Parametric generation of quadrature squeezing of mirrors in cavity optomechanics

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We propose a method to generate quadrature squeezed states of a moving mirror in a Fabry-Perot cavity. This is achieved by exploiting the fact that when the cavity is driven by an external field with a large detuning, the moving mirror behaves as a parametric oscillator. We show that parametric resonance can be reached approximately by modulating the driving field amplitude at a frequency matching the frequency shift of the mirror. The parametric resonance leads to an efficient generation of squeezing, which is limited by the thermal noise of the environment.

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I. INTRODUCTION

Cavity optomechanics [1–4], as an interaction interface between a cavity field and a moving mirror, is an exciting research area for exploring quantum behavior in macroscopic systems as well as applications in quantum information processing. With the recent advances of cooling techniques in optomechanical systems [5–12], it is becoming possible to overcome thermal noise and study quantum state engineering of mechanical mirrors. Indeed, recent studies have already shown that various kinds of non-classical states can be generated by optomechanical coupling. These include quantum superposition states [13, 14], entangled states [15–19], and squeezed states of light [20–23] and mirrors [24–28].

Specifically, achieving squeezed states in mechanical oscillators (mirrors) is an important goal because of the applications in ultrahigh precision measurements such as the detection of gravitational waves [29–31]. Several schemes have been proposed to create quantum squeezing of the moving mirror in cavity optomechanics. For example, squeezing can be transferred from a squeezed light driving the cavity to the mirror [25], and recently Mari and Eisert have shown that squeezing can be generated directly by a periodically modulated driving field [26].

We note that a basic mechanism for creating quadrature squeezing is to introduce a parametric coupling for the motional degree of freedom of the mirror. In particular, efficient squeezing can be achieved at the parametric resonance, such that the Hamiltonian in the interaction picture takes the form $H_I \propto b^2 + b^{\dagger 2}$ [where b and $b^\dagger$ are operators of the oscillator in Eq. (1)] and the corresponding evolution operator is a squeezed operator. Therefore an interesting question is how the parametric resonance can be reached in cavity optomechanical systems. One of the difficulties here is the dynamical shift of the mechanical resonance frequency due to the optomehanical coupling, which is sensitive to the intensity of the cavity field. In this paper we show that in the large detuning limit, the frequency shift can be compensated by modulating field amplitude at a suitable frequency, and hence parametric resonance can be reached approximately. We will present an explicit form of the driving amplitude,

and analyze the time development of squeezing in the presence of thermal noise.

II. MODEL

The system under consideration is an optical cavity formed by a fixed mirror and a moving mirror connected with a spring (Fig. 1). We consider a single-mode field in the cavity and model the moving mirror as a harmonic oscillator. The Hamiltonian of the system reads

$$
\begin{aligned}
H_S = {} & \hbar\omega_c a^\dagger a + \hbar\omega_m b^\dagger b - \hbar g a^\dagger a(b^\dagger + b) \\
& + \hbar\Omega(t)e^{-i\omega_d t}a^\dagger + \hbar\Omega^*(t)e^{i\omega_d t}a,
\end{aligned}
\tag{1}
$$

where $a^\dagger$ ($b^\dagger$) and a (b) are the creation and annihilation operators associated with the single-mode cavity field (mirror) with frequency ω_c (ω_m). Assuming m_{eff} is the effective mass of the mirror, then the position and momentum operators of the mirror are $x = x_{\text{zpf}}(b^\dagger + b)$ and $p = im_{\text{eff}}\omega_m x_{\text{zpf}}(b^\dagger - b)$, where $x_{\text{zpf}} = \sqrt{\hbar/(2m_{\text{eff}}\omega_m)}$ is the zero-point fluctuation of the mirror's position. The third term in Eq. (1) describes a radiation pressure coupling with the coupling strength $g = \omega_c x_{\text{zpf}}/L$, where L is the rest length of the cavity. In addition, the cavity is driven by an external field with a main frequency ω_d and the time-varying amplitude $\Omega(t)$.

