Cavity-assisted generation of entangled photons from a V-type three-level system

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Abstract. We propose a new type of entangled-photon generation from a V-type system in a microcavity. In contrast to the entangled-photon generation until now, all four Bell states can be freely generated from an identical cavity system by simply selecting applied-field polarizations and frequencies due to the excitation of dressed states in cavity quantum electrodynamics (CQED). CQED effects play a crucial role in providing a high degree of entanglement: (i) spectral filtering can be used to extract entangled photons due to the vacuum Rabi splitting and (ii) non-entangled co-polarized photons are strongly suppressed due to the photon blockade effect. The proposed system efficiently generates a high degree of entangled photons by moderately increasing the applied-field intensity.

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1. Introduction

Nonlocal entangled states are important resources for implementing quantum information processing such as quantum key distribution, quantum teleportation and quantum logic gates [1]. Among the various types of entangled states, polarization-entangled photons are expected to be good carriers for quantum communication because they do not interact with each other.

In order to generate polarization-entangled photons, it is necessary to achieve two-photon cascade emission through degenerate intermediate states having different polarizations. An early technique for entangled-photon generation was the two-photon cascade decay of an atomic excitation [2]–[6]. An analogous cascade-decay process in a semiconductor has been pointed out by Benson et al [7], i.e. the cascade decay of a biexciton via degenerate excitons. For the first time, entangled-photon generation via biexcitons has been observed in resonant hyper-parametric scattering (RHPS) [8, 9], which was theoretically predicted by Savasta et al [10]. A drastic enhancement of the generation of the entangled photons due to the presence of a microcavity has been predicted for a quantum well in terms of cavity quantum electrodynamics (CQED) [11, 12]. Optimum enhancement occurs when the excited dressed states contain biexciton and cavity photon components at comparable levels. Recently, entangled-photon generation from a biexciton in a single quantum dot (QD) has been reported [13]–[15]. Although fine-structure splitting of cross-polarized excitons prevents entangled-photon generation, the problem can be overcome by applying a magnetic field [13, 14] or by using spectral filtering [15]. It has been demonstrated that the reliable entanglement still survives for elevated temperatures up to 30 K [16]. Another solution involves using a microcavity [17], in which degenerate exciton polaritons act as the intermediate states of a cascade emission from a biexciton. These systems provide event-ready entangled-photon generation. Furthermore, a different scheme to create quantum entanglement between two separate spins in QD–CQED systems has been proposed [18].

In this paper, we propose entangled-photon generation in RHPS via dressed states for a V-type three-level system in a microcavity. In contrast to the existing schemes of entangled-photon generation, it is interesting to note that all four Bell states can be generated from an identical cavity system by selecting applied-field polarizations and frequencies. This novel feature significantly enhances the degrees of freedom in applications of entangled-photon pairs. Furthermore, the degree of entanglement is significantly enhanced due to the photon blockade effect [19]–[21]. The flexibility to generate various Bell states and the high degree of entanglement result from dressed states consisting of two energy quanta (2e dressed states). The 2e dressed states play a crucial role in the proposed entangled-photon generation because they...
have many effects on this generation. Our study is expected to open new avenues for research on CQED based on 2e dressed states. Furthermore, because this process does not involve the use of biexcitons, various materials could possibly be used for the proposed entangled-photon generation.

2. Model and dressed states

Figure 1 shows a schematic illustration of our proposed system. The excited states with right polarization $|X_R\rangle$ and left polarization $|X_L\rangle$ are degenerate with frequency $\omega_0$. The cavity-mode frequency is tuned to $\omega_0$. The right- and left-polarized coherent fields $E_\xi e^{-i\Omega_0 t}$ ($\xi = \{R, L\}$) are applied through a cavity mirror. The coupling constant between the excitation transition and a cavity-mode photon is denoted by $g$. In the rotating-wave approximation, the system Hamiltonian is given by

$$H_V = \hbar \omega_0 \sum_{\xi=R,L} (|X_\xi\rangle\langle X_\xi| + a_\xi^\dagger a_\xi) + \left(i\hbar \sqrt{\Gamma} \sum_{\xi=R,L} E_\xi a_\xi^\dagger e^{i\Omega_0 t} + \text{H.c.}\right) + \left[i\hbar g (a_L^\dagger |g\rangle \langle X_R| + a_R^\dagger |g\rangle \langle X_L|) + \text{H.c.}\right],$$

(1)

where $a_R$ ($a_L$) is an annihilation operator of the right (left)-polarized cavity photon. The second term in equation (1) represents the coupling between coherent fields and cavity modes, and the coupling constant is expressed as $\Gamma = \omega_0/2Q$, where $Q$ is the cavity quality factor [22, 23].

