Electromagnetically induced transparency in a three-mode optomechanical system*

Yan Xiao-Bo(严晓波)[a)b)], Gu Kai-Hui(谷开慧)[a)], Fu Chang-Bao(付长宝)[a)], Cui Cui-Li(崔淬砺)[a)†], and Wu Jin-Hui(吴金辉)[a)‡]

[a)] College of Physics, Jilin University, Changchun 130012, China
[b)] College of Electronic Science, Northeast Petroleum University, Daqing 163318, China

(Received 23 January 2014; revised manuscript received 16 April 2014; published online 24 September 2014)

We study a three-mode double-cavity optomechanical system in which an oscillating membrane of perfect reflection is inserted between two fixed mirrors of partial transmission. We find that electromagnetically induced transparency (EIT) can be realized and controlled in this optomechanical system by adjusting the relative intensity and the relative phase between left-hand and right-hand input (probe and coupling) fields. In particular, one perfect EIT window is seen to occur when the two probe fields are exactly out of phase and the EIT window's width is very sensitive to the relative intensity of two coupling fields. Our numerical findings may be extended to achieve optomechanical storage and switching schemes applicable in quantum information processing.

Keywords: cavity optomechanics, electromagnetically induced transparency, radiation pressure coupling, intensity and phase control

PACS: 42.50.Gy, 03.65.Ta, 42.50.Wk **DOI:** 10.1088/1674-1056/23/11/114201

1. Introduction

Cavity optomechanics has quickly developed over the past few years as an intersection field of nanophysics and quantum optics dealing with the coherent interaction between light fields and micro- or nano-mechanical motions. Relevant studies allow the high-sensitivity detection of tiny mass, force, and displacement by virtue of the radiation-pressure coupling between optical modes of cavities and mechanical degrees of freedom.[1–4] The standard and simplest optomechanical setup is a Fabry–Perot cavity in which one end mirror is a micro- or nano-mechanical vibrating object.[5–7] Other optomechanical devices were also designed and tested such as silica toroidal optical microresonators with the radiation-pressure coupling[8–11] and typical optomechanical cavities confining a Bose–Einstein condensate (BEC).[4,12–14] Recently, three-mode or multi-mode optomechanical systems have been further studied to attain hybrid quantum entanglement,[15] optomechanically induced light transparency,[16] single-photon nonlinearities,[17] and ground-state cooling of mechanical modes.[18–21]

The very interesting phenomena, electromagnetically induced transparency (EIT) and related normal mode splitting (NMS) have been predicted and observed in certain optomechanical systems[7,16,22–30] where the output probe fields depend on the input control fields via nonlinear optomechanical interactions. EIT in optomechanical systems (OEIT) is an analogue of that in coherent atomic systems[31] where one medium of multi-level atoms is made completely transparent to a weak probe field as simultaneously illuminated with a strong coupling field. Then slowing down light signals and even mapping them[32–34] into the long-lived mechanical vibrations may be realized by the dynamic OEIT technique.

Here, we are interested in the engineering of EIT in a three-mode double-cavity optomechanical system with an in-between movable membrane of perfect reflection in the presence of two coupling fields and two probe fields. We find that one perfect EIT window can be realized in this optomechanical system if appropriate parameters are taken in the coherent interaction. In addition, it is eas y to control the EIT window's width by adjusting the relative intensity of two coupling fields. We expect that the realization of dynamically controlled OEIT could be explored to build new photonic devices in quantum information networks.

2. Model and method

We consider a three-mode optomechanical system with one movable membrane of perfect reflection inserted between two fixed mirrors of partial transmission (see Fig. 1). The membrane oscillator has an eigenfrequency $\omega_{\rm m}$, a decay rate $\gamma_{\rm m}$, and a mechanical quality factor $Q = \omega_{\rm m}/\gamma_{\rm m}$. Two optical cavities of the same length L and the same frequency ω_0 happen when the membrane oscillator is at its equilibrium position in the absence of any external excitation. We describe the two optical modes, respectively, by annihila-

