical quantum measurement

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As continuous displacement measurements of a harmonic oscillator read out its two quadratures simultaneously, the standard quantum limit constrains the precision with which displacement can be measured. Pulsed measurements allow in principle for precision below the quantum limit in one quadrature, increasing the uncertainty in the other quadrature, leading to mechanical squeezing [1]. In order to measure below the quantum limit, a photonic crystal cavity with high quality factor Q and extreme vacuum optomechanical coupling rate g_0 is wanted[2]. We show the design of nanocavities which simultaneously optimize optical Q and g_0. We characterize the realized samples experimentally using both the optical spring effect and the nonlinearity of optomechanical transduction. Our research paves the way to realize pulsed measurement below the quantum limit by using photonic crystal cavities, and mechanical quantum state preparation based on such measurements.

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P15

Quantum teleportation and dynamics of quantum correlation for two qubits open systems

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Abstract

We investigate the dynamics of non-classical correlations and quantum coherence in open quantum systems by employing metrics like local quantum Fisher information, local quantum uncertainty, and quantum Jensen-Shannon divergence. Our focus here is on a system of two qubits in two distinct physical situations: the first one when the two qubits are coupled to a cavity field whether the system is closed or open, while the second consists of two qubits immersed in dephasing reservoirs. Our study places significant emphasis on how the evolution of these quantum criterion is influenced by the initial state's purity (whether pure or mixed) and the nature of the environment (whether Markovian or non-Markovian). We observe that a decrease in the initial state's purity corresponds to a reduction in both quantum correlations and quantum coherence, whereas higher purity enhances these quantumness. Furthermore, we establish a quantum teleportation strategy based on the two different physical scenarios. In this approach, the resulting state of the two qubits functions as a quantum channel integrated into a quantum teleportation protocol. We also analyze how the purity of the initial state and the Markovian or non-Markovian regimes impact the quantum teleportation process.

P16

Deterministic Fock states in Brillouin optomechanics

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Brillouin devices have emerged recently as a novel perspective platform for optomechanics, including applications like sensing, transducers and memories. Combining high mechanical quality with high mechanical oscillations frequency (and consequently very low equilibrium thermal occupation) they hold promise to be used as quantum memories and for fundamental studies of quantum mechanics at the macroscopic scale. Simultaneous optomechanical and piezoelectric control of mechanical motion can potentially enable microwave-to-optical conversion at the quantum level. For such applications, reaching quantum non-Gaussian mechanical states deterministically is crucial but has been challenging. Here, inspired by the recent experimental progress of Brillouin optomechanics, we consider the pulsed deterministic optomechanical conversion of optical single- and two-photon Fock states to the quantum states of mechanical oscillations. We investigate the conditions necessary to achieve the mechanical Wigner function negativity and the mechanical-state quantum non Gaussianity. As a practical recipe, we provide concrete thresholds for relevant parameters of the optomechanical interaction required to reach quantum non-Gaussian mechanical states and address applications in quantum sensing, transducers and memories.

P17

Amplification and squeezing in parametrically-driven resonators near instability based on Floquet theory and Green's functions

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Here we calculate the response of parametrically-driven resonators to an added external AC signal or white noise using Floquet theory [1]. We provide new estimates, based on the Green's function method, for the response of the system in the frequency domain. The response consists of three parts: elastic, down, and up parametric conversions. Furthermore, we present novel expressions for the power and noise spectral densities. Additionally, we characterize noise squeezing by calculating the statistical properties of the real and imaginary parts of the Fourier transform of the resonator response to added noise [2]. We observe that the squeezing effects occur only at half the parametric pump frequency. For a single parametric resonator, due to correlation, the squeezing limit of -6 dB can be reached even with pump detuning around resonance near the instability threshold. We have preliminary results that indicate that squeezing beyond the -6 dB limit with coupled resonators, in which at least one of them is parametrically driven, can be achieved. We validate our theoretical predictions of squeezing with results obtained from the numerical integration of the stochastic differential equations of our model.

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P18

Coherent Modulation of Microcavity Polaritons at Liquid Nitrogen Temperatures

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Polaromechanics refers to the emerging field that combines cavity exciton-polariton and cavity optomechanics, leading to hybrid systems with interesting new physics [1]. By integrating the mechanical degree of freedom, polaromechanics introduces the variable of time into polaritonic systems, paving the way for quantum state modulation at GHz frequencies and optical-to-microwave conversion.

In polaromechanical systems, photons are strongly coupled to excitons, forming quasi-particles known as a polaritons. The exciton component significantly enhances the polariton's coupling to vibrations through the deformation potential mechanism. Furthermore, the transition to a highly coherent polariton condensate —a Bose Einstein-like macroscopic coherent state— brings the system into the optomechanical sideband-resolved regime. In this regime, the polariton's coherence time is long enough to remain stable throughout a full oscillation cycle of the modulating acoustic field. This allows for coherent energy exchange between the phonons and the polaritons, as has been demonstrated at cryogenic temperatures (10 K) [2]. In this work, we show that this coherent regime can be extended to higher temperatures eliminating the need for cryogenic liquid cooling by properly engineering the system at the microscale.

Our system consists of a hybrid (Al, Ga) As optomechanical microcavity confining both polaritons and phonons in a micro-sized trap. We use bulk acoustic wave resonators driven by a microwave electrical signal to inject GHz phonons into the polaromechanical cavity. We show that the sideband-resolved regime can be maintained by confining the polaritons in 0D structures (polariton dots). Confinement prevents decoherence of polariton lines due to scattering with acoustic phonons, ensuring narrow linewidths up to temperatures as high as 200K and facilitating the transition into a polariton condensate. With this approach, we have shown efficient modulation of polariton lines up to 80 K showing proof of concept coherent microwave-to-optical signal conversion above cryogenic temperatures.

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P19

Abstract: Self induced oscillations in non-linearly coupled magnetomechanical systems

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Backaction effects in optomechanical systems can be exploited to efficiently cool thermally excited mechanical states towards their ground state [1]. However, within specific operational regimes, the resulting backaction can give rise to a negative damping rate, consequently leading to heating of the mechanical mode and subsequently to a break-down of the linear theory [2]. The interplay of nonlinear effects and dissipation can lead to self induced oscillations with a fixed amplitude. Our current study focuses on the theoretical modelling of a nonlinear magnetomechanical system that exhibits self-induced oscillations. In such inductively-coupled electromechanical systems, the interaction between the mechanical mode and the microwave cavity mode is effectively mediated via a SQUID loop [3], thus the nonlinear aspect of the system is strongly enhanced as the cavity mode is itself nonlinear. We compare our theoretical predictions with experimental data.

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P20

Low optical noise for single-photon detection in a mechanically-mediated electro-optic transducer

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Superconducting transmons are well-established as a platform for quantum applications, but the ability to build larger quantum networks is precluded by room-temperature noise at microwave frequencies. Our work uses mechanical membrane oscillators to transduce between microwave and optical frequencies, the latter of which has photon energies higher than thermal energy and thus can be used to send quantum signals. The mechanical system is a 500 μm Si_3N_4 membrane, one corner of which contains a pad of a capacitor to couple the mechanical motion with an LC circuit on the chip below. The other corner of the membrane is placed within an optical Fabry-Perot cavity, so that membrane motion pulls on the cavity frequency. These two interactions are enhanced by microwave and optical pumps red-detuned from their respective cavity frequencies by the mechanical frequency, efficiently sending single excitations through the transducer device. Previous work has demonstrated 50% efficiency and input-referred added noise of 3 photons in these devices [1, 2].

We have been setting up to create interactions between separate qubits using a heralding process in which two microwave excitations would be upconverted to optical frequencties and then interfered on a detector. As opposed to direct signal upconversion then downconversion, heralding quantum states is robust to photon loss after the tranducer. To perform these heralding schemes, we have incorporated non-linear detection into the optical setup using single-photon detectors. But single-photon detectors are not frequency-selective, which necessitates additional considerations for these schemes. Firstly, the strong optical pump that enhances the optomechanical interaction follows the same optical path as the signal at only 1.5 MHz detuned. To filter out this pump, we have incorporated three cascaded filter cavities, which reduce detected pump photons by 100 dB. Secondly, single-photon detection is more susceptible to broadband noises, the largest of which in the optical system is mirror thermal motion.

