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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 multistability [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 its 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

Fig. 1. Schematic representation of the optomechanical system. A strong pump field with frequency ω_l (amplitude ε_l) and a weak probe field with frequency ω_p (amplitude ε_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 origins from variable magnetic field (amplitude B) in an energized solenoid (radius R and distance D), is imposed on the charge.

An optomechanical system shown in Fig.1 is considered in our paper. For the IEF, based on the Maxwell equation $\oint \mathbf{E}_k \cdot d\mathbf{l} = -\oint \frac{d\mathbf{B}}{dt} \cdot d\mathbf{s}$, we can get IEF strength $E_k = \frac{R^2}{2D} \frac{dB}{dt}$. 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 ω_l , the system Hamiltonian can be written as [28,53,63],

$$H = \hbar \Delta_c c^\dagger c + \left(\frac{p^2}{2m} + \frac{1}{2} m \omega_m^2 q^2 \right) + Q E_k q + \hbar g c^\dagger c q^2 + i \hbar \varepsilon_l (c^\dagger - c) + i \hbar \varepsilon_p (c^\dagger e^{-i\delta t} - c e^{i\delta t}) \quad (1)$$

where, the first term denotes the free Hamiltonian of the optical cavity with c ($c^\dagger$) being the

annihilation (creation) operator and ω_c being the frequency of the cavity field. $\Delta_c = \omega_c - \omega_l$

($\delta = \omega_p - \omega_l$) 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 ω_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,

$$\frac{d}{dt} q = \frac{p}{m}, \quad (2a)$$

$$\frac{d}{dt} p = -\gamma p - (m\omega_m^2 + 2\hbar g c^+ c) q - Q E_k, \quad (2b)$$

$$\frac{d}{dt} c = -[k + i(\Delta_c + g q^2)] c + \varepsilon_l + \varepsilon_p e^{-i\delta t}, \quad (2c)$$

where the decay rate for the mechanical resonator (γ) and the cavity (κ) 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],

$$\frac{d}{dt} \langle q \rangle = \frac{\langle p \rangle}{m}, \quad (3a)$$

$$\frac{d}{dt} \langle p \rangle = -\gamma \langle p \rangle - (m\omega_m^2 + 2\hbar g \langle c^+ \rangle \langle c \rangle) \langle q \rangle - Q E_k, \quad (3b)$$

$$\frac{d}{dt} \langle c \rangle = -[k + i(\Delta_c + g \langle q^2 \rangle)] \langle c \rangle + \varepsilon_l + \varepsilon_p e^{-i\delta t}, \quad (3c)$$

$$\frac{d}{dt} \langle q^2 \rangle = \frac{1}{m} \langle pq + qp \rangle, \quad (3d)$$

$$\frac{d}{dt} \langle p^2 \rangle = -2\gamma \langle p^2 \rangle - (m\omega_m^2 + 2\hbar g \langle c^+ \rangle \langle c \rangle) \langle pq + qp \rangle - 2Q E_k \langle p \rangle + \gamma(2n+1)m\hbar\omega_m, \quad (3e)$$

$$\frac{d}{dt} \langle pq + qp \rangle = -\gamma \langle pq + qp \rangle + \frac{2}{m} \langle p^2 \rangle - 2(m\omega_m^2 + 2\hbar g \langle c^+ \rangle \langle c \rangle) \langle q^2 \rangle - 2Q E_k \langle q \rangle, \quad (3f)$$

where, $\gamma(2n+1)m\hbar\omega_m$ describes the coupling between the NR with thermal reservoir, and

$n = 1 / (e^{\hbar\omega_m/k_B T} - 1)$ is the mean photon occupation number of the energy $\hbar\omega_m$ [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: $\langle O \rangle = O_s + O_+ e^{-i\delta t} + O_- e^{i\delta t}$, 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,

$$\begin{aligned} q_s &= -\frac{QE_k}{m\omega_m^2 + 2\hbar g c_s^2}, p_s = 0, c_s = \frac{\varepsilon_l}{k + i\Delta}, \\ X_s &= \frac{Y_s - mQE_k q_s}{mM}, Y_s = (2n + 1)\frac{m\hbar\omega}{2}, Z_s = 0, \end{aligned} \quad (4)$$

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

$$q_+(-m\delta^2 - i\delta + M) = -2\hbar g[c_s c_-^* + c_+ c_s^*]q_s, \quad (5a)$$

$$q_-(-m\delta^2 + i\delta + M) = -2\hbar g[c_s c_+^* + c_- c_s^*]q_s, \quad (5b)$$

