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Nonreciprocal Single Photon Frequency Conversion via Chiral Coupling between a V-Type System and a Pair of Waveguides *

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The single photon frequency conversion is investigated theoretically in the system composed of a V-type system chiral coupling to a pair of waveguides. The single photon scattering amplitudes are obtained using the real-space Hamiltonian. The calculated results show that the probability of single photon frequency down- or up-conversion can reach a unit by choosing appropriate parameters in the non-dissipative system with perfect chiral coupling. We present a nonreciprocal single photon beam splitter whose frequency of the output photon is different from that of the input photon. The influences of dissipations and non-perfect chiral coupling on the single frequency conversion are also shown. Our results may be useful in designing quantum devices at the single-photon level.

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Frequency conversion plays important roles in many quantum technologies, such as quantum information processing,[1] photon dection[2] and storage.[3] Many different systems and methods are proposed to realize photon frequency conversion, such as the cavity opto-mechanics system[4,5] and multi-wave mixing.[6–9] Based on the Sagnac interferometer, Bradford *et al.* proposed a scheme to realize frequency conversion at the single-photon level.[10,11] The frequency conversion efficiency can reach around a unit. Later, several groups developed the scheme[12] and investigated its applications in generation of entangled states.[13–15] Recently, the schemes based on superconducting quantum circuits[16,17] and coupled-resonator waveguides[18] to realize frequency conversion at the single-photon level with high conversion efficiency are also proposed.

Waveguide QED is a good platform to investigate quantum optical effects and attracts much attention in recent years.[19,20] The single photon scattering properties in one-dimensional waveguide coupled to quantum emitters have been investigated widely.[21–35] Recently, the chiral coupling between waveguide and quantum emitters has been proposed.[36–38] Here the chiral coupling can be understood as the coupling strength between the quantum emitter and the left-propagation, which is different from the one between the quantum emitter and the right-propagation photon.[39] The applications of the chiral coupling are also investigated widely,[40] such as enhancement of entanglement between two emitters,[39,41] realization of single photon circulators,[42] nonreciprocal few-photon router,[43] and construction of quantum networks.[44]

In this Letter, we propose a nonreciprocal single-photon frequency conversion using a V-type system chiral coupling to a pair of waveguides. It shows that the down- or up-conversion efficiency can reach unit in the ideal case. Compared with other proposals,[10–18] our scheme has following properties: (1) the down- or up-frequency converter is nonreciprocal. (2) The photons with frequency conversion and without frequency conversion are respectively in different waveguides. Thus it is easy to distinguish them. (3) As stated in Ref. [17], in most proposals with a Λ-system,[13–15] the coupling strengths between the atoms and the waveguide should satisfy some particular conditions to realize high conversion efficiency. However, for the system with a V-type system, the conversion efficiency can reach unit in the ideal case for arbitrary coupling strengths just by controlling the Rabi frequency of the classical driving field. Furthermore, we also propose a sing-photon beam splitter whose frequency of the output photon is different from that of the input photon in this study. Our results may find applications in designing quantum devices at the single-photon level.

The system considered is shown in Fig. 1. A V-type system with ground state $|0\rangle$ and two excited states ($|1\rangle$ and $|2\rangle$) couples chirally to a pair of waveguides. The two excited states are coupled by a classical field.[17,28,45] The transition $|0\rangle \leftrightarrow |1\rangle$ couples chirally to waveguide A (WA) while the transition $|0\rangle \leftrightarrow |2\rangle$ couples chirally to waveguide B (WB). Here ω_1 (ω_2) is the transition frequency between $|0\rangle \leftrightarrow |1\rangle$ ($|0\rangle \leftrightarrow |2\rangle$). We take $\omega_1 > \omega_2$ in this work. Thus the single photon frequency down-conversion is realized when the

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photon with frequency ω_1 incidents from the WA and output from WB with frequency ω_2.

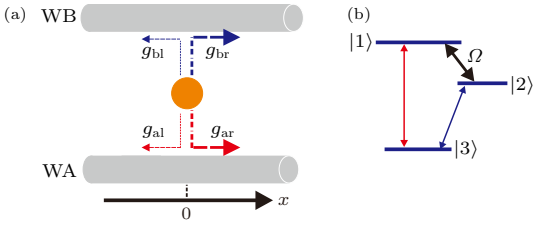


Fig. 1. (Color online) (a) Schematic studied in this work. A V-type system chirally coupling to a pair of waveguides. (b) The energy-level configuration of the V-type system. The transitions $|0\rangle \leftrightarrow |1\rangle$ and $|0\rangle \leftrightarrow |2\rangle$ couple chirally to the WA and WB, respectively.

