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Absorption interferometer of two-sided cavity*

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We propose a scheme in which an arbitrary incidence can be made perfectly reflected/transmitted with a phase modulator. We analyze the variation of intracavity field as well as output field with closed-loop phase ϕ_1 of the control fields and relative phase ϕ_2 of the probe beams. With two phases, medium absorption and light interference can be controlled so that photon escape from the cavity can be manipulated, thus an intensity switching based on phase modulation can be realized. And the condition for perfect transmitter or reflector is obtained. Then based on the transmission/reflection analysis, the total absorption of this system can be investigated. Therefore our scheme can be used as an absorption interferometer to explore the optical absorption in some complicated system. The state delay of the output light intensity, which is dependent on ϕ_1 or ϕ_2, can be applied in the realization of quantum phase gate and subtle wave filter. And based on this scheme, we implement the state transfer between perfect transmitter/reflector and non-perfect coherent photon absorber via relative-phase modulation.

Keywords: cavity quantum electrodynamics (QED), optical switching, quantum interference

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1. Introduction

Optical interference is a direct evidence for wave theory of light, based on which many precise instruments and technologies have been developed, e.g., Michelson interferometer, Mach–Zehnder interferometer, interferometry, and holography. With the development of quantum mechanics and cavity quantum electrodynamics (cavity-QED), quantum interference, which is based on the uncertainty of different transition channels, is becoming more and more important in the interaction of light and matter. One famous phenomenon of quantum interference is electromagnetically induced transparency (EIT),[1–3] which can be used to realize light switching.[4–9] When an EIT system has a closed interaction loop, it shows phase-dependent property.[10–14] This brings a more sophisticated way of manipulating optical fields. In addition, some studies, such as beam splitter[15] and entanglement between collective fields,[16] are based on phase-dependent EIT. By controlling the phase shift of input lasers in atomic system, one can operate the nonadiabatic optical transitions and quantum mechanical superposition states.[17,18] With the aid of Kerr cross-phase modulation, one can also realize the polarization selection in EIT medium.[19,20] Besides quantum interference, phase shift also plays a vital role in traditional optical interference. Putting wave interference together with quantum system, the manipulation of optical absorption can reach a new era.[21–23]

Here we propose a scheme to manipulate optical intensity in cavity-QED system via phase controlling devices. Using the closed interaction loop and two coherent incident beams, we manipulate the field intensity through the interaction of medium absorption and wave interference. Intracavity field and output field can be periodically modulated by a relative phase and two output channels can be operated at the same pace or at fixed pace delay versus the relative phase. We make theoretical analysis of this cavity-QED system and obtain the solutions for intracavity field and output fields, respectively. We also explain the principle for our scheme to be implemanted as an absorption interferometer and an optical switching based on phase modulation in Section 2. The detailed theoretical simulated results are presented in Section 3. At last, we make a simple summary in Section 4.

2. Theoretical analysis

The scheme proposed here is depicted as in Fig. 1. Two control lasers drive the atomic transitions $|2\rangle \rightarrow |3\rangle$ and $|2\rangle \rightarrow |4\rangle$ with frequency detunings $\Delta_1 = \omega_{1c} - \omega_{32}$ and $\Delta_2 = \omega_{2c} - \omega_{42}$. Microwave field as a third control field couples atomic levels $|3\rangle$ and $|4\rangle$ with a frequency detuning $\Delta_m = \omega_m - \omega_{43}$. Three control fields form a closed interaction contour with atomic levels shown in Fig. 1(b). Because of the closed loop, an interaction phase ϕ_1, which can be defined as the relative phase of the three control fields (its expression is obtained in the following), will exist in the interaction terms of the master equations. A probe laser (ω_p), which has a frequency detuning $\Delta_c = \omega_p - \omega_c$ from cavity mode (ω_c), is split by a beam splitter (BS). The split beams $\alpha_{in,l}$ and $\alpha_{in,r}$ are injected into the cavity