We describe here the first measurements of mirror noise at dilution refrigerator temperatures. These measurements were facilitated by reduction of the phase noise on the optical pump by adding an additional 100 kHz filter cavity before the beam enters the refrigerator and device. Once reducing the phase noise levels, we characterized the mirror noise in the optical cavity geometry of the transducer. These measurements show that while the mirrors are reaching 400 mK, the thermal noise of the mirrors is broadband and could contribute noise close to signal levels in single-photon detection.

With these characterizations and improvements to the optical setup, we are looking toward non-classical optomechanical measurements. We are exploring protocols both to herald single-phonon states on one mechanical mode, as well as to generate entanglement between multiple modes on the same membrane. Alongside concurrent work to reach the transducer threshold of one photon of input-referred added noise [3], this improved optical setup will then be further incorporated into a larger optically-connected superconducting qubit experiment.

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P21

MEMs for magnetic characterization of micro-nano structures.

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Modern techniques allow synthesize or fabricate different types of magnetic structures: nano-wires [1], nano-tubes [2], mesoscopic samples, etc. In general, experiments of these systems are carried out on samples that contain a large number of these entities. The main drawback that arises in these investigations is that it is only possible to determine the collective physical properties of assemblages. And from these macroscopic measurements, it is very difficult to infer what is the individual physical behavior of each microstructure. Fortunately, nowadays, using micromagnetometers, it is possible to measure the magnetic characteristics of a single microstructure. There are different types of microsensors that can be used as highly sensitive magnetometers, for example MEMs (Micro Electro Mechanical Systems).

In this work, I present the use of micro-mechanical oscillators to characterize mesoscopic superconductors [3], isolated magnetic nano-tubes [4] and nano-wires [5]. The small size of these sensors allows to study the physical processes and the analysis of a single microstructure, not achieved by macroscopic devices. These micro-oscillators works as unidirectional micro-magnetometers. I also present a new design and characterization of an vectorial micromagnetometer.

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P22

SWIFT : Standing Wave Fibre Interference Trap

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The Standing Wave Fibre Interference Trap (SWIFT) is a levitated optomechanical trap employing fibre optics and a planar geometry to create a standing wave optical field in which individual nanoparticles can be trapped [1]; phase coherent light, sent through three single-mode fibres, converges on a common central point. This geometry offers is compact, stable, and offers fast and accurate 2D positioning, including active feedback cooling, via relative phase control of the optical fields. Our device uses a silicon wafer with diced trenches, created in collaboration with the Optical Engineering Group (Southampton) [2], to provide accurate alignment of the fibres, which are glued in place, over a millimeter-sized through hole. In contrast with other work [3], the hexagonal arrangement offers a standing-wave without counter-propagating light so that scatter from the nanoparticle can be more easily separated from the strong laser field used for trapping, enabling homodyne detection with a single optical wavelength. I will report on the challenges and overall progress of realising this device.

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P23

Time-reversal symmetry and adiabatic processes

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We study time reversibility during the adiabatic preparation of populations in the few-level quantum system. The validation of time-reversal symmetry is studied in the various regimes during adiabatic processes by considering various sweep functions and system configurations. The counterdiabatic control and Berry curvature are investigated. The results will be useful for the optimization and acceleration of experimental protocols for efficient population transfer.

Brillouin Scattering in Subwavelength Silicon Waveguides

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Brillouin scattering (BS) is the strongest third-order optical non-linearity in dielectric materials that couples the optical fields and mechanical vibration in the media. Interestingly, in silicon the near-infrared photons and GHz phonons have the same wavelength scale (near 1 µm), leading to the possibility of confining both on the same structure simultaneously. Thus, silicon-based devices attracted the interest of the community due to the optomechanical interactions and CMOS technology compatibility. Yet, silicon-on-insulator (SOI) waveguides suffers from strong phonon leakage towards the silica cladding. Current solution consist of removing the silica layer and isolating the active silicon, which either negatively impacts the fabrication tolerance or rely on extremely low optical loss to compensate for a moderate Brillouin gain.

Our solution consist of subwavelength and suspended waveguide that requires a single-etch step to facilitate fabrication. We propose a geometry comprising a suspended central strip anchored to the lateral silicon slabs by a subwavelength lattice of arms followed by a phononic crystal. Based on COMSOL simulations, the bandgap of the crystal serve as a mirror preventing phonon leakage, and effectively coupling the breathing modes in the core, while the subwavelength arm ensure a low loss propagation of the fundamental TE mode, as depicted in figure (a). This design yields a significant Brillouin gain of $G_B \approx 1800\ W^{-1}m^{-1}$ for a mechanical Q-factor of 1000. We probe our geometry using the three-tone gain experiment [1], we observe a Lorentzian shape, characteristic of Brillouin interactions, centered at $\Omega/2\pi = 7.0453$ GHz, from which a quality factor of 1100 ± 36 is obtained, and using an accurate fitting of the experimental value we obtain a Brillouin coefficient of $1390 \pm 35\ W^{-1}m^{-1}$.

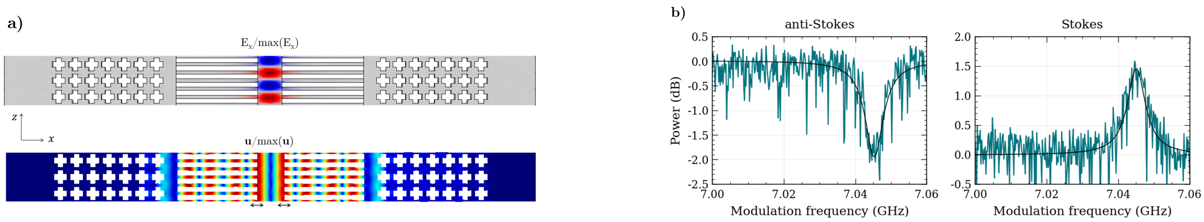

Figure 1: a) Geometry of the structure. b) Power spectral density (PSD) as a function of the modulating frequency for an input power of 35.5 mW.

Although these values are still far from a net gain scenario due to the moderate optical linear losses, they open interesting perspectives sufficient to create a narrow-linewidth notch filter [2]. Further reducing the optical propagation loss, e.g. by post-processing to reduce sidewall roughness, could allow for achieving net Brillouin gain.

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P25

Unveiling the Quantum Speed Limit: Detuning and Initial Coherence Effects in Optomechanical Systems

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In this paper, we investigate the quantum speed limit (QSL) within the framework of the Jaynes-Cummings model with detuning, focusing particularly on arbitrary initial states. Our analysis delves into the impact of detuning, the width of Lorentzian spectral density, and the coherence of the initial state on the non-Markovian speedup evolution within an open quantum system, specifically within optomechanical systems.

Our results highlight that, even in the Markovian regime, increasing the detuning parameter leads to quantum speedup. Moreover, we uncover an inverse correlation between the QSL and the population of the initial excited state. Notably, we demonstrate that the QSL is contingent upon the quantum coherence of the system's initial state, with the maximal coherent state capable of saturating its bound.

P26

Investigating classical and quantum losses in HBARs

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High-overtone bulk acoustic wave resonators (HBARs) are a compelling nanomechanical platform with promising applications. For instance, the mechanical modes in HBARs can be coupled to superconducting qubits in the quantum regime [1]. This coupling enables the coherent control and readout of the mechanical modes, featuring a rich cQAD toolbox of non-classical states and interactions [2, 3, 4, 5] which could be extended to design protocols for quantum sensing, simulation, or the implementation of a quantum memory. Furthermore, the optomechanical coupling of HBARs could enable microwave-to-optical transduction of quantum signals, an important ingredient in long-distance quantum networks. However, all of these applications strongly rely on the low losses of the mechanical modes in the HBARs. Therefore, understanding the origin of these losses and implementing mitigation strategies is key to their success.