The Hamiltonian in this system is given by $H = H_0 + H_{\rm int}$,[45] with

$$\begin{aligned} H_0 =& \sum_{m=1,2} \hbar\omega_m \sigma_{mm} + \sum_k \sum_{n=a,b} \hbar\omega_{k,n} \\ & \cdot [r^\dagger_{k,n} r_{k,n} + l^\dagger_{k,n} l_{k,n}], \end{aligned} \tag{1}$$

$$\begin{aligned} H_{\rm int} =& \sum_k \hbar(g_{\rm al} l^\dagger_{ka}\sigma_{01} + g_{\rm ar} r^\dagger_{ka}\sigma_{01} + g_{\rm bl} l^\dagger_{kb}\sigma_{02} \\ & + g_{\rm br} r^\dagger_{kb}\sigma_{02} + {\rm H.c.}) \\ & + 2\hbar\Omega(\cos\nu t)(\sigma_{12} + \sigma_{21}), \end{aligned} \tag{2}$$

where $r^\dagger_{k,n}$ ($l^\dagger_{k,n}$) denotes creating a photon in waveguide n ($n = {\rm a}, {\rm b}$) propagating along in the right (left) direction with momentum k, $g_{n,{\rm r}}$ ($g_{n,{\rm l}}$) is the coupling strength, $\sigma_{\rm pq}(p, q = 0, 1, 2)$ is the dipole operator, and Ω is the Rabi frequency of the driving field. The frequency of the driving field is chosen as $\nu = \omega_1 - \omega_2$ for simplicity. Setting $\hbar = 1$ and transferring the Hamiltonian H into real space, we obtain

$$\begin{aligned} H =& \sum_{a,b} \int dx(-iv_{\rm g}) c^\dagger_{\rm Rn} \frac{\partial}{\partial x} c_{\rm Rn}(x) \\ & + \sum_{a,b} \int dx(-iv_{\rm g}) c^\dagger_{Ln} \frac{\partial}{\partial x} c_{Ln}(x) \\ & + \sum_{m=1,2} (\omega_m - i\gamma_m/2)\sigma_{mm} + \Omega(\sigma_{12} + \sigma_{21}) \\ & + g_{\rm ar} \int dx\delta(x)[c^\dagger_{\rm Ra}(x)\sigma_{01} + c_{\rm Ra}(x)\sigma_{10}] \\ & + g_{\rm al} \int dx\delta(x)[c^\dagger_{\rm La}(x)\sigma_{01} + c_{\rm La}(x)\sigma_{10}] \\ & + g_{\rm br} \int dx\delta(x)[c^\dagger_{\rm Rb}(x)\sigma_{02} + c_{\rm Rb}(x)\sigma_{20}] \\ & + g_{\rm bl} \int dx\delta(x)[c^\dagger_{\rm Lb}(x)\sigma_{02} + c_{\rm Lb}(x)\sigma_{20}], \end{aligned} \tag{3}$$

where $c^\dagger_{\rm R(L)a(b)}(x)$ denotes creating a photon propagating in the right (left) direction in WA (B) at x. We have supposed that the photons in WA and WB have the same group velocity $v_{\rm g}$, and γ_1 (γ_2) is added phenomenally to describe the energy loss from state $|1\rangle$ ($|2\rangle$) to the non-waveguide modes.

