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Stimulated raman adiabatic passage in optomechanics

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2 Squeezed mechanical state

In this chapter we demonstrate strong optomechanical squeezing of a thermal state in the membrane-in-the-middle setup. Parametric modulation is used to squeeze the in-phase quadrature. The out-of-phase quadrature is restrained from diverging by a single-quadrature active feedback cooling. The parametric modulation is accomplished by modulating the detuning of a red-detuned pump light fields at twice the frequency of the mechanical mode, while the feedback cooling is provided by electrostatic forces from a sharp metallic tip in the vicinity of the mechanical mode.

This chapter is based on: S. Sonar, **V. Fedoseev**, M.J. Weaver, F. Luna, E. Vlieg, H. van der Meer, D. Bouwmeester and W. Löffler, Strong thermomechanical squeezing in a far-detuned membrane-in-the-middle system, Physical Review A 98, 013804 (2018). The experiment was performed together with Sameer Sonar.

2.1 Introduction

Non-classical states of a mechanical oscillator are of considerable interest to improve the measurement sensitivity of an optical interferometer with mirrors attached to a mechanical resonator (as needed for example for gravitational wave detectors such as LIGO and VIRGO), and for fundamental tests of quantum mechanics [19]. Here we discuss a method to produce a mechanical state where one of the motional quadratures is diminished at the expense of the other quadrature. The method is applied to a thermal state while generally it works also in the quantum regime. Methods have been proposed to generate squeezing in the classical [20, 21] and in the quantum regimes [2, 22, 23, 24, 25]. Experimental demonstrations [26, 27, 28, 29, 30] of squeezing include an observation of 4.7 dB squeezing below the zero point motion [19].

The idea of squeezing is based on a parametric oscillator, where the spring constant is modulated at twice the mechanical frequency Ω_m. Let's consider a response of such an oscillator to the in-phase excitation $f_s \sin \Omega t$ and out-of-phase excitation

$f_c \cos\Omega t$ for frequencies Ω:

$$\ddot{x} + \frac{\Omega_m}{Q}\dot{x} + \Omega_m^2(1 + \epsilon \sin 2\Omega_m t)x = f_s \sin\Omega t + f_c \cos\Omega t. \tag{2.1}$$

Let's find the steady state solution of this equation in the form

$$x = A\sin\Omega t + B\cos\Omega t \tag{2.2}$$

and in the limit of high quality factor $Q \gg 1$, where A and B are mechanical susceptibilities. Noticing that

$$\begin{aligned} \sin^2\Omega t\cos\Omega t &= \frac{1}{4}\cos\Omega t - \frac{3}{4}\cos 3\Omega t, \\ \sin\Omega t\cos^2\Omega t &= \frac{1}{4}\sin\Omega t + \frac{3}{4}\sin 3\Omega t \end{aligned} \tag{2.3}$$

and neglecting terms rotating at 3Ω, for $\Omega \approx \Omega_m$ we get

$$\begin{aligned} A &= \frac{Qf_c}{\Omega_m^2}\frac{1}{1+g}, \\ B &= -\frac{Qf_s}{\Omega_m^2}\frac{1}{1-g}, \end{aligned} \tag{2.4}$$

where we introduced gain $g = \frac{\epsilon Q}{2}$. Therefore, in the presence of the parametric modulation the response of the oscillator depends on the phase of the modulation relative to the excitation force acting on the oscillator. Significantly, in the presence of the in-phase excitation and $g > 1$ the motion of the oscillator becomes unstable: the amplitude of motion grows exponentially with time. If $g < 1$, a steady state solution exists with different susceptibilities A and B.