In the present work, we use classical coplanar waveguide antennas and flux-tunable superconducting qubits to characterize the quality factors and phonon T_1s of hundreds of HBAR modes in a few GHz frequency span. Our current micro-fabrication process, materials, and HBAR plano-convex geometry [6] allow us to observe typical Q-factors in the order of 1 million and phonon T_1s in the order of 100 μs at cryogenic temperatures. The trends and spread in our preliminary data point towards different loss mechanisms, which we discuss.

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P27

Optomechanical oscillator network for neuromorphic computation

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As neural networks develop to tackle increasingly complex tasks, we are witnessing a rapid growth in the computational resources required. In this context, designing a physical implementation of a neural network provides an exciting alternative [1]. We consider a system of coupled phase oscillators, namely optomechanical oscillators [2,3], with the aim of leveraging their non-linear behaviour to perform neuromorphic computing. We investigate the possibility of using this kind of network to execute simple tasks based on supervised learning.

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P28

Parametric feedback cooling of levitated optomechanics: A perturbative path integral approach

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Levitated optomechanics is emerging as a fascinating topic in experimental and theoretical physics due to its promising applications in fundamental science, quantum sensing, gravitational effect investigation [1-4]. Here we consider a typical massive nanoparticle which is trapped in a tightly focused Gaussian beam in vacuum [2]. We calculate the perturbation corrections to the correlation function of the nanoparticle under the influence of an effective feedback generated potential. The effect of feedback delay is investigated from the perturbation theory of Brownian particle under the action of an optical gradient force. The Langevin force acting on the particle is considered to be velocity dependent. We use path integral method to calculate the moments of the probability density function of a stochastic differential equations associated with the motion of the trapped particle [3].

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P29

Entanglement dynamics of levitated nanoparticle in coupled cavities in PT-symmetric regime

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In recent years, levitated systems have become interesting platforms for exploring quantum sensing, entanglement and non-equilibrium physics as well as testing fundamental limits in physics [1-6]. In our work, we focus on entanglement, which has potential for applications in quantum metrology and quantum information processing [7, 8].

Studies on entanglement in various conventional optomechanical systems [9] and cavity-based levitated systems [6] have already been initiated by many researchers. Previous work on a cavity-based levitated system by Chang *et al*. showed that a levitated nanoparticle trapped inside a single cavity can be entangled with the cavity field [6]. In our work, we study the effect of an auxiliary cavity, coupled to this single cavity, on the entanglement between the nanoparticle and the cavity field. We show that the entanglement between the nanoparticle and the cavity field can be significantly enhanced when the whole system works in a PT-symmetric regime i.e., when the single cavity and the auxiliary cavity has equal gain and loss rates. Enhancement of entanglement using PT symmetry is an interesting technique that can be applied to other optomechanical systems as well. Moreover, our findings on the enhancement of entanglement may bring benefits for the mentioned applications in quantum information quantum communication and quantum sensing.

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P30

Quantum Teleportation Using Nanomechanical Oscillators

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Abstract:

This paper explores the integration of quantum nanomechanical systems with quantum teleportation protocols, focusing on the potential of nanomechanical oscillators as a medium for quantum state transfer. Quantum teleportation, a process that allows the transfer of quantum states between distant particles without physical transmission of the particles themselves, is a cornerstone of quantum communication and computing. Concurrently, advancements in quantum nanomechanics have introduced highly controllable and integratable nanomechanical oscillators, such as carbon nanotubes and graphene sheets, which can serve as quantum bits (qubits). We provide a comprehensive review of the principles of quantum teleportation, followed by an in-depth discussion on the properties and advantages of nanomechanical oscillators. The paper examines theoretical models and experimental setups that demonstrate the feasibility of entangling nanomechanical oscillators with other quantum systems, highlighting their potential for high-frequency operations and robust integration with existing quantum technologies. We address the challenges associated with coherence and decoherence in nanomechanical systems, and present recent experimental results that show promising advancements in this hybrid approach. Through analysis of current research and case studies, we evaluate the efficacy of using nanomechanical oscillators for teleporting quantum states, supported by simulations and theoretical models. Finally, we discuss the future directions and applications of this technology in quantum computing, sensing, and communication, outlining a roadmap for overcoming technical barriers. This paper aims to underscore the synergy between quantum nanomechanics and quantum teleportation, proposing that this interdisciplinary approach could pave the way for significant advancements in the field of quantum information science.

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P31

Optomechanical Microwave Isolator in Room Temperature

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We demonstrate a frequency-converting microwave isolator using synthetic nonreciprocity [1] in a microwave cavity optomechanical system. Our device, consisting of a 3D reentrant cavity and a silicon nitride membrane coupled via tunable vacuum gap, can accumulate a large number of photons up to 2×10^{14}. Strong optomechanical interaction arises to result in efficient nonreciprocal phonon transfers to demonstrate reverse isolation between two microwave ports even at room temperature.

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P32

Quantum squeezing in a nonlinear mechanical oscillator

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Mechanical resonators offer many applications in quantum information processing due to their bosonic nature. The modes of these resonators can be manipulated using tunable bilinear interactions, including beamsplitter and squeezing operations. To engineer these interactions, bosonic modes can be coupled to a nonlinear element, such as a transmon ancilla, driven by two parametric drives [1]. Recently, a beamsplitter-type interaction has been demonstrated in our circuit quantum acoustodynamics (cQAD) system [2]. To provide a universal gate set for continuous variable quantum information processing within one cQAD device, we also introduced single-mode squeezing (SMS) to our tool box [3].

In this poster, we present SMS and two-mode squeezing of bosonic modes of a mechanical resonator. We show that off-resonant coupling to the qubit leads to a tunable nonlinearity in our resonator mode. This allows us to prepare non-Gaussian quantum states with high quantum Fisher information, with applications in for example quantum metrology and sensing [3].

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P33

A mechanical qubit

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Strong nonlinear interactions between quantized excitations are an important resource for quantum technologies based on bosonic oscillator modes. However, most electromagnetic and mechanical nonlinearities arising from intrinsic material properties are far too weak compared to dissipation in the system to allow for nonlinear effects to be observed on the single-quantum level. To overcome this limitation, electromagnetic resonators in both the optical and microwave frequency regimes have been coupled to other strongly nonlinear quantum systems such as atoms and superconducting qubits, allowing for the demonstration of effects such as photon blockade [1, 2] and coherent quantum protocols using the Kerr effect [3]. Here, I will present the realization of a single-phonon nonlinear regime in a solid-state mechanical system. The single-phonon anharmonicity in our system exceeds the decoherence rate by a factor of 6.8, allowing us to use the lowest two energy levels of the resonator as a mechanical qubit, for which we show initialization, readout, and a complete set of direct single qubit gates. This work adds another unique capability to a powerful quantum acoustics platform for quantum simulations [4], sensing [5, 6], and information processing [7, 8, 9].

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P34

Attenuation of flexural phonons in crystalline two-dimensional materials

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This work explores the dynamic behavior of flexural phonons in two-dimensional crystalline membranes at the room temperature. We studied the attenuation of flexural phonons due to interaction with in-plane phonons with the help of the Matsubara diagram technique.

At first we found that the decay rate of flexural phonons in the free-standing membrane is independent of temperature, unlike the standard lifetime in three-dimensional crystals due to three-phonon processes. Our analysis show that this unexpected result is because of the strong screening of the interaction at small momenta $q < q_*$ where $q_* \sim \sqrt{YT}/\varkappa$. Here Y and $\varkappa$ denote the Young's modulus and the bending rigidity, respectively.

For static out-of-plane deformations the strong screening of the interaction results, as well-known, in power-law dependence of the Young's modulus and the bending rigidity on momentum, $Y \sim q^{2-2\eta}$ and $\varkappa \sim q^{-\eta}$ [1]. These power-law scaling of elastic moduli persits in the dynamic. We also obtained the exact relation for the dynamical exponent: $\mathsf{z} = 2 - \eta/2$. For long-wave in-plane phonons we obtained non-trivial dynamical exponent $\mathsf{z}'{=}(2{-}\eta)/(1{-}\eta/2)$, contrary to the result of [3].

We studied the effect of an applied stress σ on the attenuation of flexural phonons, which is usually present in the experiments when studying nanoelectromechanical properties of graphene [2]. For sufficiently large flakes the spectral line quality factor Q_k (the ratio of the spectrum to its width) is parametrically large and strongly depends on the temperature and the stress ([5]).

