Letter

Controllable double optical bistability via photon and phonon interaction in a hybrid optomechanical system

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Abstract

Optical bistability has been studied theoretically in a multi-mode optomechanical system with two mechanical oscillators independently coupled to two cavities in addition to direct tunnel coupling between cavities. It is shown that the bistable behavior of the mean intracavity photon number in the right cavity can be tuned by adjusting the strength of the pump laser beam driving the left cavity. In addition, the mean intracavity photon number is relatively larger in the red sideband regime than that in the blue sideband regime. Moreover, we show that the double optical bistability of the intracavity photon in the right cavity and the two steady-state positions of the mechanical resonators can be observed when the control field power is increased to a critical value. In addition, the critical values for the observation of bistability and double bistability can be tuned by adjusting the coupling coefficient between the two cavities and the coupling rates between cavity mode and mechanical mode.

Keywords: optical bistability, intracavity photon number, mechanical resonator

(Some figures may appear in colour only in the online journal)

1. Introduction

Optomechanical systems, in which the light field interacts with a mechanical resonator via radiation pressure, are a fast developing area in the quantum optics domain due to promising applications in ultrasensitive detection [1–3], mirror ground-state cooling [4–7], and quantum entanglement generation [8, 9], etc. In particular, the typical optomechanical cavities with one or more movable mirrors are attracting increasing attention [10–13] as the hybrid optomechanical coupling is well exploited in the realization of quantum information processing [14–16] and in the observation of macroscopic quantum behavior [17].

Among the numerous nonlinear phenomena in cavity optomechanical systems, optical bistability, which is characterized by the intracavity mean photon number, has been investigated in different optomechanical systems [18–20] and under the effect of different types of interactions [21–23].
Optical bistability denotes that it is possible to deliver two different outputs for an applied power to the system. The essence of the observed bistability in optomechanical systems is referred to as the nonlinear nature of the coupling between radiation pressure and mechanical oscillations [24, 25]. It is worth mentioning that optical bistability can be controlled by a strong laser field and was first experimentally observed by Dorsel et al [26]. Subsequently, the bistable behavior of the mean intracavity photon number in optomechanical systems with Bose–Einstein condensates [27, 28], ultracold atoms [29, 30], and quantum wells [31] have also been extensively studied. In particular, optical bistability and dynamic instability have been experimentally observed and studied in a system consisting of three-level L-type rubidium atoms in an optical ring cavity. The bistable behavior and self-pulsing frequency are experimentally manipulated by changing the controlling and cavity field parameters [32]. The nonlinear phenomenon of optical bistability inside a ring resonator, formed with a silicon-waveguide nanowire, has been theoretically analyzed, and an exact parametric relation connecting the output intensity to the input intensity has been derived [33]. The optical bistability in coupled optomechanical cavities in the presence of the Kerr effect has been studied, and it was found that the atomic medium has a profound effect on the bistable behavior of intracavity intensity for the optomechanical cavity.

Meanwhile, a critical value for the Kerr coefficient to observe bistability in intracavity intensity of the optomechanical cavity is determined [20].

Moreover, certain works concerning multi-mode optomechanical systems have been extensively investigated. Specifically, in three-mode optomechanical systems, where one mechanical mode is optomechanically coupled to two linearly coupled optical modes and one mechanical mode [34]. Additionally, the non-reciprocal conversion between microwave and optical photons in an electro-optomechanical system, where a microwave mode and an optical mode are coupled indirectly via two nondegenerate mechanical modes, has been demonstrated. The electro-optomechanical system can also be used to construct a three-port circulator for three optical modes with distinctively different frequencies by adding an auxiliary optical mode coupled to one of the mechanical modes [35]. In [36], Malz et al realized the implementation of phase-preserving and phase-sensitive directional amplifiers for microwave signals in an electromechanical setup comprising two microwave cavities and two mechanical resonators. It is an important step toward flexible and on-chip integrated nonreciprocal amplifiers of microwave signals. With regard to the preceding efforts, in this paper we intend to study the bistable behavior of hybrid optomechanical systems consisting of two optomechanical cavities coupled via two mechanical resonators in addition to direct tunnel coupling. Next, we shall theoretically investigate the bistability of the intracavity photon number and mechanical steady-state positions in the hybrid optomechanical systems. The bistable behavior of the steady-state photon number and the mechanical steady-state positions can be effectively adjusted by the power of the pump field, the coupling between the cavity and the mechanical resonator, and the detuning between the cavity and the pump field.

