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Controllable optical bistability in a three-mode optomechanical system with a membrane resonator*

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We study the optical bistability (OB) in a three-mode cavity optomechanical system, where an oscillating membrane of perfect reflection is inserted between two fixed mirrors of partial transmission. By investigating the behavior of steady state solutions, we find that the left and right cavities will exhibit the bistable behavior simultaneously in this optomechanical system by adjusting the left and right coupling fields. In addition, one can control the OB threshold and the width of the OB curve via adjusting the coupling strength, the detuning, and the decay rate. Moreover, we further illustrate the OB appearing in the cavity by the effective potential as a function of the position.

Keywords: optical bistability, oscillating membrane, optomechanical system

PACS: 42.65.Pc, 42.50.–p, 42.50.Pq, 42.65.–k **DOI:** 10.1088/1674-1056/27/7/074214

1. Introduction

In the past decade, great progress has been made in cavity optomechanics due to the fabrication of high-quality mechanical resonators. Many significant advances have been made in this emerging field, including the optical bistability (OB),[1–8] sideband effects,[9–12] optomechanically induced transparency,[13–17] quantum ground state cooling,[18–21] and so on. Especially, the OB, as a nonlinear phenomenon which shows two output states for the same input state, has received considerable attention due to its promising application in the all-optical switch. For instance, many theoretical studies for the OB have been done in the quantum-well systems,[22,23] ultracold atoms,[24] optomechanical systems with a Bose–Einstein condensate (BEC),[3,7,8] and so on.[25,26] Furthermore, the OB phenomenon has also witnessed huge experimental progress in the past few years.[27–32]

The OB in a two-mode cavity optomechanical system has been explored extensively in the past.[3,4,7,8] In an optomechanical cavity with a BEC, the optical bistable behaviors has been studied theoretically by Seyedeh *et al.*[3] The effects of the decay rate of the cavity and the coupling strength between the cavity and the BEC as well as the pump–atom detuning on the optical bistable behaviour of the system were discussed in detail. In a two-mode optomechanical system, Jiang *et al.*[4] theoretically investigated the optical bistable behavior of the intracavity photon number. They mainly explored the OB in the right cavity. By numerical calculation, they found that the optical bistable behavior of the system could be effectively modulated by tuning the power and the frequency of the pump beams, and that the cavity with low photon numbers could also exhibit the bistable behavior.

Motivated by these works, we investigate theoretically the optical bistable behavior in a three-mode optomechanical system which is formed by inserting a moveable membrane into two fixed mirrors with partial transmission. We mainly focus on the OB of the mean photon number in the left and the right cavity together, and explore the dependence of the OB on the parameters of the system, such as the power of the pump beam, the coupling strength between the cavity and the membrane, the decay rate of the cavity, and so on. The obtained results show that, when driving the system by the left and the right pump beam simultaneously, the bistable curve of the mean photon number versus the cavity–pump detuning has two characteristic peaks, one of which is located in the stable region while the other in the bistable region. Moreover, with the increase of the power of the left pump beam, the bistable curve of the left cavity suffers a completely opposite change to the one of the right cavity. These phenomena are important and have not been reported in the related references as far as we know.

2. Model and theory

The three-mode optomechanical system where one moveable membrane of perfect reflection is inserted between two fixed mirrors with partial transmission is depicted schematically in Fig. 1. Two optical cavities have the same length L and frequency ω_0. The membrane oscillator is at its equilibrium position in the absence of any external exciting conditions. The membrane oscillator has a frequency ω_m and a decay rate γ_m. In a rotating frame at a driving field frequency ω_c,

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the Hamiltonian of the system can be expressed as[33]

$$\begin{aligned} H &= \hbar\Delta_{\rm c}\left(c_1^{\dagger}c_1+c_2^{\dagger}c_2\right)+\hbar\omega_{\rm m}b^{\dagger}b \\ &+\hbar g_0\left(c_2^{\dagger}c_2-c_1^{\dagger}c_1\right)\left(b^{\dagger}+b\right) \\ &+{\rm i}\hbar\varepsilon_{\rm L}\left(c_1^{\dagger}-c_1\right)+{\rm i}\hbar\varepsilon_{\rm R}\left(c_2^{\dagger}-c_2\right). \end{aligned} \tag{1}$$

