Tightly Confined Surface Acoustic Waves as Microwave-to-Optical Transduction Platforms in the Quantum Regime

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(Dated: May 4, 2022)

Surface acoustic waves (SAWs) coupled to quantum dots (QDs), trapped atoms and ions, and point defects have been proposed as quantum transduction platforms, yet the requisite coupling rates and cavity lifetimes have not been experimentally established. Although the interaction mechanism varies, small acoustic cavities with large zero-point motion are required for high efficiencies. We experimentally demonstrate the feasibility of this platform through electro- and opto-mechanical characterization of tightly focusing, single-mode Gaussian SAW cavities at ~3.6 GHz on GaAs in the quantum regime, with mode volumes approaching 6 λ³. Employing strain-coupled single InAs QDs as optomechanical intermediaries, we measure single-phonon optomechanical coupling rates g₀ > 2π × 1 MHz, implying zero-point displacements >1 fm. In semi-planar cavities, we obtain quality factors >18,000 and finesse >140. To demonstrate operation at mK temperatures required for quantum transduction, we use a fiber-based confocal microscope in a dilution refrigerator to perform single-QD resonance fluorescence sideband spectroscopy showing conversion of microwave phonons to optical photons with sub-natural linewidths. These devices approach or meet the limits required for microwave-to-optical quantum transduction.

I. INTRODUCTION

Mesoscopic systems that mediate interactions between mechanical motion and light (optomechanical) or electrical signals (electromechanical) have enabled substantial advances in the control, measurement, and transfer of quantum states [1–14]. Popular architectures include membranes or phononic crystals – defining the mechanical modes of the system – which capacitively or piezoelectrically couple to electrical circuits and parametrically interact with optical resonators [8]. Such systems have been used to cool mechanical oscillators to their quantum ground states [2, 3], produce squeezed states of light [6, 7], prepare, store, and transfer quantum states [5], and to transduce quanta between electrical, mechanical, and optical domains [8, 15–18]. Acoustic modes in bulk structures are also suitable for these purposes [1, 15–21] and often offer the benefit of simple fabrication and on-chip integrability, while maintaining long coherence times approaching, and even exceeding, 1 ms.

Recently, surface acoustic waves (SAWs) — propagating acoustic waves naturally confined to a medium’s surface — have emerged as exciting and versatile mechanical modes for quantum systems [22–26]. As electromechanical elements, SAWs efficiently interact piezoelectrically with external microwave circuits — typically through periodic metallic structures called interdigital transducers (IDTs) — and strongly couple with superconducting qubits at GHz frequencies [22, 25, 27, 28]. When confined within cavities [29, 30], discreet standing-wave eigenmodes can be selectively and coherently populated [12]. As optomechanical elements, acoustic waves parametrically modulate a wide variety of optical systems, e.g., semiconductor quantum dots (QDs) [31–33], atoms [22], defect centers [24, 34, 35], and optical cavities [10, 15–17], and thus effectively mediate electro-optic interactions. SAWs can also be focused, offering opportunities for generating wavelength-scale confinement of phonons in three dimensions [35–37]. Indeed, because of their innate capacity to couple to a wide variety of optical- and microwave-frequency qubits, SAWs have been recognized as “universal quantum transducers” [22].

Within the framework of microwave-to-optical quantum transduction, owing to inherently strong electromechanical interactions, efficient transduction draws attention to optomechanical coupling. A critical threshold to be reached is that where the single-phonon optomechanical coupling rate (g₀) exceeds the intrinsic loss rate of the mechanical and optical subsystems. Similarly, when the system’s quantum cooperativity (C_q) exceeds unity, the optomechanical state transfer exceeds the mechanical decoherence rate. Realized values vary widely depending on the specific platform, but achieving these goals is a very challenging task [8, 18]. Regardless of the optical intermediary (e.g., quantum emitter...
or optical cavity, \( g_0 (C_{Qm}) \) grows linearly (quadratically) with the zero-point motion, \( u_{zpm} \), of the mechanical mode, motivating the development of SAW microcavities with the smallest feasible mode volumes. The ultimate limits of SAW confinement and SAW optomechanical coupling rates with various optical systems have not yet been established.

Here we design, fabricate and characterize high-performance single-mode GaAs SAW cavities at 3.6 GHz for quantum transduction applications. First, we demonstrate semi-planar cavities with internal quality factors \( (Q_i) \) exceeding 18,000 and finesse \( (F) \) exceeding 140 and quantify the dominant mechanical loss mechanisms in order to establish several basic design principles. We then fabricate high-finesse cavities with volumes as small as \( 6\lambda^3 \). By using InAs QDs as local strain probes, we measure zero-point displacements of \( \sim 1.3 \) fm in our smallest cavities. The reported performance is comparable to anticipated ultimate limits of the platform \cite{22}, and we argue that these systems are suitable for quantum transduction. Further, we deploy these devices in a dilution-refrigerated, fiber-based, confocal microscope to convert microwave phonons to optical photons that are resonantly and coherently scattered from a single QD. This demonstrates compatibility of this optomechanical system with sample temperatures corresponding to occupancies of less than one quantum without the need for additional active cooling techniques.

II. DESIGN PRINCIPLES OF SAW CAVITY SYSTEMS

SAW cavities are based on a traditional Fabry-Perot design in which SAWs are confined between two acoustic reflective regions (“mirrors”), resulting in standing-wave strain profiles \cite{1a}. We consider SAWs on the (001) GaAs surface propagating predominantly along the [110] direction. SAW mirrors are defined by periodic rectangular etched grooves on the surface with a 50% duty cycle. This periodicity creates a SAW propagation stop band \cite{1b; gray shaded region}. The stop-band width and the reflectance of each mirror element increases with the etch depth, resulting in a shorter mirror penetration depth. However, bulk-scattering losses also increase with etch depth \cite{30}. We find that a 20 nm etch depth (2.5% of the SAW wavelength, \( \lambda \)) \cite{1b; vertical dashed line} results in a good balance between confinement and bulk loss. A typical penetration depth, \( L_p \), into the mirror region for this etch depth is \( L_p \approx 9\lambda \approx 7 \) μm for SAWs of wavelength 800 nm at 3.6 GHz. Stop-band widths are approximately 80-100 MHz.