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from two surfaces of the cavity. With a phase controlling device, a relative phase ϕ_2 exists between $\alpha_{\rm in,l}$ and $\alpha_{\rm in,r}$. Two detectors are applied to receive the output signals from the right and left cavity mirrors. The atomic levels $|1\rangle$, $|2\rangle$, $|3\rangle$, and $|4\rangle$ shown in Fig. 1(b) correspond to $5S_{1/2}$ $F=1$ and $F=2$, $5P_{1/2}$ $F=1$ and $F=2$ of ^{87}Rb, respectively. $\Delta_{\rm ac}=\omega_{\rm c}-\omega_{31}$ is frequency detuning of the cavity mode and atomic transition $|1\rangle\rightarrow|3\rangle$. $g\sqrt{N}$ is the collective coupling coefficient of the cavity-QED system. $\Omega_1(\omega_{1\rm c})$, $\Omega_2(\omega_{2\rm c})$, and $\Omega_{\rm m}(\omega_{\rm m})$ are Rabi frequencies (angular frequencies) of control laser 1, control laser 2, and the microwave field. ω_{31}, ω_{32}, ω_{42}, and ω_{43} are angular frequencies of the corresponding atomic transitions.

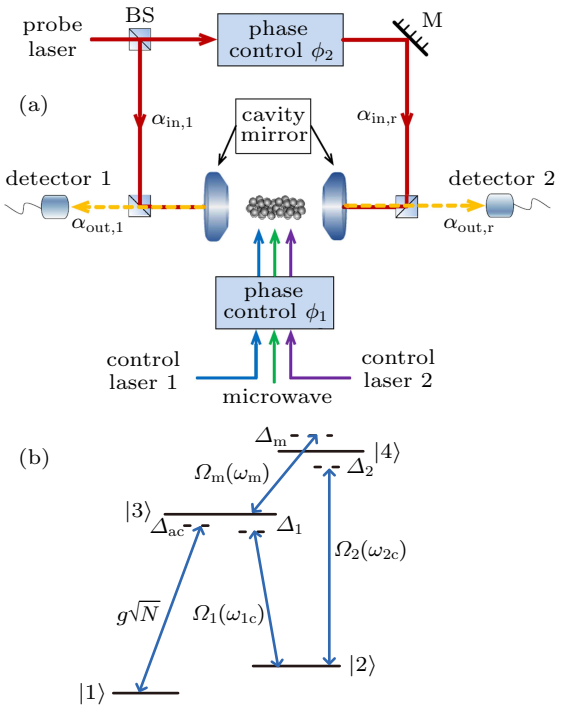


Fig. 1. (a) Theoretical scheme and (b) four-level atomic energy-level structure of ^{87}Rb.

Under rotating wave approximation, the Hamiltonian of this scheme is as follows:

$$\begin{aligned}H=&-\hbar\Delta_{\rm c}a^{\dagger}a-\hbar\sum_{j=1}^{N}[(\Delta_{\rm p}-\Delta_1)\sigma_{22}^{j}+(\Delta_{\rm p}-\Delta_1+\Delta_2-\Delta_{\rm m})\sigma_{33}^{j}\\&+(\Delta_{\rm p}-\Delta_1+\Delta_2)\sigma_{44}^{j}]-\hbar\sum_{j=1}^{N}(ga^{\dagger}\sigma_{13}^{j}{\rm e}^{{\rm i}\phi_2}+\Omega_1\sigma_{23}^{j}{\rm e}^{{\rm i}\varphi_1}\\&+\Omega_2\sigma_{24}^{j}{\rm e}^{{\rm i}\varphi_2}+\Omega_{\rm m}\sigma_{34}^{j}{\rm e}^{{\rm i}\varphi_{\rm m}})+{\rm H.C.},\end{aligned}\tag{1}$$

where $\Delta_{\rm p}=\omega_{\rm p}-\omega_{31}$ is frequency detuning of the probe laser and atomic transition $|1\rangle\rightarrow|3\rangle$, $g=\mu_{13}\sqrt{\omega_{\rm c}/2\hbar\varepsilon_0 V}$ is the cavity-QED coupling coefficient, $a^{\dagger}$ (a) is the creation (annihilation) operator of cavity photons, $\sigma_{mn}^{j}=|m\rangle\langle n|$ ($m,n=1,2,3,4$) is the atomic operator, ϕ_2 is the relative phase of two splitting probe lasers, and φ_1, φ_2, and $\varphi_{\rm m}$ are phases of control laser 1, control laser 2, and the microwave field, respectively.