The rest of the work is arranged as follows: in section 2, we introduce the theoretical model, the Hamiltonian, and the nonlinear quantum Langevin equations associated with the Hamiltonian. In section 3, the numerical results are presented and discussed in detail according to the steady-state solution of the Langevin equations. The last section is devoted to our conclusions.

2. Description of the systems

2.1. Theoretical model and Hamiltonian

The system under consideration is shown in figure 1, which consists of two optical cavities coupled via two mechanical resonators, respectively, in addition to direct tunnel coupling [35, 36].

To investigate the optical response of the hybrid systems, we assume that the two cavity modes are driven simultaneously by a strong pump field with frequency $\omega_p$ and a weaker control field with frequency $\omega_c$, respectively. The Hamiltonian describing the system is given as

$$H = \sum_{l=1}^{2} \frac{\hbar}{2} (\omega_l a_l^{\dagger} a_l + \omega_{pl} b_l^{\dagger} b_l) - \sum_{k,l=1}^{2} \hbar g_{kl} a_l^{\dagger} a_k (b_k^{\dagger} + b_k) - \hbar J (a_1^{\dagger} a_2 + a_1 a_2^{\dagger}) + H_{dr},$$

(1)

where $a_l$ ($a_l^{\dagger}$) and $b_l$ ($b_l^{\dagger}$) are the creation (annihilation) operators of the $l$th cavity mode and mechanical resonator, respectively. The $\omega_l$ and $\omega_{pl}$ are the frequencies of the $l$th cavity mode and the mechanical resonator mode. The $g_{kl}$ represents the coupling rate between the $l$th optical cavity and the $l$th mechanical oscillator. And $J$ is the photon tunneling amplitude through the two central mirrors. The last term $H_{dr}$ describes the interaction between the driving fields and the optomechanical system: a strong pump field $E_p$ of frequency $\omega_p$ and a weak probe field of frequency $\omega_c$ are simultaneously employed to drive the cavity mode $a_1$, and another strong control field $E_c$ of frequency $\omega_c$ is applied to drive the cavity mode $a_2$, i.e.

$$H_{dr} = i\hbar \sqrt{\kappa_1} E_p e^{-i \omega_p t} a_1^{\dagger} + i\hbar \sqrt{\kappa_2} E_c e^{-i \omega_c t} a_2^{\dagger} + H.c.,$$

(2)

where $E_p$ and $E_c$ are the laser amplitudes, i.e. $|E_p| = \sqrt{\frac{2\kappa_1 P_p}{\hbar \kappa_{ac}}}$ and $|E_c| = \sqrt{\frac{2\kappa_2 P_p}{\hbar \kappa_{ac}}}$, where $P_p$ is the power of the laser corresponding to the pump field, $P_c$ is the power of the laser corresponding to the control field, and $\kappa_{ac}$ is the cavity decay rate associated with the $l$th cavity mode $a_l$ ($l = 1, 2$).

In the rotating frame at the pump frequency $\omega_p$, the Hamiltonian of the hybrid optomechanical systems reads:
2.2. Heisenberg–Langevin equations

According to the Heisenberg–Langevin equations of motion [37], after introducing the corresponding damping and noise terms to the equations of motion associated with the Hamiltonian in equation (3), one can obtain the following set of nonlinear equations, which read as

\[
\frac{d\hat{a}_1}{dt} = -\left( i \Delta_1 + \frac{\kappa_1}{2} \right) \hat{a}_1 + i g_{11} \hat{a}_1 X_1 + i g_{12} \hat{a}_1 X_2 + iJ\hat{a}_2
+ \sqrt{\kappa_1} \hat{E}_{pu}\text{,}
\]

\[
\frac{d\hat{a}_2}{dt} = -\left( i \Delta_2 + \frac{\kappa_2}{2} \right) \hat{a}_2 + i g_{22} \hat{a}_2 X_2 + i g_{21} \hat{a}_2 X_1 + iJ\hat{a}_1
+ \sqrt{\kappa_2} \hat{E}_{co}\text{,}
\]

\[
\frac{d^2X_1}{dt^2} = -\gamma_{m,1} \frac{dX_1}{dt} - \left( \omega_{m,1} \right)^2 X_1 + 2\omega_{m,1} g_{11} \hat{a}_1^\dagger \hat{a}_1
+ 2\omega_{m,1} g_{12} \hat{a}_1^\dagger \hat{a}_2 + \xi_1\text{,}
\]