Cavity design begins by specifying a desired operating frequency, \( f_0 \). For this frequency, the mirror periodicity, \( \lambda \), is chosen to lie in the center of the stop band \cite{1b; dotted curve}. The SAW wavelength for this frequency along the [110] direction of the bare GaAs surface, \( \lambda(0) \), is calculated from the phase velocity at propagation angle \( \theta_r = \phi_{\text{phase}}(\theta) \), according to \( \lambda(0) = \phi_{\text{phase}}(\theta = 0)/f_0 \) \cite{[Supplementary Information Section A]. In this work, the angle \( \theta \) is referenced with respect to the GaAs [110] direction. The cavity length, \( L_c \), is chosen to be an integer multiple of \( \lambda(0) \): \( L_c = n\lambda(0) \). Defining the cavity center to lie at \( x=0 \), the \( x \)-axis position of the first mirror element (index \( m = 0 \)), \( x_{M,0} \), is simply \( x_{M,0} = L_c/2 \). Subsequent mirror elements are positioned incrementally along the \( x \) axis: \( x_{M,m} = x_{M,0} + m\lambda \) \cite{1a}. An equivalent mirror structure is defined on the opposite side of the cavity with mirror elements at \( x = x_{M,m} = x_{M,0} - m\lambda \).

To excite SAWs and to characterize the cavity performance, an interdigital transducer (IDT) is fabricated within the cavity. We specifically use a “double finger” IDT design in order to eliminate reflections from the individual IDT fingers \cite{23, 25}. The IDT is strategically positioned within the cavity so that the periodic electrical potential applied to the IDT overlaps maximally with the periodic potential of the SAW standing wave \cite{1a}. Specifically, for the standing-wave mode with \( n \) (integer) wavelengths, the IDT fingers are positioned at \( x_{\text{IDT},m} = (-1/8 + m/4)\lambda(0) \) for arbitrary integers \( m \) which keep \( x_{\text{IDT},m} \) within the cavity.

For “linear” (no curvature) cavities, these basic 1D design principles are simply extended an arbitrary distance along the \( y \) axis. For focusing cavities, the structure must be consistent with Gaussian beam physics. Fig. 1c illustrates the structure of a 2D Gaussian beam in the \( x-y \) plane. The mode structure is uniquely defined by a “mode angle”, \( \theta_{\text{mode}} \), which describes the asymptotic behavior of the beam waist (Gaussian half-width), \( w(x) \), far away from the beam focus at \( x = 0 \) \cite{1c; dashed black line}. Ignoring wave velocity anisotropy, the phase fronts of this beam intersecting the \( x \) axis at position \( x_i \) are described by circular arcs of radius \( R(x_i) = x_i[1 + (x_R/x_i)^2] \), where \( x_R = \lambda(0)/(\pi\theta_{\text{mode}}^2) \) is the Rayleigh length of the beam \cite{1c; solid blue curves}. Wave velocity anisotropy on the GaAs (001) surface modifies the mode curvature \cite{37, 38}. The calculated angular dispersion of the phase velocity, \( \phi_{\text{phase}}(\theta) \), and the radial component of the group velocity, \( v_{\text{group},r}(\theta) \), are shown in Fig. 1d \cite{[Supplementary Information Section A]. The curvature correction for \( R(x_i) \) depends on \( \theta \) and is given by: \( c(\theta) = v_{\text{group},r}(\theta)/v_{\text{group},r}(0) \) \cite{1d; inset} \cite{[Supplementary Information Section A]. Fig. 1c illustrates two such phase fronts — one at \( x = 3\lambda(0) \) \cite{[left] and one at \( x = 3\lambda(0) \) \cite{[right] — for a beam with \( \theta_{\text{mode}} = 7.5^\circ \) with (dashed blue curves) and without (solid blue curves) curvature corrections. Numerical calculations of the SAW cavity strain fields \cite{1c] illustrate the described mode shape. The mirror and IDT structures essentially must follow the phase fronts of this mode profile. Our fabricated devices take these details fully into account without any further approximations. Additionally, we take into account variations in the SAW wavelength under the IDT and consequent corrections to the total cavity length.
FIG. 1. Design principles of Gaussian focusing SAW cavities. (a) Cross-sectional illustration of the SAW cavity with the standing-wave pattern along the x [110] direction and the substrate normal in the z [001] direction. White regions represent etched mirror elements. IDT fingers are represented by gold rectangles. Blue sinusoids illustrate the out-of-plane displacement, \( u_z \), of the SAW standing wave. (b) Surface-wave eigenmodes of the periodic etched-groove system defining the SAW mirrors. The spacing between the etched grooves is \( \Lambda \). The mode’s spatial periodicity, \( 2\Lambda \), is calculated at a fixed frequency, \( f_0 \) (here, \( f_0 = 3.6 \text{ GHz} \)). Mode 1 and Mode 2 (solid black curves) become nondegenerate as the mirror etch is introduced. For periodicities \( 2\Lambda \) between the two modes (filled gray region), SAWs cannot propagate and are reflected. Our designs use \( 2\Lambda \) values at the \( \sim \) FWHM) of \( Q \). (c) Illustration of the Gaussian beam profile in the x-y plane. Gray region designates the 1/e field region, i.e., beam waist (GaAs half-widths) \( w(x) \), for \( \theta_{\text{mode}} = 7.5^\circ \). Two phase fronts, at \( x_i = 3\lambda(0) \) [left] and \( x_i = 35\lambda(0) \) [right], are indicated by blue curves. Insets: phase-front curvatures with (dashed) and without (solid) curvature corrections. (d) SAW phase velocity (solid black curve) and the radial component of the group velocity (dashed black line) calculated as a function of the geometric angle, \( \theta \), with respect to the [110] direction on the bare GaAs (001) surface. Inset: \( \theta \)-dependent radial correction function for Gaussian mode curvature on the GaAs (001) surface. (e) Finite-element calculation of the out-of-plane displacement field, \( u_z \), in a focusing cavity, illustrating the Gaussian mode profile described above.

[Supplementary Information Section A]. Device fabrication is described in ref. [33].

III. CHARACTERIZATION OF LOSS MECHANISMS IN LINEAR CAVITIES

In the limit of no focusing, SAWs propagate with a single momentum component — i.e., along the GaAs [110] direction — and losses due to the pseudo-confinement of off-[110] propagating SAWs are negligible [39]. In this case we can reliably quantify losses due to propagation and bulk scattering from mirrors.

Figure 2a shows a scanning electron microscope (SEM) image of a fabricated planar SAW cavity device. The 10-period IDT (i.e., spanning 10 SAW wavelengths in the x dimension) is positioned at the center of a cavity of length \( L_c = 50\lambda(0) \approx 41.29 \mu\text{m} \). The width (y dimension) of the IDT is \( W = 33 \mu\text{m} \). The small number of IDT periods offers a broad bandwidth (~500 MHz) that enables us to excite all cavity modes within the mirrors’ stop band (~100 MHz) and allows the fabrication of shorter cavities. Even with few IDT periods, we have achieved electromechanical conversion efficiencies up to 90% in planar cavities due to resonant enhancement.

