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Extended Abstracts

Track 5: Optomechanics

Phononics 2011: First International Conference on Phononic Crystals, Metamaterials and Optomechanics

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Phoxonic Crystals: a Review

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Abstract: Periodically structured materials exhibiting simultaneous photonic and phononic band gaps offer unprecedented ways to tailor photon–phonon interactions. A review of the works reported on these materials, sometimes termed "phoxonic crystals", is presented before highlighting theoretical and experimental results demonstrating phoxonic band gaps in structures relying on guided elastic waves.

The last two decades have witnessed a considerable breakthrough in the field of management of wave propagation through the fabrication and use of materials exhibiting periodical micro- or nano-structures. If it remains clear that photonic crystals have been at the forefront of this research effort, their elastic counterparts, phononic crystals, have also arisen significant interest. From an exploratory point of view, phononic crystals open the possibility to manage elastic waves but also high frequency phonon propagation and dispersion. The two types of structures rest upon the same underlying physical principle: taking advantage of the scattering phenomena occurring in a periodical composite material to give rise to frequency bands in which wave propagation is completely forbidden.

Still, photonic and phononic crystals have been studied in a quite independent fashion for the greatest part of their young existence. It is only a few years ago, with the pioneering experience of Trigo *et al.* in 2002[1], that the community started to realize that the strong velocity mismatch between electromagnetic and elastic waves actually implied that optical and elastic waves could exhibit the same wavelength and hence coexist in a same volume. Trigo and his co-workers reported on a one-dimensional doubly-resonant cavity ensuring the confinement of photons and Raman-generated high frequency phonons. The subsequent works of P. Santos' group in the Paul Drude Institut, Berlin, introduced still greater latitude in the management of the interaction by using surface acoustic waves to modulate the properties of light propagating in 1D semiconductor superlattices[2]. If these last two works obviously deserve to be mentioned, their limitations to 1D structures do not allow to make the most out of the photonic or phononic crystal concepts, as these latter do not offer the possibility to tune light or sound dispersion relations and hence, for instance, do not permit to toy with slow wave effects. P. Russell *et al*. proposed sensibly at the same period the idea to extend these highly confined acousto-optical interactions to a bi-dimensional configuration by showing experimentally that elastic waves could be confined in defect modes of a photonic fibre preform with a lattice parameter of some tens of microns[3]. Theoretical works by V. Laude *et al.* proposed an actual microstructured optical fiber geometry that would allow for simultaneous optical and elastic waveguiding[4]. None of these groups did however proceed at the time to any experimental demonstration of genuine elastic waveguiding in an on-scale "phoxonic" crystal fibre (the "x" referring indifferently to "t" or "n"), and hence did not report on the corresponding acousto-optical interactions, although control of guided acoustic waves or of acoustic resonances generated *via* nonlinear optical effects (e.g. Brillouin scattering or electrostriction) was reported[5,6,7]. It is only in 2006 that E. L. Thomas' group at the Massachusetts Institute of Technology theoretically designed a crystal blind to electromagnetic waves with wavelengths of several hundreds of nanometers and deaf to sound at similar wavelengths[8]. They also reported on the simultaneous localisation of photons and phonons in a cavity managed in the designed 2D phoXonic crystal without, however, considering interactions between sound and light. All these pioneering works now stand as amongst the starting points of a growing field dedicated to photon-

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phonon interactions in periodically structured materials, that encompasses traditional photonic and phononic band gaps as well as the more recently introduced "opto-mechanical" structures[9].

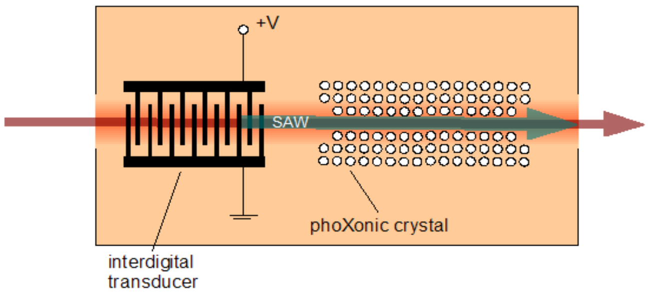

Figure 1 Schematic of a phoxonic waveguide, allowing for a joint confinement of sound and light. An integrated optics waveguide is used to channel the optical wave in the crystal while the elastic waves consists of surface-guided waves, generated by an interdigital transducer. The periodical structure should exhibit a simultaneous photonic and phononic band gap that would allow for a joint guidance of both types of waves, possibly involving slow-light and slow-sound effects.

This paper will mostly focus on phoxonic crystals: a significant series of works has indeed been dedicated to mostly theoretical, sometimes experimental, investigations of simultaneous photonic and phononic band gap materials and on the acousto-optical interaction phenomena likely to occur in such artificial media.

We will hence present a brief review of the relevant literature, including the works reported on planar structures but also on acousto-optical interactions in microstructured optical fibers. We will then more specifically highlight some results obtained in the case of potential phoxonic crystals involving guided optical and elastic waves in materials particularly relevant in integrated optics and acoustics, namely silicon[10,11,12] and lithium niobate[13]. In addition to band diagram calculations in the usual bi-dimensional case, we will present some theoretical and (possibly) experimental works showing that phoxonic band gaps can be observed in periodically structured materials in which elastic waveguiding is preliminary ensured by propagation in a slab or through the use of surface acoustic waves, in the case of a semi-infinite medium. Throwing evidence of a phoxonic band gap obviously goes through the experimental demonstration of phononic band gaps in the hypersonic frequency regime, which is an essential, but non trivial step towards a joint confinement of sound and light, and we will hence provide with additional details regarding the fabrication and characterization of phononic crystals exhibiting pitches at the micro-scale.

This work has been supported by the French National Agency (Agence Nationale de la Recherche – ANR) in the frame of the phoXcry project (n°ANR-09-NANO-004) and by the European Commission Seventh Framework Programme (FP7) under grant agreement n°233883 (TAILPHOX).

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Forward Stimulated Light Scattering by Acoustic Resonances in Photonic Crystal Fiber

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Abstract: Forward stimulated light scattering by transverse acoustic resonances tightly trapped in a photonic crystal fiber core is a recently reported nonlinear-optical optoacoustic phenomenon. The principles and characteristics of the scattering are described. Some potential applications are also discussed.

Photonic crystal fibers (PCFs) with a micron-sized glass core and a high air-filling fraction allow tight confinement of both acoustic phonons and light in the tiny core. Thanks to resulting strong optoacoustic interactions, forward stimulated light scattering by GHz acoustic resonances (ARs) tightly trapped in a PCF core has been recently demonstrated at modest optical powers [1,2]. When pump (frequency f_P) and Stokes (frequency f_S) waves are co-launched together into the fiber, their frequency difference being tuned to the AR frequency ($f_{AR} = f_P - f_S$), a coherent AR is efficiently generated via electrostriction, which in turn transfers power from pump to Stokes. In the dispersion diagram, the phase matching point corresponding to the driven AR is close to cut-off of the higher-order acoustic mode (where the acoustic displacement is purely in the transverse plane). Since the acoustic dispersion around the phase matching point is almost flat, forward stimulated scattering is strongly Raman-like, i.e., the frequency shift is independent of the pump laser frequency [Figure 1(a)], in strong contrast to conventional (backward) stimulated Brillouin scattering (SBS) [Figure 1(b)] [3,4].

