The mechanism of producing energy-polarization entangled photon pairs in the cavity-quantum electrodynamics scheme*

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We investigate theoretically two photon entanglement processes in a photonic-crystal cavity embedding a quantum dot in the strong-coupling regime. The model proposed by Johne *et al.* (Johne R, Gippius N A, Pavlovic G, Solnyshkov D D, Shelykh I A and Malpuech G 2008 *Phys. Rev. Lett.* **100** 240404), and by Robert *et al.* (Robert J, Gippius N A and Malpuech G 2009 *Phys. Rev.* B **79** 155317) is modified by considering irreversible dissipation and incoherent continuous pumping for the quantum dot, which is necessary to connect the realistic experiment. The dynamics of the system is analysed by employing the Born–Markov master equation, through which the spectra for the system are computed as a function of various parameters. By means of this analysis the photon-reabsorption process in the strong-coupling regime is first observed and analysed from the perspective of radiation spectrum and the optimal parameters for observing energy-entangled photon pairs are identified.

Keywords: cavity-quantum electrodynamics scheme, entangled photon pairs, pure dephasing, incoherent pumping

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1. Introduction

Quantum information processing based on all-optical theory is the inevitable development tendency of future high-speed information processing in which the source of entangled photon pairs is a key element.[1−5] In general, the entangled photon pairs are experimentally generated by spontaneous parametric down-conversion (SPDC) based on the nonlinear effects of the optical crystal.[6−9] However, an SPDC source is disadvantaged by inherent randomness that hardly meets the requirement of deterministic sources of entangled photon pairs in quantum date processing schemes.[10] Recently, extensive attention has been attracted in developing a desired solid-state source of entangled photon pairs using single quantum dots (QDs) embedded in a microcavity, first proposed by Benson *et al.*[11] In such a dot–cavity system, the entangled photon pairs are emitted from the biexciton cascade via two intermediate exciton states.[12,13] In the ideal case, the two exciton states are degenerate so that the two decay paths are indistinguishable thereby forming energy-entangled photon pairs. However, the two exciton states are nondegenerate in the realistic case due to the fine structure splitting (FSS), resulting from the anisotropic electron–hole exchange interaction[14,15] so that the two decay paths can be distinguished through measuring their energy. Much effort has been made to search for solutions to overcome this splitting, and many effective methods have been proposed, e.g., selected QDs with smaller FSS,[16,17] exciton state degeneration induced by external field,[18−23] and filtering the distinguishable photon pairs.[24]

Based on the proposal of Benson *et al.*,[11] Johne *et al.*[25] and Robert *et al.*[26] have presented a cavity-quantum electrodynamics scheme, using a single QD embedded in a photonic-crystal cavity to obtain entangled photon pairs. In the strong coupling regime, the two exciton states are respectively dressed with the two orthogonal linearly polarized cavity modes:

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horizontal and vertical, forming polariton states, which can be controlled in a wide range through changing the properties of the cavity and the QDs, e.g., the exciton energy can be experimentally tuned by changing the temperature of the material.[27,28] In this way, the fine structure splitting (FSS) can be overcome and then entangled photon pairs can be achieved.

According to the proposal of Johne *et al.*,[25] we modify the model by considering the irreversible dissipation caused by the cavity decay, the radiation decay and pure dephasing of exciton (biexciton) in the framework of a Born–Markov master equation. Furthermore, we consider the continuous pumping for the QD by an incoherent field as it has proved that the incoherent continuous pumping is a determinative ingredient in the description and achievement of strong coupling.[29] The dynamics of the system, cavity mode and QD, are studied in steady state by analysing the radiation spectra of biexciton and exciton and the cavity mode as a function of various parameters. By means of this analysis we are able to observe the photon-reabsorption process in the strong coupling regime and specify the effects of pure dephasing and incoherent pumping on system spectra, and we also identify the optimal parameters for obtaining entangled photon pairs.

The rest of the present paper is organized as follows. In Section 2, we investigate the coherent process by means of Jaynes–Cummings model and analyse all the four possible cases of generating energy-polarization entangled photon pairs in such a QD-cavity scheme. In Section 3, we employ the Born–Markov master equation to deal with the incoherent process and the spectra for the QD-cavity system are computed and analysed as a function of various parameters. In Section 4, the results and conclusions are presented.