Microwave reflection measurements \( (S_{11}) \) at 20 mK reveal a series of evenly spaced cavity modes [Fig. 2b] where the reflectance \( |S_{11}|^2 \) is sharply reduced. The reflection around each mode is well fit by a single Lorentzian lineshape [Fig. 2b; inset]. Our fitting procedure allows us to simultaneously extract the internal quality factor of each mode, \( Q_i \), and the electromechanical coupling rate, \( c_{\text{EM}} \) [23]. Here we focus on \( Q_i \) as this informs on the internal loss rate of phonons in each cavity mode. For this specific device \( (L_c = 50\lambda(0) \approx 41.29 \mu\text{m}; \text{mirror etch depth 18 nm}) \), we measure \( Q_i,\)s exceeding 10,000 at the highest frequencies [Fig. 2c], corresponding to linewidths (full width at half maximum; FWHM) of \( \approx 350 \text{ kHz} \). Interestingly, \( Q_i \) generally increases as the cavity mode approaches the high-frequency edge of the mirror’s stop band. This effect is consistent with numerical calculations and likely originates from decreased bulk scattering as the standing-wave field profile in the mirror regions approaches high-frequency mode structure shown.
in Fig. 1b. This effect can be exploited to optimize cavity lifetimes in single-mode cavities by positioning the mode frequency near the top of the stop band. Comparing similar results across various cavity design parameters (e.g., cavity lengths and etch depths) allows us to identify the dominant loss mechanisms. For example, for long cavities with shallow mirrors, one anticipates propagation losses due to surface imperfections, material defects, or inherent material absorption to dominate. For short cavities with deep mirror etches, bulk scattering from mirror elements is predicted to dominate. We consider propagation loss ($\Gamma_p$), mirror scattering ($\Gamma_m$), and diffraction losses. Each source is modeled in terms of known geometrical parameters and the SAW velocity [22, 23]. Expressions for $Q_i$ and $F$ for a cavity mode of frequency $f_0$ are given by [Supplementary Information Section B]

$$Q_i = \left( \frac{\Gamma_p}{f_0} + 2\beta \frac{v_{\text{phase}}(0)}{f_0} \right)^{-1}$$

$$F = \left( \frac{\Gamma_p}{v_{\text{phase}}(0)} + 2\beta \right)^{-1}$$

$$\Gamma_m = 2\beta \frac{v_{\text{phase}}(0)}{2(L_C + 2L_p)}$$

where $\beta$ (0 $< $ $\beta$ $< $ 1) is a scalar fit parameter that describes the proportional phonon loss per reflection from the mirrors. The expression $v_{\text{phase}}(0)/(2(L_C + 2L_p))$ is equivalent to the cavity free spectral range (FSR). Fig. 2d shows the measured $Q_i$ (upper panel) and $F$ (lower panel), for several mirror etch depths, as a function of cavity length. The most striking result here is that $F$ monotonically increases as $L_c$ decreases toward 40 $\mu$m, although $Q_i$ decreases. Fits to Eqs. 1-2 reveal that propagation loss is the dominant mechanism even for the shortest cavity lengths of 41 $\mu$m [Fig 2d; solid curves]; we estimate absolute loss rates from propagation as $\Gamma_p = 2\pi \times 279.7$ kHz and from mirror scattering as $\Gamma_m = 2\pi \times 161.4$ kHz (for the 41 $\mu$m cavity, 18 $\mu$m etch). Therefore, further reduction to the cavity sizes will improve the finesse. Increased etch depths lead to stronger confinement and thus effectively shorter total cavity lengths ($L_c + 2L_p$), but we find that both $Q_i$ and $F$ are generally reduced as etch depths exceed 18 $\mu$m.

Diffraction loss is difficult to quantify by similar methods, but analytical estimates [23, 29] suggest that for planar devices, diffraction loss rates (~2$\pi$ $\times$ 270 kHz) are comparable to measured propagation loss rates even for these wide
The analyses of planar cavities suggest that further reductions in cavity size benefit cavity finesse, and that cavity performance may be optimized by properly accounting for beam diffraction. Previous work has demonstrated focusing of SAWs on GaAs [37], AlAs/Diamond [35], and AlN [40] substrates. We first assess the limits of SAW focusing by fabricating a series of devices with conservative cavity lengths and a range of mode angles, which nonetheless produce small-mode-volume SAW cavities with \( W \approx 37\lambda(0) \). A slight inward mirror curvature can effectively mitigate diffraction losses, substantially increasing \( Qs \) in Fabry-Perot cavities. Fig. 2a (panel iii) shows a fabricated SAW cavity with mirrors adopting a very slight curvature. The radius of curvature is approximately 10 times the cavity half-length, and the overall cavity dimensions are comparable to that in Fig. 1a. Nonetheless, for an 18 nm etch depth, \( Q_i \left( F \right) \) increases by more than a factor of two, to a value of \(~18,000 (~140)\). To our knowledge, these are the highest reported values for \( Q_i \) and \( F \) in SAW cavities on GaAs reported at these frequencies to date.

