Force-induced transparency and conversion between slow and fast light in optomechanics

Zhen Wu,[1] Ren-Hua Luo,[2] Jian-Qi Zhang,[3,*] Yu-Hua Wang,[4] Wen Yang,[5] and Mang Feng[3,6,†]

[1]*City College, Wuhan University of Science and Technology, Wuhan 430083, China*

[2]*Hubei Electric Engineering Corporation (POWERCHINA HEEC), Wuhan 430040, China*

[3]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China*

[4]*Hubei Province Key Laboratory of Science in Metallurgical Process, Wuhan University of Science and Technology, Wuhan 430081, China*

[5]*Beijing Computational Science Research Center, Beijing 100084, China*

[6]*Department of Physics, Zhejiang Normal University, Jinhua 321004, China*

(Received 17 May 2017; published 19 September 2017)

The optomechanics can generate fantastic effects of optics due to appropriate mechanical control. Here we theoretically study effects of slow and fast lights in a single-sided optomechanical cavity with an external force. The force-induced transparency of slow and fast lights and the force-dependent conversion between the slow and fast lights result from effects of the rotating-wave approximation (RWA) and the anti-RWA, which can be controlled by properly modifying the effective cavity frequency due to the external force. These force-induced phenomena can be applied to control the light group velocity and to detect the force variation, which are feasible using current laboratory techniques.

DOI: 10.1103/PhysRevA.96.033832

I. INTRODUCTION

The cavity optomechanics (COM), combining mechanical modes with optical modes via radiation pressure, has attracted considerable attention recently. Extensive research efforts have presented interesting quantum properties and nonlinear effects by optomechanics, such as entanglement [1–3], squeezing [4,5], normal mode splitting [6], the Kerr effect [7], optomechanically induced transparency (OMIT) [8–12], optical solitons [13], and chaos [14,15], which are associated with potential applications in quantum information processing [16,17] and precision measurements [18–20].

Among the above mentioned items, the OMIT, a kind of induced transparency arising from the interference of excitation pathways in optomechanical systems, is the research focus of the present paper. We have noticed that the electromagnetically induced transparency (EIT) in atoms can produce slow and fast lights [21], which is the technique with appealing applications in optical storage [22,23], optical telecommunication [24], signal processing [25], and interferometry [26]. So we wonder if the OMIT, with analogy to the EIT, could also work for producing slow and fast lights and even beyond. In fact, there have been publications [27–33] for slow and fast light effects associated with the COM using similar behavior to those with multilevel atoms. As shown below, however, we will go a further step with the COM by presenting an experimentally feasible proposal for a force-induced transparency with slow and fast lights and a conversion between the slow and fast lights.

Specifically, different from the traditional transparency proposals [34–37], where the slow and fast lights can only be adjusted with an external optical field, e.g., the power and frequency of the pump field, our study shows that we can control exactly by an external force the group velocity of lights with a fixed pump field. This external force employed for the control could be Coulomb-relevant [18] or magnetic effects [38].

Two kinds of external forces are usually employed in the optomechanics. One is the constant force [39,40], including electric field force [18], magnetic field force [38], elastic force [41,42], and optical gradient force [43]; the other is the time-harmonic-driving force [44,45], which could be achieved with piezoelectric coupling [46] and Lorentz force [47]. In our scheme, we choose a constant force as the external force, which can modify the eigenfrequencies of the cavity by adjusting the cavity length. Such an external force is similar to the one in Ref. [40], where the force is applied to balance the effective force from the nonlinear optical effect.

Compared with the optical manipulations on the group velocity of lights [34–37], which are limited by the power and frequency ranges of the laser field, the external force in our scheme works in a larger regime. Due to the external force, the effective eigenfrequency of the optomechanical cavity is modified, and thus we may achieve the conversion between slow and fast lights in this way. This conversion is physically governed by the conditions for the rotating-wave approximation (RWA) and the anti-RWA which are present as anti-Stokes and Stokes processes in the optomechanics, respectively.