*Project supported by the National Natural Science Foundation of China (Grant No. 61378094).
†Corresponding author. E-mail: cuicuili@jlu.edu.cn
‡Corresponding author. E-mail: jhwu@jlu.edu.cn
© 2014 Chinese Physical Society and IOP Publishing Ltd

tion (creation) operators c_1 ($c_1^\dagger$) and c_2 ($c_2^\dagger$) while we represent the mechanical mode with b ($b^\dagger$). Annihilation and creation operators of the two cavity modes of the same frequency ω_0 and the mechanical mode are restricted by the commutation relation $[c_i, c_i^\dagger] = 1$ $(i = 1,2)$, $[c_1, c_2] = 0$ and $[b, b^\dagger] = 1$. The system is driven by two coupling (probe) fields from the left and right sides with amplitudes denoted by $\varepsilon_{\rm cL} = \sqrt{2\kappa\wp_{\rm cL}/(\hbar\omega_{\rm c})}$, $\varepsilon_{\rm cR} = \sqrt{2\kappa\wp_{\rm cR}/(\hbar\omega_{\rm c})}$ ($\varepsilon_{\rm L} = \sqrt{2\kappa\wp_{\rm L}/(\hbar\omega_{\rm p})}$, and $\varepsilon_{\rm R} = \sqrt{2\kappa\wp_{\rm R}/(\hbar\omega_{\rm p})}$). Here, $\wp_{\rm L}$, $\wp_{\rm R}$, $\wp_{\rm cL}$, and $\wp_{\rm cR}$ are the relevant field powers, κ is the common decay rate of both optical modes, and $\omega_{\rm p}$ ($\omega_{\rm c}$) is the probe (coupling) field frequency.

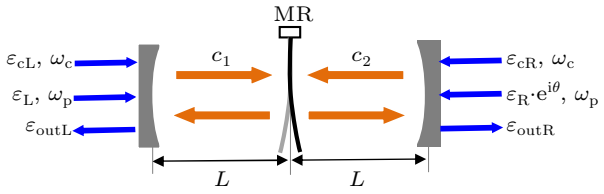


Fig. 1. (color online) A three-mode optomechanical system with an oscillating membrane inserted between two fixed mirrors. The two cavities have identical cavity lengths L and mode frequencies ω_0 in the absence of radiation pressure from external driving fields. Two coupling (probe) fields with the same frequency $\omega_{\rm c}$ ($\omega_{\rm p}$) but different amplitudes $\varepsilon_{\rm cL,cR}$ ($\varepsilon_{\rm L,R}$) act upon opposite sides of the movable membrane after entering either left or right cavities. The two input probe fields have a fixed relative phase θ while the two output fields are denoted by $\varepsilon_{\rm outL}$ and $\varepsilon_{\rm outR}$, respectively.

In the rotating frame at the coupling frequency $\omega_{\rm c}$, the system Hamiltonian is

$$\begin{aligned} H =\ & \hbar\Delta_{\rm c}(c_1^\dagger c_1 + c_2^\dagger c_2) + \hbar g_0(c_2^\dagger c_2 - c_1^\dagger c_1)(b^\dagger + b) \\ & + \hbar\omega_{\rm m} b^\dagger b + {\rm i}\hbar\varepsilon_{\rm cL}(c_1^\dagger - c_1) + {\rm i}\hbar(c_1^\dagger \varepsilon_{\rm L}\, {\rm e}^{-{\rm i}\delta t} - c_1\varepsilon_{\rm L}^*\, {\rm e}^{{\rm i}\delta t}) \\ & + {\rm i}\hbar\varepsilon_{\rm cR}(c_2^\dagger - c_2) + {\rm i}\hbar(c_2^\dagger \varepsilon_{\rm R}\, {\rm e}^{{\rm i}\theta}\, {\rm e}^{-{\rm i}\delta t} - c_2\varepsilon_{\rm R}^*\, {\rm e}^{-{\rm i}\theta}\, {\rm e}^{{\rm i}\delta t}), \end{aligned} \tag{1}$$

where $\Delta_{\rm c} = \omega_0 - \omega_{\rm c}$ is the detuning between the cavity-mode and the coupling fields

$$g_0 = \frac{\omega_0}{L}\sqrt{\frac{\hbar}{2m\omega_{\rm m}}}$$

is the coupling constant between the two optical modes and the mechanical mode, $\delta = \omega_{\rm p} - \omega_{\rm c}$ is the detuning between probe fields and coupling fields, and θ is the relative phase between the left-hand and right-hand probe fields.

With Eq. (1), it is straightforward to obtain the quantum Langevin equations for mechanical- and optical-mode annihilation operators

$$\begin{aligned} \dot b =& -{\rm i}\omega_{\rm m} b - {\rm i}g_0(c_2^\dagger c_2 - c_1^\dagger c_1) - \frac{\gamma_{\rm m}}{2}b + \sqrt{\gamma_{\rm m}}b_{\rm in}, \\ \dot c_1 =& -[\kappa + {\rm i}\Delta_{\rm c} - {\rm i}g_0(b^\dagger + b)]c_1 + \varepsilon_{\rm cL} + \varepsilon_{\rm L}\, {\rm e}^{-{\rm i}\delta t} + \sqrt{2\kappa}c_1^{\rm in}, \\ \dot c_2 =& -[\kappa + {\rm i}\Delta_{\rm c} + {\rm i}g_0(b^\dagger + b)]c_2 + \varepsilon_{\rm cR} + \varepsilon_{\rm R}{\rm e}^{{\rm i}\theta}{\rm e}^{-{\rm i}\delta t} + \sqrt{2\kappa}c_2^{\rm in}, \end{aligned} \tag{2}$$

where $b_{\rm in}$ is the thermal noise on the movable membrane with zero mean value while $c_1^{\rm in}$ ($c_2^{\rm in}$) is the vacuum noise in the left (right) cavity with zero mean value.

