Stimulated Brillouin-like Optomechanics with Surface Acoustic Wave Cavities

Arjun Iyer[1], Yadav Kandel[2], Wendao Xu[1], John Nichol[2], and William H. Renninger[1,2]
1 Institute of Optics, University of Rochester, Rochester, NY 14627, USA
2 Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
Author e-mail address:aiyer2@ur.rochester.edu

Abstract: Stimulated Brillouin-like optomechanical coupling to Gaussian surface acoustic wave (SAW) cavity modes with record-low losses, is predicted and observed, enabling contact-free optical control of SAW cavities for a wide range of frequencies and material platforms.

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1. Introduction

Surface acoustic waves (SAWs) are elastic excitations bound to the free surface of a solid. The ability to manipulate SAWs on piezoelectric substrates has proved critical to the development of modern electronic devices like compact RF filters, delay lines and oscillators in communication systems [1]. More recently, SAWs have emerged as a pivotal resource in the quest to develop novel hybrid quantum systems and qubit interconnects [2], owing to their strong coupling to most solid-state qubit platforms. Cavity optomechanics, which seeks to mediate strong coherent nonlinear-optical coupling between mechanical and optical cavity fields has emerged as a powerful tool for applications including quantum transduction, and quantum-limited force and displacement-sensors [3]. Engineering robust customizable optical coupling to long-lived surface acoustic waves on planar substrates could pave the way for new strategies for quantum transduction schemes, SAW based chemical sensors, as well as materials spectroscopy. While limited optomechanical coupling to SAWs has been demonstrated through scattering from thermally initiated spontaneous interactions [4], in whispering gallery modes in microspheres [5], or through electrically driven modes on piezoelectric substrates [6], desirable strong and versatile optomechanical control of SAWs on planar substrates has not been demonstrated, to our knowledge.

Here, we demonstrate a novel Brillouin-like stimulated optomechanical interaction between two non-collinear optical fields and high-Q (~ 18,000) surface acoustic modes of a Gaussian SAW cavity on a crystalline GaAs substrate. Additionally, in contrast to most previous studies of SAW cavities, the presented optomechanical technique does not require piezoelectricity, and can be applied to most materials, which we demonstrate by coupling to a non-piezo crystalline direction, enabling the access and control of high-Q surface phonon modes on substrates like diamond and silicon, which, while critical to quantum applications show negligible electromechanical response.

2. Theory

The optomechanical system consists of a Gaussian SAW cavity formed by a series of equally spaced curved metallic Bragg mirrors on a GaAs substrate (Fig. 1a), which mediates coupling between two non-collinear optical beams (pump and Stokes). Analogous to Brillouin interactions with bulk acoustic waves, SAWs can mediate coupling between two optical fields provided phase matching and energy conservation is satisfied. If the pump and Stokes optical fields with wavevectors k_p and $k_s(\approx k_p = k_0)$ are incident at an angle, θ, from the surface normal, the phase matched phonon wavevector magnitude is given by $q = |\overrightarrow{k_p} - \overrightarrow{k_s}| = 2k_0 \sin\theta$ (Fig.1b), which when combined with the Rayleigh SAW dispersion relation yields the phonon frequency $\Omega = qv_R = 2k_0 v_R$. To allow for extended interactions and enhanced acousto-optic coupling, we design Gaussian SAW cavities formed by periodically spaced metallic reflectors.

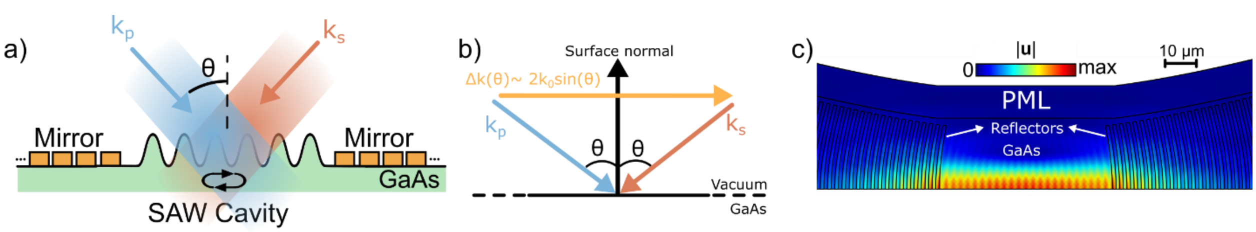

Figure 1: a) SAW cavity mode in a Gaussian cavity on GaAs substrate driven by non-collinear phase matched pump and Stokes optical beams. (b) Vectorial phase matching diagram. (c) FEM calculation of magnitude of displacement for a 500-MHz Gaussian SAW cavity on GaAs with Al reflectors.