Under semiclassical approximation, the expectation values of the field operators are appropriate to be considered as the corresponding fields, so we have $\langle a\rangle=\alpha$ ($\langle a^{\dagger}\rangle=\alpha^{*}$) and $\langle a_{\rm in,l}\rangle=\alpha_{\rm in}^{\rm l}$ ($\langle a_{\rm in,r}\rangle=\alpha_{\rm in}^{\rm r}$) for intracavity field and incident probe field, respectively.[24] Furthermore, we have $\rho_{mm}=\langle\sigma_{mm}\rangle$, $\rho_{12}=\langle\sigma_{12}\rangle{\rm e}^{{\rm i}(\phi_2-\varphi_1)}$, $\rho_{13}=\langle\sigma_{13}\rangle{\rm e}^{{\rm i}\phi_2}$, $\rho_{14}=\langle\sigma_{14}\rangle{\rm e}^{{\rm i}(\phi_2-\varphi_1+\varphi_2)}$, $\rho_{23}=\langle\sigma_{23}\rangle{\rm e}^{{\rm i}\varphi_1}$, $\rho_{24}=\langle\sigma_{24}\rangle{\rm e}^{{\rm i}\varphi_2}$, and $\rho_{34}=\langle\sigma_{34}\rangle{\rm e}^{{\rm i}\varphi_{\rm m}}$ for atoms under slowly-varying-amplitude approximation. To explore how two phase-controlling setups affect the transmission or reflection, we need to solve the following equations of motion for density operator ρ and intracavity field operator a:

$$\begin{aligned}\dot{\rho}_{11}&={\rm i}g(\alpha^{*}\rho_{13}-\alpha\rho_{31})+\frac{\Gamma_3}{2}\rho_{33}+\frac{\Gamma_4}{2}\rho_{44},\\\dot{\rho}_{12}&=[{\rm i}(\Delta_{\rm p}-\Delta_1)-\gamma_{12}]\rho_{12}-{\rm i}g\alpha\rho_{32}+{\rm i}\Omega_1\rho_{13}+{\rm i}\Omega_2\rho_{14},\\\dot{\rho}_{13}&=[{\rm i}(\Delta_{\rm p}-\Delta_1+\Delta_2-\Delta_{\rm m})-\gamma_{13}]\rho_{13}+{\rm i}g\alpha(\rho_{11}-\rho_{33})\\&\quad+{\rm i}\Omega_1\rho_{12}+{\rm i}\Omega_{\rm m}\rho_{14}{\rm e}^{{\rm i}\phi_1},\\\dot{\rho}_{14}&=[{\rm i}(\Delta_{\rm p}-\Delta_1+\Delta_2)-\gamma_{14}]\rho_{14}-{\rm i}g\alpha\rho_{34}{\rm e}^{-{\rm i}\phi_1}+{\rm i}\Omega_2\rho_{12}\\&\quad+{\rm i}\Omega_{\rm m}\rho_{13}{\rm e}^{-{\rm i}\phi_1},\\\dot{\rho}_{22}&={\rm i}\Omega_1(\rho_{23}-\rho_{32})+{\rm i}\Omega_2(\rho_{24}-\rho_{42})+\frac{\Gamma_3}{2}\rho_{33}+\frac{\Gamma_4}{2}\rho_{44},\\\dot{\rho}_{23}&=[{\rm i}(\Delta_2-\Delta_{\rm m})-\gamma_{23}]\rho_{23}+{\rm i}g\alpha\rho_{21}+{\rm i}\Omega_1(\rho_{22}-\rho_{33})\\&\quad-{\rm i}\Omega_2\rho_{43}{\rm e}^{{\rm i}\phi_1}+{\rm i}\Omega_{\rm m}\rho_{24}{\rm e}^{{\rm i}\phi_1},\\\dot{\rho}_{24}&=({\rm i}\Delta_2-\gamma_{24})\rho_{24}-{\rm i}\Omega_1\rho_{34}{\rm e}^{-{\rm i}\phi_1}+{\rm i}\Omega_2(\rho_{22}-\rho_{44})\\&\quad+{\rm i}\Omega_{\rm m}\rho_{23}{\rm e}^{-{\rm i}\phi_1},\\\dot{\rho}_{33}&={\rm i}g(\alpha\rho_{31}-\alpha^{*}\rho_{13})+{\rm i}\Omega_1(\rho_{32}-\rho_{23})\\&\quad+{\rm i}\Omega_{\rm m}(\rho_{34}-\rho_{43})-\Gamma_3\rho_{33},\\\dot{\rho}_{34}&=({\rm i}\Delta_{\rm m}-\gamma_{34})\rho_{34}-{\rm i}g\alpha^{*}\rho_{14}{\rm e}^{{\rm i}\phi_1}-{\rm i}\Omega_1\rho_{24}{\rm e}^{{\rm i}\phi_1}\\&\quad+{\rm i}\Omega_2\rho_{32}{\rm e}^{{\rm i}\phi_1}+{\rm i}\Omega_{\rm m}(\rho_{33}-\rho_{44}),\\\dot{\rho}_{44}&={\rm i}\Omega_2(\rho_{42}-\rho_{24})+{\rm i}\Omega_{\rm m}(\rho_{43}-\rho_{34})-\Gamma_4\rho_{44},\\\dot{\alpha}&={\rm i}\Delta_{\rm c}\alpha+{\rm i}gN\rho_{13}-(\kappa_{\rm l}+\kappa_{\rm r})\alpha\\&\quad+\sqrt{2\kappa_{\rm l}/\tau}\alpha_{\rm in}^{\rm l}+\sqrt{2\kappa_{\rm r}/\tau}\alpha_{\rm in}^{\rm r}.\end{aligned}\tag{2}$$

