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Optomechanically induced transparency with Bose–Einstein condensate in double-cavity optomechanical system*

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We propose a novel technique of generating multiple optomechanically induced transparency (OMIT) of a weak probe field in hybrid optomechanical system. This system consists of a cigar-shaped Bose–Einstein condensate (BEC), trapped inside each high finesse Fabry-Pérot cavity. In the resolved sideband regime, the analytic solutions of the absorption and the dispersion spectrum are given. The tunneling strength of the two resonators and the coupling parameters of the each BEC in combination with the cavity field have the appearance of three distinct OMIT windows in the absorption spectrum. Furthermore, whether there is BEC in each cavity is a key factor in the number of OMIT windows determination. The technique presented may have potential applications in quantum engineering and quantum information networks.

Keywords: optomechanically induced transparency, Bose–Einstein condensate, cavity optomechanical

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1. Introduction

Electromagnetically induced transparency (EIT) is an interesting quantum interference phenomenon, which occurs when a weak probe-laser field and a strong driving laser field are resonantly excited and two different atomic transitions share the common state.[1–4] Absorption of a weak probe-laser field can be reduced or eliminated by a strong driving laser beam. The EIT effect achieved during the experimental process forms a valuable contribution in a variety of physical processes, such as nonlinear susceptibility modulation,[5] group velocity control,[6,7] quantum computation, and quantum communication.[8,9]

Recent research in cavity optomechanical systems (OMS) attracted scientific interest in both theoretical and experimental level.[10,11] Ordinary structure of OMS consists of various forms, such as two fixed mirrors,[12] one fixed and another movable,[13] a micro-mechanical membrane oscillating,[14] a Bose–Einstein condensate (BEC) inside two fixed cavity,[15–17] two optical cavities, and photonic crystal systems.[18,19] These kinds of systems, which do not use atomic resonance, revealed that coherent effects in OMS are remarkably similar to those in atoms. This phenomenon (similar to EIT) is widely called the optomechanically induced transparency (OMIT). Worldwide research in OMIT includes four-wave mixing,[20] superluminal and ultraslow light propagation,[21,22] single photon quantum router,[23] charge measurement, and so on.[24] Furthermore, double or multiple OMIT has been a hot topic of high scientific interest during recent years, such phenomenon would find some new physics and applications.[25–29] Tunable optomechanically induced transparency has been extensively studied in different models, e.g., nonlinear optomechanical system with two movable mirrors,[25] charged nanomechanical resonator,[26] optomechanical system consisting of two tunneling-coupled resonators,[27] the quantized field in the system[28] and multi-cavity optomechanical system with and without one two-level atom.[29]

In this work, we observe multiple OMIT in an OMS. In this OMS, coupled optical cavity with a cigar-shaped BEC is trapped separately within an optical cavity. A BEC-optomechanical system has been proposed and attracted much attention.[30–34] Using this kind of system, the intracavity laser field excites a momentum side-mode of the condensate.[30,31] Furthermore, in the BEC-optomechanical system, a strong coupling range can be achieved, even with an ultra-low pump power.[32–34] More importantly, the BEC can be trapped on a small scale, and thus a robust miniature device can be easily implemented.[35–37] The BEC-optomechanical system has been studied under this condition:[38,39] when the optical cavity is fed by both a detuned strong pump field and a weak probe field. In this case, it can serve as a single photon router, and it may have potential applications in optical communication and quantum information processing. In the research below, firstly, three OMIT windows in the absorption line of the probe field is obtained. Secondly, by tuning the system parameters, a switch from triple OMIT windows to double

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and a single occurs. Furthermore, OMS parameters used in our study are validated in laboratory experiments.

The structure of the paper is as follow. In Section 2, we derive the Hamiltonian of the optomechanical systems, consisting of a BEC trapped inside each optical cavity. We give the absorption and the dispersion spectrum of the probe field with a BEC in each cavity. In Section 3, the numerical results exhibit that the absorption and the dispersion spectrum are influenced by the tunneling the strength of the two resonators and the coupling parameters of the each BEC with the cavity field. A summary is presented in Section 4.

2. Model

The optomechanical system consisting of two coupled optical cavity is presented in Fig. 1, where a cigar-shaped BEC of N_i ^{87}Rb atoms in the ground state, is trapped separately within an optical cavity. Two cavity fields are connected through photon tunneling parameters J. The first cavity is separately driven by a strong pump laser with frequency $\omega_{\rm pu}$ and a weak probe laser with frequency $\omega_{\rm pr}$. The Hamiltonian of the optomechanical system consisting of a BEC trapped inside each optical cavity is illustrated below,