Mean values of the three mode operators in the absence of probe fields $\varepsilon_{\rm L}$ and $\varepsilon_{\rm R}$ can be obtained from Eq. (2) with the factorization assumption $\langle bc_i\rangle = \langle b\rangle\langle c_i\rangle$ as

$$\begin{aligned} \langle b\rangle &= b_{\rm s} = \frac{-{\rm i}g_0(|c_{2\rm s}|^2 - |c_{1\rm s}|^2)}{\frac{\gamma_{\rm m}}{2} + {\rm i}\omega_{\rm m}}, \\ \langle c_1\rangle &= c_{1\rm s} = \frac{\varepsilon_{\rm cL}}{\kappa + {\rm i}\Delta_1}, \\ \langle c_2\rangle &= c_{2\rm s} = \frac{\varepsilon_{\rm cR}}{\kappa + {\rm i}\Delta_2}, \end{aligned} \tag{3}$$

where $\Delta_{1,2} = \Delta_{\rm c} \mp g_0(b_{\rm s} + b_{\rm s}^*)$ denotes the effective detuning between the two optical modes and the two coupling fields. Mean values $b_{\rm s}$ and $c_{1\rm s}$ ($c_{2\rm s}$) determine the micro- or nano-mechanical displacement and the left- (right-) hand cavity field amplitude in the steady state, respectively. Note, in particular, that $g_0(b_{\rm s} + b_{\rm s}^*)$ is typically very small as compared to $\omega_{\rm m}$ and becomes even exactly zero in the case of $|c_{1\rm s}| = |c_{2\rm s}|$ ($|\varepsilon_{\rm cL}| = |\varepsilon_{\rm cR}|$).

To solve the nonlinearly coupled Eq. (2), we can write each mode operator as the sum of its mean value and its small fluctuation ($b = b_{\rm s} + \delta b, c_1 = c_{1\rm s} + \delta c_1, c_2 = c_{2\rm s} + \delta c_2$) when both coupling fields are sufficiently strong. Inserting these expressions into Eq. (2), keeping only the linear terms, and moving into another interaction picture by introducing $\delta b \to \delta b\, {\rm e}^{-{\rm i}\omega_{\rm m}t}$, $\delta b_{\rm in} \to \delta b_{\rm in}\, {\rm e}^{-{\rm i}\omega_{\rm m}t}$, $\delta c_1 \to \delta c_1\, {\rm e}^{-{\rm i}\Delta_1 t}$, $\delta c_2 \to \delta c_2\, {\rm e}^{-{\rm i}\Delta_2 t}$, $\delta c_1^{\rm in} \to \delta c_1^{\rm in}\, {\rm e}^{-{\rm i}\Delta_1 t}$, $\delta c_2^{\rm in} \to \delta c_2^{\rm in}\, {\rm e}^{-{\rm i}\Delta_2 t}$, we then obtain the linearized quantum Langevin equations

$$\begin{aligned} \delta\dot b =\ & -{\rm i}g_0(c_{2\rm s}^*\delta c_2\, {\rm e}^{-{\rm i}(\Delta_2 - \omega_{\rm m})t} - c_{1\rm s}^*\delta c_1\, {\rm e}^{-{\rm i}(\Delta_1 - \omega_{\rm m})t}) \\ & - {\rm i}g_0(c_{2\rm s}\delta c_2^\dagger\, {\rm e}^{{\rm i}(\Delta_2 + \omega_{\rm m})t} - c_{1\rm s}\delta c_1^\dagger\, {\rm e}^{{\rm i}(\Delta_1 + \omega_{\rm m})t}) \\ & - \frac{\gamma_{\rm m}}{2}\delta b + \sqrt{\gamma_{\rm m}}b_{\rm in}, \\ \delta\dot c_1 =\ & -\kappa\delta c_1 + {\rm i}g_0 c_{1\rm s}(\delta b\, {\rm e}^{-{\rm i}(\omega_{\rm m} - \Delta_1)t} + \delta b^\dagger\, {\rm e}^{{\rm i}(\omega_{\rm m} + \Delta_1)t}) \\ & + \varepsilon_{\rm L}\, {\rm e}^{-{\rm i}(\delta - \Delta_1)t} + \sqrt{2\kappa}c_1^{\rm in}, \\ \delta\dot c_2 =\ & -\kappa\delta c_2 - {\rm i}g_0 c_{2\rm s}(\delta b\, {\rm e}^{-{\rm i}(\omega_{\rm m} - \Delta_2)t} + \delta b^\dagger\, {\rm e}^{{\rm i}(\omega_{\rm m} + \Delta_2)t}) \\ & + \varepsilon_{\rm R}\, {\rm e}^{{\rm i}\theta}\, {\rm e}^{-{\rm i}(\delta - \Delta_2)t} + \sqrt{2\kappa}c_2^{\rm in}. \end{aligned} \tag{4}$$