We first discuss single photon frequency down-conversion. When a photon with frequency ω_1 incidents from the left of WA, after interacting with the atom, the photon may either remain at the same frequency in WA or be routed to WB with frequency ω_2, i.e., single photon frequency down-conversion due to $\omega_1 > \omega_2$. Following the method given in Refs. [22,46], we solve the Schrödinger equation and obtain

$$\begin{aligned} t_{\rm a} =& [4\Omega^2 + (J_{\rm al} - J_{\rm ar})(J_{\rm br} + J_{\rm bl} - 2iQ_1) \\ & - 2iQ_1(J_{\rm br} + J_{\rm bl} - 2iQ_2)]/[4\Omega^2 \\ & + (J_{\rm ar} + J_{\rm al})(J_{\rm br} + J_{\rm bl} - 2iQ_1) \\ & - 2iQ_1(J_{\rm br} + J_{\rm bl} - 2iQ_2)], \end{aligned} \tag{4a}$$

$$\begin{aligned} r_{\rm a} =& -[2\sqrt{J_{\rm ar}J_{\rm al}}(J_{\rm br} + J_{\rm bl} - 2iQ_2)]/[4\Omega^2 \\ & + (J_{\rm ar} + J_{\rm al})(J_{\rm br} + J_{\rm bl} - 2iQ_1) \\ & - 2iQ_1(J_{\rm br} + J_{\rm bl} - 2iQ_2)], \end{aligned} \tag{4b}$$

$$\begin{aligned} t_{\rm b} =& [4i\sqrt{J_{\rm ar}J_{\rm br}}\Omega]/[4\Omega^2 + (J_{\rm ar} + J_{\rm al})(J_{\rm br} + J_{\rm bl} \\ & - 2iQ_1) - 2iQ_1(J_{\rm br} + J_{\rm bl} - 2iQ_2)], \end{aligned} \tag{4c}$$

$$\begin{aligned} r_{\rm b} =& [4i\sqrt{J_{\rm ar}J_{\rm bl}}\Omega]/[4\Omega^2 + (J_{\rm ar} + J_{\rm al})(J_{\rm br} + J_{\rm bl} \\ & - 2iQ_1) - 2iQ_1(J_{\rm br} + J_{\rm bl} - 2iQ_2)], \end{aligned} \tag{4d}$$

where $t_{\rm a}$, $r_{\rm a}$, $t_{\rm b}$ and $r_{\rm b}$ are the four possible output probability amplitudes, as exhibited in Fig. 1(a), $J_{\rm nd} \equiv g^2_{\rm nd}/v_{\rm g}$ ($n = {\rm a}, {\rm b}$; $d = {\rm r}, {\rm l}$), and $Q_{1(2)} \equiv (\omega - \omega_1 + i\gamma_{1(2)}/2)$. To realize the frequency down-conversion with probability of 100%,

$$|t_{\rm b}|^2 + |r_{\rm b}|^2 = 1 \tag{5}$$

should be satisfied. In the following we discuss how to realize Eq. (5).

When the coupling is non-chiral, i.e., $J_{\rm ar} = J_{\rm al} = J_{\rm a}$, $J_{\rm br} = J_{\rm bl} = J_{\rm b}$, Eq. (4) degenerates into

$$t_{\rm a} = \frac{\Omega^2 - i\Delta(J_{\rm b} - i\Delta)}{\Omega^2 + J_{\rm a}(J_{\rm b} - i\Delta) - i\Delta(J_{\rm b} - i\Delta)}, \tag{6a}$$

$$r_{\rm a} = -\frac{J_{\rm a}(J_{\rm b} - i\Delta)}{\Omega^2 + J_{\rm a}(J_{\rm b} - i\Delta) - i\Delta(J_{\rm b} - i\Delta)}, \tag{6b}$$

$$t_{\rm b} = \frac{i\sqrt{J_{\rm a}J_{\rm b}}\Omega}{\Omega^2 + J_{\rm a}(J_{\rm b} - i\Delta) - i\Delta(J_{\rm b} - i\Delta)}, \tag{6c}$$

$$r_{\rm b} = \frac{i\sqrt{J_{\rm a}J_{\rm b}}\Omega}{\Omega^2 + J_{\rm a}(J_{\rm b} - i\Delta) - i\Delta(J_{\rm b} - i\Delta)}, \tag{6d}$$

where $\Delta \equiv \omega - \omega_1$. The energy loss is neglected temporarily to capture the main physics. When $\Omega = 0$, the population cannot transfer to state $|2\rangle$, thus $t_{\rm b} = r_{\rm b} = 0$. The system degenerates to the single two-level system coupling to a waveguide, and the expressions of $t_{\rm a}$ and $r_{\rm a}$ are the same as those reported in Ref. [22]. The frequency down-conversion cannot be realized in this case.

