Counter-polarized single-photon generation from the auxiliary cavity of a weakly nonlinear photonic molecule

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We propose a scheme for the resonant generation of counter-polarized single photons in double asymmetric cavities with a small Kerr optical nonlinearity (as that created by a semiconductor quantum well) compared to the mode broadening. Due to the interplay between spatial intercavity tunneling and polarization coupling, by weakly exciting with circularly polarized light one of the cavities, we predict strong antibunching of counter-polarized light emission from the non-pumped auxiliary cavity. This scheme due to quantum interference is robust against surface scattering of pumping light, which can be suppressed both by spatial and polarization filters.

Figure 1. (a) Sketch of the system consisting of two coupled micropillars: due to the shape anisotropy, the photon eigenmodes have orthogonal linear polarizations. The mode with \(\xi\) polarization in pillar \(j\) is denoted as \(j\xi\), and the energy levels for the single photon states in each pillar are depicted. By illuminating circularly polarized light on pillar A, counter-polarized single photons are emitted from pillar B even with a small nonlinearity. (b) The equal-time second-order correlation functions \(g^{(2)}(0)\) are plotted as functions of nonlinearity \(U\) normalized to broadening \(\gamma\). The tunneling strength is \(J = 5\gamma\), the polarization splitting is \(\Delta = 2.5\gamma\), and the pump frequency is tuned as \(\delta E = E - \hbar\omega_p = 0.2772\gamma\). In addition to the antibunching of the pumped mode \(A^+\), nearly perfect antibunching is obtained in mode \(B^-\) with the relatively small nonlinearity \(U = 0.0438\gamma\).

As a realistic system, we consider two spatially separated semiconductor micropillars with asymmetric shape,\textsuperscript{10} coupled with a photonic tunneling strength \(J\). Each pillar has two different linearly polarized photonic modes \((x\) and \(y\) directions), energetically split by \(2\Delta\) due to the shape anisotropy. Fig. 1(a) shows a sketch of the photonic molecule approach by taking advantage of the polarization degree of freedom in asymmetric cavities having a frequency splitting between modes with orthogonal linear polarizations. We show how to get counter-polarized single-photons from the non-pumped auxiliary cavity, thus providing a way to get rid of the pump spurious scattering by both spatial and polarization filtering.

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sidered system. The Hamiltonian is represented as
\[ \hat{H} = \sum_{j=\{A,B\}}[(E + \Delta \hat{a}_{jx}^\dagger \hat{a}_{jx} + (E - \Delta) \hat{a}_{jy}^\dagger \hat{a}_{jy}) + \sum_{\xi=(x,y)} J(\hat{a}_A^\dagger \hat{a}_B \xi + \text{H.c.}) + (F e^{i\omega_p \tau} \hat{a}_{A+}^\dagger + \text{H.c.}) + \sum_{j=\{A,B\}, \xi=(+,-)} U \hat{a}_{j\xi}^\dagger \hat{a}_{j\xi}^\dagger \hat{a}_{j\xi} \hat{a}_{j\xi}. \] (1)

Here, \( \hat{a}_{j\xi} \) is the annihilation operator of a photon with polarization \( \xi \) in pillar \( j \). The relation between circularly and linearly polarized modes is given by the standard operator expression \( \hat{a}_{j\pm} = (\hat{a}_{jx} \pm i\hat{a}_{jy})/\sqrt{2} \). We consider the configuration where pillar \( A \) is pumped with \( \sigma_+ \)-circular polarization, being \( \omega_p \) and \( F \) the pump frequency and amplitude respectively. The pumping strength is mod-

terate to guarantee the average number of photons in the system not exceeding unity. If the average number is increased, antibunching is worsened, because the quantum interference in the present scheme is valid if three-photon subspace can be neglected, as in the previous considerations.8,9 The nonlinearity is repre-

sented by the last term in Eq. (1) conserving the total spin of two photons. The effective nonlinearity can be mediated by the presence of a quantum well excitonic resonance,11 but this effective Kerr term is quite general for systems with a third-order nonlinearity. The cross-polarized term such as \( U_{\text{cross}} \hat{a}_{j\xi}^\dagger \hat{a}_{j\xi} \hat{a}_{j\xi}^\dagger \hat{a}_{j\xi} \) is not considered in the present paper, because \( U_{\text{cross}} \) is usually much smaller than \( U \),12 but it could be added without qualitative changes (not shown). By using the theoretical method detailed in Ref. 7, we have numerically calculated second-order correlation functions \( g^{(2)}_{\xi\eta}(\tau) = \langle \hat{a}_{j\xi}^\dagger \hat{a}_{j^\prime\eta}^\dagger(\tau) \hat{a}_{j^\prime\eta}(\tau) \hat{a}_{j\xi}(\tau) \rangle / \langle \hat{a}_{j\xi}(\tau) \hat{a}_{j\xi}(\tau) \rangle \) at the steady state under continuous pumping and a dissipation of photons with a rate \( \gamma / h \) in each mode.