If each coupling field drives one cavity mode at the mechanical red sideband ($\Delta_1 \approx \Delta_2 \approx \omega_{\rm m}$), the optomechanical system is operating in the resolved sideband regime ($\omega_{\rm m} \gg \kappa$), the membrane has a high mechanical quality factor ($\omega_{\rm m} \gg \gamma_{\rm m}$), and the mechanical frequency $\omega_{\rm m}$ is much larger than $g_0|c_{1\rm s}|$ and $g_0|c_{2\rm s}|$, equation (4) will be simplified into

$$\begin{aligned} \delta\dot b &= -{\rm i}g_0(c_{2\rm s}^*\delta c_2 - c_{1\rm s}^*\delta c_1) - \frac{\gamma_{\rm m}}{2}\delta b + \sqrt{\gamma_{\rm m}}b_{\rm in}, \\ \delta\dot c_1 &= -\kappa\delta c_1 + {\rm i}g_0 c_{1\rm s}\delta b + \varepsilon_{\rm L}\, {\rm e}^{-{\rm i}xt} + \sqrt{2\kappa}c_1^{\rm in}, \\ \delta\dot c_2 &= -\kappa\delta c_2 - {\rm i}g_0 c_{2\rm s}\delta b + \varepsilon_{\rm R}\, {\rm e}^{{\rm i}\theta}\, {\rm e}^{-{\rm i}xt} + \sqrt{2\kappa}c_2^{\rm in}, \end{aligned} \tag{5}$$

where $x = \delta - \omega_{\rm m}$ is the detuning of the probe field from the cavity resonance.

Now we begin to examine the expectation values of small fluctuations. Considering that the mean values of vacuum and thermal noise terms are zero, we have

$$\begin{aligned}\langle\delta\dot{b}\rangle &= -\mathrm{i}g_0(c_{2\mathrm{s}}^*\delta c_2 - c_{1\mathrm{s}}^*\delta c_1) - \frac{\gamma_\mathrm{m}}{2}\delta b,\\ \langle\delta\dot{c}_1\rangle &= -\kappa\delta c_1 + \mathrm{i}g_0 c_{1\mathrm{s}}\delta b + \varepsilon_\mathrm{L}\,\mathrm{e}^{-\mathrm{i}xt},\\ \langle\delta\dot{c}_2\rangle &= -\kappa\delta c_2 - \mathrm{i}g_0 c_{2\mathrm{s}}\delta b + \varepsilon_\mathrm{R}\,\mathrm{e}^{\mathrm{i}\theta}\,\mathrm{e}^{-\mathrm{i}xt},\end{aligned} \tag{6}$$

whose solutions are expected to have the following form

$$\langle\delta s\rangle = \delta s_+\,\mathrm{e}^{-\mathrm{i}xt} + \delta s_-\,\mathrm{e}^{\mathrm{i}xt}, \tag{7}$$

with $s = b$, c_1, or c_2. Note that δs_+ and δs_- are the components of $\langle\delta s\rangle$ oscillating at $\omega_\mathrm{p}-\omega_\mathrm{c}$ and $\omega_\mathrm{c}-\omega_\mathrm{p}$ in the rotating frame at frequency ω_c, respectively.

