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A universal quantum frequency converter via four-wave-mixing processes

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ABSTRACT

We present a convenient and flexible way to realize a universal quantum frequency converter by using nondegenerate four-wave-mixing processes in the ladder-type three-level atomic system. It is shown that quantum state exchange between two fields with large frequency difference can be readily achieved, where one corresponds to the atomic resonant transition in the visible spectral region for quantum memory and the other to the telecommunication range wavelength (1550 nm) for long-distance transmission over optical fiber. This method would bring great facility in realistic quantum information processing protocols with atomic ensembles as quantum memory and low-loss optical fiber as transmission channel.

1. Introduction

Efficient and effective quantum state exchange between light and light, light and matter, as well as matter and matter plays an essential role in realistic quantum information processing [1–3]. As is well known, light is the best long-distance quantum information carrier, whereas the atomic ensembles provide an alternative attractive medium for storage and manipulation of quantum information. A real quantum information network would be composed of many quantum nodes and channels. At the nodes of quantum networks, multiple entangled fields with narrow bandwidth and different frequencies are quite necessary for connecting different physical systems. Due to the broad bandwidth and degenerate feature of multipartite entanglement produced through the conventionally-used way of combining the entangled twin beams via spontaneous parametric down-conversion in nonlinear crystals with the linear optical elements (polarizing beam splitters) [4,5], thus, limiting its application in realistic quantum information processing, the generation of nondegenerate multiple entangled fields with narrow bandwidths has also been intensively studied by either cascaded nonlinearities [6–9], concurrent optical parametric oscillation [10], or nondegenerate four-wave mixing (FWM) [11–21] in an atomic ensemble.

The distribution of quantum states over long distance can be performed either in free space or with low-loss optical fiber as quantum channels. Most of the studies have been focused on the former case, where the light wavelength corresponding to the atomic resonant transition to the lower excited state is usually in the visible region; however, the unavoidable loss of quantum information due to spatial obstacle in free space would bring trouble to realistic quantum information processing. Moreover, the required light wavelength for low-loss transmission over optical fiber is about 1550 nm or 1310 nm, which is not easily obtained with the atomic resonant transition to the lower excited state.

To overcome these limitations, here, we present a convenient and flexible way to realize a universal quantum frequency converter in the ladder-type three-level atomic system. By using the nondegenerate FWM processes, quantum state exchange between two fields at different frequency regions (one corresponding to the atomic resonant transition in the visible spectral region for quantum memory and the other to the wavelength of 1550 nm for low-loss optical fiber communication) can be readily achieved, which is superior to that realized in the Λ-type configuration in Refs. [11–21], where the frequency difference between two entangled fields is limited to the frequency separation of the lower doublet. In principle, any desired number of entangled fields at optical fiber communication and atomic storage wavelengths can be obtained through multiple FWM processes. This method would bring great convenience to quantum repeater for distributing quantum states over long distance and mapping quantum state into atomic memory, thereby having potential applications in realistic quantum information processing.

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2. Theoretical mode and evolution equations

The considered ladder-type three-level model is shown in Fig. 1 Levels $|1\rangle$, $|1\rangle$, and $|1\rangle$ correspond, respectively, to the states $5S_{1/2}$, $5P_{3/2}$, and $4D_{5/2,3/2}$ of ^{85}Rb atom. The strong coupling field E_c (with frequency ω_c and Rabi frequency Ω_c) couples the atomic resonant transition $|1\rangle$–$|3\rangle$ via two-photon excitation with the two-photon detuning $\Delta=2\omega_c-\omega_{31}$, and its one-photon detuning from the atomic resonant transition $|1\rangle$–$|2\rangle$ (corresponding resonant wavelength of about 780 nm) is denoted as $\Delta_c=\omega_c-\omega_{21}$. By applying a mixing field E_{m1} (with frequency ω_1) tuned to near resonance with the atomic transition $|1\rangle$–$|2\rangle$ with the detuning of $\Delta_1=\omega_1-\omega_{21}$, a field E_F with a detuning equal to $\Delta-\Delta_1$ with respect to the atomic resonant transition $|2\rangle$–$|3\rangle$ (corresponding resonant wavelength of about 1530 nm) can be generated through the nondegenerate FWM process. In what follows, by using the Heisenberg–Langevin method with the mixing field and generated FWM field treated quantum mechanically and the coupling field treated classically, we show how quantum state exchange between two laser fields with large frequency difference can be realized.