2. Coherent process for the adiabatic system

In the biexciton–exciton cascade, the biexciton state $|B\rangle$ decays to the ground state $|G\rangle$ after emitting two photons through two possible channels: one via the intermediate exciton state $|H\rangle$, emitting two horizontally polarized (H-polarized) photons; the other via the intermediate exciton state $|V\rangle$, emitting two vertically polarized (V-polarized) photons. The exciton states $|H\rangle$ and $|V\rangle$ respectively couple to the orthogonally polarized cavity modes $\omega_{\rm c}^{\rm H}$ and $\omega_{\rm c}^{\rm V}$ via the transitions to the ground state. In the general situation, the biexciton binding energy is at least ten times larger than the cavity coupling strength, thus, we ignore the coupling between the biexciton and the cavity-mode.[26,28] Therefore, in the discussion below we just consider the coupling of the exciton→ground transition with the cavity mode. The energy-level diagram of the QD embedded in the photonic-crystal cavity is shown in Fig. 1, where δ is the FSS, $\Delta_{\rm c}^{\rm H}$ and $\Delta_{\rm c}^{\rm V}$ represent the detuning between the exciton states and cavity modes, and Δ denotes the biexciton binding energy.

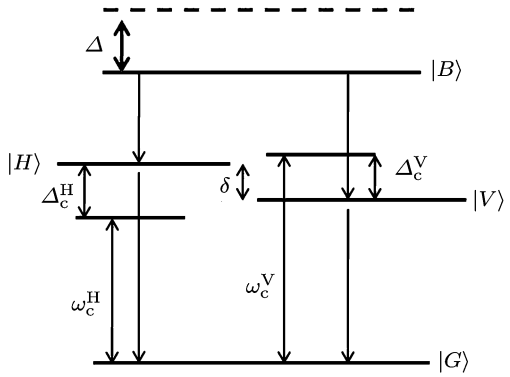


Fig. 1. Energy-level diagram for the biexciton–exciton cascade.

The Hamiltonian for the QD-photonic crystal cavity system can be given by analogy with the Jaynes–Cummings Hamiltonian for a two-level atomic transition coupled to a single cavity mode. For simplicity, we just give the consideration on the strong-coupling of $|H\rangle \rightarrow |G\rangle$ transition with the corresponding cavity mode $\omega_{\rm c}^{\rm H}$, and the Hamiltonian is given by

$$\hat{H} = \frac{\hbar\omega_{\rm H} + \hbar\omega_{\rm c}^{\rm H}}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\hbar}{2}\begin{pmatrix} \Delta_{\rm c}^{\rm H} & {\rm i}g \\ {\rm i}g & -\Delta_{\rm c}^{\rm H} \end{pmatrix}, \quad (1)$$

where $\omega_{\rm H}$ is the frequency of the exciton, $\Delta_{\rm c}^{\rm H} = \omega_{\rm H} - \omega_{\rm c}^{\rm H}$, and g is the coupling strength. In addition, the corresponding eigenequation for the system can be written as

$$\hat{H}\psi = E\psi. \quad (2)$$

Combining Eqs. (1) and (2), the eigenenergies are calculated by

$$E_{\pm}^{\rm H} = \frac{\hbar\omega_{\rm H} + \hbar\omega_{\rm c}^{\rm H}}{2} \pm \frac{\hbar\sqrt{4g^2 + (\Delta_{\rm c}^{\rm H})^2}}{2}, \quad (3)$$

which are the energies of the two polariton states resulting from the strong-coupling between the exciton

state and the cavity mode. $E_+^{\rm H}$ represents the upper polariton state and $E_-^{\rm H}$ denotes the lower polariton state.