Substituting Eq. (7) into Eq. (6), we can finally obtain

$$\begin{aligned}\delta b_+ &= \frac{-\mathrm{i}G(n\varepsilon_\mathrm{R}\,\mathrm{e}^{\mathrm{i}\theta}-\varepsilon_\mathrm{L})}{(\kappa-\mathrm{i}x)(\frac{\gamma_\mathrm{m}}{2}-\mathrm{i}x)+G^2(n^2+1)},\\ \delta c_{1+} &= \frac{(n\varepsilon_\mathrm{R}\,\mathrm{e}^{\mathrm{i}\theta}+n^2\varepsilon_\mathrm{L})G^2+\varepsilon_\mathrm{L}(\kappa-\mathrm{i}x)\left(\frac{\gamma_\mathrm{m}}{2}-\mathrm{i}x\right)}{(\kappa-\mathrm{i}x)^2\left(\frac{\gamma_\mathrm{m}}{2}-\mathrm{i}x\right)+G^2(n^2+1)(\kappa-\mathrm{i}x)},\\ \delta c_{2+} &= \frac{(n\varepsilon_\mathrm{L}+\varepsilon_\mathrm{R}\,\mathrm{e}^{\mathrm{i}\theta})G^2+\varepsilon_\mathrm{R}\,\mathrm{e}^{\mathrm{i}\theta}(\kappa-\mathrm{i}x)\left(\frac{\gamma_\mathrm{m}}{2}-\mathrm{i}x\right)}{(\kappa-\mathrm{i}x)^2\left(\frac{\gamma_\mathrm{m}}{2}-\mathrm{i}x\right)+G^2(n^2+1)(\kappa-\mathrm{i}x)},\end{aligned} \tag{8}$$

where $c_{1\mathrm{s}}$ and $c_{2\mathrm{s}}$ are assumed to be real-valued with $c_{2\mathrm{s}}/c_{1\mathrm{s}} = n$. In addition, $G = g_0 c_{1\mathrm{s}}$ is the effective optomechanical coupling rate related to the coupling power $\wp_{\mathrm{cL}}$.

3. Electromagnetically induced transparency

In this section, we examine whether EIT can be achieved in terms of the left-hand output probe field based on the equations derived above. Similar results apply to the right-hand output probe field due to the symmetric driving configuration of our optomechanical system. Defining $\varepsilon_\mathrm{T} = 2\kappa\delta c_{1+}/\varepsilon_\mathrm{L}$ as in Ref. [7], it is easy to obtain from Eq. (8), that

$$\varepsilon_\mathrm{T} = \frac{2\kappa\left(n\frac{\varepsilon_\mathrm{R}}{\varepsilon_\mathrm{L}}\,\mathrm{e}^{\mathrm{i}\theta}+n^2\right)G^2+2\kappa(\kappa-\mathrm{i}x)\left(\frac{\gamma_\mathrm{m}}{2}-\mathrm{i}x\right)}{(\kappa-\mathrm{i}x)^2\left(\frac{\gamma_\mathrm{m}}{2}-\mathrm{i}x\right)+G^2(n^2+1)(\kappa-\mathrm{i}x)}, \tag{9}$$

whose real and imaginary parts, $\mathrm{Re}[\varepsilon_\mathrm{T}]$ and $\mathrm{Im}[\varepsilon_\mathrm{T}]$, represent absorptive and dispersive behaviors of the left-hand output probe field, respectively.

We will implement numerical calculations to investigate dynamic effects of the right-hand probe and coupling fields on EIT spectra of the left-hand probe field with realistic parameters in a recent optomechanical experiment.[35] We have, in particular, $L = 25$ mm, $m = 145$ ng, $\kappa = 2\pi\times 215$ kHz, $\omega_\mathrm{m} = 2\pi\times 947$ kHz, and $\gamma_\mathrm{m} = 2\pi\times 141$ Hz. In addition, the laser wavelength is $\lambda = 2\pi c/\omega_\mathrm{c} = 1064$ nm and the mechanical quality factor is $Q = \omega_\mathrm{m}/\gamma_\mathrm{m} = 6700$. We stress that the expected EIT phenomenon is a result of quantum destructive interference between incident probe photons and generated Stokes photons in the left cavity.[26,36] In the presence of an efficient optomechanical coupling, probe photons and Stokes photons are phase locked on one side of the membrane because they are coupled to the same cavity mode. Then quantum destructive interference will occur to result in a deep EIT window when probe photons are modulated to be matched in frequency with Stokes photons.

First, we consider the case of $\varepsilon_\mathrm{R} = 0$ in the absence of a right-hand probe field. In this case, the optomechanical interaction in the left cavity will be somewhat weakened by the right-hand coupling field if we have $n \neq 0$ because the radiation pressure is partially counteracted. Consequently, there are not enough Stokes photons generated to contribute to a perfect destructive interference with incident probe photons when the first term in the numerator of Eq. (9) is non-vanishing. This is why the EIT window of the left-hand output probe field becomes shallower and shallower when the value of n is increased from $n = 0.5$ (black-solid) first to $n = 1.0$ (red-dotted) and then to $n = 1.5$ (blue-dashed) [see Fig. 2]. Note that we always work in the optomechanical red-sideband regime and relevant experiments are usually implemented in the cryostat environments.[23,24] Thus the membrane may approach its quantum ground state via the resolved sideband cooling mechanism. As a result, we can safely ignore the effects of thermal noise on the mechanical dephasing rate and our EIT results.