IV. FOCUSING SAW CAVITIES

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V. SAW MICROCAVITIES AND APPLICATIONS TO QUANTUM TRANSDUCTION

Upon reducing cavity lengths to \(~28\lambda(0) \approx 22 \pm \mu m\), devices show only a single standing-wave mode within the mirror stop bands, indicating an FSR approaching or exceeding \(~40 MHz\). Linewidths (in power, \(|S_{11}|^2\)) remain smaller than 1 MHz, indicating \( F \approx 40 \), even for tightly focusing cavities with designed beam waists of \( w_0 \leq 1.0 \mu m \). Fig. 4a illustrates the geometry of a fabricated small-mode-volume SAW cavity with \( L_c \approx 19\lambda(0) \approx 18.37 \mu m \). A single cavity mode with a FWHM of 739 kHz at \( f_0=3.550 \text{ GHz} \left( Q_i = 4800 \right) \) is observed as a sharp dip in the \(|S_{11}|^2\) spectrum (Fig. 4b). Calculated estimates of the cavity FSR (44.2 MHz) in combination with this measured linewidth.
FIG. 4. Quantifying high optomechanical coupling rates between SAWs and QDs in small-mode-volume cavities. (a) Device structure of a cavity with $\theta_{\text{mode}} = 14.9^\circ$, $w_0 = 1.0 \, \mu m$ [-1.25$m(0)$], and $L_c = 18.4 \, \mu m$. This device has 10 total IDT periods, divided into two symmetric portions across the cavity’s center. Pink: SAW mirrors. Dark purple: IDTs. Light purple: microwave waveguide traces (truncated here for illustration purposes). Gray scale bar is 40 \, \mu m wide. Inset panels (i) and (ii) are false-color atomic force microscope images of a fabricated device in regions specified by purple and green rectangles, respectively. (b) Microwave reflectance [$10 \log(|S_{11}|^2)$] of the cavity shown in panel a at 1.7K. Upper panel: Spectrum showing only a single cavity mode over an 80 MHz range. Lower panel: Spectrum showing data (open circles) and Lorentzian fit (solid curve) of the single mode around 3.550 GHz. The extracted linewidth (FWHM in power, $|S_{11}|^2$) is 739 kHz. (c) PL spectra of a single QD at the cavity center when driving the SAW cavity on resonance ($f_{\text{SAW}} = 3.53547 \, \text{GHz}$; black) and off resonance (3.53267 GHz; red) at a constant microwave power of $-50.6 \, \text{dBm}$ Markers: data. Solid curves: fits. Reference is averaged with respect to the QD’s center frequency. The cavity used for this measurement has $L_c = 22.5 \, \mu m$, $\theta_{\text{mode}} = 16.6^\circ$, and 20 total IDT periods (distinct from the device used or panels a-b). The estimated on-resonance steady-state phonon number in the cavity is specified by $n$ [Supplementary Information Section D]. (d) Modulation index, $\chi$ (blue), and modulation index squared, $\chi^2$ (orange), as a function of SAW driving frequency at $-50.6 \, \text{dBm}$. $\chi$ ($\chi^2$) is proportional to the local strain field (intensity) at the QD’s location. Error bars on blue markers correspond to $3\sigma$ confidence intervals derived from the fitting algorithm. Solid curves are Lorentzian fits to the data showing a 1 MHz cavity FWHM.

indicate $F > 60$.

The short IDTs with few periods offer relatively weak electromechanical coupling, as seen by the shallowness of the dip in the $|S_{11}|^2$ spectrum. These small cavities were fabricated on substrates containing InAs QDs, and we exploit the inherently strong optomechanical interaction between SAWs and QDs to internally quantify the cavity performance. Indeed, we measure remarkably large internal strain fields under weak external microwave driving. These measurements also directly relate to properties fundamental to applications in quantum transduction, highlighting the potential to use QDs as efficient microwave-to-optical transducers.

The QD exciton energy is modulated by the SAWs strain field, and the luminescence spectrum acquires a series of phonon-mediated sidebands [31–33]. QDs thus act as local strain probes where the relative intensity of the various sidebands corresponds to the local strain field [Supplementary Information Section C]. Fig. 4c shows example photoluminescence (PL) spectra with the SAW cavity driven on resonance (black) and 3 MHz away from resonance (red) at a constant incident microwave power of $-50.6 \, \text{dBm}$ ($\sim 8.7 \, \text{nW}$). On resonance, spectra correspond to a modulation index $\chi=2.29$ and thus a zero-point field amplitude of $u_{\text{ZPF}} \approx 1.3 \, \text{fm}$ [Supplementary Information Section D] [22].

Previous work required significantly greater than $-5 \, \text{dBm}$ (0.3 mW) [41] to $+14 \, \text{dBm}$ (25 mW) [32] to achieve comparable modulation strengths. That is, the strong SAW confinement here provides greater than $10^4$–$10^6$ enhancement in the local strain field around the QD compared to SAWs launched on bare GaAs. This is particularly remarkable considering the very few (~10) periods of short (~5 \, \mu m) IDT fingers used here compared to typically ~100 periods of ~25–40 \, \mu m long IDT fingers. Identical measurements at microwave frequencies spanning the SAW cavity resonance [Fig. 4d] reveal the very strong frequency dependence of the local strain field, originating from the high-Q cavity. These curves correspond to a local SAW intensity ($\sim \chi^2$) contrast of $>100$ when driving on resonance vs. off resonance and again revealing the high-quality SAW resonance. In general, this illustrates a remarkably sensitive method for measuring internal strain fields in SAW cavities.

The efficient transduction of microwave-frequency electromagnetic signals to the optical domain is a critical step toward the realization of large-scale quantum networks [19] [32]. Self-assembled InAs/GaAs QDs mediate this microwave-to-optical transduction process, wherein the SAW-induced periodic modulation of the QD’s energy leads to a series of phonon-mediated sidebands on a resonant and coherent optical pump [31] [33]. The coupling rate and efficiency have been shown to be enhanced by orders of magnitude by positioning the QD at the focus of a confined SAW cavity mode, with single-phonon optomechanical coupling rates, $g_0$, exceeding $2\pi \times 42 \, \text{kHz}$ [33], in line with and even exceeding many other state-of-the-art platforms [8] [18].
From our modulation data shown in Fig. 4c-d, we derive $g_0 = 2\pi \times 1.2$ MHz for this specific cavity [Supplementary Information Section D]. A reasonable error range for this estimate is ±0.25 MHz, arising largely from uncertainty in the equilibrium cavity phonon number [Supplementary Information Section D]. The current improvement largely originates from the significantly decreased mode volume and favorable QD position in the standing-wave SAW field. From this experimental estimate of $g_0$ and literature values for the deformation potential ($G \approx 6.5 \times 10^{14}$ Hz) [22], we estimate $u_{zpm} \approx 1.3$ fm. Purely theoretical estimates of $u_{zpm} \approx 1$ fm and $g_0 \approx 0.82$ MHz are obtained for this specific cavity when taking into account the focusing SAW mode structure [22, 33] [Supplementary Information Section D]. It is interesting to note that the smallest feasible cavity (area $\sim 1.3^2$) is expected to have $u_{zpm} \approx 2.5$ fm and $g_0 \approx 2\pi \times 2$ MHz [22, 61]; our experimentally derived values for $g_0$ and $u_{zpm}$ are approaching these anticipated limits.

