Targeted photonic routers with chiral photon-atom interactions

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The photonic router is a key device in optical quantum networks. Conventional routers, however, can only transfer a photon from the input port to the desired port probabilistically. Here, we propose to use chiral photon-atom interactions for targeted routing that can transfer a single photon from the input port to an arbitrarily selected output port deterministically, i.e., with 100% probability. The configuration of the proposed router consists of a driven three-level atom which is chirally coupled to two photonic waveguides simultaneously. It is shown that, by properly adjusting the driving field on the atom, a single photon inputting from one port of the first waveguide can be deterministically transferred to one of the selected output ports of the second waveguide. Both resonant and nonresonant photons can be deterministically routed to the desired ports. We also examine how the routing fidelity is influenced by dissipations and imperfections, and investigate the transmission characters of two resonant photons.

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I. INTRODUCTION

Quantum networks are the main physical platforms for scalable quantum information processing and quantum communication [1–3]. The routers, which coherently transfer the information carrier between distant quantum nodes, are key components in a quantum network.

Various single-photon routing schemes based on qubits [4–6], cavity-atom [7–9], coupled resonators [10], optomechanical systems [11], or atomic mirrors [12] have been proposed. However, in all previous schemes the probability of successful routing is typically limited [4–12], and it usually decreases with increasing the number of routing ports [6]. This restricts the scalability of these schemes. Another restriction of previous routers is the limited window of frequencies, which is typically a small window around the resonant frequency [6–8,11,12]. A router that can transport a single photon deterministically from the input port to any targeted output port is highly desirable and vital for practical applications.

In this article, we propose to utilize the chiral interactions between the atom and the waveguide to realize a single-photon router that can route the photon deterministically [13,14]. The photon-atom chiral interaction makes the coupling between the photon and the atom asymmetric with respect to the direction of photon propagation and the polarization of the transition dipole moment of the atom [15,16]. We note that chiral interactions have been previously demonstrated in certain on-chip nonreciprocal photonic elements, such as optical isolators [17], circulators [18], transistors [19], switches [20], quantum networks [21,22], etc., and it is thus practically realizable. We will show that by properly adjusting the driving field applied to the three-level atom, the photon injected in a waveguide can be deterministically transferred into any selected output port of another waveguide. The fidelity of the router remains unchanged when the number of the ports increases, which makes this scheme scalable.

This article is organized as follows: In Sec. II, a real-space Hamiltonian of the system is introduced, while the exact one-photon solution is given. Section III discusses the transmission properties with the atom symmetrically coupled to the two waveguides. In Sec. IV, the conditions of incident single photons routed to desired ports are discussed. The feasibility of a single-photon router is also demonstrated with the current waveguide photonic technique. We examine the effects of dissipations and imperfections on the fidelity of the router in Sec. V. Finally, two photons scattered by the atom of ideal chiral couplings are investigated in Sec. VI.

II. MODEL AND SOLUTIONS

The configuration of the photonic router is shown in Fig. 1. It can be described by the Hamiltonian (with $\hbar = 1$)

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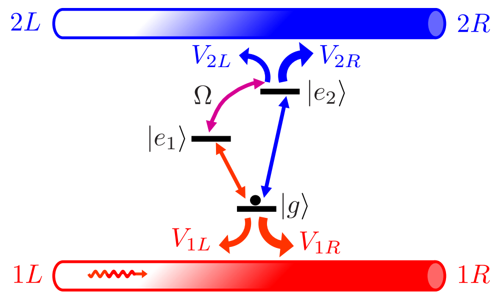

FIG. 1. Schematic of a targeted single-photon router. A single photon depicted as a wiggly wave incident from port $1L$ along the first waveguide is scattered by a three-level atom. The transition depicted in red (blue) is only chirally coupled to the waveguide 1(2) with $V_{nR} \neq V_{nL}$ ($n = 1,2$). A control field with a Rabi frequency Ω is used to couple the excited states $|e_1\rangle$ and $|e_2\rangle$. The atom is assumed initially to be at its ground state $|g\rangle$.

