Control of single-photon transport in a one-dimensional waveguide by a single photon

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We study controllable single-photon transport in a one-dimensional waveguide with a nonlinear dispersion relation coupled to a three-level emitter in a cascade configuration. An extra cavity field is introduced to drive one of the level transitions of the emitter. In the resonance case, when the extra cavity does not contain photons, the input single photon will be reflected; when the cavity contains one photon, the full transmission of the input single photon can be obtained. In the off-resonance case, the single-photon transport can also be controlled by the parameters of the cavity. Therefore, we show that single-photon transport can be controlled by an extra cavity field.

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I. INTRODUCTION

Single photons are considered as one of the most suitable carriers for quantum information. It is important to control the single-photon transport in quantum information processing. Recently, controllable single-photon transport in a one-dimensional (1D) waveguide with linear and nonlinear dispersion relations has been extensively investigated both theoretically [1–31] and experimentally [32–40]. In a 1D waveguide, the photons are confined to propagating only forward or backward in 1D space. By coupling an emitter to the waveguide, the strong photon-emitter interaction can be obtained and the photon transport in the 1D space can be affected by the interaction. It is known that for a 1D waveguide coupled to a two-level emitter [1,2], the injected single photon will be completely reflected in the resonance case due to the interference between the wave function of the input photon and the spontaneously emitted photon. The single-photon transport in a 1D waveguide coupled to a multilevel emitter [18,23] has also been studied. Compared to a two-level system, the multilevel system provides more controllable parameters. For instance, when a 1D waveguide is coupled to a Λ-type emitter, a strong pulse is employed to drive one of the atomic transitions. Since the single-photon transport can be controlled by the extra pulse, the all-optical device can be achieved. However, most of the controls need a strong pulse containing many photons or rely on other parameters. It is interesting to study the controllable single-photon transport by another photon without the classical field.

In this paper we propose a scheme to study the control of single-photon transport in a 1D waveguide with a nonlinear dispersion relation at the single-photon level. In our scheme the single-photon transport can be controlled by a cavity field. When the control cavity field is in the vacuum state, our scheme can be considered as a 1D waveguide coupled to a two-level system. Therefore, the input single photon will be reflected in the resonance case. When the control cavity contains one photon, our scheme becomes a 1D waveguide coupled to a three-level system with a cascade configuration. The full transmission of the input single photon can be obtained in the resonance case. It should be noted that the control of single-photon transport by another photon without a classical field in a 1D waveguide with a linear dispersion relation has been studied in Ref. [26]. We also study the single-photon transport controlled by the parameters of the control cavity, such as the coupling strength to the emitter, photon number, and resonance frequency. Incidentally, the quantum control of single-photon transport in a 1D waveguide with a linear dispersion relation by the cavity-emitter coupling strength has been studied in Ref. [27]. Our scheme does not contain inelastic scattering. Our scheme can be considered as a 1D waveguide with a nonlinear dispersion relation coupled to a V-type atom in the dressed-state representation. Some outcomes can be understood better than in the bare-state representation.

II. MODEL AND HAMILTONIAN

The schematic diagram of the considered system is shown in Fig. 1. The 1D waveguide is composed of a coupled-cavity array with a very large number of single-mode cavities and one two-mode cavity [41,42]. The cavity modes of the 1D coupled cavities are represented by the annihilation operators a_j, with j the label of the site. Here we take the site of the two-mode cavity to be 0. Hence, one mode of the two-mode cavity, which is coupled to the nearest-neighbor single-mode cavities, is represented by the annihilation operators a_0. We represent the other mode of the two-mode cavity by the annihilation operator b. For simplicity, we assume that the cavity modes a_j have the same resonance frequency ω_a. The cavity mode b has the resonance frequency ω_b. A three-level system in a cascade configuration is doped in the two-mode cavity. The three-level system can be a real atom or a manual atomlike object [43–45]. In the circuit quantum electrodynamics system, the promising candidate of the three-level system coupled to the two-mode cavity is that two transmission lines are connected by the Josephson junctions [46,47]. The three-level system will be mentioned as an atom below. We represent atomic states $|1\rangle$, $|2\rangle$, and $|3\rangle$ with frequencies ω_1, ω_2, and ω_3, respectively. We choose the ground-state energy for reference and hence take ω_1 to be zero. The level transitions between $|1\rangle \leftrightarrow |2\rangle$ and