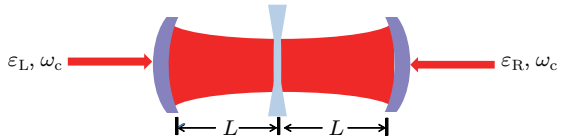


Fig. 1. (color online) Schematic depiction of a three-mode optomechanical system where two cavities have identical cavity lengths L and mode frequencies ω_0. The oscillating membrane is inserted between two fixed mirrors. Two cavities are driven by two pump beams with the same frequency $\omega_{\rm c}$ but different amplitude $\varepsilon_{\rm L}$ and $\varepsilon_{\rm R}$.

The first term of Eq. (1) represents the energy of the two optical cavity modes with the same resonance frequency ω_0, where $\Delta_{\rm c}=\omega_0-\omega_{\rm c}$ is the detuning between the cavity-mode and the coupling fields. The second term gives the energy of the mechanical mode with resonance frequency $\omega_{\rm m}$ and effective mass m. The third term describes the coupling between the membrane oscillator and the cavities, and g_0 is the corresponding coupling strength. The last two terms describe the interaction between the input fields and the cavity fields, where the left and right sides with amplitudes denoted by $\varepsilon_{\rm L}=\sqrt{2\kappa P_{\rm L}/(\hbar\omega_{\rm c})}$, $\varepsilon_{\rm R}=\sqrt{2\kappa P_{\rm R}/(\hbar\omega_{\rm c})}$. Here, $P_{\rm L}$ and $P_{\rm R}$ are the relevant field powers, and κ is the common decay rate of both optical modes.

According to the Heisenberg equation of motion and the communication relations $\left[c_1,c_1^{\dagger}\right]=1$, $\left[c_2,c_2^{\dagger}\right]=1$, and $\left[b,b^{\dagger}\right]=1$, the temporal evolutions of c_1, c_2, X, and p can be obtained, where $X=\left(b+b^{\dagger}\right)/\sqrt{2}$, $p={\rm i}\left(b^{\dagger}-b\right)/\sqrt{2}$. In the following paragraphs, we deal with the mean response of the system to the coupling field, and let $\langle c_1\rangle$, $\langle c_1^{\dagger}\rangle$, $\langle c_2\rangle$, $\langle c_2^{\dagger}\rangle$, and $\langle X\rangle$ be the expectation values of operators c_1, c_2, and X, respectively.

Taking the damping terms into consideration, Langevin equations for the optomachanical system are given by

$$\frac{{\rm d}\langle c_1\rangle}{{\rm d}t} = -\left[\kappa+{\rm i}\Delta_c-\sqrt{2}{\rm i}g_0\langle X\rangle\right]\langle c_1\rangle+\varepsilon_{\rm L}, \tag{2}$$

$$\frac{{\rm d}\langle c_2\rangle}{{\rm d}t} = -\left[\kappa+{\rm i}\Delta_c+\sqrt{2}{\rm i}g_0\langle X\rangle\right]\langle c_2\rangle+\varepsilon_{\rm R}, \tag{3}$$

$$\begin{aligned} &\frac{{\rm d}^2\langle X\rangle}{{\rm d}t^2}+\gamma_{\rm m}\frac{{\rm d}\langle X\rangle}{{\rm d}t}+\omega_{\rm m}^2\langle X\rangle \\ &=\sqrt{2}\omega_{\rm m}g_0\left(\langle c_1{}^{\dagger}\rangle\langle c_1\rangle-\langle c_2{}^{\dagger}\rangle\langle c_2\rangle\right), \end{aligned} \tag{4}$$

where $\gamma_{\rm m}$ is the damping rate of the membrane oscillator. To solve these equations, we make the ansatz as

$$\begin{aligned} \langle X(t)\rangle &= X_0+X_+{\rm e}^{-{\rm i}\delta t}+X_-{\rm e}^{{\rm i}\delta t}, \\ \langle c_1(t)\rangle &= c_{10}+c_{1+}{\rm e}^{-{\rm i}\delta t}+c_{1-}{\rm e}^{{\rm i}\delta t}, \\ \langle c_2(t)\rangle &= c_{20}+c_{2+}{\rm e}^{-{\rm i}\delta t}+c_{2-}{\rm e}^{{\rm i}\delta t}. \end{aligned} \tag{5}$$