Similarly, for the same coupling strength,[23] eigenenergies for the vertical exciton state can be given by Eq. (3) just replacing $\omega_{\rm H}$, $\omega_{\rm c}^{\rm H}$, and $\Delta_{\rm c}^{\rm H}$ with $\omega_{\rm V}$, $\omega_{\rm c}^{\rm V}$, and $\Delta_{\rm c}^{\rm V}$ and written as

$$E_\pm^{\rm V} = \frac{\hbar\omega_{\rm V} + \hbar\omega_{\rm c}^{\rm V}}{2} \pm \frac{\hbar\sqrt{4g^2 + (\Delta_{\rm c}^{\rm V})^2}}{2}. \qquad (4)$$

Obviously, there are four possible paths of the biexciton decaying to the ground state via four polariton states resulting from the strong-couplings between two excitons and two optical cavity modes. Of them, two decay paths are by the two upper polaritons generating polarization-entangled photon pairs while the other two decay paths are by the two lower polaritons generating polarization-entangled photon pairs. Therefore, there are two independent polarization-entangled photon pairs. Moreover, if we let the two photons in pairs have the same frequency, the energy-polarization entangled photon pairs will be obtained.

According to Eqs. (3) and (4), assuming $\delta > 0$, there are four possible cases for obtaining energy-polarization entangled photon pairs as shown in Fig. 2. In case (a), both horizontal-polariton (H-polariton) states and both vertical-polariton (V-polariton) states are all degenerate, requiring $E_+^{\rm H} = E_+^{\rm V}$ and $E_-^{\rm H} = E_-^{\rm V}$ as shown in Fig. 2(a); in case (b), only the upper H-polariton state and the lower V-polariton state are degenerate, requiring $E_-^{\rm H} = E_+^{\rm V}$ as shown in Fig. 2(b); in case (c), the lower H-polariton state and the lower V-polariton state are degenerate, requiring $E_-^{\rm H} = E_-^{\rm V}$ as shown in Fig. 2(c); in case (d), the upper H-polariton state and the upper V-polariton state are degenerate, requiring $E_+^{\rm H} = E_+^{\rm V}$ as shown in Fig. 2(d).

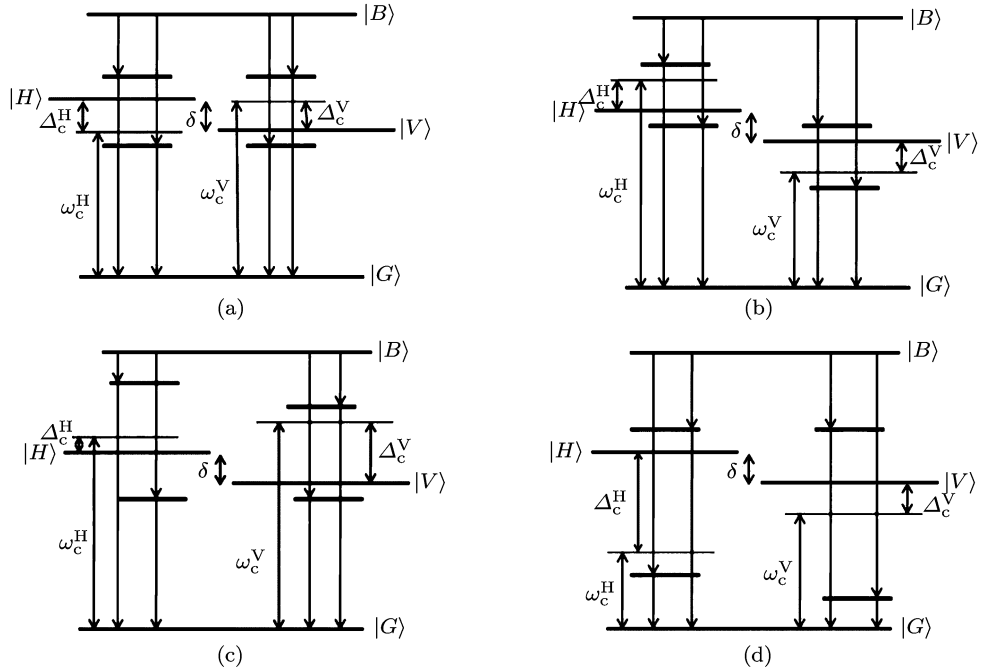


Fig. 2. Four possible cases for obtaining energy-entangled photon pairs, with $\Delta_{\rm c}^{\rm H} = -\Delta_{\rm c}^{\rm V}$ ((a) and (b)), $\Delta_{\rm c}^{\rm H} = -\Delta_{\rm c}^{\rm V}$ (c), and $\Delta_{\rm c}^{\rm H} > \Delta_{\rm c}^{\rm V}$ (d).

