

Controlling multiple optomechanically induced transparency in the distant cavity-optomechanical system

Rui-Jie Xiao(肖瑞杰), Gui-Xia Pan(潘桂侠), and Xiao-Ming Xiu(修晓明)
Citation: Chin. Phys. B, 2021, 30 (**3**): 034209. DOI: 10.1088/1674-1056/abc7a4
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Ground-state cooling based on a three-cavity optomechanical system in the unresolved-sideband regime

Jing Wang(王婧)
Chin. Phys. B, 2021, 30 (**2**): 024204. DOI: 10.1088/1674-1056/abc159

Optical nonreciprocity in a piezo-optomechanical system

Yu-Ming Xiao(肖玉铭), Jun-Hao Liu(刘军浩), Qin Wu(吴琴), Ya-Fei Yu(於亚飞), Zhi-Ming Zhang(张智明)
Chin. Phys. B, 2020, 29 (**7**): 074204. DOI: 10.1088/1674-1056/ab8abf

The optical nonreciprocal response based on a four-mode optomechanical system

Jing Wang(王婧)
Chin. Phys. B, 2020, 29 (**3**): 034210. DOI: 10.1088/1674-1056/ab6836

Electro-optomechanical switch via tunable bistability and four-wave mixing

Kamran Ullah
Chin. Phys. B, 2019, 28 (**11**): 114209. DOI: 10.1088/1674-1056/ab4580

Double-passage mechanical cooling in a coupled optomechanical system

Qing-Xia Mu(穆青霞), Chao Lang(郎潮), Wen-Zhao Zhang(张闻钊)
Chin. Phys. B, 2019, 28 (**11**): 114206. DOI: 10.1088/1674-1056/ab48f1

Controlling multiple optomechanically induced transparency in the distant cavity-optomechanical system*

Rui-Jie Xiao(肖瑞杰)[1,†], Gui-Xia Pan(潘桂侠)[2], and Xiao-Ming Xiu(修晓明)[1]

[1] College of Physical Science and Technology, Bohai University, Jinzhou 121013, China
[2] School of Science, Anhui University of Science and Technology, Huainan 232001, China

(Received 7 June 2020; revised manuscript received 20 September 2020; accepted manuscript online 5 November 2020)

We theoretically investigate a two-cavity optomechanical system in which each optical cavity couples to a mechanical resonator via radiation pressure force, and the two optical cavities couple to each other via a distant waveguide. Our study shows that the multiple optomechanically induced transparency can be observed from the output field at the probe frequency. The number and width of the transparent windows can be tuned by the classical driving power P_l. We also analyze the distance of the two outermost transparency windows, which shows a linear relation with the parameters P_l and λ. Our approach is feasible for controlling multipartite induced transparency, which represents a valuable step towards quantum networks with photonic and phononic circuits.

Keywords: optomechanical system, optomechanically induced transparency, optical mode

PACS: 42.50.pq, 42.15.Eq, 42.62.Fi **DOI:** 10.1088/1674-1056/abc7a4

1. Introduction

Cavity optomechanics,[1–7] which combines the mechanical and optical degrees of freedom via radiation pressure force, has recently arisen as a rapidly developing field. Many fascinating phenomena, such as optomechanically induced transparency,[8,9] signal amplification,[10] slow and fast light,[11,12] optical bistability,[13] and weak force measurement,[14,15] have been investigated in various cavity optomechanical systems. A wealth of possible applications for such devices in phonon lasers,[16] photon blockade,[17,18] and gravitational wave detectors[19] have also been proposed.

Optomechanical induced transparency (OMIT) as a novel optical phenomenon is analogous to electromagnetically induced transparency,[20] which plays an important role in quantum memories and repeaters.[1] In the presence of the pump field, a transparency window occurs in the probe transmission spectrum, which derives from the quantum interference effect. OMIT has been explored theoretically[21] and observed experimentally.[9,11,22] It can be employed for slowing and stopping light,[23] signal amplifications,[24] charge measurement,[25] and single-photon routers.[26]

Recently, double-OMIT and even multiple-OMIT have been studied extensively.[27–34] For example, double-OMIT has been carried out in the charged-resonators optomechanical system,[24,27] two mechanical resonators optomechanical system,[28] coupled-disks structure,[30] and two-cavity optomechanical system.[31] Meanwhile, the multiple-OMIT has been achieved in N-resonators optomechanical system,[32,33] the atomic-media assisted single optomechanical system,[34] and two-cavity double resonators optomechanical system.[35] Double- and multiple-OMIT also have new applications, such as the all-optical quantum network and multi-channel quantum information processing.[36]

In addition, the mutual coupling between two mechanical resonators in hybrid optomechanical systems has also attracted widespread interest both in theory and experiment.[24,27,37–42] The two mechanical resonators can be coupled to each other via Coulomb interaction or the common coupling overhang. More importantly, the coupling strength can be modulated flexibly.[41,42] Based on these reasons, the natural question is: can we control the effect of OMIT by modulating the mutual coupling between the mechanical resonators?