When $\Omega \neq 0$, the population from state $|1\rangle$ can transfer to state $|2\rangle$, thus $t_{\rm b} = r_{\rm b} \neq 0$. Then, the frequency down-conversion can be realized. From Eq. (6), one can obtain that when $\Omega^2 = J_{\rm a}J_{\rm b}$ and

$\Delta = 0$, $T_a \equiv |t_a|^2$ and $R_b \equiv |r_b|^2$ reach the maximum value 0.25. Thus the maximum probability to realize the single frequency down-conversion from ω_1 to ω_2 is 0.5 in the non-chiral coupling case. It is notable that there is no special requirement for the relationship between J_a and J_b,[17] which is different from the case for the Λ system. Here $J_a = J_b$ is often a necessary condition to reach the maximum frequency transition[10] and population transfer[46] in the system of the Λ-type atom coupling to waveguides. Figure 2 shows $T_a = |t_a|^2$, $R_a = |r_a|^2$ and $T_b + R_b^2$ varying with $\omega - \omega_1$ and Ω. It exhibits that T_a and R_a can change from 0 to 1. However, $T_b + R_b$ is only in the region of [0, 0.5]. It is also conformed that $T_a = R_a = 0.25$ and $T_b + R_b = 0.5$ when $\Omega^2 = J_a J_b$ and $\Delta = 0$.

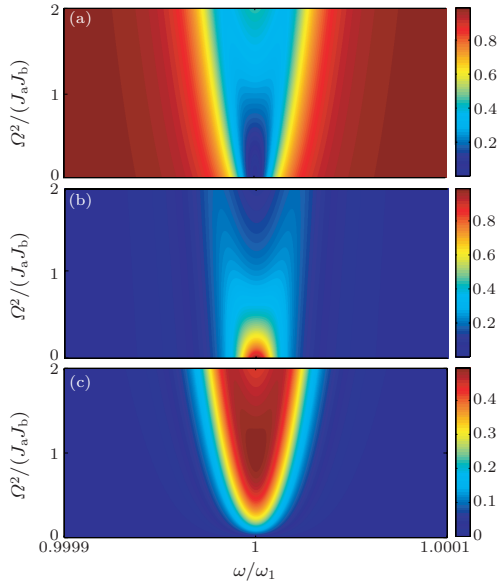


Fig. 2. (Color online) The values of T_a (a), R_b (b) and $T_b + R_b$ (c) varying with ω and Ω^2 for the non-chiral coupling system. In the calculation, $J_a = 10^{-5}\omega_1$, $J_b = 2J_a$, and $\gamma_1 = \gamma_2 = 0$.

To realize the frequency down-conversion with probability of 100%, the chiral coupling (i.e., $J_{ar} \neq J_{al}$, $J_{br} \neq J_{bl}$) should be considered. Let us discuss the case of perfect chiral coupling firstly. Here $J_{al} = J_{bl} = 0$ is assumed for the perfect chiral coupling. Then, Eq. (4) degenerates into

$$t_a = \frac{4\Omega^2 - J_{ar}(J_{br} - 2i\Delta) - 2i\Delta(J_{br} - 2i\Delta)}{4\Omega^2 + J_{ar}(J_{br} - 2i\Delta) - 2i\Delta(J_{br} - 2i\Delta)}, \tag{7a}$$

$$t_b = \frac{4i\sqrt{J_{ar}J_{br}}\Omega}{4\Omega^2 + J_{ar}(J_{br} - 2i\Delta) - 2i\Delta(J_{br} - 2i\Delta)}, \tag{7b}$$

$$r_a = r_b = 0. \tag{7c}$$

From Eq. (7), one can obtain that T_b reaches the maximum 1 when

$$J_{ar}J_{br} = 4\Omega^2, \tag{8a}$$

$$\Delta = 0. \tag{8b}$$

This means that when the single photon with frequency ω_1 is incident from the left of WA, the photon will output from the right of WB with frequency ω_2 after the scattering process when Eq. (8) is satisfied. Figure 3 exhibits T_a and T_b varying with $\Omega^2/(J_{ar}J_{br})$ and $\omega - \omega_1$. Both of T_a and T_b are in the region of [0, 1]. Furthermore, it is shown clearly that when the condition of Eq. (8) is satisfied, $T_b = 1$, which means that the single photon frequency down-conversion is realized with an efficiency of 100%.