Finally, behaviour of mean squared displacement, $\langle (h(t) - h(0))^2 \rangle$, was analysed as a function of time ([4]). At long times, $t \gg \sqrt{\rho/(\varkappa q_*^4)}$ (ρ is the mass density), we obtain $\langle (h(t) - h(0))^2 \rangle \propto t^{1-\beta}$, where $\beta = \frac{\eta}{4-\eta} > 0$. The latter implies that fluctuations behave subdiffusively in quantitative agreement with the experiment.

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P35

Inverse design of nanomechanical resonators for quantum optomechanics

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Nanomechanical resonators as an optomechanical platform have emerged as promising components in various applications, including sensing, signal processing, and quantum information technologies. The optimization of these resonators to achieve desired mechanical and optical properties, and to minimize dissipative contribution poses a significant challenge due to the complex interplay between their geometric, material, and environmental parameters. Traditional design approaches, often based on iterative simulations and empirical adjustments, can be time-consuming and computationally expensive. This research explores the potential of Artificial Neural Networks (ANN) for the inverse design of Nanomechanical resonators, offering a more efficient and targeted approach to achieve specified performance metrics.

To this end, we have successfully demonstrated the potential of CNN-based machine learning models to accurately predict resonance frequencies, dissipation dilution, and buckling instabilities in randomly etched thin plate resonators.

To further advance these concepts, we will develop a neural network model trained on an extensive dataset of nanomechanical resonator designs and their corresponding performance characteristics. This model will employ inverse design techniques to map desired mechanical and optical properties to optimal design parameters. Additionally, we will optimize mechanical performance while maintaining a high degree of optomechanical coupling. Utilizing a deep learning framework, our approach can capture complex nonlinear relationships within the design space, enabling rapid and accurate predictions.

P36

Exploring Multi-Tone Driven Duffing Resonators: Towards a New Paradigm in Nonlinear System Analysis

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The study of nonlinear processes has applications in wide-ranging fields spanning different timescales and dimensions. Here, we present an investigation into the dynamics of a Duffing resonator driven by a combination of two drives at adjacent frequencies as shown in Fig.1a, advancing beyond the traditional pump-probe approach [1]. We introduce a model that accounts for the change in the relative phase between the two drives due to their close, incommensurate frequencies which results in an effective amplitude modulation of the primary drive. Our study explores the effect of the relative strength and detuning of the secondary drive on the resulting relaxation-like cycles depicted in Fig.1b, induced by periodic jumps between bistable response branches, and leads to unexplored parameter regimes. These findings are supported by experimental data, offering new insights into nonlinear resonator behaviour [2]. This work forms part of a broader effort to refine the theoretical framework for multi-tone driven nonlinear systems and harness their nonlinearity for advanced applications in nanomechanical systems.

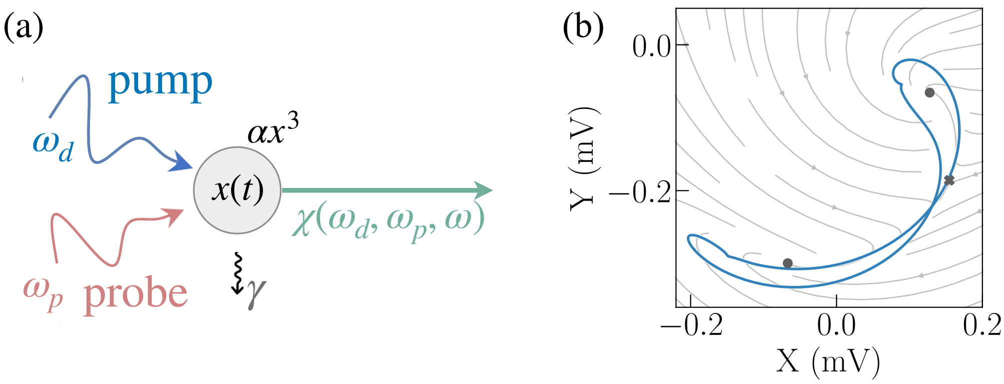

Figure 1: (a) A schematic of a Duffing resonator with natural bandwidth γ driven with a primary "pump" drive at frequency ω_d and a secondary "probe" drive at ω_p, where $\omega_d - \omega_p < \gamma$. (b) Phase-space trajectory depicting a relation-like cycle obtained by tuning the strength of the secondary drive and its frequency.

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P37

Electrostatically transduced 1D Silicon Phononic Crystals and Cavity Interactions

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Phononic crystals have emerged as tools for manipulating phonons in vibrating micro/nanostructures and have found numerous applications in acoustic filtering, waveguiding, multiplexing, quantum sensing, biosensing, etc. [1]–[3]. The other known application is to enhance the quality factor by confining the energy that can be dissipated by the anchor [4]. We proposed electrostatic actuation and readout-based 1D phononic crystals with frequency ranges in MHz and verified them by bandgap measurements. The demonstration was carried out in a p+-doped silicon-on-insulator substrate, where we induced mechanical vibrations electrostatically through fixed-fixed beams connected by coupling beams. The transmission response is electrostatically sensed via a transimpedance amplifier using a network analyzer, which shows the bandgap regions formed by the interactions of the structures in the phononic crystals. Later, we used a double-ended tuning fork (DETF) resonator inside the bandgap of the phononic crystals to reduce the clamping loss. The resonator consists of two degenerate modes; one, i.e., in-phase mode, is within the bandgap, whereas the other, i.e., out-of-phase mode, is in the band region as compared to both frequencies that are close by and are within the bandgap frequency range while anchored. The implication of such a system demonstrates the efficacy of the phononic crystals, as the in-phase mode quality factor enhanced by ~2 times compared to that when it was anchored, whereas the out-of-phase mode quality factor remained the same at the temperature where the thermal expansion coefficient of the silicon decreased to zero, i.e., 110 K, after eliminating the thermoelastic dissipation completely. The degenerate modes Q show an ~ 7-times improvement as placed in the phononic crystals.

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P38

Microwave Frequency Comb Generation in High Kinetic Inductance Superconducting Coplanar Waveguide

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Microwave frequency comb, a source with a constant frequency interval, has made many advances in science and technology. They are characterized by their accuracy and wide range of applications. Integrated frequency comb can provide scalability for precise on-chip microwave photonics. Here, we present a microwave frequency comb driven purely by the Kerr nonlinearity of the kinetic inductance without a complex Josephson junction. This opens the door to the development of other devices in the future, such as parametric amplifiers and directional couplers.

P39

Membrane Resonators: a Promising Platform for Sensing Applications

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Recently, high aspect-ratio membrane nano-resonators, established themselves as versatile platform in science and technology. The exceptional mechanical properties enabled by the introduction of techniques such as dissipation dilution [1] and mode-shape engineering [2] combined with the high susceptibility to a large variety of external triggers makes them excellent candidates for state-of-the-art sensors. Membrane-based sensors have been used, among others, for force sensing [3], photothermal sensing [4], and mass sensing [5].

The aforementioned properties set the nano-mechanical membrane resonators as viable candidates to outperform existing sensing devices, however commercial applications based on such devices are still rare. Within our project, we aim to accelerate their industrial diffusion by providing a playground for testing sensing resonators as well as further pushing the development of membrane devices to sense various quantities, including mass and pressure.

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P40

MEMS oscillators at Bosch Research

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MEMS devices are widely used in both automotive and consumer applications. They are not only key enablers for miniaturization of consumer products like smartphones and in-ear headphones but also allow safety-relevant sensing in mobility applications with inertial measurement units. The ever-increasing product requirements result in complex mechanical designs that require a deep understanding of the underlying physics. Especially in the case of resonant sensors like MEMS gyroscopes, insights in nonlinear dynamics are essential. At Bosch Research, we tackle these challenges by using modern optimization techniques. Additionally, we are constantly looking for new methodologies like topology optimization to improve designs and increase engineering efficiency. This poster gives an overview of the research topics on MEMS oscillators and related fields at Bosch.