In this work, we theoretically investigate a two-cavity optomechanical system in which the two cavities couple to each other via a distant waveguide, which is similar to Ref. [43]. Each cavity couples to a mechanical resonator via radiation pressure force, and each mechanical resonator couples to an auxiliary mechanical resonator. Our study shows that the output probe field of the compound optomechanical system may have five transparent windows. It is worth mention that our scheme is essentially different from the previous studies,[32,33] where a multiple-EIT is caused by the mechanical arrays with different frequencies and different positions of the oscillators in the cavity. Our study is also different from the previous proposals,[44,45] where a multiple-EIT is caused by optical arrays and atom media. Furthermore, we find that the properties of the multiple-OMIT can be effectively tuned by several system parameters, including the classical driving power and

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11704042 and 11674037) and the LiaoNing Revitalization Talents Program (Grant No. XLYC1807206).

†Corresponding author. E-mail: xrjxrj2003@163.com

© 2021 Chinese Physical Society and IOP Publishing Ltd

the coupling strength between the two mechanical modes. Simultaneously, we find that the two furthest windows of the multiple-OMIT are apart near linearly with respect to the classical driving power P_l and the coupling strength λ. Our scheme provides a method to control multiple electromagnetically induced transparency.

2. Model and analytical solution

The system being considered is sketched in Fig. 1. It comprises a cavity optomechanical system composed of two optical cavities and four mechanical resonators. The two cavities a_1 and a_2 are coupled to each other via the distant waveguide with a coupling strength J. The mechanical resonator b_1 (c_1) is not only coupled to the cavity a_1 (a_2) via radiation pressure force with the coupling strength g_b (g_c), but also coupled to the other mechanical resonator b_2 (c_2) via the common coupling overhang or Coulomb interaction[39] with the coupling strength λ_1 (λ_2). The optical cavities a_1 and a_2 are driven by a strong coupling field and a weak classical probe field, respectively. The amplitude is $\varepsilon_i = \sqrt{\frac{2\kappa_j P_i}{\hbar\omega_i}}$, where κ_j ($j = 1,2$) is the decay of the cavity a_j ($j = 1,2$), P_i and ω_i ($i = l, p$) are the power and the frequency of the input laser field, respectively.

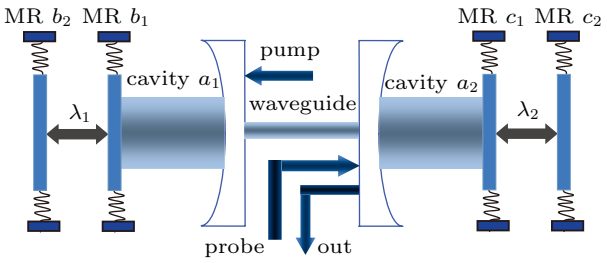


Fig. 1. Schematic diagram of the compound optomechanical system. It consists of two cavities and four mechanical resonators. The two cavities couple to each other with the interactive coupling strength J, and the two mechanical oscillators couple to each other with the coupling strength λ. The system is driven by a strong pump field and a weak probe field.

The Hamiltonian of the compound optomechanical system in a frame rotating with $H' = \sum_{j=1,2}\hbar\omega_l a_j^\dagger a_j$ is written as

$$H = H_0 + H_\mathrm{i} + H_\mathrm{d}, \tag{1}$$

where

$$\begin{aligned}
H_0 &= \hbar\sum_{j=1,2}(\Delta_j a_j^\dagger a_j + \omega_{bj} b_j^\dagger b_j + \omega_{cj} c_j^\dagger c_j),\\
H_\mathrm{i} &= \hbar\lambda_1(b_1^\dagger b_2 + b_2^\dagger b_1) + \hbar\lambda_2(c_1^\dagger c_2 + c_2^\dagger c_1)\\
&\quad -\hbar g_b a_1^\dagger a_1(b_1^\dagger + b_1) - \hbar g_c a_2^\dagger a_2(c_1^\dagger + c_1),\\
&\quad +\hbar J(a_1^\dagger a_2 + a_2^\dagger a_1),\\
H_\mathrm{d} &= \mathrm{i}\hbar\varepsilon_l(a_1^\dagger - a_1) + \mathrm{i}\hbar\varepsilon_p(\mathrm{e}^{-\mathrm{i}\Delta t}a_2^\dagger - \mathrm{e}^{\mathrm{i}\Delta t}a_2).
\end{aligned}$$

Here H_0 is the free Hamiltonian of the system, where a_j is the annihilation operator of the cavity field, b_j or c_j ($j = 1,2$) is the annihilation operator of the mechanical resonator. ω_{bj} or ω_{cj} ($j = 1,2$) is the frequency of the four mechanical resonators. $\Delta_j = \omega_{aj} - \omega_l$ ($j = 1,2$) is the frequency-detuning of the pump field from the optical cavity, and ω_{aj} is the frequency of the cavity field a_j ($j = 1,2$). H_i describes the interaction Hamiltonian, where the first line denotes the interaction terms between the two mechanical modes of each cavity optomechanical system, the second line indicates the interaction terms between the mechanical mode and optical mode, and the third line is the distant interaction terms between the two optical modes. The corresponding long-distance coupling coefficient can be expressed as $J = \eta\sqrt{\kappa_1'\kappa_2'}$, which can be realized by the long-distance optical fiber or waveguide.[46–48] It has been demonstrated experimentally in nano-systems.[43] η denotes the power transmittance, and κ_j' is the coupling coefficient between the waveguide and the j-th cavity. H_d describes the energy of the input fields. $\Delta = \omega_p - \omega_l$ is the frequency-detuning of the probe field from the pump field.