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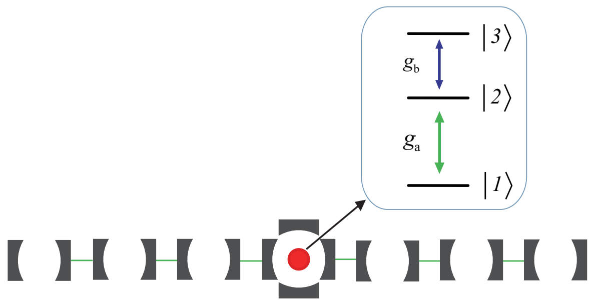

FIG. 1. (Color online) Schematic diagram of single-photon transport in a one-dimensional coupled-resonator waveguide. A three-level system with cascade configuration is coupled to the waveguide.

$|2\rangle \leftrightarrow |3\rangle$ are coupled to the modes a_0 and b with strengths g_a and g_b, respectively. In the rotating-wave approximation, the system Hamiltonian has the form

$$H = H_C + H_A + H_I, \tag{1}$$

with

$$H_C = \sum_j \omega_a a_j^\dagger a_j + \omega_b b^\dagger b - \xi \sum_j (a_{j+1}^\dagger a_j + \text{H.c.}),$$
$$H_A = \omega_2 \sigma^{22} + \omega_3 \sigma^{33},$$
$$H_I = g_a \sigma^{21} a_0 + g_b \sigma^{32} b + \text{H.c.},$$

where $\sigma^{m,m'} = |m\rangle\langle m'|$ $(m,m' = 1,2,3)$ represents the atomic raising, lowering, and energy-level population operators. Here we have taken $\hbar = 1$. The Hamiltonian H_C denotes the cavity photons, H_A is the atomic free Hamiltonian, and H_I describes the interaction of the atom with the two-mode cavity. The second sum of H_C describes the hopping of the a_j-mode photons to the nearest-neighbor cavities with strength ξ. Here we have assumed that all the hopping strengths are equal. By introducing the Fourier transform $a_k = \frac{1}{\sqrt{N}} \sum_k e^{ikj}$ and taking the distances between two nearest-neighbor cavity units, the term $\sum_j \omega_a a_j^\dagger a_j - \xi \sum_j (a_{j+1}^\dagger a_j + \text{H.c.})$ can be diagonalized as $\sum_k \Omega_k a_k^\dagger a_k$, with $\Omega_k = \omega_a - 2\xi \cos k$ and N being the cavity number. This implies the nonlinear dispersion relation of the 1D coupled-cavity waveguide.

III. CONTROL OF SINGLE-PHOTON TRANSPORT

We assume that, initially, a photon is injected into the waveguide from the left side, the atom is in its ground state $|1\rangle$, and the two-mode cavity contains n b-mode photons. We note that the value of n cannot be very large, i.e., $g_b\sqrt{n} \ll \{\omega_2,\omega_3\}$. This is because we have employed the rotating-wave approximation in the Hamiltonian (1). The input single photon will transport along the waveguide and be scattered due to the atom-cavity interaction. Obviously, when $n = 0$, the atom will absorb the injected photon while making a transition from level $|1\rangle$ to $|2\rangle$ and then reemit a photon while making a transition from level $|2\rangle$ to $|1\rangle$. In this case, the atomic level $|3\rangle$ never participates in the dynamic process because the atomic transition from level $|2\rangle$ to $|3\rangle$ needs to absorb a b-mode photon. Hence, our scheme is equal to a coupled-cavity waveguide coupled to a two-level system when $n = 0$. However, when $n \neq 0$, the transition $|2\rangle \leftrightarrow |3\rangle$ participates in the dynamic process, revealing different behavior from the $n = 0$ case due to the quantum interference between different atomic transitions.

The arbitrary state governed by the Hamiltonian (1) can be written as

$$|\Psi\rangle = \sum_j \alpha_j a_j^\dagger |1,n\rangle|\phi\rangle + \beta|2,n\rangle|\phi\rangle + \zeta|3,n-1\rangle|\phi\rangle, \tag{2}$$

with α_j, β, and ζ probability amplitudes. The state $|m,n\rangle$ denotes that the atom is in the state $|m\rangle$ and the two-mode cavity contains n b-mode photons. The state $|\phi\rangle$ denotes that the 1D waveguide does not contain any a_j-mode photon. From the eigenequation $H|\Psi\rangle = E|\Psi\rangle$, we can obtain a set of equations of the probability amplitudes. Then, by eliminating the probability amplitudes β and ζ, we can obtain the equation of the probability amplitude α_j, which reveals the single-photon transport property, as

$$[E - (\omega_a + n\omega_b) - V\delta_{j,0}]\alpha_j = -\xi(\alpha_{j+1} + \alpha_{j-1}), \tag{3}$$

with

$$V = \frac{g_a^2\{E - [\omega_3 + (n-1)\omega_b]\}}{[E - (\omega_2 + n\omega_b)]\{E - [\omega_3 + (n-1)\omega_b]\} - g_b^2 n}.$$

