Optomechanically induced transparency and possible application in a quadratic-coupling optomechanical system with an induced electric field

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Optomechanically induced transparency and possible application in a quadratic-coupling optomechanical system with an induced electric field

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Tunable optomechanically induced transparency (OMIT) with an induced electric field (IEF) in a quadratic-coupling optomechanical system is theoretically investigated. The system transmission rate under different controlling parameters has been discussed. It is revealed that both phase and group delay of the probe field can be adjusted by the IEF and pump field. Such a system may be used in tunable optical buffer, IEF detector, modulator or other optical devices.

Keywords: optomechanical system; optomechanically induced transparency; induced electric field

1. Introduction

Recently, many researches have been carried out on the optomechanical system, which explores the quantum-mechanical interaction via the radiation pressure. So far, many promising applications of the optomechanical system have been reported, such as ground state cooling [1-6], photon blockade [7-11], optical switching and buffer [12-16], detector [17-22], and so on. One recent research is spin detection which improves the force sensitivity by almost 2 orders of magnitude than with tensioned resonators [21]. Another recent research is mass detection up to femtogram level resolution by nonlinear sum-sideband in a dispersive optomechanical system [22].

On the other hand, many interesting phenomena have been studied thoroughly, such as quantum entanglement [6, 23-25], high-order sidebands [26-31], optical bistability and multibility [16, 32-38], OMIT [14, 39-61], and so on. One interesting review of OMIT is by Xiong et al. [48] which has examined the fundamentals and utilities of OMIT. Many different physical mechanisms of OMIT allow it potential application in future quantum networks such as filter, optical buffering, amplification, and so on. Especially, for quadratic coupling between the optomechanical cavity and mechanical resonator [10,50-54], OMIT has also been explored involving two-photon process. Zhang et al. [54] presented double OMIT in a compound optomechanical system due to the linear and quadratic coupling between the cavity and the membrane. Khan et al. [58] recently reported controllable OMIT in a two-cavity optomechanical system due to the interference between the two possible routes for excitations. Liao et al. [59] investigated OMIT in a hybrid optomechanical system with Kerr medium which could be tuned from slow light to fast light. In addition, Huang et al. [63] studied the Fano resonance in a quadratic coupling optomechanical system with a
nonlinear Kerr medium.

In comparison with previous work, coulomb-interaction effect [28] and magnetic-field sensing [62] in an optomechanical system are demonstrated. To the best of our knowledge, few research has been carried out on the IEF interacting with the optomechanical system. In this paper, we investigate OMIT with IEF which originates from an energized solenoid in a quadratic-coupling optomechanical system. We also discuss its transmission rate and possible applications such as optical buffer, IEF detector, and so on.

2 Model and theory

![Schematic representation of the optomechanical system. A strong pump field with frequency $\omega_i$ (amplitude $\varepsilon_i$) and a weak probe field with frequency $\omega_p$ (amplitude $\varepsilon_p$) drive the optomechanical system. The electrode with charge $Q$ on nanomechanical resonator (NR) can be charged by the bias gate voltage (not shown). An IEF (strength $E_k$), which originates from variable magnetic field (amplitude $B$) in an energized solenoid (radius $R$ and distance $D$), is imposed on the charge.](image)

An optomechanical system shown in Fig.1 is considered in our paper. For the IEF, based on the Maxwell equation $\nabla \times \nabla \times E = -\mu \frac{d}{dt} B$, we can get IEF strength $E_k = \frac{R^2 dB}{2D}$. In our system, assuming the membrane position is located exactly at an antinode of the intracavity field, we can ignore the linear coupling between the cavity field and the membrane displacement. And we just need consider the probe field optical response to the quadratic interaction by the radiation pressure in the optomechanical system[53,63]. In the rotating frame at the frequency of the pump frequency $\omega_i$, the system Hamiltonian can be written as [28,53,63],

$$H = \hbar \Delta \epsilon_c c^+c + \left( \frac{\hbar^2}{2m} + \frac{1}{2} m \omega^2 q^2 \right) + QE_c q + \hbar g c^+c q^2 \quad + i\hbar \epsilon_{i,c} (c^+ - c) + i\hbar \epsilon_{p,c} (c^+ e^{-i\delta t} - c e^{i\delta t})$$