The eigenstates of Hamiltonian (1) without the input fields $E_\xi$ represent the dressed states, which are classified into $n$-excitation ($n$e) manifolds, where $n$ is the number of energy quanta inside the cavity. The 1e manifold consists of two dressed states (1e states) with frequencies $\omega^{1e}_\pm = \omega_0 \pm g$; each state has twofold degeneracy with respect to polarization. For example, each 1e state having right polarization is represented as

$$|R\pm\rangle = \frac{1}{\sqrt{2}} (|1_R\rangle \mp i|X_R\rangle), \quad \omega^{1e}_\pm = \omega_0 \pm g,$$

(2)

where $|1_R\rangle$ denotes the Fock state with one right-polarized photon in the cavity. The 2e manifold is further classified into cross-polarized and co-polarized 2e manifolds. The cross-polarized 2e manifold consists of three dressed states (cross-polarized 2e states):

$$|RL0\rangle = \frac{1}{\sqrt{2}} (|X_R; 1_L\rangle - |X_L; 1_R\rangle), \quad \omega^{0e}_0 = 2\omega_0$$

(3)

$$|RL\pm\rangle = \frac{1}{2}(\sqrt{2} i|1_R 1_L\rangle \pm |X_R; 1_L\rangle \pm |X_L; 1_R\rangle), \quad \omega^{2e}_\pm = 2\omega_0 \pm \sqrt{2}g.$$

(4)
The co-polarized 2e manifold consists of two dressed states (co-polarized 2e states) with frequencies $\omega_{2e}$; each state has twofold degeneracy. For example, co-polarized 2e states with right polarization are represented as $|RR\pm\rangle = \frac{1}{\sqrt{2}}(|2\text{R}\rangle \mp i|X\text{R}\rangle; 1\text{R})$. Figure 2 shows a schematic diagram of the dressed states in this system. Energy levels of the co-polarized 2e states and 1e states with left polarization are represented by blue horizontal lines, those with right polarization are represented by red horizontal lines, and the levels of the cross-polarized 2e states are represented by black lines.

### 3. Entangled-photon states

The interaction Hamiltonian $H_{\text{int}}^{\text{vac}}$ between the cavity photons and the vacuum field outside the cavity is expressed as

$$H_{\text{int}}^{\text{vac}} = i\hbar \sqrt{\Gamma} \int_{-\infty}^{\infty} d\omega \sum_{\xi = \{R, L\}} b_{\xi}^\dagger(\omega) a_\xi + \text{H.c.},$$

where $b_R(\omega)$ [$b_L(\omega)$] is the annihilation operator of the right (left)-polarized photons outside the cavity and H.c. represents the Hermitian conjugate. We approximately recast $H_{\text{int}}^{\text{vac}}$ in terms of the dressed states up to the cross-polarized 2e states as follows:

$$H_{\text{int}}^{\text{vac}} \approx i\hbar \sqrt{\Gamma} \sum_{i=\pm} b_R^{\dagger}(\omega_i^{1e}) A_{G;Ri} + b_L^{\dagger}(\omega_i^{1e}) A_{G;Li}$$

$$+ \sum_{j=0,\pm} \left[ b_R^{\dagger}(\omega_{i;j}) A_{Li;Rlj} + b_L^{\dagger}(\omega_{i;j}) A_{Ri;Rlj} \right] + \text{H.c.},$$

with $\omega_{i;j} = \omega_{2e}^{\pm} - \omega_i^{1e}$ and $|G\rangle = |g; 0_L 0_R\rangle$. The operator $A_{\alpha;\beta} = \gamma_{\alpha;\beta}|\alpha\rangle\langle\beta|$ with $\gamma_{\alpha;\beta} = \langle\alpha|a_\xi|\beta\rangle$ represents a transition between $|\alpha\rangle$ and $|\beta\rangle$ belonging to different manifolds. In
Figure 3. Concurrence of photon pairs as a function of $g/\Gamma$ and $\Delta \Omega_R/\Gamma$, where $\Omega_L = \omega_L^{1e}$ is fixed. The generation process is illustrated in the upper-left corner. The solid lines show the resonant conditions for exciting the cross-polarized 2e states $|RL\pm\rangle$ and $|RL0\rangle$. This approximation, we select $b_{R(L)}(\omega)$ and $b_{R(L)}^\dagger(\omega)$ that have transition frequencies. This approximation is valid for $g/\Gamma \gg 1$, where the dressed states are well separated from each other. The entangled-photon states are obtained as follows:

$$\begin{align}
(H_{\text{int}})^2 |RLj\rangle &\propto \sum_{i=\pm} \left[ \gamma_{GL} \gamma_{LI} b_R^\dagger(\omega_i^{1e}) b_L^\dagger(\omega_{i;j}) + \gamma_{GR} \gamma_{RL} b_R^\dagger(\omega_i^{1e}) b_L^\dagger(\omega_{i;j}) \right] |\Omega\rangle |G\rangle, \\
&\text{(8)}
\end{align}$$

where $|\Omega\rangle$ represents a vacuum state outside the cavity. Then, we obtained the generated photon states $|\Psi\rangle$ as follows:

$$|\Psi\rangle \propto \sum_{i=\pm} s_i j (|L\omega_i^{1e}\rangle |R\omega_{i;j}\rangle + |R\omega_i^{1e}\rangle |L\omega_{i;j}\rangle),$$

(emission from $|RLj\rangle$, $j = \pm$),

$$(9)$$

$$|\Psi\rangle \propto \sum_{i=\pm} s_{i0} (|L\omega_i^{1e}\rangle |R\omega_{i;0}\rangle - |R\omega_i^{1e}\rangle |L\omega_{i;0}\rangle),$$

(emission from $|RL0\rangle$),

$$(10)$$

where $|R(L)\omega\rangle = b_{R(L)}^\dagger(\omega)|\Omega\rangle$, $s_{++} = s_{--} = \sqrt{2} + 1$, $s_{+-} = s_{-+} = \sqrt{2} - 1$ and $s_{\pm0} = \pm 1$. The index $i$ in the summations in equations (9) and (10) indicates intermediate 1e states; thus the photon pairs become entangled as superpositions of four two-photon states.

Because the V-type level is strongly coupled with the single-cavity mode, most of the photons are scattered in the same direction as that of the input fields. Therefore, the generated entangled photons should be separated from the scattered photons in the linear response regime. The entangled photons can be extracted by spectral filtering. Let us assume that either of the input-field frequencies $\Omega_R$ or $\Omega_L$ is tuned to the lower 1e state. Then, the photon pairs generated via the upper 1e state would have frequencies that are different from $\Omega_R$ and $\Omega_L$ (see the level diagram in figure 3). After spectral filtering, the entangled-photon pairs are represented by
Table 1. Entangled-photon states for cross-polarized input fields \((R, L), (H, V)\) and \((D, \bar{D})\). \(|\xi_\xi\pm\rangle\) and \(|\xi_\xi0\rangle\) represent excited cross-polarized 2e states depending on the set of cross-polarizations. Frequencies of photon states are omitted.

| \(|\xi_\xi\pm\rangle\) | \(|\xi_\xi0\rangle\) |
|----------------|----------------|
| \((R, L)\) | \(|LR\rangle + |RL\rangle\) | \(|LR\rangle - |RL\rangle\) |
| \((H, V)\) | \(|LL\rangle - |RR\rangle\) | \(|LR\rangle - |RL\rangle\) |
| \((D, \bar{D})\) | \(|LL\rangle + |RR\rangle\) | \(|LR\rangle - |RL\rangle\) |

equation (9) or (10) without summation over the negative value of \(i\). Similarly, spectral filtering of the entangled photons is also possible when the 2e states are excited via the upper 1e state. In both cases, the sign of superposition is positive for the entangled photons via \(|RL\rangle\) (see equation (9)) and negative for those via \(|RL0\rangle\) (see equation (10)).