The effective potential V resulting from the atom-cavity interaction located at site $j = 0$ modifies the single-photon transport property. If the two-mode cavity does not contain b-mode photons, we find $V = \frac{g_a^2}{E-\omega_2}$, in line with the outcome in Ref. [2]. We consider the simple case that the atomic transition $|1\rangle \leftrightarrow |2\rangle$ is driven resonantly by the input photon. The potential is derived as $V \to \infty$ when $n = 0$. However, if we inject a b-mode photon into the two-mode cavity initially, i.e., $n = 1$, the potential is obtained as $V = -\frac{g_a^2(E-\omega_3)}{g_b^2}$. In particular, when the b-mode photon resonantly drives the atomic transition, i.e., $\omega_{32} = \omega_b$, the potential equals zero. Therefore, we can modify the effective potential between ∞ and 0 by one b-mode photon. This implies that the single-photon transport can be controlled by only one b-mode photon.

For the single-photon transport in the 1D waveguide, the spatial dependence of the amplitude α_j can be expressed as

$$\alpha_j = (e^{ikj} + re^{-ikj})\theta(-j) + te^{ikj}\theta(j), \tag{4}$$

where r is the reflection amplitude and t is the transmission amplitude. The Heaviside step function $\theta(x)$ equals 1 when x is larger than 0 and 0 when x is smaller than 0. From Eqs. (3) and (4), when $|j| > 1$, we can find $E = n\omega_b + \omega_a - 2\xi\cos k_a$, which corresponds to the dispersion relation derived above; when $j = 0$, we can derive the expression of the reflection and transmission amplitudes as

$$\begin{aligned} r &= \frac{-g_a^2(\delta_a + \delta_b)}{2i\xi\left[\delta_a(\delta_a + \delta_b) - g_b^2 n\right]\sin k + g_a^2(\delta_a + \delta_b)}, \\ t &= \frac{2i\xi\left[\delta_a(\delta_a + \delta_b) - g_b^2 n\right]\sin k}{2i\xi\left[\delta_a(\delta_a + \delta_b) - g_b^2 n\right]\sin k + g_a^2(\delta_a + \delta_b)}, \end{aligned} \tag{5}$$

with the detunings $\delta_a = \omega_2 - \Omega_k$ and $\delta_b = \omega_{32} - \omega_b$. Here we have employed the continuity condition $\alpha_0^+ = \alpha_0^-$. The

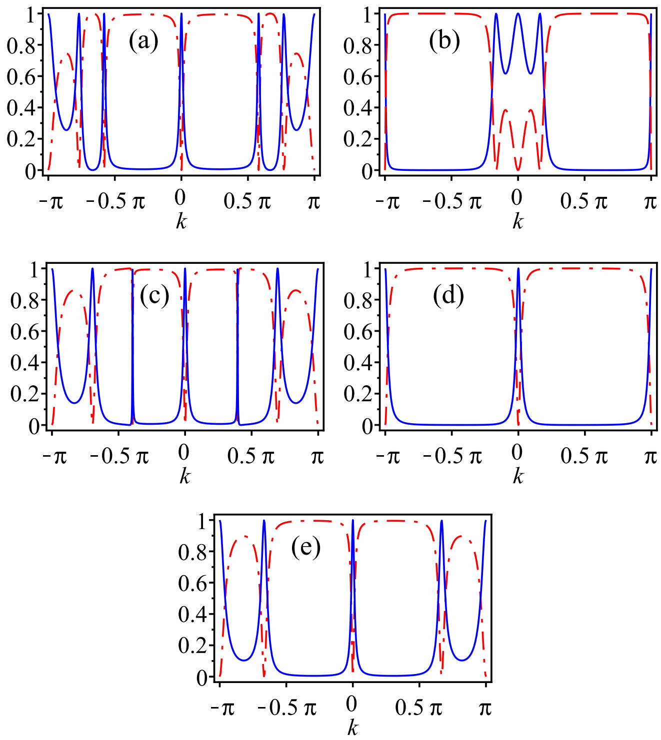

FIG. 2. (Color online) Reflection and transmission coefficients against the wave number k for various values of δ_b and n. The blue solid and red dash-dotted lines represent the reflection and transmission coefficients, respectively. We set (a) and (c) $n = 1$, (b) and (d) $n = 30$, and (e) $n = 0$, with (a) and (b) $\delta_b = 0$ and (c) and (d) $\delta_b = -3$. The other parameters are $g_b = 1$, $\omega_2 - \omega_a = 2$, and $\xi = 2$. All the parameters but n are in units of g_a.