By substituting Eq. (5) into Eqs. (2), (3), and (4) respectively, we can get

$$c_{10}\left(\kappa+{\rm i}\Delta_{\rm c}-\sqrt{2}X_0g_0{\rm i}\right)=\varepsilon_{\rm L}, \tag{6}$$

$$c_{20}\left(\kappa+{\rm i}\Delta_{\rm c}+\sqrt{2}X_0g_0{\rm i}\right)=\varepsilon_{\rm R}, \tag{7}$$

$$\omega_{\rm m}^2X_0=\sqrt{2}\omega_{\rm m}g_0\left(|c_{10}|^2-|c_{20}|^2\right). \tag{8}$$

From Eqs. (6) and (7), we obtain

$$n_1=\frac{\varepsilon_{\rm L}^2}{\kappa^2+\left(\Delta_{\rm c}-\sqrt{2}X_0g_0\right)^2}, \tag{9}$$

$$n_2=\frac{\varepsilon_{\rm R}^2}{\kappa^2+\left(\Delta_{\rm c}+\sqrt{2}X_0g_0\right)^2}, \tag{10}$$

where $n_1=|c_{10}|^2$ and $n_2=|c_{20}|^2$ are the number of photons.

3. Results and discussion

In this section, we present the numerical results of the bistable behavior for this three-mode optomechanical system based on the equations derived above. The parameters used are[34,35] $\omega_{\rm m}=2\pi\times947$ kHz, $g_0=2\pi\times6.75$ Hz, and $\kappa=2\pi\times80$ kHz.

In the first case, the left input light is present while the right input light is turned off. In Fig. 2(a), the mean intracavity photon number in the left cavity is present as a function of the left cavity–pump detuning $\Delta_{\rm c}$ for different pump powers. From this figure, it can be clearly observed that when the power of the left pump beam is tuned as 0.1 mW, a nearly symmetrical Lorentzian curve centred at $\Delta_{\rm c}=0$ is shown. However, when the power increases beyond the critical value, the system will exhibit the bistable behavior as shown by the dot line in the figure. For this case, the equation (9) has three real roots. For example, when the cavity–pump detuning $\Delta_{\rm c}$ is tuned to 1.2 MHz and the left pump power $P_{\rm L}$ is increased to 0.54 mW, the bistable behavior of the system appears, which can be seen obviously in Fig. 2(b). With the above parameters, the mean photon number n_1 can be obtained by solving Eq. (9) as $n_1=5.12\times10^8$ (corresponding to the dot A in Fig. 2(b)), 13.70×10^8 (dot B), and 20.87×10^8 (dot C). Figure 2(b) also shows us that the cavity–pump detuning $\Delta_{\rm c}$ is an important parameter influencing the bistability of the system. Only when the detuning $\Delta_{\rm c}$ is larger than the critical value, can the system driven by a suitable pump light be bistable. To intuitively show the bistable behavior of the system, the bistability diagram of the photon number n_1 with respect to $P_{\rm L}$ and $\Delta_{\rm c}$ is plotted in Fig. 2(c), which obviously presents the stable and the unstable regions. As shown in this figure, the bistability of the mean photon number in the left cavity can be determined

by the pump power P_L and the cavity–pump detuning Δ_c together.