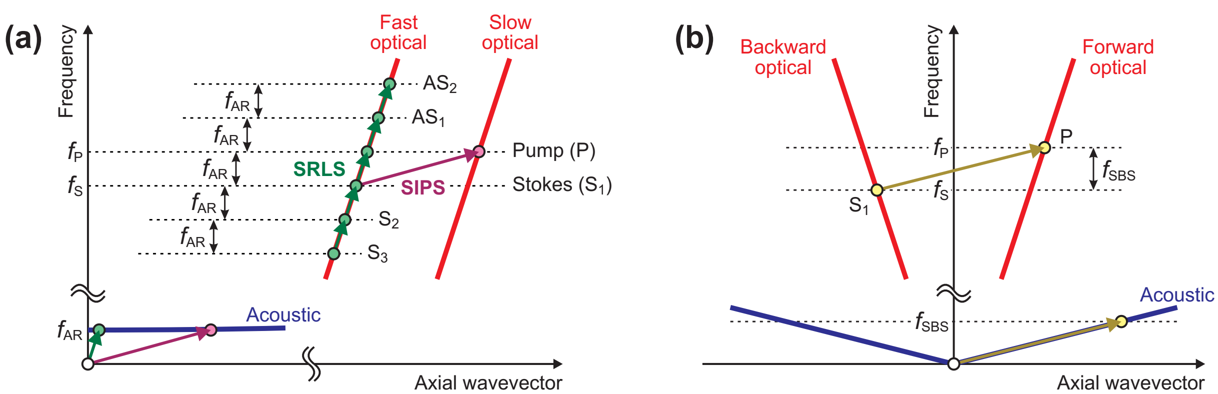

Figure 1 Dispersion diagrams (not to scale) for the optical and acoustic modes guided in a fiber, comparing forward stimulated Raman-like scattering (SRLS) and stimulated inter-polarization scattering (SIPS) (a) to conventional (backward) stimulated Brillouin scattering (SBS) (b). Circles and arrows represent phase-matched optical and acoustic waves. P: pump, S: Stokes, AS: anti-Stokes.

Two types of forward stimulated scattering have been investigated: forward stimulated Raman-like scattering (SRLS) between pump and Stokes waves in the same optical mode [1], and forward stimulated inter-polarization scattering (SIPS) between orthogonally polarized pump and Stokes waves [2]. In forward SRLS, the driven AR is automatically phase-matched with successive Stokes and anti-Stokes orders, the frequency spacing between them being constant. As a result, an equidistant comb of higher-order Stokes and anti-Stokes waves can be generated via cascaded coherent Stokes and anti-Stokes scattering at high optical powers [Figure 2(b)]. This simultaneous generation of many sidebands can be useful in applications such as frequency comb generation, pulse synthesis and laser mode-locking. On the other

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hand, in forward SIPS, the driven AR does not have the correct axial wavevector to cause scattering into higher-order Stokes and anti-Stokes waves. Therefore, the SIPS process transfers pump power only to the Stokes wave, generation of higher-order sidebands being highly suppressed [Figure 2(c)], which is similar to the case of conventional SBS. Since the orthogonally polarized pump and Stokes waves can be easily combined and separated out by using simple polarization optics, forward SIPS can be useful in applications such as variable optical attenuation/amplification, optical signal processing and optical sensing.

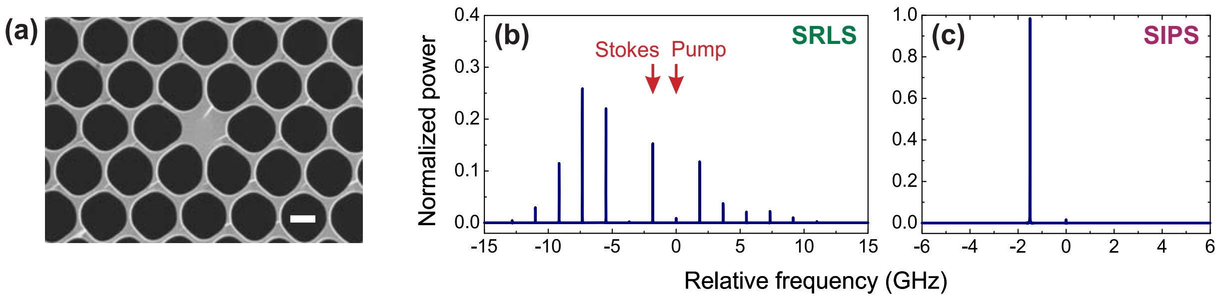

Figure 2 (a) Scanning electron micrograph of a PCF with the core diameter of 1.8 µm. The white horizontal bar corresponds to 1 µm. (b) Typical output spectrum as co-polarized pump and Stokes waves with the same optical power are launched into the PCF. The red downward-pointing arrows indicate the two incident optical waves. (c) Typical output spectrum as orthogonally-polarized pump and Stokes waves with the same optical power are coupled into the different polarization eigenmodes of the PCF.

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Fundamental Limits of Transduction Efficiency and Bandwidth in Nano-Optomechanics

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Abstract: Through systematic examination of material and topological degrees of freedom in nano-optomechanical systems, we identify the fundamental barriers and opportunities for the creation of large photon-phonon coupling.

Coherent phonon generation in dielectric waveguides and media was demonstrated some four decades ago via laser induced electrostrictive forces [1,2]. With the advent of nanophotonics, nano-enhanced radiation pressure from highly confined modes has been shown to produce efficient phonon generation at low powers with chip scale-devices [3]. Optomechanical photon-phonon coupling of this form has caught the attention of many since nanoscale light confinement produced remarkably large forces within miniscule volumes [3-5], and it is known to produce high frequency phonon transduction [3-5]. Furthermore, the unique range of length-scales and time-scales accessible with such nano-scale systems show the potential for benefit to numerous RF and signal processing applications, fuelling the investigation of such physical mechanism for use in high frequency signal transduction. However, without a unified framework through which optical forces and optomechanical parametric processes can be understood, it is difficult to determine whether technologically relevant data rates can be achieved through use of such phenomena.

In this paper, we develop a unified framework through which optomechanical transduction can be understood in virtually all optomechanical systems, elucidating the bandwidth and efficiency limitations of such technologies. Through examination of material and geometric degrees of freedom, we develop scaling laws which describe the magnitude of optical forces produced by electrostriction and radiation pressure in any optomechanical system [4,5]. Using these scaling laws, we explore the practical upper-bounds of light-induced forces, and identify materials systems with favourable characteristics for optomechanical transduction. Through generalized treatment of photon-phonon coupling, a fundamental scaling law that governs the efficiency and bandwidth limitations *of all radiation pressure driven optomechanical devices* can be derived, enabling the comparison of all optomechanical systems in a unified framework. With this theory, we show that the maximum transduction bandwidth and phononic power output (i.e. photon-phonon coupling) of any optomechanical device is determined by: (1) the maximum possible magnitude of radiation pressure, (2) the device dimension, and (3) the effective mechanical impedance of the system.

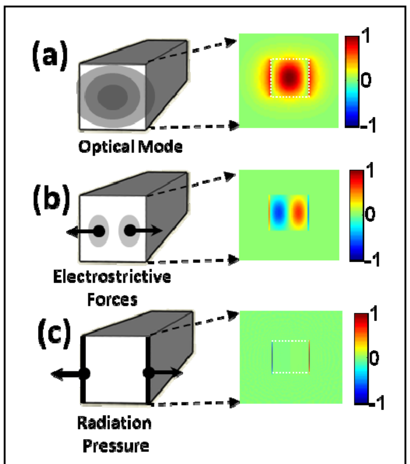

Figure 1. (a) E_x field component of TE-like mode of silicon nanowire. (b) and (c) are the x-directed force densities produced by electrostriction and radiation pressure respectively.

Simply stated, the challenges associated with broadband stimulated phonon emission in optomechanical systems arise from: (1) *limited optical forces,* and (2) the high *mechanical impedance of naturally occurring media*. One can show the maximum driving force produced by light within any optomechanical system is fundamentally limited by the optical power and energy density limitations of optical materials. However, the maximum obtainable force is highly dependent on the physical mechanism which produces the optical forces. Within dielectric media, optical forces generally arise from either (1) radiation pressure and (2) electrostrictively induced forces, both of which have historically played a very important role in the understanding of transduction with light [1-3]. In contrast to radia-

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tion pressure, which originates from the momentum transfer from scattered photons at dielectric boundaries, electrostriction is derived from the strain-dependence of dielectric permittivity and such forces are present in all dielectric media [4,5]. For example force distributions see Fig. 1.