relation $|r|^2 + |t|^2 = 1$ can be easily verified. Obviously, when $\delta_a + \delta_b = 0$ and $n \neq 0$, the full transmission of the input single photon is obtained due to the interferences. When $\delta_a(\delta_a + \delta_b) = g_b^2 n$, the input single photon is completely reflected.

To show the details of the single-photon transport property, we plot the reflection and transmission coefficients as a function of the wave number k in Fig. 2 for various values of δ_b and n. The region of k from $-\pi$ to π is enough due to the fact that r and t are periodic functions of k with the same period 2π. This periodic behavior, which results from the nonlinear dispersion relation of the 1D coupled-cavity waveguide, does not exist when the waveguide has a linear dispersion relation. Consequently, the photon transport property against the wave number when the atom is coupled to a waveguide with a nonlinear dispersion relation shows different behavior from that when the atom is coupled to a waveguide with a linear dispersion relation. Besides, the photon incident into the coupled-cavity waveguide has the group velocity $v_g = 2\xi \sin k$ due to the nonlinear dispersion relation [22]. This may be used to realize the photon buffer [48]. The lines in Fig. 2 show rich shapes. Figures 2(a) and 2(c) show the photon transport property when the b-mode cavity contains one photon, compared to the case when the b-mode cavity contains many photons in Figs. 2(b) and 2(d). The lines in Figs. 2(a) and 2(c) show quite different shapes compared to the lines in Figs. 2(b) and 2(d), respectively. Hence, the photon transport property is closely related to the b-mode photon number. In Figs 2(a) and 2(b) the b-mode photon resonantly drives the atomic transition, compared to the detuned case in Figs 2(c) and 2(d). The lines in Figs. 2(a) and 2(c) have a similar shape. However, when the number of b-mode photons is large, the line shapes in Figs. 2(b) and 2(d) are quite different. Figure 2(e) shows the case when the b-mode cavity does not contain photons, which denotes the case when a two-level atom is coupled to a waveguide with a nonlinear dispersion relation.

We proceed to investigate the dependence of the single-photon transport property on the b-mode photon number. We first study the resonance case. When the two-mode cavity does not contain b-mode photons, we can find $r = -g_a^2/[2i\xi \sin k\delta_a + g_a^2]$ and $t = 2i\xi \sin k\delta_a/[2i\xi \sin k\delta_a + g_a^2]$. Obviously, when $\delta_a = 0$, the input single photon will be completely reflected. This outcome has been obtained in a waveguide coupled to a two-level system [2]. However, when the two-mode cavity contains one or more b-mode photons resonantly driving the atomic transition $|2\rangle \leftrightarrow |3\rangle$, i.e., $\delta_a = \delta_b = 0$ and $n > 0$, the full transmission is achieved. We note that in the $n > 1$ case, the single-photon transport is not affected by the number of b-mode photons in the resonance case. Therefore, the single-photon switch can be achieved by only one b-mode photon.

In the off-resonance case, the single-photon transport relates to the number of b-mode photons even when $n > 1$. Here we assume that g_a and g_b have the same order of magnitude. This assumption is reasonable in an experiment. It can be seen that when the number of b-mode photons is large enough, the nearly full transmission of a single photon can be obtained. This can be understood from the fact that $g_b\sqrt{n}$ is the effective coupling strength of the transition $|2,n\rangle \leftrightarrow |3,n-1\rangle$. When n is large enough, the coupling strength to the transition $|2,n\rangle \leftrightarrow |3,n-1\rangle$ is much larger than the strength to $|1,n\rangle \leftrightarrow |2,n\rangle$. These behaviors can be understood better in the dressed representation as shown below.