(1)

where, the first term denotes the free Hamiltonian of the optical cavity with $c$ ($c^+$) being the
annihilation (creation) operator and $\omega_\ell$ being the frequency of the cavity field. $\Delta_c = \omega_c - \omega_\ell$ ($\delta = \omega_p - \omega_\ell$) is the detuning between the optical cavity (probe laser) and the pump laser. The second term denotes the free Hamiltonian of the mechanical resonator with $\omega_m$, $p$ and $q$ being the resonator frequency, momentum and position operator respectively. The third term denotes the coupling between the IEF and NR[28]. The fourth term denotes the coupling between optical cavity and the mechanical resonator with quadratic coupling strength $g$. The fifth (last) term denotes the interaction between the optical cavity and the pump (probe) laser.

Considering the decay terms, one can obtain the Heisenberg-Langevin equations of the operators as follows,

$$\frac{d}{dt} q = \frac{p}{m}, \quad \tag{2a}$$
$$\frac{d}{dt} p = -\gamma p - (m\omega_m^2 + 2hg c^c c)q - QE_k, \quad \tag{2b}$$
$$\frac{d}{dt} c = -[k + i(\Delta_c + gq^2)]c + \epsilon_i + \epsilon_p e^{-i\delta t}, \quad \tag{2c}$$

where the decay rate for the mechanical resonator ($\gamma$) and the cavity ($\kappa$) are introduced phenomenologically.

To study OMIT, the steady-state solutions of the expectation values $\langle q \rangle, \langle p \rangle, \langle c \rangle, \langle q^2 \rangle, \langle p^2 \rangle$ and $\langle pq + qp \rangle$ should be calculated. Assuming $\langle AB \rangle = \langle A \rangle \langle B \rangle$, we can obtain the following mean value equations from Eqs. 2 [10, 50, 51],

$$\frac{d}{dt} \langle q \rangle = \frac{\langle p \rangle}{m}, \quad \tag{3a}$$
$$\frac{d}{dt} \langle p \rangle = -\gamma \langle p \rangle - (m\omega_m^2 + 2hg \langle c^c \rangle \langle c \rangle) \langle q \rangle - QE_k, \quad \tag{3b}$$
$$\frac{d}{dt} \langle c \rangle = -[k + i(\Delta_c + g \langle q^2 \rangle)] \langle c \rangle + \epsilon_i + \epsilon_p e^{-i\delta t}, \quad \tag{3c}$$
$$\frac{d}{dt} \langle q^2 \rangle = \frac{1}{m} \langle pq + qp \rangle, \quad \tag{3d}$$
$$\frac{d}{dt} \langle p^2 \rangle = -2\gamma \langle p^2 \rangle - (m\omega_m^2 + 2hg \langle c^c \rangle \langle c \rangle) \langle pq + qp \rangle - 2QE_k \langle p \rangle + \gamma(2n+1)h\omega_m, \quad \tag{3e}$$
$$\frac{d}{dt} \langle pq + qp \rangle = -\gamma \langle pq + qp \rangle + \frac{2}{m} \langle p^2 \rangle - 2(m\omega_m^2 + 2hg \langle c^c \rangle \langle c \rangle) \langle q^2 \rangle - 2QE_k \langle q \rangle. \quad \tag{3f}$$

where, $\gamma(2n+1)h\omega_m$ describes the coupling between the NR with thermal reservoir, and $\frac{n}{n} = 1/(e^{\hbar\omega_m/k_BT} - 1)$ is the mean photon occupation number of the energy $h\omega_m$[10,50,51] with $T$ being the temperature and $k_B$ being the Boltzmann constant. To be simple, $X = q^2, Y = p^2$ and $Z = pq + qp$ are defined in the following.
Then, based on the perturbation method and using the ansatz:

\[ \langle O \rangle = O_q + O_p e^{-i\delta t} + O_e e^{i\delta t}, \]

where \( O \in \{q, p, c, X, Y, Z\} \). Substituting the ansatz into Eqs.(3) and omitting the high-order small terms, we can get the steady-state solutions firstly.

\[
q_s = -\frac{Q E_k}{m\omega_m^2 + 2hgc_s^2}, p_s = 0, c_s = \frac{\varepsilon_t}{k + i\Delta},
\]

\[
X_s = \frac{Y_s - mQ E_k q_s}{mM}, Y_s = (2n + 1) \frac{m\hbar \omega}{2}, Z_s = 0.
\]