Here $\phi_1=\varphi_1-\varphi_2+\varphi_{\rm m}$ represents the relative phase of the two control lasers and microwave field induced by the closed loop and $\Gamma_3=\Gamma_4=\Gamma$ is the natural decay rate of excited states $|3\rangle$ and $|4\rangle$. γ_{12}, which is much smaller than Γ_3, is the decoherence rate between ground states $|1\rangle$ and $|2\rangle$, $\gamma_{14}=\gamma_{23}=\gamma_{24}=\Gamma$ stands for the decay rates between corresponding atomic levels and $\gamma_{34}=\sqrt{\Gamma_3\Gamma_4}=\Gamma$ describes the coupling rate between states $|3\rangle$ and $|4\rangle$.[25]

For simplicity, we consider a symmetric Fabry–Perot cavity with field loss rate $\kappa_{\rm l}$ ($\kappa_{\rm r}$) from left (right) cavity mirror ($\kappa_{\rm l}=\kappa_{\rm r}$) and $\kappa_i=T_i/2\tau$, where T_i is the mirror transmission and τ is the photon round-trip time inside the cavity.[26] By solving the above motion equations under steady-state condition, the intracavity field amplitude can be derived as

$$\alpha=\frac{\sqrt{2\kappa_{\rm l}/\tau}\alpha_{\rm in}^{\rm l}+\sqrt{2\kappa_{\rm r}/\tau}\alpha_{\rm in}^{\rm r}}{(\kappa_{\rm l}+\kappa_{\rm r})-{\rm i}\Delta_{\rm c}-{\rm i}\chi},\tag{3}$$

where

$$\chi = \frac{g^2 N(\Omega_2^2 - AB)}{2\Omega_1\Omega_2\Omega_m \cos\phi_1 - A\Omega_m^2 - B\Omega_1^2 - C\Omega_2^2 + ABC}$$

is the susceptibility of the atomic medium and $A = \Delta_p - \Delta_1 + i\gamma_{12}$, $B = (\Delta_p - \Delta_1 + \Delta_2) + i\Gamma_4$, $C = (\Delta_p - \Delta_1 + \Delta_2 - \Delta_m) + i\Gamma_3$. According to input–output relations[27]

$$a_{out,l} + a_{in,l} = \sqrt{2\kappa_l\tau}a, \quad a_{out,r} + a_{in,r} = \sqrt{2\kappa_r\tau}a, \quad (4)$$

the analytical solutions for the intracavity field and the output fields through the right and left mirrors are

$$I_c = I_{in}\left|\frac{\kappa(1+e^{i\phi_2})}{\kappa - i\Delta_c - i\chi}\right|^2, \quad I_{out}^r = I_{in}\left|\frac{\kappa(1+e^{i\phi_2})}{\kappa - i\Delta_c - i\chi} - 1\right|^2,$$
$$I_{out}^l = I_{in}\left|\frac{\kappa(1+e^{-i\phi_2})}{\kappa - i\Delta_c - i\chi} - 1\right|^2. \quad (5)$$

