

Strong thermomechanical noise squeezing stabilized by feedback

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Squeezing the quadrature noise of a harmonic oscillator enhances its sensitivity. Stabilization of the anti-squeezed quadrature can overcome the 3 dB squeezing limit by parametric modulation. Here, we apply this method to soft-clamped membrane resonators, which hold promise for both classical and quantum sensing applications. We compare piezoelectric and capacitive parametric modulation and observe thermomechanical squeezing by up to 17 and 21 dB, respectively. Finally, we provide a full quantum theory of combining this approach with quantum-limited motion measurement. We conclude that quantum squeezing is feasible at moderate cryogenic temperatures and realistic device parameters.

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Introduction. Mechanical resonators can sense a variety of physical entities—including force [1], acceleration [2], mass [3], voltage [4], and magnetic fields [5]—with astounding sensitivity. As technical improvements continue, sensors now approach limits dictated by quantum mechanics. Common techniques to read out a mechanical resonator position add noise subject to the standard quantum limit (SQL) [6,7]. However, techniques to overcome the latter have been demonstrated recently [8,9].

Sensitivity can be limited by fluctuations intrinsic to the mechanical resonator, primarily thermal fluctuations and, ultimately, vacuum fluctuations. When such limits are reached, squeezing the measured mechanical quadrature noise can improve the sensitivity. This is possible through parametric modulation of the elastic constant, as demonstrated previously [10–14]. Recently, this principle has been extended to the quantum regime for single trapped ions [15], and has been shown with superconducting micromechanical resonators, using microwave reservoir engineering [16–18].

In contrast, our goal is to demonstrate strong parametric squeezing—ultimately squeezing also quantum noise—in a versatile sensor platform, namely soft-clamped nanomechanical membrane resonators. They offer large sensing areas on the order of $(0.3 \text{ mm})^2$, combined with nanogram effective masses and quality factors that can exceed 10^9 [19]. Since their recent advent [20], they have been used for nanoscale force imaging [21], measurement of quantum fluctuations of

optical forces [22,23], and are promising candidates for sensing minute forces, e.g., from individual spins [1,24,25].

Given the large thermal occupancy of such resonators even at cryogenic temperatures, a potential limitation of conventional squeezing protocols is that in the steady state, parametric systems reach an oscillation instability when the target quadrature is squeezed by 3 dB. However, this limit can be overcome using a detuned parametric drive [14] or actively stabilizing the antisqueezed quadrature [26,27]. In a proof-of-principle experiment, the latter protocol has been used to demonstrate squeezing of up to 15 dB [28].

In this Letter, we benchmark a similar protocol applied to our membrane force sensor and compare the performance of two parametric modulation methods: piezoelectric actuation and capacitive coupling. By applying quadrature feedback stabilization, we demonstrate a maximum squeezing of 17 and 21 dB, respectively, with moderate device parameters at room temperature. Furthermore, we develop a model that predicts the behavior of the protocol in the quantum regime under continuous quantum-limited monitoring. We estimate that squeezing below the zero-point fluctuations is attainable with realistic parameters and at a moderate bath temperature $T = 10 \text{ K}$.

Protocol. A mechanical oscillator, characterized by an effective mass m , mechanical damping rate Γ_m , and natural elastic constant k_m is driven around resonance by a force $F_d = F_0 \cos(\Omega t)$. The angular frequency Ω of the drive is set by an electronic oscillator, which is phase locked to the mechanical motion. The parametric drive, offset by a phase ϕ_p relative to the electronic oscillator, modulates the mechanical stiffness at twice the drive frequency 2Ω with an amplitude k_p .

We express the apparent mechanical motion, referenced to the phase-locked electronic oscillator, as

$$\ddot{x} + \Gamma_m \dot{x} + \frac{1}{m} [k_m + k_p \sin(2\Omega t + \phi_p)] x = \frac{F_{th} + F_d + F_{fb}}{m}, \quad (1)$$

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where F_{th} is the thermomechanical noise force and F_{fb} is an effective force representing the action of the phase-locked loop that stabilizes the relative phase between the mechanical oscillation and the electronic oscillator drive.