An ideal quantum transduction platform must be able to transfer a quantum state between microwave and optical domains without additional thermal noise [10, 18] and with low background photon count rates. At 3.6 GHz, our mechanical resonators are expected to contain fewer than one thermal phonon for temperatures below 250 mK. To demonstrate the feasibility of this platform for microwave-to-optical quantum transduction, we use a fiber-based confocal microscope system to perform resonance fluorescence sideband spectroscopy on a single QD in a SAW cavity in a dilution refrigerator [Fig. 5; Supplementary Information Section E]. The device is held on a sample stage mounted to the dilution refrigerator’s mixing chamber held at 125 mK [Fig. 5a]. The single QD is illuminated by a continuous-wave focused optical pump, and a SAW cavity mode at frequency $f_0=3.658$ GHz is coherently driven with an external microwave source. We tune the optical pump frequency by $+f_0$ (blue detuned) from the QD’s bare exciton frequency, and collect and count inelastically scattered photons through a tunable Fabry-Perot etalon with a $\sim 25$ MHz linewidth. Reflected pump light is rejected by $\sim 10^3$ via polarization [Supplementary Information Section E] and an additional $\sim 10^3$ via spectral filtering [Fig. 5b]. Single-phonon events are detected as photons scattered predominantly at the QD’s resonance energy [Fig. 5c]; very weak scattering at $+2f_0$ indicates that single phonons are created in each scattering event [Supplementary Information Section E] and verifies operation in the resolved-sideband limit [31, 33]. Scattering linewidths ($\sim 25$ MHz) are significantly narrower than the lifetime-limited QD width ($\sim 200$ MHz), indicating coherent photon scattering from a single-photon emitter [33]. Photon count rates $\gtrsim 2$ kHz are measured; accounting for system transmission efficiencies ($\sim 0.01$) and light-trapping effects in the device structure ($\sim 0.06$ collection efficiency), we estimate a photon collection rate of $\sim 200$ kHz and a total sideband scattering rate of $\gtrsim 3.3$ MHz for this steady-state phonon occupation under microwave driving [Supplementary Information Section E]. Phonons can be removed from the cavity at comparable rates under red-detuned pumping [Supplementary Information Section E]. The device used for this specific measurement is similar to the planar cavity shown in Fig. 1, thus requiring relatively high microwave driving powers compared to the tightly focusing cavities shown in Figs. 3-4. The base temperature of 125 mK is higher than typical base temperatures ($\sim 20$ mK) due to additional optical and electrical dissipation in the system and sub-optimal thermal contact between the sample stage and the mixing chamber of the dilution refrigerator.

VI. DISCUSSION AND CONCLUSIONS

Distributing entanglement between computing nodes, e.g. as per the DLCZ protocol [41], is expected to be the most viable initial use for this system. In this case, quantum state transfer must occur before mechanical decoherence and without added thermal noise, but the condition that successful transfer occurs once every cavity lifetime is relaxed. For our mechanical resonators at 3.6 GHz, a typical dilution refrigerator temperature of 20 mK corresponds to a mechanical occupancy of $10^{-4}$. Single QDs efficiently scatter photons at low optical pump powers of $\sim 10 - 100$ nW, compared to $\sim \mu W$ or $\sim$ mW pump powers used in optical cavities [45]. Further, in contrast to photonic crystal cavities [10, 11, 45], the optical field in our system is not highly localized in the host material nor near etched interfaces thus making our system less susceptible to optical heating. Improvements can be made in the mechanical, electrical, and optical performance of our systems. Mechanically, we may further optimize the position of the QD within the SAW’s strain field, minimize bulk SAW scattering using strategic phase mismatching layers or by using Lamb-wave resonators [46], and perhaps by engineering the static strain of the QDs during growth. Electrically, impedance-matching networks may improve electromechanical coupling [23, 47]. Optically, vertical or lateral cavities may be used to optimize the QD’s radiative decay rate and photon collection efficiencies [48, 49]. The QDs’ spectral properties can be improved using charge-control structures [49]. Background levels in our resonance fluorescence sideband measurements can be improved by more strategically preparing the polarization state of the incident beam [50] and by using additional spectral filters in the collection line [51]. Lower base temperatures at our dilution refrigerator’s sample stage can be reached through better thermal contact to the heavy sample stage and by eliminating all unnecessary sources of heat dissipation during the measurement. These results suggest that quantum optomechanical measurements with SAW cavities and QDs is a plausible near-future endeavor.
FIG. 5. Microwave-to-optical transduction from a QD in a SAW cavity. (a) Schematic of a fiber-based confocal microscope for single-QD resonance fluorescence spectroscopy in a dilution refrigerator. A custom-built objective is fixed above a position-controlled SAW cavity device. The objective couples the tip of a single-mode polarization-maintaining (PM) optical fiber to a diffraction-limited focused spot at the device surface. A wavelength-tunable laser transmits through a series of polarizing optics (λ/4 and λ/2 waveplates) before being coupled into the fiber. Reflected pump light and resonance fluorescence is collected through the same fiber. Collected photons transmit through a polarizing beam splitter (PBS) for pump rejection [Supplementary Information Section E] and through a voltage-tunable Fabry-Perot etalon (25 MHz linewidth) before being counted by either a superconducting nanowire single photon detector (SNSPD) or an avalanche photodiode (APD). Scattering spectra are acquired by scanning the etalon over the pump and sideband frequencies. The SAW cavity is driven on resonance by a coherent external microwave source. Inset: Schematic QD energy spectrum when coupled to SAWs under weak microwave driving showing a no-phonon scattering process (green) and single-phonon scattering processes (red/blue). LP: linear polarizer. (b) Collected pump light is spectrally rejected by approximately 5 orders of magnitude with the etalon tuned approximately 3.5 GHz from the pump frequency, resulting in approximately $10^7$ to $10^8$ total rejection of pump photons at the first-order sideband frequencies. (c) Resonance fluorescence sideband spectra as a function of frequency detuning for various microwave driving powers ($P_{\text{micro}}$) and an optical pump power of $\approx 300$ nW. The pump frequency is tuned by $+f_0$ from the QD’s bare exciton frequency (blue sideband pumping); photons are collected around the QD’s bare exciton frequency (set to 0 frequency). The dark count level of the APD is specified by black markers. Filled colored regions represent 1σ variation of count levels over several measurements.

SUPPLEMENTARY INFORMATION: TIGHTLY CONFINED SURFACE ACOUSTIC WAVES AS MICROWAVE-TO-OPTICAL TRANSDUCTION PLATFORMS IN THE QUANTUM REGIME

A. SAW velocity calculations

SAW phase and group velocities as a function of propagation direction on the GaAs [001] surface were calculated using a commercially available finite element method solver. We calculated wave velocities on the bare GaAs surface, in etched mirror regions, and under the superconducting interdigital transducers. For all calculations, the two-dimensional (2D) environment consisted of a rectangle of height ($y$ dimension) 5λ and a width ($x$ dimension) of 1λ ($\lambda=820$ nm). A lower rectangle perfectly matched layer (PML) region was included to account for power dissipation into the substrate bulk. GaAs piezomechanical matrix elements were taken from ref. [10]. These piezomechanical matrices correspond to a coordinate system {$x, y, z$} aligned with the GaAs (100), (010), and (001) directions. Periodic boundary conditions were applied to both material boundaries in the $x$ dimension. Solid mechanics and electrostatics modules were used with piezoelectricity multiphysics coupling. A rotated coordinate system was applied to the rectangle in order to align GaAs [001] with the $y$ axis and GaAs [110] with the $x$ axis. Eigenfrequency calculations were performed around 3.5 GHz. SAW modes were identified by their inherently large quality factors and by visualizing
the resulting mode structures. Such calculations were performed at each of a series of angles by rotating the coordinate system by an angle \( \theta \) about the \( y \) axis (the [001] direction) with respect to the [110] direction. The phase velocity, \( v_{\text{phase}}(\theta) \), was calculated from each result through the relationship \( v_{\text{phase}}(\theta) = \lambda f_0(\theta) \) where \( f_0(\theta) \) is the eigenfrequency calculated at angle \( \theta \).