Introducing the corresponding dissipation and fluctuation terms, the quantum Heisenberg–Langevin equations can be written as

$$\begin{aligned}
\dot{a}_1 &= -(\kappa_1 + \mathrm{i}\Delta_1)a_1 + \mathrm{i}g_b a_1(b_1^\dagger + b_1) - \mathrm{i}Ja_2 + \varepsilon_l,\\
\dot{a}_2 &= -(\kappa_2 + \mathrm{i}\Delta_2)a_2 + \mathrm{i}g_c a_2(c_1^\dagger + c_1) - \mathrm{i}Ja_1 + \varepsilon_p\mathrm{e}^{-\mathrm{i}\Delta t},\\
\dot{b}_1 &= -(\gamma_{b1} + \mathrm{i}\omega_{b1})b_1 + \mathrm{i}g_b a_1^\dagger a_1 - \mathrm{i}\lambda_1 b_2,\\
\dot{b}_2 &= -(\gamma_{b2} + \mathrm{i}\omega_{b2})b_2 - \mathrm{i}\lambda_1 b_1,\\
\dot{c}_1 &= -(\gamma_{c1} + \mathrm{i}\omega_{c1})c_1 + \mathrm{i}g_c a_2^\dagger a_2 - \mathrm{i}\lambda_2 c_2,\\
\dot{c}_2 &= -(\gamma_{c2} + \mathrm{i}\omega_{c2})c_2 - \mathrm{i}\lambda_2 c_1,
\end{aligned} \tag{2}$$

where κ_j, γ_{bj} and γ_{cj} ($j = 1,2$) are the decay rates of the two optical modes and the four mechanical modes, respectively. In the case of $\varepsilon_l \gg \varepsilon_p$, we express the dynamical variables as the sum of their steady-state mean values and small fluctuations,[1] i.e., $\Theta_j = \Theta_{j\mathrm{s}} + \delta\Theta_j$ ($j = 1,2$), where Θ represents the operators a, b, and c. The steady-state values of the dynamical variables are

$$\begin{aligned}
a_{1\mathrm{s}} &= \frac{\varepsilon_l - \mathrm{i}Ja_{2\mathrm{s}}}{\kappa_1 + \mathrm{i}\bar{\Delta}_1},\quad a_{2\mathrm{s}} = \frac{-\mathrm{i}Ja_{1\mathrm{s}}}{\kappa_2 + \mathrm{i}\bar{\Delta}_2},\\
b_{1\mathrm{s}} &= \frac{\mathrm{i}g_b|a_{1\mathrm{s}}|^2}{\gamma_{b1} + \mathrm{i}\omega_{b1} + \frac{\lambda_1^2}{\gamma_{b2}+\mathrm{i}\omega_{b2}}},\quad b_{2\mathrm{s}} = -\frac{\mathrm{i}\lambda_1 b_{1\mathrm{s}}}{\gamma_{b2} + \mathrm{i}\omega_{b2}},\\
c_{1\mathrm{s}} &= \frac{\mathrm{i}g_c|a_{2\mathrm{s}}|^2}{\gamma_{c1} + \mathrm{i}\omega_{c1} + \frac{\lambda_2^2}{\gamma_{c2}+\mathrm{i}\omega_{c2}}},\quad c_{2\mathrm{s}} = -\frac{\mathrm{i}\lambda_2 c_{1\mathrm{s}}}{\gamma_{c2} + \mathrm{i}\omega_{c2}},
\end{aligned} \tag{3}$$

where $\bar{\Delta}_1 = \Delta_1 - g_b(b_{1\mathrm{s}} + b_{1\mathrm{s}}^*)$ and $\bar{\Delta}_2 = \Delta_2 - g_c(c_{1\mathrm{s}} + c_{1\mathrm{s}}^*)$ are the effective detuning between the cavity a_1 (a_2) and the coupling field, including the frequency shift caused by the mechanical motion.

Up to now, most experimental realizations of cavity optomechanics are still in the single-photon weak coupling limit.[1] We ignore the high order terms of the fluctuation part,

and the linearized quantum Langevin equations can be written as

$$\begin{aligned}
\delta\dot{a}_1 &= -(\kappa_1+\mathrm{i}\bar{\Delta}_1)\delta a_1+\mathrm{i}G_1(\delta b_1+\delta b_1^{\dagger})-\mathrm{i}J\delta a_2,\\
\delta\dot{a}_2 &= -(\kappa_2+\mathrm{i}\bar{\Delta}_2)\delta a_2+\mathrm{i}G_2(\delta c_1+\delta c_1^{\dagger})-\mathrm{i}J\delta a_1\\
&\quad+\varepsilon_p\,\mathrm{e}^{-\mathrm{i}\Delta t},\\
\delta\dot{b}_1 &= -(\gamma_{b1}+\mathrm{i}\omega_{b1})\delta b_1+\mathrm{i}(G_1^{*}\delta a_1+G_1\delta a_1^{\dagger})-\mathrm{i}\lambda_1\delta b_2,\\
\delta\dot{b}_2 &= -(\gamma_{b2}+\mathrm{i}\omega_{b2})\delta b_2-\mathrm{i}\lambda_1\delta b_1,\\
\delta\dot{c}_1 &= -(\gamma_{c1}+\mathrm{i}\omega_{c1})\delta c_1+\mathrm{i}(G_2^{*}\delta a_1+G_2\delta a_1^{\dagger})-\mathrm{i}\lambda_2\delta c_2,\\
\delta\dot{c}_2 &= -(\gamma_{c2}+\mathrm{i}\omega_{c2})\delta c_2-\mathrm{i}\lambda_2\delta c_1,
\end{aligned}\tag{4}$$