Now, extending this analysis to the case of a mechanical oscillator excited by thermal forces, we get the variances of the oscillator quadratures of motion $x(t) = X_2(t)\sin\Omega_m t + X_1(t)\cos\Omega_m t$ [31, 9]:

$$\begin{aligned} \langle X_2^2\rangle &= \frac{k_B T}{m_{\text{eff}}\Omega_m}\frac{1}{1+g}, \\ \langle X_1^2\rangle &= \frac{k_B T}{m_{\text{eff}}\Omega_m}\frac{1}{1-g}, \end{aligned} \tag{2.5}$$

where m_{eff} is the effective mass of the oscillator, T is its temperature. In the absence of the modulation $g = 0$ the oscillator is in a thermal state with equal quadrature variances

$$\sigma_0 = \langle X_1^2\rangle = \langle X_2^2\rangle = \frac{k_B T}{m_{\text{eff}}\Omega_m}. \tag{2.6}$$

It can be seen that modulating the oscillator with $g < 1$ the thermal state becomes squeezed. Maximal squeezing is achieved when $g \to 1$: in this case $\langle X_2^2\rangle \to +\sigma_0^2/2$ and $\langle X_1^2\rangle \to \infty$.

Thus parametric modulation squeezing is limited to $1/2$ or $\sim$ 3 dB. This limit is not universal, it can be overcome by cooling the diverging quadrature. In this approach g may become larger than 1. This was demonstrated experimentally using active feedback on the diverging quadrature [31, 32].

How can parametric modulation be achieved in an optomechanical system? The intracavity light fields modify the spring constant and the damping rate of an optomechanically coupled oscillator via the optical spring effect. This effect can be used to modulate the overall spring constant of an oscillator and perform the parametric modulation. The optical spring effect is a function of the light fields detuning $\Delta = \omega_L - \omega_{\text{cav}}$. If the detuning is modulated at twice the mechanical frequency, then the frequency of the mechanical mode is also modulated at twice the mechanical frequency. This approach was demonstrated in a sideband-unresolved system [33] by modulation of the pump light fields detuning. Here we demonstrate 8.5 dB squeezing of a mechanical state using the same technique but in a sideband-resolved regime.

The remainder of this chapter is structured as follows. First we describe our setup, the realization of the parametric modulation and active feedback cooling. Next we show the experimental results of the parametric modulation only. Finally we stabilize the diverging quadrature and show a beyond 3 dB squeezing.

2.2 Setup

Our setup consists of a high mechanical quality transparent membrane placed in the middle of a high-finesse 98 mm optical cavity. The membrane is a high-stress (1 GPa) $\mathrm{Si_3N_4}$ 50 nm thick membrane attached to a silicon chip available commercially from NORCADA Inc, see Fig. 2.1. A sharp metallic tip is positioned in the vicinity of the membrane. Generally, there are charges on the membrane, application of a voltage to the tip induces a force on the membrane. The cavity consists of two DBR mirrors with 10 ppm transmission (specs) from Laseroptik GmbH implying optical finesse of 3×10^5, but optical ringdown measurements showed finesse of 6×10^4 and much smaller than expected transmission consistent with 40 ppm of absorption. This can be explained by dust particles visible by naked eye in the mirror holding box as delivered from the company. The mirrors were cleaned by blowing clean He gas. Insertion of the membrane in the cavity reduced the optical finesse further to 3.3×10^4. The setup is placed in a room temperature vacuum chamber pumped by an ion pump to pressure of $\sim 10^{-6}$ mbar. The membrane holder can be tip-tilted in situ by three rotary piezo stick-slip motors with a step size of about 20 nm, see Fig. 2.2. The motors are used to maximize the transmission signal and membrane positioning.

The membrane is positioned $\sim 30\ \mu$m from the exact center along the optical axis of the cavity by measuring the 2FSR value. The detailed description can be found in the next chapter.

We performed experiments with the fundamental vibrational mode of the membrane having resonance frequency $\Omega_m = 385$ kHz, effective mass $m_{\text{eff}} = 30$ ng and mechanical quality factor $Q = 3 \times 10^5$, further called mechanical mode.

The optical setup is shown in figure 2.3. A weak probe laser (10 μW) is used to trace the resonance of the cavity via the Pound-Drever-Hall locking technique

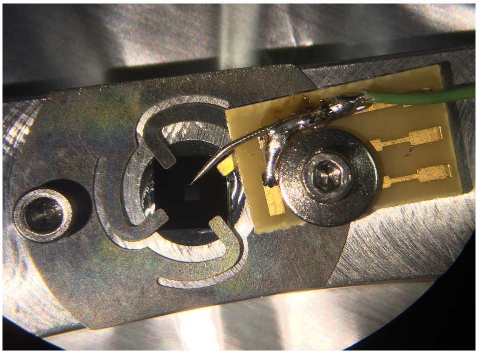

Figure 2.1: Photo of the membrane on a sample holder. The sharp tip does not touch the membrane.