As pointed out below, the slow and fast lights are originally from the effect of the RWA and the anti-RWA of the parameters in the system, which is a more fundamental factor than the anti-Stokes and Stokes processes as mentioned in Refs. [32,33]. The latter is valid only for the situation of the third-order nonlinear coupling, but the former can explain the fast and slow light effects in various physical systems including both the linear [34–37] and the nonlinear coupling systems [27–33]. Moreover, our proposal is more simplified and effective and experimentally feasible using current techniques [39] since it is only required to apply an external force on the optomechanical resonator, much more easily adjusted than the idea with an additional atom [32] or nanoresonator [33]. In Ref. [32], the

*changjianqi@gmail.com

†mangfeng@wipm.ac.cn

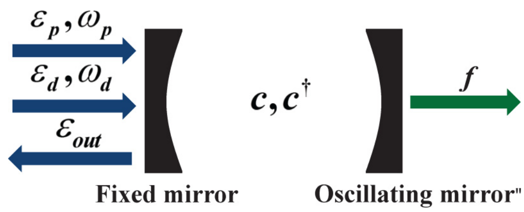

FIG. 1. Schematic diagram of the system. The COM consists of a fixed mirror and an oscillating mirror. The arrow with labels ε_p, ω_p is for a weak probe field and the arrow with labels ε_d, ω_d for a strong pump field. The output field is with the field amplitude $\varepsilon_{\rm out}$. An external force is applied on the oscillating mirror for producing the slow and fast light effects as discussed in the text.

slow and fast lights are adjusted by the detuning between the optomechanical cavity and a cavity-confined atom, which is hard to manipulate experimentally. The control of the slow and fast lights in [33] is made by Coulomb coupling between two nanomechanical resonators (NRs), which is also experimentally challenging.

Furthermore, the effects in our work can be observed even at room temperature since the noise is much less than the mean value of the output field [48]. In particular, due to one-to-one correspondence between the external force and the group velocity of the light in some special regimes, our proposal could be used to achieve precision measurements and operations. As such, our work provides an effective way to control the group velocity of the light in optomechanical systems with an external force.

The rest of the paper is structured as follows. In Sec. II, we present the Hamiltonian and the steady state of the optomechanics. In Sec. III, we deduce the output of the probe field and its time delay. In Sec. IV, we give some simulations and discussions for the force-induced light transparency and the force-dependent conversion between the slow and fast lights under some experimentally available conditions. The conclusion is given in the last section.

II. HAMILTONIAN AND STEADY STATES

As sketched in Fig. 1, an optomechanical cavity is driven by a strong pump field with frequency ω_d and power P_d, and by a weak probe field with frequency ω_p and power P_p. The oscillating mirror with mass m and frequency ω_m couples to the Fabry-Perot cavity with frequency ω_c via radiation pressure force, and experiences an external force f. As mentioned above, this force must be a constant force, such as a Coulomb force [18] or a magnetic force with a steady electric current [45].

In the rotating frame at frequency ω_d of the pump field, the Hamiltonian of the system is given by [18,45]

$$H = \hbar\Delta_c c^\dagger c + \left(\frac{p^2}{2m} + \frac{1}{2}m\omega_m^2 q^2\right) - \chi q c^\dagger c - fq + i\hbar[(\varepsilon_d + \varepsilon_p e^{-i\delta t})c^\dagger - \text{H.c.}], \tag{1}$$

with detunings $\Delta_c = \omega_c - \omega_d$ and $\delta = \omega_p - \omega_d$. The first term is the free Hamiltonian for the cavity with the annihilation (creation) operator $c\,(c^\dagger)$. The second term describes the energy for the oscillating mirror with q (p) being the position (momentum) operator. The third term represents the radiation pressure effect between the cavity and the oscillating mirror with a coupling strength $\chi = \frac{\hbar\omega_c}{L}$, where L is the cavity length. The fourth term is associated with the external force on the oscillating mirror. The last two terms are the interactions between the cavity and two input fields with strengths $\varepsilon_d = \sqrt{\frac{2\kappa P_d}{\hbar\omega_d}}$ and $\varepsilon_p = \sqrt{\frac{2\kappa P_p}{\hbar\omega_p}}$, respectively, where κ is cavity decay rate.