where $G_1=g_b a_{1\mathrm{s}}$ and $G_2=g_c a_{2\mathrm{s}}$ are the effective optomechanical coupling rate between optical mode a_1 (a_2) and the corresponding mechanical mode b_1 (c_1). As the steady-state mean values $a_{1\mathrm{s}}$ and $a_{2\mathrm{s}}$ can be obtained by Eq. (3), we have

$$\begin{aligned}
G_1 &= g_b a_{1\mathrm{s}}=\frac{g_b(\kappa_2+\mathrm{i}\bar{\Delta}_2)\varepsilon_l}{(\kappa_1+\mathrm{i}\bar{\Delta}_1)(\kappa_2+\mathrm{i}\bar{\Delta}_2)+J^2},\\
G_2 &= g_c a_{2\mathrm{s}}=-\frac{\mathrm{i}g_c J\varepsilon_l}{(\kappa_1+\mathrm{i}\bar{\Delta}_1)(\kappa_2+\mathrm{i}\bar{\Delta}_2)+J^2}.
\end{aligned}\tag{5}$$

The mechanical resonators b_j (c_j) have a high quality factor $\omega_m/\gamma_m\gg 1$, and the system is operated in the resolved sideband regime $\omega_m\gg\kappa_j$. Transforming the equations into the interaction picture by introducing $\delta\Theta_j\to\delta\Theta_j\,\mathrm{e}^{-\mathrm{i}\Delta t}$. Under the condition that the steady-state solution is equal to zero, i.e., $\langle\delta\dot{a}_1\rangle=\langle\delta\dot{a}_2\rangle=\langle\delta\dot{b}_1\rangle=\langle\delta\dot{b}_2\rangle=0$ in Eq. (4), and ignoring the fast oscillating terms $\mathrm{e}^{2\mathrm{i}\Delta_p t}$, we obtain

$$\delta a_2=\frac{\varepsilon_p}{\kappa_2+\mathrm{i}\omega_2+\dfrac{|G_2|^2}{\gamma_{c1}+\mathrm{i}\omega_5+\dfrac{\lambda_2^2}{\gamma_{c2}+\mathrm{i}\omega_6}}+\dfrac{J^2}{\kappa_1+\mathrm{i}\omega_1+\dfrac{|G_1|^2}{\gamma_{b1}+\mathrm{i}\omega_3+\dfrac{\lambda_1^2}{\gamma_{b2}+\mathrm{i}\omega_4}}}},\tag{6}$$

where $\omega_1=\bar{\Delta}_1-\Delta$, $\omega_2=\bar{\Delta}_2-\Delta$, $\omega_3=\omega_{b1}-\Delta$, $\omega_4=\omega_{b2}-\Delta$, $\omega_5=\omega_{c1}-\Delta$, $\omega_6=\omega_{c2}-\Delta$. Equation (6) reduces to the Eq. (22) in Ref. [35] when the coupling strength $\lambda_1=\lambda_2=0$.

We assume that all oscillators have the same frequencies (ω_m), and the cavity is driven by a pump field at the mechanical red sideband with $\bar{\Delta}_1=\bar{\Delta}_2=\omega_m$. With $\omega=\omega_1=\omega_2=\omega_3=\omega_4=\omega_5=\omega_6$, we can rewrite Eq. (6) in a more concise form

$$\delta a_2=\frac{\varepsilon_p}{\kappa_2+\mathrm{i}\omega+\dfrac{|G_2|^2}{\gamma_{c1}+\mathrm{i}\omega+\dfrac{\lambda_2^2}{\gamma_{c2}+\mathrm{i}\omega}}+\dfrac{J^2}{\kappa_1+\mathrm{i}\omega+\dfrac{|G_1|^2}{\gamma_{b1}+\mathrm{i}\omega+\dfrac{\lambda_1^2}{\gamma_{b2}+\mathrm{i}\omega}}}}.\tag{7}$$

Now, we study the transmission of a weak-probe field through an optomechanical system. Employing the input–output relation[49]

$$\varepsilon_{\mathrm{out},p}=2\kappa_2\delta a_2-\varepsilon_p,\tag{8}$$

we redefine the output field as

$$\varepsilon_T=\varepsilon_{\mathrm{out},p}/\varepsilon_p+1.\tag{9}$$

According to the knowledge of the absorption and dispersion, it is clear that the real part $v_p=\mathrm{Re}(\varepsilon_T)$ and the imaginary part $u_p=\mathrm{Im}(\varepsilon_T)$ denote the absorption and dispersion of the probe field,[34] respectively. The quadratures can be measured via the homodyne technique.[49]

3. Numerical results and discussion

In the following part, we choose the experimental parameters to calculate the transmission spectrum of cavity a_2 to the probe field. To simplify, we chose $g_b=g_c=g$, $\lambda_1=\lambda_2=\lambda$, and $\gamma_{b1}=\gamma_{b2}=\gamma_{c1}=\gamma_{c2}=\gamma_m$. In a realistic cavity optomechanical system comprising of an optical cavity and a mechanical resonator,[22] these parameters are: $\omega_m/2\pi=51.8$ MHz, $\gamma_m/2\pi=141$ Hz, $\kappa_1/2\pi=0.2$ MHz, $\kappa_2/2\pi=15$ MHz, $J/2\pi=15$ MHz, $g/2\pi=5$ kHz, $P_l=5$ mW, $\lambda_c=1064$ nm, and the coupling strength between two interacting mechanical modes $\lambda/2\pi=5$ MHz, which is slightly larger than the one given in Refs. [24,37].