\[
\frac{d^2X_2}{dt^2} = -\gamma_{m,2} \frac{dX_2}{dt} - \left( \omega_{m,2} \right)^2 X_2 + 2\omega_{m,2} g_{12} \hat{a}_1^\dagger \hat{a}_1
+ 2\omega_{m,2} g_{22} \hat{a}_2^\dagger \hat{a}_2 + \xi_2\text{,}
\]

where \(X_1 = \hat{a}_1^\dagger + \hat{a}_1\) and \(X_2 = \hat{a}_2^\dagger + \hat{a}_2\) are the quantum vacuum fluctuations of the cavity modes \(a_1\) and \(a_2\), which are fully characterized by the correlation \(\langle \hat{a}_{m,l}(t) \hat{a}_{m,l}^\dagger(t') \rangle = \delta(t-t')\), \(\langle \hat{a}_{m,l}^\dagger(t) \hat{a}_{m,l}(t') \rangle = 0\), \(\xi_j\) is the Brownian stochastic force with a zero mean value that obeys the correlation function \(\langle \xi_j(t) \xi_j(t') \rangle = \frac{\gamma_j}{m} \int \frac{d\omega_t}{2\pi} \omega_t e^{-i\omega(t-t')} \coth \left( \frac{\hbar \omega_t}{2 k_B T_j} \right) + 1\) with \(l = 1, 2\). Here, \(k_B\) is the Boltzmann constant and \(T_j\) is the temperature of the reservoir of the \(l\)th mechanical resonator. The cavity modes decay at the rate \(\kappa_j\) and are affected by the input vacuum noise operator \(\hat{a}_{m,l}\) with a zero mean value. The mechanical mode is affected by a viscous force with a damping rate \(\gamma_{m,l}\) and by a Brownian stochastic force with a zero mean value \(\xi\) [5]. To study the bistability of the presented system, we are interested in the steady-state solutions to equation (4). In addition, the mean intracavity photon number \(n_{p,l} = \langle \hat{a}_{l}^\dagger \hat{a}_l \rangle (l = 1, 2)\) can be determined by the coupled equations as follows

\[
n_{p,1} = \frac{\kappa_{e1} (E_{pu})^2 + E_{pu}^2 n_{p,2}}{\left( \frac{\gamma_1}{2} \right)^2 + \left( \Delta_1 - g_{11} X_1 + g_{12} X_2 \right)^2},
\]

\[
n_{p,2} = \frac{\kappa_{e2} (E_{co})^2 + E_{co} n_{p,1}}{\left( \frac{\gamma_2}{2} \right)^2 + \left( \Delta_2 - g_{21} X_1 + g_{22} X_2 \right)^2}.
\]

3. Results and discussion

In this section, we shall numerically investigate the bistable behavior when the two cavities are respectively coupled by two mechanical resonators in addition to direct tunnel coupling. We consider an experimentally realized optomechanical system. Thus, we choose parameters that are similar to those in [38]: \(\omega_{pu} = 2 \pi \times 205.3\text{THz}, \omega_{co} = 2 \pi \times 194.1\text{THz}, \omega_{m,1} = 2 \pi \times 1.73\text{GHz}, \kappa_{e1} = 2 \pi \times 0.26\text{MHz}, \text{and } \kappa_{e2} = 2 \pi \times 8.0\text{MHz}.

3.1. Intracavity photon number

Firstly, we investigate the optical bistability in the left cavity by adjusting the strength of the pump beam. The variations of the intracavity photon in the left cavity and right cavity, respectively, versus the left cavity-pump field detuning \(\Delta_1\) for different pump strengths are shown in figures 2(a) and (b). As seen in figure 2(a), the curve is an almost Lorentzian peak when the strength of the left pump beam is lower; however, when the strength increases above a critical value, the system exhibits obvious bistable behavior, as shown in the curves for a range of values of the driving laser strength. Specifically, the initially almost Lorentzian resonance curve becomes clearly asymmetric at the pump beam strength \(E_{pu} = 0.10\mu W\) and \(E_{pu} = 0.20\mu W\). In this case, the coupled cubic equation (5) for the mean intracavity photon

\[
X_{1,s} = \frac{2}{\omega_{m,1}^2} \left( g_{11} n_{p,1} + g_{21} n_{p,2} \right),
\]