For a high-quality factor oscillator and $\Omega \sim \Omega_m$, the motion is described in the frame rotating at the frequency Ω in terms of the two slowly varying quadratures $X_1(t)$ and $X_2(t)$, defined as [10]

$$x(t) = X_1(t) \sin(\Omega t) + X_2(t) \cos(\Omega t). \quad (2)$$

When the parametric modulation and the stabilization are turned off, the oscillator is driven by the thermomechanical noise and the drive F_d . The phase quadrature X_2 as a function of the frequency difference $(\Omega - \Omega_m)$ shows a dispersive shape, providing an error signal for frequency stabilization.

With both the feedback and parametric modulation turned on, the phase space vector—whose components are represented by a sum of a coherent amplitude $\bar{X}_i$ and a fluctuating component δX_i —fluctuates around the equilibrium position $(\bar{X}_1, \bar{X}_2)^T = [F_0/m\Omega_m\Gamma_m(1+g_s), 0]^T$, where $g_s = \Gamma_s/\Gamma_m$ and $\Gamma_s = k_p/(2m\Omega_m)$ is the squeezing rate. The equations for the residual fluctuations of the two quadratures in the Fourier domain read [29]

$$\begin{aligned} \delta \bar{X}_1(\omega) &= \frac{1}{2m\Omega_m} \frac{1}{-i\omega + \frac{\Gamma_m}{2}(1+g_s)} \tilde{F}_{\text{th}2}(\omega), \\ \delta \bar{X}_2(\omega) &= -\frac{1}{2m\Omega_m} \frac{1}{-i\omega + \frac{\Gamma_m}{2}(1-g_s+g_{\text{fb}})} \tilde{F}_{\text{th}1}(\omega), \end{aligned} \quad (3)$$

where $g_{\text{fb}} = \Gamma_{\text{fb}}/\Gamma_m$, with the feedback force expressed as $F_{\text{fb}} = m\Omega_m\Gamma_{\text{fb}}X_2 \sin(\Omega t)$, and the thermal force $F_{\text{th}}(t) = F_{\text{th}1}(t) \sin(\Omega t) + F_{\text{th}2}(t) \cos(\Omega t)$. Equation (3) shows that the two quadratures have different mechanical susceptibilities. The amplitude quadrature X_1 , which is in phase with the parametric modulation, experiences an increased damping rate. As the squeezing increases, the phase quadrature X_2 damping is reduced. The system reaches the instability threshold when $\Gamma_s = \Gamma_m$, limiting the maximum squeezing of $\delta \bar{X}_1$ to 3 dB, unless the feedback is turned on.

The thermal force quadratures are uncorrelated, and the double-sided power spectral density (PSD) reads $S_{F_{\text{th}1}} = S_{F_{\text{th}2}} = 2S_{F_{\text{th}}}$, with $S_{F_{\text{th}}} = 2m\Gamma_m k_B T$. For the system in thermal equilibrium, the variances for the quadratures are

$$\left(\frac{\sigma_1}{\sigma_0}\right)^2 = \frac{1}{1+g_s}, \quad \left(\frac{\sigma_2}{\sigma_0}\right)^2 = \frac{1}{1-g_s+g_{\text{fb}}}, \quad (4)$$

where $\sigma_0^2 = k_B T/m\Omega_m^2$.

The protocol allows a displaced squeezed state to be obtained from an initial thermal state, and the amplitude fluctuations can be squeezed below the standard 3 dB limit.

Experimental results. We employ highly stressed Si_3N_4 soft-clamped membrane resonators patterned with a phononic crystal. The resonators are operated at room temperature and a pressure of 10^{-7} mbar. We devise two alternative configurations to drive the membranes parametrically. First, we use a membrane hosting a single defect in the center. The membrane is glued on the four sides of the silicon frame to a ring piezoelectric actuator. When a voltage is applied to the actuator, the membrane experiences a modulation of the

stress, and therefore of the resonance frequency, via the shear force applied to the frame, resulting in parametric driving.

