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Photonic coherent perfect transmission, absorption, and synthesis in a bimodal cavity quantum electrodynamics system

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ABSTRACT

In this paper, we investigate an optical hybrid system in which a single quantum emitter is coupled to both modes of a bimodal optical microcavity, and propose a scheme for coherent perfect transmission, coherent perfect absorption, and coherent perfect synthesis of optical photons by utilizing such a bimodal cavity quantum electrodynamics (QED) system. In the present scheme, each mode of the bimodal microcavity can be coherently driven by an external monochromatic continuous-wave driving laser and the two cavity modes are not directly coupled to each other due to their orthogonal polarizations. It is found that three important phenomena, i.e., photonic coherent perfect transmission, absorption, and synthesis can be achieved in the optical hybrid system under appropriate conditions. We discuss in detail the theoretical model and present results of numerical simulation of the system in the steady state with experimentally achievable system parameters. Also, the possible experimental realization of the scheme in a solid-state approach is analyzed based on the semiconductor quantum dot and the photonic crystal defect microcavity. This study may provide further insight into the understanding of bimodal cavity QED system and find potential applications in quantum information processing and future quantum networks.

1. Introduction

In recent years, cavity quantum electrodynamics (cavity QED), which studies light–matter interactions inside resonators, provides a promising micro- or nano-photonic platform for both constructing devices and developing techniques for quantum information processing (QIP) and future quantum networks [1–5]. Tremendous progress has been made by coupling different quantum emitters such as atoms, quantum dots (QDs), and nitrogen-vacancy (NV) centers to different optical resonators [6–14]. Among them, the optical hybrid systems consisting of photonic crystal (PC) defect microcavities and semiconductor QDs embedded into the microcavities may be promising [15]. The PC defect microcavities usually exhibit highly confined ultrasmall mode volumes V in the order of the qubic wavelength and ultrahigh quality factors Q (i.e., a high

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Q/V ratio), representing an ideal environment for strong light-matter interactions. Also, it is shown that photonic waveguides can be easily incorporated into PCs, which offer an easy way for the efficient in- and out-coupling of light into the microcavities. In two-dimensional planar PC structures, the microcavities can be formed by point defects and the waveguide modes can be formed by line defects [16,17]. Moreover, PCs offer the possibility to tune resonant cavity frequencies by changing the geometrical parameters of the defects. Hence, complex on-chip coupled systems of PC waveguides and microcavities can be produced [18–20], and these PC waveguide-coupled microcavity systems are compatible with large-scaled integration and are tunable over a wide optical wavelength range, which exhibit broad prospects in QIP [21–29]. On the other hand, the semiconductor QDs are similar to artificial atom systems exhibiting a high density of states embedded in PC microcavities. Strong couplings between a PC microcavity and a single QD have been observed experimentally [30–34].

One of the important developments in recent cavity QED studies via semiconductor QDs coupled to PC microcavities is the investigation of QD-cavity coupling between a single QD and a bimodal PC microcavity. In 2012, Majumdar et al. [35] proposed an implementation of a source of strongly sub-Poissonian light from the cavity emission in a system consisting of a QD coupled to both modes of a lossy bimodal optical cavity. Subsequently, they proposed another scheme to perform high fidelity spin initialization and manipulation using the system [36]. In 2014, Li et al. [37] put forward a scheme for coherent optical mode conversion by using the coupling between a single QD and a bimodal PC microcavity via a waveguide. Recently, they proposed another scheme for optical high-order sideband comb generation and efficient sideband information transfer from one optical mode to the other in a similar hybrid system [38]. In all these studies, a bimodal PC microcavity with both of its cavity modes coupled to a QD was analyzed and utilized from different perspectives, for such a composite system offers more degrees of freedom and is compatible with large-scaled integration for developing complex photonic devices on a chip.