In Fig. 2, we simulate the absorption (v_p) and dispersion (u_p) of the probe field with the effective detuning ω/ω_m. From Fig. 2(a), we can see that five transparency windows emerge from the absorption spectrum of the probe field in the presence of the coupling strength λ and g. The five transparency windows show that the hybrid optomechanical system becomes simultaneously transparent to the probe field at five different frequencies. The emergence of multiple OMIT windows in the hybrid optomechanical system can be understood analytically through inspecting the structure of the output field. From Eq. (7), we can see that the denominator becomes the fifth

power in ω, so it has at most five different roots, which corresponding to five transparent windows.

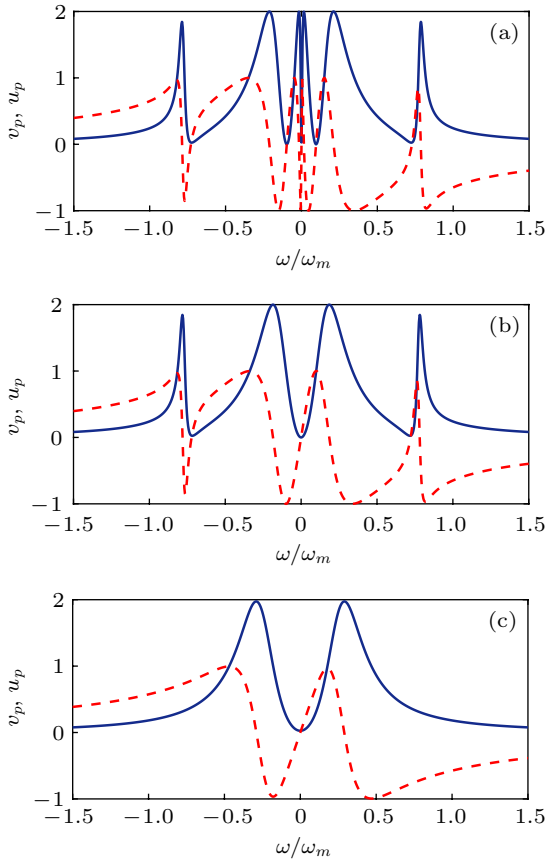


Fig. 2. The absorption v_p (solid line) and dispersion u_p (dashed line) as a function of detuning ω/ω_m. With the parameters (a) $g/2\pi = 5$ kHz, $\lambda/2\pi = 5$ MHz; (b) $\lambda = 0$ Hz, $g/2\pi = 5$ kHz; (c) $g = 0$ Hz. For all plots, $\omega_m/2\pi = 51.8$ MHz, $\gamma_m/2\pi = 141$ Hz, $\kappa_1/2\pi = 0.2$ kHz, $\kappa_2/2\pi = 15$ MHz, $J/2\pi = 15$ MHz, $P_l = 5$ mW, and $\lambda_c = 1064$ nm.

When the coupling between two resonators is switched off, i.e. , $\lambda = 0$, the term ε_T is

$$\varepsilon_T = \frac{2\kappa_2}{\kappa_2 + i\omega + \dfrac{|G_2|^2}{\gamma_{c1} + i\omega} + \dfrac{J^2}{\kappa_1 + i\omega + \dfrac{|G_1|^2}{\gamma_{b1} + i\omega}}}. \quad (10)$$

The behavior of the probe field becomes triple-OMIT, which is the same as the transparency induced by a two-cavity-two-resonator optomechanical system.[35] Its real and imaginary parts are shown in Fig. 2(b). Obviously, the disappearance of the coupling strength λ causes two transparency window to disappear.

Next, when the coupling between the cavity and the resonator is switched off, i.e., $g = 0$, the form of the ε_T becomes

$$\varepsilon_T = \frac{2\kappa_2}{\kappa_2 + i\omega + \frac{J^2}{\kappa_1 + i\omega}}. \quad (11)$$

We can see that Eq. (11) has the standard form of the spectral response for OMIT, and the behavior of the probe field becomes the single coupled resonator-induced transparency.[50] Without any mechanical driving, a standard single OMIT in a two-cavity system emerges around the resonance point $\omega_m = 0$, see Fig. 2(c).