The fundamental connection between the maximum optical driving force and the energy density handling of materials becomes apparent once it is understood that the *exact form of the radiation pressure induced optical force density within any dielectric medium* can be expressed as [5]:

$$F_j^{rp} = \partial_i T_{ij} = \tfrac{1}{2}\varepsilon_o \,|\mathbf{E}(\mathbf{r})|^2\, \partial_j \varepsilon(\mathbf{r}). \qquad (1)$$

Here, T_{ij} is the Maxwell stress, ε_o is the free space permeability, $\mathbf{E}(\mathbf{r})$ is the electric field distribution, and $\partial_j \varepsilon(\mathbf{r})$ is the gradient of the dielectric distribution. Clearly, large dielectric gradients (i.e. high index-contrast) benefit the production of large optical forces, and optical forces occur only at dielectric surfaces in step-index structures. More importantly, optical force density is fundamentally limited by the achievable electromagnetic energy density $\frac{1}{2}\varepsilon\,|\mathbf{E}|^2$. Energy density is typically bound to 10^4 J/m^3 in high-index materials, such as silicon, before the onset of appreciable two-photon absorption and the associated heating which limit practically achievable powers. Consequently radiation pressure is fundamentally restricted to a maximum value of $\sim 10^4$ N/m^2, which we term the “Radiation Pressure Limit". Bear in mind that the “Radiation Pressure Limit " is only attainable by *optimally confined modes* which interact *very* strongly with the boundaries of the system [4,5].

Stimulated phonon emission, of the type recently reported utilizes such forces to produce stimulated phonon emission. In its most basic form, optomechanically mediated stimulated phonon emission is a third-order nonlinear process through which the interference between optical waves of two different frequencies (ω_p, ω_s) produces a time-harmonically modulated optical driving force of frequency, $\Omega = (\omega_p - \omega_s)$. In describing stimulated phonon generation, the optical powers (particle fluxes) P_p (Φ_p), P_s (Φ_s), corresponding to an optical pump (ω_p) and a Stokes waves (ω_s) are coupled by way of acoustic phonons of frequency $\Omega = (\omega_p - \omega_s)$ and power (particle flux) P_Ω (Φ_Ω). From the time-varying optical force distributions, the generated elastic wave power can be computed the parametric conversion for both photons and phonons.

Through generalized treatment, we show that a fundamental scaling law that governs the efficiency and bandwidth limitations *of all radiation pressure driven optomechanical devices* can be derived, enabling the comparison of all optomechanical systems in a unified framework. Within the constraints posed by the Radiation Pressure Limit, our scaling law reveals that the maximum quantum efficiency obtained via a radiation pressure mediated process within a unit length (Δz) of guided wave optomechanical interaction is of the form,

$$\eta^{\max} = \frac{d\Phi_\Omega}{dz}\frac{\Delta z}{\Phi_p} \cong \alpha \cdot \frac{u_{em}^{\max}}{c}\frac{\omega_s}{\Omega} \cdot \frac{(n_g - n_g)^2}{n_g \cdot Z(\Omega)} \Delta z \qquad (2)$$

Here Φ_p (Φ_Ω) is the incident (generated) photon (phonon) flux, $Z(\Omega)$ is the frequency dependent mechanical impedance of the body into which the phonon is being transduced, and α is a factor that depends weakly on geometry. Within nanoscale waveguides and cavities, u_{em}^{max} can be easily obtained at miliwatt laser powers. Thus, for energy densities corresponding to u_{em}^{max}, or the “Radiation Pressure Limit,” the only means by which transduction efficiency can be increased is through: (1) an increase in modal dispersion $(n_g - n_p)$, (2) a decrease in mechanical impedance $Z(\Omega)$, or (3) an increase in interaction length, Δz. The role of dispersion $(n_g - n_p)$, is derived from its fundamental connection to radiation pressure [5]. While Eq. 2 describes a fundamental limit associated with radiation pressure induced parametric processes.

Through this talk, we describe the energy density limitations posed by various materials for the generation of both electrostrictive forces and radiation pressure. Within this framework, and by use of the above scaling law, we analyze several concrete optomechanical systems to illustrate the interplay between transduction efficiency, bandwidth, and size.

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Mechanical Transduction in Periodic Media

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Abstract: The possibility of increasing mechanical transduction efficiencies via periodic patterning of the material density is investigated. A 2D simulation suggesting low mechanical impedance over a relatively large bandwidths is presented.

Recently there has been a surge in interest in acoustic meta-materials. In analogy to optical meta-materials, much of the interest is centered on the possibility of periodically patterning materials to create negative effective densities and moduli, with possible applications in superlensing, cloaking and liquid crystal sensing[1-4]. Here, we examine a different possibility: that periodically patterned materials may also allow for dramatic increases in the mechanical transduction efficiency of signals into and out of the mechanical domain.

Mechanical transduction is of primary importance in the fields of acousto-optics, electro-mechanics, opto-mechanics and others. In general, one would like to transfer energy efficiently from one domain to another over a given bandwidth. The usual method to increase transduction efficiency is by using resonant phenomena, which limits the usable band-width of the transducer. An example is the use of electrical tank circuits in many commercially available acousto-optic modulators. Here we examine a technique to increase the mechanical transduction efficiency by modifying the mechanical impedance of the material via periodic patterning, offering the potential for broadband, coherent mechanical transduction.

When a time-harmonic force F is applied uniformly to the boundary of a uniform elastic medium of area A, the resulting time-averaged harmonic power P_m within the medium is inversely proportional to a quantity defined as the specific mechanical impedance Z:

$$P_m = \frac{F^2}{2AZ} \tag{1}$$

In media with uniform density ρ, Z is simply the ratio of the restoring pressure K (the effective bulk modulus) to the phase velocity v_p of the mechanical waves: $Z_0 = K/v_p$. Identifying the phase velocity v_p of the mechanical waves as $\sqrt{K/\rho}$, we may write the mechanical impedance as

$$Z_0 = \rho_{eff} v_p \tag{2}$$

When the material density is not uniform, however, this definition requires modification. Frequency-dependent mechanical reflection and refraction occur, giving rise to frequency-dependent phase velocities (i.e mechanical dispersion). For normal, linear mechanical dispersion, the mechanical energy propagates at the *group* velocity v_g, which can be much lower than v_p. As a result, the mechanical energy density within the material can be very high, leading to large harmonic displacements. Hence, even though the average power flux through the material may not change appreciably, the time-averaged harmonic power $P_m$can be dramatically increased. A more general expression for the mechanical impedance is

$$Z = \rho_{eff} v_g \tag{3}$$

where ρ_{eff} is the effective density of the material (i.e. spatially weighted according to the amplitude of the mechanical waves, analogous to an effective index). In the context of mechanical transduction, this simple result leads to an important conclusion: transduction mechanisms that scale with displacement amplitude can be made dramatically more efficient by lowering the group velocity and matching the forcing function to the resulting displacement field.