The second design is illustrated in Fig. 1(b). The membrane hosts a phononic dimer, which gives rise to a symmetric and an antisymmetric mode whose envelopes span both defects [30]. One of the two defects is metallized with a 50-nm-thick aluminum pad, with a diameter of 100 μm [19]. The membrane is then bonded to a silicon chip with a printed circuit consisting of a circular signal electrode surrounded by a grounding rim. The metallized defect forms a capacitor with the underlying electrodes. A voltage $V(t)$ applied to the circuit creates a modulation of the elastic constant,

$$k_p = -\frac{1}{2} \left(\frac{\partial^2 C(x)}{\partial x^2} \right) \bigg|_{x_{\text{eq}}} V^2(t), \quad (5)$$

where $C(x)$ is the total capacitance and x_{eq} is the equilibrium position of the membrane.

The membrane is first driven at resonance, and the mechanical motion is detected using a Mach-Zender interferometer at a wavelength of 1535 nm [30], with a sensitivity of 700 fm/ $\sqrt{\text{Hz}}$. The signal, demodulated by a lock-in amplifier, has a phase offset from the resonant force given by the overall delay caused by the electronics. The resonant force phase is optimized using a PLL such that the demodulated quadratures correspond to the phase (X_2) and amplitude (X_1) quadratures. The signal is frequency doubled and sent to the actuator to apply the parametric drive.

Parametric drive with piezoelectric actuation. We first study the resonator's response to the drive scheme shown in Fig. 1(a). The resonator design uses a so-called Dahlia-class defect [22] centered in a phononic crystal structure approximately 3.3 mm $\times$ 3.3 mm in size, etched into a 41-nm membrane of stoichiometric Low Pressure Chemical Vapor Deposition (LPCVD) Si_3N_4 with a stress of 1.25 GPa. The resonator has a frequency $\Omega_m = 2\pi \times 1.33$ MHz and a quality factor $Q = (28 \pm 5) \times 10^6$. We first measure the tuning of the resonance frequency with the dc voltage applied to the ring piezoelectric actuator. The shift is linear, with a slope that is typically $\simeq -300$ Hz/V [inset of Fig. 2(a)].

We increase the amplitude of the parametric modulation V_p while recording the X_1 quadrature. The phase of the parametric drive is chosen to get either deamplification ($\phi_p = 0$) or amplification ($\phi_p = \pm\pi/2$) of $\bar{X}_1$. The resulting amplitude gain curves, with the gain defined as $|\bar{X}_1/\bar{X}_{1,V_p=0}|$, are plotted in Fig. 2(a). When $\bar{X}_1$ is amplified, the quadrature reaches the parametric threshold for $g_s \equiv V_p/V_t = 1$, where V_t is the threshold voltage. Conversely, when $\phi_p = 0$, the threshold can be overcome by turning on the resonant drive and the PLL as part of the stabilization scheme. This results in a maximum quadrature amplitude reduction of $\simeq -17$ dB observed at $V_p = 10$ V. Fitting the measured curves results in an estimated $V_t = (151 \pm 1)$ mV. We verify the performance of the protocol by directly measuring the squeezing of the thermal fluctuations $\delta X_1(t)$. We extract σ_1^2 from the PSD $S_{X_1}(\omega)$, at increasingly larger parametric drive voltage [Fig. 2(b)]. Each resonance is fit with a Lorentzian function and a constant background to account for shot noise, limiting the interferometer's sensitivity while discarding the data at 0 Hz. The variance as a function of V_p is shown in Fig. 2(c).

