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Tunable continuous-variable steady entanglement via an atom in a microcavity

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ABSTRACT

We consider a single two-level atom and exciton mode in a microcavity system. The second-order correlation function and the continuous-variable entanglement between the cavity and exciton mode are investigated. It is found that nonclassical (antibunching) effect and continuous-variable entangled light can be generated. One advantage of this system is that the generation of continuous-variable entanglement can be controlled by tuning the frequency of the pumping field.

1. Introduction

It has been proved that continuous-variable (C-V) entanglement is an important part of quantum information theory [1]. The main motivation to deal with continuous variables in quantum information originates from a more practical observation: utilizing continuous quadrature amplitudes of the quantized electromagnetic field, efficient implementation of the quantum communication protocols are achieved in quantum optics. After the first demonstration of the C-V entanglement [2], the generation of C-V entanglement has been implemented in experiments [1]. The classical scheme to produce the C-V entanglement is parametric down-conversion. However, it remains a challenge to generate macroscopic entangled light rather than few photon numbers. Promising candidates for generating of macroscopic entangled light are optical amplifier [3–9]. In this setup, the main medium can be thought of as a stream of suitably prepared atom(s).

On the other hand, with the development of semiconductor optical microcavities, strong interest has been attracted in exciton–cavity coupled systems [10–15]. Microcavity polaritons, which have been observed for the first time in Ref. [10], play a central role in understanding the linear optical properties of quantum wells embedded in semiconductor microcavities [16]. Wang et al. [17] have studied the effects of homogeneous broadening of excitons on normal mode oscillations in semiconductor microcavity. A quantum well with a single exciton mode in a microcavity driven by squeezed vacuum has been investigated in the low exciton density regime [15]. Savasta et al. [18] have shown the possibility that entangled photons can be produced by biexciton-resonant hyper-parametric scattering in semiconductors quantum well, which has been experimentally realized in a CuCl bulk by Edamatsu et al. [19]. The increase of entangled-photon generation from a CuCl quantum well (QW) confined in a planar microcavity has been theoretically discussed by Ajiki et al. It has been demonstrated that the generation efficiency can be strongly enhanced when the biexciton–cavity coupling is realized [11].

The recent theoretical and experimental studies have brought the proof of squeezing in semiconductor microcavities with quantum wells [20–24]. However, to our knowledge, few authors investigate the entanglement property between the cavity and exciton in semiconductor microcavity system. Contrasted with previous work [15], in this Letter a single two-level atom is introduced. We consider a single two-level atom and exciton mode in a microcavity driven by an external field. Using the Fokker–Planck approach which has some

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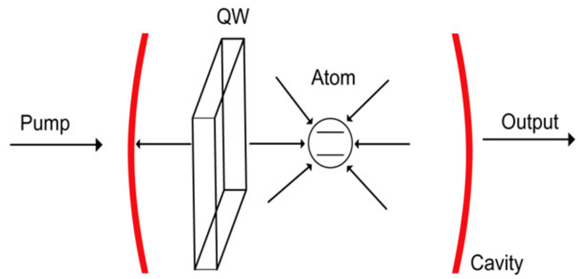

Fig. 1. An outline of a single two-level atom and exciton mode in a microcavity driven by an external classical field.

appealing features [15,26], and following the solution of a generalized second-order Fokker–Planck equation, we study the second-order correlation function and the C-V entanglement between the cavity and exciton in the bad-cavity (exciton) limit. It shows that our system can exhibit nonclassical (antibunching) effect as well as generate C-V entanglement in steady state. Especially, this two-level atom can be used to control the generation of C-V entanglement.

2. Model and master equation

We consider a single two-level atom and exciton mode in a microcavity driven by an external classical field. The configuration of this system is depicted in Fig. 1. A semiconductor quantum well and a single two-level atom are inserted into two Bragg reflecting mirrors (the atom is trapped in this microcavity). The internal two side of Bragg reflecting mirrors are separated by a distance about the order of the wavelength λ. It is noted that inside the cavity the atom and the quantum well are not interact with each other. The atom is coupled to a broadband squeezed vacuum centered about the atomic resonance frequency ω_a. The model of our system can be implemented by assuming a short microcavity, which subtends a large solid angle at the atom. We assume the density of excitons is so small that exciton-exciton interaction can be ignored. The excitons in microcavity can be approximated a dilute boson gas [25]. Thus in this approximation and the electric-dipole and the rotating-wave approximation the full Hamiltonian for this system can be written as [26–28]

$$H = \Delta_c \hat{a}^\dagger \hat{a} + \Delta_\omega \hat{b}^\dagger \hat{b} + \Delta_a \hat{\sigma}_z + ig_1\big(\hat{a}^\dagger \hat{\sigma}_- - a\hat{\sigma}_+\big) + i\varepsilon\big(\hat{a}^\dagger - \hat{a}\big) + ig_2\big(\hat{a}^\dagger \hat{b} - \hat{a}\hat{b}^\dagger\big), \tag{1}$$

