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Tunable single photon and two-photon emission in a four-level quantum dot-bimodal cavity system

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ABSTRACT

We investigate the generation of single photons and photon pairs in a cavity quantum electrodynamics system of a four-level quantum dot coupled to bimodal cavity. By tuning frequencies and intensity ratio of the driving lasers, sub-Poissonian and super-Poissonian photon statistics are obtained in each nondegenerate cavity mode respectively. Single photon emission is characterized as zero-delay second-order correlation function $g^2(0) \sim 0.15$. Photon pair emission under the two-photon resonance excitation is quantified by Mandel parameter as Q~ 0.04. The mean cavity photon number in both scenarios can maintain large around 0.1. As a result, single photon emission and two-photon emission can be integrated in our proposed system only by tuning the external parameters of the driving lasers.

1. Introduction

Rapid developments in quantum communication and quantum information processing in recent years provide a significant incentive to develop practical non-classical light sources generating single and paired photons. A single quantum dot (QD) in a cavity has been proved to be a very promising single photon source with high brightness and indistinguishability and plays a significant role in quantum communication [1,2], quantum metrology [3] and fundamental quantum mechanics [4]. Also, quantum light sources exhibiting two-photon emission, especially entangled photon pairs, are essential building blocks for quantum information processing protocols [5], teleportation [6], cryptography or imaging [7,8]. To date, most sources of photon pairs employed are based on parametric down-conversion [9–11]. However, these sources suffer from the major drawback that the number of photon pairs generated in each process exhibits Poissonian statistics, with a non-zero probability of generating zero pair or more than one pair [12]. Promising candidate to overcome this difficulty is the QD-cavity coupled system which naturally emit photon pairs in a radiative cascade [13]. And moreover, as it is based on semiconductors, the QD-cavity coupled system has great potential for optical access, on-chip integration and scalable technological implementations [14].

Therefore, a tunable quantum light sources can be constructed by integrating the single-photon emission with two-photon emission in one device based on QD-cavity system [15]. Two-photon generation has been demonstrated by tuning the cavity frequency into resonance with half the biexciton energy [16]. Due to large biexciton binding energy, the single-photon processes are detuned and suppressed, while simultaneous two-photon emission is Purcell enhanced [17]. On the other hand, the single-photon emission of QD-cavity coupled system is mainly relied on photon blockade effect (the transition of quanta number from 1 to 2 is inhibited due to the presence of the first one), due to the strong nonlinear interaction between QD and cavity [18,19].

We propose a quantum light source scheme that integrates single-photon emission with two-photon emission by means of a four-level QD-bimodal cavity system. Thanks to the diamond type four-level energy structure of the QD, we manage to excite the single-photon and two-photon transitions separately in the same system. By studying the second-order correlation function and Mandel parameter of each cavity modes, we demonstrate the single photon and two-photon emission by tuning the ratio and frequency of the driving lasers.

2. Theoretical model and calculation method

The system under consideration consists of a nondegenerate bimodal microcavity containing a single four-level QD. The QD is coupled to both orthogonally polarized cavity modes a and b. We assume that the cavity modes are nondegenerate and there is no coupling between them as an ideal. Fig. 1 shows the energy level scheme of the QD-bimodal cavity coupled system. The QD states are composed of a biexciton state $|XX\rangle$, two single exciton states with orthogonal polarizations $|X\rangle$, $|Y\rangle$, and a ground state $|G\rangle$. The frequencies of two cavity modes are set to the frequency of the exciton $\omega_a = \omega_X$ and half frequency of the biexciton $\omega_b = \omega_X - \chi/2$ respectively, where χ is the biexciton binding

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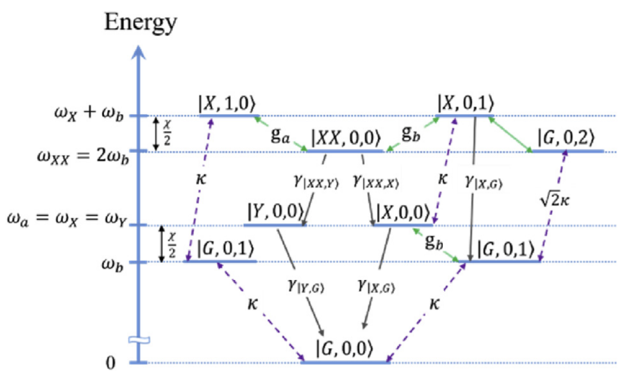

