Cavity optomechanics with surface acoustic waves

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Status

The growth of the field of cavity optomechanics [1] has been partly brought about by advances in micro and nano-electromechanical systems (MEMS/NEMS) and nanophotonics. These systems, in which optics and mechanics interact via radiation pressure, photothermal, and electrostrictive forces, have been developed across many material platforms and geometries. As the field pushes towards higher mechanical mode frequencies in an effort to achieve stronger interactions and sideband resolution (single-sideband operation), surface acoustic wave devices provide a natural platform for exciting high frequency motion and exploring optomechanics with travelling acoustic waves (the regime of stimulated Brillouin scattering) [2].

The rationale for integrating surface acoustic wave (SAW) transducers (and more generally, piezoelectric devices) with cavity optomechanics is also driven by other trends. One is the desire to interface radio frequency (RF) electromagnetic fields with optics. This has relevance to classical applications, such as microwave photonics, as well as quantum information science, where efficient and low-noise frequency conversion between the microwave and optical domains could remotely connect, via optical links, superconducting quantum circuits. A proof-of-principle demonstration combined capacitive electromechanical transduction with dispersive optomechanical transduction [3], where the latter used a free-space Fabry-Perot cavity modulated by a thin membrane vibrating at MHz frequencies. Realizing a fully chip-integrated transducer will likely require a mechanical frequency in the hundreds of MHz or GHz range, to be sideband-resolved and enable broader conversion bandwidths. At GHz frequencies, capacitive transduction is inefficient, whereas piezoelectric approaches are more naturally suited, as evidenced by the many existing technologies in the GHz domain (e.g. SAW and film bulk acoustic resonator (FBAR) filters).

The integration of such approaches with nanocavity optomechanics has recently been explored. Bochmann et al. [4] used integrated electrodes to drive an AlN optomechanical resonator at 4.2 GHz, while Fong et al. [5] drove an AlN microdisk resonator at 780 MHz. Balram et al. [6] directly integrated SAW technology by using an interdigitated transducer (IDT) to generate 2.4 GHz propagating acoustic waves that resonantly excited a GaAs optomechanical crystal cavity (Fig. 1). The integration of SAW devices in free-space optical resonators, which can have much narrower linewidths than integrated resonators, has also been considered [7], and SAW-based acousto-optic modulators [8] (see also section 5) have been pushed to >10 GHz operating frequency [9].

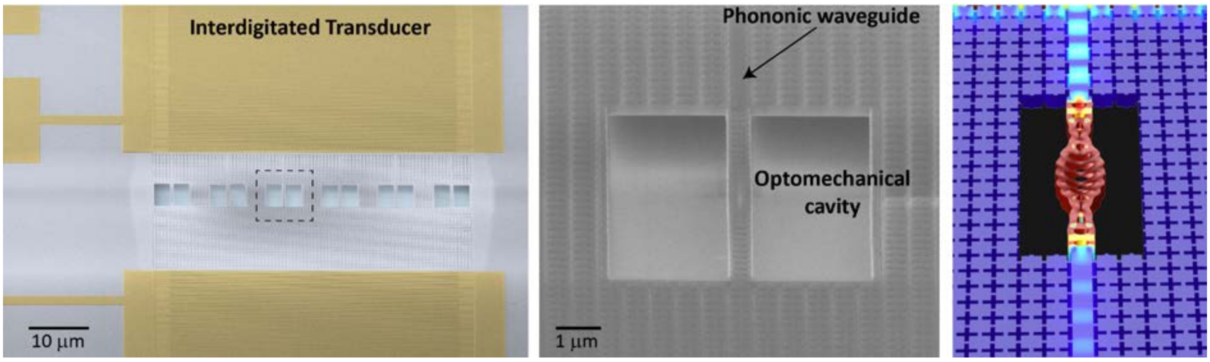


Figure 1. Integration of a SAW transducer with a cavity optomechanical system, as in Ref. [6]. An interdigitated transducer (left) generates a 2.4 GHz SAW that is coupled through a phononic waveguide and resonantly excites an optomechanical cavity (center), whose mechanical breathing mode (right) strongly interacts with a localized optical mode at 1550 nm.

Current and Future Challenges

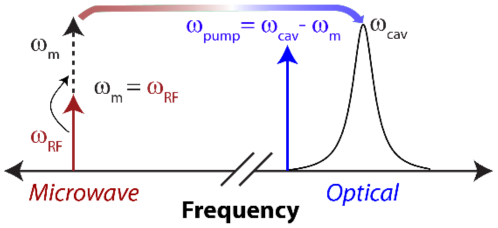
First piezoelectric cavity optomechanical systems [4-9] illustrated the coherent interplay of the RF, acoustic, and optical fields, and new contexts in which this can be valuable, such as non-reciprocal optical systems, continue to be explored [10]. In general, microwave-to-optical transduction efficiencies have been low (< 0.1 %) [11], and their improvement is an important challenge, particularly for quantum applications.

A schematic illustrating the microwave-to-optical conversion process is shown in Fig. 2a. An RF drive resonantly excites an acoustic excitation, which is then upconverted to the optical domain by a pump whose frequency is detuned from the optical cavity by the mechanical (acoustic) frequency. The optical cavity enhances the coupling between optical and acoustic modes, and its linewidth must be narrow enough so that only the higher frequency anti-Stokes sideband is effectively created. Optical and mechanical quality factors, piezoelectric and optomechanical coupling rates, and coupling of the input RF signal and output optical signal determine the overall efficiency.