What is discussed above is under the ideal conditions regardless of decays resulting from the interaction with the environment, and through analyzing we obtain all the four possible cases for generating entangled photon pairs corresponding to different various parameters. In the following section, we discuss the incoherent process of the system in cases of Figs. 2(a) and 2(b) (Figs. 2(c) and 2(d) can be obtained in a similar way).

3. Incoherent process for the open system

3.1. Basic model

Frequently, the Born–Markov master equation is used to describe the coupling between the environment and the system. The environment is assumed to be a reservoir with a large number of degrees of freedom. In this paper, the master equation for the

density matrix of the coupled system, cavity modes, and QD degrees of freedoms can be written as

$$\frac{\partial}{\partial t}\rho = \frac{1}{\mathrm{i}\hbar}[H,\rho] + L\rho, \tag{5}$$

where H is the Hamiltonian responsible for the coherent evolution and L is the superoperator describing the effect of irreversible dissipations and incoherent pumping on the coupled system. The Hamiltonian H takes the following form in which we also ignore the coupling between the biexciton–exciton transition and the cavity-mode just as we mentioned above:

$$\begin{aligned} \mathrm{H} = {} & \hbar\omega_{\mathrm{c}}^{\mathrm{H}} a_{\mathrm{H}}^{\dagger} a_{\mathrm{H}} + \hbar\omega_{\mathrm{c}}^{\mathrm{V}} a_{\mathrm{V}}^{\dagger} a_{\mathrm{V}} \\ & + \sum_{j=\mathrm{H,V}} \hbar\omega_j |j\rangle\langle j| + \hbar\omega_B |B\rangle\langle B| \\ & + \hbar g \sum_{j=\mathrm{H,V}} \Big[(|G\rangle\langle j|) a_j^{\dagger} + \mathrm{H.c} \Big], \end{aligned} \tag{6}$$

where H.c is the Hermitian conjugate term; $\hat{a}_{\mathrm{H}}$ and $\hat{a}_{\mathrm{V}}$ ($\hat{a}_{\mathrm{H}}^{\dagger}$ and $\hat{a}_{\mathrm{V}}^{\dagger}$) are the annihilation (creation) operators for the orthogonally polarized cavity modes; g is the coupling strength between each of the two cavity modes and exciton states, which we assume to be equal for simplicity of discussion; ω_{H}, ω_{V}, and ω_{B} are the frequencies of the excitons and biexciton, respectively.

The superoperator L is responsible for the reservoir–system coupling, which describes the non-hermitian evolution of the system given by

$$\begin{aligned} L\rho = {} & \sum_{j=\mathrm{H,V}} \frac{\kappa}{2} L(a_j)\rho \\ & + \sum_{j=\mathrm{H,V}} \Big[\frac{\gamma}{2} L(|G\rangle\langle j|) + \frac{\gamma_B}{4} L(|j\rangle\langle B|) \Big] \rho \\ & + \frac{\Gamma_{\mathrm{d}}}{2} \sum_{j=\mathrm{H,V}} L(|j\rangle\langle j|)\rho + \Gamma_{\mathrm{d}} L(|B\rangle\langle B|)\rho \\ & + \frac{P}{2} \sum_{j=\mathrm{H,V}} [L(|j\rangle\langle G|) + L(|B\rangle\langle j|)]\rho, \end{aligned} \tag{7}$$

where the first term represents the two cavity mode decay and κ is the cavity-mode decay rate; the second term refers to the QD energy level decay including radiative and nonradiative losses; γ and γ_{B} are the decay rates of exciton and biexciton respectively and we assume $\gamma_{\mathrm{B}} = 2\gamma$ for simplicity in the following; the third term describes the QD decay as a result of exciton pure dephasing caused by the interaction with bulk photons; Γ_{d} is the exciton dephasing rate; the last term describes the continuous incoherent pumping for the quantum QD; P is the injection rate.

In addition, we have defined

$$L(m)\rho = 2m\rho m^{\dagger} - m^{\dagger}m\rho - \rho m^{\dagger}m, \tag{8}$$

which represents the so-called Lindblad loss form of the system, and m is an operator acting on the Hilbert space of the QD-cavity system.

