Nano-opto-mechanics: utilizing light forces within guided-wave nanostructures

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The fact that light carries momentum and can exert a mechanical force was first proposed by Kepler and Newton. The interaction of light with mechanical vibrations, in the form of Brillouin and Raman scattering, has been known since the 1920's and has many practical applications in the fields of spectroscopy and optoelectronics. With the advent of the laser in 1960's, it became possible to manipulate micron-scale dielectric particles using optical "tweezers" as pioneered by Art Ashkin[1]. This was also the beginning of the use of laser beams for the trapping and manipulation of gas-phase atoms, which ultimately led to the demonstration of atomic Bose-Einstein Condensates. More recently, it has been realized that laser light, with its very low intrinsic noise, may be used as an effective method of cooling a macroscopic mechanical resonant element, with hopes of reaching effective temperatures suitable for measuring inherently quantum mechanical behavior[2]. In duality to the cooling effect, it has also been demonstrated that optical amplification from a continuous-wave laser beam can be used to form regenerative mechanical oscillators[3]. With these developments, interest in the new field of cavity-optomechanics has been piqued, with myriad of different materials, devices, and techniques currently being developed.

There is now a wide-spread realization that optical gradient forces, as opposed to the scattering radiation pressure force, may be utilized within guided wave nanostructures to create very large optomechanical coupling to micro- or nano-mechanical motion[4]. In contrast to the scattering radiation pressure force, which one can intuit from the reflection of momentum-carrying photons, the gradient force as its names suggests results from gradients

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in the intensity of light, which in the near-field can be substantial. A nanophotonic platform for utilizing the strong gradient optical force has recently been developed[5,6] in which light and sound are manipulated through a common nano-structuring. We call these devices "optomechanical crystals" (OMCs) due to the simultaneous realization of phononic and photonic bandgap states (similar to the electronic bandgaps that form in regular crystalline materials). These new structures enable the engineering of various integrated functionalities not possible in other systems. Ultimately, one may come to view these systems as fully integrated planar light and sound wave circuits. In what follows we introduce the OMC concept, and discuss a "photon-phonon translator" which may find use in a variety of applications from RF-over-optical communication to the study of mesoscopic quantum systems.

Introduction to Optomechanical Crystals (OMCs) –

Applied to the propagation of light, periodicity gives rise to photonic crystals, which can be used to engineer broad- and narrow-band dispersion, to confine optical modes to small volumes with high optical quality factors, and to build planar lightwave circuits[7]. Periodicity applied to mechanical vibrations yields *Phononic* crystals[8], which harness mechanical vibrations the same way that photonic

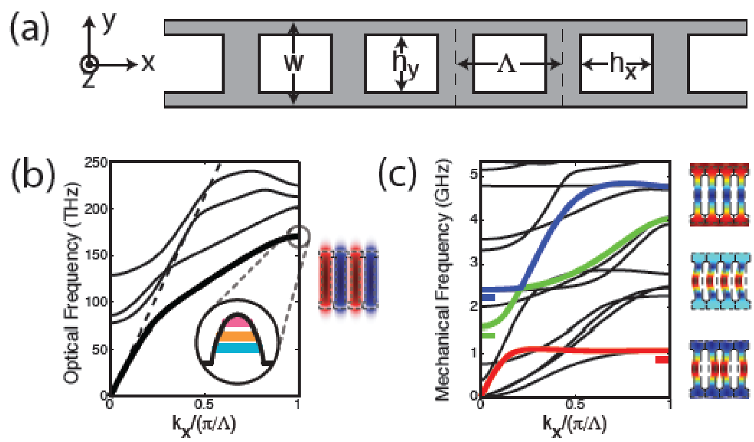

Fig. 1: (a) General geometry of the periodic nanobeam structure's projection (infinite structure, no defect). (b) Optical band diagram of the nanobeam's projection. The band from which all localized optical modes will be derived is shown in dark black, with Ey of the optical mode at the X point shown to the right of the diagram. The harmonic spatial potential created by the defect, along with the first three optical modes are shown as emanating from the X-point band-edge. (c) Mechanical band diagram of the nanobeam's projection. The three bands that form defect modes that will be discussed in this work are colored. The bottom-most mode is from the X point of the red band; the Γ points of the green and blue bands correspond to the middle and top mechanical modes, respectively. The frequencies of the defect modes that form from the band edges are shown as short, horizontal bars.

crystals harness optical waves, allowing tantalizing possibilities such as phononic band gaps, nonlinear phononics, coherent sources of phonons, and planar sound wave circuits. It has been proposed that periodic structures can be used to simultaneously confine mechanical and optical modes [9]. Here we endeavor to take this one step further, and to use cavity-optomechanics concepts to marry mechanics and optics in ways that make both more powerful.