Fig. 1. Energy level scheme of a four-level QD coupled to a bimodal cavity. The microscopic configuration includes QD–cavity coupling g_a and g_b, decay rate of cavity modes κ, excitonic spontaneous decay γ. Here, $|l, m, n$ represents the Fock state with m photons in cavity mode a, n photons in cavity mode b and the QD at the ground state (l = G), exciton state ($l = X, Y$) or biexciton state (l = XX).

energy. A convenient way of pumping the QD-cavity system is via a continuous excitation of the wetting layer, which will result in homogeneous broadening of the excited state and reduction of coherence time. Here, we use coherent excitation (two continuous-wave lasers with the same frequency and orthogonal polarizations are applied to excite two cavity modes respectively) in order to preserve the phase relation in the dynamics [20,21]. The driving strength for each cavity mode can be adjusted by the strength and the polarization of the lasers.

The Hamiltonian of the system under the rotating wave approximation with the laser frequency is described by ($\hbar = 1$)

$$H = H_0 + +E_a(a^\dagger + a) + E_b(b^\dagger + b), \tag{1}$$

with

$$\begin{aligned} H_0 = {} & (2\Delta{-}\chi)\sigma_{\mathrm{XX,XX}} + \Delta(\sigma_{\mathrm{X,X}} + \sigma_{\mathrm{Y,Y}}) + \Delta(a^\dagger a) + (\Delta - \chi/2)(b^\dagger b) \\ & + \mathrm{g_a}(\sigma_{\mathrm{G,X}} a^\dagger + \mathrm{H.\,c.}) + \mathrm{g_a}(\sigma_{\mathrm{X,XX}} a^\dagger + \mathrm{H.\,c.}) + \mathrm{g_b}(\sigma_{\mathrm{G,Y}} b^\dagger + \mathrm{H.\,c.}) \\ & + \mathrm{g_b}(\sigma_{\mathrm{Y,XX}} b^\dagger + \mathrm{H.\,c.}). \end{aligned} \tag{2}$$

Here, $a(b)$ and $a^\dagger(b^\dagger)$ are annihilation and creation operators of the cavity mode a (b); $\sigma_{i,j} = |ij|_{i,j=G,X,Y,XX}$ is the pseudo Pauli spin operator for the QD. The exciton state of QD is assumed to be resonant to cavity mode a as the detuning between the QD and cavity modes can be prevented by temperature control [22] or electrical field manipulation [23]. Δ is the detuning of the exciton state $|X$ or $|Y$ with respect to the driving lasers; $\mathrm{g_a}(\mathrm{g_b})$ is the coupling strength between the QD and cavity mode $a(b)$. E_a and E_b are the driving laser strength for the two cavity modes, respectively. The Hamiltonian of the system states explicitly that each cavity mode only couples to photons of its corresponding mode. The dynamics of the system can be calculated using the master equation under Born-Markov approximation

$$\dot{\rho} = -i[H, \rho] + L\rho, \tag{3}$$

where L is the Lindblad superoperator which represents the incoherent loss of the system [24]. $L\rho$ takes the form

$$L\rho = \frac{\kappa}{2}L(a)\rho + \frac{\kappa}{2}L(b)\rho + \frac{\gamma}{2}\{L(\sigma_{\mathrm{G,X}}) + L(\sigma_{\mathrm{G,Y}}) + L(\sigma_{\mathrm{X,XX}}) + L(\sigma_{\mathrm{Y,XX}})\}\rho, \tag{4}$$

with the definition of $L(\varphi)\rho = 2\varphi\rho\varphi^\dagger - \varphi^\dagger\varphi\rho - \rho\varphi\varphi^\dagger$. Here, κ is the decay rate for both cavity modes and γ is the excitonic spontaneous decay between two energy states. The coupling strength are set to be equal, i.e., g= $\mathrm{g_a} = \mathrm{g_b}$, which can be achieved when the electromagnetic field magnitudes of both modes are equal at the location of the QD and the polarization angles between the QD diploe and both modes are equal [25]. For simplicity, the excitonic spontaneous decay γ between different energy states are set to be equal for the four-level QD.