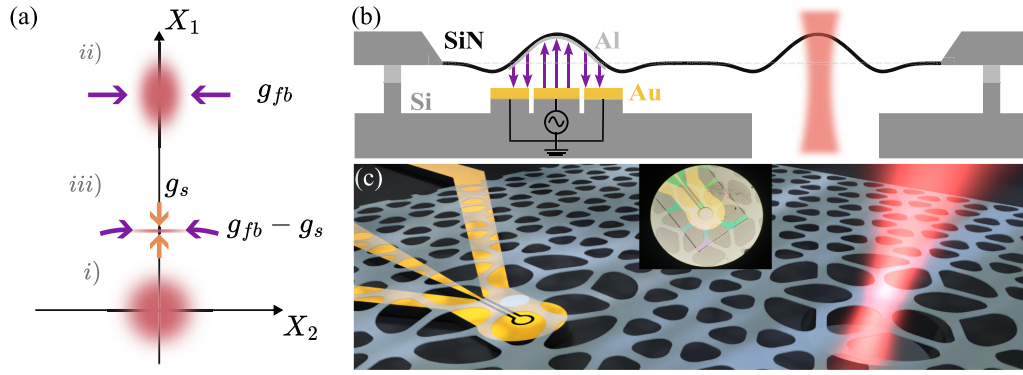


FIG. 1. Experimental protocol and platform for capacitive parametric driving. (a) A sketch of the experimental protocol. A mechanical resonator in a thermal state (i) is displaced along the amplitude quadrature X_1 by a resonant drive while the phase quadrature X_2 is stabilized through a phase-locked loop (PLL), as depicted in (ii). The X_2 quadrature is dampened by a feedback rate $\Gamma_b \propto g_b$ (purple arrows). By applying a parametric drive, the mean value of the X_1 quadrature is deamplified, while the variance is squeezed by a rate $\Gamma_s \propto g_s$ (orange arrows), shown in (iii). The PLL counteracts the antisqueezing of the X_2 quadrature variance, preventing the system from undergoing self-oscillation. (b) A double-defect silicon nitride (SiN) membrane lies on aluminum (Al) pillars of a silicon (Si) chip with a printed gold (Au) electrode circuit. An aluminum pad is deposited onto one of the defects, forming a capacitor with the underlying electrodes. For detection purposes, a hole is etched on the side of the electrode chip beneath the nonmetallized defect. (c) A rendered angled view of the capacitive platform with an inset of a microscopic image.

Fitting the model in Eq. (4) returns $V_t = (148 \pm 4)$ mV. This threshold is significantly higher than anticipated based on the static frequency response shown in the inset of Fig. 2(a). This discrepancy arises from the reduced piezoelectric response at high-frequency parametric drives.

Despite the strong squeezing that can be achieved through piezoelectric actuation, reaching even larger values is experimentally challenging. Applying larger $V_p \gg 10$ V is not a viable option due to increased noise levels of the detected mechanical motion, likely attributable to the heating of the actuator. Nonetheless, on a few assemblies, we observed an increase in the squeezing performance—corresponding to a fourfold drop in V_t —when measuring specific piezoelectric offset voltage V_{dc} . We attribute this enhancement to the presence of an in-plane mode with angular frequency $\Omega_{ip}(V_{dc}) \approx 2\Omega_m$ (see Supplemental Material [31]).

Capacitive parametric drive. Next, we analyze the performance of the capacitor-based design. We use a $4.8 \text{ mm} \times 5.4 \text{ mm}$ Lotus-class dimer membrane [32], with a thickness of 50 nm. The dimer symmetric mode has a resonance frequency $\Omega_m = 2\pi \times 1.3 \text{ MHz}$, with $Q = (0.67 \pm 0.04) \times 10^6$. The frequency shift has a quadratic dependence on the applied dc voltage, as shown in the inset of Fig. 3 [33]. To generate squeezing, we apply a bias voltage $V(t) = V_{dc} + V_p \cos(\Omega_p t + \varphi)$ [33] with $V_{dc} = 8$ V. We observe an increase in the quality factor to $Q(V) \approx 2Q(V_{dc} = 0)$ at the chosen bias voltage.