The dispersive interaction induced by mechanical motion[6] is responsible for coupling the photonic and phononic crystal properties of the material to yield optomechanical crystals. For the complex motion allowed in these periodic structures, the origin of the optomechanical coupling can be subtle, and in many cases even counter-intuitive. Nonetheless, understanding the nature of the coupling is crucial, since the degree of coupling between different optical-mechanical mode pairs can vary by many orders of magnitude within the same structure. Moreover, subtle changes in the geometry can induce enormous changes in the optomechanical coupling, which can be used to engineer the coupling if the system is well-understood. A perturbation theory of Maxwell's equations with shifting material boundaries[10] provides a simple and computationally-robust method of calculating the optomechanical coupling of these complex motions. Here we describe how this perturbation theory can be used to create an intuitive, graphical picture of the optomechanical coupling of simultaneously localized optical and

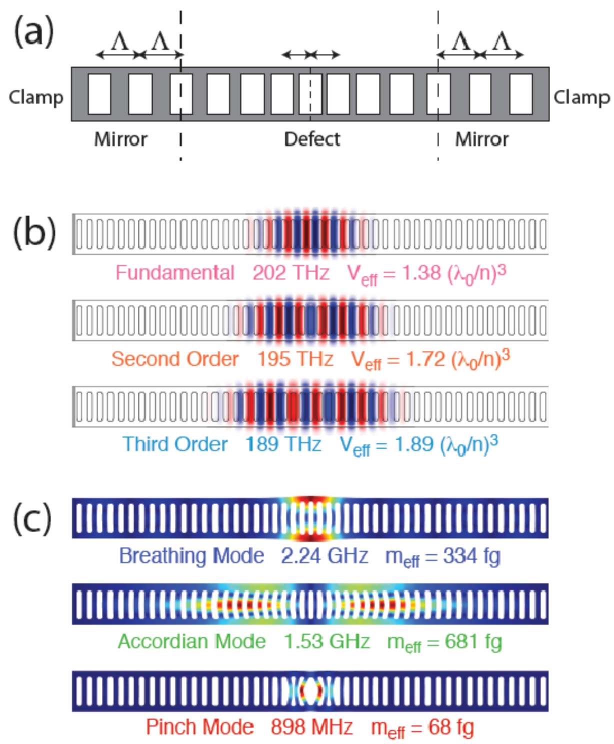

Fig. 2. (a) Schematic illustration of actual nanobeam optomechanical crystal with defect and clamps at substrate. (b) Localized optical modes of the nanobeam OMC. The colors of the names correspond to the illustration of the inverted potential in Fig. 2(b). Localized, optomechanically-coupled mechanical modes of the nanobeam OMC. The colors of the names correspond to the colored bands and horizontal bars showing the modal frequencies in Fig. 2(c).

mechanical modes in periodic systems. We use this graphical representation to illustrate methodologies for optimizing the coupling of the mechanical and optical modes.

Figure 1 shows the bandstructure for photons and phonons (mechanical vibrations) of a quasi-1D patterned Silicon nanobeam. Just as localized optical resonances can be formed in "flat-band" regions (regions of low optical dispersion in which the energy velocity of light approaches zero) close to the zone-boundaries, so to can phonon states be localized. As the wavelength of the optical mode and the mechanical vibration must be the same (they live on the same 1D lattice!), the ratio of the frequency of optical to phonon modes is simply given by the ratio of the speed of light to that of the speed of sound (or more generally whatever type of vibration is involved). It so happens that for the Silicon nanobeam example of Fig. 1 operating at an optical wavelength of 1.5 microns, this yields a mechanical mode frequency in the 1-5 GHz range (shrinking the width of the nanobeam offers the intriguing possibility of reaching frequencies in the X-band (10-12 GHz) or even higher). The colored bands in Fig. 1(c) correspond to those bands which have large optomechanical coupling. By forming a "defect" in the periodic lattice through a slow reduction in the hole-to-hole pitch within the center of a patterned beam, one may form localized photon and phonon states. This is shown in Fig. 2. We label the three primary phononic localized resonances as pinch, accordion, and breathing modes (see caption).