To get the mean response of the system, we employ the Heisenberg-Langevin equations and the mean-field approximation [8]. Then the mean-value equations of our model can be written as

$$\begin{aligned}
\langle\dot{q}\rangle &= \frac{\langle p\rangle}{m},\\
\langle\dot{p}\rangle &= -m\omega_m^2\langle q\rangle + \chi\langle c^\dagger c\rangle + f - \gamma_m\langle p\rangle,\\
\langle\dot{c}\rangle &= -\left[\kappa + i\left(\Delta_c - \frac{\chi}{\hbar}\langle q\rangle\right)\right]\langle c\rangle + \varepsilon_d + \varepsilon_p e^{-i\delta t},
\end{aligned} \tag{2}$$

where γ_m is the decay rate of the movable mirror. The steady-state response of Eq. (2) contains many Fourier components, where we are only interested in the linear response of the system for the probe field.

To obtain steady-state solutions to Eq. (2), we assume the equation [49] $\langle s\rangle = s_0 + s_+\varepsilon_p e^{-i\delta t} + s_-\varepsilon_p^* e^{i\delta t}$ with $s = q,p,c$, and these three terms $s_{0,\pm}$ are associated with the frequencies $\omega_d, \omega_p, 2\omega_d - \omega_p$, respectively. Inserting the three equations into Eq. (2), we obtain

$$\begin{aligned}
q_0 &= \frac{\chi|c_0|^2 + f}{m\omega_m^2}, \quad c_0 = \frac{\varepsilon_d}{\kappa + i\Delta},\\
c_+ &= \frac{(\delta^2 - \omega_m^2 + i\gamma_m\delta)[\kappa - i(\Delta+\delta)] - 2i\omega_m\beta}{(\delta^2 - \omega_m^2 + i\gamma_m\delta)[\Delta^2 + (\kappa - i\delta)^2] + 4\Delta\omega_m\beta},
\end{aligned} \tag{3}$$

where $\beta = \chi^2|c_0|^2/(2m\hbar\omega_m)$, and $\Delta = \Delta_c - \chi q_0/\hbar$ is the effective cavity-pump detuning, depending on the steady-state position q_0 of the mirror. Assuming that the above solutions are based on the mean value much larger than the noise, we consider that the effects resulting from those solutions could be observed at room temperature, similar to the one in Ref. [48].

With the steady-state solution in Eq. (3), the steady-state equation for the position q_0 can be rewritten as

$$\begin{aligned}
&m\omega_m^2\frac{\chi^2}{\hbar^2}q_0^3 - \left(f\frac{\chi^2}{\hbar^2} + 2m\omega_m^2\frac{\chi}{\hbar}\Delta_c\right)q_0^2 + \Big[m\omega_m^2(\kappa^2 + \Delta_c^2)\\
&\quad + 2f\frac{\chi}{\hbar}\Delta_c\Big]q_0 - \left[f(\kappa^2 + \Delta_c^2) + \chi\varepsilon_d^2\right] = 0,
\end{aligned} \tag{4}$$

which means that the steady state for the position q_0 depends on two tunable parameters: the pump power ε_d and the external force f (see Fig. 2). In other words, the effective cavity frequency (cavity-pump detuning) $\omega_c' = \omega_c - \chi q_0/\hbar$ $(\Delta = \Delta_c - \chi q_0/\hbar)$ can be adjusted by controlling the pump power and the external force. It reminds us of the possibility to realize some force-induced and/or dependent physics.

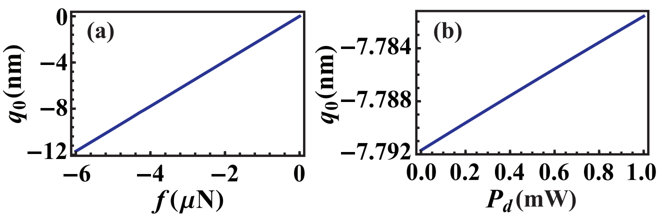

FIG. 2. (a) The steady state for the position q_0 vs the external force f in the case of the pump field power $P_d = 0.2$ mW. (b) The steady state for the position q_0 as a function of the pump field power in the case of the external force $f = -4 \times 10^{-6}$ N. Other parameters used are $\omega_d = 2\pi c/\lambda$ with $\lambda = 1064$ nm, $\Delta_c = -10\omega_m$, $\kappa = 2\pi \times 215$ kHz, $m = 145$ ng, $\omega_m = 2\pi \times 947$ kHz, and $\gamma_m = 2\pi \times 141$ Hz.