[23,24]

$$H = \omega_g a_g^\dagger a_g + \sum_{n=1,2} \omega_{e_n} e_n^\dagger e_n + \int dx \sum_{n=1,2} \times \Big[-iV_g C_{nR}^\dagger(x) \frac{\partial}{\partial x} C_{nR}(x) + iV_g C_{nL}^\dagger(x) \frac{\partial}{\partial x} C_{nL}(x) + V_{nR}\delta(x)[C_{nR}^\dagger(x) a_g^\dagger e_n + C_{nR}(x) e_n^\dagger a_g] + V_{nL}\delta(x)[C_{nL}^\dagger(x) a_g^\dagger e_n + C_{nL}(x) e_n^\dagger a_g] \Big] + \Omega(e_1^\dagger e_2 + e_2^\dagger e_1). \quad (1)$$

Here, $\omega_{g(e_n)}$ is the frequency of the atom with the creation operator of $a_g^\dagger(e_n^\dagger)$, and $C_{nR(L)}^\dagger(x)$ is the creation operator for the right-moving (left-moving) photon along the waveguide n at position x. The group velocities for the photon propagating along different waveguides have been assumed to be the same, which are then all denoted as V_g. $V_{nR(L)}$ is the photon-atom coupling strength for the photon propagating along the right (left) direction, and due to the chiral interactions, here $V_{nR} \neq V_{nL}$ ($n = 1,2$). Correspondingly, $\Gamma_{nR(L)} = V_{nR(L)}^2/V_g$ is the rate of the atom decaying to the nth waveguide along the direction $R(L)$. As we are only interested in a narrow range in the vicinity of the atomic resonant frequency, $V_{nR(L)}$ is safely assumed to be independent of frequency [23,24]. Physically, such an assumption is equivalent to the Markovian approximation [25]. Therefore, the frequency conversion between the incident and the routed photon is limited effectively by the bandwidths of the photon-atom couplings. The Dirac delta function $\delta(x)$ indicates that the atom is located at $x = 0$. Ω is the Rabi frequency of the control field applied to couple the atomic states $|e_1\rangle$ and $|e_2\rangle$.

We first show that by making use of chiral interactions, a single photon of a fixed frequency can be deterministically routed from the first waveguide to the second waveguide. The eigenstates of the Hamiltonian take the form

$$|\Psi_k\rangle = \sum_{m=1,2} \sum_{n=R,L} \int dx \phi_{mn}(x) C_{mn}^\dagger(x) |0,g\rangle + d_{e_1}|0,e_1\rangle + d_{e_2}|0,e_2\rangle, \quad (2)$$

where $\phi_{mn}(x)$ is the probability amplitude of the right- or left-moving photon, $d_{e_{1(2)}}$ the amplitude for the excited state of the atom, and $|0,g\rangle$ denotes the ground state, wherein there is no photon in the waveguides and the atom is at the ground state $|g\rangle$. The spatial dependence of the amplitudes in Eq. (2) can be expressed as

$$\begin{aligned} \phi_{1R}(x) &= e^{ik_1x}[\theta(-x) + t_1\theta(x)], \\ \phi_{1L}(x) &= e^{-ik_1x} r_1 \theta(-x), \\ \phi_{2R}(x) &= e^{ik_2x} t_2 \theta(x), \\ \phi_{2L}(x) &= e^{-ik_2x} r_2 \theta(-x), \end{aligned} \quad (3)$$

where $k_1 = \omega_1/V_g$, $k_2 = \omega_2/V_g$. Physically, $T_1 = |t_1|^2$ ($R_1 = |r_1|^2$) and $T_2 = |t_2|^2$ ($R_2 = |r_2|^2$) describe the probabilities of the incident photon being transmitted (reflected) along different directions of the waveguides, leaving the atom to return to the ground state $|g\rangle$.