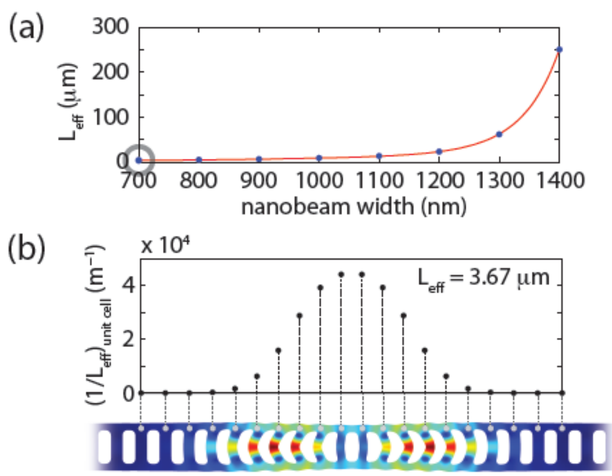

Fig. 3: For the accordion mode with the fundamental optical mode, (a), the effective length as a function of total beam width, (b), a breakdown of individual unit cell contributions to the total optomechanical coupling for a structure with a beam width of 700 nm (circled in (a)), mode frequency of 3.97 GHz and effective motional mass of 0.334 pg, with accompanying mechanical mode plot. The narrower mechanical mode envelope results in drastically different optomechanical coupling contributions compared to the wider beam.

The optomechanical coupling between mechanical and optical degrees of freedom is given to lowest order by the dispersive term, $g_{OM} = \delta\omega/\delta\alpha = \omega_c/L_{OM}$, where ω_c is the unperturbed optical cavity frequency, L_{OM} is an effective length over which a photon's momentum is transferred to the mechanical structure (equal to the cavity length in the case of a Fabry-Perot cavity), and α parameterizes the maximum displacement of the mechanical motion for the mode of interest. The perturbation theory of Maxwell's equations with shifting material boundaries[10] allows one to calculate the derivative of the resonant frequency of a structure's optical modes, with respect to the α-parameterization of a surface deformation perpendicular to the surface of the structure. As an example of the power of the perturbative method to engineer the optomechanical coupling strength, we show in Fig. 3 the optomechanical coupling strength of the fundamental accordian mechanical mode at ~1.5 GHz as a function of beam width. One can see that the optomechanical coupling length approaches a minimum value close to the wavelength of light for a beam width of 700 nm, whereas it increase to well over 300 times this value for a beam only twice as wide

The OMC "traveling photon-phonon translator" –

The OMC concept naturally lends itself to a microchip integration platform for the routing, interaction, and exchange of light and mechanics, with possible application in photonics and RF-over-optical communication. At the heart of such applications is a device we have termed the "traveling photon-phonon translator". This device is shown schematically in Fig. 4, and consists of two optical cavities coupled together by a single phonon cavity. An input/output *optical* waveguide is strongly coupled to one of the optical cavities (top cavity, labeled $\boldsymbol{a}$), as is a *phononic* waveguide to the phononic cavity (labeled $\boldsymbol{b}$). The second (bottom, labeled $\boldsymbol{\alpha_p}$) optical cavity is pumped to some large coherent state amplitude via a second optical waveguide (of lesser importance and not shown). In order for the "traveling

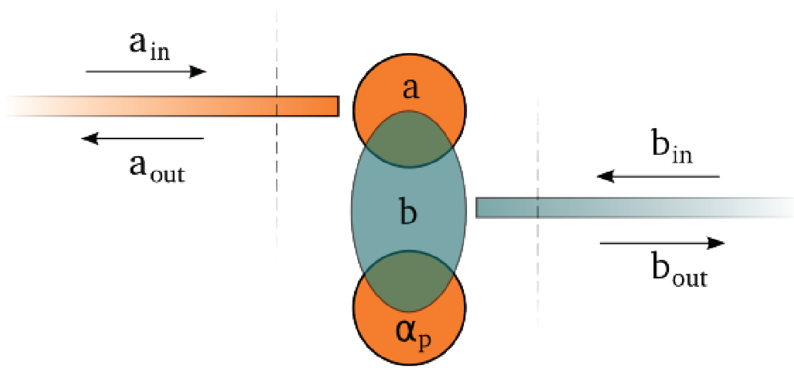

Fig. 4: Traveling photon-phonon converter, optical cavities and waveguides are colored orange while the phononic cavity and waveguide are blue.