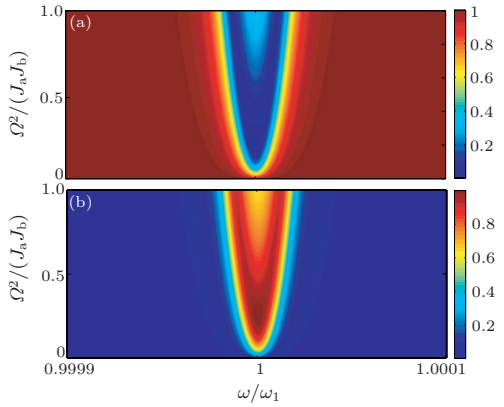


Fig. 3. (Color online) The values of T_a (a) and T_b (b) varying with ω and Ω^2 for the case of perfect chiral coupling. In the calculation, $J_{ar} = 10^{-5}\omega_1$, $J_{br} = 2J_{ar}$, $J_{bl} = J_{al} = 0$ and $\gamma_1 = \gamma_2 = 0$.

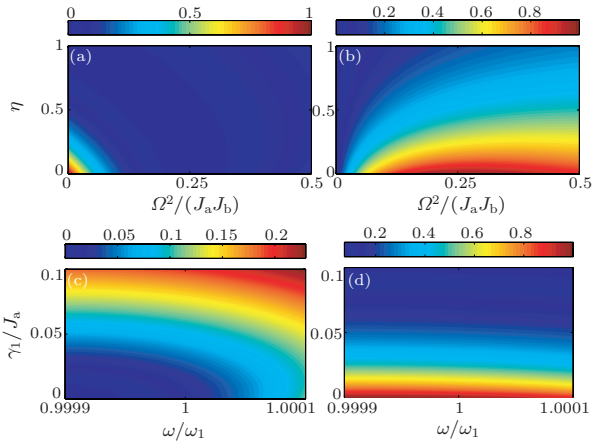


Fig. 4. (Color online) The values of T_a (a) and T_b (b) varying with $J_{al}/J_{ar} = J_{bl}/J_{br} = \eta$ and Ω^2 for the non-dissipation system. Here $\omega = \omega_1$ is taken in the calculation. The values of T_a (c) and T_b (d) varying with γ_1 and ω for the case of perfect chiral coupling. We set $\gamma_2 = \gamma_1$. In both of the calculations, $J_{ar} = 10^{-5}\omega_1$ and $J_{br} = 2J_{ar}$.

In the real physical system, the perfect chiral coupling may be difficult to realize and the dissipations are non-avoidable. We introduce $J_{al}/J_{ar} = J_{bl}/J_{br} = \eta$ to describe the chiral coupling. When $\eta = 0$, the coupling is perfectly chiral. When $\eta = 1$, the coupling is non-chiral. Figures 4(a) and 4(b) exhibit T_a and T_b varying with η and $\Omega^2/(J_{ar}J_{br})$. It shows that T_b is still very large even when η deviates from 0 and Ω^2 deviates from $J_{ar}J_{br}/4$. Figures 4(c) and 4(d) show how energy loss affects T_a and T_b, respectively. When

γ_1 (γ_2) is less than $0.01J_{\rm ar}$, $T_{\rm b}$ is still larger than 0.9. However, $T_{\rm b}$ decreases quickly with the increase of γ_1 (γ_2). Thus to realize single photon frequency conversion with high probability, one should design a system with low energy loss.

The single photon frequency up-conversion can also be designed in this system with the same physical mechanism. When the single photon with frequency ω_2 is incident from the left of WB, the probability of the single photon output from WA with frequency ω_1 will be 1 if the condition of Eq. (8) is satisfied.

The chiral coupling plays an important role in frequency conversion in this system. Here we suppose that the atom only interacts with the right prorogation photon. When the photon with frequency ω_1 (ω_2) is incident from the left of WA (WB), it can be transferred to WB (WA) to realize the frequency down- or up-conversion with probability of 1 in the ideal case. However, when the photon incident from the right of WA (WB), it will not interact with the atom and will transmit directly. Thus the frequency conversion proposed here is nonreciprocal.