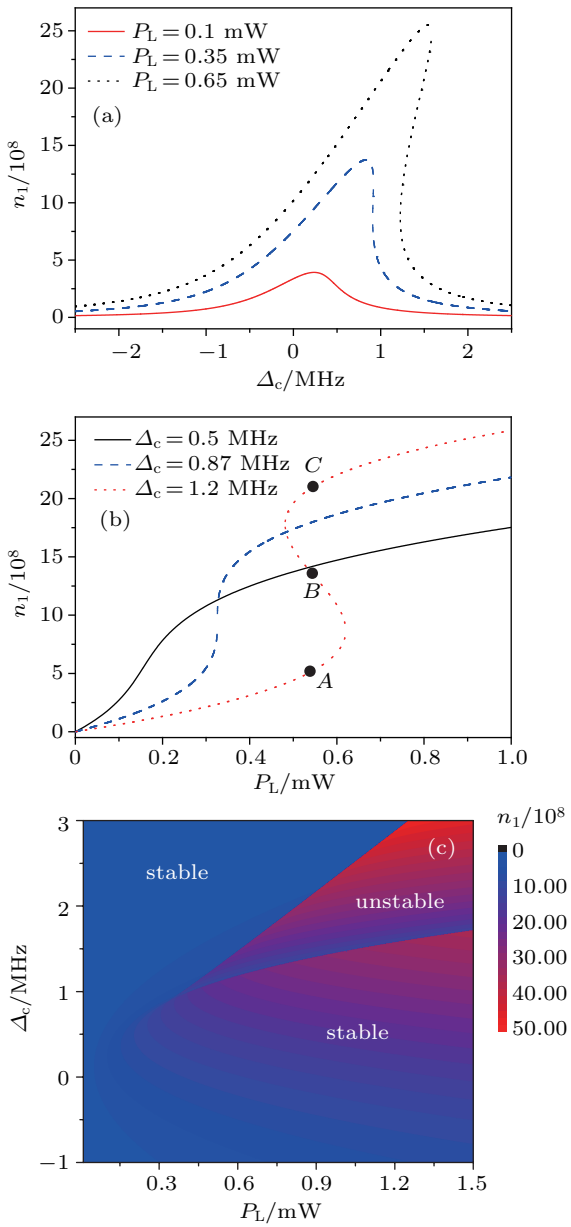


Fig. 2. (color online) (a) Mean intracavity photon number n_1 in the left cavity as a function of the cavity–pump detuning Δ_c for the left pump power $P_L = 0.1$, 0.35, and 0.65 mW. (b) Mean intracavity photon number n_1 as a function of the left pump power P_L for different cavity–pump detuning $\Delta_c = 0.5$, 0.87, and 1.2 MHz. (c) The bistability diagram of the mean intracavity photon number n_1 with respect to P_L and Δ_c. The right pump power is equal to 0 mW.

When the right pump light is turned off as discussed in the first case, it is found that only the left cavity can exhibit the bistable behavior. In the following, we mainly discuss the second case that the left pump beam and the right one are turned on at the same time. For this case, both the left cavity and the right one will exhibit the bistable behavior simultaneously as shown in Figs. 3(a) and 3(b), which respectively show the photon number in the left and right cavity as a function of the cavity–pump detuning Δ_c for different left pump power. The right pump power P_R is fixed as 0.11 mW. It is obvious that the bistable curve of the left and right cavity has two peaks, one of which is located in the stable region (peak A in Figs. 3(a) and 3(b)) and the other in the bistable region (peak B in Figs. 3(a) and 3(b)). This phenomenon is very different from the results in the references.[2–5] By comparing Figs. 2(a) and 3(a), it can be clearly seen that when the right pump light is present, a new peak (peak A as shown in Fig. 3(a)) emerges. This means that the right pump light has significant effects on the mean photon number n_1 in the left cavity. To demonstrate this conclusion, figure 3(c) is plotted, which shows n_1 as a function of the cavity–pump detuning Δ_c with different right pump power P_R. Obviously, with the increase of P_R, the peak A suffers a noticeable rise but the peak B keeps unchanged. Moreover, as shown in Fig. 3(b), when driving the left cavity by the left pump light with $P_L = 0.1$ mW, the mean photon number n_2 in the right cavity is stable. However, when P_L is increased to a reasonable value, for example $P_L = 0.65$ mW, the bistable behavior of n_2 takes place. In addition, it can also be found that, with the increase of the left pump power P_L, peak A has no significant change except an obvious left shift while peak B undergoes a great change. Thus, it can be concluded that the mean photon number n_2 in the right cavity can be effectively modulated by the left pump beam. The physical mechanism for these phenomena can be explained as follows. For this three-mode optomechanical system, the left cavity and the right one couple together indirectly with the help of the middle oscillating membrane due to the radiation pressure. When the left (right) cavity is driven by the left (right) pump beam, the circulating light induces a radiation pressure force that moves the middle membrane. As a result, the length of the right (left) cavity is changed and thereby the circulating intensity is modulated. Therefore, the bistable behavior in the left cavity can be effectively modulated by the right pump beam, and vice verse.