If a single photon with frequency ω_1 enters port $1L$, after the interaction with the atom, the photon can either retain the same frequency or convert to the frequency $\omega_2 = \Delta + \omega_{e_2g}$, where $\Delta = \omega_1 - \omega_{e_1g}$ and $\omega_{e_ng} = \omega_{e_n} - \omega_g$. The coefficients in Eq. (3) can be obtained by exactly solving the equation $H|\Psi_k\rangle = E|\Psi_k\rangle$, which are

$$\begin{aligned} t_1 &= \frac{(\Delta + i\tilde{\Gamma}_2)(\Delta + i\tilde{\Gamma}_1') - \Omega^2}{(\Delta + i\tilde{\Gamma}_2)(\Delta + i\tilde{\Gamma}_1) - \Omega^2}, \\ r_1 &= \frac{-i\sqrt{\Gamma_{1L}\Gamma_{1R}}(\Delta + i\tilde{\Gamma}_2)}{(\Delta + i\tilde{\Gamma}_2)(\Delta + i\tilde{\Gamma}_1) - \Omega^2}, \\ t_2 &= \frac{-i\sqrt{\Gamma_{2R}\Gamma_{1R}}\Omega}{(\Delta + i\tilde{\Gamma}_2)(\Delta + i\tilde{\Gamma}_1) - \Omega^2}, \\ r_2 &= \frac{-i\sqrt{\Gamma_{2L}\Gamma_{1R}}\Omega}{(\Delta + i\tilde{\Gamma}_2)(\Delta + i\tilde{\Gamma}_1) - \Omega^2}, \end{aligned} \quad (4)$$

with

$$\tilde{\Gamma}_n = \frac{\Gamma_{nL} + \Gamma_{nR}}{2}, \quad \tilde{\Gamma}_n' = \frac{\Gamma_{nL} - \Gamma_{nR}}{2}.$$

We can then route the photon to the desired output port of the network by tuning these coefficients.

III. CONVENTIONAL SCHEME

For comparison, let us first consider the case where the atom is symmetrically coupled to the two waveguides, i.e., the relevant photon-atom interactions are not chiral but symmetric, $\Gamma_{1R} = \Gamma_{1L} = \Gamma_1$, $\Gamma_{2R} = \Gamma_{2L} = \Gamma_2$. For simplicity, we assume $\Gamma_1 = \Gamma_2 = \Gamma$. In this case, the coefficients in Eq. (4) are simply $t_2 = r_2 = -i\frac{\Gamma\Omega}{M}$, $t_1 = \frac{(\Delta+i\Gamma)\Delta-\Omega^2}{M}$ $r_1 = -i\frac{\Gamma(\Delta+i\Gamma)}{M}$, with $M = (\Delta + i\Gamma)(\Delta + i\Gamma) - \Omega^2$. In the absence of a driving field (i.e., $\Omega = 0$), the three-level atom can be treated as a two-level system with the transition $|e_1\rangle \leftrightarrow |g\rangle$. In this case [23], the incident resonant photon is completely reflected to the $1L$ port, i.e., $T_1 = 0$ and $R_1 = 1$. When a driving field with Rabi frequency Ω is applied, the excited state $|e_1\rangle$ could be transmitted into the state $|e_2\rangle$. Especially, if $\Omega \geqslant \Gamma$, the atom can be treated as an effective two-level system with the eigenfrequencies as $\Omega_{\text{TLA}} = \omega_{e_1g} \pm \sqrt{\Omega^2 - \Gamma^2}$ and a splitting with $\Delta = \pm\sqrt{\Omega^2 - \Gamma^2}$ can be observed [26,27] in the

