Exciton-Polariton mediated nonlinear optics in a hybrid optomechanical system

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1. Introduction

- Cavity optomechanics, a hybrid system composed of an optical resonator and a mechanical oscillator, is intended to test fundamental quantum physics at the mesoscopic level.
- Polaritonics, which results from the strong light-matter interaction between microcavity photons and excitonic transitions, is promising field of study in cavity optomechanics.
- Despite the fact that research with exciton-polariton condensate has been addressed in cavity optomechanics, a study on quantum nonlinear optics mediated by exciton-polariton in an optical cavity is highly desirable in order to bring exciton-polariton in the quantum information science, which we intend to present in this article.
- We investigate the properties of an outgoing probe field in an optomechanical system composed of an optical cavity and a quantum well (QW).
- Nonlinear effects in the considered system, such as EITs, Fano resonances, and slow light enhancement, have been discussed.

2. Theoretical Method

- We consider a generic optomechanical model in which a cavity is coupled with a mechanical resonator (MR), supplemented with a QW.
- QW is constructed of GaAs/AlAs (two-level artificial atoms) coupled to cavity-confined optical and vibrational modes.
- A strong pump field of frequency ω_l and weak probe field of frequency ω_p are interacting with cavity.
- The cavity is coupled to the mechanical movement of the MR and to the exciton mode in the QW via the radiation pressure force. Under the rotating-wave approximation, the Hamiltonian of the system is given as

$$\begin{aligned} H =& \frac{1}{2}\hbar\omega_{\mathrm{m}}\left(p^2+q^2\right)+\hbar\Delta_a a^\dagger a \\ &+\hbar\Delta_b b^\dagger b-\hbar g_{\mathrm{am}}a^\dagger a q \\ &+\hbar G_{\mathrm{ab}}\left(a^\dagger b+b^\dagger a\right)+\mathrm{i}\hbar\varepsilon_l\left(a^\dagger-a\right) \\ &+\mathrm{i}\hbar\varepsilon_p\left(a^\dagger e^{-\mathrm{i}\Delta_p t}-a e^{\mathrm{i}\Delta_p t}\right). \end{aligned} \quad (1)$$

The first term shows the MR energy represented by the dimensionless position (q) and momentum (p) operators that satisfy the commutation relation $[q,p]=\mathrm{i}\hbar$. The second and third terms describe the energy of cavity mode and exciton energy in the QW, respectively. Where $\Delta_a=\omega_c-\omega_p$ is the cavity-laser dectuning ,$\Delta_b=\omega_b-\omega_p$ is the exciton-laser detuning, and a ($a^\dagger$) and b ($b^\dagger$) are the annhilation (creation) operators of cavity and mechanical mode, respectively; for simplicity, we omit the operator sign. The fourth term represents the coupling of cavity mode with MR (with coupling strength $g_{\mathrm{am}}=\beta\sqrt{\hbar/2\omega_{\mathrm{m}}m}$, where $\beta=\partial\omega_c/\partial x$ and x depicts the motion of the MR having mass m). The fifth term describes the coupling between cavity mode and the excitons in the QW having coupling constant G_{ab}. Finally, the last two terms describe the external driving fields (pump and probe laser fields) with frequencies ω_l and ω_p with corresponding amplitudes $|\varepsilon_l|=\sqrt{2\kappa P_l/\hbar\omega_l}$ and $|\varepsilon_p|=\sqrt{2\kappa P_p/\hbar\omega_p}$, respectively, where κ is the cavity decay rate. In Eq. (1), a and b denote the annhilation operators of the cavity and exciton mode that satisfy the commutation relation $[a,a^\dagger]=1$ and $[b,b^\dagger]=1$, respectively.

- The Heisenberg-Langevin equations of motion

$$\begin{aligned} \dot{q} =& \omega_{\mathrm{m}}p, && (2)\\ \dot{p} =& -\gamma_{\mathrm{m}}p-\omega_{\mathrm{m}}q+g_{\mathrm{am}}a^\dagger a+\xi(t), && (3)\\ \dot{a} =& -(\kappa+\mathrm{i}\Delta_a)a+\mathrm{i}g_{\mathrm{am}}qa-\mathrm{i}G_{\mathrm{ab}}b+\varepsilon_l && (4)\\ &+\varepsilon_p e^{-\mathrm{i}\Delta_p t}+\sqrt{2\kappa}a_{\mathrm{in}}, && (5)\\ \dot{b} =& -(\gamma+\mathrm{i}\Delta_b)b-\mathrm{i}G_{\mathrm{ab}}a+\sqrt{2\gamma}b_{\mathrm{in}}, && (6) \end{aligned}$$