\[
X_{2,s} = \frac{2}{\omega_{m,2}^2} \left( g_{12} n_{p,1} + g_{22} n_{p,2} \right).
\]
number yields three real roots. The largest and smallest roots are stable, and the middle one is unstable, which is represented by the dashed lines in figure 2(a). Furthermore, we can see that the larger cavity pump detuning is necessary to observe the optical bistable behavior with the increasing pump beam strength. The mean intracavity photon number $n_{p,2}$ in the right cavity as a function of $\Delta_1$ with $J = 2\pi \times 0.09$ GHz, $g_{11} = 2\pi \times 850$ kHz, $g_{12} = 2\pi \times 860$ kHz, $g_{21} = 2\pi \times 400$ kHz, $g_{22} = 2\pi \times 405$ kHz, $\Delta_1 = 2\pi \times 2.0$ GHz, and $P_{co} = 0.03 \mu$W for different values of $P_{pu}$: $P_{pu} = 0.01 \mu$W, $0.10 \mu$W, and $0.20 \mu$W, respectively.

The optical bistability in the two cavities can be equivalently seen from the hysteresis loop for the mean intracavity photon number versus the pump power for a range of control power, as shown in figures 3 and 4. The solid and dashed curves, respectively, correspond to stable and unstable solutions. It is shown in figure 3 that the mean intracavity photon number $n_{p,1}$ initially lies in the lower stable branch (corresponding to the smallest root). When the input pump power is gradually increased, the intracavity intensity in the left cavity initially scans the lower branch of the curve. When it arrives at the end of the lower branch, i.e. the first critical value, it then jumps to the upper stable branch. Therefore, an increase in the input pump power leads to an increase in the intracavity photon number. After jumping to the upper branch, the intracavity intensity starts decreasing if the input pump power is decreased, but it still follows the upper stable branch. When the intracavity intensity reaches the second critical point, it will jump down to the lower stable branch. Moreover, with the strengthening of the control power, the pump power needed to observe optical bistability is relatively lower.

The bistable behavior in the right cavity can be alternatively seen from the hysteresis loop for the mean intracavity photon number $n_{p,2}$ versus the pump power curve shown in figure 4. In contrast to the left cavity, as the power of the control field is increased, it is interesting to observe the emergence of double bistability in the right cavity. Specifically, the intracavity intensity in the right cavity $n_{p,2}$ initially scans the first lower branch of the curve when the input pump power is gradually increased. When it arrives at the end of the first lower branch, it then jumps to the first upper stable branch. After jumping to the upper branch, the intracavity intensity starts to increase if the input pump power is further increased; however, if the input pump power is further increased, then the intracavity intensity in the right cavity will jump to the second upper stable branch. It is obvious that, with increasing control power, the second cavity switches from a bistable to a double bistable regime. The physical concept behind this result can be expressed as follows. A higher control power value leads to enhanced nonlinearity in the right cavity, and then the
The mean intracavity photon number in the right cavity $n_{p,2}$ as a function of $P_{pw}$ with $J = 2\pi \times 0.09$ GHz, $g_{11} = 2\pi \times 850$ kHz, $g_{12} = 2\pi \times 860$ kHz, $g_{21} = 2\pi \times 400$ kHz, $g_{22} = 2\pi \times 405$ kHz, and $\Delta_1 = \Delta_2 = 2\pi \times 2.0$ GHz for different values of $P_{co}$: $P_{co} = 0.010\mu W$, $0.015\mu W$, and $0.020\mu W$, respectively.

Bistability in the systems is also sensitively affected by the coupling rate $J$ between the two cavities, as depicted in figure 5. In the weak coupling regime, the pump beam driving the left cavity cannot have enough impact on the photon numbers in the right cavity via the waveguide, thus the threshold value to observe bistability is relatively larger compared with the situation in the stronger coupling regime. Thus, with the strengthening of the coupling between the two cavities, the pump intensity needed to observe the optical bistability is relatively lower. It should be noted that the upper stable branches in the hysteresis loop of the left cavity for different coupling intensities $J$ eventually approach each other in the larger pump beam intensity. The physical mechanism lies in the fact that the intracavity photon numbers are not only affected by the pump field but also affected by the control field through the tunnel coupling between the two cavities. Thus, the threshold of the pump intensity required to observe optical bistability is relatively lower when there is stronger coupling. Additionally, the control field has little effect on the photon number in the left cavity in instances of stronger pump driving. Thus, it results in the phenomenon in which the upper stable branches of the hysteresis loop approach each other at larger pump beam intensities for different coupling intensities. Meanwhile, the pump intensity required to observe the optical bistability of the photon number in the right cavity will become lower with the increase in the coupling intensity between the two cavities. This is similar to the case in the left cavity. The reason for this is that, with the increasing tunneling coupling between the two cavities, there are more photons from the left cavity tunneling to the right cavity. Then we are more likely to observe the bistable phenomenon in the right cavity, and thus the pump intensity required to observe the bistability is relatively lower.