In Fig. 4, the mean intracavity photon number (n_1 the left cavity and n_2 the right cavity) as a function of the left pump power P_L is plotted with different cavity–pump detuning. From this figure, it can be clearly seen that the photon number n_1 initially lies in the lower stable branch but n_2 lies in the upper branch. However, when the left pump power increases to a critical value, n_1 jumps to the upper branch and at the same time n_2 jumps down to the lower branch. Therefore, just by modulating the left pump power, the bistable behaviors in both the left cavity and the right one can be controlled simultaneously. This property makes the system have potential value in the application of optical switching devices. Moreover, this figure also shows us that with the increase of the cavity–pump detuning, the threshold of the bistable behavior suffers an obvious increase in both of the two cavities. Thus, the cavity–pump detuning can play an effective role in modu-

lating the bistable behavior of this system.

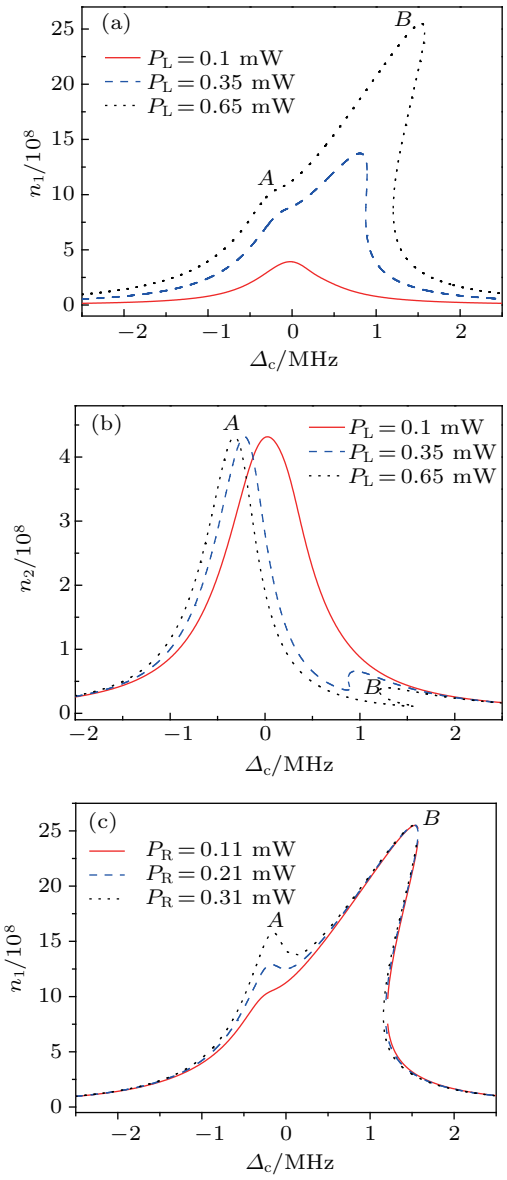


Fig. 3. (color online) Mean intracavity photon number of (a) the left cavity and (b) the right cavity as a function of the cavity–pump detuning for the left pump power $P_L = 0.1$, 0.35, and 0.65 mW. The right pump power is equal to 0.11 mW. (c) Mean intracavity photon number n_1 versus the cavity–pump detuning Δ_c for different right pump power $P_R = 0.11$, 0.21, and 0.31 mW. The left pump power is fixed as 0.65 mW.

In Fig. 5, the effects of the coupling strength between the cavity and the membrane on the OB is examined. Figures 5(a) and 5(b) depict the mean intracavity photon numbers n_1 and n_2 as functions of the left pump power P_L for $g_0 = 2\pi \times 6.75$ Hz, $2\pi \times 7.29$ Hz, and $2\pi \times 7.83$ Hz. From this figure, it can be clearly observed that by increasing the coupling strength the threshold of the bistable behavior of the system can be reduced greatly, i.e., with a strong coupling strength, the bistable behavior of the system can be induced even at lower input power. This behavior opens the possibility of the optical switching with lower pump power. Thus, this three-mode optomechanical system may have potential applications in a quantum device working at lower power.