We assume that the coupling field is substantially strong, so that different mixing fields have negligible influence on the atomic population and coherence. As done in Refs. [22–24], we use the perturbation analysis to treat the interaction of the atoms with the light fields. In the zeroth-order perturbation expansion, by semiclassically treating the interaction of the atoms with the strong coupling field in the ladder-type configuration, we get the steady-state mean values of $\sigma_{11}^{(0)}$, $\sigma_{22}^{(0)}$, $\sigma_{33}^{(0)}$, $\sigma_{12}^{(0)}$, $\sigma_{13}^{(0)}$and $\sigma_{23}^{(0)}$. In the case of the interaction of the atoms with the mixing and FWM fields, the Heisenberg–Langevin equations for describing the evolution of the collective atomic operators $\sigma_{12}(z,t)$ and $\sigma_{23}(z,t)$ can be written as [22–24]

$$\dot{\sigma}_{12}(z,t) = -(\gamma_{12}+i\Delta_1)\sigma_{12} + ig_1a_1(z,t)(\sigma_{11}-\sigma_{22}) + ig_2a_2^{+}\sigma_{13} + F_{12}(z,t), \quad (1)$$

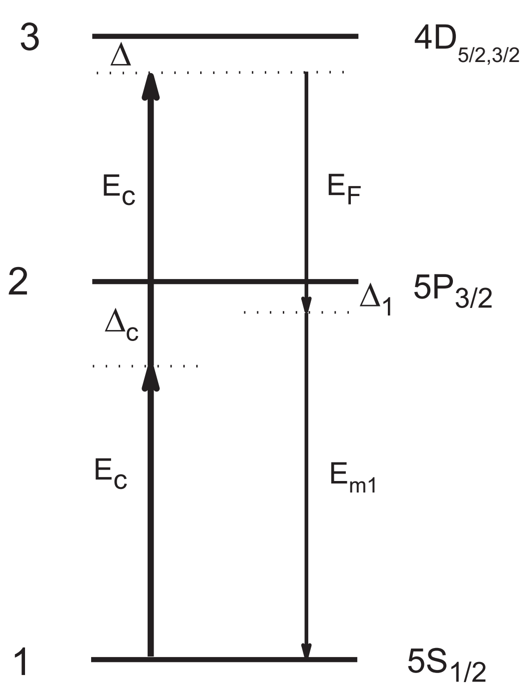

Fig. 1. The ladder-type three-level system in ^{85}Rb atom coupled by the strong coupling (E_c) and weak mixing (E_{m1}) field, where the field E_F is generated through the four-wave-mixing process by absorbing two photons from the coupling field and emitting one mixing field photon.

$$\dot{\sigma}_{23}(z,t) = -(\gamma_{23}+i(\Delta-\Delta_1))\sigma_{23} + ig_2a_2(z,t)(\sigma_{22}-\sigma_{33}) - ig_1a_1^{+}\sigma_{13} + F_{23}(z,t), \quad (2)$$

where $\gamma_{12}=\frac{\gamma_2}{2}$, $\gamma_{23}=\frac{\gamma_2+\gamma_3}{2}$ with γ_2 and γ_3 being the population decay rates from level 2 to level 1 and from level 3 to level 2, a_1 and a_2 are the quantum operators of mixing field E_{m1} and the FWM field E_F, respectively, $g_{1(2)}=\mu_{12(23)}\cdot\varepsilon_{1(2)}/\hbar$ is the atom-field coupling constant with $\mu_{12(23)}$ as the dipole moment for the 1–2 (2–3) transition and $\varepsilon_{1(2)}=\sqrt{\hbar\omega_{1(2)}/2\varepsilon_0V}$ as the electric field of a single mixing (FWM) photon with V as the interaction volume with length L and beam radius r, and $F_{ij}(z,t)$ are the collective atomic δ-correlated Langevin noise operators. The evolution of the operators a_1 and a_2 can be described by the coupled propagation equations