The mean intracavity photon number in (a) the left cavity $n_{p,1}$ as a function of $P_{pw}$ and (b) the right cavity $n_{p,2}$ as a function of $P_{pw}$ with $P_{co} = 0.01\mu W$, $g_{11} = 2\pi \times 850$ kHz, $g_{12} = 2\pi \times 860$ kHz, $g_{21} = 2\pi \times 400$ kHz, $g_{22} = 2\pi \times 405$ kHz, $\Delta_1 = \Delta_2 = 2\pi \times 2.0$ GHz for different values of $J$: $J = 2\pi \times 0.001$ GHz and $2\pi \times 0.190$ GHz, respectively.

The photon number of the right cavity is affected by both the pump field and the control field. With the increasing coupling strength, the effect of the pump field becomes stronger, which leads to a larger intracavity photon number in the upper stable branch of the hysteresis. As depicted in figure 6, in the stronger control field, compared with that in figure 5, with the increasing strengthening in the coupling rate between the two cavities, it is much easier to observe the double bistability, because the threshold value of the pump power required to generate bistability is lower. The reason for the observation of optical bistability at lower pump power in the larger coupling intensity is a result of the enhanced interaction of the control field through the tunnel effect.

If the right cavity is pumped on the red sideband, i.e. $\Delta_2 = \omega_{m,2}$, then it can be seen in figure 7 that the threshold value to observe the optical bistability in the left cavity is lower compared with that in the blue sideband, i.e. $\Delta_2 = -\omega_{m,2}$. However, the upper stable branches of the hysteresis loop in the blue sideband are larger than that in the red sideband. The mean intracavity photon number in the right cavity $n_{p,2}$ under
the conditions of the red sideband is manifestly smaller than the value obtained in the blue sideband, as shown in figure 8.

In this section, we analyze the double bistability of the mean intracavity photon number in the right cavity under different coupling rates between the left cavity and the first resonator. As shown in figure 9, the variation of the coupling rate will lead to the modulation of the threshold value in the observation of bistability. Specifically, as the coupling rate increases, the first critical value of the pump power for observation of the first bistable behavior is becoming lower; however, the second critical value of the pump power for the emergence of bistability becomes larger with the strengthening of the coupling rate.

3.2. Steady-state position of mechanical resonator

It is shown in equation (6) that the two steady-state positions of the mechanical resonator, i.e. $X_1$ and $X_2$, are directly related to the mean intracavity photon numbers $n_{p,1}$ and $n_{p,2}$. Thus, it can be inferred that the steady-state positions should exhibit similar bistable behavior to the mean intracavity photon number. According to the above analysis of the bistable properties of the intracavity photon number, it is found that the large photon number is necessary when the objective is to realize the bistable phenomenon; however, it can be seen in figure 10 that the double bistability can also be observed in relatively smaller photon numbers. For further illustration, in figure 10, the
two steady-state positions of the mechanical resonator changing versus the pump field driving strength $P_{pu}$ for different control beam strengths are presented, respectively. Initially, the steady-state positions display bistability; however, when the control beam power is increased to $P_{co} = 0.02 \mu W$, the double optical bistability in the two steady-state positions of the mechanical resonator can be observed. The increasing control field power will result in a stronger nonlinear effect on the photon number in both cavities, and then the radiation pressure on the mechanical resonators is increased; therefore, double optical bistability can occur in the two steady-state positions of the mechanical resonator.

The bistability in the steady-state position of the mechanical resonators is also sensitively affected by the coupling coefficient $J$ between the two cavities, as depicted in figure 11.

Specifically, it can be clearly seen that the two critical points required to observe the double optical bistability become smaller as the coupling coefficient is strengthened between the two cavities.