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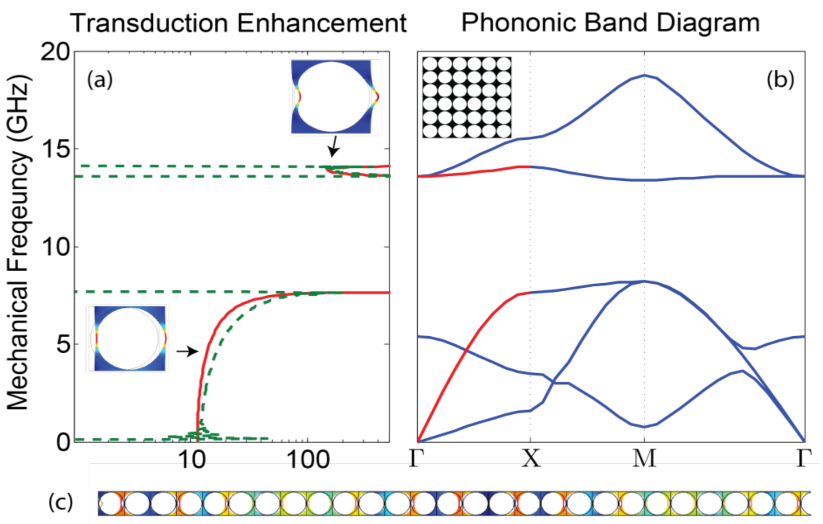

Figure 1 Mechanical transduction enhancement in 2D phononic crystals. (a) Transduction enhancement Z/Z_0 calculated from dispersion diagram (solid red) and time-harmonic 1-D forcing (dashed green). Insets show displacement profile for a single unit cell with momentum $\vec{k} = \hat{x}a/2$ (b) Mechanical dispersion in a 2d rectangular lattice of holes with a lattice constant $a = 250$ nm and hole radius $r/a = 0.48$. Longitudinal modes along the $\hat{x}$ direction are highlighted in red, as those are the modes preferentially excited in the time-harmonic forcing model. The inset shows the geometry of a 6x6 array of unit cells simulated. (c) Displacement field profile for time-harmonic forcing simulation in which a uniform harmonic force is applied to the leftmost boundary. After 20 lattice periods, isotropic loss is phenomenologically added, and increases quadratically along the $\hat{x}$ direction. The material density $\rho = 3100\ \mathrm{kg/m^3}$, Young's modulus $E = 250$ GPa, and Poisson ratio $\eta = 0.23$ are chosen to be similar to that of stoichiometric silicon nitride for all simulations.

As an illustrative numerical example, consider a two-dimensional phononic crystal consisting of a square lattice of circular holes, as shown in Fig. 1. Figure 1(a) shows the transduction enhancement Z/Z_0 calculated in two ways. The dashed green line is calculated by simulating a uniform time-harmonic forcing function applied to an array of unit cells with appropriate boundary conditions to excite longitudinal (compression) modes. The resulting mechanical power within the medium is then calculated and divided by the same quantity for the case with no patterning (i.e. $r = 0$) The low frequency oscillations result from the inability to simulate an infinitely long structure (i.e. the simulation behaves badly for wavelengths longer than the structure). The solid red line is calculated from the mechanical dispersion using a mechanical eigenmode solver for a unit cell, and then inserting the derived effective density and group velocity into Eq. (3). The small discrepancy between the two curves may be attributed to the fact that the forcing function was not perfectly matched to the resonant displacement field. Only the bands corresponding to longitudinal motion are used to generate the curves. Figure 1(b) shows the mechanical band diagram calculated from a single unit cell of the structure. The derivative of the longitudinal modes (highlighted in red) is used to calculate the mechanical impedance via Eq. (3). Figure 1(c) shows are representative displacement amplitude in a longitudinal array of cells used in the time-harmonic simulation. Periodic boundary conditions are used in the $\hat{y}$ direction (i.e. $k_y = 0$) to ensure elastic wave propagation along the $\hat{x}$ direction, and isotropic phenomenological loss is quadratically added beginning after 20 unit cells to ensure the absence of reflections and accurately simulate the power flow.

While these simulations are two-dimensional, they point to the possibility using effective phononic media as a means to enhance transduction efficiencies over relatively broad bandwidths. The result may find applications in electro-optic and acousto-optic devices, and optomechanical devices. Acousto-optic modulators, for example, rely on resonant electro-mechanical actuation and therefore operate over very limited bandwidths. Similarly, cavity based optomechanical transduction[5,6] relies on resonant mechanical and optical confinement, and faces bandwidth limitations.

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Integrated Transduction and Active Manipulation Methods for Nanoelectromechanical Systems

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Abstract: This talk will discuss integrated NEMS transduction schemes that have been developed by my research group. Methods for achieving active control and manipulation of nanomechanical motion will be also presented.

In its acronym NEMS inherited an "S" (systems) from MEMS. However, so far the impacts of nanosystems technology remain on the device or component level. Complex nanosystems consisting of integrated sensors, actuators and signal processing circuitry are still beyond our reach. Major obstacles remain in the development of suitable actuation and transduction methods that perform efficiently at nanoscale and under non-laboratory setting. From system control point of view, it is also highly desirable nanomechanical motion can be coherently manipulated, ideally not only in frequency domain but also in real time so that the large bandwidth of nanomechanical systems can be fully utilized.

This presentation first provides an overview of NEMS transduction schemes that have been developed by my research group, and then aims at establishing essential transduction criteria for building fully integrated nanoelectromechanical systems. On the component level, emphasis for NEMS transduction is focused on attaining high actuation efficiency, high sensitivity, and wide bandwidth. On the system level, I will address the more stringent requirements of NEMS integration in transduction and actuation, such as low power consumption, high dynamic range, low insertion loss, device level isolation, the ability to fan out, cascade, and fan in, as well as transduction robustness against environmental change.

In this abstract we use silicon optomechanics as a specific example platform to illustrated integrated actuation and sensing. In this platform, the actuation is based upon gradient optical force – which is generated through evanescent coupling of light in a waveguide to an adjacent structure. [1-4] Microscopically, it results from interactions between dynamic dipoles induced by the propagating light field. This optomechanical interaction not only provide efficient actuation, but also enable very sensitive detection of mechanical motion of the devices are embedded in an interferometer configuration or cavity configuration; in the latter case the transduction efficiencies (both actuation and detection) are enhanced by the cavity finesse.

Nanophotonic waveguides can manipulate light in multiple paths with very low loss and low crosstalk. Therefore our scheme is capable of parallel and serial integration of a multitude of NEMS devices in a single photonic circuit. Figure 1 illustrates the concept of parallel multiplexed cantilever arrays (The same principle is also applicable to beams). The input and output structures are designed to be 1×N and N×1 splitter and combiners, diverting the light to N independent cantilever pairs. Fig. 2a shows the FDTD simulation result of such a design. The length of the ten cantilevers varies from 2.5 to 3.5 μm. Ten resonance peaks, corresponding to the thermomechanical resonance of each cantilever, can be clearly observed as shown in Fig. 1c. The center resonance frequencies of the cantilevers

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vary from 11 MHz to 21 MHz, showing the linear dependence with the inverse square of the cantilever lengths, as expected from the simple beam theory. Given the high signal to noise ratio and the minimum background cross talk (Fig. 1c), hundreds of mechanical resonators can be multiplexed on the photonic bus with resonance frequencies designed at fixed intervals. Therefore individual cantilever sensors can be addressed by their resonant frequencies.

This presentation will further explore examples of achieving real-time control of nanomechanical motion, in both electromechanical devices and optomechanical devices.

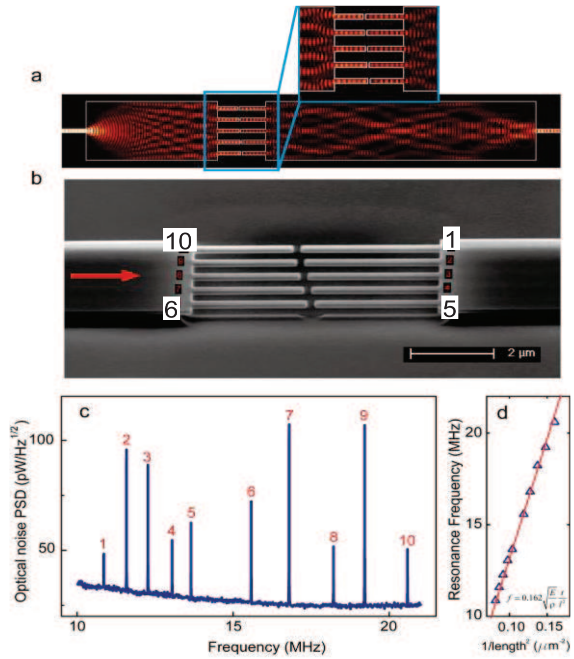

FIG. 1. Multiplexed integration of a ten-cantilever array in a photonic circuit. All the resonances are simultaneously detected at expected frequencies.