And Eqs.(3) can be transformed into the following.

\[
q_s (-m\delta^2 - i\delta + M) = -2hgc_s [c_s^* + c_s^*] q_s, \quad (5a)
\]

\[
q_s (-m\delta^2 + i\delta + M) = -2hgc_s [c_s^* + c_s^*] q_s, \quad (5b)
\]

\[
-i\delta c_s = -igX_s c_s - [k + i(\Delta_c + gX_s)] c_s + \varepsilon_p, \quad (5c)
\]

\[
i\delta c_s = -igX_s c_s - [k + i(\Delta_c + gX_s)] c_s. \quad (5d)
\]

\[
\begin{align*}
X_s (-m\delta^2 - i\gamma m\delta + 2M) & = \frac{2}{m} Y_s - 4hgc_s [c_s^* + c_s^*] X_s - 2Q E_k q_s, \quad (5e) \\
X_s (-m\delta^2 + i\gamma m\delta + 2M) & = \frac{2}{m} Y_s - 4hgc_s [c_s^* + c_s^*] X_s - 2Q E_k q_s, \quad (5f)
\end{align*}
\]

\[
Y_s (-i\delta + 2\gamma) = -2hgc_s [c_s^* + c_s^*] Z_s + i\delta mX_s + i2 \delta Q E_k m q_s, \quad (5g)
\]

\[
Y_s (i\delta + 2\gamma) = -2hgc_s [c_s^* + c_s^*] Z_s - i\delta mX_s - i2 \delta Q E_k m q_s. \quad (5k)
\]

By solving Eqs (5), we can get the expression for \( c_s \),

\[
c_s = \frac{\varepsilon_p}{k + i(\Delta + g) - \delta}
\]

\[
K_s = \frac{igc_s}{c_s} - \frac{c_s}{K_s} - \frac{i\gamma c_s}{k - i(\Delta + \delta)}
\]

where, \( K_1 = \frac{2hgc_s}{m\delta^2 + i\delta - M} \), \( K_2 = \frac{(m\delta^2 + i\gamma m\delta - 2M)(2\gamma - i\delta) + i2\delta M}{(4hgc_s + 2Q E_k K_1)(2\gamma - i\delta) - i4\delta Q E_k K_1} \).

\[
M = m\omega_m^2 + 2hgc_s^*, \Delta = \Delta_c + gX_s.
\]

The transmission rate of the probe light can be defined as

\[
T = \left| t_p (\delta) \right| = \left| 1 - \frac{\kappa c_s}{\varepsilon_p} \right|^2.
\]

In addition, we can also calculate the system group delay by [54].
$$\tau_g = \frac{d}{d\delta} \arg [t_p(\delta)].$$  \hspace{1cm} (8)

where $\arg [t_p(\delta)]$ is the phase of the transmitted field.

3 Results and discussions

In the following, we will investigate the OMIT of our system. The system parameters are chose experimentally as follows: $Q = 10^{-10} \, C$, $\omega_m = 2\pi \times 10^8 \, Hz$, $m = 10^{-12} \, kg$, $\gamma = 20Hz$, $\kappa = 2\pi \times 10^4 \, Hz$ [50-53]. The wavelength of the coupling field is $\lambda_c = 2\pi c / \omega_c = 532nm$ and the temperature is $T = 90K$ [50-53]. $\Delta = 2\omega_m$ is selected under the resonant condition.

![Fig. 2. Transmission rate as a function of $\delta / \omega_m$ for different induced electric field strength $E_k$.](image-url)

The other parameters are, $g = 2\pi \times 1.8 \times 10^{21} \, Hz / m^2$, $e_j = 5 \times 10^9 \, Hz$.

First, Fig. 2 shows the transmission rate as a function of $\delta / \omega_m$ for different IEF strength $E_k$. We can see that there is a transparency window i.e. OMIT, near the resonance condition $\Delta = 2\omega_m$. And the transparency window in the probe transmission spectrum becomes more and more obvious with the increasing of $E_k$. What is more, the position of the transparency window does not change with the increasing of $E_k$. 