The variance of X_1 at different parametric drive amplitudes (Fig. 3) is obtained following the steps described above. Despite the considerably lower Q factor compared to the resonator used to study the piezoelectric-actuated drive, the fitted threshold voltage is almost one order of magnitude less, with a

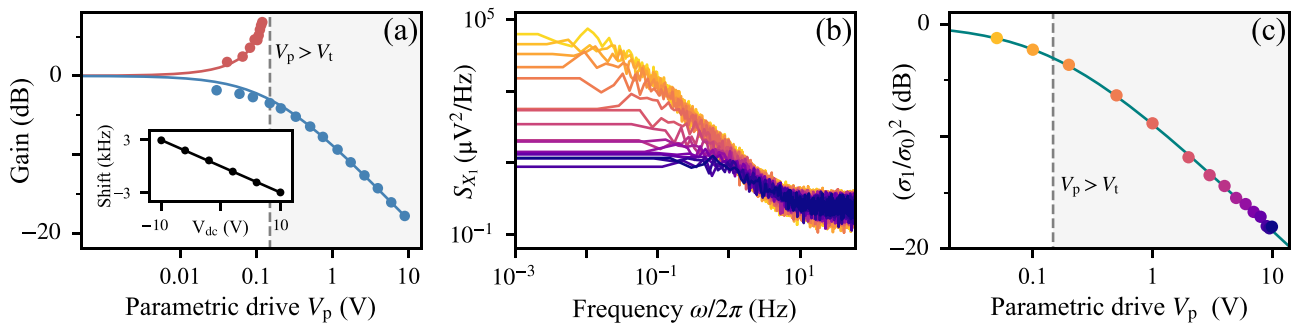


FIG. 2. Parametric modulation of a membrane resonator using a piezoelectric actuator. (a) Gain of the amplitude quadrature $\bar{X}_1$ as a function of the parametric drive, for $\phi_p = \pi/2$ (red dots) and $\phi_p = 0$ with phase stabilization (blue dots). When the quadrature is amplified, it diverges at the threshold (dashed gray line), while the 3 dB limit can be overcome (gray shaded area) when X_1 is deamplified. The inset shows the resonance frequency tuning as a function of dc piezoelectric voltage. All data are downsampled for visual clarity. The solid lines are fits to the experimental data. (b) Power spectral density of the X_1 quadrature for increasing parametric drive voltage. When the parametric drive voltage is increased from 0 V (yellow line) to large values (increasingly dark lines), the total mode damping increases. (c) Variance σ_1^2 obtained from fitting the PSDs in (b) normalized by the variance at $V_p = 0$ V, σ_0^2 . The markers have the same color coding as in (b). The solid line is a fit to the experimental data based on Eq. (4).

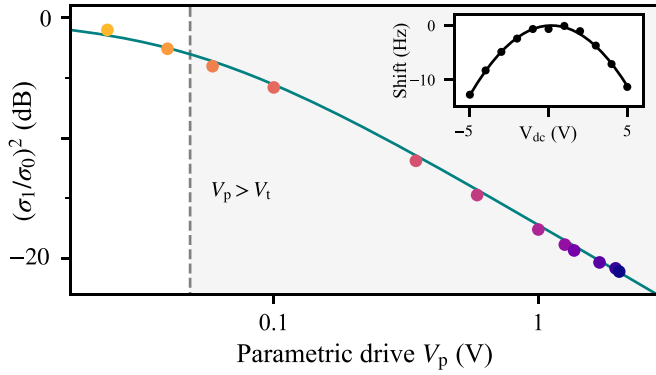


FIG. 3. Parametric modulation using a capacitive drive. Normalized variance of the amplitude quadrature $(\sigma_1/\sigma_0)^2$ as a function of the parametric drive voltage, where σ_0^2 is the variance at $V_p = 0$, using the same protocol described in Fig. 2 and in the text. The inset shows the frequency tuning of the mode as a function of the bias voltage V_{dc} . The solid lines are fits to the experimental data based on Eq. (4).

value $V_t = (39 \pm 3)$ mV. This results in a maximum observed squeezing of the variance $(\sigma_1/\sigma_0)^2 = -21$ dB.