$$\begin{aligned}\hat{H} =& \sum_{i=1,2}\int_0^L {\rm d}x_i \Psi_i^\dagger(x_i)\left[\frac{-\hbar^2}{2m_{ai}}\frac{{\rm d}^2}{{\rm d}x_i^2}+V_{\rm ext}(x_i)\right.\\ &\left.+\hbar U_{0i}\cos^2(kx_i)\hat{c}_i^\dagger\hat{c}_i\right]\Psi_i(x_i)\\ &+\hbar\sum_{i=1,2}\omega_{{\rm c}i}\hat{c}_i^\dagger\hat{c}_i+J(\hat{c}_1^\dagger\hat{c}_2+\hat{c}_2^\dagger\hat{c}_1)\\ &+{\rm i}\hbar\varepsilon_{\rm c}\left(\hat{c}_1^\dagger {\rm e}^{-{\rm i}\omega_{\rm pu}t}-\hat{c}_1 {\rm e}^{{\rm i}\omega_{\rm pu}t}\right)\\ &-{\rm i}\hbar\varepsilon_{\rm p}\left(\hat{c}_1 {\rm e}^{{\rm i}\omega_{\rm pr}t}-\hat{c}_1^\dagger {\rm e}^{-{\rm i}\omega_{\rm pr}t}\right). \end{aligned} \tag{1}$$

The first term describes the Hamiltonian of the BEC in each optical cavity in the case of shallow external trapping potential assumption. Equation factors are represented as follows: Ψ_i is a bosonic field annihilation operator, m_{ai} is the atomic mass, $V_{\rm ext}$ is the external potential, $k=\frac{2\pi}{\lambda}$ is the wave vector and $\cos(kx_i)$ is the cavity mode function. Here $U_{0i}=g_{0i}^2/\Delta_{ai}$ is the maximum light shift that an atom experiences in the cavity mode with the atom-photon coupling constant g_{0i}, Δ_{ai} is the detuning of the atomic frequencies from the cavity fields. The second term represents the energy of the intra-cavity field in each optical cavity, $\hat{c}_1$ and $\hat{c}_2$ are the annihilation operators for the two optical cavities, $\omega_{\rm c1}$ and $\omega_{\rm c2}$ are the cavity frequencies. The third term describes the energy between the two optical cavity with photon tunneling parameters J. The last two terms describes the interaction of the cavity driven by the pump field $\varepsilon_{\rm c}$ and probe laser field $\varepsilon_{\rm p}$. The amplitude of the pump laser field is $|\varepsilon_{\rm c}|=\sqrt{2P_{\rm pu}\kappa/\hbar\omega_{\rm pu}}$, and the probe laser field is $|\varepsilon_{\rm p}|=\sqrt{2P_{\rm pr}\kappa/\hbar\omega_{\rm pr}}$, where $P_{\rm pu}$ and $P_{\rm pr}$ are the power of the pump and probe field, $\omega_{\rm pu}$ and $\omega_{\rm pr}$ are the frequency of the pump and probe field, and κ is the cavity decay rate.

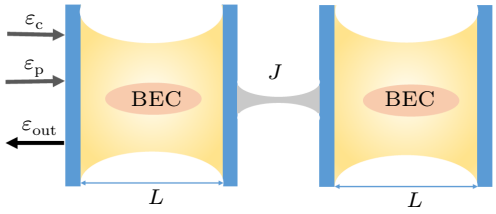


Fig. 1. (color online) Coupled resonator optomechanical system consisting of a Bose–Einstein condensate trapped inside an optical cavity. The left cavity is driven by a strong pump laser with frequency $\omega_{\rm pu}$ and a weak probe laser with frequency $\omega_{\rm pr}$.

By using the discrete mode approximation, under the most simple situation, it is concluded that the optical field was weak enough. Moreover, only the first two symmetric momentum side modes with moment $\pm 2\hbar k$ are excited by fluctuations as a result of the atom–light interaction. We can expand $\Psi(x)$ as follows:

$$\Psi(x)=\sqrt{\frac{1}{L}}\hat{a}_0+\sqrt{\frac{2}{L}}\cos(2kx)\hat{a}_2. \tag{2}$$

The effective Hamiltonian of the optomechanical systems consisting of a BEC trapped inside each optical cavity by transferring into the rotating frame at the pump frequency and using Bogoliubov approximation, is expressed as follows:

$$\begin{aligned}\hat{H} =& \hbar\sum_{i=1,2}\left(\Delta_{ci}\hat{c}_i^\dagger\hat{c}_i+\omega_{{\rm m}i}\hat{a}_i^\dagger\hat{a}_i+g_i(\hat{a}_i^\dagger+\hat{a}_i)\hat{c}_i^\dagger\hat{c}_i\right)\\ &+J\left(\hat{c}_1^\dagger\hat{c}_2+\hat{c}_2^\dagger\hat{c}_1\right)+{\rm i}\hbar\varepsilon_{\rm c}\left(\hat{c}_1^\dagger-\hat{c}_1\right)\\ &-{\rm i}\hbar\varepsilon_{\rm p}\left(\hat{c}_1 {\rm e}^{{\rm i}\delta t}-\hat{c}_1^\dagger {\rm e}^{-{\rm i}\delta t}\right). \end{aligned} \tag{3}$$