Achieving superlative performance across the optical, mechanical, and electrical domains requires appropriate isolation of the individual sub-systems. High optical quality factor resonators cannot be achieved if the optical field overlaps with the electrodes used in the piezoelectric device. Recent demonstrations of piezo-optomechanical systems [4-6] have avoided electrode-optical field overlap, and the relative ease with which this is accomplished is a strength of the piezoelectric approach. On the other hand, the extent to which piezoelectric substrates can achieve the ultra-high mechanical quality factors observed in materials like silicon [1] at low temperatures is not yet known.

The choice of material starts with a consideration of its piezoelectric and photoelastic properties, and although the effective coupling strengths can be enhanced by geometry (via strong confinement and high quality factor), materials properties set basic tradeoffs (Fig. 2b). For example, AlN and $LiNbO_3$ have significantly larger piezoelectric coefficients than GaAs. However, GaAs-based devices have exhibited >10x larger optomechanical coupling rates, due to its larger refractive and photoelastic coefficients [6]. In general, the optomechanical and electromechanical coupling rates should be equal for optimizing conversion efficiency (achieving impedance matching between the RF and optical domains).

(a)



(b)

Material	Electro-mechanical coupling ($k^2 = e^2/\varepsilon c$) [%]	Opto-mechanical coupling ($M_2 = n^6 p^3/\rho v_L^3$)*1e16 [s^3/kg]
Silicon	0	300
Quartz	1.0	17
GaAs	0.38	2000
GaP	0.2	630
GaN	1.3	1.3
$GaPO_4$	1.7	500
AlN	7.2	0.2
$LiNbO_3$	17	26
$BaTiO_3$	60	1200

Figure 2. (a) Schematic for microwave-to-optical conversion. $\omega_{RF}/\omega_m/\omega_{pump}/\omega_{cav}$ are the frequencies of the RF drive/mechanical system/optical pump/optical cavity. (b) Table showing the bulk electromechanical and optomechanical coupling coefficients of some commonly used materials: the electromechanical coupling coefficient (k^2) is defined in terms of the piezoelectric coefficient (e), the dielectric constant (ε), and the elastic coefficient (c). The optomechanical figure of merit (M_2) is defined ($\lambda = 1.55\ \mu m$) in terms of the refractive index (n), the photoelastic coefficient (p), density (ρ) and the speed of sound (v). Displayed values are based on the maximum piezoelectric/photoelastic coefficient for the materials.

Advances in Science and Technology to Meet Challenges

As noted above, efficiently mapping the RF input to an acoustic wave that is well-coupled to the optical mode is a major challenge. This can sub-divided into two tasks: converting the RF drive to an acoustic excitation, and coupling that acoustic excitation into a suitable optomechanical cavity. For example, optimizing the approach of Ref. [6] might combine more efficient IDTs with acoustic waveguide tapers (or use focusing IDTs), or may require a different type of piezoelectric actuator (e.g., a resonator-based geometry) altogether. Moving from GaAs to a stronger piezoelectric material is another solution. Hybrid platforms that could combine a very efficient piezoelectric material ($LiNbO_3$) with a high-performance optomechanical material (Si) might be the ultimate solution (Fig. 2b), though fabrication and design complexity need to be considered. Alternatively, continued development of materials that show both a strong piezoelectric and photoelastic response, such as $BaTiO_3$, within a thin-film platform suitable for chip-integrated nanophotonics and nanomechanics is another approach [12].

Continued development of nanofabrication processes that limit sources of dissipation (both optical and acoustic) and excess heating, which leads to a non-zero thermal population of the mechanical resonator, ultimately serving as a source of added noise, are also needed. In general, the combination of these different physical domains (RF, acoustic, and optical) in the context of quantum applications is a new field, with many basic experiments (e.g., ultra-low temperature performance of different piezoelectric transducer geometries) still to be performed.

No less important than fabrication and measurement developments is the design of the overall transducer system, which requires both fundamental knowledge and detailed simulation capabilities that address the multiple physical processes involved. Current approaches largely focus on being able to break up the problem into sub-systems that can treated individually, enabling separate optimization steps. Given the recent progress in the RF MEMS community in developing piezoelectric resonators [13], and in the nanophotonics community in achieving record optical performance in piezoelectric platforms [14], the appeal of this approach is quite evident. However, as indicated above, the multiple tradeoffs and considerations involved when integrating the two types of devices suggests that this approach may not yield the best solution, and a more integrated design approach may provide benefits.

Concluding Remarks

The integration of surface acoustic wave devices (and more generally, piezoelectric actuation) with cavity optomechanics enables the coherent interaction of RF electrical waves, acoustic waves, and optical waves in a common platform. This short overview has focused on quantum-limited microwave-to-optical transduction, but the general potential of this platform lies in the possibility of combining desirable characteristics of each of these domains in a way that can be tailored for different applications. However, numerous challenges abound in being able to appropriately combine these sub-systems together while retaining the level of performance available to each in isolation. Continued development of nanophotonics and NEMS, combined with strong interest in the applications of these devices from the quantum information science community, suggests that interest in this topic will continue to increase.

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