Here we set $\kappa_l = \kappa_r = \kappa/2$, $\alpha_{in}^l = |\alpha_{in}|e^{i\varphi_l}$, and $\alpha_{in}^r = |\alpha_{in}|e^{i\varphi_r}$. $\phi_2 = \varphi_l - \varphi_r$ is the relative phase of the two incident probe beams, I_{in} is the input field intensity, and I_c, I_{out}^r (I_{out}^l) are field intensities of the intracavity field and the output field from the right (left) mirror, respectively. In this cavity-QED system, the output field intensity is generally manipulated by intensities or frequencies of the control lasers, but in this paper, we focus on the optical switching based on phase modulation. As indicated in Eq. (5), varying the closed-loop phase ϕ_1 existed in χ we can control medium absorption at different frequency and also we can modulate the output intensity via optical interference induced by the relative phase ϕ_2 between two incident probe lasers α_{in}^l and α_{in}^r. In brief, when the medium absorption is decided, we can manipulate the total optical absorption of this system by means of wave interference. In this sense, the output spectra is also an interference fringe of absorption in this scheme.

3. Results

We consider our system at the threshold of the strong collective-coupling regime ($g^2N = \kappa\Gamma$) and assume that the cavity mode is resonant with atomic transition $|1\rangle \to |3\rangle$ ($\Delta_{ac} = 0$, i.e., $\Delta_c = \Delta_p$). Then the output spectra under resonance condition $\Delta_1 = \Delta_2 = \Delta_m = 0$ can be presented as in Fig. 2. The parameters are $g\sqrt{N} = \Gamma$, $\Omega_1 = \Omega_2 = \Omega_m = \Gamma$, $\kappa = \Gamma$, $\gamma_{12} = 0.001\Gamma$. Figure 2(a) shows that the output field intensity from right mirror I_{out}^r varies with relative phase ϕ_2, for which the reason is that the reflection from the right beam interferes destructively or constructively with the transmission from the left beam at the right interface of the cavity for different ϕ_2. Due to the frequency-dependence absorption in medium, the output field intensity varies with Δ_p for the same ϕ_2. In Fig. 2(b), the output spectrum is symmetrical about $\phi_1 = \pi$, which is based on the similar principle in Ref. [14]. And it is easy to be predicted from the susceptibility of the atomic medium. With phase-controlling setup of ϕ_1, the medium absorption can be modulated. Via phase-controlling setup of ϕ_2, the photon escape from cavity can be manipulated through the optical interference at the interface of the cavity mirror. Therefore, combining medium absorption with optical interference, we will focus on all-phase controlling on output spectra in the following.

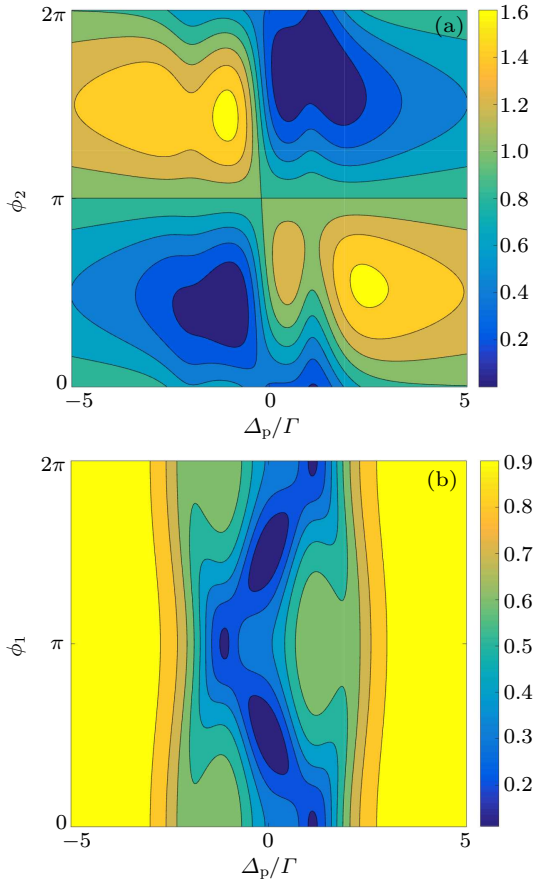


Fig. 2. Contour plots of I_{out}^r as a function of frequency detuning Δ_p and (a) relative phase ϕ_2, (b) closed-loop phase ϕ_1. The parameters are (a) $\phi_1 = 0$ and (b) $\phi_2 = 0$.