Furthermore, when only one transition couples chirally to the photon in the waveguide and the other transition is non-chiral, one can obtain the quantum single-photon beam splitter with two outputs, and the frequency of the output photon is different from the input photon. To show this property more clearly, we consider the case of $J_{\rm al}=0$ and $J_{\rm br}=J_{\rm bl}=J_{\rm b}$. Under this condition, from Eq. (4) we obtain

$$t_{\rm a}=\frac{4\Omega^2-J_{\rm ar}(2J_{\rm b}-2i\Delta)-2i\Delta(2J_{\rm b}-2i\Delta)}{4\Omega^2+J_{\rm ar}(2J_{\rm b}-2i\Delta)-2i\Delta(2J_{\rm b}-2i\Delta)} \tag{9a}$$

$$t_{\rm b}=r_{\rm b}=\frac{4i\sqrt{J_{\rm ar}J_{\rm b}}\Omega}{4\Omega^2+J_{\rm ar}(2J_{\rm b}-2i\Delta)-2i\Delta(2J_{\rm b}-2i\Delta)}, \tag{9b}$$

$$r_{\rm a}=0. \tag{9c}$$

It is easy to check that when

$$J_{\rm ar}J_{\rm b}=2\Omega^2, \tag{10a}$$

$$\Delta=0 \tag{10b}$$

are satisfied, $t_{\rm a}=0$ and $t_{\rm b}=r_{\rm b}=\sqrt{2}i/2$. This means that when a photon is incident from the left of WA with frequency ω_1, it will be transferred to WB and the probabilities of the photon with frequency ω_2 output from the left and right of WB are both equal to 0.5. Thus a nonreciprocal single photon quantum beam splitter with two outputs can be realized. The frequency of the output photon is different from that of the input photon. Figures 5(a) and 5(b) show $T_{\rm a}$ and $T_{\rm b}(R_{\rm b})$ varying with Ω^2 and ω, respectively. It exhibits clearly that when Eq. (10) is satisfied, $T_{\rm br}=T_{\rm bl}=0.5$. Figures 5(c) and 5(d) show $T_{\rm a}$ and $T_{\rm b}(R_{\rm b})$ as a function of γ_1, respectively. When γ_1 increases to $0.1J_{\rm ar}$, $T_{\rm b}(R_{\rm b})$ can still be larger than 0.4.

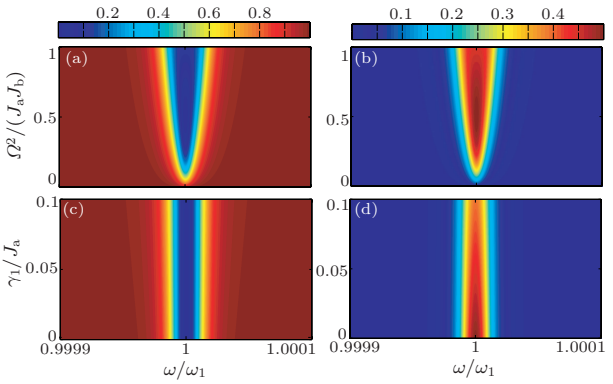


Fig. 5. (Color online) The values of $T_{\rm a}$ (a) and $T_{\rm b}=R_{\rm b}$ (b) varying with ω and Ω^2 for the ideal case without decay. The values of $T_{\rm a}$ (c) and $T_{\rm b}=R_{\rm b}$ (d) as functions of ω and γ_1 with $J_{\rm ar}J_{\rm b}=2\Omega^2$ and $\gamma_1=\gamma_2$. Here $J_{\rm ar}=10^{-5}\omega_1$ is taken for the two cases.

In summary, we have theoretically investigated single-photon frequency conversion using a V-type system coupled to a pair of waveguides. When the coupling between the atom and waveguide is non-chiral, the probability of realizing the frequency down- or up-conversion is no more than 0.5 even when the energy loss is neglected. However, when the couplings between the atom and the photons in the waveguides are perfectly chiral, the photon frequency down- or up-conversion with unit efficiency can be realized by choosing the appropriate Rabi frequency of the classical driving field when the dissipations are neglected. A single-photon beam splitter whose frequency of output photon is different from that of input photon can also be realized when only one transition of the atom chirally couples to the photon in a perfect way, while the other transitions nonchirally couple to the other waveguides. Our results may find applications in designing quantum devices and quantum information processing at the single-photon level.

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