The first term represents the energy of the intra-cavity field in each optical cavity with the effective Stark-shift detuning, where $\Delta_{ci}=\omega'_{ci}-\omega_{\rm pu}$, and $\omega'_{ci}=\omega_{ci}+\frac{1}{2}U_{0i}N_i$. The second term defines the energy of the collective oscillation of the BEC, $\omega_{{\rm m}i}=4\omega_{{\rm rec}i}=4\frac{\hbar k^2}{2m_{ai}}$, and $\hat{a}_i(\hat{a}_i^\dagger)$ denotes the annihilation (creation) operator of the Bogoliubov mode. The third term defines the energy of the optomechanical coupling between the Bogoliubov and the optical modes, $g_i=\frac{U_{0i}}{2}\sqrt{\frac{N_i}{2}}$ is the effective coupling strength of each optical cavity and the BEC. The last two terms describe the interaction of the cavity driven by the pump field and probe laser field with pump–probe detuning $\delta=\omega_{\rm pr}-\omega_{\rm pu}$.

According to the Heisenberg equations of motion and including the corresponding damping and noise terms,[40,41] the coupled quantum Langevin equations can be obtained as follows:

$$\begin{aligned}\frac{{\rm d}\hat{c}_1}{{\rm d}t} =& -({\rm i}\Delta_{\rm c1}+\kappa_1)\hat{c}_1-{\rm i}J\hat{c}_2-{\rm i}g_1\hat{c}_1(\hat{a}_1^\dagger+\hat{a}_1)\\ &+\varepsilon_{\rm c}+\varepsilon_{\rm p}{\rm e}^{-{\rm i}\delta t}+\sqrt{2\kappa_1}\hat{c}_{\rm 1in},\\ \frac{{\rm d}\hat{c}_2}{{\rm d}t} =& -({\rm i}\Delta_{\rm c2}+\kappa_2)\hat{c}_2-{\rm i}J\hat{c}_1-{\rm i}g_2\hat{c}_2(\hat{a}_2^\dagger+\hat{a}_2)+\sqrt{2\kappa_2}\hat{c}_{\rm 2in}, \end{aligned}$$

$$\begin{aligned}\frac{\mathrm{d}\hat{a}_1}{\mathrm{d}t} &= -(\mathrm{i}\omega_{\mathrm{m}1}+\gamma_{\mathrm{m}1})\hat{a}_1 - \mathrm{i}g_1\hat{c}_1^{\dagger}\hat{c}_1 + \sqrt{2\gamma_{\mathrm{m}1}}\xi_{\mathrm{m}1},\\ \frac{\mathrm{d}\hat{a}_2}{\mathrm{d}t} &= -(\mathrm{i}\omega_{\mathrm{m}2}+\gamma_{\mathrm{m}2})\hat{a}_2 - \mathrm{i}g_2\hat{c}_2^{\dagger}\hat{c}_2 + \sqrt{2\gamma_{\mathrm{m}2}}\xi_{\mathrm{m}2},\end{aligned} \tag{4}$$

where $\kappa_{1,2}$ are decay rates for cavity modes, and $\gamma_{\mathrm{m}1,2}$ are the damping rates of the Bogoliubov mode of the collective oscillation of each BEC. $\hat{c}_{1\mathrm{in}}$, $\hat{c}_{2\mathrm{in}}$, $\xi_{\mathrm{m}1}$, and $\xi_{\mathrm{m}2}$ illustrate the corresponding quantum noise operators with zero average values. Using the factorization assumption $\langle\hat{P}\hat{Q}\rangle = \langle\hat{P}\rangle\langle\hat{Q}\rangle$, where $\hat{P}$ and $\hat{Q}$ are two arbitrary operators. First, the Langevin equations are linearized by plugging the ansatz,

$$\langle\hat{O}\rangle = O_{\mathrm{s}} + \delta\hat{O}, \tag{5}$$

where $\hat{O} = \hat{c}_1, \hat{c}_2, \hat{a}_1, \hat{a}_2$. Furthermore, substituting Eq. (5) into Eq. (4) and neglecting the second-order terms. The steady values are be given by

$$\begin{aligned}c_{1\mathrm{s}} &= \frac{\varepsilon_{\mathrm{c}}}{\kappa_1 + \mathrm{i}\Delta_1 + \frac{J^2}{\kappa_2+\mathrm{i}\Delta_2}},\\ c_{2\mathrm{s}} &= \frac{-\mathrm{i}Jc_{1\mathrm{s}}}{\kappa_2+\mathrm{i}\Delta_2},\\ a_{1\mathrm{s}} &= \frac{-\mathrm{i}g_1|c_{1\mathrm{s}}|^2}{\mathrm{i}\omega_{\mathrm{m}1}+\gamma_{\mathrm{m}1}},\\ a_{2\mathrm{s}} &= \frac{-\mathrm{i}g_2|c_{2\mathrm{s}}|^2}{\mathrm{i}\omega_{\mathrm{m}2}+\gamma_{\mathrm{m}2}}.\end{aligned} \tag{6}$$