III. OUTPUT LIGHT AND TIME DELAY

With the application of the input-output relation [50] $\varepsilon_{\text{out}} = \varepsilon_{in} - 2\kappa\langle c\rangle$, we have the output field

$$\varepsilon_{\text{out}} = (\varepsilon_d - 2\kappa c_0) + (1 - 2\kappa c_+)\varepsilon_p e^{-i\delta t} - 2\kappa c_- \varepsilon_p^* e^{i\delta t}. \quad (5)$$

For simplicity, we assume the quadrature of the output field as

$$\varepsilon_T = 2\kappa c_+ = \frac{2\kappa}{[\kappa - i(\delta - \Delta)] + \frac{2i\omega_m\beta}{\left(\delta^2 - \omega_m^2 + i\gamma_m\delta\right) - \frac{2i\omega_m\beta}{\kappa - i(\delta + \Delta)}}}, \quad (6)$$

whose real and imaginary parts are associated with the absorption and dispersion, respectively [8]. Moreover, the output field varies with both the pump strength ε_d and the external force f, implying that the external force, in addition to the pump field, can construct the light transparency [see Eq. (4) and Fig. 2].

To follow the force-induced transparency of the probe light, we suppose the system working in the resolved-sideband regime due to $\omega_m \gg \kappa$. This is the condition for the normal mode splitting in optomechanics, and the strongest radiation coupling can be achieved when the system reaches the first-order red (blue) sideband with $\delta = \omega_m(\delta = -\omega_m)$ and $\delta = \Delta(\delta = -\Delta)$.

In the case of $\Delta \simeq \omega_m$ (i.e., the RWA case), the optomechanics works in the first-order red sideband. With the application of $\delta^2 - \omega_m^2 \simeq 2\omega_m(\delta - \omega_m)$, we neglect the small term $2i\omega_m\beta/[\kappa - i(\delta + \Delta)]$. Thus Eq. (6) is rewritten as

$$\varepsilon_T \simeq \frac{2\kappa}{[\kappa - i(\delta - \Delta)] + \frac{2i\omega_m\beta}{\delta^2 - \omega_m^2 + i\gamma_m\delta}} \simeq \frac{2\kappa}{[\kappa - i(\delta - \Delta)] + \frac{\beta}{\frac{\gamma_m}{2} - i(\delta - \omega_m)}}, \quad (7)$$

which is the expression for the slow light [see Figs. 3(a) and 3(b)].

Similarly, in the case of $\Delta \simeq -\omega_m$ (i.e., the case of the anti-RWA), the system is governed by the first-order blue sideband, and we have $\delta^2 - \omega_m^2 \simeq -2\omega_m(\delta + \omega_m)$,

$$\varepsilon_T \simeq \frac{2\kappa}{[\kappa - i(\delta - \Delta)] - \frac{\beta}{\frac{\gamma_m}{2} - i(\delta + \omega_m)}}, \quad (8)$$