3.2. Spectrum simulation for the cavity and biexciton radiation

Figures 3(a) and 3(b) describe the spectra of cavity and biexciton radiation corresponding to cases of Figs. 2(b) and 2(a), which are in agreement with those obtained by Pathak and Hughes.[30] As is known, in the strong coupling regime, there are two peaks in the spectrum corresponding to two polariton states and in Fig. 3(a) only one of two peaks has the same energy from which case the entangled photon source we obtain is probabilistic. While in Fig. 3(b) the two peaks both have the same energy and the deterministic entangled photon source can be achieved.

Figure 3(c) describes the effect of the pure dephasing on cavity radiation spectrum and as pure dephasing becomes larger the radiation amplitude becomes smaller so that the strong coupling condition is even disturbed, resulting in only one radiation peak in the spectrum. The effect of the incoherent pumping on cavity radiation spectrum is indicated in Fig. 3(d). Enlarging incoherent pumping appropriately, the system coupling can be even so strong that the cavity radiation is strengthened with spectrum being expanded, otherwise, if the incoherent pumping is enlarged to a certain extent, the strong coupling regime for the system may disappear as dephasing resulting from pumping becomes larger than the coupling strength.

3.3. Radiation spectra simulation for exciton

Figure 4 shows V-polarized exciton radiation spectra, whose corresponding energy level diagrams are shown in Fig. 2(b), for different coupling strengths in a steady state (H-polarized can be obtained in a similar way.). Figure 4(a) indicates that for small coupling strength the system is in the weak coupling regime where the photons leaking out of the cavity are far more than the photons reabsorbed by the QD (the dot line); while for larger coupling strength the system is in the strong coupling regime where polariton states

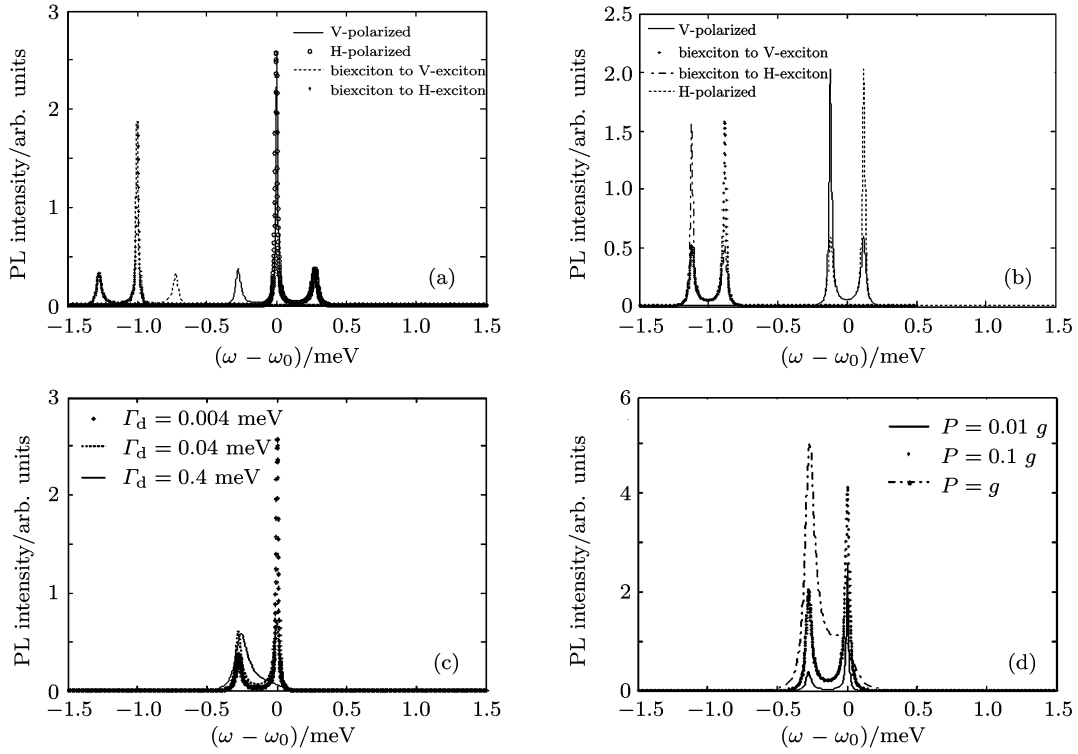


Fig. 3. Biexciton and cavity radiation spectra. For the calculation, we have used $\delta = 0.1$ meV, $\gamma = 0.002$ meV, $\kappa = 0.05$ meV, $g = 0.11$ meV, $p = 0.01\ g$, $\Gamma_d = 0.004$ meV, for (a) $\Delta_c^H = -\Delta_c^V = -0.175$ meV, and for (b) $\Delta_c^H = -\Delta_c^V = \delta = 0.1$ meV. Panels (c) and (d) show the cavity radiation spectra respectively with different pure dephasings and incoherent pumpings.