The 2e dressed states are classified into singlet Bell excitation \(|RL0\rangle\) and triplet Bell excitations \{|\(|RL+\rangle, |RR+\rangle, |LL+\rangle\}\} and \{|\(|RL-\rangle, |RR-\rangle, |LL-\rangle\}\}. The singlet Bell excitation is also accessible by other sets of classical cross-polarized input fields such as horizontal \((H)\) and vertical \((V)\) polarizations or +45° \((D)\) and −45° \((\bar{D})\) polarizations. The resulting entangled-photon state from the singlet Bell excitation is independent of the set of cross-polarizations. In contrast, various types of triplets of entangled photons can be obtained by selecting the set of cross-polarizations (see table 1). This peculiar feature arises from the degeneracy of the triplet Bell excitations, which provides various states by the superpositions of these excitations. The form of the triplet Bell excitation is determined from the set of cross-polarizations. It should be noted that the triplet entangled-photon state generated from a bound biexciton is fixed as \(|LR\rangle + |RL\rangle\) irrespective of the set of cross-polarizations. This is because of the fact that the biexciton level is separated from the other two-exciton states due to the Coulomb interaction. In the following, we focus on the generation of entangled-photon pairs applying circularly cross-polarized input fields.

4. Concurrence

It should be noted that non-entangled co-polarized photons are also generated in this configuration because classical laser fields contain more than one photon. Then, the degree of entanglement of the photon pairs as a mixed state would be suppressed by the co-polarized non-entangled photon pairs. In order to investigate the degree of entanglement, we evaluate the concurrence \(C\). The concurrence increases monotonically from 0 to 1 with the degree of entanglement. A photon pair is maximally entangled at \(C = 1\). The concurrence is calculated from the reduced density matrix \(\rho\) of two photons after spectral filtering, where we extract the photons by cascade emission via the upper 1e states. In order to take into account the cavity-photon leakage \(\Gamma\) and the damping \(\gamma\) of the excited states, we use a standard master equation for the calculation of the reduced density matrix. In this model, the density matrix has the form

\[
\rho = \begin{pmatrix}
\rho_a & \rho_b & 0 & 0 \\
\rho_b^* & \rho_c & 0 & 0 \\
0 & 0 & \rho_d & 0 \\
0 & 0 & 0 & \rho_e
\end{pmatrix},
\]
where the bases are in the following order: $|L \omega_1 |e \rangle$, $|R \omega_1 |e \rangle$, $|L \omega_2 |e \rangle$, $|R \omega_2 |e \rangle$, and $|R \omega_3 |e \rangle$. Then, the concurrence $C(\rho)$ is obtained from $C(\rho) = \max(0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4})$; here, $\lambda_i$ denotes the eigenvalues, in decreasing order, of the Hermitian matrix $\rho (\sigma_e \otimes \sigma_e) \rho^* (\sigma_e \otimes \sigma_e)$ with $\sigma_e$ being the Pauli matrix. By the input–output theory, annihilation operators for right-polarized photons outside the cavity are derived as $b_R = \sqrt{\Gamma} (A_{L+; RLi} + A_{R+; RRj} + A_{G; R^+})$, where $j = 0, \pm$. The annihilation operators for the left-polarized photons are obtained in a similar manner. Then, $\rho_a$, for example, is given by

$$\rho_a \propto | \gamma_{G; L} |^2 \sum_{i, j = (0, \pm)} \gamma_{L+; RLi}^* \gamma_{L+; Rlj} \langle \langle RLi | \langle Rlj \rangle \rangle.$$

(12)

Figure 3 shows the concurrence of the photon pairs generated from the cascade emission from the 2e states via the upper 1e states, where the 2e states are excited via the lower 1e state (see the level diagram in figure 3). The concurrence is calculated as a function of $g / \Gamma$ and $\Delta \Omega_R / \Gamma \equiv (\Omega_R - \omega_0) / \Gamma$ under the condition $\Omega_R = \omega_1^e$ in the weak-field limit of $\mathcal{E}_g$. We set the damping constant of the excited states as $\gamma / \Gamma = 0.01$. The solid lines in the figure represent resonant conditions for the excitation of the cross-polarized 2e states. Under these conditions, the concurrence tends to 1 with an increase in $g / \Gamma$. This behavior originates from the significant reduction in the excitation of the co-polarized 2e states. The reduction is due to the photon blockade effect, where the excitation of a dressed state by the first photon blocks the transmission of the second photon that has the same polarization and frequency. This photon blockade has been theoretically pointed out [19] and has been demonstrated for optical cavity containing one trapped atom [20]. Recently, this effect has been observed using a QD in a photonic crystal resonator [21]. Figure 2 shows excitation processes indicated by blue and red arrows for left- and right-polarized input fields, respectively. Input field frequency of left polarization is tuned to the resonant excitation condition $| G \rangle \rightarrow | L \rangle$, and that of right polarization is tuned to the resonant excitation condition $| L \rangle \rightarrow | R L \rangle$ in this figure. Resonant excitation processes are indicated by solid arrows. Then, the cross-polarized 2e states $| R L \rangle$ show double resonant excitation. However, the co-polarized 2e states $| L L \rangle$ and $| R R \rangle$ cannot be excited double resonantly due to the anharmonicity of the JC ladder; the Rabi splitting of the co-polarized 2e manifold is $2 \sqrt{2} g$, while that of the 1e manifold (vacuum Rabi splitting) is $2 g$. As a result, the excitation of the co-polarized 2e states becomes non-resonant when the photon frequency is tuned to a dressed state in the 1e manifold. The anharmonicity increases with $g$; thus, there is significant reduction in co-polarized photon generation for large $g$.