We account for the anisotropy of the underlying GaAs substrate to minimize diffraction losses within the cavity [7]. The design protocol is validated with 3D FEM simulations. One such simulation result is shown in Fig. 1c for a 500 MHz SAW cavity oriented along the [110] direction on a [100]-cut GaAs substrate formed by aluminum reflectors. Additionally, the finite size of the optical fields allows for coupling to the same SAW mode over a range of incident angles around the phase matching angle. For Gaussian optical beams the resulting coupling strength at the resonant frequency depends on the incident angle as $\boldsymbol{G(\theta)} \sim \mathbf{exp}\left(-\frac{(\boldsymbol{\theta}-\boldsymbol{\theta_0})^2}{\boldsymbol{\Delta\theta^2}}\right)$, where θ_0 and $\Delta\theta$ are the phase matched angle and the phase matching bandwidth respectively.

3. Experimental Results

A phonon-mediated four-wave mixing measurement technique is developed, building off related techniques used for measuring conventional Brillouin interactions [8]. The SAW mode is driven with two optical drive tones which are incident at their respective phase-matched angles. A probe beam at a disparate wavelength incident along the direction of one of the drive tones, scatters off the driven SAW cavity mode. The angle of incidence of the optical tones is controlled through off-axis incidence on an aspheric focusing lens. The optomechanically scattered signal is collected on a single mode collimator and spectrally filtered using a fiber-Bragg grating to reject excess drive light. The resulting signal is combined with a local oscillator and measured with a balanced detector. The measured signal is a coherent sum of frequency-independent four-wave mixing and the optomechanical resonance, giving rise to Fano-shaped resonances [8]. Measurements at 4 K are made for two types of SAW cavities on [100] GaAs, a 500 MHz cavity along the piezo-active [110] direction and a 460 MHz cavity along the piezo-inactive [100] direction (Fig. 2). Both cavities display at least two distinct resonances separated by 8.2 MHz, corresponding to the free-spectral range of the SAW cavities. The highest quality factor of the resonances observed is ~18,000, for the non-piezo cavity. The most recent measurements for cavities fabricated under improved conditions yield record Q-factors exceeding 100,000**.** The calculated travelling-wave coupling rate [9], $g_{0,}$ for the measured optomechanical interactions is $>2\pi \times 1$ kHz. In addition, higher order gaussian SAW modes resonances are clearly observed at the predicted offset frequency (Fig. 2b). Finally, the coupling strength is maximized at a specific incident angle and exhibits a Gaussian dependence with a phase-matching bandwidth of $\sim 1°$, in agreement with theoretical predictions.

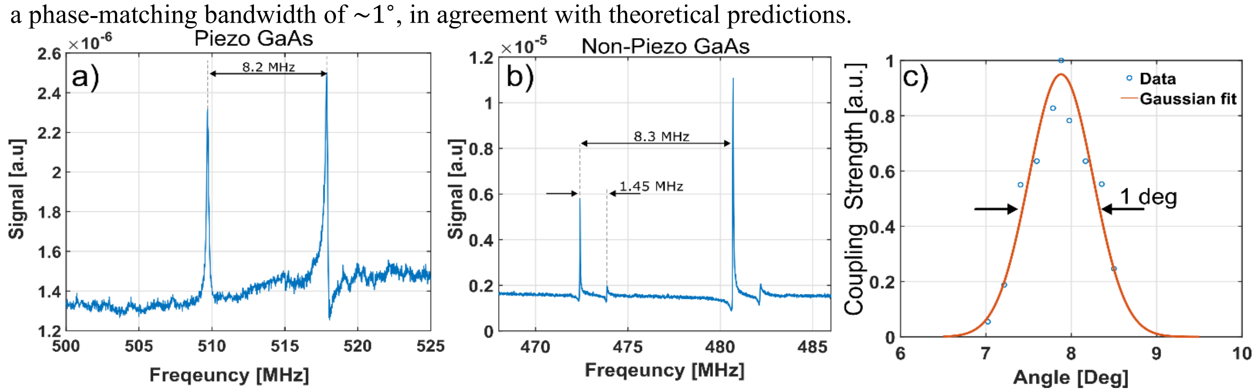

Figure 2: Measured optomechanical response for Gaussian SAW cavities along a) piezo-active [110] direction and b) piezo-inactive [100] direction on [100]-cut GaAs. c) Coupling strength as a function of incident angle with the predicted Gaussian dependence overlaid.

In summary, we demonstrate a stimulated Brillouin-like optomechanical interaction coupling two out-of-plane non-collinear optical fields to ~500 MHz SAW modes of a planar Gaussian cavity, for the first time. Experiments and matching predictions reveal coupling to multiple high-Q longitudinal Gaussian SAW modes along both electromechanically accessible and inaccessible directions. In contrast to previous techniques, this approach is agnostic to wavelength, to the piezoelectricity of the substrate, and it allows for customizable interactions over a wide range of phonon frequencies by simply varying the optical incident angle. These results may be valuable for novel hybrid quantum systems, SAW-based sensors free of electrical constraints, and for studying basic material properties.

4. References

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