P41

Two-membrane etalon

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We propose the theoretical and experimental investigation of an optical cavity formed by two (nominally identical) parallel semi–transparent membranes. In this scenario the "good–cavity" approximation does not hold, due to the low reflectivity of the mirrors, and the oscillations of the membranes introduce dynamical boundary conditions for the cavity field.
The experiment consists in laser-driving the cavity, detecting interferometrically the field reflected by the etalon, and measuring the intensity of the transmitted field, for different distances within the two membranes. A complete characterization of the membrane sandwich is provided.
On the other hand, we developed an analytical model to describe the fields, which is consistent with the experimental results. Moreover, as a proof of its validity, it leads to the known results when high–reflectivity, and/or fixed mirrors conditions are restored.
This work paves the way for a complete and analytical model to describe multi-oscillators "membrane-in-the-middle" optomechanics.

P42

Optomechanical Strong-Coupling between a Planar Microwave Cavity and a High-Stress Silicon Nitride Membrane in a Flip-Chip Device

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The field of cavity optomechanics investigates interactions between mechanical and electromagnetic oscillators that are mediated through the radiation pressure force. It has been shown that optomechanical devices can have many applications such as: quantum sensing, quantum transduction, and quantum information processing [1, 2, 3]. Furthermore, optomechanical devices have been used to demonstrate groundbreaking quantum control of mechanical oscillators, for example, cooling into their ground state [4]. Quantum control and measurement of mechanical oscillators opens the possibility of performing fundamental tests of physics. If a mechanical oscillator of sufficient mass is prepared in an appropriate quantum superposition, the quantum state could decohere due to relativistic effects [5]. To prepare such a state, we are developing a device where the optomechanical coupling rate exceeds the dissipation rate of both oscillators, called the strong-coupling regime.

A platform for such experiment consists of two individual chips placed close to each other, which we refer to as a flip-chip device. Here, one chip contains the mechanical oscillator: a high-stress silicon nitride membrane embedded within a phononic shield. The other chip contains a planar, superconducting microwave cavity. When one chip is placed on top of the other, the membrane acts as a free-hanging capacitor plate, forming an electromechanical device with the microwave cavity. To access the strong-coupling regime, the optomechanical coupling rate of our device has to be increased by bringing the membrane closer to the capacitor pads of the cavity. Optimizing fabrication methods to achieve a gap distance between the membrane and capacitor plates of to $d \sim 200$ nm, would increase the single photon optomechanical coupling rate to $g_0 \sim 10$ Hz. This would allow access to the strong coupling regime in the presence of a strong drive. Combined with the long coherence time of the mechanical oscillator, this device is another step towards exploring the possible interplay between general relativity and quantum mechanics [5].

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P43

TLS coupling strength estimation using parametric normal mode splitting

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The dynamical characterisation of nanoelectromechanical systems has long been a great concern in different systems and applications. A plethora of studies were conducted to characterise single degree of freedom (single mode) systems, either linear or nonlinear. However, regarding two-mode, or two-level, systems another dimension must be considered, that is the coupling mechanism between both modes. The problem is even harder in this case because the coupling is implicit in the measurable hybridised coordinates. Moreover, in complex systems it is not always possible to determine the coupling strength in a generic form for all use cases. In this contribution, we present a novel method for estimating the linear coupling coefficient in any two-level system while making use of a phenomenon that occurs due to an additional parametric excitation.

The method is based on applying a parametric excitation on at least one already-resonating mode in a two-mode system. If this parametric excitation is tuned to the difference frequency between the natural frequencies of both modes, a splitting is observed in the resonance peak of the resonating mode, which is known as parametric normal mode splitting [1]. The phenomenon is analysed using the multiple scales method, a perturbation method using different time-scales, by perturbing the modal response when the parametric excitation frequency is detuned around the difference frequency. This perturbation shows the existence of the splitting phenomenon and could trace the change in the two resulting branches of the resonating mode in a wide range of coupling strength magnitudes. Moreover, this method links a measurable quantity, the splitting width, to the implicit coupling strength. Using the model developed, the coupling strength could be then estimated and validated experimentally.

The experimental validation is carried out by exciting the in-plane and out-of-plane modes of a SiN nanostring using dielectric actuation in an inhomogeneous electric field. Using a microwave cavity-assisted measurement, the two modal oscillations of the nanostring are measured at different bias dc voltages [2]. At each bias voltage, not only the natural frequencies change, but also the coupling strength. Thereby, by applying the described method at different voltages, the change of coupling strength with bias voltage is estimated. Since previously the coupling strength estimation was only attainable under the condition of the avoided crossing, this method then provides a novel method for its estimation with no need to change the system parameters.

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P44

Towards Quantum Transduction with an Integrated Gallium Phosphide Platform

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Microwave-optical transducers are devices that can link photons at gigahertz frequencies with those at terahertz telecommunication frequencies. These transducers would enable long-distance quantum-coherent communication at room temperature via optical fibers and, thus, the interconnection of remote qubits, opening opportunities for the creation of quantum networks as well as qubit control and readout. One promising avenue to realize such a transducer is via a combination of piezoelectromechanical and optomechanical interactions, exploiting an intermediary nanomechanical resonator with high coherence [1].

Our work uses gallium phosphide (GaP) [2], a dielectric with a large index of refraction ($n = 3.05$) at telecommunication frequencies, making it ideal for high-confinement photonic structures. GaP also has a wide electronic bandgap (2.26 eV) that reduces two-photon absorption and, in turn, heating of the mechanical resonator. Furthermore, the piezoelectric properties of GaP couple the mechanical and microwave domains.

The geometry of the device consists of a free-standing GaP nanobeam comprising two optomechanical crystal cavities linked by a phononic waveguide with linear dispersion, providing strong mechanical hybridization between the two cavities. The phononic waveguide also possesses an optical bandgap that prevents the optical cavities from coupling to each other. One cavity is used for optomechanical coupling, while a thin-film niobium nitride electrode on top of the second cavity is used to piezoelectrically actuate the common mechanical mode. Characterization of our devices reveals internal optical quality factors as high as 3.5×10^5 and optomechanical coupling strengths greater than 0.45 MHz, values comparable to state-of-the-art silicon devices. Our simulations predict an electromechanical coupling strength to a high-impedance microwave resonator of up to 1 MHz.

Recent results regarding room-temperature microwave-to-optical transduction will be presented. These results are promising for the subsequent integration of the devices with a tunable microwave resonator and eventually a logical qubit.

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P45

Abstract for School and Workshop on Frontiers of Nanomechanics

Measurement of Casimir Force between Gold Sphere and Graphene using a Silicon Cantilever

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The Casimir force originates from the quantum fluctuations of the electromagnetic field and the corresponding polarization fluctuations induced in the bodies. It increases rapidly with decreasing distance and becomes the dominant interaction between uncharged bodies at submicron separations. The effect of thermal fluctuations on the Casimir force has also attracted much interests [1-3]. However, for common metals like gold, thermal effects at room temperature only become significant at distances exceeding one micron, where measurement of the Casimir force and distinguishing it from other remnant forces is difficult [4]. With thickness as small as one atomic layer, graphene possesses unique optical and electrical characteristics. For example, undoped graphene is a semi-metal with dispersion of quasiparticles having Dirac nature. Thermal effects on the Casimir force have been predicted to occur at separations significantly smaller compared to metals [5-8]. At these short distances, the Casimir force is expected to be strong enough to be experimentally detected. We measure the Casimir force gradient between a gold sphere on cantilever and graphene grown by chemical vapour deposition transferred onto silicon oxide. There is good agreement with theory but the large contribution from the silicon oxide precludes clear observation of thermal Casimir effects. Ongoing attempts aim at reducing the contribution of the silicon oxide substrate.