Fig. 3. Transmission rate as a function of $\frac{\delta}{\omega_m}$ for different quadratic coupling strength $g$. The other parameters are, $E_k = 1N / C$, $\epsilon_l = 5 \times 10^9$ Hz.

Second, Fig. 3 shows the transmission rate as a function of $\frac{\delta}{\omega_m}$ for different quadratic coupling strength $g$. Similarly, a transparency window appears near $\frac{\delta}{\omega_m} = 2$ and it is widening with the increasing coupling strength $g$. It seems the maximum transmission rate in the OMIT window remains unchanged for same $E_k$, and the position of the transparency window shows blue-shifted with the increasing of the quadratic coupling strength $g$.

Fig. 4. Transmission rate as a function of $\frac{\delta}{\omega_m}$ for different pump field amplitude $\epsilon_l$. The other parameters are, $E_k = 1N / C$, $g = 2\pi \times 10^{23}$ Hz/m$^2$.

Finally, Fig. 4 shows the transmission rate as a function of $\frac{\delta}{\omega_m}$ for different pump field amplitude $\epsilon_l$. A transparency window can be found near $\frac{\delta}{\omega_m} = 2$. The position of the
transparency window shows blue-shifted and becomes more and more obvious with the increasing of the pump field amplitude $\varepsilon_l$.

4. Possible Application

OMIT, known as the destructive interference between the probe field and the anti-Stokes scattering field, can be applied in many ways such as photon blockade, ground state cooling of the mechanical resonator and so on. In the following, we will discuss possible application in the slow light, IEF detector and light modulator for our system.

\[
\begin{align*}
\text{Fig. 5. (a) Phase of the probe field } & \text{ } \arg[t_p(\delta)], \text{ and (b) group delay as a function of } \delta / \omega_m \text{ for different IEF strength } E_k. \text{ The other parameters are, } \\
& \varepsilon_l = 5 \times 10^9 \text{ Hz, } \quad g = 2\pi \times 1.8 \times 10^{23} \text{ Hz/m}^2.
\end{align*}
\]

Fig. 5 illustrates the probe field phase $\arg[t_p(\delta)]$ and the group delay vs. $\delta / \omega_m$ for different IEF strength $E_k$. In the transparency window, we find that, with the increasing of $E_k$, the phase line becomes flatter in Fig. 5(a) and the group delay becomes smaller in Fig. 5(b), which implies the light velocity becomes faster and is consistent with Fig. 2.

Fig. 6 illustrates the group delay vs. the IEF strength $E_k$. Obviously, the group delay goes down with the increasing of $E_k$. Such a trend also can be found in Fig. 5(b). So, we can adjust the system group delay by changing the IEF strength and the coupling field. Such a result may be used to design tunable optical buffer.

To design an IEF detector and optical modulator, Fig. 7 illustrates the transmission rate as a function of the IEF strength $E_k$. Clearly, the relation between the transmission rate and the IEF strength $E_k$ is nonlinear. With the increasing of the IEF strength, the transmission rate goes up. Such a feature may be used to detect whether there is an IEF or not. Certainly, it must be isolated from other forces, such as the electrostatic field force.
Fig. 6. Group delay as a function of IEF strength $E_k$. The other parameters are, $\delta / \omega_m = 2.0095$. 

$$\varepsilon_i = 5 \times 10^9 \text{Hz}, g = 2\pi \times 1.8 \times 10^{23} \text{Hz} / m^2.$$ 

However, in Fig. 7, we can also find it is approximately linear for $0.1 < E_k < 0.39 N / C$ (correspondingly $0.32 < T < 0.8$). So, we can get a linear modulator in this scope, and such a system may be attached an electrostatic field firstly to set up an operating point. And the field strength may be $0.24 N / C$ (correspondingly $T=0.56$) seeing Fig. 7. In Fig. 7, when we input a sine IEF field, the output is a sine light intensity. So it may be an optical modulator. What is more, the sine IEF field can be produced by applying a cosine current in the energized solenoid. So, it may be a differentiator for the input cosine current.

Fig. 7. Transmission rate as a function the IEF strength $E_k$. $\delta / \omega_m = 2.009$. The input is a sine IEF signal. The output is a sine light intensity signal. The other parameters are, $g = 2\pi \times 1.8 \times 10^{23} \text{Hz} / m^2, \varepsilon_i = 5 \times 10^9 \text{Hz}$.