(PDH) [34]. To accomplish this the probe laser light goes through an electro-optical modulator (EOM) modulated at 9.5 MHz. The light back-reflected from the cavity is detected by a photodetector and its signal is demodulated at 9.5 MHz to get the PDH error signal. This error signal is sent to a proportional-integral-differential controller (PID) providing feedback to the probe laser. The feedback bandwidth is much smaller than Ω_m. The PDH error signal is also demodulated at Ω_m to get the two motional quadratures $X_1(t)$ and $X_2(t)$ of the mechanical mode.

A strong pump laser is used to modulate the frequency of the mechanical mode by dynamic backaction. The optical fields back-reflected from the optical cavity are directed towards detectors using an optical circulator. The pump and probe fields are separated by a polarizing beam splitter (PBS). To decrease possible interference effects at the detectors even further, different cavity resonances are used for the probe and pump lasers. The pump laser is locked to the probe laser with a frequency difference $\sim$ 3 GHz by a phase-locked-loop: the light from both lasers interferes on a fast photodiode which produces a beat electronic signal, see Fig. 2.4. This beat signal is mixed with a reference radio-frequency (RF) signal produced by a signal generator and sent to a low pass filter. The resulting signal is sent to a PID controller which provides feedback to the pump laser maintaining the frequency difference of the lasers equal to the RF signal frequency. This frequency difference is set to 2FSR + Δ, where Δ is the required detuning of the pump laser from the cavity resonance. We chose 2FSR because the consecutive resonance frequency difference 1FSR is a function of the membrane position x (see Fig. 1.3 from Chapter 1), while 2FSR is not in the case when the membrane is exactly in the middle of the cavity. The pump frequency detuning Δ is modulated at $2\Omega_m$ using a signal $\propto \sin{(2\Omega_m t + \phi)}$, this signal is added to the pump feedback signal. The feedback bandwidth of the phase-locked-loop is much smaller than $2\Omega_m$ and thus the added modulation does not affect the frequency locking between the lasers. The phase ϕ is adjusted to align the squeezing axis such that X_2 quadrature is squeezed.

A change in the detuning of the pump laser Δ with fixed light intensity outside the cavity leads also to a change in the effective quality factor of the oscillator. Figure 2.5 shows the measured frequency shift $\delta\Omega_m$ and the effective damping