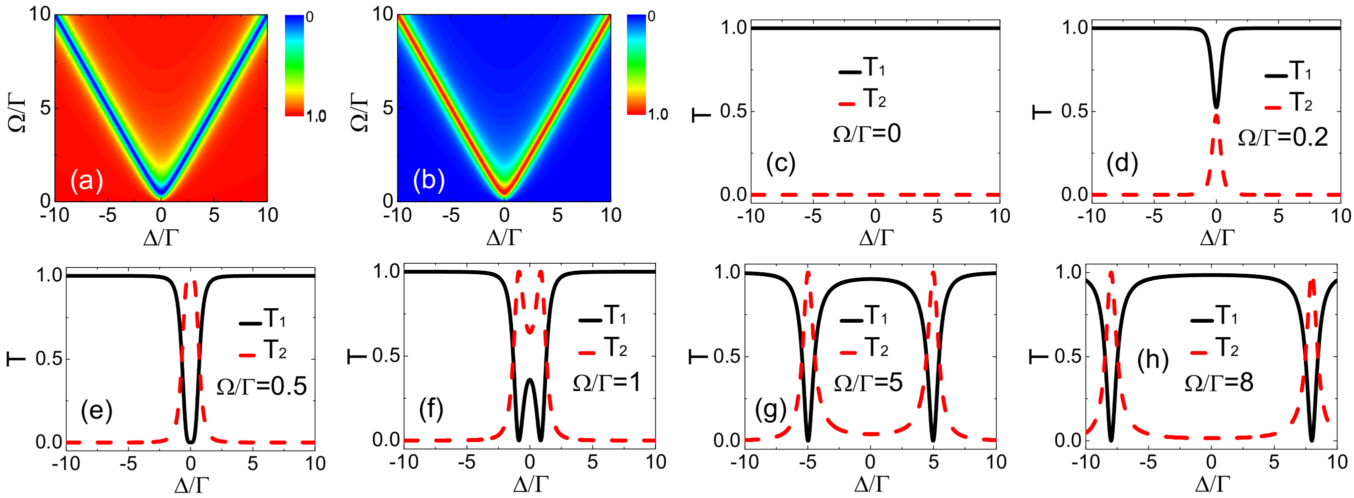

FIG. 2. Transmission spectra of the waveguide single photons with specific chiral photon-atom interactions, $\Gamma_{1R} = \Gamma_{2R} = \Gamma$ and $\Gamma_{1L} = \Gamma_{2L} = 0$, vs the effective Rabi frequency Ω/Γ and detuning Δ/Γ. (a) T_1. (b) T_2. (c)–(h) T_1 and T_2 for different Ω/Γ (0, 0.2, 0.5, 1, 5, 8). It is shown in (e) that the desired targeted single-photon routings, i.e., the resonant single-photon incident from port $1L$ is deterministically routed into port $2R$, can be realized. Obviously, targeted single-photon routers can still be realized for different detuning parameters, as diagramed in (f)–(h).

transmission spectra of the photons. This indicates the photon can be reemitted into either the first or second waveguide, for example, the photon with the frequency $\omega_1 = \omega_{e_1 g} \pm \sqrt{\Omega^2 - \Gamma^2}$ can be reemitted into either waveguide with the same probability. This is the conventional scheme for single-photon routing, which has an equal probability of routing the photon to either of the two waveguides, specifically, $T_n = R_n = 0.25$ [10]. Thus, with the symmetrical photon-atom couplings, the conventional routing scheme cannot route the photon to the targeted port of the network deterministically.

IV. TARGETED SINGLE-PHOTON ROUTINGS BY UTILIZING CHIRAL PHOTON-ATOM INTERACTIONS

Now, we show how to route the photon in a deterministic way, for example, route the single photon from port $1L$ deterministically to port $2R$. Without loss of generality, we assume the chiral photon-atom couplings are $\Gamma_{1R} = \Gamma_{2R} = \Gamma$, $\Gamma_{1L} = \Gamma_{2L} = 0$. In this case, Eq. (4) can be simplified as

$$t_1 = \frac{[(\Delta + i\Gamma/2)(\Delta - i\Gamma/2) - \Omega^2]}{\Lambda}, \quad t_2 = -i\frac{\Gamma\Omega}{\Lambda}, \quad (5)$$

with $\Lambda = (\Delta + i\Gamma/2)(\Delta + i\Gamma/2) - \Omega^2$. Figure 2 shows the probabilities of routing the incident photon to various output ports, with respect to the effective Rabi frequency Ω/Γ and the effective detuning Δ/Γ. We discuss the different regimes below.

It can be seen from Fig. 2(c) that if $\Omega = 0$, the atom in the excited state $|e_1\rangle$ only reemits the photon into the right direction of the first waveguide due to the chiral interaction, so the incident photon is deterministically transmitted into port $1R$. Without the leakage of photons out of the waveguide, the amplitude of the reemitted photon chirally coupled to the first waveguide is twice as strong as that of the direct transmission [28]. Note that reemitted and direct transmission photons have the same frequency but differ with a π phase [16]. This leads to a nonperfect destructive interference between them. Consequently, the resonant incident photon absorbed by the atom is completely reemitted along the right direction of the first waveguide with $T_1 = 1$.