The origin of the five-OMIT windows can also be revealed by the quantum interference effect between different energy level pathways, and the effective energy structure for the hybrid system is shown in Fig. 3. For a coupled two-cavity system (i.e., $g = 0$), the normal optical mode splits into two modes and the single transparency window of the output field appears, which is based on the destructive interference effect.[51] If $g \neq 0$ and $\lambda = 0$, the resonators b_1 and c_1 are coupled to the cavity a_1 and a_2 via optomechanical interaction, respectively. The additional optomechanical coupling will break down the two symmetry of the EIT-like level,[35] where the single transparency window is split into three windows. Moreover, when the coupling between the resonator b_1 and b_2, as well as c_1 and c_2 is present, the energy level of each original mechanical resonator is split into two new dressed levels b_+ (c_+) and b_- (c_-). The quantum interference between different energy level pathways occurs, which means five transparency windows appear, and the relevant mechanisms have been studied extensively.[38,45]

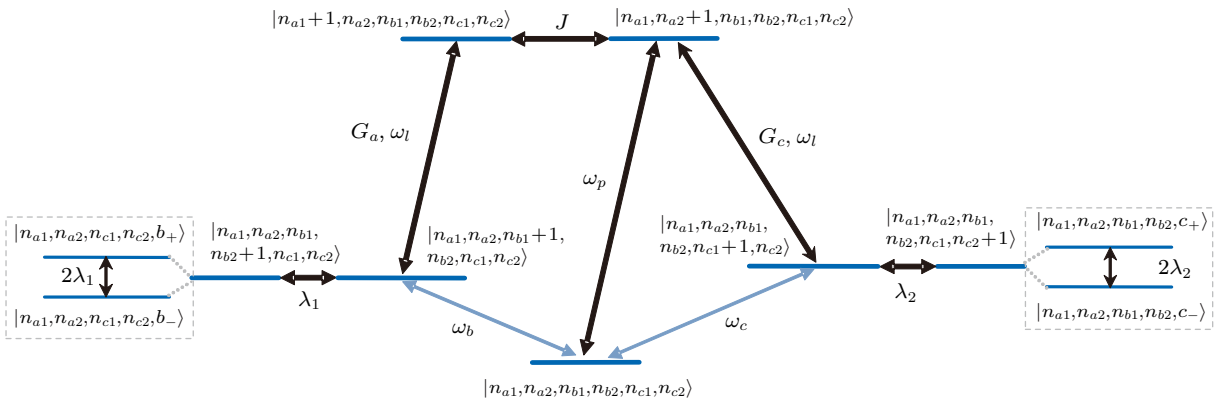


Fig. 3. Energy-Level diagram of the total system with $\omega_{b1} = \omega_{b2} = \omega_{c1} = \omega_{c2} = \omega_m$ and the coupling strength $\lambda_1 = \lambda_2 = \lambda \neq 0$ and $g_1 = g_2 = g \neq 0$. $|n_i\rangle$ $(i \to a_1, a_2, b_1, b_2, c_1, c_2)$ denotes the number state of each cavity modes and mechanical modes, respectively.

4. Tunable multiple-OMIT controlled by system parameters

To further explore the multiple-OMIT properties, we plot the absorption spectrum v_p as functions of ω/ω_m and the classical driving power P_l, as well as the coupling strength λ, as shown in Fig. 4. Here, the effect of the coupling strength J between two cavities on transparency windows is not described, because it has been studied in detail in Refs. [7,35,38]. In Fig. 4(a), we plot the absorption of the probe field for different values of the classical driving power P_l. For the classical driving power $P_l = 0$, which means that there is no classical driving in the hybrid system, the absorption spectrum is the single OMIT in the standard two-cavity system.[31] With the increase of the classical driving power P_l, the effective coupling G_1 and G_2 are not equal to zero from Eq. (5), the correlation is established between the cavity a_1 (a_2) and the oscillator b_1 (c_1) as well the oscillator b_1 (c_1) and the oscillator b_2 (c_2), and the interference path is increased from one to five. As a result, the absorption spectrum exhibits five transparency windows. The existence of the classic driving power P_l induces the splitting effect. The larger the P_l, the wider the transparency windows besides the middle one, the larger the separation between outermost transparent points.

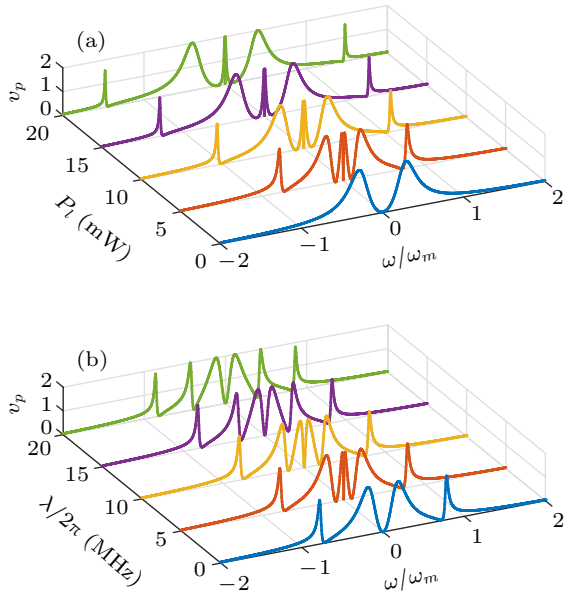


Fig. 4. The absorption v_p as functions of ω/ω_m and (a) the classical driving power P_l, (b) the coupling coefficient λ. The other parameters are the same as in Fig. 2.