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Strong Optomechanical Coupling in Slot-type Photonic Crystal Cavities

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Abstract: Strong dispersive optomechanical coupling of an air-slot mode-gap photonic crystal cavity is demonstrated. The zero-point motion coupling rate can be as high as 2.56MHz. Optical and 10s of MHz mechanical frequency spectra are shown experimentally, supported by theory and numerical models.

The effects of optical forces in various mechanical and optical structures and systems have attracted intense and increasing interest for investigation. Recent studies covering a vast span of fundamental physics and derived applications. Photonic crystals nanocavity is a good candidate to realize the coupling since it exhibits an extremely high Q with a very small cavity volume[1]. Here we illustrate the properties of strong coupling of an air-slot photonic crystal cavity. Both numerical analysis and experimentally observation are illustrated.

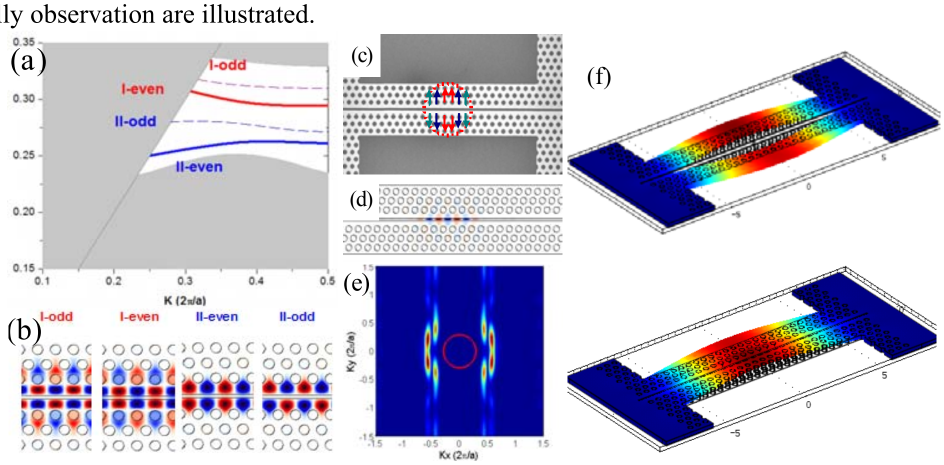

Figure 1 (**a**) Band structure of base W1.2 waveguide. (**b**) Electrical field distribution of the four waveguide mode at the mode edge in the band gap. (**c**) SEM image of the fabricated sample. The cavity region is indicated by the dashed circle and the directions of the hole shifting in the cavity are indicated by the arrows. (**d**) Optical cavity field distribution. (**e**) The spatial Fourier-transform of the cavity field. (**f**) the mechanical field distribution of the first in-plane differential and common mode pair.

The photonic crystal (PhC) cavity considered here has a similar design with that in Ref. 2-4. W1.2 waveguide is used. The PhC lattice geometrical parameters are a=450nm and r=0.29a. The slot-width is 80 nm which is narrow to achieve large optical intensity in the air slot[2-4]. The cavities are fabricated using a Silicon-On-Insulator wafer with thickness t=250 nm. There are only three layers of holes on each side of the waveguide. The band structure of this W1.2 waveguide is shown in Figure 1 (a). The electrical fields of the waveguide modes are shown in Figure 1 (b). The I-even mode is engineered to form a cavity indicated by the red dashed circle in Figure 1 (c) which is the SEM of a fabricated sample. The central holes are shifted by 10 nm, 20/3 nm, 10/3 nm respectively in the same way as in Ref. 2-4. Three-dimensional FDTD simulations show that the optical quality factor Q can be $>1.3\times10^6$. The modal volume is $\sim0.05(\lambda/n_{\mathrm{air}})^3$ with the maximum square electrical field in the center of the cavity as is shown in Figure 1(d). The two-dimensional spatial Fourier-transform of the electrical field is shown in Figure 1 (e) with red circle indicating the light corn. It shows that almost all the spatial components of the cavity field are well confined in the cavity. To study the mechanical properties, the finite-element-method is used. Figure 1 (f) shows the mechanical displacement field of the first in-plane differential mode and common mode. According to the symmetry selection rule, only the differential mechanical mode can have a strong optomechanical coupling. The corresponding mechanical

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frequency is 65.4 MHz. The effective volume and the effective mass for this mode are 3.14 μm^3 and 7.31 pg respectively. Mechanical quality factors are estimated to be ~10^4 based on the theory of thermoelasticity damping in a vibrating beam. The length of this cavity is larger than the one in Ref.4. The optical Q is higher. The mechanical frequency is much lower.

The optomechanical coupling rate gom is defined as $g_{om}=d\omega/d\alpha$, which represents the differential frequency shift of the cavity resonance with the mechanical displacement[5]. Using perturbation theory[6], we can calculate the coupling rate. The calculated $g_{om}/2\pi$=574 GHz/nm, the corresponding zero-point motion optomechanical coupling rate ($g_{om,zm}/2\pi$) is 2.56MHz.

Optomechanical coupling provides an optical contribution to the stiffness of the spring-mass system. The corresponding change in spring constant leads to a frequency shift relative to the unperturbed mechanical oscillator eigenfrequency. The non-adiabatic contribution in coupled equations is proportional to the velocity of the spring-mass system. The optical gradient force induced damping rate modifies the intrinsic mechanical resonator loss rate Γ_m, yielding an effective damping rate. With this classical model, the laser introduces a damping without introducing a modified Langevin force. This is a key feature and allows the enhanced damping to reduce the mechanical oscillator temperature, yielding as a final effective temperature T_{eff} for the mechanical mode under consideration: $T_{eff} \cong \left(\Gamma_m/\Gamma_{eff}\right)T_R$. To characterize the mechanical properties of the oscillator, the power spectrum density of the optical transmission is usually needed.

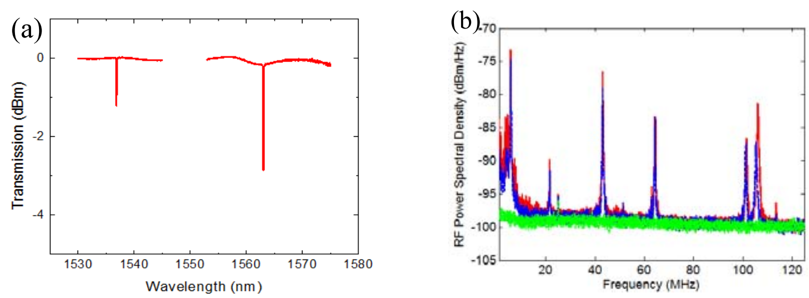

Figure 2 (**a**) Normalized optical transmission showing the intrinsic Qs for the device with resonance at 1536.65nm and 1562.75nm are 1.54×10^5 and 1.68×10^5 respectively. (**b**) RF PSD of the fiber-taper transmission for the device resonance at 1562.75nm. The detuning is set to maximize the PSD amplitude for the red line. The blue line is for a slight different detuning, while the green line indicates the noise floor of our measurements.

The devices we fabricated are characterized using a fiber-taper probe. A tunable external cavity diode laser is employed. The transmission spectrums for two adjacent devices are shown in Figure 2 (a). The two devices have different hole radius. The resonance shifts ~30nm. The intrinsic optical Qs of these two cavities are all higher than 1.5×10^5 with loaded Qs about 9×10^4. The radio frequency (RF) power spectral densities (PSD) of the optical transmission are measured by using a low-noise fast detector and a RF spectrometer. The detuning is tuned (close to the half-line width detuning) to get the maximum PSD signal as shown by the red curve in Figure 2 (b). At another detuning, we found that there are slight shift of resonances with smaller PSD peaks. The noise floor is shown by the green curve. The peaks at ~65MHz indicate the expected mechanical modes. The other peaks indicate either flexural modes or higher order in-plane and out-of-plan mechanical modes.