When the driving field $\Omega > 0$, as shown in Fig. 2(d), the incident photon can be transferred to the second waveguide along the right direction with $T_2 > 0$. This is because the driving field can pump the atom to state $|e_2\rangle$ from state $|e_1\rangle$. The atom thus has an additional channel decaying into the second waveguide. Comparing to the case when the photon is reemitted back to the first waveguide, the second waveguide can be regarded as the environment to collect the decaying photon. This leakage suppresses the amplitude of the reemitted photon to the first waveguide, which makes $T_1 < 1$ and $T_2 > 0$.

When the Rabi frequency of the driving field is taken as $\Omega = \Gamma/2$, then the incident photon from port $1L$ can be deterministically routed into port $2R$, as shown in Fig. 2(e). Under this condition $\Omega = \Gamma/2$, the excited atom reemits the photon into the two waveguides with the same probability, i.e., the right-emitted photon in the first waveguide has the same amplitude as that of the direct transmission. Consequently, no photon is routed into port $1R$ (i.e., $T_1 = 0$) due to the perfect destructive interference between these paths. Meanwhile, the chiral photon-atom interactions induce an imbalance between the reemitting photons to the right and left directions of the second waveguide, and this yields a perfect transmission of the photon to port $2R$, i.e., $T_2 = 1$.

When the driving field is large enough such that $\Omega > \Gamma/2$, as shown in Figs. 2(f)–2(h), the transmission spectra of the photon split as $\omega_{1\pm} = \omega_{e_1 g} \pm \sqrt{\Omega^2 - \Gamma^2/4}$, and the system can be described effectively as a two-level system coupled chirally to the double waveguides. In this case, the probabilistic amplitudes of the photon reemitted by the excited atom along the two waveguides are equal. This results in a perfect destructive interference along port $1R$, yielding $T_1 = 0$. This can also be seen from Eq. (5), when $\Delta = \Delta_\pm = \pm\sqrt{\Omega^2 - \Gamma^2/4}$, the probability of the photon being routed into the $2R$ port, is

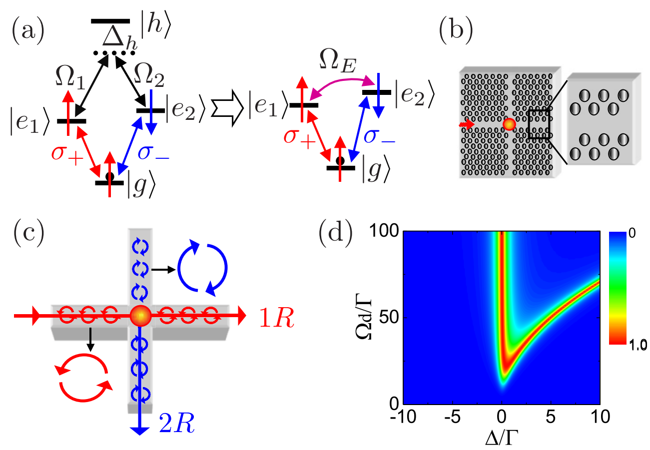

FIG. 3. The feasibility of the designed targeted single-photon routings. (a) Two fields (Ω_1 and Ω_2) with a large detuning Δ_h are applied to a four-level quantum dot (QD). By adiabatically eliminating the upper level $|h\rangle$, an effective field (Ω_E) is obtained to drive the transition $|e_1\rangle \leftrightarrow |e_2\rangle$, for realizing the desirable spin rotations. (b) The QD (depicted as a red ball) is chirally coupled to two photonic-crystal glide-plane waveguides. (c) The photon with polarization of $\sigma\pm$ emitted by the corresponding dipole transition is only coupled to the waveguide of a left-hand (right-hand) circularly polarized mode. (d) Transmission spectra of photons routing to port $2R$ (i.e., T_2) controlled by the two driving fields, with $\Omega_1 = \Omega_2 = \Omega_d$, $\Gamma_{1R} = \Gamma_{2R} = \Gamma$, and $\Delta_h = 1000\Gamma$.

given by

$$T_2(\Delta_\pm) = \frac{\Gamma^2\Omega^2}{\left[\Delta^2 - \left(\frac{\Gamma^2}{4} + \Omega^2\right)\right]^2 + \Delta^2\Gamma^2} \equiv 1. \qquad (6)$$

This shows that targeted photon routing can be achieved deterministically for an incident photon with a nonresonant frequency, as long as the condition $\Omega > \Gamma/2$ is satisfied. This router can thus overcome the limitations of the previous routers, wherein they are only able to route photons with the same frequency as the atom [6,8], cavity [7,8], and mirror [11,12].