5. Conclusion

In summary, we have theoretically investigated the transmission rate, group delay and
possible application in an quadratic-coupling optomechanical system with an IEF. Solving the nonlinear Heisenberg-Langevin equations approximately, the expression of the probe field and group delay can be obtained. The system transmission rate under different controlling parameters, such as the IEF strength $E_k$, the pump field $E_l$, the quadratic coupling strength $g$, has been studied. The phase and group delay can be adjusted by the IEF and the coupling field. Such a system may be used as an optical buffer, IEF detector and optical modulator.

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References
[1] Schliesser A, Del'Haye P, Nooshi N, et al. Radiation pressure cooling of a micromechanical oscillator using dynamical backaction [J]. Physical Review Letters, 2006, 97(24): 243905.
[2] Gigan S, Böhm H R, Paternostro M, et al. Self-cooling of a micromirror by radiation pressure[J]. Nature, 2006, 444(7115): 67.
[3] Teufel J D, Donner T, Li D, et al. Sideband cooling of micromechanical motion to the quantum ground state[J]. Nature, 2011, 475(7356): 359.
[4] O’Connell A D, Hofheinz M, Ansmann M, et al. Quantum ground state and single-phonon control of a mechanical resonator[J]. Nature, 2010, 464(7289): 697.
[5] Guo Y, Li K, Nie W, et al. Electromagnetically-induced-transparency-like ground-state cooling in a double-cavity optomechanical system[J]. Physical Review A, 2014, 90(5): 053841.
[6] Li G, Nie W, Li X, et al. Dynamics of ground-state cooling and quantum entanglement in a modulated optomechanical system[J]. Physical Review A, 2019, 100(6): 063805.
[7] Rabl P. Photon blockade effect in optomechanical systems [J]. Physical review letters, 2011, 107(6): 063601.
[8] Nunnenkamp A, Børkje K, Girvin S M. Single-photon optomechanics [J]. Physical review letters, 2011, 107(6): 063602.
[9] Wang H, Gu X, Liu Y, et al. Tunable photon blockade in a hybrid system consisting of an optomechanical device coupled to a two-level system [J]. Physical Review A, 2015, 92(3): 033806.
[10] Shi H Q, Zhou X T, Xu X W, et al. Tunable phonon blockade in quadratically coupled optomechanical systems [J]. Scientific reports, 2018, 8(1): 2212.
[11] Huang R, Miranowicz A, Liao J Q, et al. Nonreciprocal photon blockade [J]. Physical review letters, 2018, 121(15): 153601.
[12] Chen B, Jiang C, Zhu K D. Tunable all-optical Kerr switch based on a cavity optomechanical system with a Bose–Einstein condensate [J]. JOSA B, 2011, 28(8): 2007-2013.
[13] Zou X, Hocke F, Schliesser A, et al. Slowing, advancing and switching of microwave signals using circuit nanoelectromechanics[J]. Nature Physics, 2013, 9(3): 179-184.
[14] Yan X B, Yu K H, Fu C B, et al. Optical switching of optomechanically induced transparency and normal mode splitting in a double-cavity system [J]. The European Physical Journal D, 2014, 68(5): 126.
[15] Liu L, Yue J, Li Z. All-optical switch based on a fiber-chip-fiber opto-mechanical system with
ultrahigh extinction ratio [J]. IEEE Photonics Journal, 2017, 9(3): 1-8.

[16]Bhattacherjee A B, Hasan M S. Controllable optical bistability and Fano line shape in a hybrid optomechanical system assisted by kerr medium: possibility of all optical switching [J]. Journal of Modern Optics, 2018, 65(14): 1688-1697.

[17]Forstner S, Prams S, Knittel J, et al. Cavity optomechanical magnetometer[J]. Physical review letters, 2012, 108(12): 120801.

[18]Mirza I M, van Enk S J. Single-photon time-dependent spectra in quantum optomechanics [J]. Physical Review A, 2014, 90(4): 043831.

[19]Reinhardt C, Müller T, Bourassa A, et al. Ultralow-noise SiN trampoline resonators for sensing and optomechanics[J]. Physical Review X, 2016, 6(2): 021001.

[20]Kaviani H, Ghobadi R, Behera B, et al. Optomechanical Detection of Light with Orbital Angular Momentum[J]. arXiv preprint arXiv:1912.08413, 2019.