Figure 4 shows concurrence as a function of input-field amplitude under the resonant conditions for the excitation of the 2e states at $g / \Gamma = 30$. The inset of figure 4 shows generation efficiency of cross-polarized photon pairs. The efficiency is normalized by that in the absence of the cavity, and thus, the value represents the enhancement ratio of generation efficiency due to the cavity. In the calculation, we extend the Fock space of the cavity photons sufficiently in order to include the higher dressed states up to 5e states. The concurrence decreases with the input-field amplitude and eventually becomes 0. On the other hand, the generation efficiency of cross-polarized photon pairs increases rapidly and almost saturates at a high-field amplitude due to the saturation of the 2e states. In the range $0 < \mathcal{E} / \sqrt{\Gamma} < 1.0$, the concurrence of entangled photons via $| RL+ \rangle$ and $| RL0 \rangle$ scarcely decreases; however, the generation efficiency increases rapidly with $\mathcal{E}_g^2 \mathcal{E}_l^2$ and saturates. Thus, the proposed system efficiently generates entangled-photon pairs without loss of concurrence.
Figure 4. Concurrence as a function of input-field amplitudes $\varepsilon_R = \varepsilon_L = \varepsilon$ under three resonant conditions exciting cross-polarized 2e states at $g/\Gamma = 30$ (see figure 3). The inset shows $\rho_a$ normalized by $\rho_a(\varepsilon/\sqrt{\Gamma} = 10^{-2})$ via $|RL\rangle$, which is the generation efficiency of cross-polarized photon pairs.

5. Discussion and conclusion

The proposed entangled-photon generation is carried out in the atoms in the microcavity. For example, $4s4p\,^1P_1(M = \pm 1) \rightarrow 4s\,^1S_0$ transitions in a calcium atom are one of the good candidates. These transitions have been partly utilized for entangled-photon generation in the $4p\,^1S_0 \rightarrow 4s4p\,^1P_1(M = \pm 1) \rightarrow 4s\,^1S_0$ cascade [6]. Another candidate is a QD in the microcavity. In contrast to the atomic levels, we must consider the two-exciton states in a QD, i.e. bound and unbound biexcitons that can be generated by cross-polarized and co-polarized excitations, respectively. Even so, our scheme shown in figure 2 will remain unchanged as long as the levels of biexciton states are separated to a considerable extent from the 2e manifold, to which the excitation is tuned. Under this condition, the concerned levels can still be treated as the V-type system (figure 2); thus, the proposed entangled-photon generation would be effective. These desirable situations are realized, for example, in GaAs or In(Ga)As QDs; it has been observed that the vacuum Rabi splitting is of the order of $100\,\mu$eV [24]–[26], whereas the exciton–biexciton separation is of the order of a few meV [13]–[15].

In conclusion, we have theoretically shown that the V-type system in a microcavity can generate cross-polarized entangled photons in RHPS via dressed states. The entangled-photon states can be controlled by selecting appropriate input-field polarizations and cross-polarized 2e states. The generated entangled photons can be extracted by spectral filtering due to vacuum Rabi splitting in the 1e manifold. Although co-polarized non-entangled photons are also generated, their generation is considerably suppressed in the strong-coupling regime owing to the photon blockade effect. Thus, the concurrence, which indicates the degree of entanglement, tends to 1 with an increase in the coupling constant. It should be noted that these characteristic features, including the generation mechanism, originate from the CQED.

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