Here, we remark that the observed value is currently limited by experimental factors, such as a low signal-to-noise ratio, heating due to leakage currents in the electrodes, and a low mechanical quality factor.

Outlook on quantum squeezing. To assess the experimental feasibility of reaching—and observing—quantum squeezing, we consider a resonant, high finesse optical cavity operating in the bad cavity regime, characterized by a linewidth $\kappa/2\pi \gg \Omega_m/2\pi$. Monitoring the output of a resonantly driven cavity allows measuring mechanical displacements characterized by a rate $\Gamma_{\text{meas}} = \eta_{\text{det}} 4g^2/\kappa$, where g is the optomechanical coupling strength [7], $x_{\text{ZPF}} = \sqrt{\hbar/(2m\Omega_m)}$, and η_{det} is the detection efficiency. The quantum noise of the probe has two detrimental effects on the performance. Its amplitude fluctuations lead to the quantum backaction force with a (double-sided) power spectral density given by $S_{\text{QBA}}(\omega) = \hbar^2 \Gamma_{\text{QBA}}/x_{\text{ZPF}}^2$ where $\Gamma_{\text{QBA}} = 4g^2/\kappa$. The detected signal, referred to the mechanics, is $\hat{y}(t) = \hat{x}(t) + \hat{x}_{\text{imp}}(t)$. The quantum uncertainty in the phase of the probe results in an imprecision noise floor in the detection ($\delta\hat{y} = \hat{x}_{\text{imp}}$), not correlated with the mechanics, which the feedback loop attempts to cancel by actuating the mechanical motion (see Supplemental Material [31]). This results in a force on the phase quadrature in the Fourier domain,

$$\delta\tilde{F}_{\text{fb}}(\omega) = m\Omega_m \Gamma_{\text{fb}} \delta\tilde{y}_2(\omega), \quad (6)$$

where the quadrature of the detected noise signal $\delta\tilde{y}_2$ is defined with the same convention as in Eq. (2).

Adding the backaction of the feedback and of the optical readout in Eq. (3), the variances of the two quadratures read

$$\begin{aligned} \sigma_1^2 &= \frac{x_{\text{ZPF}}^2}{1 + g_s} [(2\bar{n} + 1) + 2\gamma_{\text{QBA}}], \\ \sigma_2^2 &= \frac{x_{\text{ZPF}}^2}{1 - g_s + g_{\text{fb}}} \left[(2\bar{n} + 1) + \frac{1}{2} \left(\frac{g_{\text{fb}}^2}{4\gamma_{\text{meas}}} + 4\gamma_{\text{QBA}} \right) \right], \end{aligned} \quad (7)$$