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Cavity Quantum Optomechanics

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Abstract: The overarching research objective of cavity quantum optomechanics is to investigate quantum effects of micro- and nanoscale systems and their implications for the foundations and applications of quantum physics. Our ultimate goal is to gain access to a completely new parameter regime for experimental physics with respect to both size and complexity.

Cavity optomechanics has recently emerged as one of the most dynamic fields in experimental physics. In this presentation I will outline the fascinating perspectives of this area of research and present proof-of-concept experiments performed using high-reflectivity low-loss mechanical resonators coupled to high-finesse cryogenic optical cavities. Along the path towards the ultimate goal of macroscopic quantum state preparation, our research has led to a number of interesting technological applications including the development of a numerical solver for support-mediated losses in mechanical resonators [1] as well as new strategies for the development of low-noise multilayer mirrors for high performance optical reference cavities.

The idea that the properties of a mechanical object can be modified by radiation pressure forces in an optical cavity goes back to the pioneering work of Braginsky [2]. In essence, the response of an optical cavity to the motion of a mechanical object leads to forces that both depend on the position of the mechanics and are retarded in time (due to the finite cavity lifetime). For sufficiently strong forces, this results in a modification of the mechanical susceptibility and is the underlying mechanism for optical control over mechanical degrees of freedom and vice versa. In combination with quantum optics, such interactions allow for the realization of *quantum* control of mechanical resonators. The consequences of this realization are wide ranging, impacting such diverse fields as mechanical sensing, by enabling resolution at or even beyond the quantum limit [3], and quantum information, where optomechanical devices may act as transducers for otherwise incompatible quantum systems [4]. From a fundamental point of view, preparing superposition states of massive objects (containing $\sim 10^{20}$ atoms) provides a new avenue for novel tests of macroscopic quantum physics [5], where spatially distinct states of mechanical quantum systems could serve as a paradigm example of Schrödinger's cat.

Approaching and eventually entering the quantum regime of mechanical resonators through optomechanical interactions essentially requires the following three conditions to be fulfilled: (1) sideband-resolved operation [6] in which the cavity amplitude decay rate is small with respect to the mechanical frequency (note that recent schemes have been proposed alleviating this requirement), (2) both an ultra-low noise cooling laser and low absorption of the optical cavity field (phase noise at the mechanical frequency can act as a finite-temperature thermal reservoir while absorption may increase the mode temperature and even diminish the overall cavity performance), and (3) sufficiently small coupling of the mechanical resonator to the thermal environment entailing a low environmental temperature T and large mechanical quality factor Q. The thermal coupling rate is given by $k_B T/\hbar Q$, where k_B is the Boltzmann constant and $\hbar$ is the reduced Planck constant. Ultimately, the individual dissipation rates of the mechanical and optical systems should be exceeded by the optomechanical coupling. Currently, the major experimental hurdle in reaching the quantum ground state is the limitation in Q, thus "phononic engineering" of optimized mechanical resonators is paramount to the success of the field.

In 2006 a milestone was achieved with the first demonstration of laser-cooling of micromechanical resonators via passive radiation-pressure interactions in a high-finesse optical cavity [7]. The experimental realization in Vienna employed an optical cavity incorporating a high reflectivity micro-resonator as one of the end mirrors and achieved a final mode temperature of 8 K with 2 mW of detuned extra-cavity laser power. These initial results prompted a rapid expansion of the nascent field of cavity optomechanics with a proliferation of international groups working towards the ultimate goal of observing quantum effects in macroscopic mechanical resonators. In order to further reduce the

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minimum phonon occupation, a second generation of devices was developed shortly thereafter. These structures utilized an ultra-low absorption SiO_2/Ta_2O_5 Bragg mirror in order to significantly improve the optical performance of the resonators. Furthermore, to minimize the mechanical damping from the optical coating, a specifically engineered mechanical resonator was devised, employing a mechanical resonator based on low-stress silicon nitride. Utilizing this separately-optimized design, a reflectivity >99.99% was realized (along with the complete elimination of photothermal effects), while maintaining a cryogenic Q of ~3×10^4. Operating the optical cavity in a continuous flow ^{4}He cryostat, the fundamental mode of the resonator (eigenfrequency near 1 MHz) was cooled from an initial temperature of 5 K to a final phonon occupation of ~30 [8]. Owing to their excellent optomechanical properties, these devices were additionally employed for the first demonstration of strong coupling between an optical field and a mechanical resonance [9].

In order to further reduce the mechanical damping in these structures, two generations of monocrystalline resonators have additionally been realized. These devices are etched directly from a single-crystal Bragg reflector composed of an alternating stack of ternary $Al_xGa_{1-x}As$ alloys with varying aluminum content, grown via MBE. Resonators fabricated from this material system utilized an identical geometry to the early dielectric devices (employing simple singly- and doubly-clamped beams) and exhibited nearly an order of magnitude improvement in the mechanical dissipation as compared with Ta_2O_5-based devices of similar geometry, reaching Q-values greater than 2×10^4 at eigenfrequencies up to 2 MHz at 4 K [10]. Further investigation indicated that Q was ultimately limited by support-induced losses for the geometries studied. Moving to a novel free-free resonator design has led to the demonstration of cryogenic quality factors approaching 10^5 (9.5×10^4 at 2.4 MHz) [11]. The simultaneous achievement of high reflectivity and low mechanical loss in these crystalline mirrors makes this materials system promising for application in high-performance optical reference cavities, where coating thermal noise currently represents a significant roadblock to the overall stability [12].

In order to gauge the design-limited Q in our devices we have recently completed a theoretical and experimental effort aimed at quantifying the effects of support-induced damping, a key dissipation mechanism in high-quality-factor micro- and nanomechanical resonators [1]. Such studies are vitally important not only for advancing optomechanical experiments, but additionally for pushing the limits of general micro- and nanomechanical resonators, which have emerged as ubiquitous devices for use in advanced technological applications. To numerically predict the design limited Q in mechanical resonators we have developed an efficient FEM-enabled numerical solver, which employs the recently introduced “phonon-tunneling” approach [13]. This solver represents a substantial simplification over previous methods, allowing for the investigation of complex geometries, as well as taking proper account of interference effects between the radiated waves. To experimentally verify the results generated from the solver we characterize sets of custom resonators which exhibit a significant variation in geometry, while approximately preserving the frequencies and effective surface-to-volume ratios of the resonators. As these characteristics are kept constant, one can rule out the influence of additional damping mechanisms on the variation in Q and hence isolate support-induced losses. The results from these devices show excellent agreement with the theoretical predictions, thus, in combination with existing models for other damping channels, our phonon-tunneling solver makes further strides towards *a priori* prediction of Q in micro- and nanoscale mechanical resonators.

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Strain Based Tuning of Ring Resonators via Hydrostatic Pressure Actuation of Membranes

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Abstract: In this poster, we propose a strain based tuning method of ring resonators based via pressure gradients based on a device composed of a ring resonator structure cantered on a membrane. By applying a pressure to the membrane, one can tune the resonator to a specific desired resonance that is otherwise difficult to obtain due to manufacturing defects and temperature variation in the environment.

In this poster, we discuss the development of a novel type of micromechanically tunable ring resonator, whose frequency can be swept over ultra-large fractional bandwidths by varying the hydrostatic gas pressure applied to a membrane suspended microring resonator. Variation of the hydrostatic pressure exerted on the membrane causes the membrane to deform, straining the waveguides and resulting in significant resonance frequency tuning due to both waveguide boundary deformation and photoelastically induced refractive index changes. Such tuning mechanisms are unique as they enable frequency tuning to compensate for manufacturing defects and temperature variation in the environment, enabling the resonator to be tuned to a specific wavelength that would otherwise be difficult to obtain due to aforementioned effects, and do not inherently require temperature tuning or steady-state power dissipation.