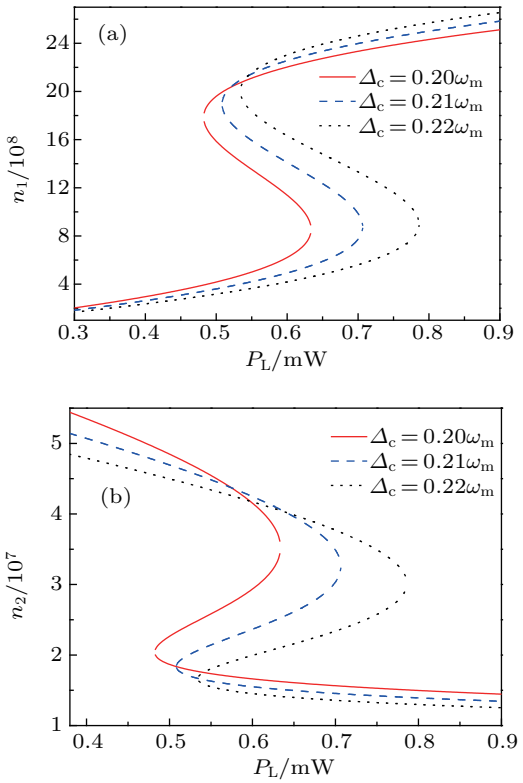


Fig. 4. (color online) The mean intracavity photon number n_1 (in the left cavity) and n_2 (in the right cavity) as a function of the left pump power for different detuning $\Delta_c = 0.2\omega_m$, $0.21\omega_m$, and $0.22\omega_m$. The power of the right pump beam is fixed as $P_R = 0.11$ mW.

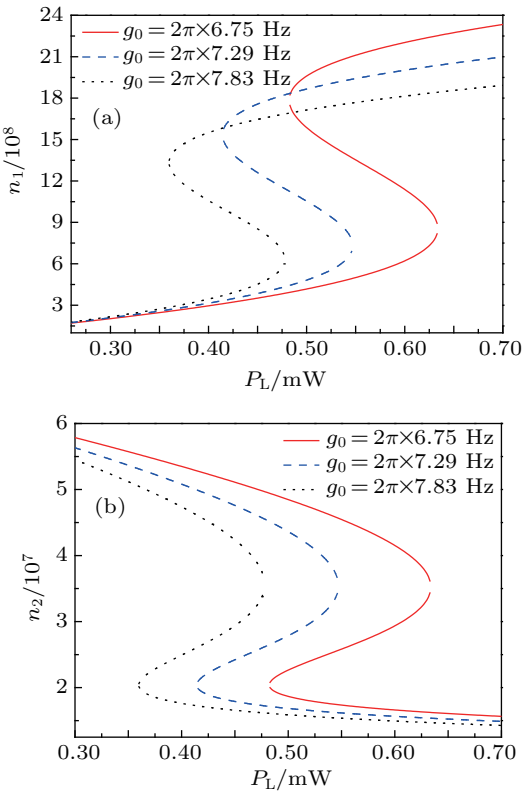


Fig. 5. (color online) Mean intracavity photon numbers n_1 and n_2 as functions of the left pump power for different coupling strengths $g_0 = 2\pi \times 6.75$ Hz, $2\pi \times 7.29$ Hz, and $2\pi \times 7.83$ Hz. The power of the right pump beam is fixed as $P_R = 0.11$ mW and $\Delta_c = 0.2\omega_m$.

In what follows, we will investigate the effects of the cavity decay rate on the OB. The mean intracavity photon numbers n_1 and n_2 as functions of the left pump power P_L for various cavity decay rates are plotted in Figs. 6(a) and 6(b), respectively. As shown in this figure, increasing the decay rate causes a great decrease in the width of the bistability curve in both cavities, and at the same time the OB threshold is reduced. Therefore, by controlling the cavity decay rate, the threshold of the OB and the width of the bistable region can be effectively modulated.