The phase velocity on bare GaAs was calculated as described immediately above without further modifications; the results are shown in Fig. 1b of the main text. For the mirror etch regions, two rectangular regions of width \( \lambda/4 \), depth \( d \), and spacing \( \Delta = \lambda/2 \) were removed from the simulation environment (symmetrically about the center of the simulation environment). Calculations were performed at each of a series of values of \( d \). Two modes were identified from each result, corresponding to the two modes illustrated in Fig. 1a of the main text, and the phase velocity of each mode was calculated using \( v_{\text{phase}}(\theta) = \lambda f_0(\theta) \). For IDT regions, four rectangles of width \( \lambda/8 \), height 20 nm, and spacing \( \lambda/4 \) were added to the simulation environment. Niobium material parameters were applied to the four additional rectangles.

The phase velocity differs in each region. How the phase velocity is applied to the bare GaAs regions and in mirror regions is described in the main text. In our fabricated devices, we also take into account changes in the phase velocity under the IDT region. Specifically, for a given design frequency, the SAW wavelength under the IDTs is reduced by an amount \( \delta \lambda \), and the total cavity length is thus reduced by an amount \( N_{\text{IDT}} \delta \lambda \) for an IDT with \( N_{\text{IDT}} \) periods. That is, the total number of standing-wave wavelengths across the entire cavity length, \( L_c \), is preserved in this procedure.

To calculate the group velocity, we first define the frequency-momentum dispersion relationship for SAWs on GaAs [001] according to \( \omega(k) = \omega(k, \phi) = v_{\text{phase}}(\phi)k \), where \( k = k\{\cos \phi, \sin \phi\} \). The group velocity vector, \( \mathbf{v}_{\text{group}} \), is defined as usual by \( \mathbf{v}_{\text{group}} = \nabla_k \omega(k) \). To take the derivatives, we model the phase velocity over the entire angular range as

\[
v_{\text{phase}}(\phi) = v_0 + v_n \sin^2(2\pi p/\phi)^2\]

where \( \phi \) is the \( k \)-space angle coordinate defined with respect to the [110] direction. The rotational symmetry properties of GaAs [001] require \( p = \pi \). However, best agreement with numerical calculations requires \( v_0 = 2866 \) m/s, \( v_n = -149 \) m/s, and \( p = 1.06 \pi \). The model fit to the numerical data is shown in Fig. 6. To define the anisotropy-based curvature correction at geometric angle \( \theta \) (inset of Fig. 1b), we take the radial component of the group velocity at angle \( \phi(\theta) \): \( v_{\text{group},r}(\theta) = v_{\text{group},x}(\phi(\theta)) \cos \theta + v_{\text{group},y}(\phi(\theta)) \sin \theta \). Here, \( \phi(\theta) \) is an angle in \( k \)-space that differs from the angle \( \phi \) due to the fact that the group velocity vector does not point radially inward/outward on an anisotropic surface [30]. The function \( \phi(\theta) \) is the solution to the equation derived by setting \( \mathbf{v}_{\text{group}}(\phi) \) to be parallel to \( \mathbf{v}_{\text{phase}}(\theta) = v_{\text{phase}}(\theta)\hat{r} \). Specifically, \( \phi(\theta) \) is the solution to:

\[
\tan^{-1}[v_{\text{group},y}(\phi)/v_{\text{group},x}(\phi)] = \theta
\]

At this angle, \( v_{\text{group},r}(\theta) = |\mathbf{v}_{\text{group}}(\theta)| \).

**B. Expressions for the internal quality factor and finesse for SAW cavities**

We consider two loss mechanisms and derive expressions for the quality factor and finesse for a cavity of length \( L_c \). The loss rate due to propagation is independent of the geometry of the SAW cavities, and is thus essentially a constant. Define the constant rate of propagation loss as \( \Gamma_p \). The loss rate due to mirror scattering, \( \Gamma_m \), depends on the number of mirror reflections per unit time, schematically:

\[
\Gamma_m = \text{loss/time} = \text{loss/reflection} \times \text{reflections/time}
\]

We define a constant factor \( \beta \) to describe the phonon loss per reflection. The number of reflections per time depends on the SAW velocity and the total cavity length \( L_c + 2L_p \) via:

\[
\text{reflections/time} = 1/[(L_c + 2L_p)/v_{\text{phase}}(0)]
\]

The factor
\( \nu_{\text{phase}}(0)/(L_c + 2L_p) \) is identified as 2×FSR where FSR is the cavity’s free spectral range. The loss rates add at a specific cavity frequency \( f_0 \), and so the total internal quality factor, \( Q_i \), is \( Q_i = f_0/(\Gamma_p + \Gamma_m) \). The finesse is defined by replacing \( f_0 \) by the FSR in the previous expression. The model shown in Fig. 2b was fit to the measured \( F \). We take a constant value \( L_p=7 \) \( \mu \text{m} \) in our model, which was derived from independent measurements of the cavity FSR for an 18 nm etch depth.