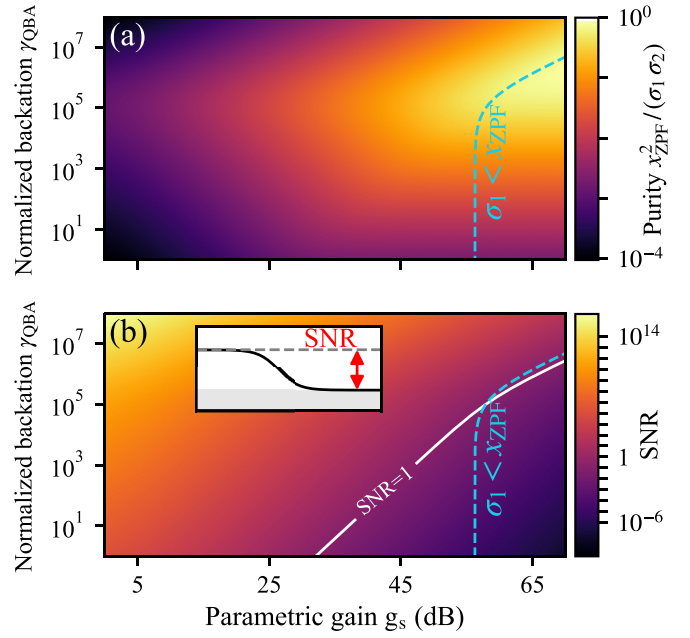


FIG. 4. Prospect for purity and signal-to-noise ratio (SNR) of the detection. The simulations assume $T = 10$ K, $\Omega_m = 2\pi \times 1$ MHz, $Q = 10^9$, $\eta_{\text{det}} = 0.77$. (a) Purity of the mechanical state at the optimal feedback minimizes σ_2^2 , as a function of the normalized squeezing rate and the backaction rate. In the region to the right of the light-blue dashed line, the expected amplitude standard deviation is below the quantum zero-point fluctuations. (b) Signal-to-noise ratio (SNR) of the detected X_1 quadrature as a function of the normalized squeezing rate and backaction rate. The SNR is defined as the ratio of the amplitude of the mechanical peak, $S_{X_1}(0)$, and the imprecision noise floor, $S_{\text{nn}} = x_{\text{ZPF}}^2/2\Gamma_{\text{meas}}$, as shown in the inset, which illustrates the spectrum of the amplitude quadrature of the mechanical motion in log-log scale [see Fig. 2(b)]. The white line marks the contour at which $\text{SNR} = 1$.

where $\gamma_{\text{meas}} = \eta_{\text{det}} \gamma_{\text{QBA}}$, $\gamma_{\text{QBA}} = \Gamma_{\text{QBA}}/\Gamma_m$, and $\bar{n}$ is the average occupancy of the thermal bath.

Through Eq. (7), we can estimate the expected purity of the state as a function of the quantum backaction and the parametric gain [Fig. 4(a)] for realistic device parameters [22]. For each value of γ_{QBA} and g_s , the feedback gain is tuned to minimize σ_2^2 . The purity approaches $\sqrt{\eta_{\text{det}}}$ in the limit of strong squeezing and fast measurement rate.

The expected detection signal-to-noise ratio (SNR) for the amplitude quadrature is reported in Fig. 4(b). In the limit of strong measurement rate, where the quantum backaction dominates the mechanical motion, it is possible to squeeze the amplitude quadrature below x_{ZPF} and detect it with a unity signal-to-noise ratio (SNR) above the imprecision noise.

Conclusions. By applying active stabilization of the anti-squeezed quadrature, we have shown that both piezoelectric and capacitively actuated parametric driving can be used to squeeze the mechanical motion far beyond the 3 dB limit, reaching 17 and 21 dB, respectively. In the case of piezoelectric actuation, improvements in the device design are not expected to vastly improve the maximum parametric gain. In contrast, we envision that in the case of capacitive drive, realistic improvements—in terms of larger mechanical quality

factor, smaller membrane-electrode separation, and reduced leakage current within the circuit—will result in much larger attainable squeezing, with a scaling of $\sigma_1^2 \propto d_0^3/V_{dc}V_pQ$ for $g_s \gg 1$. Under such modifications, the device will remain compatible with force sensing applications [21].

We also provide a theoretical model to predict the system's behavior in the quantum regime and discuss the feasibility of squeezing below the zero-point motion. At a moderate bath temperature of 10 K, quantum squeezing requires thermomechanical squeezing by more than 56 dB. We find this can be reached with conservative device parameters ($d_0 = 1 \mu\text{m}$,

$m_{\text{eff}} = 30 \text{ ng}$, $\Omega_m = 2\pi \times 1 \text{ MHz}$, and $Q = 10^9$) with voltages below the threshold for (e.g., pull-in) instability.

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