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

$$i\delta c_- = -igX_- c_s - [k + i(\Delta_c + gX_s)]c_-, \quad (5d)$$

$$X_+(-m\delta^2 - i\gamma m\delta + 2M) = \frac{2}{m}Y_+ - 4\hbar g[c_s c_-^* + c_+ c_s^*]X_s - 2QE_k q_+, \quad (5e)$$

$$X_-(-m\delta^2 + i\gamma m\delta + 2M) = \frac{2}{m}Y_- - 4\hbar g[c_s c_+^* + c_- c_s^*]X_s - 2QE_k q_-, \quad (5f)$$

$$Y_+(-i\delta + 2\gamma) = -2\hbar g[c_s c_-^* + c_+ c_s^*]Z_s + i\delta mMX_+ + i2\delta QE_k m q_+, \quad (5g)$$

$$Y_- (i\delta + 2\gamma) = -2\hbar g[c_s c_+^* + c_- c_s^*]Z_s - i\delta mMX_- - i2\delta QE_k m q_-, \quad (5k)$$

By solving Eqs (5), we can get the expression for c_+ ,

$$c_+ = \frac{\varepsilon_p}{k + i(\Delta + g \frac{c_s c_s^*}{K_2 - \frac{ig c_s c_s^*}{k - i(\Delta + \delta)}} - \delta)}, \quad (6)$$

$$\text{where, } K_1 = \frac{2\hbar g q_s}{m\delta^2 + i\delta - M}, \quad K_2 = \frac{(m\delta^2 + i\gamma m\delta - 2M)(2\gamma - i\delta) + i2\delta M}{(4\hbar g X_s + 2QE_k K_1)(2\gamma - i\delta) - i4\delta QE_k K_1},$$

$$M = m\omega_m^2 + 2\hbar g c_s c_s^*, \Delta = \Delta_c + gX_s.$$

The transmission rate of the probe light can be defined as

$$T = |t_p(\delta)| = \left| 1 - \frac{\kappa c_+}{\varepsilon_p} \right|^2, \quad (7)$$

In addition, we can also calculate the system group delay by [54],

$$\tau_g = \frac{d}{d\delta} \arg[t_p(\delta)], \quad (8)$$

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: $Q = 10^{-10} C$, $\omega_m = 2\pi \times 10^5 Hz$, $m = 10^{-12} kg$, $\gamma = 20 Hz$, $\kappa = 2\pi \times 10^4 Hz$ [50-53]. The wavelength of the coupling field is $\lambda_l = 2\pi c / \omega_l = 532 nm$ and the temperature is $T = 90 K$ [50-53]. $\Delta = 2\omega_m$ is selected under the resonant condition.

Fig. 2. Transmission rate as a function of δ / ω_m for different induced electric field strength E_k .

The other parameters are, $g = 2\pi \times 1.8 \times 10^{23} Hz / m^2$, $\varepsilon_l = 5 \times 10^9 Hz$.

First, Fig. 2 shows the transmission rate as a function of δ / ω_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 δ / ω_m for different quadratic coupling strength g . The other parameters are, $E_k = 1N / C$, $\varepsilon_l = 5 \times 10^9 \text{ Hz}$.

Second, Fig. 3 shows the transmission rate as a function of δ / ω_m for different quadratic coupling strength g . Similarly, a transparency window appears near $\delta / \omega_m = 2$ 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 δ / ω_m for different pump field amplitude ε_l . The other parameters are, $E_k = 1N / C$, $g = 2\pi \times 1.8 \times 10^{23} \text{ Hz} / \text{m}^2$.

Finally, Fig. 4 shows the transmission rate as a function of δ / ω_m for different pump field amplitude ε_l . A transparency window can be found near $\delta / \omega_m = 2$. The position of the

transparency window shows blue-shifted and becomes more and more obvious with the increasing of the pump field amplitude ε_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.

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

Fig. 5 illustrates the probe field phase $\arg[t_p(\delta)]$ and the group delay vs. δ/ω_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, $\delta / \omega_m = 2.0095$.

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

However, in Fig. 7, we can also find it is approximately linear for $0.1 < E_k < 0.39 \text{ N/C}$ (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, $g = 2\pi \times 1.8 \times 10^{23} \text{ Hz} / \text{m}^2, \varepsilon_l = 5 \times 10^9 \text{ Hz}$.

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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Figures

Figure 1

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Figure 2

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