### C. QD photoluminescence sideband measurements

Single-QD photoluminescence (PL) measurements were performed using the system described in ref. 33. The SAW cavity device was held at \( \sim 5 \) K in an evacuated cryostation. QDs near the SAW cavity’s center were optically pumped with a diffraction-limited focused beam of a 632 nm laser. Collected pump light was rejected using a long-pass optical filter. Photons from a single QD were isolated using a 2 nm bandpass filter and a voltage-tunable Fabry-Perot etalon filter with a \( \sim 600 \) MHz bandwidth. The SAW cavity was actively driven at a specified microwave power and frequency using an external vector network analyzer (VNA). PL spectra were collected at each microwave frequency while keeping the microwave power constant. The spectrum corresponding to each microwave power and frequency was independently fit for the modulation index, \( \chi \), using the expression available in ref. 31. The QD width and amplitude and the SAW frequency were constrained to independently measured values. A parameter corresponding to a linear dependence on the SAW field. We estimate \( \bar{\kappa} \) from from the incident microwave power, the measured cavity linewidth, and the estimated microwave coupling using

\[
n = \frac{n_p \times P_{\text{micro}}}{h \omega_m} \frac{1}{2\pi \Gamma_{\text{mech}}/2}
\]

where \( h \) is the reduced Planck’s constant, \( P_{\text{micro}} \) is the microwave power incident on the IDTs, \( \omega_m = 2\pi f_0 \) is the SAW frequency in angular units, \( \eta \) is the proportion of incident microwave power coupled into the cavity (determined from the microwave reflectance spectrum, \( |S_{11}|^2 \)), and \( \Gamma_{\text{mech}}/2\pi \) is the internal loss rate of the SAW cavity mode. To calculate \( g_0 \), we use the following values, derived from the in situ microwave reflectance spectrum at 5K (Fig. 8; top panel): \( f_0=3.536 \) GHz; \( \Gamma_{\text{mech}} = 2\pi \times 1 \) MHz; \( \eta=0.0091 \) (corresponding to a 0.04 dB variation in the \( |S_{11}|^2 \) spectrum); \( P_{\text{micro}} \) (calibrated)=−50.6 dBm. The estimate \( \Gamma_{\text{mech}} = 2\pi \times 1 \) MHz is verified precisely by the internal strain measurement shown in Figs. 4c-d. The result is \( g_0 = 1.2 \) MHz ± 0.25 MHz. Uncertainty arises largely from the estimates of the equilibrium phonon number due to \( \sim \pm 1.5 \) dB uncertainty in attenuation from coaxial cables, connections, wirebonds, and co-planar waveguides in our setup and devices. A dispersive lineshape, likely arising from increased electrical resistance in the optical cryostat setup at 5K, complicates a precise estimate of the external electromechanical coupling rate, but we assume a reasonable uncertainty of \( \sim \pm 0.01 \) dB.

We alternatively estimate \( g_0 \) using the microwave characterization of a very similar device in a different cryostat at 1.6K (Fig. 8; bottom panel) via

\[
n = \frac{4P_{\text{micro}} \kappa_{\text{ext}}}{h \omega_m} \kappa^2
\]

where \( \kappa_{\text{ext}} \) is the external electromechanical coupling rate and \( \kappa = \kappa_{\text{int}} + \kappa_{\text{ext}} \) where \( \kappa_{\text{int}} \) is the internal loss rate of the cavity [45]. We derive \( \kappa_{\text{ext}} = 2\pi \times 5.645 \) kHz from a Lorentzian fit to the microwave reflectance data [Fig. 8; lower panel]. An internal loss rate \( \kappa_{\text{int}} = 2\pi \times 1 \) MHz is assumed from the internal strain characterization shown in Figs 4c-d. The result is \( g_0 = 1.158 \) MHz.

The zero-point displacement amplitude, \( u_{\text{zpnm}} \), was estimated from our experimentally derived \( g_0 \) via the relationship \( g_0 = [2\pi/\lambda(0)]G u_{\text{zpnm}} \), where \( G \) is the strain susceptibility (deformation potential) of the QD exciton. The exact value of \( G \) in this scalar treatment depends on the specific position of the QD within the SAW strain field; we use \( 6.5 \times 10^{14} \) Hz [31]. Purely theoretical estimates of the zero-point displacement were also derived via \( u_{\text{zpnm}} = 2 \text{fm}/\sqrt{A[\mu m^2]} \) [22] where \( A[\mu m^2] \) is the mode area expressed in units of \( \mu m \). We calculated \( A \) from \( A = V/\lambda \) where \( V \) is the SAW cavity mode volume [22]. Mode volume was calculated using methods detailed in ref. 33. For a cavity length of 18
μm, a penetration length of 7 μm and a mode angle of 0.26 radians, the results are $V \approx 3\mu m^3 \approx 6\lambda^3$ and $u_{zpm} \approx 1$ fm and $g_0 \approx 0.81$ MHz. Significant differences between theoretical and experimental estimates may arise from the position dependence of the QD-SAW coupling in the non-uniform SAW strain distribution. Nonetheless, we find fair agreement between theoretical and experimental estimates.

E. Resonance Fluorescence Sideband Measurements in a Dilution Refrigerator

Resonance fluorescence sideband spectroscopy was performed using a custom-built fiber-based confocal microscope setup with polarization and spectral filtering, illustrated in Fig. 5. The basic optical setup is motivated by the designs described in refs. 33 [52]. The critical modification is the replacement of the sample objective with a single-mode polarization-maintaining (PM) optical fiber. Additionally, we use both a $\lambda/4$ plate and a $\lambda/2$ plate to prepare the polarization state of the excitation laser beam before coupling into the PM fiber. We use 850 nm elliptical-clad PM optical fiber with a 100-μm coating and no external jacket. This fiber is fed into our dilution refrigerator (DR) through a fixed vacuum feedthrough and connected to a custom-built objective with 0.5 numerical aperture comprising two aspheric lenses. The fiber tip is positioned in the focal plane of one of the lenses. The objective is fixed above the sample/device. The sample/device is mounted to the sample post of a position-controllable cryo positioning stage.
FIG. 8. Top: In situ microwave reflectance spectrum \([10\log(\|S_{11}\|^2)]\) from the device used for the optical measurements shown in Figs. 4c-d at \(\sim5K\). Slow background variations have been subtracted. Bottom: Microwave reflectance spectrum from a similar device in a different cryostat at 1.6K. The fit internal loss rate \(\kappa_{\text{int}}\) and external coupling rate \(\kappa_{\text{ext}}\) are specified in the plot.

and positioned in the focal plane of the second lens of the objective. Basically, the fiber tip is coupled to a diffraction-limited spot at the sample surface. The IDT in the device is contacted electrically via coplanar waveguides to coaxial cables to an external microwave source.

To perform sideband spectroscopy, reflected and collected pump light must be maximally rejected. For polarization rejection, the basic goal is to prepare the incident beam in one of the polarization-maintaining modes of the PM fiber. While there are typically two orthogonal linearly polarized modes that satisfy this criteria, we find that the significant temperature variation along the fiber between the mixing chamber \((\sim100\ \text{mK})\) and ambient \((\sim293\ \text{K})\) causes polarization rotation and ellipticity. Though unpredictable, we can compensate for it \textit{in situ} using the external wave plates while keeping the fiber tip fixed. The frequency of a single QD is first identified, and then the pump frequency is chosen depending on the desired scattering process. With this pump frequency fixed, we monitor the reflection signal and rotate the external polarizing optics until the signal is maximally rejected. We typically find relatively stable behavior with \(\sim10^3 - 10^4\) polarization rejection, with occasional spontaneous transient hops up to \(\sim10^2\) rejection, presumably due to thermal fluctuations or vibrations along the fiber [Fig. 9].