With $\Delta_i = \Delta_{ci} - \frac{2\omega_{\mathrm{m}i}g_i^2|c_{is}|^2}{\omega_{\mathrm{m}i}^2+\gamma_{\mathrm{m}i}^2}$, the first order in $\delta\hat{c}_i$ and $\delta\hat{a}_i$ are

$$\begin{aligned}\frac{\mathrm{d}\delta\hat{c}_1}{\mathrm{d}t} &= -(\mathrm{i}\Delta_1+\kappa_1)\delta\hat{c}_1 - \mathrm{i}J\delta\hat{c}_2 - \mathrm{i}G_1(\delta\hat{a}_1^{\dagger}+\delta\hat{a}_1)\\ &\quad + \varepsilon_{\mathrm{p}}\mathrm{e}^{-\mathrm{i}\delta t},\\ \frac{\mathrm{d}\delta\hat{c}_2}{\mathrm{d}t} &= -(\mathrm{i}\Delta_2+\kappa_2)\delta\hat{c}_2 - \mathrm{i}J\delta\hat{c}_1 - \mathrm{i}G_2(\delta\hat{a}_2^{\dagger}+\delta\hat{a}_2),\\ \frac{\mathrm{d}\delta\hat{a}_1}{\mathrm{d}t} &= -(\mathrm{i}\omega_{\mathrm{m}1}+\gamma_{\mathrm{m}1})\delta\hat{a}_1 - \mathrm{i}(G_1\delta\hat{c}_1^{\dagger}+G_1^*\delta\hat{c}_1),\\ \frac{\mathrm{d}\delta\hat{a}_2}{\mathrm{d}t} &= -(\mathrm{i}\omega_{\mathrm{m}2}+\gamma_{\mathrm{m}2})\delta\hat{a}_2 - \mathrm{i}(G_2\delta\hat{c}_2^{\dagger}+G_2^*\delta\hat{c}_2),\end{aligned} \tag{7}$$

where $G_i = g_i|c_{is}|$ is the effective coupling rate. In order to solve the dynamics, we suppose $\delta\hat{O} = \delta\hat{O}_+\mathrm{e}^{-\mathrm{i}\delta t} + \delta\hat{O}_-\mathrm{e}^{\mathrm{i}\delta t}$ induced by the weak probing field, where $\delta\hat{O} = \delta\hat{c}_1, \delta\hat{c}_2, \delta\hat{a}_1, \delta\hat{a}_2$. We consider the system in the resolved sideband regime in order to gain more physical insight. Off-resonance terms were neglected so far, which means that $\delta\hat{O}_- \approx 0$ and the form $\delta\hat{O}_+$ of the equations are given by

$$\begin{aligned}-\mathrm{i}\delta\hat{c}_{1+} &= -(\mathrm{i}\Delta_1+\kappa_1)\delta\hat{c}_{1+} - \mathrm{i}J\delta\hat{c}_{2+} - \mathrm{i}G_1\delta\hat{a}_{1+} + \varepsilon_{\mathrm{p}},\\ -\mathrm{i}\delta\hat{c}_{2+} &= -(\mathrm{i}\Delta_2+\kappa_2)\delta\hat{c}_{2+} - \mathrm{i}J\delta\hat{c}_{1+} - \mathrm{i}G_2\delta\hat{a}_{2+},\\ -\mathrm{i}\delta\hat{a}_{1+} &= -(\mathrm{i}\omega_{\mathrm{m}1}+\gamma_{\mathrm{m}1})\delta\hat{a}_{1+} - \mathrm{i}G_1^*\delta\hat{c}_{1+},\\ -\mathrm{i}\delta\hat{a}_{2+} &= -(\mathrm{i}\omega_{\mathrm{m}2}+\gamma_{\mathrm{m}2})\delta\hat{a}_{2+} - \mathrm{i}G_2^*\delta\hat{c}_{2+}.\end{aligned} \tag{8}$$

In the resolved sideband regime, we let $\omega_{\mathrm{m}i} \gg \kappa_i$, $\omega_{\mathrm{m}1} = \omega_{\mathrm{m}2} = \omega_{\mathrm{m}}$, and $\Delta_1 = \Delta_2 = \omega_{\mathrm{m}}$. Thus, equation (8) can be written as

$$\begin{aligned}&-(\kappa_1-\mathrm{i}\lambda)\delta\hat{c}_{1+} - \mathrm{i}J\delta\hat{c}_{2+} - \mathrm{i}G_1\delta\hat{a}_{1+} + \varepsilon_{\mathrm{p}} = 0,\\ &-(\kappa_2-\mathrm{i}\lambda)\delta\hat{c}_{2+} - \mathrm{i}J\delta\hat{c}_{1+} - \mathrm{i}G_2\delta\hat{a}_{2+} = 0,\\ &-(\gamma_{\mathrm{m}1}-\mathrm{i}\lambda)\delta\hat{a}_{1+} - \mathrm{i}G_1^*\delta\hat{c}_{1+} = 0,\\ &-(\gamma_{\mathrm{m}2}-\mathrm{i}\lambda)\delta\hat{a}_{2+} - \mathrm{i}G_2^*\delta\hat{c}_{2+} = 0,\end{aligned} \tag{9}$$