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P46

Optomechanical resource for fault-tolerant quantum computing

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Fusion-based quantum computing with dual-rail qubits is the leading candidate for scalable quantum computing using linear optics. This computing paradigm requires single photons which are entangled into small resource states before being fed into a fusion network. The most popular sources for single optical photons (e.g., spontaneous parametric down-conversion) and for small entangled states (e.g., linear optics) are probabilistic and heralded. It is possible to effect deterministic sources of these photonic resources from many probabilistic, heralded resource generators, but this requires complex optical networks. Alternatively, successfully generated resources can be stored in quantum memories to be retrieved as needed. In this work, we show how optomechanics can be harnessed to implement such quantum memories. The acoustic modes act as caches of quantum resources—single-particle states and even small entangled states—with on-demand read-out. I will show how the resource states can be prepared directly in the acoustic modes using optical controls. This will still be probabilistic and heralded, as the all-optical approach, but the acoustic modes store the quantum states with no extra effort. The quantum states may be transferred from acoustic modes to optical modes, as needed, with another optical drive. The advantages of acoustic modes as optical quantum memories, compared to other technologies, include their intrinsically long lifetimes, as well as being solid state, highly tailorable, and insensitive to electronic or magnetic noise.

P47

Graphene Josephson Junctions for Quantum Metrology

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We propose a hybrid quantum device based on the graphene Josephson junctions where the vibrational degrees of freedom of a graphene membrane couples to the superconducting circuits. The flexural mode controlled tunneling of the Cooper pairs introduces a strong and tunable coupling even in the zero-point fluctuations level. By employing this interaction we show that a parametric cooling process can be efficiently implemented. We then investigate the application of our hybrid quantum device in quantum metrology, with critically enhanced sensing under suitable quantum control. Our work provide new ways to extend the recent research on quantum electromechanical systems.

P48

Abstract for “Microwave to optical transduction based on opto-electro-magneto-mechanics”

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Quantum transduction schemes are essential for realizing quantum control in quantum networks of several platforms, i.e. ions, single atoms or spins to superconducting circuits. Each single system may excel in a particular task, i.e. quantum information processing is best accomplished with superconducting qubits or cavities in the microwave energy range, whereas optical signals are more favorable in transferring quantum information over long distances. Combining both energy regimes is quintessential for quantum networks. Engelhardt et al. presents such a two-stage microwave to optical photon conversion protocol [1] utilizing the excitation degrees of freedom of a magnetic material. They employ a resonant interaction between magnetic and mechanical excitations as a mediator between microwave and optical photons. Here, we describe the design and fabrication of a single crystalline ferrimagnetic yttrium iron garnet (YIG)-chip-based optomechanical crystal (OMC) [2] capable of realizing the multipartite coupling scheme. Typically to get the best magnetic properties, single crystalline YIG is grown on gadolinium gallium garnet (GGG), due to its low lattice mismatch with YIG. However, both garnets are challenging in a top-down fabrication as they are very stable with respect to chemical gases. To this end, two possible fabrication schemes of single crystalline YIG on sacrificial layers are discussed. The first one is the lateral solid phase epitaxial (LSPE) growth of YIG over a silicon dioxide sacrificial layer [3] engineered by our collaborators S. Sailler et al. from the University of Konstanz. The second approach is adapted from the smart cut process well established in the silicon industry. Helium ion implantation is conducted at a depth of 10 µm in GGG of a commercially purchased liquid-phase-epitaxy-grown bulk YIG film by our collaborator Jeffrey McCallum et al. from the University of Melbourne. The induced defect layer is then sliced by thermal spalling or phosphoric acid treatment [4]. We plan to transfer the separated layer to a semiconductor substrate realized by a direct wafer bonding [5]. A chemical mechanical polisher smoothens the GGG-YIG-semiconductor film surface. Electron-beam lithography (EBL) for etch mask layering is conducted in LSPE-films. A sequence of anisotropic argon milling etch and isotropic hydrofluoric etch suspends the OMC. Finally, we conduct a critical point drying which prevents the adhesion of the nanobeam to the substrate during phase transition from water.

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P49

Amplitude and phase noise in two-membrane cavity optomechanics

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Cavity optomechanics is a vibrant field in physics, it allows to explore fundamental quantum physics even in macroscopic objects and also promises to realize a pletora of applications, essential for the upcoming quantum revolution. In this work we study a Fabry-Perot cavity, with two SiN membranes inserted in the "membrane in the middle" configuration [1]. The effective coupling between the two mechanical resonators, mediated by the electromagnetic field, features a variety of effects such as, amoung others, enhancement of single-photon optomechanical coupling [1], heat transfer [2], cooperativity competition [3].
In order to reach control in the quantum regime, it is mandatory to take into account, and possibly avoid, all kind of noises of the system, even technical laser noises, which are often neglected in the literature. This work provides a method for modelizing amplitude and phase laser noises in a multimode optomechanical system driven by two laser fields. We add terms in the Langevin equations which describe the laser noise sources, and check the validity of the model experimentally by exploiting an artificial noise source on the pump beam. Moreover we calibrate and quantify the corresponding noise spectra in order to make a proper match between theory and experiment [4].

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P50

Release-Free Subwavelength Optomechanical Resonators for Quantum Transduction between Microwave Phonons and Optical Photons

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Interconnecting quantum processors to create quantum networks is an essential step towards the secure internet of the future. While conventional optical fibres can propagate quantum information, the quantum processors are not operating at the telecom wavelengths. Quantum transducers based on electro-opto-mechanical conversion have been proposed as an efficient system to bridge the 5-orders of magnitude difference between microwave and optical frequencies. Integrating these transducers into photonic chips requires developing geometries capable of providing strong optomechanical coupling.

Stimulated Brillouin Scattering is the nonlinear interaction involving the scattering of an optical field by acoustic phonons, and has led to several developments [1] in sensing, communications and quantum technologies [3]. Efficient Brillouin Scattering requires simultaneous confinement of photons and phonons which, in Silicon-on-Insulator (SOI) waveguides, is challenging due to strong phonon leakage towards the silica cladding. Typically, this is overcome by using suspended membranes that are created by removing the silica cladding. However, using subwavelength structures we can avoid these suspended membranes, thus ensuring an easier, CMOS-compatible fabrication process as well as co-integration with other photonic and electronic components.

Previous work [2] demonstrated in our group uses subwavelength silicon pillars consisting of a unit cell of two pillars with π-shifted mechanical motion that results in suppression of the acoustic radiation by 20 dB. This radiation cancellation confines the mechanical modes effectively, with Quality Factors $> 10^3$ for mechanical modes. The optomechanical coupling, driven primarily by the radiation pressure exerted by the optical mode, is high with $g_0/2\pi \approx 108 \pm 6$ kHz. The goal of my PhD is to demonstrate higher optomechanical coupling and larger mechanical frequency (∼GHz) in non-suspended designs, for monolithic integration with superconducting transmon qubits.

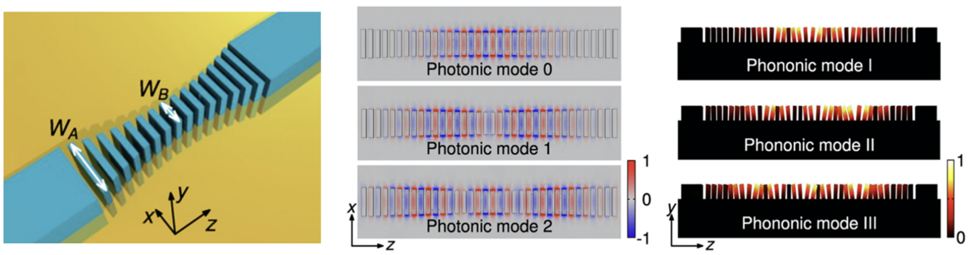

Figure 1: Cavity with parabolically decreasing width of the silicon pillars, and the corresponding optical modes (E_z component) and phononic modes (mechanical displacement).

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P51

Abstract template for Double-Quantum-Dot Qubit Strongly Coupled to Mechanical Vibrations in a Suspended Carbon Nanotube

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Mechanical resonators are systems which present high quality factors and can easily couple to a wide range of forces, which makes them excellent candidates for quantum information processing and quantum sensing. In our group, we are developing a hybrid platform where a charge qubit defined in a double-quantum-dot is coupled to the mechanical vibrations of a suspended carbon nanotube. The nature of the coupling allows to reach the so-called ultrastrong coupling regime, that could open the possibility of exploring and realizing new regimes in a circuit quantum electrodynamics (cQED) framework.