This collected signal containing both residual reflected pump light (polarization-reduced) and light scattered by the QD is transmitted through a voltage-tunable Fabry-Perot etalon with a \(\sim25\ \text{MHz}\) linewidth (full width at half max) before being fiber-coupled once more and sent to a photon counter. The desired phonon scattering process is selected by tuning the etalon transmission frequency with respect to the pump. We estimate a total system transmission efficiency of 0.01 between the collection optics and the photon counter. We use transfer-matrix methods to account for light-trapping effects in our device structure [?] and calculate collection efficiencies of \(\lesssim0.06\) into our NA=0.5 objective from QDs emitting in a \(\lambda\)-thick cavity between two DBRs. Therefore, from measured count rates on the APD, we estimate total sideband scattering rates exceeding \(\sim3\ \text{MHz}\) under these specific experimental conditions.

For the measurement shown in Fig. 5, the optical pump power incident on the sample interface was approximately 300 nW at 911.8949 nm (1st-order blue sideband of the QD). An electromechanical coupling efficiency of \(\sim60\%\) was measured for this particular cavity mode. A cavity phonon population of \(16.6\times10^9\) \((2.6\times10^{12})\) is estimated when driving the cavity at \(-42\ \text{dBm}\) \((-20\ \text{dBm})\). Photons were collected around the QD’s center energy. Under blue-detuned pumping at \(+f_0\) (Fig. 10; blue curves) the rate of scattering to \(+2f_0\) with respect to the QD is relatively weak, illustrating the resonant enhancement of scattering to the QD’s center frequency and verifying that our system lies in the resolved sideband limit. A similar spectrum is acquired under red-detuned pumping at \(-f_0\) (Fig. 10; red curve), highlighting the potential for sideband cooling in this system. The difference in count rates between red-detuned pumping and blue-detuned pumping arises from a pump spectral misalignment with the red sideband and from contributions from other quasi-resonant QDs in the pump spot.
FIG. 9. Reflected and collected pump light over a ∼24 minute time interval during polarization alignment of the two wave plates. The four power spikes indicated by arrows were caused by intentional polarization scrambling. The peak power of ∼4 μW is approximately half of the total collected reflected pump power because of the linear polarizers in the collection path. The final ∼3-4 minutes in this plot (designated by a gray ellipse) were recorded with the wave plates at their optimized angles. The typical power in this region is ∼10 nW, corresponding to ∼10^3 polarization rejection and showing good stability.

FIG. 10. Resonance fluorescence sideband measurements under (blue curves) first-order blue-detuned pumping at +f_0 and (red curve) red-detuned pumping at −f_0 with respect to the QD’s center frequency (set to 0). Microwave driving power was −26 dBm at f_0=3.65765 GHz. Optical pump power was approximately 300 nW. The large asymmetry in counts between the blue curves around 0 and 2f_0=7.315 GHz is due to resonant enhancement of the phonon-creating scattering process for blue-detuned pumping in the presence of the QD, verifying operation in the resolved-sideband limit. Counts at +2f_0 largely arise from first-order scattering from the Lorentzian tail of the QD and may have a small contribution from other quasi-resonant QDs in the pump spot. The red curve originates from a phonon-annihilating process when pumping the system at −f_0.

[1] A. D. O’Connell, M. Hofheinz, M. Ansmann, R. C. Bialczak, M. Lenander, E. Lucero, M. Neeley, D. Sank, H. Wang, M. Weides, J. Wenner, J. M. Martinis, and A. N. Cleland, [Nature 464, 697 (2010)].
[2] J. Chan, T. P. M. Alegre, A. H. Safavi-Naeini, J. T. Hill, A. Krause, S. Gröblacher, M. Aspelmeyer, and O. Painter, [Nature 478, 89 (2011)].
[3] J. D. Teufel, T. Donner, D. Li, J. W. Harlow, M. S. Allman, K. Cicak, A. J. Sirois, J. D. Whittaker, K. W. Lehnert, and R. W. Simmonds, [Nature 475, 359 (2011)].
[4] E. Verhagen, S. Deléglise, S. Weis, A. Schliesser, and T. J. Kippenberg, [Nature 482, 63 (2012)].
[5] T. A. Palomaki, J. W. Harlow, J. D. Teufel, R. W. Simmonds, and K. W. Lehnert, [Nature 495, 210 (2013)].
[6] A. H. Safavi-Naeini, S. Gröblacher, J. T. Hill, J. Chan, M. Aspelmeyer, and O. Painter, [Nature 500, 185 (2013)].
[7] T. P. Purdy, P.-L. Yu, R. W. Peterson, N. S. Kampel, and C. A. Regal, [Physical Review X 3, 031012 (2013)].
[8] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, [Reviews of Modern Physics 86, 1391 (2014)].
[9] R. W. Andrews, R. W. Peterson, T. P. Purdy, K. Cicak, R. W. Simmonds, C. A. Regal, and K. W. Lehnert, [Nature Physics 10, 321 (2014)].
[10] K. C. Balram, M. I. Davañjo, J. D. Song, and K. Srinivasan, [Nature Photonics 10, 346 (2016)].
[11] M. J. Weaver, F. Buters, F. Luna, H. Eerkens, K. Heeck, S. de Man, and D. Bouwmeester, [Nature Communications 8, 824 (2017)].
[49] N. Tomm, A. Javadi, N. O. Antoniadis, D. Najer, M. C. Löbl, A. R. Korsch, R. Schott, S. R. Valentin, A. D.Wieck, A. Ludwig, and R. J. Warburton, Nature Nanotechnology 10.1038/s41565-020-00831-x (2021).

[50] J. Phoenix, L. Gaudreau, M. Korkusinski, P. Zawadzki, A. Bogan, S. Studenikin, R. L. Williams, and A. S. Sachrajda, Review of Scientific Instruments 91, 083107 (2020).

[51] G. S. MacCabe, H. Ren, J. Luo, J. D. Cohen, H. Zhou, A. Sipahigil, M. Mirhosseini, and O. Painter, Science 370, 840 (2020).

[52] A. V. Kuhlmann, J. Houel, D. Brunner, A. Ludwig, D. Reuter, A. D. Wieck, and R. J. Warburton, Review of Scientific Instruments 84, 073905 (2013).