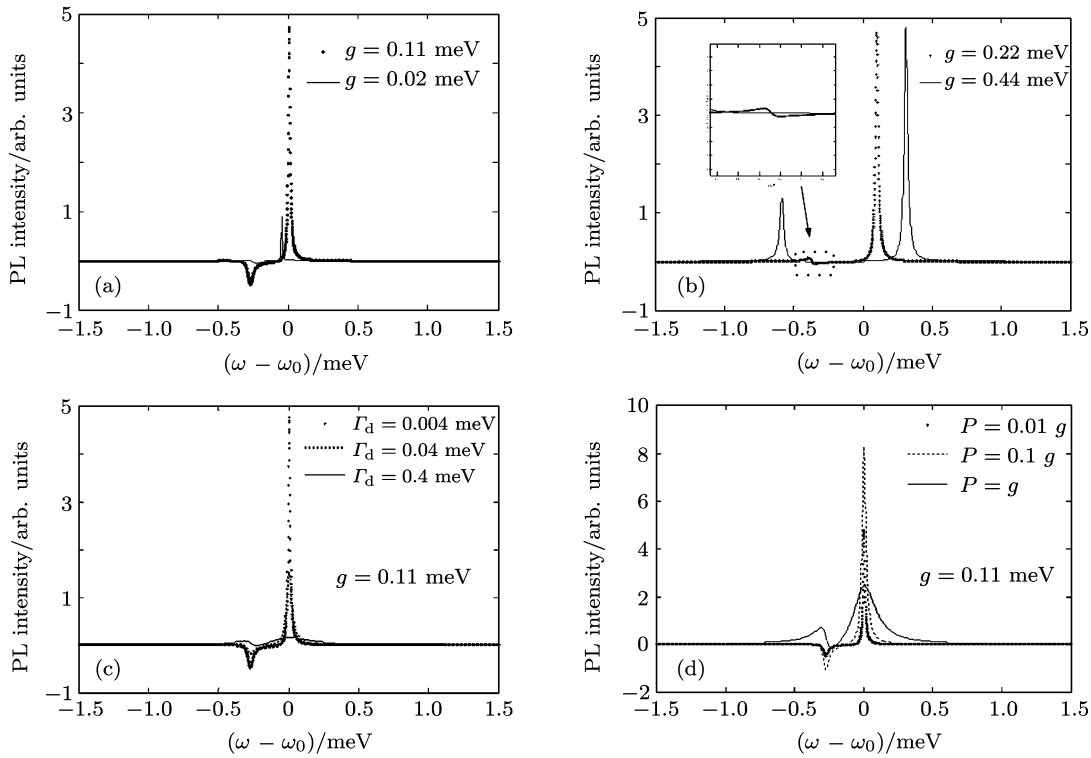


Fig. 4. V-exciton radiation spectra each as a function of various parameters. For the calculation, the following parameters are used: $\delta = 0.1$ meV, $\gamma = 0.002$ meV, $\kappa = 0.05$ meV, $\Delta_c^H = -\Delta_c^V = -0.175$ meV. For (a) and (b) $p = 0.01\ g$, $\Gamma_d = 0.004$ meV with different coupling strengths; and for (c) $p = 0.01\ g$ and for (d) $\Gamma = 0.004$ meV, respectively with different pure dephasings and incoherent pumpings.

are formed. From the energy level diagram we can see that the lower V-polariton state is nearly at resonance with the V-polarized cavity-mode, thus, the reabsorption process can be observed obviously (the solid line) and be easily explained via the theory of resonance absorption. Specifically, if the coupling strength is larger, the reabsorption changes from weaker even to zero, i.e., no reabsorption exists, just as shown in Fig. 4(b), which is because as coupling strength becomes larger, the formed polariton state is further beyond the cavity-mode so that the condition for resonance absorption is hardly met.