Here we choose three representative frequencies $\Delta_p = -\Gamma$, $\Delta_p = 0$, and $\Delta_p = \Gamma$ to analyze the phase controlling on the output field intensity. We show the contour plots of output field intensity I_{out}^r versus ϕ_1 and ϕ_2 in Fig. 3. They present the symmetry about ϕ_1 which is the same with that shown in Fig. 2(b) for three frequency detunings above. While the situation for $\phi_2 = 0 \to \pi$ is very different from that for $\phi_2 = \pi \to 2\pi$, it shows the frequency relevance of the optical interference. When it is at negative frequency detuning as in Fig. 3(a), the photon-escape enhancement appears at $\phi_2 = \pi \to 2\pi$. Increasing absorption causes the decreasing of the output intensity with changing ϕ_1 from 0 to π (or from 2π to π.) When $\Delta_p = 0$ (Fig. 3(b)), the enhancement of the output intensity disappears and the maximum output intensity appears around $\phi_2 = \pi$. This is because the closer to $\phi_2 = \pi$, the closer to $I_c = 0$ as indicated in Eq. (5), namely, $\phi_2 = \pi$ is the condition of per-

fect transmitter/reflector. According to Fig. 2(b), it is easy to understand why the maximum output intensity for $\Delta_p = 0$ appears at $\phi_1 \approx 0$, π, and 2π respectively. While for positive frequency detuning as in Fig. 3(c), the output enhancement occurs when ϕ_2 is $0 \to \pi$ and the enhancement is weakening with $\phi_1 = \pi \to 0$ or $\phi_1 = \pi \to 2\pi$ which is opposite to the results in Fig. 3(a). For $\phi_2 = 0 \to 2\pi$, Fig. 3 presents a remarkable sign of optical interference and the interference fringes become more similar with general fringes when the probe frequency is non-resonant with atomic transition $|1\rangle \to |3\rangle$. The nonuniform intensity distribution of the interference fringes is due to the nonlinear absorption and multiple diffraction of the input light and transmission (reflection).[28]

Since the output spectra are always symmetrical about $\phi_1 = \pi$ no matter what the probe frequency is, we modify the closed-loop-phase device to make $\phi_1 = 0$, $\pi/2$, π in turn, then we analyze the intensity of the intracavity field and the output fields from the right and left mirrors for both resonant and non-resonant frequencies. The results are shown in Fig. 4. Here we present the result for $\phi_1 = \pi/2$ in consideration that the varying tendencies for $\phi_1 = 0$ and $\phi_1 = \pi$ are similar with that for $\phi_1 = \pi/2$ except one phenomenon that $I^{\rm r}_{\rm out} = I^{\rm l}_{\rm out}$ for the whole range of ϕ_2 ($0 \to 2\pi$) at $\Delta_p = 0$ as shown in Fig. 4(a). The situation for negative frequency detuning is not presented here, because the only difference is that the output field from the right (left) mirror for negative frequency detuning has a fixed pace delay with the situation for positive frequency detuning. In Fig. 4, when $\phi_2 = \pi$, the perfect transmitter/reflector condition is satisfied. Therefore, the intracavity field intensity is always zero, the output field intensity from the right mirror is the same as that from the left mirror and the total output intensity ratio is always the maximum value 2, which manifests the frequency independence as well as medium irrelevance of field intensity for $\phi_2 = \pi$.