In this work, we explore coherent perfect transmission (CPT), coherent perfect absorption (CPA), and coherent perfect synthesis (CPS) of optical photons for all-optically controlled photonic devices in an optical hybrid system consisting of a lossy bimodal optical microcavity, nearby photonic waveguides serving for in- and out-coupling of light into the microcavity, and a single two-level quantum emitter coupled to both modes of the microcavity. Here each mode of the bimodal microcavity can be coherently driven by an external monochromatic continuous-wave (CW) driving laser and the two cavity modes are not directly coupled to each other due to the orthogonality of their polarizations. It is clearly shown that three important phenomena, i.e., photonic coherent perfect transmission, absorption, and synthesis can be achieved in such an optical hybrid system under appropriate conditions. We discuss in detail the theoretical model and present results of numerical simulation of the system in the steady state with experimentally achievable system parameters. Also, the possible experimental realization of the scheme in a solid-state approach is analyzed based on the photonic platform proposed in Ref. [35]. This study may provide further insight into the understanding of bimodal cavity QED system and find potential applications in QIP and future cavity-QED-based photonic quantum networks.

This paper is organized as follows. In Section 2, we describe the theoretical model under investigation, derive the quantum Heisenberg–Langevin equations, and give the steady-state solutions of the cavity fields. In Section 3, we calculate the output fields, show the phenomena of CPT, CPA, and CPS in the output fields, and discuss the experimental feasibility of the proposed scheme. Finally we present our summary in Section 4.

2. Model and method

A simplified schematic of the optical hybrid system under investigation is illustrated in Fig. 1. In the system, a single quantum emitter with two levels $|1\rangle$ and $|2\rangle$ is embedded in a bimodal optical microcavity. The microcavity is supposed to support two orthogonally polarized modes, both of the cavity modes are coupled to the two-level emitter, while the two cavity modes are not directly coupled to each other, with a setup arrangement similar to the one proposed and analyzed in Refs. [35–38]. The $|1\rangle rightarrow |2\rangle$ transition of the emitter is simultaneously coupled to the two cavity modes with respective resonance frequencies ω_{c1}, ω_{c2} and coupling strengths g_1, g_2. The Hamiltonian describing this system is given by

$$\begin{aligned} H \;=\; & \hbar\omega_0\hat{\sigma}_{22} + \hbar\omega_{c1}\hat{c}_1^\dagger\hat{c}_1 + \hbar\omega_{c2}\hat{c}_2^\dagger\hat{c}_2 \\ & +\hbar g_1(\hat{c}_1\hat{\sigma}_{21} + \hat{c}_1^\dagger\hat{\sigma}_{12}) + \hbar g_2(\hat{c}_2\hat{\sigma}_{21} + \hat{c}_2^\dagger\hat{\sigma}_{12}) \\ & +i\hbar\sqrt{\kappa_{e1}}(E_1 e^{-i\omega_p t}\hat{c}_1^\dagger - H.c.) \\ & +i\hbar\sqrt{\kappa_{e2}}(E_2 e^{-i\omega_p t + i\phi}\hat{c}_2^\dagger - H.c.), \end{aligned} \tag{1}$$

where the electric-dipole approximation (EDA) and rotating-wave approximation (RWA) have been used. In the above Hamiltonian, the first term represents the energy of the excited state $|2\rangle$, while the energy of the ground state $|1\rangle$ is set to zero for the sake of simplicity. ω_0 is the frequency of the optical transition of the emitter between the ground state $|1\rangle$ and the excited state $|2\rangle$. $\hat{\sigma}_{22} = |2\rangle\langle 2|$ represent the electronic population operator involving the excited-state level of the emitter. The second and third terms account for the energies of the bare cavity modes 1 and 2. $\hat{c}_1, \hat{c}_2$ and $\hat{c}_1^\dagger, \hat{c}_2^\dagger$ are the photon annihilation and creation operators of the two cavity modes. The fourth and fifth terms describe the coherent interactions of the two-level emitter with the cavity modes 1 and 2. The symbols $\hat{\sigma}_{mn} = |m\rangle\langle n|$ $(m, n = 1, 2)$ for $m \neq n$ are the electronic transition or projection operators between the states $|m\rangle$ and $|n\rangle$. The sixth and seventh terms denote the driving of the cavity modes 1 and 2 by the input CW driving lasers. The parameters κ_{e1} and κ_{e2} are the waveguide-cavity coupling rates,