Figure 4(c) shows the effect of pure dephasing on the exciton radiation spectrum. As pure dephasing becomes larger, the amplitudes of exciton radiation and reabsorption both become smaller. The effect of the incoherent pumping on the exciton spectrum is indicated in Fig. 4(d). Enlarging incoherent pumping appropriately, the system coupling can be even stronger that both exciton radiation and reabsorption are strengthened with the spectrum being expanded, otherwise, if incoherent pumping is enlarged to a certain extent, the polariton state is not close to the cavity-mode any more, so that photons will not be reabsorbed by the QD either. Furthermore, as incoherent pumping is comparable to dephasing, the radiation amplitude of the exciton becomes smaller with the enlargement of pumping.

4. Results and conclusions

As discussed in the above coherent process, there are four possible cases for obtaining energy-polarization entangled photon pairs (see Fig. 2). In case (a), there are two independent energy-polarization entangled photon pairs with different frequencies emitted from both cavity and biexciton when two polariton states are degenerate, which can be realized by setting $\delta = -\delta_{\rm c} = \Delta_{\rm c}^{\rm H} = -\Delta_{\rm c}^{\rm V}$, where $\delta = \omega_{\rm H} - \omega_{\rm V}$, and $\delta_{\rm c} = \omega_{\rm c}^{\rm H} - \omega_{\rm c}^{\rm V}$, i.e., the FSS equals the detuning between the two cavity modes with opposite signs (see Fig. 3(b)). In case (b), only one energy-polarization entangled photon pair is emitted as the lower H-polariton state is degenerate with the upper V-polariton state, which is realized under the condition of $\Delta_{\rm c}^{\rm H} = -\Delta_{\rm c}^{\rm V}$, $\delta_{\rm c} > \delta$ [see Fig. 3(a)]. In case (c), an energy-polarization entangled photon pair is emitted as the lower H-polariton state is degenerate with the lower V-polariton state, which can be obtained with $\Delta_{\rm c}^{\rm H}$, $\Delta_{\rm c}^{\rm V} < 0$, $\Delta_{\rm c}^{\rm H} > \Delta_{\rm c}^{\rm V}$, $-\delta_{\rm c} > \delta$. In case (d), also an energy-polarization entangled photon pair is emitted as the upper H-polariton state is degenerate with the upper V-polariton state, which can be achieved with $\Delta_{\rm c}^{\rm H}$, $\Delta_{\rm c}^{\rm V} > 0$, $\Delta_{\rm c}^{\rm H} > \Delta_{\rm c}^{\rm V}$, $-\delta_{\rm c} > \delta$. Of all the four cases, case (a) is the most ideal. In the case we can obtain a deterministically entangled photon source, however, the condition that $\delta = -\delta_{\rm c}$ is not easily fulfilled because of the structure limitation. By contrast, photon source under the conditions of the last three cases is easier to implement, nevertheless, they are probabilistic in that they require a spectral window to filter the distinguishable photon pairs in order to reach a high entanglement degree.[23]

We also discussed the effects of pure dephasing and incoherent pumping on the system radiation spectrum. As pure dephasing increases, the amplitude of cavity radiation spectrum becomes smaller and when pure dephasing dominates over the system, the strong coupling regime disappears (see Fig. 3(c)) which is disadvantageous in generating entangled photon pairs. Through analysing, we can see that the incoherent pumping also strongly affects the cavity radiation spectrum. With the pumping strength increasing appropriately (smaller than coupling strength), the spectrum width is broadened and the amplitude is enlarged, otherwise, when the pumping dominates over the system, the regime for strong coupling becomes fuzzy (see Fig. 3(d)). Therefore, the appropriate increasing of pumping strength could strengthen the photon-pair entanglement process. For the exciton radiation spectrum, the reabsorption amplitude and the radiation amplitude largely depend on coupling strength (see Figs. 4(a) and 4(b)). In this paper, we also similarly analyse the effects of pure dephasing and incoherent pumping on the exciton radiation spectrum (see Figs. 4(c) and 4(d)).

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