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Analysis of Optomechanical Forces in Nano-Photonic Waveguides

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Abstract: We present a theoretical analysis of optomechanical forces in nano-scale photonic waveguides. In particular, we show that significant forces due to radiation pressure can be generated in dielectric slab and photonic crystal waveguides having sub-micron dimensions. We also investigate how such forces can be optimized for optomechanical transduction.

Optomechanical forces created by radiation pressure have been studied extensively in the context of optical traps and tweezers. The interaction of photons and phonons has also been observed in nano-scale devices, where high-Q cavities are used to enhance the forces generated by the optical fields [1]. However, the optomechanical forces generated in nano-photonic travelling-wave systems have largely been neglected in literature. In addition, the common technique for calculating optical forces in such structures involves a numerical Maxwell stress tensor (MST) computation, which requires knowledge of the full electromagnetic field distribution in the computational domain surrounding the structure.

In this work, we calculate the expected optically induced forces in an ordinary dielectric slab wave-guide due to radiation pressure analytically using the response theory of optical forces (RTOF) [2]. The prediction that the resulting forces are confined to the boundaries of the waveguide where there is a discontinuity in refractive index is confirmed, and values of the force density agree well between the analytical approach using RTOF and using the brute-force method (i.e., MST). It is shown through a scaling-law argument that the optical forces are directly related to the group index of the waveguide. Thus, the optomechanical forces in a photonic crystal (PhC) waveguide, which can exhibit anomalous dispersion and hence large group index values in the "slow-light" regime, were calculated using the same formalisms. We show that the distribution of forces due to radiation pressure is again isolated to the regions of discontinuous refractive index, in this case at the boundaries of the air holes, as shown in Figure 1.

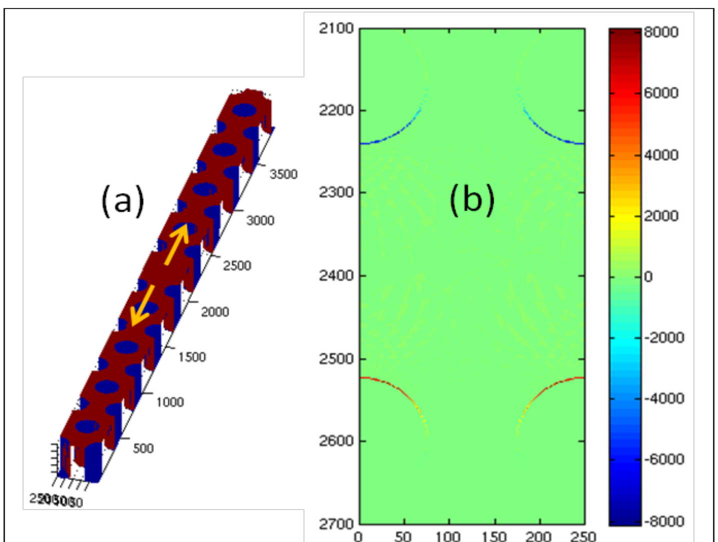

Figure 1 (a) Schematic showing the unit cell of a PhC waveguide; yellow arrows indicate the mean direction of the optical forces due to radiation pressure. **(b)** Plot of the optical forces in the region of the air holes closest to the guiding region of the PhC waveguide.

To extend the generality of these results, scaling-law theory is used to examine the dependence of optical forces from radiation pressure on the topological parameters of the PhC waveguide. Using this theory, we can relate the dispersion of the waveguide to its dimensions as

$$\mathrm{n_g} - n_{eff} = \frac{\partial n_{eff}}{\partial w} w + \frac{\partial n_{eff}}{\partial a} a + \frac{\partial n_{eff}}{\partial r} r \quad (1)$$

where n_g is the group index of the waveguide, n_{eff} is the effective index, w is the hole edge to hole edge width, a is the lattice constant of the PhC, and r is the radius of the air holes. In particular, a trend for the ideal thickness of the PhC waveguide for optimal optomechanical forces can be found and related to the dispersion of the waveguide.

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Our technique outlines a generalized method for optimizing optomechanical forces due to radiation pressure in nano-photonic waveguides using analytical expressions that avoid full-wave electromagnetic calculations. We demonstrate that optical forces in such systems are optimized in highly dispersive waveguides that exhibit large values of group refractive index. Finally, we show how the geometrical parameters of a PhC waveguide can be related to the optical forces due to radiation pressure in a straightforward analytical manner, enabling an intuitive approach to engineering larget optical forces in nano-photonic systems.

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Cooling of a Micromechanical Oscillator into the Quantum Regime

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Abstract: Using optical sideband cooling, a micromechanical oscillator is cooled to a phonon occupancy below 10 phonons, corresponding to a probability of finding it in its quantum ground state more than 10% of the time.

The control of low-entropy quantum states of a micro-oscillator could not only allow researchers to probe quantum mechanical phenomena—such as entanglement and decoherence—at an unprecedentedly large scale, but also enable their use as interfaces in hybrid quantum systems. Preparing and probing an oscillator in the conceptually simplest low-entropy state, its quantum ground state, has now become a major goal in Cavity Optomechanics[1]. However, to experimentally achieve this goal, two challenges have to be met: its effective temperature T has to be reduced sufficiently so that $\hbar\Omega_m > k_B T$ ($\hbar$ is the reduced Planck constant, k_B the Boltzman constant, and Ω_m the mechanical resonance frequency). Second, quantum-limited measurements of the oscillator's displacement must be performed at the level of the zero-point displacement fluctuations $x_{zpf} = \sqrt{\hbar/2m\Omega_m}$. Using conventional cryogenic refrigeration, a nanomechanical oscillator has recently been cooled to the quantum regime and probed by a superconducting qubit to which it was coupled through its specific piezoelectric properties[2].

Here, we demonstrate a different technique, applying optical sideband cooling[3] to a cryogenically precooled silica toroidal optomechanical micoresonator (Fig. 1). This versatile technique, conceptually similar to laser cooling techniques known in atomic physics, can be applied to a wide range of opto- and electromechanical systems which exhibit parametric coupling of high-quality electromagnetic and mechanical modes.

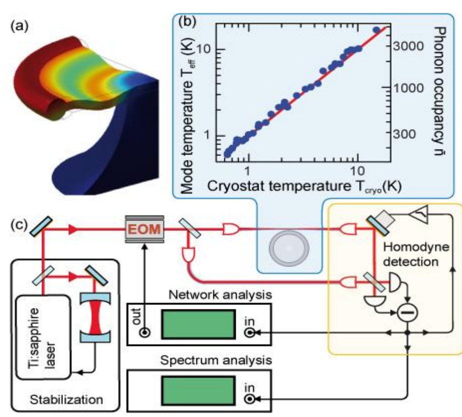

Figure 1 Cooling a micromechanical oscillator. (a) High-Q mechanical and optical modes are co-located in a silica mi- crotoroid, and are mutually coupled by radiation pressure exerted by the mechanical mode. (b) Thermalization of the mechanical mode to the temperature of the 3He gas in the cryostat down to an occupancy of 200 quanta. (c) Optical setup used for displacement monitoring of the mechanical mode, based on homodyne analysis of the light re-emerging from the optical resonance.

With a resonance frequency of $\Omega_m/2\pi$=72 MHz of the mechanical radial breathing mode (RBM), and an optical linewidth of $\kappa/2\pi$=6 MHz, the used toroidal resonator resides deeply in the resolved sideband regime, as required for ground-state cooling[4]. Thermalizing the resonator to a 850-mK cold ^{3}He buffer gas, the RBM is already cooled to an occupation of 190 quanta as determined by noise thermometry (Fig. 1). A low-noise cooling laser (λ~780 nm) is

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subsequently coupled to a whispering gallery mode (WGM) using a tapered fiber. Figure 2 shows the optically measured mechanical resonance frequency and damping when the detuning Δ of the cooling laser is tuned through the lower mechanical sideband of the (split) optical WGM at a power of 2 mW[5]. The strong modification of the oscillator's properties can be modeled with the well-understood radiation pressure-induced dynamical backaction. This allows extracting the additional mechanical damping due to defects in the glass described as an ensemble of two-level systems (TLS)[6]. Its strong temperature dependence enables an independent determination of the toroids' temperature, which can be compared to the noise temperature of the mechanical mode (Fig. 2c). We find excellent agreement between the two methods. At a higher cooling laser power (4 mW) both methods congruently yield a minimum occupation below 10 quanta, corresponding to a >10% probability to find the oscillator in its quantum ground state.