- Using the mean-field approximation, the Eqs. (2)-(6) can be written as

$$\begin{aligned} \langle\dot{q}\rangle =& \omega_{\mathrm{m}}\langle p\rangle, \\ \langle\dot{p}\rangle =& -\gamma_{\mathrm{m}}\langle p\rangle-\omega_{\mathrm{m}}\langle q\rangle+g_{\mathrm{am}}\langle a^\dagger\rangle\langle a\rangle, \\ \langle\dot{a}\rangle =& -(\kappa+\mathrm{i}\Delta_a)\langle a\rangle+\mathrm{i}g_{\mathrm{am}}\langle q\rangle\langle a\rangle \\ &-\mathrm{i}G_{\mathrm{ab}}\langle b\rangle+\varepsilon_l+\varepsilon_p e^{-\mathrm{i}\Delta_p t}, \\ \langle\dot{b}\rangle =& -(\gamma+\mathrm{i}\Delta_b)\langle b\rangle-\mathrm{i}G_{\mathrm{ab}}\langle a\rangle. \end{aligned} \quad (7)$$

- The optical properties of the outfield is calculated by using the standard input-output relation $\varepsilon_{\mathrm{out}}=\varepsilon_{\mathrm{in}}-\sqrt{2\kappa}a$, where $\varepsilon_{\mathrm{in}}$ and $\varepsilon_{\mathrm{out}}$ are the input and output field operators, respectively. We can express the out-going optical field as

$$\langle\varepsilon_{\mathrm{out}}\rangle=\varepsilon_0+\varepsilon_- e^{-\mathrm{i}\Delta_p t}+\varepsilon_+ e^{\mathrm{i}\Delta_p t}. \quad (8)$$

- Further, the relation for the out-going optical field is

$$\varepsilon_T=\frac{\sqrt{2\kappa}a_-}{\varepsilon_p}-1. \quad (9)$$

The optical field ε_T has both real and imaginary parts describing the absorption (in-phase behavior) and dispersion (out-of-phase behavior) of the probe field through the cavity, respectively.

- Rapid phase dispersion, such as $\Phi_t\left(\Delta_p\right)=\arg\left[\mathcal{E}_T(\Delta_p)\right]$, can cause transmission group delay in the vicinity of a narrow transparency window in an optomechanical system, as defined

$$\tau_{\mathrm{g}}=\frac{\mathrm{d}\Phi_t\left(\Delta_p\right)}{\mathrm{d}\Delta_p}=\frac{\mathrm{d}\left\{\arg\left[\mathcal{E}_T(\Delta_p)\right]\right\}}{\mathrm{d}\Delta_p}. \quad (10)$$

The sign of τ_{g} determines the property of the light, with positive and negative signs representing slow and fast light, respectively.

3. Results and Discussion

- The photon-exciton coupling strength that generates quasiparticle-polaritons is important in causing the electromagnetic induced transparency (EIT) phenomenon. The amplitude of the EIT window increases as the photon-exciton coupling strength increases, implying that the quantum interference phenomenon in exciton-polaritons condensate is enhanced.