noted that we have assumed that there is no interaction between the atom and exciton. Where $\hat{a}$ ($\hat{a}^\dagger$) and $\hat{b}$ ($\hat{b}^\dagger$) represent the annihilation (creation) operators of cavity field and exciton. g_1 and g_2 are the atom-field and exciton–cavity coupling constants, respectively, and ε is the amplitude of the external driving field. $\hat{\sigma}_+$, $\hat{\sigma}_-$ and $\hat{\sigma}_z$ are the Pauli spin operators which describe the two-level atom and satisfy the communication relations $[\hat{\sigma}_+, \hat{\sigma}_-] = 2\hat{\sigma}_z$, $[\hat{\sigma}_\pm, \hat{\sigma}_z] = \mp\hat{\sigma}_\pm$. The atomic detuning Δ_a, the cavity detuning Δ_c and the exciton detuning Δ_ω are defined by

$$\Delta_a = \omega_a - \omega_0, \qquad \Delta_c = \omega_c - \omega_0, \qquad \Delta_\omega = \omega_e - \omega_c, \tag{2}$$

where ω_e, ω_c, ω_a and ω_0 are the frequencies of exciton, cavity, atom and external field, respectively. Now considered the loss of the cavity (exciton) and the spontaneous emission of the atom, the master equation for the density operator $\hat{\rho}(t)$ of our system can be written as

$$\begin{aligned}\frac{d\rho}{dt} &= -i\Delta_c\big[\hat{a}^\dagger\hat{a}, \rho\big] - i\Delta_\omega\big[\hat{b}^\dagger\hat{b}, \rho\big] - i\Delta_a[\hat{\sigma}_z, \rho] + g_1\big[\hat{a}^\dagger\hat{\sigma}_- - \hat{a}\hat{\sigma}_+, \rho\big] + g_2\big[\hat{a}^\dagger\hat{b} - \hat{a}\hat{b}^+, \rho\big] + \varepsilon\big[\hat{a}^\dagger - \hat{a}, \rho\big] \\ &\quad + \frac{\gamma}{2}(2\hat{\sigma}_-\rho\hat{\sigma}_+ - \hat{\sigma}_+\hat{\sigma}_-\rho - \rho\hat{\sigma}_+\hat{\sigma}_-) + \kappa_1\big(2\hat{a}\rho\hat{a}^\dagger - \hat{a}^\dagger\hat{a}\rho - \rho\hat{a}^\dagger\hat{a}\big) + \kappa_2\big(2\hat{b}\rho\hat{b}^\dagger - \hat{b}^\dagger\hat{b}\rho - \rho\hat{b}^\dagger\hat{b}\big),\end{aligned} \tag{3}$$

where γ is the spontaneous emission rate of the two-level atom in the cavity. κ_1 (κ_2) is the cavity (exciton) loss.

3. The solution of the master equation

In this section we will derive the solution of the master equation following the method introduced by Jordon [29]. For a two-level atom the atomic density operator Γ_a can be expressed as

$$\Gamma_a = \sum_{i,j=1}^{2} s_{ij}|i\rangle\langle j| = s_{11}|1\rangle\langle 1| + s_{22}|2\rangle\langle 2| + s_{21}|2\rangle\langle 1| + s_{12}|1\rangle\langle 2|, \tag{4}$$

where s_{ij} is constant. Using the relations between the elements $s_{21} = s_{12}^*$, $s_{11} + s_{22} = 1$ and introducing $s_{22} - s_{11} = 2m$, $s_{21} = \mu$, we can express the density operator $\rho(t)$ as

$$\begin{aligned}\hat{\rho}(t) &= \int P(\alpha, \alpha^*, \beta, \beta^*, \mu, \mu^*, m, t)|\alpha\beta\rangle\langle\alpha\beta|\Gamma_a\, d^2\alpha\, d^2\beta\, d^2\mu\, dm \\ &= \int P(\alpha, \alpha^*, \beta, \beta^*, \mu, \mu^*, m, t)|\alpha\beta\rangle\langle\alpha\beta|[2m\hat{\sigma}_z + 1/2 + \mu\hat{\sigma}_+ + \mu^*\hat{\sigma}_-]\, d^2\alpha\, d^2\beta\, d^2\mu\, dm,\end{aligned} \tag{5}$$

where $|\alpha\rangle$ ($|\beta\rangle$) is a coherent state of operator $\hat{a}$ ($\hat{b}$) with the eigenvalue α (β). μ, μ^* and m represent c-number variables corresponding to the quantum operators $\hat{\sigma}_-$, $\hat{\sigma}_+$ and $\hat{\sigma}_z$, respectively. In order to determine the weight function P, followed the procedure used in the Ref. [26], the Fokker–Planck equation can be obtained