Due to the presence of the biexciton binding energy, the frequencies of the two cavity modes are separated so that the single-photon and two-photon processes will not interfere with each other. When χ is large enough, the decay processes contributing to single-photon emission will be reduced and only two-photon decay processes survive [26]. However, at the meantime, the single-photon processes from the same system should be reserved to achieve tunable photon source. Therefore, we set $\omega_b = \omega_X - \chi/2$ to be adjusted by χ so that the two-photon resonance will maintain with various χ and cavity mode a can still be in resonance with single-photon process. We adopt the experimental parameter of $\chi = 400\mu eV$ for our following calculation, which can be achieved by a layer of InAs QDs buried at the center of a PhC double heterostructure cavity made from GaAs at the temperature of 4.5 K [27].

The zero-delay second-order correlation functions $\mathrm{g}_a^2(0) = a^\dagger a^\dagger aa/a^\dagger a^2$ for cavity mode a and $\mathrm{g}_b^2(0) = b^\dagger b^\dagger bb/b^\dagger b^2$ for cavity mode b are defined to quantify the antibunching character. For cavity mode b, the Mandel parameter is defined as Q= $\frac{n_b^2 - n_b^2}{n_b} - 1 = n_b(\mathrm{g}_b^2(0) - 1\Big)$, where $n_b = b^\dagger b$ is the mean cavity photon number (similar definition for cavity mode a is $n_a = a^\dagger a$). Since Q changes sign with the nature of the correlations (positive for bunching, negative for antibunching), it is preferred to describe the two-photon character. The steady-state density matric ρ can be obtained by numerically solving the master equation within a truncated Fock space, and the correlation function can be calculated using $O = \mathrm{Tr}(O\rho)$ which evaluates the average value of an arbitrary operator O in steady state [28–30].

3. Results and discussions

First, we study the characteristic spectral profile of the QD-bimodal cavity system. Fig. 2 shows the normalized emission intensity of the proposed system, with different excitation scenarios corresponding to the emission spectrum peaks depicted in the inset. The emission intensity is strongly enhanced at Δ = 10 g= $\chi/2$, and two minor peaks occur at Δ = ±g. According to the energy structure of the system, Δ = $\chi/2$ corresponds to the resonant excitation of cavity mode b which gives rise to two-photon emission. The peaks at Δ = ±g can be the scenario of the off-resonant excitation to cavity mode a. This is similar

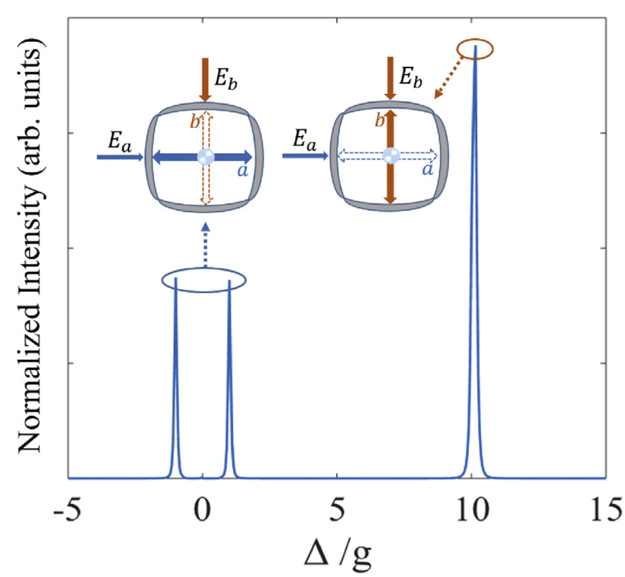

Fig. 2. Normalized emission spectrum as a function of Δ. We set κ = g= $\chi/20 = 20\mu eV$ and $\gamma = 0.01$ g= $0.2\mu eV$ for the numerical calculation. Insets show the different excitation scenarios for single photon and two-photon resonance.