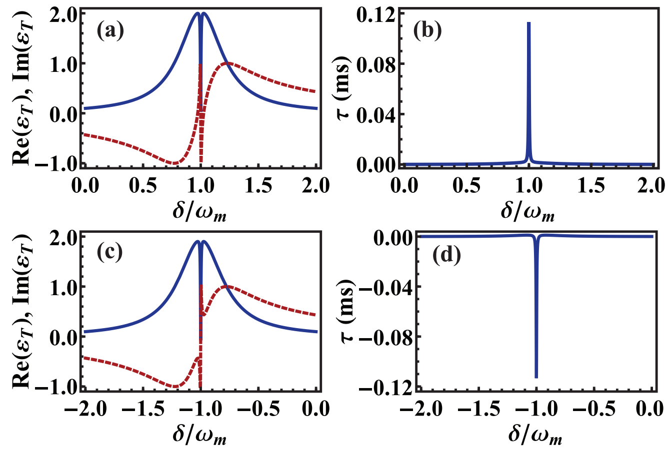

FIG. 3. (a) The real (solid line) and imaginary (dashed line) parts of ε_T as functions of δ/ω_m with $f_1 = -4.74 \times 10^{-6}$ N. (b) The corresponding group velocity delay τ vs the normalized frequency δ/ω_m for $f_1 = -4.74 \times 10^{-6}$ N. (c) The real (solid line) and imaginary (dashed line) parts of ε_T as functions of δ/ω_m for $f_2 = -3.88 \times 10^{-6}$ N. (d) The corresponding group delay τ vs the normalized frequency δ/ω_m for $f_2 = -3.88 \times 10^{-6}$ N. Other parameters are the same as in Fig. 2.

which is the solution for the fast light [see Figs. 3(c) and 3(d)]. In this situation, a very small gain can be achieved in the absorption of the output field (Re[ε_T]). This gain of the probe light originates from the anti-RWA process with both a photon and a phonon simultaneously created or annihilated. Due to the large cavity decay, however, the photon-phonon creation dominates the system evolution, which is supported by the external field. As such, we have the gain in the absorption of the output field.

The slow and fast light conversion in our scheme is very different from the previously proposed transparencies using atoms [34,35], coupled cavities [36], and atom-cavity hybrids [37]. Compared with Eq. (7), Eq. (8) has a sign difference in the denominator, which can be understood as a switch between the effects of the RWA and the anti-RWA. Since the two solutions of ε_T under the RWA and the anti-RWA take two fast changes in absorption or dispersion (Re[ε_T]/Im[ε_T]) with the slopes in different signs, the conversion between the slow and fast lights can be achieved by controlling the parameters to reach the RWA and anti-RWA regimes. This viewpoint is different in Refs. [32,33], where the fast and slow lights are explained as a characteristic in the anti-Stokes and Stokes processes. Actually, the anti-Stokes and Stokes processes [32,33] own the fast and slow lights due to the third-order nonlinear coupling as the radiation coupling. In contrast, by the fact that Eq. (6) is reduced to Eq. (7) under the RWA and to Eq. (8) under the anti-RWA, we consider that the slow and fast effects originate fundamentally from the RWA and the anti-RWA employed for the parameters. This is a more fundamental reason than the anti-Stokes and Stokes effects for the slow and fast lights in general systems. For example, the slow light effect observed in the previous publications [34–37] is due to the involvement of only the RWA.

The transmission of the probe field, defined by the ratio of the output and input field amplitudes at the frequency of the probe light [11,28], is given by

$$\varepsilon = 1 - 2\kappa c_+. \tag{9}$$

In the regime of the narrow transparency window, there is a rapid variation of the probe phase $\Phi(\omega_p) = \arg[\varepsilon] = \frac{1}{2i}\ln(\frac{\varepsilon}{\varepsilon^*})$. This variation is associated with the group velocity delay as [31,51]

$$\tau = \frac{\partial \Phi}{\partial \omega_p}\bigg|_{\bar{\omega}} = \mathrm{Im}\left[\frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial \omega_p}\right]\bigg|_{\bar{\omega}} = \mathrm{Im}\left[\frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial \delta}\right]\bigg|_{\delta=\pm\omega_m}, \tag{10}$$

where $\bar{\omega} = \omega_d \pm \omega_m$, and $\delta = \pm\omega_m$ is the condition for the two-photon resonance. $\tau > 0$ and $\tau < 0$ correspond to the slow and fast light propagations, respectively.