To include damping in our model, we follow the standard approach by coupling the system with oscillator baths such that the quantum Langevin equations (in a rotating frame with frequency ω_d) for the operators a and b are given by

$$
\dot{a} = -i\Delta_c a + iga(b^\dagger + b) - i\Omega(t) - \frac{\gamma_c}{2}a + a_{in}, \tag{2a}
$$

$$
\dot{b} = -i\omega_m b + iga^\dagger a - \frac{\gamma_m}{2}b + b_{in}, \tag{2b}
$$

with the detuning $\Delta_c = \omega_c - \omega_d$ and the cavity (mirror) decay rate γ_c (γ_m). Under the assumption of Markovian baths, the noise operators a_{in} and b_{in} have zero mean values and they are characterized by the correlation functions $\langle a_{in}(t)a_{in}^\dagger(t')\rangle = \gamma_c\delta(t-t')$, $\langle a_{in}^\dagger(t)a_{in}(t')\rangle = 0$, $\langle b_{in}(t)b_{in}^\dagger(t')\rangle = \gamma_m(\bar{n}_m+1)\delta(t-t')$, and $\langle b_{in}^\dagger(t)b_{in}(t')\rangle =$
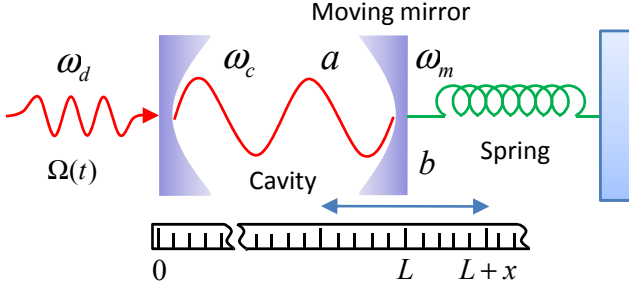
FIG. 1: (Color online) Schematic diagram of the cavity optomechanical system. An externally driven Fabry-Perot cavity is formed by a fixed end mirror and a harmonically bound end mirror.

$\gamma_m \bar{n}_m \delta(t - t')$, where $\bar{n}_m = \{\exp[\hbar\omega_m/(k_B T_m)] - 1\}^{-1}$ is thermal excitation number of the mirror's bath at temperature T_m and k_B is the Boltzmann constant. Here we have assumed that the bath coupled to the cavity field is effectively a vacuum, and the rotating-wave approximation has been employed to describe the system-bath interaction [32, 33].

III. LINEARIZED SYSTEM: FORMAL SOLUTION OF FLUCTUATIONS

Next we write $a = \langle a \rangle + \delta a$ and $b = \langle b \rangle + \delta b$ such that the fluctuations about the expectation values are described by operators δa and δb. Assuming the fluctuations are sufficiently small, then we may linearize Eq. (2) to obtain the equation of motion for δa and δb:

$$\dot{\delta a} = -i\Delta(t)\delta a + ig\langle a(t)\rangle(\delta b^\dagger + \delta b) - \frac{\gamma_c}{2}\delta a + a_{in}, \quad (3a)$$

$$\dot{\delta b} = -i\omega_m\delta b + ig[\langle a^\dagger(t)\rangle\delta a + \langle a(t)\rangle\delta a^\dagger] - \frac{\gamma_m}{2}\delta b + b_{in}, \quad (3b)$$

where $\Delta(t) = \Delta_c - g[\langle b(t)\rangle + \langle b^\dagger(t)\rangle]$. The expectation values $\langle a(t)\rangle$ and $\langle b(t)\rangle$ are governed by equations of motion: $\langle \dot{a} \rangle = -[i\Delta(t) + \frac{\gamma_c}{2}]\langle a\rangle - i\Omega(t)$ and $\langle \dot{b} \rangle = -(i\omega_m + \frac{\gamma_m}{2})\langle b\rangle + ig|\langle a\rangle|^2$.

For convenience, we introduce the quadrature operators by $\delta X_{s=a,b} = (\delta s^\dagger + \delta s)/\sqrt{2}$ and $\delta Y_{s=a,b} = i(\delta s^\dagger - \delta s)/\sqrt{2}$. Then Eq. (3) can be concisely expressed as

$$\dot{\mathbf{v}}(t) = \mathbf{M}(t)\mathbf{v}(t) + \mathbf{N}(t) \quad (4)$$

where $\mathbf{v} = (\delta X_a, \delta Y_a, \delta X_b, \delta Y_b)^T$, and $\mathbf{M}$ is

$$\mathbf{M}(t) = \begin{bmatrix} -\frac{\gamma_c}{2} & \Delta(t) & -\sqrt{2}g\langle Y_a(t)\rangle & 0 \\ -\Delta(t) & -\frac{\gamma_c}{2} & \sqrt{2}g\langle X_a(t)\rangle & 0 \\ 0 & 0 & -\frac{\gamma_m}{2} & \omega_m \\ \sqrt{2}g\langle X_a(t)\rangle & \sqrt{2}g\langle Y_a(t)\rangle & -\omega_m & -\frac{\gamma_m}{2} \end{bmatrix}, \quad (5)$$