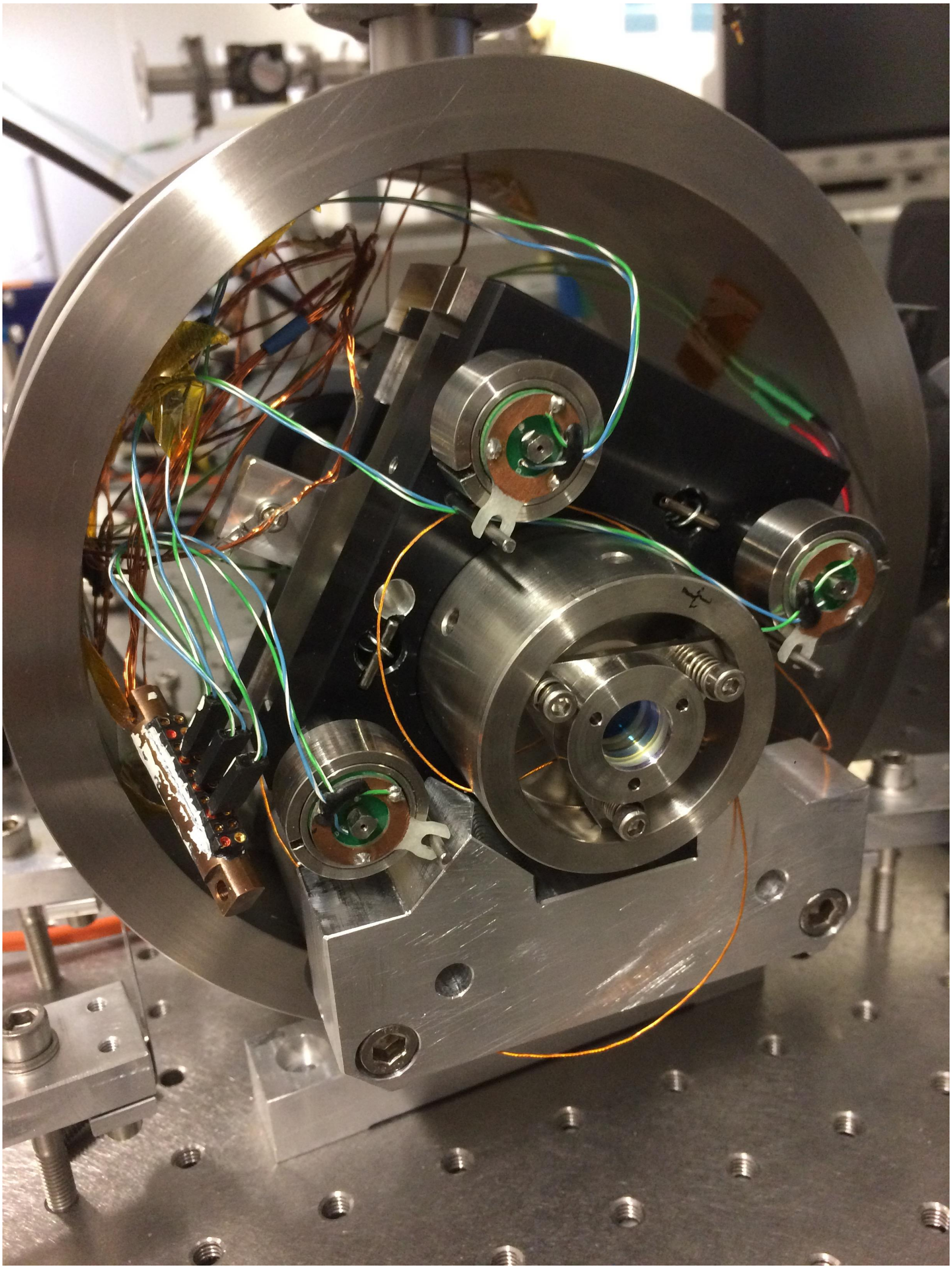

Figure 2.2: Setup in a room temperature vacuum chamber. The first cavity mirror is visible pressed against the Invar body. The sample holder is mounted on a motorized tip-tilt stage (black).

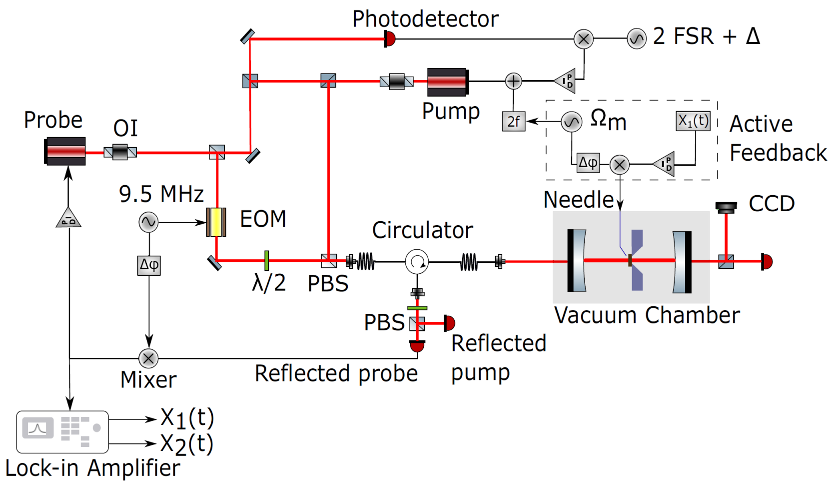

Figure 2.3: Optical setup.

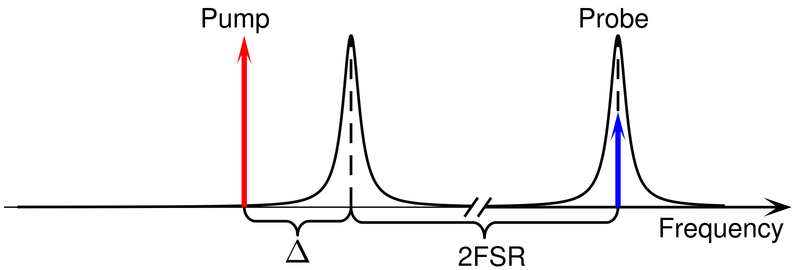

Figure 2.4: The probe and pump laser frequencies.

