A Simple Optomechanical Platform with Ultra-Wide Phonon-Frequency Tunability

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Abstract: Phonon-frequency-tunable optomechanical interactions are demonstrated in shaped bulk acoustic resonators. Non-collinear all-optical coupling enables access to phonons with novel mode-selection rules, high quality factors (>10^7), and frequency tunability over 10 GHz.

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1. Introduction

A variety of cavity optomechanical systems have now been established, enabling novel classical [1] and quantum technologies [2], including for transduction, sensing and computing. However, current optomechanical systems are generally fixed to a specific acoustic frequency by geometric or material constraints. For example, in microscale and nanoscale systems, the resonant acoustic frequencies are largely determined by the device geometry which is challenging to tune after fabrication. Alternatively, in bulk optomechanical systems [3], accessible phonon frequencies are fixed by intrinsic material parameters such as the refractive index and the acoustic velocity, which limits their applicability to quantum systems including qubits, with different characteristic frequencies. While in nano-scale systems, recent techniques have been developed to tune acoustic frequencies either through the use of strong electric fields to induce stress, or through thermal heating, the demonstrated tunability is typically low (e.g. ~50 MHz [4]) and requires additional mechanical structures which could adversely impact the acoustic cavity lifetime. Optomechanical systems with the capability to dynamically tune the accessed acoustic frequency over a wide range would be highly desirable for flexible quantum networks, frequency tunable radio-frequency oscillators and filters, and for the study of frequency dependent phonon physics.

Here we demonstrate a frequency-tunable Brillouin-like stimulated optomechanical interaction between two non-collinear optical fields and ultra-high-quality factor (~ 30 million) longitudinal acoustic modes of a plano-convex phononic resonator (Fig. 1a). By controlling the angle between optical fields, we demonstrate >10 GHz phonon frequency tunability and investigate the optomechanical response in high (> 10 GHz), and low (< 1 GHz) frequency regimes. Novel phase-matching effects from the wavevector uncertainty of the optical fields are also briefly explored.

2. Phonon-Frequency Tunable Optomechanical System

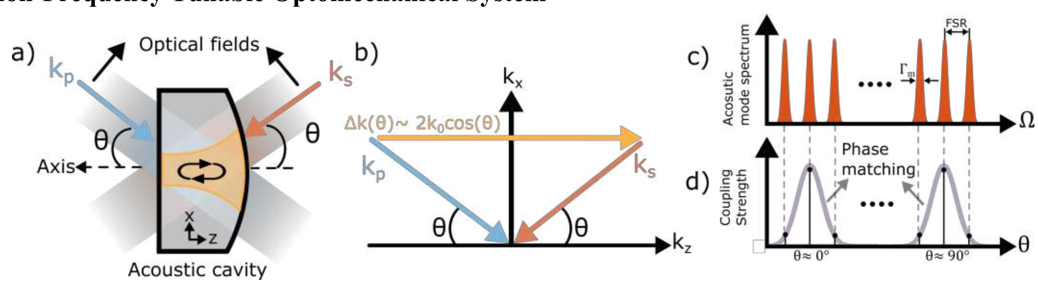

Figure 1: a) Axial longitudinal modes of a bulk crystalline phononic resonator are driven by non-collinear phase-matched pump (k_p) and Stokes (k_s) optical beams. (b) Vectorial optomechanical phase-matching diagram. (c) Acoustic mode spectrum. (d) Tuning the angle allows selective excitation of acoustic cavity modes within the optical phase matching response.

The optomechanical system consists of a plano-convex single-crystal resonator (Fig. 1a). Longitudinal acoustic modes of the resonator can mediate coupling between two non-collinear optical beams (pump and Stokes) provided phase matching and energy conservation is satisfied. If the pump and Stokes optical fields with wavevectors k_p and k_s ($k_s \approx k_p = k_0$) are incident at an angle, θ, from the axis of the acoustic resonator, the phase-matched phonon wavevector magnitude is given by $|q| = |\overrightarrow{k_p} - \overrightarrow{k_s}| = 2k_0 \cos\theta$ (Fig.1b), which when combined with the acoustic dispersion yields the phonon frequency, $\Omega = |q| v_a = 2k_0 v_a \cos\theta$, where v_a is the longitudinal acoustic velocity. This acoustic cavity supports a large family of axial modes characterized by mode-number, m, and linewidth, Γ_m, separated by a corresponding free-spectral range (FSR) (Fig. 1c). Variation of the optical angle changes the subset of these acoustic modes which can be phase-matched to the non-collinear optical fields (Fig. 1d). The accessible phonon frequency can be tuned continuously from its maximum value ($\Omega = 2k_0 v_a$) obtained in the case of alignment collinear to the acoustic axis ($\theta = 0°$) , which is identical to standard Brillouin coupling [3], to nearly zero, in the case of alignment nearly perpendicular to the acoustic axis ($\theta \approx 90°$). Notably, in the low frequency limit, many more acoustic modes can be accessed because the reduced spatial extent of the optical drive fields yields a large optical wavevector uncertainty, significantly increasing the number of phase-matched modes (Fig. 2b).