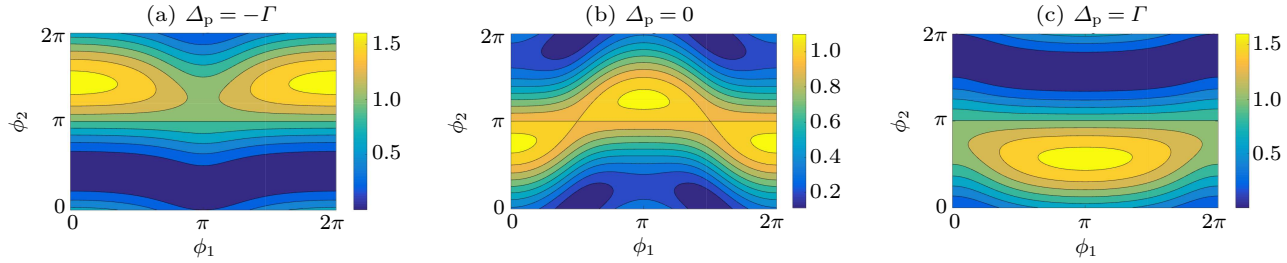


Fig. 3. Contour plots of $I^{\rm r}_{\rm out}$ as a function of closed-loop phase ϕ_1 and relative phase ϕ_2 for three representative frequency detuning: (a) $\Delta_p = -\Gamma$, (b) $\Delta_p = 0$, and (c) $\Delta_p = \Gamma$. The parameters here are $g\sqrt{N} = \Omega_1 = \Omega_2 = \Omega_m = \Gamma$, $\gamma_{12} = 0.001\Gamma$.

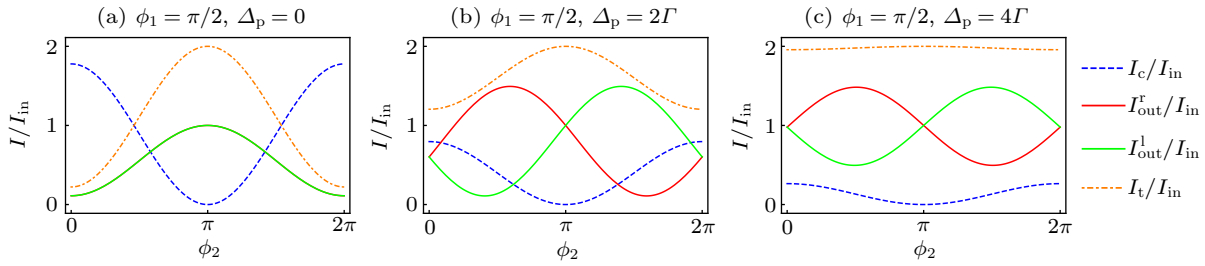


Fig. 4. Field intensity ratio versus incident relative phase ϕ_2 for intracavity field ($I_c/I_{\rm in}$), output field from right or left mirror ($I^{\rm r}_{\rm out}/I_{\rm in}$ or $I^{\rm l}_{\rm out}/I_{\rm in}$), and total output field ($I_t/I_{\rm in}$) . The parameters are $\phi_1 = \pi/2$ and (a) $\Delta_p = 0$, (b) $\Delta_p = 2\Gamma$, (c) $\Delta_p = 4\Gamma$. The other parameters are the same as those in Fig. 3.

In Fig. 4(a), when $\phi_2 = 0$ (2π) the incident probe photon is nearly all trapped in the cavity. The perfect photon trapping condition[22] is not met in this scheme, as a result, there is tiny output light from the two mirrors at $\Delta_p = 0$. However, if two control lasers and the microwave field are absent, the total output intensity for $\phi_2 = 0$ (2π) in Fig. 4(a) is zero (fully destructive interference of transmission and reflection from two phased beams) and this atom–cavity system is implemented as a coherent perfect absorber (CPA). A CPA is related to the time-reversed lasing process where incident coherent optical fields are perfectly absorbed within a resonator that contains a loss medium instead of a gain medium.[28,29] Increasing the frequency detuning Δ_p, the total output intensity becomes less sensitive to ϕ_2 and the pace delay between $I^{\rm r}_{\rm out}$ and $I^{\rm l}_{\rm out}$ is visible. When Δ_p is up to 4Γ, the total output intensity is almost insensitive to ϕ_2 and the output intensities from the two mirrors have a pace delay (π) on ϕ_2. Figure 4 shows the property of wave interference which is relevant to medium absorption in this scheme. That is why our scheme may be implemented as an absorption interferometer. It can also be used to realize state transfer between two output channels via phase modulation on ϕ_2. Moreover the manipulation on field intensity versus frequency detuning makes this scheme a subtle frequency filter.