Figure 4(b) presents the variation of the absorption v_p with ω/ω_m for different coupling strengths λ between two oscillators. By choosing the same parameters except for the values of λ as in Fig. 2(a), we obtain Fig. 4(b). For $\lambda = 0$ Hz, the absorption spectrum is the triple-OMIT, and the middle dip locates at $\omega = 0$.[35] For the case of $\lambda \neq 0$ Hz, it is interesting that we can get five OMIT because of the dressed mechanical modes formation, and the middle window splits into three from Fig. 4(b). Once λ exists, the coupling between the two mechanical oscillators is established, and the mode splitting effect of the coupling of the two oscillators appears, which can be seen from Fig. 3. In addition, with the increasing of the coupling parameter λ, the width of the middle three windows increases,[27] and the two outermost transparency windows are further and further.

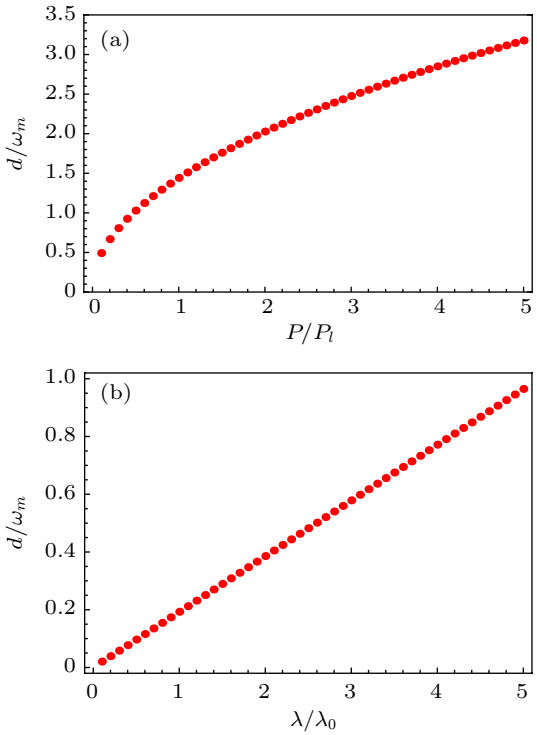


Fig. 5. The separation d (units of $\omega_m = 2\pi \times 51.8$ MHz) between the minima of the two outermost dips in the absorption spectrum as a function of: (a) the classical driving power P (units of $P_l = 5$ mW); (b) the coupling strength λ (units of $\lambda_0 = 2\pi \times 5$ MHz). Other parameters take the same values as in Fig. 2.

In order to verify that the separation between the two outermost windows is affected by the classical driving power P_l and the coupling strengths λ, we draw Fig. 5. The two minima of absorption in Fig. 5 can be evaluated by

$$\left.\frac{\mathrm{d}v_p}{\mathrm{d}\omega}\right|_{\omega_{\max+}} = 0, \quad \left.\frac{\mathrm{d}v_p}{\mathrm{d}\omega}\right|_{\omega_{\min-}} = 0, \tag{12}$$

here, the detunings $\omega_{\max+}$ and $\omega_{\min-}$ are the points with absorption minima. As a result, the separation of the outmost minima is $d = |\omega_{\max+} - \omega_{\min-}|$. Figures 5(a) and 5(b) show that the separation d between the two maxima increases almost linearly with increasing P_l and λ. The conclusion is consistent with the performance in Figs. 4(a) and 4(b). So, we can draw a conclusion that the multiple-OMIT can be tuned by the classical driving power P_l and the coupling strength λ.

5. Conclusion

In summary, we have investigated the optomechanically induced transparency in two distant optomechanical systems. The presence of coupling strength between two oscillators

causes five transparent windows in the optomechanical system. If the coupling strength λ or g is vanishing, the number of the transparent windows will be reduced to three or one. In addition, we have also investigated the influence of various factors on multiple-OMIT, including the classical driving power P_l and the mechanical coupling strength λ. We observe that the width and the transparent point of the five windows can be controlled by the classical driving power P_l and the coupling strength λ, respectively. The larger the P_l and λ, the wider the transparent windows, and the further the separation between the two outermost windows. This result can be extended to multi-cavity systems, where the storage, transportation, and control of light are in prospect.