$\Gamma_{\rm eff} = \Omega_m/Q + \Gamma_{\rm opt}$, where $\Gamma_{\rm opt}$ is the optical damping due to dynamic backaction in a detuning Δ sweep. Note, the intracavity light intensity also changes when the detuning is changed. $\delta\Omega_m$ and $\Gamma_{\rm eff}$ were extracted from fitting the noise spectrum of the mechanical mode. We highlight three different detuning regions in this plot where the slope of the frequency shift is much larger than the slope of the damping curve as required by our model Eq. 2.1. Region I was hard to realize for our system because due to fluctuations in the detuning the detuning occasionally becomes positive and the lock of the probe laser is lost. In region II the second derivative of the frequency shift is significant which makes the modulation non-linear. Region III where $\Delta = -1.43\Omega_m$ is most practical due to stability considerations of our system.

In the case of an ideal membrane the modulation of the intracavity light intensity at $2\Omega_m$ should excite the 2,2 vibrational mode. For our membrane the frequency of the 2,2 mode is however a few hundred Hertz away from $2\Omega_m$, so this mode is not excited due to the parametric modulation.

Figure 2.6 shows phase-space trajectories under different conditions. Figure 2.6(a) shows a thermal state with effective temperature $T = 120$ K when the pump light is on and is not modulated, providing a weak cooling effect only. When the pump modulation is on, the X_2 quadrature becomes squeezed and the X_1 quadrature becomes enhanced, Fig. 2.6(b). When the modulation strength is increased even further to surpass the limit $g = 1$, the motion becomes bi-stable probably due to non-linear mechanical effects in the membrane, Fig. 2.6(c) and 2.6(d).

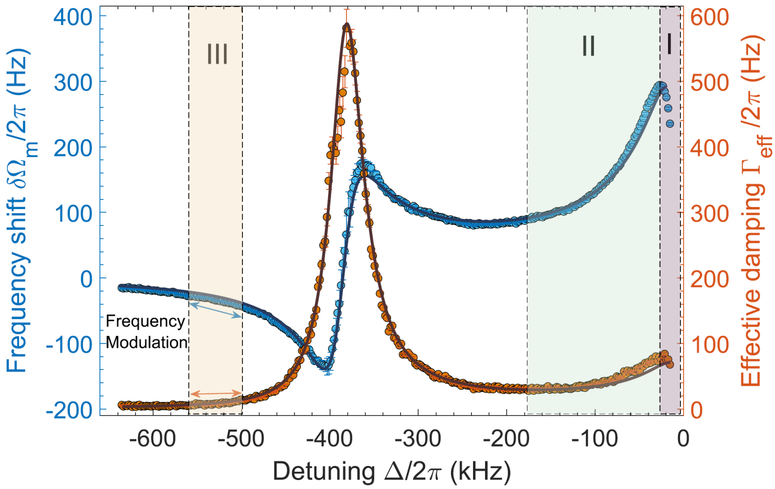

Figure 2.5: Optical spring effect as a function of the pump detuning Δ showing three regions I, II and III where frequency modulation can be realized.

2.3 Active feedback

To achieve stronger squeezing we applied active feedback to cool the diverging mode X_1 only.

The mechanical mode can be cooled by applying active feedback via the introduction of a viscose damping force $f \propto -\dot{x}$ [9]. In the limit of a high-Q oscillator

$$\begin{aligned} x(t) &= X_2(t)\sin\Omega_m t + X_1(t)\cos\Omega_m t, \\ \dot{x}(t) &\approx \Omega_m X_2(t)\cos\Omega_m t - \Omega_m X_1(t)\sin\Omega_m t, \\ \dot{x}(t) &\approx \Omega_m x(t + \frac{\pi}{2\Omega_m}) \approx -\Omega_m x(t - \frac{\pi}{2\Omega_m}), \end{aligned} \tag{2.7}$$