The deterministic single-photon router described above can be realized by chiral quantum optical systems. Specifically, we discuss its feasibility with a photonic crystal coupled to semiconductor quantum dots (QDs) on chip, as shown in Fig. 3. First, to get the model with a driven three-level atom as shown in the configuration of Fig. 1, we use a four-level QD with circularly polarized excited states (with the two dipole transitions emitting $\sigma_\pm$-polarized photons [29,30]), which can be obtained by applying a magnetic field along the direction of growth for the QD. Two external fields with Rabi frequencies Ω_1 and Ω_2 can be applied to the QD, respectively, yielding a stimulated Raman transition [31] with an effective Rabi frequency Ω_E, and generating an effective spin rotation between the states $|e_1\rangle$ and $|e_2\rangle$ [32–34]. As shown in Fig. 3(b), two chiral waveguides can be fabricated on chip by shifting one side of the photonic-crystal waveguides by half the lattice constant [16]. In such a case, the photon emitted through the atomic $\sigma_\pm$ transition is only coupled to the waveguide with left- and right-circularly polarized modes, respectively [see, e.g., Fig. 3(c)].

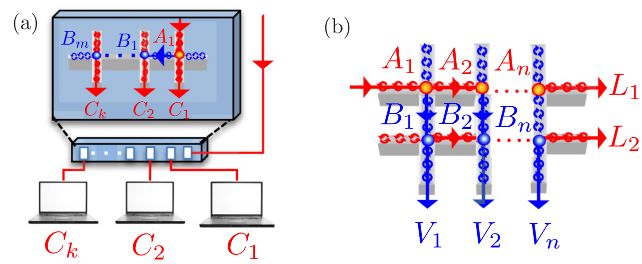

FIG. 4. Cartoon of cascaded router distributing photons to many channels. (a) A possible targeted single-photon router with multiple ports connected to different computers, i.e., $C_1, C_2, \ldots,$ and C_k. The spin of the QDs diagramed in red (blue) balls is initialized up (down). (b) Cascading the routers to construct quantum networks.

Specifically, if $\Omega_1 = \Omega_2 = \Omega_d$, the amplitudes of the photon being transmitted into ports $1R$ and $2R$ of the present photonic-crystal waveguides read

$$t_1 = \frac{4\Delta_h^2\Delta^2 - 8\Omega_d^2\Delta_h\Delta + \Gamma^2\Delta_h^2}{\Upsilon}, \quad t_2 = \frac{-i4\Gamma\Delta_h\Omega_d^2}{\Upsilon}, \qquad (7)$$

with $\Upsilon = 4\Delta_h^2\Delta^2 - 8\Omega_d^2\Delta_h\Delta - \Gamma^2\Delta_h^2 + i4\Gamma\Delta_h(\Delta\Delta_h - \Omega_d^2)$. The detuning Δ_h [see schematically in Fig. 3(a)] is set as $\Delta_h \gg \Omega_d$, to minimize the undesired population of the QD in the excited state of $|h\rangle$ [34]. Figure 3(d) clearly shows that, not only the resonant photon (with $\Delta = 0$) but also the off-resonant one [with $\Delta = \Omega_d^2/\Delta_h \pm \sqrt{\Omega_d^4 - \Gamma^2\Delta_h^2/4}/\Delta_h \neq 0$], inputting from the first waveguide, can be transferred to the second waveguide with $T_2 = 1$. This indicates that the targeted single-photon routings designed above could be implemented experimentally with the current photonic-crystal waveguide network with a driven QD.

The proposed targeted single-photon router can be easily extended to a network with multiple ports [see, e.g., Fig. 4(a)], wherein a single incident photon can be deterministically routed into the computer C_2 by driving two QDs A_1 and B_1, sequentially. When all the conditions are fulfilled as discussed above, the present router can be cascaded in a network with arbitrary multiple outports, while the routing efficiency η_k of a k-port router remains deterministic. Typically, Fig. 4(b) shows the proposed router can also be integrated in complex quantum networks without sacrificing the routing fidelity.