where $\lambda = \delta - \omega_{\mathrm{m}}$ is the detuning from the center line of the sideband and the solution of the $\delta\hat{c}_{1+}$ is

$$\delta\hat{c}_{1+} = \frac{\varepsilon_{\mathrm{p}}}{\kappa_1 - \mathrm{i}\lambda + \dfrac{G_1^2}{\gamma_{\mathrm{m}1}-\mathrm{i}\lambda} + \dfrac{J^2}{\kappa_2 - \mathrm{i}\lambda + \dfrac{G_2^2}{\gamma_{\mathrm{m}2}-\mathrm{i}\lambda}}}. \tag{10}$$

By using the input–output relation, the amplitude of the output field, corresponding to the weak probe field is given by

$$\epsilon_{\mathrm{T}} = \frac{\sqrt{2\kappa_1}\delta\hat{c}_{1+}}{\varepsilon_{\mathrm{p}}}. \tag{11}$$

The real and imaginary parts of the output field are $\mathrm{Re}[\epsilon_{\mathrm{T}}] = \frac{\kappa_1(\delta\hat{c}_{1+}+\delta\hat{c}_{1+}^*)}{\varepsilon_{\mathrm{p}}}$ and $\mathrm{Im}[\epsilon_{\mathrm{T}}] = \frac{\kappa_1(\delta\hat{c}_{1+}-\delta\hat{c}_{1+}^*)}{\varepsilon_{\mathrm{p}}}$. These factors describe the absorption and the dispersion of the systems, respectively.

3. Results and discussion

In this section we discuss the multiple OMIT phenomenon in hybrid optomechanical systems. In this systems, there are many parameters that can be manipulated to control the number of OMIT windows, such as: the tunneling strength of the two resonators, the decay rates of the cavity photons and the interaction between the each BEC and the cavity field. We considered the parameters derived from the experimentally realistic of the BEC cavity reported in Refs. [30] and [31]. The wavelength of each cavity field is $\lambda = 780$ nm and each cavity length is $L = 1.25\times10^{-4}$ m. We consider each BEC trapped inside the optomechanical cavity with a recoil of $\omega_{\mathrm{res}1} = \omega_{\mathrm{res}2} = 2\pi\times3.8$ kHz, and each BEC acts as the mechanical oscillator mode with a damping rate $\gamma_{\mathrm{m}1} = \gamma_{\mathrm{m}2} = 2\pi\times0.21$ kHz.

Firstly, we plot the spectrum of the absorption $\mathrm{Re}[\epsilon_{\mathrm{T}}]$ and the dispersion $\mathrm{Im}[\epsilon_{\mathrm{T}}]$ as function of the normalized detuning $\lambda/\omega_{\mathrm{m}}$. In the presence of the tunneling strength of the two resonators J, the interaction between the each BEC and the cavity field G_1 and G_2, the absorption line of the probe field presents three OMIT windows in Fig. 2. However, in the absence of the tunneling strength of the two resonators, the single transparency window is obvious with only a BEC in one cavity in Fig. 3. While in the presence of one BEC in the second cavity, the absorption line of the probe field demonstrates double transparency window with the tunneling strength $J = \kappa_1$ in Fig. 4.

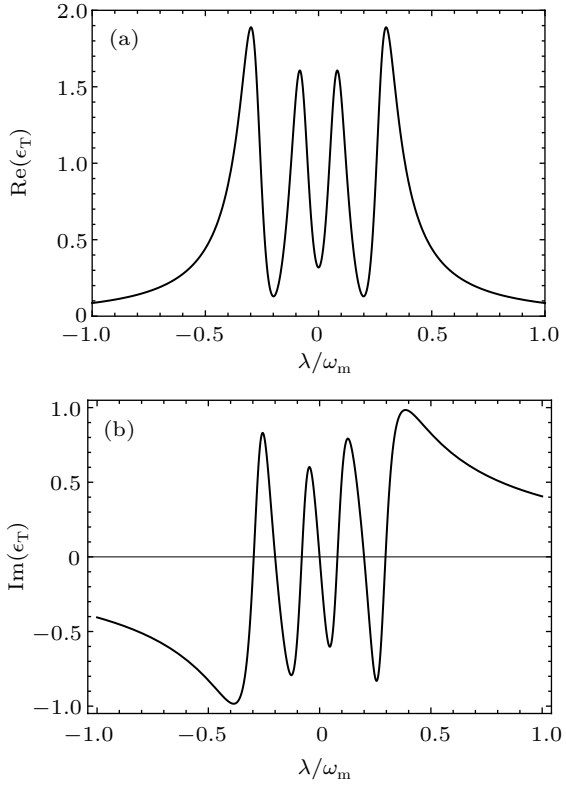


Fig. 2. (a) Absorption Re$[\epsilon_T]$ and (b) dispersion Im$[\epsilon_T]$ as functions of the normalized detuning λ/ω_m in the coupled resonators optomecanical system, with the parameters: $\omega_m = 2\pi \times 15.2$ kHz, $\kappa_1 = 0.2\omega_m$, $\kappa_2 = 0.001\omega_m$, $G_1 = 0.12\omega_m$, $G_2 = 0.2\omega_m$, $J = \kappa_1$, and $\gamma_{m1} = \gamma_{m2} = 2\pi \times 0.21$ kHz.