As shown in figure 12(a), for a range of coupling rates $g_{11}$, the lower driving strength is needed to observe the first bistable behavior in the steady-state position of the first mechanical resonator $X_{1,1}$ in the larger coupling strength $g_{11}$, while the second threshold value to observe the bistable phenomenon becomes larger in the larger coupling strength $g_{11}$. Similar events have occurred in the steady-state positions of the second mechanical resonator $X_{2,2}$, as shown in figure 12(b): the steady-state position of the second mechanical resonator $X_{2,2}$ versus pump strength for several quantities in the coupling strength $g_{11}$. Thus, the changing of the coupling rate between the first mechanical resonator and the left cavity yields effective controllability over the behavior in the steady-state position of the second mechanical resonator.

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**Figure 10.** The mechanical steady-state position $X_{1,1}$ as a function of $P_{pu}$ with $J = 2\pi \times 0.09 \text{ GHz}$, $g_{11} = 2\pi \times 850 \text{ kHz}$, $g_{12} = 2\pi \times 860 \text{ kHz}$, $g_{21} = 2\pi \times 400 \text{ kHz}$, $g_{22} = 2\pi \times 405 \text{ kHz}$, and $\Delta_1 = \Delta_2 = 2\pi \times 2.0 \text{ GHz}$ for different values of $P_{co}$: $P_{co} = 0.010 \mu W, 0.015 \mu W, \text{ and } 0.020 \mu W$, respectively.

**Figure 11.** The first mechanical steady-state position $X_{1,1}$ as a function of $P_{pu}$ with $P_{co} = 0.02 \mu W, g_{11} = 2\pi \times 850 \text{ kHz}$, $g_{12} = 2\pi \times 860 \text{ kHz}$, $g_{21} = 2\pi \times 400 \text{ kHz}$, $g_{22} = 2\pi \times 405 \text{ kHz}$, $\Delta_1 = \Delta_2 = 2\pi \times 2.0 \text{ GHz}$ for different values of $J$: $J = 2\pi \times 0.001 \text{ GHz}$ and $2\pi \times 0.090 \text{ GHz}$, respectively.

**Figure 12.** The first mechanical steady-state position $X_{1,1}$ (a) and the second mechanical steady-state positions $X_{2,2}$ (b) as a function of $P_{pu}$ with $P_{co} = 0.020 \mu W, J = 2\pi \times 0.09 \text{ GHz}$, $g_{12} = 2\pi \times 860 \text{ kHz}$, $g_{21} = 2\pi \times 400 \text{ kHz}$, $g_{22} = 2\pi \times 405 \text{ kHz}$, and $\Delta_1 = \Delta_2 = 2\pi \times 2.0 \text{ GHz}$ for different values of $g_{11}$: $g_{11} = 2\pi \times 850 \text{ kHz}$, $2\pi \times 900 \text{ kHz}$, and $2\pi \times 950 \text{ kHz}$, respectively.
4. Conclusions

In summary, the controllability of the optical bistability of the intracavity photon number in both cavities and the two steady-state positions of mechanical resonators have been theoretically analyzed. It is shown that the optomechanical systems considered here enable robust controllability over the bistable behavior of the intracavity photon number and steady-state positions of the mechanical resonators. Specifically, the bistable behavior of the intracavity photon number can be modulated by changing the control beam strength, the coupling coefficient between the two cavities, and the coupling rates between the cavity mode and mechanical mode, respectively. It is shown that the bistable behavior of the mean intracavity photon number in the right cavity can be tuned by adjusting the strength of the pump laser beam driving the left cavity. In addition, the mean intracavity photon number is relatively larger in the red sideband regime than that in the blue sideband regime. Moreover, we show that the interesting phenomenon of double bistability of the intracavity photon number in the right cavity can be observed when the control field power is increased to a critical value. Furthermore, the critical values required to observe bistability and double bistability can be tuned by adjusting the coupling coefficient between two cavities and the coupling rate between the cavity mode and mechanical mode. The larger coupling coefficient shall render a smaller threshold value to observe both bistability and double bistability. Meanwhile, in the coupling rates between the cavity mode and mechanical mode cases, the larger coupling rates shall render a smaller threshold value to observe the first bistability and a larger threshold value to observe the second bistability. The control of optical bistability will have practical applications in the building of more efficient all-optical switches and logic-gate devices for quantum computing and quantum information processing.

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