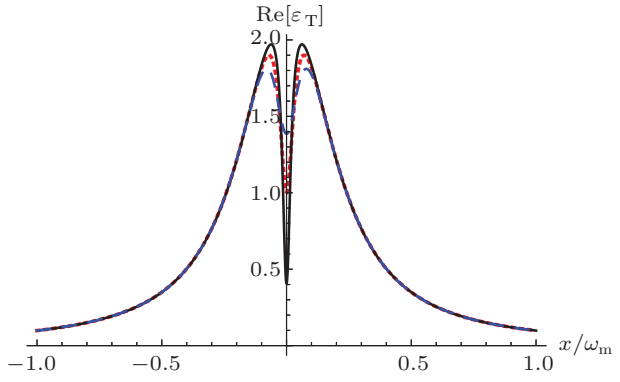


Fig. 2. (color online) Real part of the left-hand output probe field ε_T versus. normalized frequency detuning x/ω_m with $\varepsilon_\mathrm{R} = 0$ for $n = 0.5$ (black-solid), $n = 1.0$ (red-dotted), and $n = 1.5$ (blue-dashed). The left-hand coupling field has a power of $\wp_{\mathrm{cL}} = 1.0$ mW.

Then we consider the case of $\varepsilon_\mathrm{R} \neq 0$ to see effects of the right-hand input probe field on EIT of the left-hand output probe field. It is clear that we always observe a perfect EIT window with $\theta = \pi$ and $\varepsilon_\mathrm{R} = n\varepsilon_\mathrm{L}$ for $n = 0.5$ (black-solid), $n = 1.0$ (red-dotted), and $n = 1.5$ (blue-dashed) [see Fig. 3]. In fact, with $\theta = \pi$ and $\varepsilon_\mathrm{R} = n\varepsilon_\mathrm{L}$, equation (9) reduces into

$$\varepsilon_\mathrm{T} = \frac{2\kappa}{\kappa-\mathrm{i}x+G^2(n^2+1)\Big/\left(\frac{\gamma_\mathrm{m}}{2}-\mathrm{i}x\right)}, \tag{10}$$

from which the perfect destructive interference is seen to exist independently of n. To be more specific, the intensity mismatch between left-hand and right-hand coupling fields can be well compensated to recover the perfect destructive interference by applying the right-hand probe field with $\theta = \pi$ and $\varepsilon_R = n\varepsilon_L$ [see the first term in the numerator of Eq. (9)]. In this case, the EIT window's width is given by $\Gamma_{EIT} \approx G^2(n^2+1)/\kappa$[23] because the mechanical decay rate γ_m is very small in comparison with G^2/κ. This means that the EIT window's width will become larger and larger with the increase of n for a given power of the left-hand coupling field, as verified in Fig. 3 with three typical values of n.

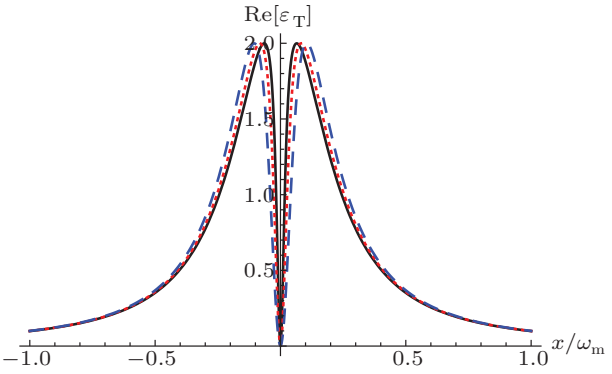


Fig. 3. (color online) Real part of the left-hand output probe field ε_T versus normalized frequency detuning x/ω_m under the condition of $\theta = \pi$ and $\varepsilon_R = n\varepsilon_L$. The other parameters are chosen to be the same as those in Fig. 2.