In particular, the anharmonicity induced by the qubit in the mechanical vibrations when the system is in the ground state could allow the realization of a mechanical qubit, i.e. a qubit based on phonon’s fock state transitions [1]. The effective mechanical non-linear potential in the ultrastrong coupling regime can also serve to realize a macroscopic quantum superposition similar to the one proposed in [2], with potential applications of studying collapse models in quantum mechanics, or the interplay of quantum effects and gravity, among others.

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P52

Fabrication and mechanical characterisation of hBN/Si_3N_4 resonator

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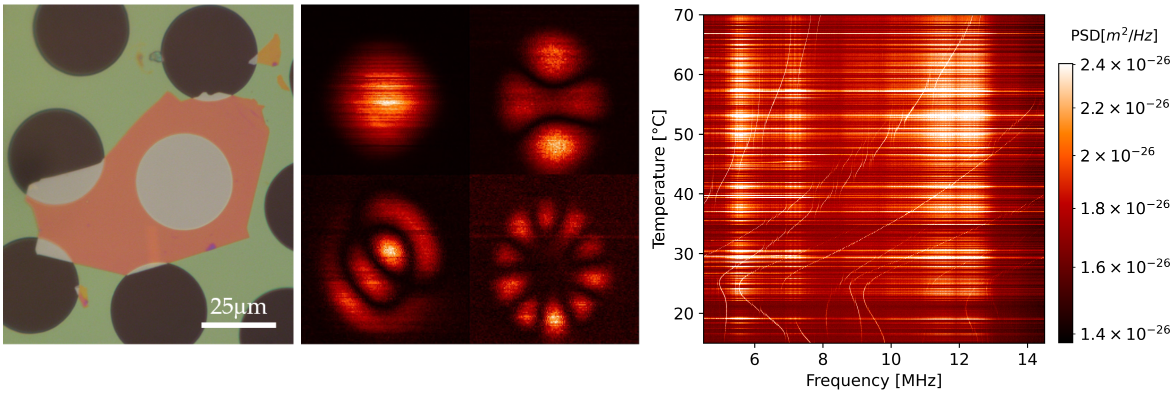
Nanomechanical resonators, including nanowires, nanotubes and two-dimensional membranes, have become essential tools in physics due to their remarkable mechanical properties, such as high fracture strength and Young's Modulus. Van der Waals materials like graphene or hexagonal boron nitride (hBN) are particularly suitable to produce 2D membranes, as they lack dangling bonds at the surface. HBN, in particular, which has comparable mechanical properties to graphene, is often utilised in optomechanics and electromechanics due to its wide bandgap of 6 eV [1].



We will show the fabrication process of 2D drum resonators made of hBN suspended over a high-stress Si_3N_4 membrane, including a hybrid wet transfer technique and the use of capacitively coupled plasma reactive ion etching (CCP-RIE) to tune the thickness of the hBN [2, 3]. We imaged and characterized the mechanical modes of these drums and will demonstrate the large temperature dependencies of the mode frequencies of hBN resonators coupled to a Si_3N_4 resonator [2]. Notably, unlike other 2D materials, hBN exhibits a negative thermal expansion coefficient (TEC). Consequently, elevated temperatures increase the internal stress within the flake, resulting in higher mode frequencies. In contrast, at lower temperatures, the internal stress decreases, causing the drum to buckle. This buckling significantly affects both the frequency and the shape of the modes. This temperature-dependent frequency tunability also enables a more detailed investigation of the hybridization state between the mechanical modes of the hBN and the Si_3N_4 membrane, as well as its effects on the quality factor and effective mass. Our study reveals how the interplay between these modes can be modulated through temperature adjustments, providing deeper insights into the behaviour of the coupled resonator system. Finally, this could have significant implications for the development of more complex heterostructure resonators, as well as for the realisation of nanomechanical devices from 2D magnets, with a focus on the rich physics of their magneto-mechanical coupling [1].

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P53

Josephson Optomechanics

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In recent years, optomechanical cooling using microwave radiation has been realized in various superconducting circuits with a microwave cavity comprising a mechanical element. Circuits provide an opportunity to engineer nonlinear cavities, by using Josephson junctions, thereby generating quantum states of light for optomechanics experiments.

In the poster, we will theoretically describe an optomechanical setup where the cavity is realized by an LC circuit driven by a dc-biased Josephson junction. By engineering the nonlinearity, such a cavity becomes an effective N-level system, with $N = 2, 3...$, where the access to Fock states N and above is blocked [1]. Consequently, the cavity emission spectrum shows Mollow-type side peaks, analogous to an optical cavity interacting with an atom. We show that at these Mollow side peaks, the system exhibits a new, nonlinear type of optomechanical cooling. We calculate the cooling rate using the spectral density of noise due to the radiation pressure [2] and highlight how its unusual features compared to conventional optomechanics, can be explained in a dressed state picture.

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P54

Bullseye C vities for Integr ted Nonline r Phononic Circuits

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Recently, logic operations were realized with parametrically excited nanomechanical resonators [1]. The parametric excitation induces one of two stable states, which can be switched by small trigger pulses. This achievement set the course for bit operations and larger logic elements build on mechanical resonators [2]. We propose the integration of a suitable nonlinear nanomechanical resonator with surface acoustic waves (S Ws) and a quantum dot (QD) membrane on one chip. The S Ws enable a higher operating frequency in the gigahertz range, while the QDs allow better access to the information via optomechanical coupling to the resonator modes [3, 4].

The acoustic resonator discussed here is designed such, that it also fulfills the second-order Bragg condition for the QD photons. Thus this cavity co-confines the photonic and acoustic modes and facilitates optomechanical measurements by increasing the vertical light extraction of the structure [5]. dditionally, the CBGs profit from the Purcell effect, which increases the photon count further [6]. Since a direct placement of the QD membrane on the $LiNbO_3$ would lead to photon leak into the substrate, a 100 nm thick u layer separated from the Ga s by 360 nm thick SiO_2 is incorporated. The final material stack is shown in Fig.1 a), alongside a heat map of the displacement amplitude of an acoustic mode in the design (Fig. 1 b)).

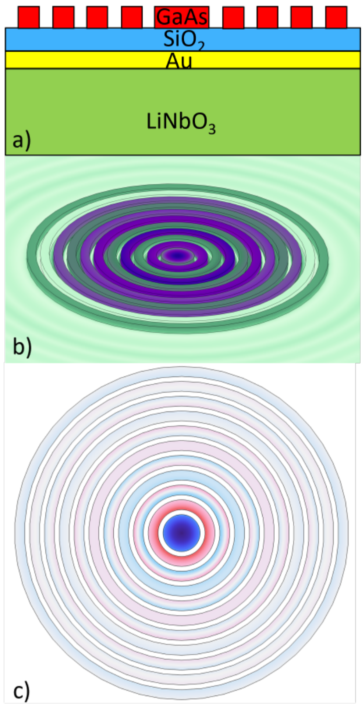

Figure 1: a Scheme of substrate design, b FEM acoustic eigenfrequency simulation of a Bullseye grating, c) 2D cut of the same mode with the strain as heat map.

We used finite element method simulations (FEMS) to prove that a co-confinement in such a Bullseye cavity is possible. Published work on CBGs for In s QDs emitting around 920 nm provided us with a starting point for the key parameters of the grating and the central disk, as well as the material stack [5]. With eigenfrequency studies, we deduced that the S Ws must operate around 2.5 GHz to fit the design conditions for the optical grating. Furthermore, we checked the strain profile (Fig. 1 c)), calculated the normalized strain in the QD plane of the disk and compared the strain in the disk to the rest of the grating to evaluate the acoustic confinement of the modes. Our Simulations show a modulation of the emission in the meV range for a vertical displacement of 1 nm at the surface of the disk [7].