[21]Fischer R, McNally D P, Reetz C, et al. Spin detection with a micromechanical trampoline: Towards magnetic resonance microscopy harnessing cavity optomechanics[J]. New Journal of Physics, 2019, 21(4): 043049.

[22]Liu S, Liu B, Yang W X. Highly sensitive mass detection based on nonlinear sum-sideband in a dispersive optomechanical system[J]. Optics express, 2019, 27(4): 3909-3919.

[23]Farace A, Giovannetti V. Enhancing quantum effects via periodic modulations in optomechanical systems [J]. Physical Review A, 2012, 86(1): 013820.

[24]Wang G, Huang L, Lai Y C, et al. Nonlinear dynamics and quantum entanglement in optomechanical systems[J]. Physical review letters, 2014, 112(11): 110406.

[25]Riedinger R, Wallucks A, Marinković I, et al. Remote quantum entanglement between two micromechanical oscillators [J]. Nature, 2018, 556(7702): 473.

[26]Xiong H, Si L G, Zheng A S, et al. Higher-order sidebands in optomechanically induced transparency[J]. Physical Review A, 2012, 86(1): 013815.

[27]Yang W X, Chen A X, Xie X T, et al. Enhanced generation of higher-order sidebands in a single-quantum-dot–cavity system coupled to a PT-symmetric double cavity[J]. Physical Review A, 2017, 96(1): 013802.

[28]Kong C, Xiong H, Wu Y. Coulomb-interaction-dependent effect of high-order sideband generation in an optomechanical system[J]. Physical Review A, 2017, 95(3): 033820.

[29]Si L G, Guo L X, Xiong H, et al. Tunable high-order-sideband generation and carrier-envelope-phase–dependent effects via microwave fields in hybrid electro-optomechanical systems [J]. Physical Review A, 2018, 97(2): 023805.

[30]Liu Z X, Xiong H, Wu Y. Generation and amplification of a high-order sideband induced by two-level atoms in a hybrid optomechanical system[J]. Physical Review A, 2018, 97(1): 013801.

[31]He L Y. Parity-time-symmetry–enhanced sideband generation in an optomechanical system [J]. Physical Review A, 2019, 99(3): 033843.

[32]Jiang C, Liu H, Cui Y, et al. Controllable optical bistability based on photons and phonons in a two-mode optomechanical system[J]. Physical Review A, 2013, 88(5): 055801.

[33]Kyrrienko O, Liew T C H, Shelykh I A. Optomechanics with cavity polaritons: dissipative coupling and unconventional bistability[J]. Physical review letters, 2014, 112(7): 076402.

[34]Yasir K A, Liu W M. Tunable bistability in hybrid Bose-Einstein condensate optomechanics[J]. Scientific reports, 2015, 5: 10612.

[35]Jiang C, Bian X, Cui Y, et al. Optical bistability and dynamics in an optomechanical system
with a two-level atom [J]. JOSA B, 2016, 33(10): 2099-2104.

[36] Sarma B, Sarma A K. Controllable optical bistability in a hybrid optomechanical system [J]. JOSA B, 2016, 33(7): 1335-1340.

[37] Bhattacherjee A B, Hasan M S. Controllable optical bistability and Fano line shape in a hybrid optomechanical system assisted by kerr medium: possibility of all optical switching [J]. Journal of Modern Optics, 2018, 65(14): 1688-1697.

[38] Wang Z, Jiang C, He Y, et al. Tunable optical bistability in multi-mode optomechanical systems [J]. JOSA B, 2020, 37(2): 579-585.

[39] Weis S, Rivièrè R, Deléglise S, et al. Optomechanically induced transparency [J]. Science, 2010, 330(6010): 1520-1523.

[40] Safavi-Naeini A H, Alegre T P M, Chan J, et al. Electromagnetically induced transparency and slow light with optomechanics [J]. Nature, 2011, 472(7341): 69.

[41] Kronwald A, Marquardt F. Optomechanically induced transparency in the nonlinear quantum regime [J]. Physical review letters, 2013, 111(13): 133601.

[42] Ma P C, Zhang J Q, Xiao Y, et al. Tunable double optomechanically induced transparency in an optomechanical system [J]. Physical Review A, 2014, 90(4): 043825.