IV. SIMULATIONS AND DISCUSSION

To demonstrate the force-induced light transparency and the force-dependent conversion between the slow and fast lights, we have made some simulations using the following experimental parameters [52]: $\lambda = 1064$ nm, $P_d = 0.2$ mW, $L = 25$ mm, $\kappa/2\pi = 215$ kHz, $m = 145$ ng, $\omega_m/2\pi = 947$ kHz, and $\gamma_m/2\pi = 141$ Hz. In what follows, to justify the feasibility of our scheme, we assume a fixed pump light which is far detuned from the cavity as $\Delta_c = -10\omega_m$.

A. Force-induced light transparency

In the absence of the external force, the effective detuning between the optomechanical cavity and the pump field is $\Delta \approx -10\omega_m$, which is far detuned from the resonator frequency ω_m. In this case, even if the pump power is set to some feasible values, no OMIT can be observed due to the large detuning of the pump light from the cavity field and the limitation of the work regime for the optical manipulation. However, if an external force $f = f_1$ is applied on the optomechanics, as shown in Fig. 3, the OMIT appears since the condition of $\Delta = \omega_m$ can be satisfied. This is due to the fact that the external force pushes the system into the red-sideband regime under the RWA by increasing the effective cavity frequency. As shown in Fig. 4, with the increase of the force, the central frequency for transparency remains unchanged, whereas the main peak of the output field moves from the low frequency to the higher due to the increase of the effective cavity frequency.

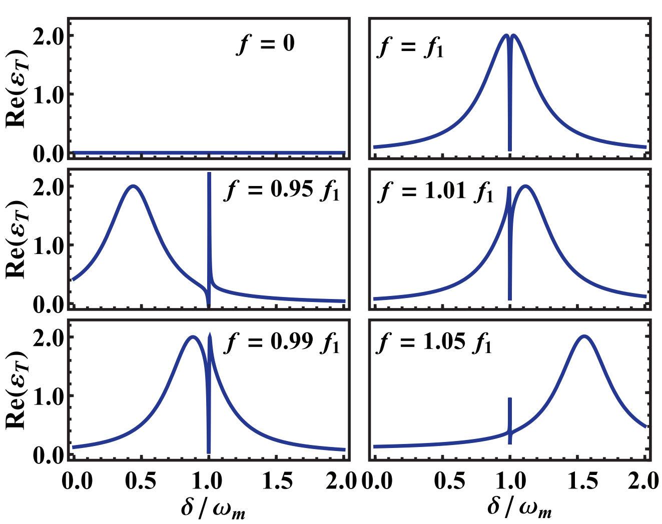

FIG. 4. The real parts of ε_T as functions of the force f under the condition of the RWA, where we consider six typical values of f/f_1 from zero to values larger than 1.0. Other parameters are the same as in Fig. 3.

In contrast, with an alternative external force $f = f_2$ applied, the system moves into the blue-sideband regime under the anti-RWA. The fast light due to force-induced transparency is thus produced.

B. Force-dependent slow and fast light conversion

As discussed above, when the external force $f = f_1$ is applied, there is a force-induced transparency for the slow light [see Fig. 3(b)]. In contrast, when the external force is $f = f_2$, the system works in the blue-sideband regime with an effective detuning $\Delta = -\omega_m$, and the fast light effect is available in this situation [see Fig. 3(d)]. In this context, it is natural to ask if there is a possibility to have a conversion between the slow light and the fast one.

The answer to this possibility is positive, as shown below. The physics for the control of the slow and fast lights can be understood from Eq. (6). There are fast changes in absorption and dispersion in very narrow spectral ranges [see Figs. 3(a) and 3(c)], which are followed by large changes in the refractive index due to Eq. (6) satisfying the Kramers-Kronig relations [53]. As a result, if $f = f_1$, the system works in the red-sideband regime with a positive change in the refractive index,