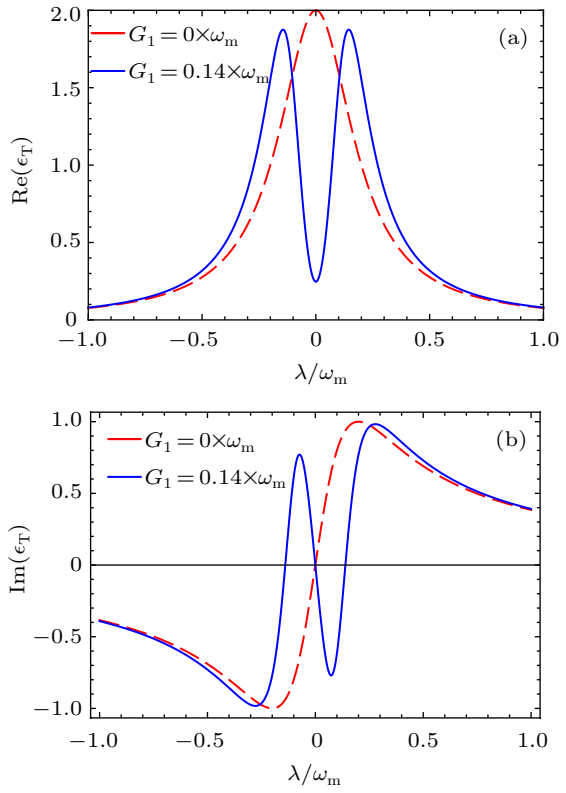


Fig. 3. (color online) (a) Absorption Re$[\epsilon_T]$ and (b) dispersion Im$[\epsilon_T]$ as functions of the normalized detuning λ/ω_m in one cavity with a BEC (solid blue) and without a BEC (dashed red) for $J = 0$. The other parameters are the same as those shown in Fig. 2.

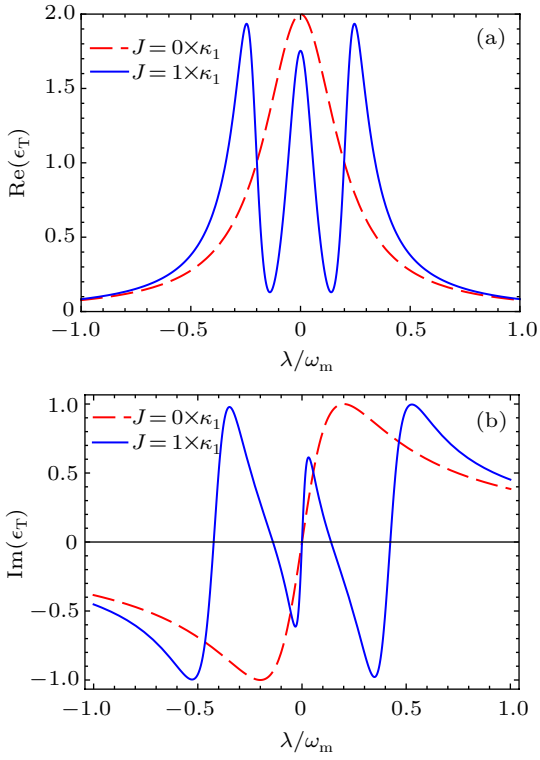


Fig. 4. (color online) (a) Absorption Re$[\epsilon_T]$ and (b) dispersion Im$[\epsilon_T]$ as functions of the normalized detuning λ/ω_m in the presence $J = \kappa_1$ (solid blue) and in the absence $J = 0$ (dashed red) of the tunneling strength. $G_1 = 0$ and the other parameters are the same as those shown in Fig. 2.

In the absence of the tunneling strength of the two resonators, the expression of $\delta\hat{c}_{1+}$ in Eq. (10) can be simplified as

$$\delta\hat{c}_{1+} = \frac{\varepsilon_p}{\kappa_1 - i\lambda + \frac{G_1^2}{\gamma_{m1} - i\lambda}}. \tag{12}$$

Furthermore, in the presence of one BEC in the second cavity, the expression of $\delta\hat{c}_{1+}$ in Eq. (10) can be simplified as

$$\delta\hat{c}_{1+} = \frac{\varepsilon_p}{\kappa_1 - i\lambda + \frac{J^2}{\kappa_2 - i\lambda + \frac{G_2^2}{\gamma_{m2} - i\lambda}}}. \tag{13}$$

It is concluded that the denominator of the function is quadruplicate in λ in Eq. (10), and it can be obtained three dips in the absorption Re$[\epsilon_T]$ under the condition of certain parameters. While in Eq. (12) the denominator of the function is quadratic in λ, one dip in the absorption Re$[\epsilon_T]$ can be obtained, and the denominator of the function in Eq. (13) is cubic in λ, two dips in the absorption Re$[\epsilon_T]$ can be obtained.