[43] Hou B P, Wei L F, Wang S J. Optomechanically induced transparency and absorption in hybridized optomechanical systems [J]. Physical Review A, 2015, 92(3): 033829.

[44] Jing H, Özdemir Ş K, Geng Z, et al. Optomechanically-induced transparency in parity-time-symmetric microresonators [J]. Scientific reports, 2015, 5: 9663.

[45] Lei F C, Gao M, Du C, et al. Three-pathway electromagnetically induced transparency in coupled-cavity optomechanical system [J]. Optics express, 2015, 23(9): 11508-11517.

[46] Sohail A, Zhang Y, Zhang J, et al. Optomechanically induced transparency in multi-cavity optomechanical system with and without one two-level atom [J]. Scientific reports, 2016, 6: 28830.

[47] Zhang X Y, Zhou Y H, Guo Y Q, et al. Double optomechanically induced transparency and absorption in parity-time-symmetric optomechanical systems [J]. Physical Review A, 2018, 98(3): 033832.

[48] Xiong H, Wu Y. Fundamentals and applications of optomechanically induced transparency [J]. Applied Physics Reviews, 2018, 5(3): 031305.

[49] He Q, Badshah F, Din R U, et al. Optomechanically induced transparency and the long-lived slow light in a nonlinear system [J]. JOSA B, 2018, 35(7): 1649-1657.

[50] He Q, Badshah F, Din R U, et al. Multiple transparency in a multimode quadratic coupling optomechanical system with an ensemble of three-level atoms [J]. JOSA B, 2018, 35(10): 2550-2561.

[51] Sun X J, Wang X, Liu L N, et al. Optical-response properties in hybrid optomechanical systems with quadratic coupling [J]. Journal of Physics B: Atomic, Molecular and Optical Physics, 2018, 51(4): 045504.

[52] Huang S, Agarwal G S. Electromagnetically induced transparency from two-phonon processes in quadratically coupled membranes [J]. Physical Review A, 2011, 83(2): 023823.

[53] Bai C, Hou B P, Lai D G, et al. Tunable optomechanically induced transparency in double quadratically coupled optomechanical cavities within a common reservoir [J]. Physical Review A, 2016, 93(4): 043804.

[54] Zhang X Y, Zhou Y H, Guo Y Q, et al. Optomechanically induced transparency in optomechanics with both linear and quadratic coupling [J]. Physical Review A, 2018, 98(5):
[55] Ullah K. Control of electromagnetically induced transparency and Fano resonances in a hybrid optomechanical system [J]. The European Physical Journal D, 2019, 73(12): 267.

[56] Chen H J, Zhao D M, Wu H W, et al. Controllable and tunable multiple optomechanically induced transparency and Fano resonance mediated by different mechanical resonators[J]. AIP Advances, 2019, 9(7): 075105.

[57] Zhu Y J, Bai C H, Wang T, et al. Optomechanically induced transparency, amplification, and fast–slow light transitions in an optomechanical system with multiple mechanical driving phases[J]. JOSA B, 2020, 37(3): 888-893.

[58] Khan S, Chatha M A. Tunable subluminal and superluminal light with optomechanical-induced transparency under steady-state configuration[J]. Journal of Physics B: Atomic, Molecular and Optical Physics, 2019, 52(13): 135504.

[59] Liao Q, Xiao X, Nie W, et al. Transparency and tunable slow-fast light in a hybrid cavity optomechanical system[J]. Optics Express, 2020, 28(4): 5288-5305.

[60] Yu C, Yang W, Sun L, et al. Controllable transparency and slow light in a hybrid optomechanical system with quantum dot molecules[J]. Optical and Quantum Electronics, 2020, 52: 1-11.

[61] Agarwal G S, Huang S. Electromagnetically induced transparency in mechanical effects of light[J]. Physical Review A, 2010, 81(4): 041803.

[62] Zhang Z, Wang Y P, Wang X. PT-symmetry-breaking-enhanced cavity optomechanical magnetometry[J]. Physical Review A, 2020, 102(2): 023512.

[63] Huang S, Chen A. Fano resonance and amplification in a quadratically coupled optomechanical system with a Kerr medium[J]. Physical Review A, 2020, 101(2): 023841.
Figures

Figure 1
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Figure 2
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