with $\langle X_{s=a,b}(t)\rangle = [\langle s^\dagger(t)\rangle + \langle s(t)\rangle]/\sqrt{2}$ and $\langle Y_{s=a,b}(t)\rangle = i[\langle s^\dagger(t)\rangle - \langle s(t)\rangle]/\sqrt{2}$. The noise vector in Eq. (4) is

defined by $\mathbf{N} = (X_a^{in}, Y_a^{in}, X_b^{in}, Y_b^{in})^T$, with $X_{s=a,b}^{in} = (s_{in}^\dagger + s_{in})/\sqrt{2}$ and $Y_{s=a,b}^{in} = i(s_{in}^\dagger - s_{in})/\sqrt{2}$.

Equation (4) is a first-order linear inhomogeneous differential equation with variable coefficients. Its formal solution is

$$\mathbf{v}(t) = \mathbf{G}(t)\mathbf{v}(0) + \mathbf{G}(t)\int_0^t \mathbf{G}^{-1}(\tau)\mathbf{N}(\tau)d\tau, \quad (6)$$

where the matrix $\mathbf{G}(t)$ satisfies $\dot{\mathbf{G}}(t) = \mathbf{M}(t)\mathbf{G}(t)$ and the initial condition $\mathbf{G}(0) = I$ (I is the identity matrix). In the present system, interesting quantities are the quadrature fluctuations of the cavity and the mirror. Hence, we define a covariance matrix $\mathbf{R}(t)$ by the elements $\mathbf{R}_{ll'}(t) = \langle \mathbf{v}_l(t)\mathbf{v}_{l'}(t)\rangle$ for $l, l' = 1, 2, 3, 4$. Obviously, the four diagonal elements of $\mathbf{R}(t)$ are the expectation values of the square of the four quadrature operators of the system. They are $\mathbf{R}_{11}(t) = \langle \delta X_a^2(t)\rangle$, $\mathbf{R}_{22}(t) = \langle \delta Y_a^2(t)\rangle$, $\mathbf{R}_{33}(t) = \langle \delta X_b^2(t)\rangle$, and $\mathbf{R}_{44}(t) = \langle \delta Y_b^2(t)\rangle$. For the mirror's rotating quadrature operator $X_b(\theta, t) \equiv \cos\theta X_b(t) + \sin\theta Y_b(t)$, the corresponding variance is given by $\langle \delta X_b^2(\theta, t)\rangle = \cos^2\theta \mathbf{R}_{33}(t) + \sin^2\theta \mathbf{R}_{44}(t) + \frac{1}{2}\sin 2\theta[\mathbf{R}_{34}(t) + \mathbf{R}_{43}(t)]$. Since $[X_b(\theta, t), X_b(\theta + \pi/2, t)] = i$, quadrature squeezing occurs when $\langle \delta X_b^2(\theta, t)\rangle < 1/2$.

To test the dynamical quadrature squeezing, we need to determine the covariance matrix $\mathbf{R}(t)$, which has the formal expression:

$$\mathbf{R}(t) = \mathbf{G}(t)\mathbf{R}(0)\mathbf{G}^T(t) + \mathbf{G}(t)\mathbf{Z}(t)\mathbf{G}^T(t). \quad (7)$$

where $\mathbf{Z}(t)$ is defined by

$$\mathbf{Z}(t) = \int_0^t \int_0^t \mathbf{G}^{-1}(\tau)\mathbf{C}(\tau, \tau')[\mathbf{G}^{-1}(\tau')]^T d\tau d\tau'. \quad (8)$$

Here $\mathbf{C}(\tau, \tau')$ is the two-time noise operator correlation matrix defined by the elements: $\mathbf{C}_{nn'}(\tau, \tau') = \langle \mathbf{N}_n(\tau)\mathbf{N}_{n'}(\tau')\rangle$ for $n, n' = 1, 2, 3, 4$. For Markovian baths, we have $\mathbf{C}(\tau, \tau') = \mathbf{C}\delta(\tau - \tau')$, where the constant matrix $\mathbf{C}$ is given by

$$\mathbf{C} = \frac{1}{2}\begin{bmatrix} \gamma_c & i\gamma_c & 0 & 0 \\ -i\gamma_c & \gamma_c & 0 & 0 \\ 0 & 0 & \gamma_m(2\bar{n}_m + 1) & i\gamma_m \\ 0 & 0 & -i\gamma_m & \gamma_m(2\bar{n}_m + 1) \end{bmatrix}. \quad (9)$$