$$\left(\frac{\partial}{\partial t}+c\frac{\partial}{\partial z}\right)a_1(z,t) = ig_1N\sigma_{12}, \quad (3)$$

$$\left(\frac{\partial}{\partial t}+c\frac{\partial}{\partial z}\right)a_2^{+}(z,t) = -ig_2N\sigma_{32}, \quad (4)$$

where N is the total number of atoms in the quantum volume. By substituting the zeroth-order solution into the Fourier-transformed Heisenberg–Langevin equations for $\sigma_{12}(z,t)$ and $\sigma_{32}(z,t)$, we can get the first-order solution $\sigma_{12}^{(1)}(z,\omega)$ and $\sigma_{32}^{(1)}(z,\omega)$, which are expressed as

$$\sigma_{12}^{(1)}(z,\omega) = \frac{1}{\gamma_{12}+i(\omega+\Delta_1)}[ig_1a_1(\sigma_{11}^{(0)}-\sigma_{22}^{(0)}) + ig_2a_2^{+}\sigma_{13}^{(0)} + F_{12}], \quad (5)$$

$$\sigma_{32}^{(1)}(z,\omega) = \frac{1}{\gamma_{23}+i(\omega-(\Delta-\Delta_1))}[-ig_2a_2^{+}(\sigma_{22}^{(0)}-\sigma_{33}^{(0)}) + ig_1a_1\sigma_{31}^{(0)} + F_{32}]. \quad (6)$$

Substituting $\sigma_{12}^{(1)}$ and $\sigma_{32}^{(1)}$ into Fourier-transformed coupled propagation equations, the output operators $a_1(L,\omega)$ and $a_2^{+}(L,\omega)$ with respect to the Fourier frequency ω can be obtained, which is a linear combination of the input operators $a_1(0,\omega)$ and $a_2^{+}(0,\omega)$ and Langevin noise terms.

3. Results and discussions

We use the criterion $V=(\Delta u)^2+(\Delta v)^2<4$ proposed in Ref. [25] to examine the entangled property between the mixing and FWM fields, where $u=x_i-x_j$ and $v=p_i+p_j$ (i=1,2) with $x_i=(a_i+a_i^{+})$ and $p_i=-i(a_i-a_i^{+})$. Satisfying the above inequality sufficiently demonstrates the generation of genuine bipartite entanglement, and the smaller the correlation V is, the stronger the degree of the bipartite entanglement gets. We assume that the mixing field is initially in a coherent state $|\alpha\rangle$, and the FWM field is initially in vacuum. In the following, the relevant parameters are scaled with m and MHz, or m^{-1} and MHz^{-1}, and set as follows: atomic density $n=5\times10^{19}$, $r=1\times10^{-4}$, $L=0.06$, $\gamma_2=\gamma_3=3$, $\Omega_p=\Omega_c=800$, $\alpha=10$, $\Delta_c=-10^8$, and $\Delta=\Delta_1=0$.

Fig. 2 shows the evolution of correlation V as a function of the Fourier frequency ω. It can be seen that, in the whole range of the Fourier frequency ω, V is always less than 4, which sufficiently demonstrates the generation of genuine bipartite entanglement between the mixing field and FWM field. V remains steady values of about 2 in a wide range (−1200 to 1200 MHz) of the Fourier frequency ω, except there exist a narrow dip with the width of about 50 MHz around the Fourier frequency $\omega=0$; moreover, the minimum value of V at $\omega=0$ is nearly equal to zero, that is, the mixing and FWM field are perfectly entangled with each other. This indicates that quantum state exchange between two light