References

[1] Aspelmeyer M, Kippenberg T J and Marquardt F 2014 *Rev. Mod. Phys.* **86** 1391
[2] Marquardt F and Girvin S M 2009 *Physics* **2** 40
[3] Chen B, Shang L, Wang X F, Chen J B, Xue H B, Liu X and Zhang J 2019 *Phys. Rev. A* **99** 063810
[4] Zhang F Y, Li W L, Yan W B and Xia Y 2019 *J. Phys. B: At. Mol. Opt. Phys.* **52** 115501
[5] Cheng J, Zhang W Z, Han Y and Zhou L 2016 *Sci. Rep.* **6** 23678
[6] Zhang W Z, Han Y, Xiong B and Zhou L 2017 *New J. Phys.* **19** 083022
[7] He Y 2015 *Phys. Rev. A* **91** 013827
[8] Xiao Y, Yu Y F and Zhang Z M 2014 *Opt. Express* **22** 17979
[9] Teufel J D, Li D, Allman M S, Cicak K, Sirois A J, Whittaker J D and Simmonds R W 2011 *Nature* **471** 204
[10] Massel F, Heikkila T T, Pirkkalainen J M, Cho S U, Saloniemi H, Hakonen P J and Sillanpaa M A 2011 *Nature* **480** 351
[11] Safavi-Naeini A H, Mayer Alegre T P, Chan J, Eichenfield M, Winger M, Lin Q, Hill J T, Chang D and Painter O 2011 *Nature* **472** 69
[12] Akram M J, Khan M M and Saif F 2015 *Phys. Rev. A* **92** 023846
[13] Sarma B and Sarma A K 2016 *J. Opt. Soc. Am. B* **33** 1335
[14] Reinhardt C, Müller T, Bourassa A and Sankey J C 2016 *Phys. Rev. X* **6** 021001
[15] Zhang W Z, Chen L B, Cheng J and Jiang Y F 2019 *Phys. Rev. A* **99** 063811
[16] Jing H, Ozdemir S K, Lü X Y, Zhang J, Yang L and Nori F 2014 *Phys. Rev. Lett.* **113** 053604
[17] Sarma B and Sarma A K 2018 *Phys. Rev. A* **98** 013826
[18] Huang R, Miranowicz A, Liao J Q, Nori F and Jing H 2018 *Phys. Rev. Lett.* **121** 153601
[19] Abramovici A, Althouse W E, Drever R W P, Gürsel Y, Kawamura S, Raab F J, Shoemaker D, Sievers L, Spero R E, Thorne K S, Vogt R E, Weiss R, Whitcomb S E and Zucker M E 1992 *Science* **256** 325
[20] Fleischhauer M, Imamoglu A and Marangos J P 2005 *Rev. Mod. Phys.* **77** 633
[21] Xiong H, Si L G, Zheng A S, Yang X and Wu Y 2012 *Phys. Rev. A* **86** 013815
[22] Weis S, Rivière R, Deléglise S, Gavartin E, Arcizet O, Schliesser A and Kippenberg T J 2010 *Science* **330** 1520
[23] Chang D, Safavi-Naeini A H, Hafezi M and Painter O 2011 *New J. Phys.* **13** 023003
[24] Lu T X, Jiao Y F, Zhang H L, Saif F and Jing H 2019 *Phys. Rev. A* **100** 013813
[25] Zhang J Q, Li Y, Feng M and Xu Y 2012 *Phys. Rev. A* **86** 053806
[26] Agarwal G S and Huang S M 2012 *Phys. Rev. A* **85** 021801
[27] Ma P C, Zhang J Q, Xiao Y, Feng M and Zhang Z M 2014 *Phys. Rev. A* **90** 043825
[28] Shahidani S, Naderi M H and Soltanolkotabi M 2013 *Phys. Rev. A* **88** 053813
[29] Wu S C, Qin L G, Jing J, Yan T M, Lu J and Wang Z Y 2018 *Phys. Rev. A* **98** 013807
[30] Jing S 2011 *Chin. Phys. Lett.* **28** 104203
[31] Gu W J and Yi Z 2014 *Opt. Commun.* **333** 261
[32] Huang S M and Tsang M 2014 arXiv: 1403.1340v1
[33] Xiao R J, Pan G X and Zhou L 2015 *J. Opt. Soc. Am. B* **32** 1399
[34] Hao H, Kuzyk M C, Ren J J, Zhang F, Duan X K, Zhou L, Zhang T C, Gong Q H, Wang H L and Gu Y 2019 *Phys. Rev. A* **100** 023820
[35] Wu S C, QIN L G, Jing J, Yang G H and Wang Z Y 2016 *Chin. Phys. B* **25** 054203
[36] Hessa M, Alotaibi M and Sanders B C 2014 *Phys. Rev. A* **89** 021802
[37] Wu S C, QIN L G, Lu J and Wang Z Y 2019 *Chin. Phys. B* **28** 074204
[38] Zhang X Y, Zhou Y H, Guo Y Q and Yi X X 2018 *Phys. Rev. A* **98** 033832
[39] Xu X W, Liu Y, Sun C P and Li Y 2015 *Phys. Rev. A* **92** 013852
[40] Karabalin R B, Cross M C and Roukes M L 2009 *Phys. Rev. B* **79** 165309
[41] Huang P, Wang P F, Zhou J W, Wang Z X, Ju C Y, Wang Z M, Shen Y, Duan C K and Du J F 2013 *Phys. Rev. Lett.* **110** 227202
[42] Barzanjeh S and Vitali D 2016 *Phys. Rev. A* **93** 033846
[43] Sato Y, Tanaka Y, Upham J, Takahashi Y, Asano T and Noda S 2012 *Nat. Photon.* **6** 56
[44] Sohail A, Zhang Y, Zhang J and Yu C S 2016 *Sc. Rep.* **6** 28830
[45] Ma J L, Tan L, Li Q, Gu H Q and Liu W M 2018 *Sci. Rep.* **8** 14367
[46] Li T, Bao T Y, Zhang Y L, Zou C L, Zou X B and Guo G C 2016 *Opt. Express* **24** 12336
[47] Cirac J I, Zoller P, Kimble H J and Mabuchi H 1997 *Phys. Rev. Lett.* **78** 3221
[48] Tan H, Buchmann L F, Seok H and Li G 2013 *Phys. Rev. A* **87** 022318
[49] Walls D F and Milburn G J 1994 *Quantum Optics* (Berlin: Springer-Verlag)
[50] Agarwal G S and Huang S M 2010 *Phys. Rev. A* **81** 041803
[51] Smith D D, Chang H, Fuller K A, Rosenberger A T and Boyd R W 2004 *Phys. Rev. A* **69** 063804