IV. GENERATION OF QUADRATURE SQUEEZING

Having obtained the formal equations for the evolution of quadrature fluctuations of the mirror, we now ask how the external driving amplitude $\Omega(t)$ can be chosen to generate a large degree of quadrature squeezing of the mirror. We approach the problem by considering the large detuning regime ($\Delta_c \gg \omega_m$) so that by adiabatic approximation we have

$$\delta a \approx \frac{g}{\Delta_c - i\gamma_c/2}\langle a(t)\rangle(\delta b^\dagger + \delta b) + F_{in}, \quad (10)$$
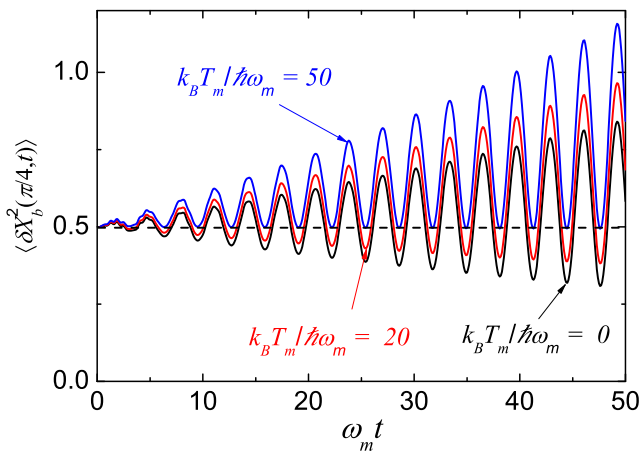
FIG. 2: (Color online) Time evolution of $\langle \delta X_b^2(\pi/4, t)\rangle$ at various temperatures T_m. From the bottom up, the three curves correspond to $k_B T_m/(\hbar\omega_m) = 0, 20$, and 50, respectively. The standard quantum limit $1/2$ is indicated by dashed black line. The parameters are given in the text.

with $F_{in} = \int_0^t a_{in}(t')e^{(i\Delta_c+\gamma_c/2)(t'-t)}dt'$. Here, we have also assumed $\Delta_c \gg g\langle X_b(t)\rangle$ and hence $\Delta(t) \approx \Delta_c$. Correspondingly, the equation of motion (3b) for δb becomes

$$\dot{\delta b} = -i\omega_m\delta b + i\eta|\langle a(t)\rangle|^2(\delta b^\dagger + \delta b) - \frac{\gamma_m}{2}\delta b + F'_{in}, \quad (11)$$

where $\eta = \frac{2g^2\Delta_c}{\Delta_c^2+\gamma_c^2/4}$ and the noise operator consists of two parts $F'_{in} \equiv F^a_{in} + b_{in}$. The part $F^a_{in} = ig\langle a^\dagger(t)\rangle F_{in} + ig\langle a(t)\rangle F^\dagger_{in}$ comes indirectly from the cavity's bath and depends on the mean field solution, while the second part b_{in} comes directly from the mirror's bath.

Next we observe that if the external driving amplitude is chosen as

$$\Omega(t) = \Omega_0 \sin\left[(\omega_m - \xi_0)t\right], \quad (12)$$

with Ω_0 being a constant and $\xi_0 = g^2\Omega_0^2\Delta_c/(\Delta_c^2+\gamma_c^2/4)^2$, then by the adiabatic solution $\langle a(t)\rangle \approx -\Omega(t)/(\Delta_c - i\gamma_c/2)$ and the assumption $\omega_m \gg \xi_0$, Eq. (11) can be approximated by

$$\dot{\delta B} = -i\frac{\xi_0}{2}\delta B^\dagger - \frac{\gamma_m}{2}\delta B + F'_{in}e^{i(\omega_m-\xi_0)t}, \quad (13)$$

where $\delta B = \delta b e^{i(\omega_m-\xi_0)t}$ is defined. In deriving Eq. (13), we have made use of a rotating wave approximation such that counter-rotating terms with the rapidly oscillating phase factors $e^{\pm 2i(\omega_m-\xi_0)t}$ and $e^{\pm 4i(\omega_m-\xi_0)t}$ have been dropped.