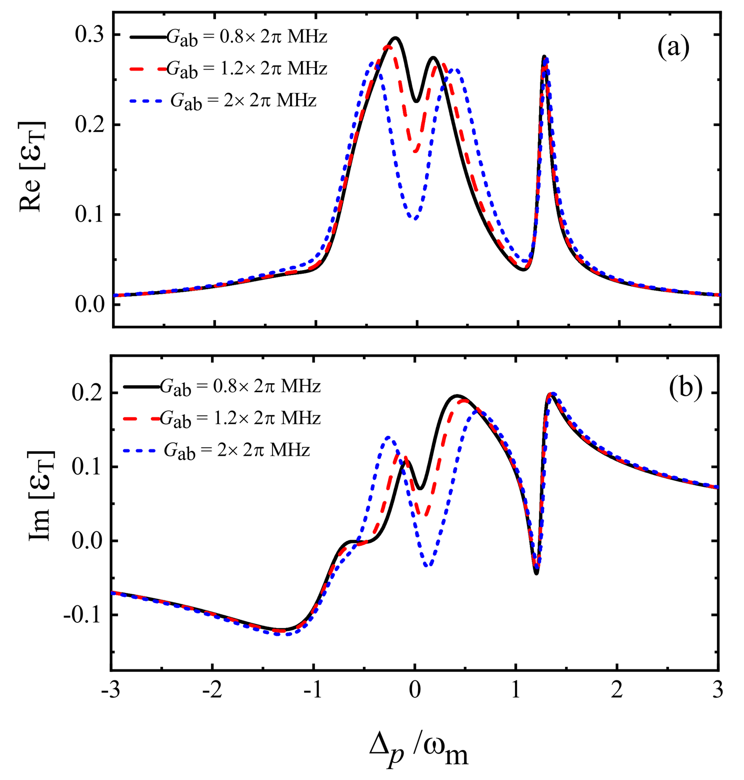

Figure 1: (a) Absorption Re$[\mathcal{E}_{\mathrm{T}}]$ and (b) dispersion Im$[\mathcal{E}_{\mathrm{T}}]$ of the probe field as a function of normalized probe detuning $\Delta_p/\omega_{\mathrm{m}}$. The black solid, red dashed and blue dotted curves correspond to photon-exciton coupling strength $G_{\mathrm{ab}}=0.2\times2\pi$ MHz, $G_{\mathrm{ab}}=1.2\times2\pi$ MHz and $G_{\mathrm{ab}}=2\times2\pi$ MHz, respectively. The photon-mirror coupling strength value is remains same $G_{\mathrm{am}}=5\times2\pi$ MHz.

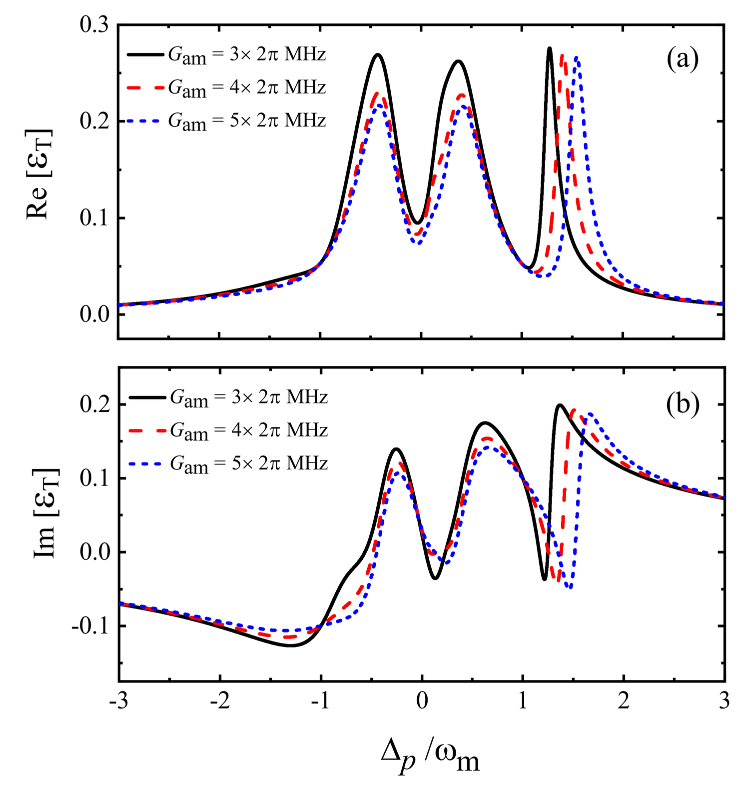

Figure 2: (a) Absorption Re$[\mathcal{E}_{\mathrm{T}}]$ and (b) dispersion Im$[\mathcal{E}_{\mathrm{T}}]$ of the probe field as a function of normalized probe detuning $\Delta_p/\omega_{\mathrm{m}}$. The black solid, red dashed and blue dotted curves correspond to photon-mirror coupling $G_{\mathrm{am}}=3\times2\pi$ MHz, $G_{\mathrm{am}}=4\times2\pi$ MHz and $G_{\mathrm{am}}=5\times2\pi$ MHz, respectively. The photon-exciton coupling strength remains the same as $G_{\mathrm{ab}}=1.5\times2\pi$ MHz.