V. ROUTING FIDELITY INFLUENCED BY DISSIPATIONS AND IMPERFECTIONS

Practically, as implementations are always beyond the perfect chiral atom-photon interactions, we need to calculate the fidelity of the single-photon router influenced by dissipations of the atom (Γ_a) and fabrication imperfections ($\Gamma_{nL} = \chi\Gamma$). The Hamiltonian in Eq. (1) is changed to $H_d = H - \sum_{n=1,2} i\Gamma_a e_n^\dagger e_n$ [24] and thus the corresponding transmission amplitudes of resonant photons ($\Delta = 0$) in Eq. (4) are reduced to

$$t_1 = \left[\left(i\Gamma_a + i\frac{\chi\Gamma + \Gamma}{2}\right)\left(i\Gamma_a + i\frac{\chi\Gamma - \Gamma}{2}\right) - \Omega^2\right]\Big/\lambda,$$
$$t_2 = -i\Gamma\Omega/\lambda, \qquad (8)$$

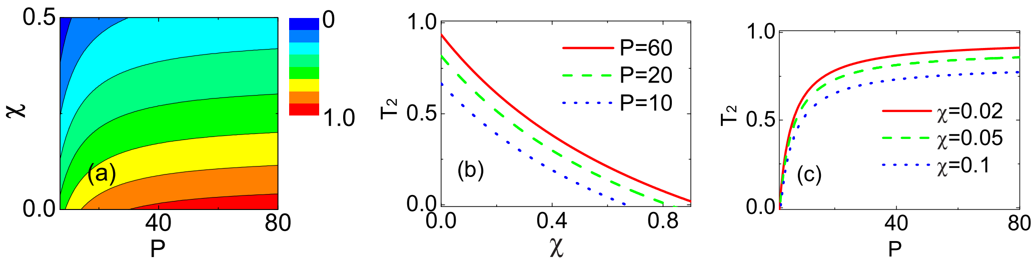

FIG. 5. Routing fidelity influenced by dissipations and imperfections. (a) The fidelity of the single-photon router (T_2) vs the Purcell factor P and imperfections of the chiral photon-atom couplings χ. (b) The routing fidelity is approximately linear decreasing vs χ increasing. (c) The routing fidelity increases rapidly to a constant value when the Purcell factor P increases.

with $\lambda = (i\Gamma_a + i\frac{\Gamma+\chi\Gamma}{2})(i\Gamma_a + i\frac{\chi\Gamma+\Gamma}{2}) - \Omega^2$. Notably, even in this situation, we can still turn the driving field as $\Omega = \sqrt{\frac{\Gamma^2}{4} - (\Gamma_a + \frac{\chi\Gamma}{2})^2}$ to ensure that the photon cannot be transported to port $1R$ with $T_1 = 0$. Consequently, the corresponding routing fidelity of the single-photon router is evaluated by $T_2 = [(1-\chi^2)P^2 - 4(1+\chi)^2 - 4\chi(1+\chi)P]/[(1+\chi)^2(P+2)^2]$ with P being the Purcell factor as $P = (1+\chi)\Gamma/\Gamma_a$. As shown in Fig. 5(a), due to the fact that dissipations of the atom leak photons into the nonwaveguide modes and the imperfections of chiral couplings make the photons be reflected to ports $1L$ and $2L$, the routing fidelity (T_2) decreases. Figures 5(b) and 5(c) reveal that the fidelity of the router decreases approximately linearly on χ and increases drastically to a constant value on P, respectively. Fortunately, benefiting from the extremely high efficiency and the robustness of the chiral photon-atom interactions, such as $P = 60$ [2] and $\chi = 0.02$ [16], the routing fidelity remains significantly high, e.g., $T_2 = 90\%$, at the single-photon level. Simultaneously, the routing efficiency η_k of a k-port router under these practical parameters can be calculated as $\eta_k = T_2^t = 0.9^t$ with t being the routing times. For example, when $t = 5$, $\eta_k \approx 0.6$.