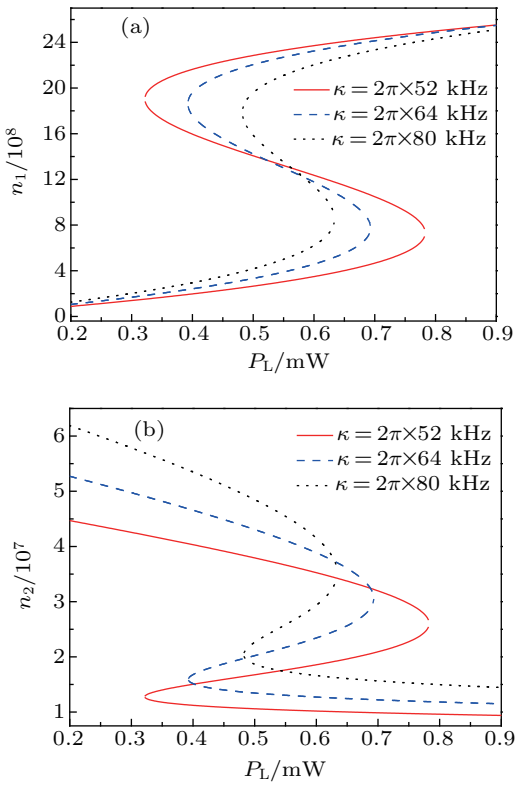


Fig. 6. (color online) Mean intracavity photon numbers n_1 and n_2 as functions of the left pump power for different decay rates $\kappa = 2\pi\times52$ kHz, $2\pi\times64$ kHz, and $2\pi\times80$ kHz. The power of the right pump beam is fixed as $P_R = 0.11$ mW and $\Delta_c = 0.2\omega_m$.

Finally, we will further illustrate the OB that appeared in the cavity by the mean-field equations

$$\frac{\mathrm{d}\langle c_1\rangle}{\mathrm{d}t} = -\left[\kappa + \mathrm{i}\Delta_c - \sqrt{2}\mathrm{i}g_0\langle X\rangle\right]\langle c_1\rangle + \varepsilon_L, \quad (11)$$

$$\frac{\mathrm{d}\langle c_2\rangle}{\mathrm{d}t} = -\left[\kappa + \mathrm{i}\Delta_c + \sqrt{2}\mathrm{i}g_0\langle X\rangle\right]\langle c_2\rangle + \varepsilon_R, \quad (12)$$

$$\frac{\mathrm{d}\langle p\rangle}{\mathrm{d}t} = g_0(\langle c_1^\dagger\rangle\langle c_1\rangle - \langle c_2^\dagger\rangle\langle c_2\rangle) - \omega_m\langle X\rangle. \quad (13)$$

Due to that the cavity decay rate κ is much larger than the decay rate of the mechanical modes and the coupling constant g_0, the equations (11) and (12) can be changed into[36]

$$\langle c_1\rangle = \frac{\varepsilon_L}{\kappa + \mathrm{i}\Delta_c - \sqrt{2}\mathrm{i}g_0\langle X\rangle}, \quad (14)$$

$$\langle c_2\rangle = \frac{\varepsilon_R}{\kappa + \mathrm{i}\Delta_c + \sqrt{2}\mathrm{i}g_0\langle X\rangle}. \quad (15)$$

Substituting Eqs. (14) and (15) into Eq. (13) then gives

$$\frac{\mathrm{d}\langle p\rangle}{\mathrm{d}t} = -\omega_m\langle X\rangle + \frac{\sqrt{2}g_0|\varepsilon_L|^2}{\left(\Delta_c - \sqrt{2}g_0\langle X\rangle\right)^2 + \kappa^2} - \frac{\sqrt{2}g_0|\varepsilon_R|^2}{\left(\Delta_c + \sqrt{2}g_0\langle X\rangle\right)^2 + \kappa^2}. \quad (16)$$

Here we employ the effective potential $U(x)$ $(x = \langle X\rangle)$ for mechanical expression, as

$$\frac{\mathrm{d}\langle p\rangle}{\mathrm{d}t} = -\frac{1}{\hbar}\frac{\partial U(x)}{\partial x}. \quad (17)$$