Now we introduce a critical value of the left-hand coupling power $\wp_{cL}$ defined by

$$\wp_{cr} = \frac{m\omega_m\omega_c L^2(\kappa^2+\omega_m^2)(\kappa-\gamma_m/2)^2}{4\omega_0^2\kappa(n^2+1)}, \qquad (11)$$

which is $\wp_{cr} \approx 1.2$ mW for $n = 1.5$. With $\wp_{cL} < \wp_{cr}$, the two roots of x in the denominator of Eq. (10) are purely imaginary such that the nontrivial quantum destructive interference results in a deep EIT window of width Γ_{EIT}. On the contrary, NMS will occur with $\wp_{cL} > \wp_{cr}$ even in the absence of quantum destructive interference (not the focus in this work). In Fig. 4, we plot Im[ε_T] of the left-hand output probe field against the normalized frequency detuning x/ω_m. It is clear that the value of n affects, remarkably, the sharp probe dispersive behavior around $x = 0$, as shown by the black-solid ($n = 0.5$), red-dotted ($n = 1.0$), and blue-dashed ($n = 1.5$) curves. Then it is viable to attain tunable slow-light signals via the controlled probe dispersion within an OEIT window with little probe absorption.

Finally we consider the case where the two probe fields are exactly in phase with $\theta = 0$. In this case, the nonlinear Stokes process in the left cavity will be dramatically suppressed, as can be seen from Eq. (8). In fact, we have $\delta b_+ = 0$ for $n = 1$, $\theta = 0$, and $\varepsilon_R = \varepsilon_L$, which indicates a complete cancellation of the optomechanical coupling. This is why we just observe a Lorentzian profile of probe absorption, as shown by the black-solid curve in Fig. 5. Tuning θ into $\pi/2$ or $3\pi/2$, the profile of probe absorption becomes very different from both the EIT spectrum and the Lorentzian profile (see the red-dotted and blue-dashed curves in Fig. 5). The essence is once again that the values of θ and ε_R affect, significantly, the effective optomechanical coupling via δb_+ and thus the probe absorption and dispersion properties.

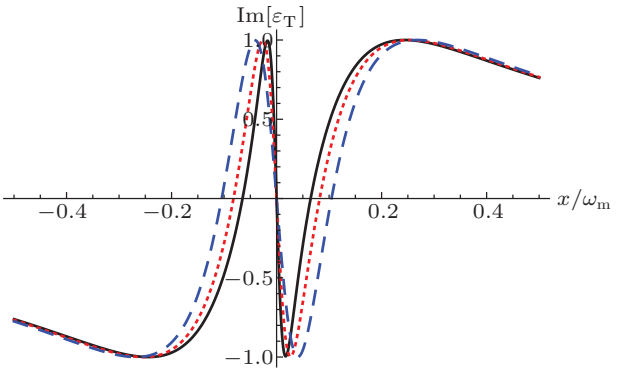


Fig. 4. (color online) Imaginary part of the left-hand output probe field ε_T versus normalized frequency detuning x/ω_m with the same parameters as those in Fig. 3.

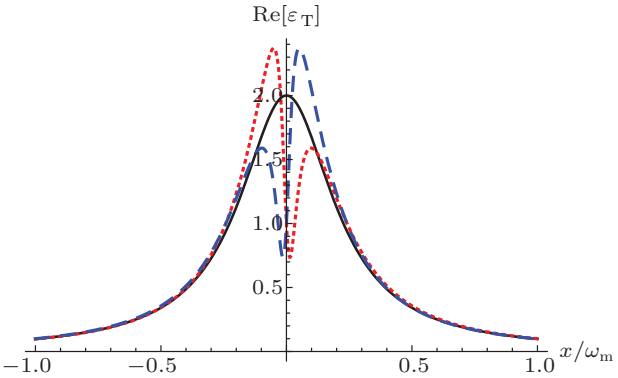


Fig. 5. (color online) Real part of the left-hand output probe field ε_T versus normalized frequency detuning x/ω_m for $\theta = 0$ (black-solid), $\theta = \pi/2$ (red-dotted), and $\theta = 3\pi/2$ (blue-dashed) with $\varepsilon_R = \varepsilon_L$, $n = 1.0$, and $\wp_{cL} = 1.0$ mW.

4. Conclusions

In summary, we have studied EIT in a three-mode double-cavity optomechanical system with a symmetric driving configuration. We find that the EIT window is not perfect in general without applying the right-hand probe field. When the right-hand probe field is turned on, however, we can observe a perfect EIT window if the two probe fields have the relative phase $\theta = \pi$ and the relative amplitude $\varepsilon_R = n\varepsilon_L$ ($n = c_{2s}/c_{1s}$). This is because the Stokes photons generated in the left-cavity interfere, destructively, with the left-hand input probe photons. We also find that it is easy to control the EIT window in depth and in width by adjusting relative phases and intensities of the left-hand and right-hand input (coupling and probe) fields. Our results may be extended to realize, e.g., slow light, optical storage, and optical switching in appropriate optomechanical systems as in multi-level atomic systems.[37,38]

