Optical Probing and Actuation of Microwave Frequency Phononic Crystal Resonators without Clamping Losses

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Abstract: We demonstrate microwave frequency mechanical modes of optomechanical crystals having arbitrarily small clamping losses. The optomechanical crystals are connected to the substrate via a phononic bandgap structure, simultaneously isolating and rigidly supporting the optomechanical resonator.

Nanooptomechanical systems (NOMS) having microwave frequency mechanical resonances[1–4] are a promising platform for applications in RF-over-optical communications applications, such as frequency references, mixers, filters, delay lines and amplifiers. On the more exotic side, microwave-frequency NOMS could be used as sub-zeptogram mass sensors, optical-to-mechanical quantum information transfer and storage devices, and testbeds for fundamental quantum mechanics in mesoscopic systems. These and virtually all other applications put a premium on reducing mechanical losses. Many fundamental processes cause dissipation for phonons in acoustic nanostructures, including Rayleigh scattering from isotopic impurities and localized lattice defects, electron-phonon scattering, non-specular surface scattering, the Akheizer effect, thermoelastic loss, anelastic effects, and multi-phonon Umklapp interactions with thermally-populated lattice phonons[5–7]. Many of these loss mechanisms are dependent upon temperature, material, surface treatment, and frequency, allowing the potential to reduce dissipation in a given material system or to choose material systems with the most favorable properties. Thus, quantitatively studying these dissipation mechanisms with the eventual goal of reducing them is an important goal for the field of microwave frequency mechanical resonators. However, before these mechanisms can be investigated, the direct loss of mechanical energy through “radiation” into the surrounding substrate, typically called *clamping loss*, must be made smaller than the loss mechanism of interest. The nanoscale resonators that are typical of microwave frequency mechanical resonances have a significant fraction of their mechanical energy in their supports, making it difficult to obviate clamping losses. However, the existence of complete phononic bandgaps in periodically-patterned single-layer thin films[8, 9] provides a way to completely eliminate mechanical losses in these systems. In this work, we show that a microwave-frequency mechanical resonator can be supported by a structure possessing a large, microwave-frequency complete phononic bandgap, simultaneously isolating and rigidly supporting the mechanical resonator.

FIG. 1: (a) Spacing between holes Λ_{nh} relative to background lattice constant, Λ , showing quadratic decrease to defect lattice constant, Λ_D . This creates the effective photonic and phononic potential wells that are the basis of the photonic and phononic bandgap cavities of the optomechanical crystal nanobeam. (b) Mechanical “accordion” ($\nu_m \approx 3.5$ GHz) and (c) fundamental optical ($\nu_o \approx 200$ THz) modes of a 220 nm thick optomechanical crystal silicon nanobeam.

In recent work[1, 2], we demonstrated that an appropriately patterned nanobeam with a central defect (Fig. 1(a)) is capable of simultaneously localizing[10] and strongly coupling microwave-frequency mechanical (Fig. 1(c)) and optical (Fig. 1(b)) modes. The optical and mechanical properties of these *optomechanical crystal* (OMC) systems include femtogram-scale motional masses and optomechanical coupling rates[11] nearly at the fundamental limit set by optical diffraction. Along with high optical and mechanical quality factors, these properties allow transduction of microwave frequency motion with a sensitivity close to the standard quantum limit. In addition, the optical field can be evanescently coupled to a nanoscale optical probe, allowing the mechanical motion to be monitored with near quantum-limited sensitivity[12] and requiring no metalization or other surface perturbative techniques for transduction. This makes OMCs ideal for studying intrinsic mechanical loss mechanisms if the mechanical clamping losses can be made smaller than the other dissipation mechanisms of interest.

Figure 2(a) shows the phononic band structure of the quasi-2D phononic crystal shown in Fig. 2(b). The phononic crystal has a large (> 1 GHz) complete phononic bandgap, the center of which has been made to coincide with the frequency of the mechanical “accordion” mode of Fig. 1(a). Mechanical radiation at the center of the bandgap is attenuated by approximately an order of magnitude per lattice period in amplitude (two orders of magnitude per period in energy), providing an extremely high degree of isolation for modes surrounded by such a material. The phononic crystal and OMC can be integrated together to form the device shown in Figs. 2(c-d). This effectively forms a highly-reflective phononic crystal radiation shield (PCRS) around the OMC device. Since the tails of the optical and mechanical modes of the OMC nanobeam overlap the PCRS, the presence of the

FIG. 2: (a) FEM simulation of irreducible first Brillouin Zone (FBZ) dispersion diagram of structure in (b) showing large complete phononic bandgap ($\Lambda = 694$ nm, $h = 602$ nm, $w = 127$ nm, $t = 220$ nm, $E = 170$ GPa, $\nu = 0.28$, $\rho = 2.33$ g/cm³). (b) Phononic crystal consisting of a square lattice of “crosses” in a 220 nm silicon film. (c-d) SEM micrographs of the phononic crystal radiation shield forming the mechanical support for an optomechanical crystal nanobeam.

PCRS has a negligible effect on the large-amplitude part of these modes mode at the center of the nanobeam, with the result that the optomechanical coupling between the modes is insignificantly affected by the PCRS. Thus, the PCRS is an effective way of simultaneously supporting and isolating the nanobeam from its surroundings without losing any of the favorable optomechanical properties.

The large microwave-frequency bandgaps of these single-layer dielectric thin films, which are *highly tunable* via geometry, provides a general method for eliminating clamping losses in arbitrary microwave frequency mechanical resonators. Moreover, with the exquisite sensitivity[1] and mechanically nonperturbative coupling possible with optomechanical crystals, these kinds of systems provide a platform for the broad investigation of acoustic dynamics and phononic processes. Thus, by fabricating such systems over a broad range of microwave frequencies in different material systems (e.g. silicon, gallium arsenide, silicon nitride, silicon oxide, indium phosphide, lithium niobate, diamond, etc.), we can begin to explore fundamental phononic dissipation processes in nanomechanical structures[7]. In this presentation, we will provide the first measurements of nonperturbatively (optically) probed microwave frequency mechanical resonances without clamping losses over a large range of frequencies (< 1 GHz – 4 GHz) and temperatures (10 K – 300 K) in silicon and silicon nitride.

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