VI. TWO-PHOTON TRANSMISSION PROPERTIES

Finally, we investigate the two photons scattered by the atom. As shown in Fig. 5, the high fidelity of the router requires the chiral photon-atom interaction to be in the strong-coupling regime, such that the majority of the spontaneously emitted photons is guided into the waveguide mode. Consequently,

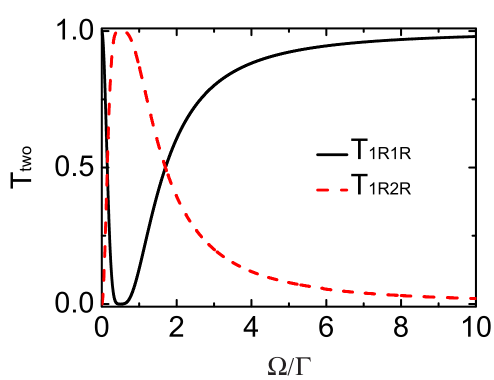

FIG. 6. The transmission probabilities of two identical photons scattered by the atom for different driving fields, with $\Delta = 0$, $\chi = 0$, and $\Gamma_a = 0$.

the atom responds to the first photon too quickly and thus the response of the second photon should be a significantly weak nonlinear effect [35]. This means that the bound state of two photons in the routing process just adds a negligible contribution to the transporting properties [19,35–37], so that two photons cannot be simultaneously routed to the same port. For simplicity, we investigate an ideal chiral photon-atom coupling case without dissipations and imperfections, i.e., $\Gamma_a = 0$ and $\chi = 0$. Then only two processes remain: (1) Two photons transport to port $1R$ and (2) one is routed to port $2R$ and the other transports freely to port $1R$. Therefore, the two-photon eigenstate of the Hamiltonian in Eq. (1) is

$$\begin{aligned} |\Psi_{\rm two}\rangle = \bigg[&\int dx_{k1}dx_{k2}\phi_{1R1R}(x_{k1},x_{k2})C^\dagger_{1R}(x_{k1})C^\dagger_{1R}(x_{k2}) \\ &+ \int dx_1dx_2\phi_{1R2R}(x_1,x_2)C^\dagger_{1R}(x_1)C^\dagger_{2R}(x_2)\bigg]|0,g\rangle \\ &+ \int dx \sum_{m=1,2}\phi_m(x)C^\dagger_{mR}(x)|0,e_m\rangle, \end{aligned} \tag{9}$$

with ϕ_{1R1R} and ϕ_{1R2R} being the wave function of the two processes, respectively. ϕ_m is the wave function for the atom in the state e_m.

Following a similar procedure as in Refs. [19,35], we get the transmission probabilities of two identical photons $T_{\rm two}$ with resonant frequencies (i.e., $\Delta = 0$) as $T_{1R1R} = (\Omega^2 - \frac{\Gamma^2}{4})^4/(\Omega^2 + \frac{\Gamma^2}{4})^4$ and $T_{1R2R} = (2\Omega^6\Gamma^2 + \frac{\Gamma^6\Omega^2}{8})/(\Omega^2 + \frac{\Gamma^2}{4})^4$. As plotted in Fig. 6, without the driving field, two photons transport freely to port $1R$ with $T_{1R1R} = 1$. When the routing condition is fulfilled as $\Omega = 0.5\Gamma$, one photon is routed to port $2R$ and the other transports freely to port $1R$. Additionally, a strong driving field will dress the energy levels of the atom, so that the coupling strength between the resonant photons and the atom becomes weak. Consequently, the photons cannot be routed to port $2R$ and then totally transport to port $1R$. In a word, the transmission properties of two photons can also be controlled by adjusting the applied driving field Ω.

VII. CONCLUSIONS

In summary, we have proposed a practically feasible approach to implement a targeted single-photon router by using a driven three-level atom coupled chirally to two photonic waveguides. The operation of such a router only requires a control field, and the nonreciprocal router can also be cascaded with high fidelities. Experimentally, a targeted single-photon router can also be realized with other various chiral devices, such as atoms coupled to optical nanofibers [38] or whispering-gallery-mode microresonators [39], etc. The targeted single-photon routers proposed here provide an effective approach to build a desired optical quantum network for scalable photonic quantum computation and communication.

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