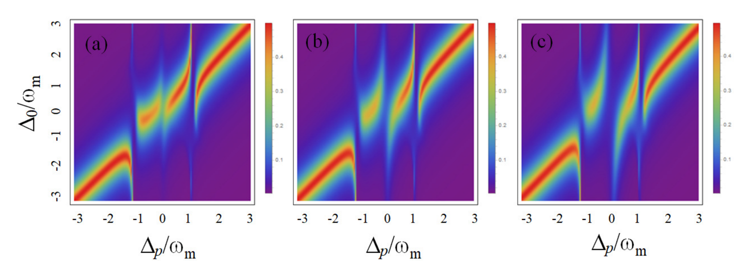

Figure 3: Density plot of Fano Resonances in Absorption (Re$[\mathcal{E}_{\mathrm{T}}]$) profile versus normalized probe field detuning ($\Delta_p/\omega_{\mathrm{m}}$) and normalized effective cavity detuning ($\Delta_0/\omega_{\mathrm{m}}$) for (a) $G_{\mathrm{ab}}=2\times2\pi$ MHz, (b) $G_{\mathrm{ab}}=3\times2\pi$ MHz and (c) $G_{\mathrm{ab}}=4\times2\pi$ MHz. The photon-mirror coupling strength is $G_{\mathrm{am}}=2\times2\pi$ MHz.

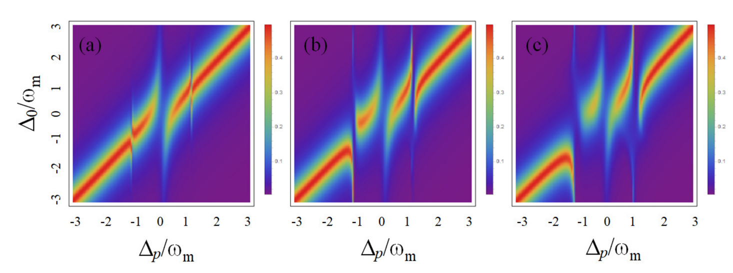

Figure 4: Density plot of Fano Resonances in Absorption (Re$[\mathcal{E}_{\mathrm{T}}]$) profile versus normalized probe field detuning ($\Delta_p/\omega_{\mathrm{m}}$) and normalized effective cavity detuning ($\Delta_0/\omega_{\mathrm{m}}$) for (a) $G_{\mathrm{am}}=0.5\times2\pi$ MHz, (b) $G_{\mathrm{am}}=1.5\times2\pi$ MHz and (c) $G_{\mathrm{am}}=2.5\times2\pi$ MHz. The photon-exciton coupling strength is $G_{\mathrm{ab}}=1\times2\pi$ MHz.

- Fast and slow light dynamics are important for introducing quantum nonlinear optical interactions into practical quantum computation. The group delay can be changed dynamically by adjusting the intensity or detuning of the control laser.

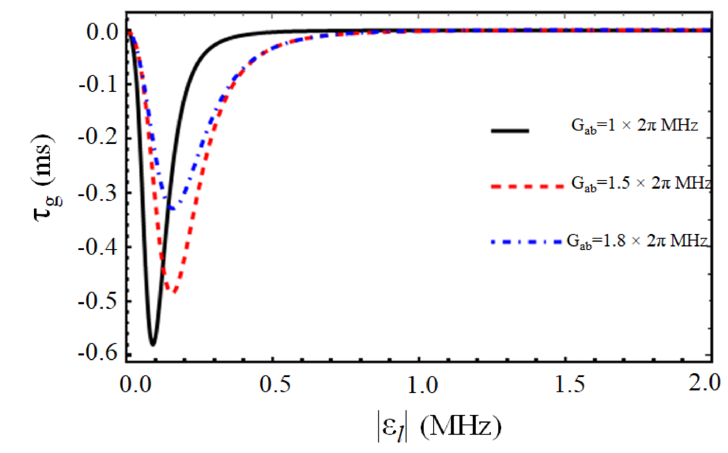

Figure 5: Group delay (τ_{g}) versus pump field is shown for (a) $G_{\mathrm{ab}}=1\times2\pi$ MHz, (b) $G_{\mathrm{ab}}=1.5\times2\pi$ MHz and (c) $G_{\mathrm{ab}}=1.8\times2\pi$ MHz. The photon-mirror coupling strength is $G_{\mathrm{am}}=5\times2\pi$ MHz.

4. Conclusion

- We have investigated electromagnetic induced transparencies, Fano resonances and enhancement of slow light for an optomechanical system additionally strongly coupled with a single QW.
- The cavity is strongly driven by an external pump laser and a weak probe laser, resulting in the mixing of cavity photons with exciton states, which generate the quasiparticles-polaritons with mechanical mode coupling.
- We show that the quantum interference phenomenon occurs only when the cavity photon is coupled with either the mechanical mode of the cavity or with an exciton in a QW.
- Recent experiments of coupling mechanical systems with microcavity pave the way for the realization of quantum nonlinear effect states in the proposed scheme, which has potential applications for example in integrated quantum optomechanical memory, cloaking devices, high efficient x-rays detection, and large scale quantum photonic circuits.

5. References

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