By combining Eqs. (16) and (17), we can get

$$U(x) = \frac{1}{2}\hbar\omega_m x^2 - \frac{\hbar|\varepsilon_L|^2}{\kappa}\arctan\left[\frac{\Delta_c - \sqrt{2}g_0 x}{\kappa}\right] + \frac{\hbar|\varepsilon_R|^2}{\kappa}\arctan\left[\frac{\Delta_c + \sqrt{2}g_0 x}{\kappa}\right]. \quad (18)$$

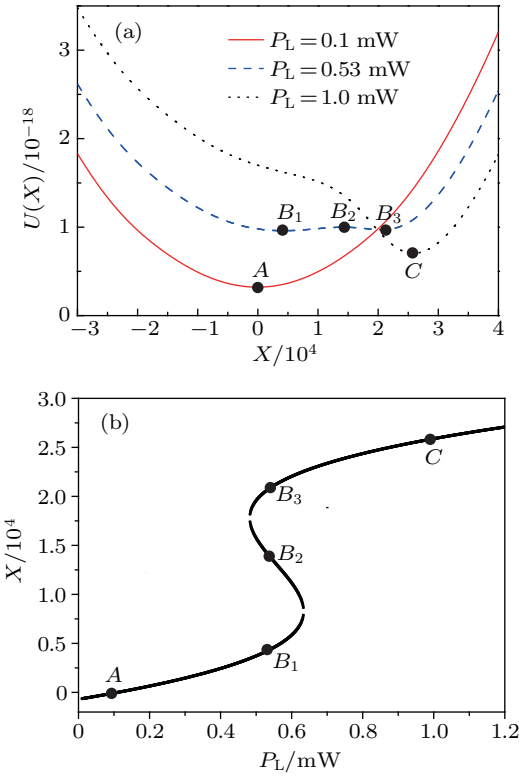


Fig. 7. (color online) (a) The effective potential $U(X)$ as a function of the position X for different left pump power as $P_L = 0.1$ mW, 0.53 mW, and 1.0 mW. The cavity–pump detuning Δ_c is equal to $0.2\omega_m$ and $P_R = 0.11$ mW. (b) The bistable behavior of X as a function of the left pump power P_L. The parameters used are similar to those in panel (a).

Figure 7(a) shows the effective potential $U(X)$ as a function of the position X for different left pump power P_L and figure 7(b) describes the bistable curve of X versus P_L. As shown in Fig. 7(a), for the lower pump power ($P_L = 0.1$ mW) the effective potential has a single stable minimum (dot A in the solid curve), which corresponds to the dot A in Fig. 7(b). With a reasonable pump power ($P_L = 0.53$ mW), however, a double-well effective potential arises with two stable minima (dot B_1 and B_3 in the dashed curve) and one unstable maximum (dot

B_2), indicating the bistable behavior, which can be seen clearly in Fig. 7(b). The dots B_1, B_2, and B_3 in Fig. 7(b) respectively correspond to the dots B_1, B_2, and B_3 in the dashed curve in Fig. 7(a). For a larger pump power $P_L = 1.0$ mW, the effective potential again exhibits a single stable minimum position (dot C in the dotted curve) displaced from the origin, which corresponds to the dot C in Fig. 7(b). Figures 7(a) and 7(b) demonstrate that the bistable behavior of the photon number in the left or right cavity can be easily understood by the double-well effective potential model.

4. Conclusion

The bistable behavior in a three-mode cavity optomechanical system is discussed in detail. It is found that the optical bistability in the left and right cavities can be simultaneously modulated by the input beam. Especially, due to two pump beams driving the system, the bistable curve shows a very different property in this system. Furthermore, the effects of the cavity–pump detuning on the bistability are investigated and it is demonstrated that the threshold of the bistable behavior can be modulated by changing the cavity–pump detuning. Importantly, the results also show us that the bistable behavior of the system can be induced even at lower input power just by enhancing the coupling strength between the cavity and the membrane. In addition, one can adjust the width and the threshold of the bistability curve by controlling the cavity decay rate. Finally, the effective potential is presented and a double-well model is discussed to illustrate the OB behavior in a three-mode cavity optomechanical system.

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