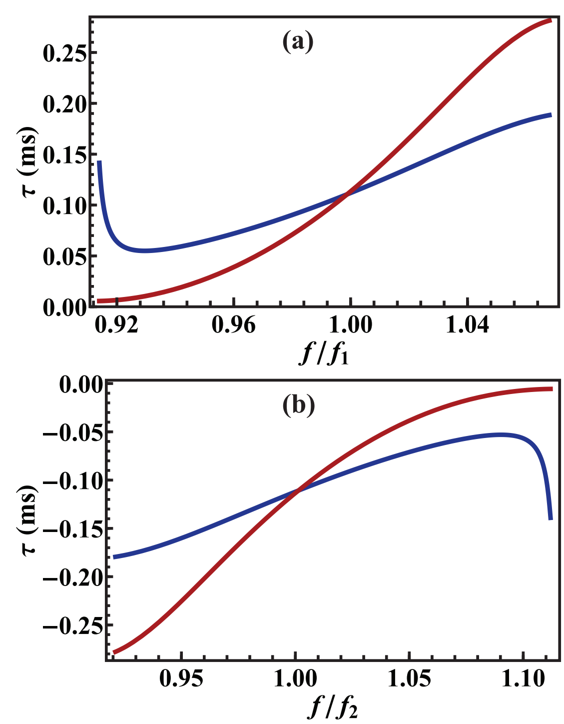

FIG. 5. (a) The group velocity delay as a function of f/f_1 with $f_1 = -4.74 \times 10^{-6}$ N and $\delta = \omega_m$. The blue (red) line is for an analytical (approximate) result by Eq. (6) [Eq. (7)]. (b) The group velocity delay as a function of f/f_2 with $f_2 = -3.88 \times 10^{-6}$ N and $\delta = -\omega_m$. The blue (red) line is for an analytical (approximate) result by Eq. (6) [Eq. (8)]. Other parameters are the same as in Fig. 3.

yielding a low group velocity [see Fig. 3(b)]. In contrast, the system turns to be in the blue-sideband regime once $f = f_2$ is applied, which creates a high group velocity [see Fig. 3(d)] due to a negative change in the refractive index.

Since the probe transmission ε depends on both the pump power and the external force in our approach, the group velocity delay τ can be tuned by both the power of the pump light and the external force, which are different from previous ideas with τ modified only by the pump power [29–32]. To show this, we plot τ as a function of the force around the detuning of $\delta = \pm\omega_m$ in Fig. 5. It implies that the external force f can be used to control the group velocity of the probe light even with a fixed pump field, and also means the possibility to measure the external force using this property. In particular, the delay τ approximately linearly varies with f at the point near $f = f_1$ ($f = f_2$) for which the slope is $d\tau/df \approx 244(242)$ s/N at $\Delta \approx \omega_m$ ($\Delta \approx -\omega_m$). Within the regime with one-to-one correspondence between the group velocity and the external force, we may perform precise control or measurement for the group velocity using a certain external force.

Moreover, in Fig. 5, with the increase of the external force f for the slow (fast) light, the approximate and analytic results intersect at the point of $f = f_1$ ($f = f_2$) where the system meets exactly the condition for the red(blue)-sideband regime. In contrast to the previous works [27–33] with the time delay expressed by reduced analytic solutions, we fully consider the contribution from the effects of both the RWA and the anti-RWA in the measurement of the group velocity using a certain external force. In this context, our work provides a further understanding of the slow and fast lights in comparison with the previous treatments [27–33].

V. CONCLUSION

In summary, we have studied and explained the slow and fast light effects in a single-sided optomechanical cavity under an external force. The two special characters of the optomechanical cavity, i.e., the force-induced light transparency and conversion related to the slow and fast lights, can be fully controlled by the effective cavity frequency modified by the external force. In particular, we pointed out that the effect of the RWA and the anti-RWA on the parameters is the fundamental reason to generate the slow and fast lights. Since our proposal is feasible using current laboratory techniques, we believe that our scheme provides a way to produce tunable fast and slow lights, which helps inspire more potential applications for optomechanics.

ACKNOWLEDGMENTS

J.Q.Z. thanks Yong Li for a helpful discussion. This work is supported by the National Key R&D Program of China No. 2017YFA0304500, by the National Fundamental Research Program of China under Grant No. 2013CB921803, by the National Natural Science Foundation of China under Grants No. 91636220, No. 91421111, No. 11674360, and No. 11375136, and by the research fund of City College, Wuhan University of Science and Technology under Grant No. 2014CYBSKY001.

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