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P55

Cavity optomechanics with polymer-based multi-membrane structures

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Despite their application in multiple fields, ranging from quantum sensing to fundamental tests of quantum mechanics, conventional state-of-the-art cavity optomechanical experiments have been limited in their scaling towards systems with multiple resonators. 3D direct laser writing offers a new approach of fabricating multi-membrane structures that can be directly integrated into fiber Fabry-Perot cavities. Here, we experimentally demonstrate direct laser-written stacks of two or more coupled membranes – with normal-mode splittings of up to a MHz – interfaced by fiber cavities. We present finite element simulations for the optimization of the mechanical coupling and investigate the collective optomechanical coupling of multi-membrane stacks (with single-membrane vacuum optomechanical coupling strengths of $\sim 30\,\mathrm{kHz}$ [1]). We present our first experimental results and give an outlook on the scalability of the system to an even larger number of coupled mechanical oscillators. Aside from tests of fundamental properties of multimode optomechanical systems, applications for sensing or routing of vibration in acoustic metamaterials and circuits are envisaged.

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P56

Towards coherent detection of a single electron spin using Magnetic Resonance Force Microscopy

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Mesoscopic physics poses fundamental questions regarding the boundary between quantum mechanics and general relativity. In this context, realization of a massive superposition is considered to be a major hallmark. In Magnetic Resonance Force Microscopy (MRFM) experiments a cantilever with a magnetic tip is used to probe bulk and surface spins in materials. We perform MRFM at milliKelvin temperatures using a SQUID-based readout of the motion of the cantilever. Using Adiabatic Magnetic Cooling we are able to cool the cantilever to less than 20 mK [1] and achieve a detection volume of less than 40 nm^3 [2]. By further pushing the limits and eliminating loss mechanisms we aim to couple to smaller number of spins with the eventual goal of coupling coherently to a single electron spin. By improving cantilever-spin coupling, MRFM becomes an increasingly attractive platform for the study of mesoscopic physics.

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[2] de Wit, M., et al. "Feasibility of imaging in nuclear magnetic resonance force microscopy using Boltzmann polarization." Journal of Applied Physics 125.8 (2019).

P57

Towards large quantum delocalization over a CNT

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Is it possible to expand the quantum delocalization of a mechanical oscillator? This project aims to address this question by exploring the quantum delocalization of a suspended carbon nanotube (CNT) resonator. Specifically, we seek to achieve delocalization of the motion of a CNT resonator up to its diameter, on the nanometer scale. Quantum delocalization of a mechanical mode, defined by its zero-point motion, is an intrinsic property given by the Heisenberg uncertainty: $z_{zp} = \sqrt{\frac{\hbar}{2\omega_m m_{eff}}}$ Where ω_m is the frequency of the mode and m_{eff} the mass that contributes to the motion of the mode. Achieving nanometer-scale quantum superposition would represent a significant advancement over current state-of-the-art results [1].

Recent theoretical proposals suggest that utilizing a non-linear double well potential can enhance quantum superposition states [2]. While these proposals focus on levitated nanoparticles, our approach applies this concept to the eigenmode vibrations of a suspended CNT. To realize this goal, we propose the following steps:

- **Quantum control:** Achieve precise control over system parameters such as tunneling amplitude, detuning, and frequency.
- **Decoherence minimization:** Identify decoherence sources and minimize them.
- **Experimental protocol:** Implement the experimental protocol.

Our research group has experience in ground state cooling of mechanical resonators and in creating double well potentials to induce strong non-linearities [3][4]. This expertise positions us well to test the proposed theory. Currently, we are enhancing our control capabilities and understanding of decoherence effects.

We propose to couple a double quantum dot to the second flexural mode of a suspended CNT. The small effective mass of this mode, with a zero-point motion amplitude in the range of 10 pm, facilitates strong coupling. Achieving the ultrastrong coupling regime will enhance non-linearities in the mechanical potential, paving the way towards macroscopic quantum physics. This research could potentially allow us to test quantum collapse models and gravitational field theories, advancing our understanding of quantum mechanics at larger scales [5].

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P58

Design of lithium niobate on silicon surface acoustic waveguide for hybrid integrated phononic circuits

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Surface acoustic waves (SAWs) have proven to be effective in the control and manipulation of elementary excitations in condensed matter [1, 2]. In particular, SAWs have been efficiently used to interact with spin waves in magnetic thin film, which shows great potential for the realization of novel microwave devices [3]. In this work, the design of a lithium niobate on silicon (LNoSi) phononic waveguide is presented. The localization of the SAW propagation inside a phononic waveguide will enhance the coupling to hybrid quantum mechanical systems, such as spin waves. Furthermore, the used LNoSi platform offers many other advantages such as high piezoelectric coupling, the capability of photonic waveguiding in addition to the phononic modes, as well as the possibility of non-linear optics. The fundamental phononic waveguide modes determined by the waveguide geometry will be simulated using finite element methods and the phononic dispersion will be studied by varying the waveguide width and height.

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[2] D. Bühler, M. Weiß et al., Nat. Commun. 13:6998 (2022)
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P59

Density-Modulated Phononic-Engineered Membranes for Room-Temperature Quantum Optomechanics

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Phononic crystal engineering is a powerful technique for enhancing the coherence of nanomechanical resonators. It facilitates the isolation of a single mode within a bandgap, a critical feature for optomechanical experiments. This isolated mode is acoustically shielded from the substrate, resulting in exceptionally high coherence. By periodically modulating the density (and consequently the speed of sound) across the membrane, we introduce an array of very small pillars, effectively minimizing additional mechanical losses and achieving quality factors around 10^9 at room temperature.
The innovation in this study lies in our new fabrication technique, which allows us to produce pillars from stoichiometric Si_3N_4. This is a significant advancement for conducting experiments with these membranes, as pillars made from other materials can lead to optical absorption and thermal instabilities. These membranes are often intended for use in Fabry-Perot cavities, where they are exposed to substantial optical power. Moreover, our fabrication process boasts a near-unity yield due to the immaculate quality of the deposited thin film. Studies on the distribution of quality factor values indicate that the primary factor affecting quality is the presence of tiny contaminants on the samples, making our fabrication process highly reproducible.
This progress is crucial for advancing towards the feedback cooling of these devices to their quantum ground state, a long-standing goal in the field of cavity optomechanics. Currently, the residual phonon occupancy of our devices is already in the single digits, and it can be further reduced with a better understanding of the experimental setup, technical noises, and small improvements in designing the mechanical resonators.

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P60

Optimizing an Integrated Photonic Racetrack Resonator for Optomechanical Synchronization

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In the field of optomechanics, light is used to alter the dynamics of mechanical resonators. Optomechanical synchronization [1] will be an important tool in fields like precision time-keeping, sensing, and quantum technologies. Towards this goal, we develop a photonic integrated optomechanical device consisting of a silicon nitride racetrack cavity with partly suspended waveguide that can vibrate freely. A second beam is added to improve the optomechanical coupling. This beam has a one-dimensional photonic crystal to prevent the light from leaking from the racetrack.

We observe four mechanical modes from the two beams: two out-of-plane (OOP) modes and two in-plane (IP) modes. The OOP are at $\sim 2.2\,\mathrm{MHz}$, but show small signal. The two IP modes are more strongly coupled. The photonic crystal beam (PhC) mode is at $\sim 2.45\,\mathrm{MHz}$, and the IP mode of the racetrack is at $\sim 2.55\,\mathrm{MHz}$; their quality factors are $\sim 4 \times 10^4$. In order to synchronize the modes, the resonance frequencies have to match. To overcome the frequency difference in the IP modes, we employ our geometric tuning technique [2] and use a predisplaced beam instead of a straight waveguide. The more it is displaced, the more the frequency shifts towards the PhC beam. The remaining frequency distance of a few kHz can be tuned by the laser power. As the light propagates in the predisplaced beam and only past the PhC beam, the predisplaced beam resonance shifts further than the photonic crystal one as a function of power due to thermal effects. We show that we can shift them to the same frequency this way. To synchronize them with optomechanical backaction, we also need to enhance the optical cavity. To improve the optical quality of the racetrack, we modify the transition from supported to suspended parts. There, the optical mode profile changes, leading to loss [3]. One approach is widening the waveguide at the transition to confine the optical mode more, and the second one is modifying the etching window to gradually change the optical mode shape. Both lead to the desired improved optical quality factor. Currently, we are investigating their impact on the mechanics. We believe that, in the next generation of devices with combined transition regions and the predisplaced beam, we can synchronize the racetrack and photonic crystal beam.

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