It has been observed that in the presence of the tunneling strength of the two resonators and the interaction between each BEC and the cavity field, a special opportunity to switch from three to double and one OMIT windows. We find that the absence of the tunneling strength of the two resonators, there is only one OMIT window. Therefore, three OMIT windows can be transformed to a single OMIT window by switching off the tunneling strength of the two resonators. This method reduced the cavity optomechanical system with a Bose–Einstein

condensate as reported in Ref. [39]. Furthermore, we also find that the presence of a BEC in one cavity and the tunneling strength of the two resonators, the absorption line of the probe field from three OMIT windows to double OMIT windows. This reduces the system to optomechanical system as reported in Ref. [27]. Hence, the presence of the tunneling strength of the two resonators J and the interaction between each BEC and the cavity field G_1 and G_2 in the hybrid optomechnical systems offers a unique opportunity to coherently control and tune the three OMIT windows to double or single OMIT window.

Furthermore, to understand the influence of the interaction between BEC and the cavity field on the absorption and the dispersion with the tunneling strength $J = \kappa_1$, we plot the absorption $\mathrm{Re}[\epsilon_\mathrm{T}]$ and the dispersion $\mathrm{Im}[\epsilon_\mathrm{T}]$ as functions of the interaction G_2 and the normalized detuning $\lambda/\omega_\mathrm{m}$ in Fig. 5. On the one hand, in the presence of a BEC in the second cavity, we see that two transparency windows appear in the absorption profile, and the two transparency windows are further apart with the increase of coupling strength between the BEC and the cavity.

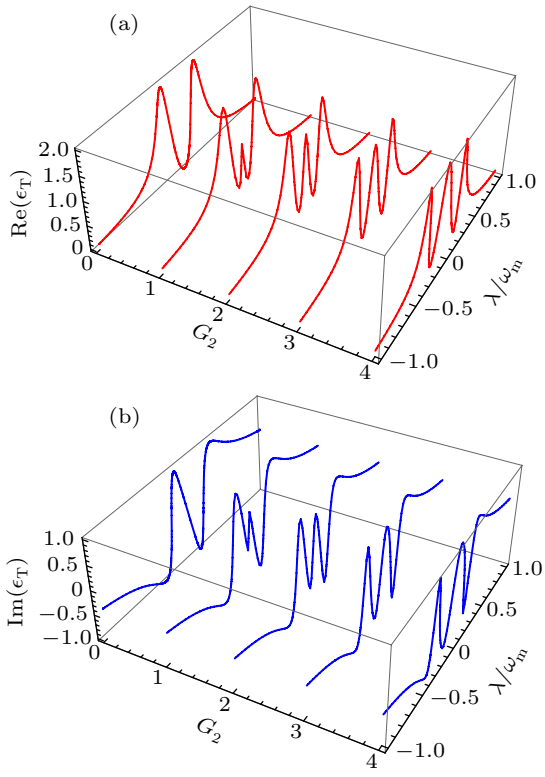


Fig. 5. (color online) (a) Absorption $\mathrm{Re}[\epsilon_\mathrm{T}]$ and (b) dispersion $\mathrm{Im}[\epsilon_\mathrm{T}]$ as functions of the normalized detuning $\lambda/\omega_\mathrm{m}$ and G_2 (units of $G_{20} = 0.05\omega_\mathrm{m}$). The parameter is $G_1 = 0$ and the other parameters are the same as those shown in Fig. 2.

In Fig. 6, we show the absorption $\mathrm{Re}[\epsilon_\mathrm{T}]$ and the dispersion $\mathrm{Im}[\epsilon_\mathrm{T}]$ as function of $\lambda/\omega_\mathrm{m}$ for different coupling strength $G_1 = 0 \times \omega_\mathrm{m}$, $G_1 = 0.08 \times \omega_\mathrm{m}$, $G_1 = 0.16 \times \omega_\mathrm{m}$. When the coupling strength $G_1 = 0 \times \omega_\mathrm{m}$, two OMIT windows are formed, while in the presence of the coupling parameters of the each BEC and the cavity field, three distinct OMIT windows are obtained in the absorption $\mathrm{Re}[\epsilon_\mathrm{T}]$.