where we neglected the terms proportional to $\dot{X}_1$ and $\dot{X}_2$. Thus by measuring $x(t)$ and applying a force proportional to the measured value with a fixed delay of one quarter of the mechanical period the mechanical mode can be cooled. Both quadratures are cooled equally. To cool $X_1(t)$ only the following feedback force should be applied:

$$f \propto X_1(t)\sin\Omega_m t. \tag{2.8}$$

For this purpose we applied a voltage signal to the sharp metal tip in the vicinity of the membrane in the form $V(t) \propto X_1(t)\sin\Omega_m t$. To realize this experimentally one of the measured quadratures is mixed with the local oscillator Ω_m and after amplification it's sent to the sharp metal tip. In this case the variance of the quadratures of a mechanical mode driven by thermal motion and parametric modulation is modified in the following way [31]:

$$\begin{aligned} \langle X_2^2 \rangle &= \frac{k_B T}{m_{\text{eff}}\Omega_m}\frac{1}{1+g}, \\ \langle X_1^2 \rangle &= \frac{k_B T}{m_{\text{eff}}\Omega_m}\frac{1}{1-g+h}, \end{aligned} \tag{2.9}$$

where h is proportional to the strength of the feedback. We see that the variance of X_2 stays unchanged. Now, the 3 dB limit can be surpassed by increasing g above unity while keeping $1-g+h>0$.

Figure 2.7 shows squeezing results for different feedback strengths h. The variances are normalized against the case of $g=0$ and $h=0$ but with the pump light on, resulting in an effective temperature $T_{\text{eff}} = 120$ K.

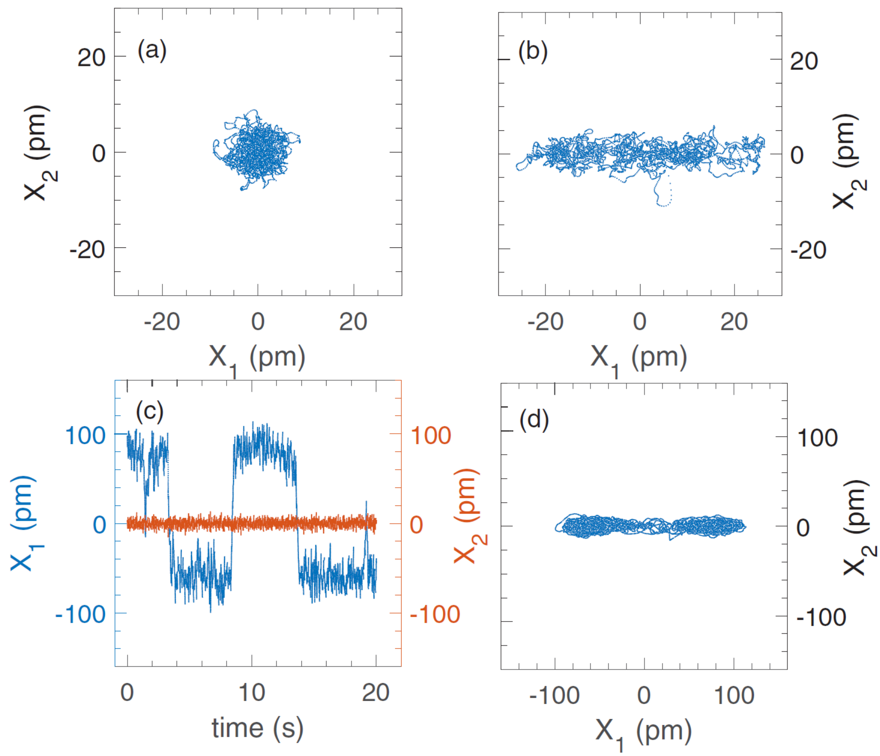

Figure 2.6: Quadratures X_1 and X_2 evolution for (a) thermal state; (b) squeezed state for parametric modulation with $g<1$; (c) and (d) parametric modulation with $g>1$.

The first measurement was done without any feedback ($h=0$), the results are shown with diamonds. A maximum squeezing of 3 dB was achieved.

The second measurement run was done with feedback strength equivalent to $h = 2.9$. A maximum squeezing of 7 dB was achieved.