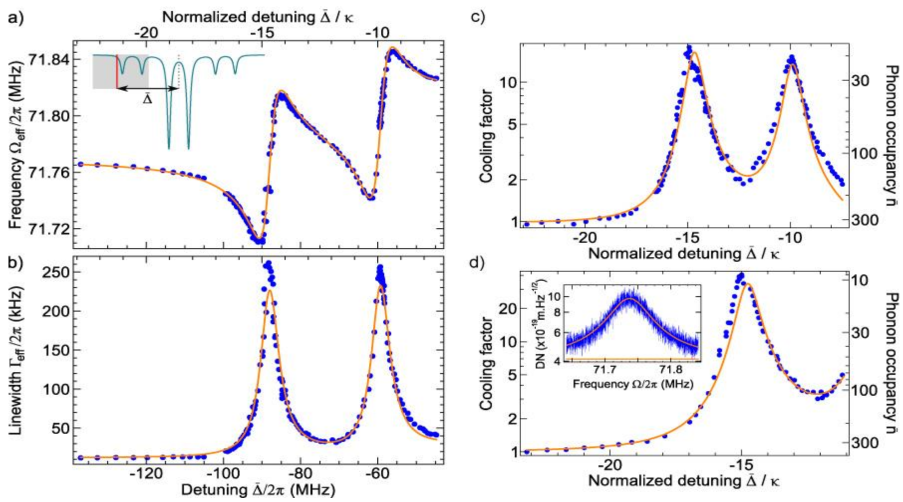

Figure 2 Cooling results. Resonance frequency (a) and linewidth (b) of the RBM when a 2 mW-power cooling laser is tuned through the lower mechanical sideband of the split optical mode (inset). Blue points are measured data extracted from the recorded spectra of thermally induced mechanical displacement fluctuations, solid lines are a coupled fit based on dynamical backaction and TLS-induced effects. c) Cooling factor (temperature reduction induced by sideband cooling) and phonon occupation of the RBM as a function of normalized detuning as determined by noise thermometry (points) and from a dynamical backaction model, taking into account possible optical heating of the structure and TLS-induced effects.

Further optimization of the silica toroids for stronger optomechanical coupling and lower dissipation can enable cooling the resonator deeper into quantum regime. It furthermore appears realistic to achieve the regime of strong coupling[7] while the resonator is in a low-entropy state. This constitutes an important step towards the coherent manipulation of the quantum state of the mechanical oscillator.

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Optomechanical Crystals

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Abstract: In the last several years, rapid advances have been made in the field of cavity optomechanics, in which the usually feeble radiation pressure force of light is used to manipulate (and precisely monitor) mechanical motion. In this talk I will describe these advances, and discuss our own work to realize radiation pressure within nanoscale structures in the form of photonic and phononic crystals.

In the last several years, rapid advances have been made in the field of cavity optomechanics, in which the usually feeble radiation pressure force of light is used to manipulate (and precisely monitor) mechanical motion. These advances have moved the field from the multi-km interferometer of a gravitational wave observatory, to the optical table top, and now all the way down to a silicon microchip. In this talk I will describe these advances, and discuss our own work to realize radiation pressure within nanoscale structures in the form of photonic and phononic crystals (dubbed optomechanical crystals). Applications of these new nano-opto-mechanical systems include: all-optically tunable photonics, optically powered RF and microwave oscillators, and precision force/acceleration and mass sensing. Additionally there is the potential for these nanomechanical systems to be used in hybrid quantum networks, enabling storage or transfer of quantum information between disparate quantum systems. I will introduce several conceptual ideas regarding phonon-photon translation and slow light effects which may be used in such quantum settings, and discuss recent experiments to realize them in practice.

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Mechanical Whispering-Gallery Modes

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Abstract: We experimentally excite mechanical Whispering-Gallery resonances that are vibrating from 50 MHz to 12 GHz rates.

Just like their optical parallel, mechanical whispering-gallery modes can offer low-loss resonances in devices from mm[1] to micron[2] in scale. The fact that the modes are propagating azimuthally, orthogonal to the radial direction where they can leak through the support, suggests a nearly material limited mechanical Q.

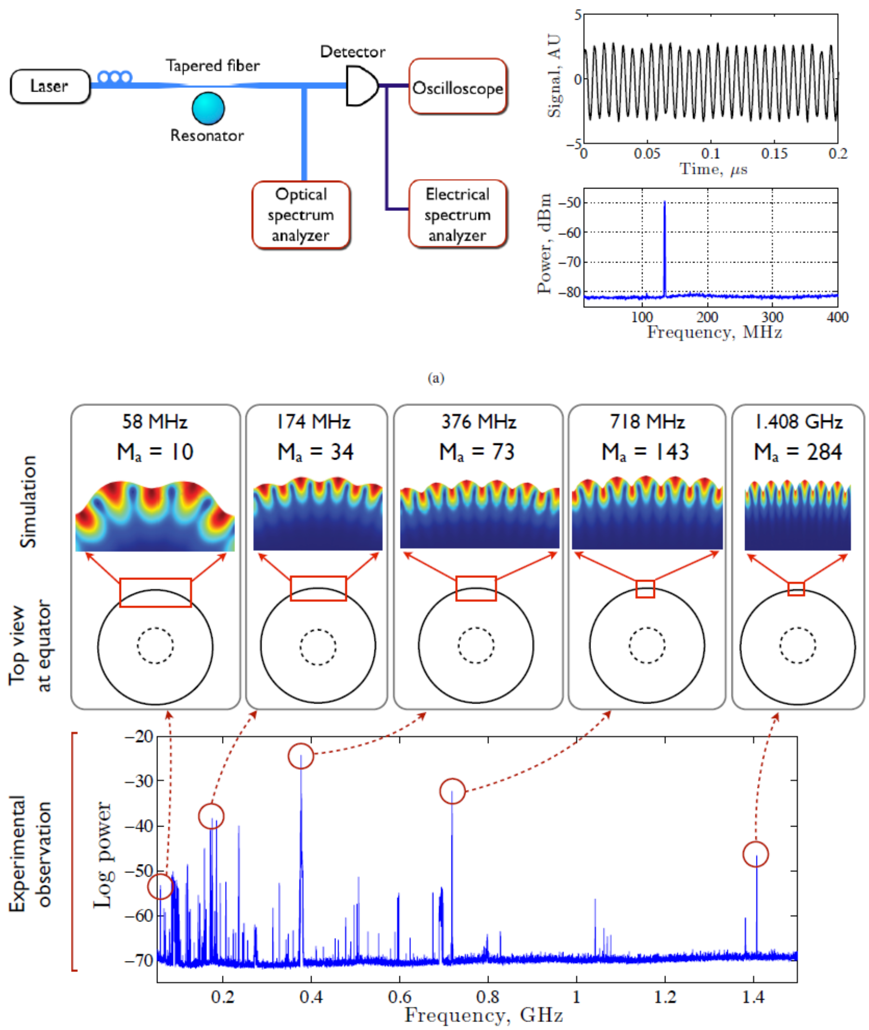

Figure 1: Experimental setup of excitation of mechanical whispering gallery modes followed by experimental observation and theoretical calculation of such modes.

Figure 1 shows the experimental setup for excitation of such modes, followed by their experimental observation and by the corresponding calculated natural vibration modes.

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