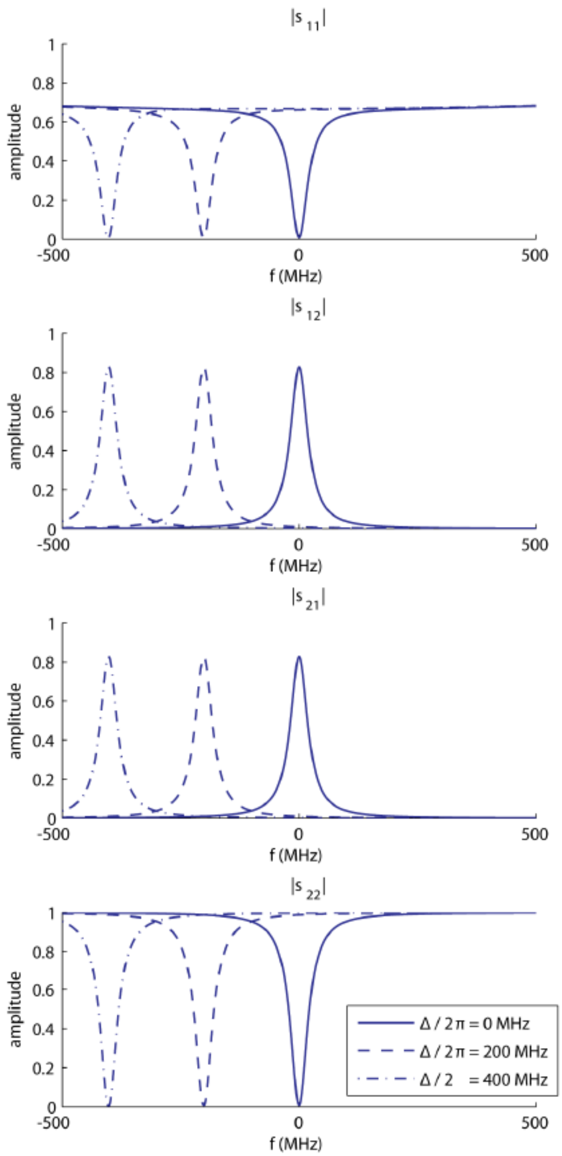

Fig. 5: Photon to phonon scattering matrix amplitudes as a function of laser detuning, Δ. $|s_{11}|$ is the reflected signal from the optical waveguide coupled to cavity a, $|s_{22}|$ is the reflected signal for the phonon input, and $|s_{12}|$ and $|s_{21}|$ are the photon-phonon interconversion amplitudes.

photon-phonon translator" to effectively work (and convert photons to phonons or vice-versa), several criteria relating to the input and output coupling rates of photons and phonons, and the internal dissipation rates, must be met.

Due to the great deal of flexibility in the OMC architecture, fulfilling these criteria is rather trivial due to the chip-scale platform in which the devices are formed. A simulation of the scattering matrix for input and output coupled power (amplitude) for both phonons and photons is shown in Fig. 5 for a structure with parameters determined from a numerical modeling of a quasi-2D OMC cavity structure. The efficiency of phonon-to-photon, or photon-to-phonon transfer (the system is symmetric, and thus equal for the two conversion efficiencies) is shown to be as high as 75%, limited by internal mechanical and optical loss. These initial theoretical results are very encouraging, and indicate that the traveling photon-phonon translator concept can be used to interconvert photons and phonons with high efficiency for applications such as optical delay lines (where the slower phonon provides the delay), dynamic optical routing/buffering[11], and narrowband RF/microwave filters[12].

Beyond classical RF-microwave photonic applications, the OMC photon-phonon translator works equally as well as a quantum translator for individual quanta of phonons or photons if the phononic cavity can be coupled to a low enough bath temperature (100mK). Such a system would be very interesting as a converter of microwave to optical photons when integrated with piezoelectric materials. In the burgeoning field of circuit QED[13], in which rapid progress has been made in realizing on-chip coupled qubits via a microwave "quantum bus", this could enable off-chip coupling via photons for long-distance quantum communication and entanglement between nodes.

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