In the third measurement run the intensity of the pump laser light was decreased. The effective temperature was measured to be 182 K with the pump light on. Using the feedback strength of $h = 21.5$, a maximum squeezing of 8.5 dB was achieved. For high values of gain g the experimentally measured squeezing starts to deviate from the theoretical predictions. Some assumptions of our model are not fulfilled in this regime, for example the quadratures are not independent any more or some linearity conditions are violated. Another possible reason is that the modulation of the pump laser light leads to a sideband with detuning $-1.43\Omega_m + 2\Omega_m = 0.57\Omega_m$. This sideband is blue-detuned and heats both quadratures. This can be avoided if the detuning $\Delta < -2\Omega_m$.

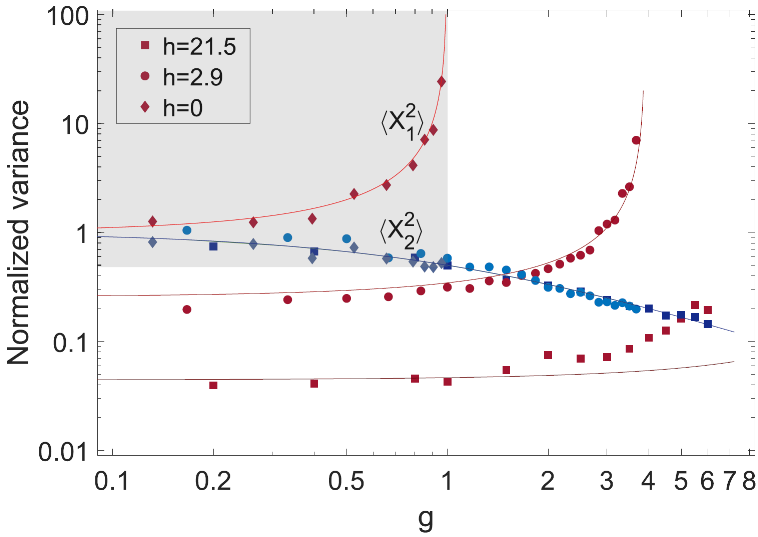

Figure 2.7: Normalized variance of X_1 (red) and X_2 (blue) as a function of parametric modulation g for $h = 0$ (diamonds), $h = 2.9$ (circles), $h = 21.5$ (squares).

2.4 Discussion

Let's consider the final state achieved with highest gain $g = 6$ and feedback strength $h = 21.5$. It has approximately equal quadrature variances for X_1 and X_2, see Fig. 2.7. Generally speaking, it can be achieved just by sideband cooling without any feedback or parametric modulation. Another thing to note is that when $g = 21.5$ and $h = 0$ (strongest feedback and no parametric modulation) the achievable state is squeezed 14 dB, which is more than the maximum squeezing reported here (8.5 dB) due to the parametric modulation. However, it is worth to note that the squeezing due to parametric modulation is in principle noiseless [31], while to achieve a quantum squeezed state via the single quadrature feedback, strong backaction-evading quantum-limited measurement of the single quadrature would be required. Such a measurement does not introduce any noise due to backaction into the measured quadrature (all the noise goes to the other quadrature [9]) and as the measured quadrature can be measured to an arbitrary precision, this quadrature becomes squeezed just by the measurement.

A limitation of a sideband-resolved system as used here is that active feedback becomes less efficient as the mechanical mode makes many oscillations within the time of light leakage from the cavity $1/\kappa$.

2.5 Conclusions

We demonstrated strong squeezing of a mechanical thermal state via parametric modulation of the effective spring constant of the mechanical mode. Single quadrature feedback was essential to achieve beyond 3 dB squeezing for high-gain modulation, which restrains the non-squeezed quadrature from unconstrained growth. The modulation is achieved by frequency modulation of a red-detuned pump, while the feedback force is generated by electrostatic forces exerted on the membrane from a sharp metallic tip.

This method can be also applied in the quantum regime to squeeze one of the quadrature of a mechanical mode below the vacuum noise level. This will increase the sensitivity of position measurements of a mechanical oscillator, and will allow for a study of decoherence and the corresponding evolution of quantum systems into classical ones [35].

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