In Fig. 1(b), we plot equal-time correlations \( \{g^{(2)}_{\xi\xi}(\tau = 0)\} \) as a function of nonlinearity \( U \) normalized to \( \gamma \). We consider the tunneling strength \( J = 5\gamma \), polarization splitting \( \Delta = 2.5\gamma \), and pump detuning \( \delta E = E - h\omega_p = 0.2772\gamma \). In addition to antibunching at the pumped mode \( A+ \) due to the previously proposed scheme8,9 strong antibunching is achieved for mode \( B- \) with the (small) optimal nonlinearity \( U = 0.0438\gamma \). In the weak pumping limit, \( g_{B-,B-}(\tau = 0) \) is reduced to zero. The underlying destructive quantum interference is different from the previous one in Refs. 8 and 9. By deriving the equations of motions for the amplitudes of the possible Fock states for the zero-, one- and two-photon states (generalizing the method in Ref. 9) we have derived the optimal conditions of the counter-polarized antibunching and found the interference paths leading to the antibunching in mode \( B- \). In Fig. 2(a), the zero-, one-, and two-photon state manifolds are depicted and labeled as \( \{|0\rangle, |\xi\rangle, |\xi,\eta\rangle\} \), respectively. The paths responsible to antibunching in mode \( |B-,B-\rangle \) are the \( \Delta \)-assisted (spatial tunneling) path from \( |\pm\rangle \) and the

\[ |A+,A-\rangle |A-,A-\rangle \]
\[ 2U |A+,A-\rangle |A+,B-\rangle |A-,B-\rangle |A-,B-\rangle |B+,B-\rangle |B-,B-\rangle \]
\[ |A+,B+\rangle |A-,B-\rangle |A-,B+\rangle |B+,B-\rangle \]
\[ |A-,A-\rangle |B+,B-\rangle |A+,B-\rangle |B+,B+\rangle \]

\[ |A+,B+\rangle |A-,B+\rangle |B-,B+\rangle |B-,B-\rangle \]

FIG. 2. (a) Sketch of all the transition paths between zero-photon \( |0\rangle \), one-photon \( |\xi\rangle \), and two-photon states \( |\xi,\eta\rangle \). The antibunching of mode \( B- \) is due to the destructive quantum interference between the two paths from \( |A-,B-\rangle \) and \( |B-,B-\rangle \) to \( |B-,B-\rangle \). (b) Pictorial representation. If there is already a "-" photon in pillar B, another "-" photon cannot exist in the same pillar because of the interference between the \( J \)-assisted (spatial tunneling) path from "-" photon in pillar A and the \( \Delta \)-assisted (polarization coupling) path from "+" photon in pillar B. This quantum interference occurs for an optimal value of the nonlinearity and laser detuning.
In conclusion, we have proposed a scheme of single-photon generation due to a destructive quantum interference effect in a weakly nonlinear double cavity system, where each cavity have two linearly polarized, frequency-split modes. Due to the spatial tunneling between the two cavities and the coupling between opposite circular polarizations, we have found that strong antibunching of counter-polarized emission can be obtained at the non-pumped auxiliary pillar. This new effect is of practical implications, because it provides a direct way to suppress the pump scattering via spatial and polarization filters. This scheme can also be exported to arrays of nonlinear photonic molecules.

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Finally, we have examined the robustness of the present scheme against dephasing of photons. Since quantum interferences are responsible in the present and previous schemes, pure dephasing can decrease the quality of the antibunching. By using the standard pure dephasing model due to quadratic coupling with a reservoir, we consider dephasing with a rate $\Gamma/\hbar$ affecting linearly polarized modes of each pillar (the results shown below are not significantly modified even if the dephasing is supposed to affect the circularly polarized modes). Fig. 3(c) shows $g_{B^-B^-}^{(2)}(\tau = 0)$ as a function of $\Gamma/\gamma$. The tunneling strength is $J = 5\gamma$, and the splitting $\Delta$ is chosen to give perfect antibunching for each nonlinearity $U$ in the absence of pure dephasing. As clearly shown, the antibunching can be significantly worsened in presence of pure dephasing for a given value of the nonlinearity. However, even if the nonlinearity is quite small, for example $U = 0.05\gamma$, antibunching is still observable if $\Gamma = 10^{-2}\gamma$ and becomes very strong if $\Gamma = 10^{-3}\gamma$. The curves in Fig. 3(c) do not strongly depend on the tunneling strength $J$ if the nonlinearity $U$ is large enough compared to the corresponding minimum shown in Fig. 3(a). Since the optimal nonlinearity can be weak in the present scheme, one can consider cavities with relatively small photon lifetime (small quality factor) in a regime where the pure dephasing time can be thus neglected, a very promising outlook.

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