If the probe laser is tuned at resonance ($\Delta_p = 0$), the variations of the output intensities versus closed-loop phase ϕ_1 are very distinct for $\phi_2 = 0$, $\pi/2$, and π as shown in Fig. 5. The output intensities $I^{\rm r}_{\rm out}$ and $I^{\rm l}_{\rm out}$ can not be distinguished from

each other with changing closed-loop phase ϕ_1 when relative phase ϕ_2 is even order of $\pi/2$ (e.g., $\phi_2 = 0$ in Fig. 5(a) and $\phi_2 = \pi$ in Fig. 5(c)). This phenomenon also happens when the probe laser is not at resonance. Only when ϕ_2 is non-even order of $\pi/2$, the complex amplitude will carry different phase information for the output fields from the right and left mirrors, and the intensity of the output field through the right mirror is separated from that through the left mirror by a pace delay (π) on ϕ_1. Here we show one special value $\phi_2 = \pi/2$ in Fig. 5(b). When ϕ_2 is increased from 0 to π, Fig. 5 shows that the photon escape from the cavity is enhanced at $\Delta_p = 0$. And the field intensities are modulated periodically by ϕ_1 when $\phi_2 \neq \pi$. When $\phi_2 = 0$ (Fig. 5(a)), the output intensity is minimum due to the destructive interference, and it can be modulated by ϕ_1 because the medium absorption can be manipulated by the closed-loop phase. When $\phi_2 = \pi$ (Fig. 5(c)), the optical interference plays the main role and the completely constructive interference of this mode at the interface of the cavity mirrors makes the output intensity maximum while the intensity of the intracavity field is equal to zero. It shows a perfect transmitter/reflector without sensitivity to closed-loop-phase. Therefore our scheme can be applied to fulfill a switching between a coherent photon absorber and a perfect photon transmitter or reflector based on phase modulation.

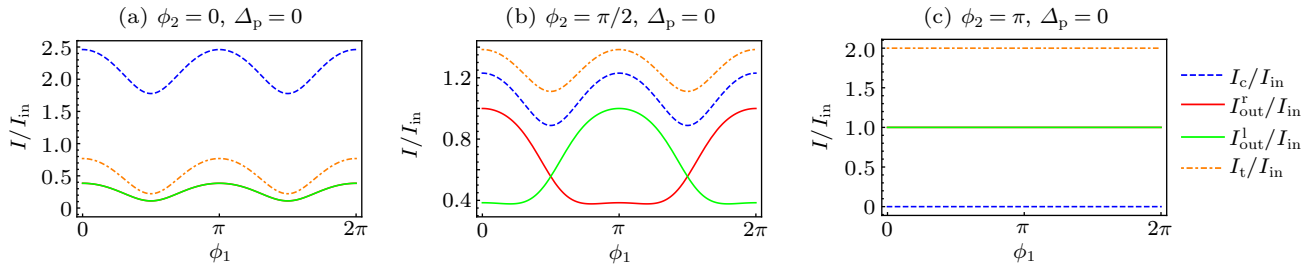


Fig. 5. With probe frequency tuned with atomic transition $|1\rangle \rightarrow |3\rangle$ ($\Delta_p = 0$), the field intensity ratio versus closed-loop phase ϕ_1 for (a) $\phi_2 = 0$, (b) $\phi_2 = \pi/2$, and (c) $\phi_2 = \pi$. The other parameters here are the same as those in Fig. 3.

4. Conclusions

At the threshold of strong collective-coupling regime, the optical field intensity of a four-level atom-cavity system is analyzed. Due to the closed loop, there will be a relative phase ϕ_1 between three control fields in susceptibility of the atomic medium, thus the intracavity field and output fields are manipulated by controlling the medium absorption via ϕ_1. Since two coherent input beams are applied with relative phase ϕ_2, the analytical solutions for both intracavity field and output fields contain two phase factors ϕ_1 and ϕ_2. Therefore, besides the absorption controlling by closed-loop phase ϕ_1, the optical interference dependent on relative phase ϕ_2 is applied to manipulate the field intensity.

Via the contour plots versus ϕ_1 and ϕ_2, the interaction of medium absorption and wave interference is analyzed, and an absorption interferometer based on phase modulation is proposed. In this scheme, the switching between perfect transmitter/reflector and non-perfect CPA is realized in theory. And the pace delay on ϕ_2 between I^r_{out} and I^l_{out} provides us a way to fulfill frequency filtering. By controlling closed-loop phase ϕ_1, the intracavity field can be modulated periodically. Therefore the scheme proposed here can be applied to operate light field more delicately in cavity-QED system.

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