We notice that Eq. (13) precisely corresponds to the equation of motion of a damped parametric oscillator at resonance. If damping can be ignored, a mirror initially prepared in the ground state would display exponential squeezing as time increases: $\langle \delta X_b^2(\pi/4, t)\rangle = \frac{1}{2}e^{-\xi_0 t}$. Such an efficient squeezing can be understood by inspecting Eq. (11) in which our choice of $\Omega(t)$ matches the average value of the shifted resonance frequency of the mirror

$\omega_m - \eta|\langle a(t)\rangle|^2$, and therefore the parametric resonance can be reached approximately. Note that ξ_0 is the average value of such a frequency shift and it also plays the role of an effective strength of the parametric process.

However, it should be noted that for practical purposes, ξ_0 in Eq. (13), which decreases as Δ_c^{-3}, has to be strong enough to overcome noises of the baths, i.e., the detuning Δ_c cannot be arbitrarily large. For realistic choices of Δ_c, the quality of squeezing has to be examined in the presence of noise without making use of the adiabatic approximation. To this end, we employ the linear formalism above and solve directly the covariance matrix in Eq. (7) numerically. For simplicity, we assume that the system is initially prepared in its ground state $|0\rangle_c \otimes |0\rangle_m$ through a state preparation process. Such an initial state may be achievable in future experiments based on ground-state cooling techniques. In addition, we consider the following systems parameters: $\omega_m = 2\pi \times 1$ MHz, $\Delta_c = 2\pi \times 10$ MHz, $\gamma_m = 2\pi \times 100$ Hz, $\gamma_c = 2\pi \times 100$ kHz, $\Omega_0 \approx 31.6$ GHz and $g = 2\pi \times 100$ Hz, which are realistic under current experimental conditions [34, 35]. In Fig. 2 we plot the time-dependence of quadrature variance of the mirror at various temperatures based on the form of $\Omega(t)$ in Eq. (12), the evidence of squeezing is clearly shown at sufficiently low temperatures. In fact, for not too large $\Delta_c = 10\omega_m$ chosen in Fig. 2, our exact numerical results agree well with the adiabatic approximation.

If the temperature of the mirror's bath is higher than a critical value, T_m^c, then there will no longer be squeezing in the mirror (Fig. 2, blue line). A rough estimation of the damping effect can be made by considering that the noise is mainly from the mirror's bath, so that

$$\langle \delta X_b^2(\pi/4, t)\rangle \approx \frac{1}{2}e^{-(\gamma_m+\xi_0)t} + \frac{\gamma_m(\bar{n}_m+1/2)}{(\gamma_m+\xi_0)}\left(1 - e^{-(\gamma_m+\xi_0)t}\right). \quad (14)$$

Therefore squeezing occurs if the thermal excitation number $\bar{n}_m$ is below a critical number, $\bar{n}_m^c = \frac{\xi_0}{2\gamma_m}$. For the parameters used in Fig. 2, our estimation gives $T_m^c \approx 4.8$ mK or $k_B T_m^c/\hbar\omega_m \approx 50.5$, and this agrees with the numerical value 50 shown in Fig. 2. We remark that in deriving Eq. (14), the effect of noise a_{in} has been neglected. This can be justified by a lengthly calculation which shows that $\langle \delta X_b^2\rangle$ due to the cavity field noise is of the order of $\xi_0(\gamma_m + \xi_0 + \gamma_c)/[4\Delta_c(\gamma_m + \xi_0)]$ in the long time limit, and hence it can be made small compared with the contribution from the thermal bath of the mirror by a large detuning.

V. CONCLUSION

To conclude, we have presented a method to generate quadrature squeezing of a mirror in cavity optomechanics. Specifically, we have shown that in the large detuning regime with $\Delta_c \gg \omega_m \gg \xi_0$ and $\Delta_c \gg g|\langle X_b(t)\rangle|$, the driving field of the form $\Omega(t)$ given in Eq. (12) can

generate squeezing dynamically [36]. The squeezing is supported by direct numerical calculations for realistic parameters. We should point out that our scheme is different from that in Ref. [26] because the large detuning regime considered here enable us to eliminate the cavity field and formally map the mirror to a parametric oscillator. In addition, parametric resonance can be fine tuned by our driving field $\Omega(t)$ so that the frequency shift of the mirror due to coupling to the cavity field can be compensated approximately.

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