3. Experimental Results

An optomechanical spectroscopy system is developed based on techniques from previous works using four-wave mixing mediated by the relevant phonon modes [5]. High frequency acoustic modes are measured with the optical fields incident near the acoustic cavity axis, from collinear ($\theta = 0°$) as in previous works [3], to small angles ($\theta \sim 2°$) off-axis (Fig. 2a inset left), demonstrating fine acoustic frequency tunability (Fig. 2a, traces are offset for clarity). Low acoustic frequencies are achieved with optical fields nearly perpendicular to the acoustic axis accessed through polished perpendicular faces (Fig. 2b-c inset left).

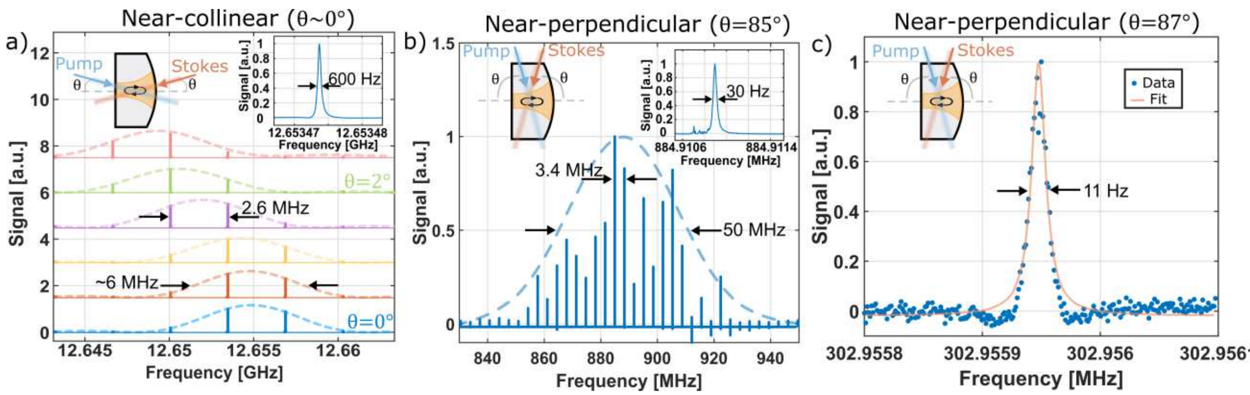

Figure 2: Representative optomechanical measurements of a) z-cut quartz with a near-collinear configuration for high frequency ($\sim 12.6\ GHz$) and b)-c) SC-cut quartz with a near-perpendicular configuration for low frequencies ($< 1\ GHz$).

Representative measurements of high frequency tunability at 3 K are demonstrated in 1.2-mm thick z-cut quartz with a 65-mm radius of curvature (Fig. 2a) and low frequency measurements are made for 1-mm thick SC-cut quartz with a 100-mm radius of curvature (Fig. 2b-c). For z (SC)-cut quartz several distinct acoustic modes are separated by the acoustic free-spectral range of 2.6 (3.4) MHz, as expected. High acoustic quality factors (narrow linewidths) are observed, as represented by $\sim 3 \times 10^7$ (~11 Hz), at 303 MHz (Fig. 2c). The calculated travelling-wave coupling rate [4], $g_{0,}$ approximately equal for both material cuts, is measured to be is $> 2\pi \times 20$ Hz for high frequency and $> 2\pi \times 5$ Hz for low frequency resonances, which differ due to differences in mode volume and acoustic-optic overlap, in agreement with predictions. In the near-collinear regime, the phase matching bandwidth is determined by the length of the 1-mm crystal giving $\sim 6\ MHz$, whereas, when near-perpendicular, the optical beam diameter further limits the interaction length to $\sim 150\ \mu m$, extending the bandwidth to over 50 MHz, allowing for new opportunities with simultaneous coupling to over >20 acoustic cavity modes (Fig. 2b). Additional optimizations of the acoustic cavities could enable access to acoustic modes with quality factors in pure crystals exceeding a billion [6].

In summary, we demonstrate a phonon-frequency-tunable traveling-wave optomechanical interaction in plano-convex bulk phononic resonators. Experiments and matching predictions reveal non-collinear optical coupling to high quality-factor (~ 30 million) longitudinal acoustic modes tunable over 10 GHz in frequency with large masses ($\sim 500\ \mu g$ shown here). This system is well suited for applications requiring customizable interactions over a wide range of phonon frequencies, including hybrid quantum systems, multimode optomechanics, tunable radio-frequency sources and filters, and material spectroscopy.

4. References

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