Finally, the variation of the absorption $\mathrm{Re}[\epsilon_\mathrm{T}]$ and the dispersion $\mathrm{Im}[\epsilon_\mathrm{T}]$ as functions of $\lambda/\omega_\mathrm{m}$ for different cavity decay rates $\kappa_1 = 0.1 \times \omega_\mathrm{m}$, $\kappa_1 = 0.2 \times \omega_\mathrm{m}$, $\kappa_1 = 0.3 \times \omega_\mathrm{m}$ is presented in Fig. 7. Comparing the three curves in Fig. 7, we can

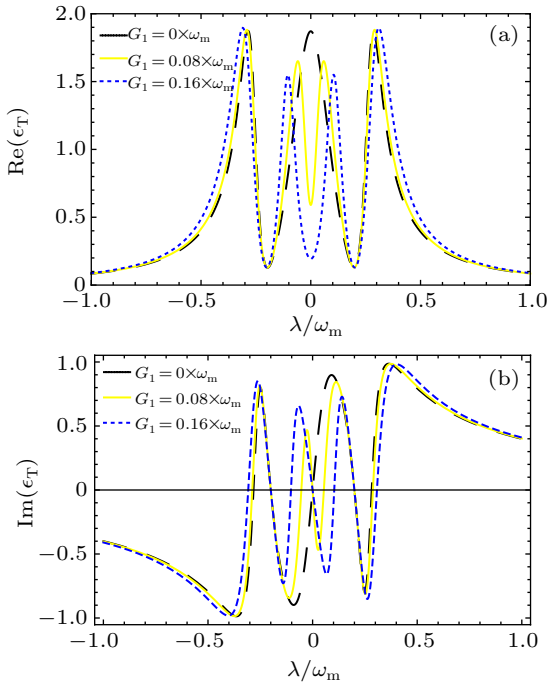


Fig. 6. (color online) (a) Absorption $\mathrm{Re}[\epsilon_\mathrm{T}]$ and (b) dispersion $\mathrm{Im}[\epsilon_\mathrm{T}]$ as functions of the normalized detuning $\lambda/\omega_\mathrm{m}$ for different coupling strength $G_1 = 0 \times \omega_\mathrm{m}$ (long dashed bleak), $G_1 = 0.08 \times \omega_\mathrm{m}$ (solid yellow), and $G_1 = 0.16 \times \omega_\mathrm{m}$ (short dashed blue). The other parameters are the same as those shown in Fig. 2.

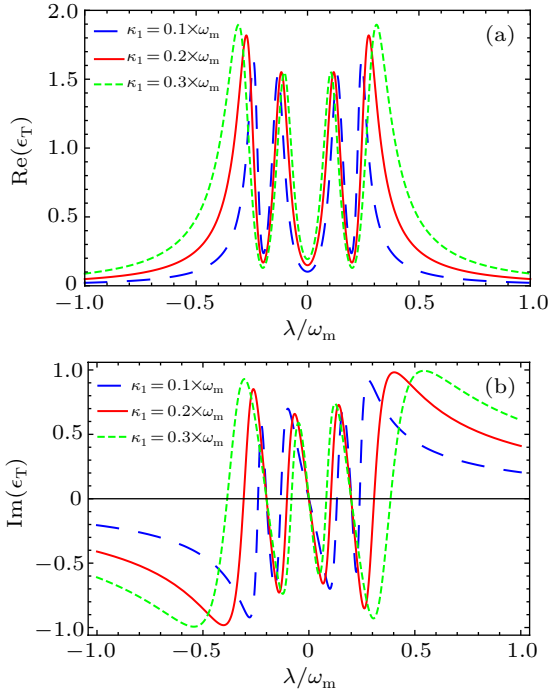


Fig. 7. (color online) (a) Absorption $\mathrm{Re}[\epsilon_\mathrm{T}]$ and (b) dispersion $\mathrm{Im}[\epsilon_\mathrm{T}]$ as functionS of the normalized detuning $\lambda/\omega_\mathrm{m}$ for different cavity decay rates $\kappa_1 = 0.1 \times \omega_\mathrm{m}$ (long dashed blue), $\kappa_1 = 0.2 \times \omega_\mathrm{m}$ (solid red), $\kappa_1 = 0.3 \times \omega_\mathrm{m}$ (short dashed green). The other parameters are the same as those shown in Fig. 2.

see that by increasing the cavity decay rates, the transparency windows progressively diverge. Secondly, the minima of the transparency windows remain unchanged with increasing cavity decay rates.

4. Conclusion

In conclusion, we have analyzed the optomechanically induced transparency phenomenon, the absorption and the dispersion in double-cavity optomechanical system with and without a Bose–Einstein condensate. We give a full analytical model of studying the absorption $\mathrm{Re}[\epsilon_{\mathrm{T}}]$ and the dispersion $\mathrm{Im}[\epsilon_{\mathrm{T}}]$ profiles of the probe field. The presence of the tunneling strength of the two resonators, the interaction between each BEC and the cavity field, there are three OMIT windows in the absorption line of the probe field. However, if system parameters are tuned, three OMIT windows switch to double and single OMIT windows. Finally, the combined effect of the optomechanical with a BEC in each cavity can expand the potential applications in quantum engineering and quantum information networks.

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