References

[1] Kippenberg T J and Vahala K J 2008 *Science* **321** 1172
[2] Marquardt F and Girvin S M 2009 *Physics* **2** 40
[3] Verlot P, Tavernarakis A, Briant T, Cohadon P F and Heidmann A 2010 *Phys. Rev. Lett.* **104** 133602
[4] Mahajan S, Kumar T, Bhattacherjee A B and ManMohan 2013 *Phys. Rev. A* **87** 013621
[5] Gigan S, Böhm H, Paternostro M, Blaser F, Langer G, Hertzberg J, Schwab K, Bäuerle D, Aspelmeyer M and Zeilinger A 2006 *Nature* **444** 67
[6] Kleckner D and Bouwmeester D 2006 *Nature* **444** 75
[7] Agarwal G S and Huang S M 2010 *Phys. Rev. A* **81** 041803
[8] Kippenberg T J and Vahala K J 2007 *Opt. Express* **15** 17172
[9] Armani D K, Kippenberg T J, Spillane S M and Vahala K J 2003 *Nature* **421** 925
[10] Schliesser A, Rivière R, Anetsberger G, Arcizet O and Kippenberg T J 2008 *Nat. Phys.* **4** 415
[11] Schmid S I, Xia K Y and Evers J 2011 *Phys. Rev. A* **84** 013808
[12] Singh S, Jing H, Wright E M and Meystre P 2012 *Phys. Rev. A* **86** 021801
[13] Rogers B, Paternostro M, Palma G M and Chiara G D 2012 *Phys. Rev. A* **86** 042323
[14] Dalafi A, Naderi M H, Soltanolkotabi M and Barzanjeh S 2013 *Phys. Rev. A* **87** 013417
[15] Wang Y D and Clerk A A 2013 *Phys. Rev. Lett.* **110** 253601
[16] Karuza M, Biancofiore C, Bawaj M, Molinelli C, Galassi M, Natali R, Tombesi P, Giuseppe G D and Vitali D 2013 *Phys. Rev. A* **88** 013804
[17] Kómár P, Bennett S D, Stannigel K, Habraken S J M, Rabl P, Zoller P and Lukin M D 2013 *Phys. Rev. A* **87** 013839
[18] Bhattacharya M and Meystre P 2007 *Phys. Rev. Lett.* **99** 073601
[19] Mari A and Eisert J 2012 *Phys. Rev. Lett.* **108** 120602
[20] Li Y, Wu L A and Wang Z D 2011 *Phys. Rev. A* **83** 043804
[21] Deng Z J, Li Y, Gao M and Wu C W 2012 *Phys. Rev. A* **85** 025804
[22] Huang S M and Agarwal G S 2009 *Phys. Rev. A* **80** 033807
[23] Weis S, Rivière R, Deléglise S, Gavartin E, Arcizet O, Schliesser A and Kippenberg T J 2010 *Science* **330** 1520
[24] Safavi-Naeini A H, Mayer A T P, Chan J, Eichenfield M, Winger M, Lin Q, Hill J T, Chang D E and Painter O 2011 *Nature* **472** 69
[25] Liu Y X, Davanco M, Aksyuk V and Srinivasan K 2013 *Phys. Rev. Lett.* **110** 223603
[26] Kronwald A and Marquardt F 2013 *Phys. Rev. Lett.* **111** 133601
[27] Shu J 2011 *Chin. Phys. Lett.* **28** 104203
[28] Chen H J and Mi X W 2011 *Acta Phys. Sin.* **60** 124206 (in Chinese)
[29] Yan X B, Cui C L, Gu K H, Tian X D, Fu C B and Wu J H 2014 *Opt. Express* **22** 4886
[30] Yan X B, Fu C B, Gu K H, Wang R and Wu J H 2013 *Opt. Commun.* **308** 265
[31] Fleischhauer M, Imamoglu A and Marangos J P 2005 *Rev. Mod. Phys.* **77** 633
[32] Chang D E, Safavi-Naeini A H, Hafezi M and Painter O 2011 *New J. Phys.* **13** 023003
[33] Fiore V, Yang Y, Kuzyk M C, Barbour R, Tian L and Wang H 2011 *Phys. Rev. Lett.* **107** 133601
[34] Fiore V, Dong C H, Kuzyk M C and Wang H L 2013 arXiv:1302.0557
[35] Gröblacher S, Hammerer K, Vanner M and Aspelmeyer M 2009 *Nature* **460** 724
[36] Kenan Q and Agarwal G S 2013 *Phys. Rev. A* **87** 063813
[37] Wu J H, Artoni M, and La Rocca G C 2010 *Phys. Rev. A* **82** 013807
[38] Heinze G, Hubrich C and Halfmann T 2013 *Phys. Rev. Lett.* **111** 033601