Obviously, the single-photon transport property is affected by other parameters of the b-mode cavity, such as the resonance frequency and atom-cavity coupling strengths. In Figs. 3(a) and 3(b) we plot the reflection and transmission coefficients against the detuning δ_b when the two-mode cavity contains b-mode photons and the input photon is off-resonance to the transition $|1\rangle \leftrightarrow |2\rangle$. The reflection and transmission coefficients can be from zero to unity by various values of δ_b. The frequency of the injected single photon is redshifted in Fig. 3(a) and blueshifted in Fig. 3(b). When the b-mode cavity field drives the atomic transition in the large detuning case, the coefficients barely depend on δ_b and tend to constant values. These constant values can be obtained from Eqs. (5). This can be understood by the b-mode cavity being nearly decoupled to the atom. The red dash-dotted (blue solid) line in Fig. 3(a) has a similar shape to the blue solid (red dash-dotted) line in 3(b). The line shapes are like Fano and anti-Fano shapes. This is in line with the conditions of full transmission and reflection obtained below Eqs. (5). The detuning δ_b depends on the atomic transition frequency and the cavity resonance frequency. The control of single-photon transport by tuning the resonance frequency of cavities has been studied in [19]. In our scheme, we bring in an extra cavity that is not in the array of the coupled cavities and is connected with the array

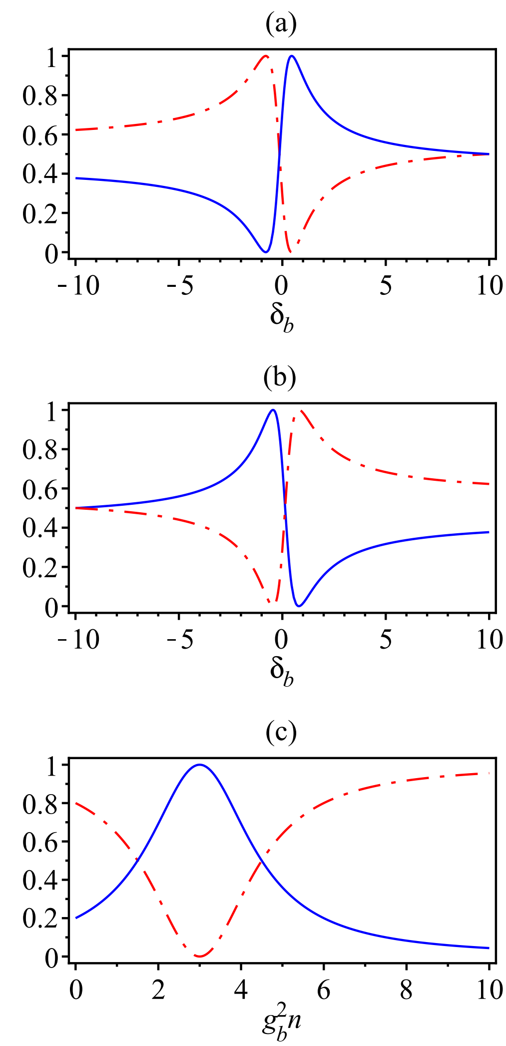

FIG. 3. (Color online) Reflection and transmission coefficients against the detuning δ_b in (a) and (b) and against $g_b^2 n$ in (c). The blue solid and red dash-dotted lines represent the reflection and transmission coefficients, respectively. We set (a) $\delta_a = 0.8$ and (b) $\delta_a = -0.8$. The other parameters are (a) and (b) $g_b = 1, k = \pi/4, \xi = 1$, and $n = 1$ and (c) $g_b = 1, k = \pi/6, \xi = 2, \delta_a = 1$, and $\delta_b = 2$. All the parameters but n are in units of g_a.

by the three-level emitter. Figure 3(c) is the reflection and transmission coefficients against the parameter $g_b^2 n$. The blue solid (red dash-dotted) line in Fig. 3(c) reaches unity (zero) at $gn^2 = \delta_a(\delta_a + \delta_b)$ and then tends to zero (unity) when gn^2 is large enough. When $\delta_a(\delta_a + \delta_b) > 0$, the coefficients can be from near zero to unity by various values of gn^2. The feasibly controllable coupling strength between the cavity and the quantum dot has been proposed in Ref. [27].

When the b-mode cavity field is replaced by a classical field, the injected photon can be controlled by the classical field. In this case, the three-level atom in a cascade configuration coupled to a waveguide is similar to the three-level Λ-type atom coupled to a waveguide. This can be understood from the fact that the Hamiltonians of the two systems have a similar form. Adjusting the Rabi frequency of the classical field corresponds to adjusting the parameter $g\sqrt{n}$ in our scheme. However, these two systems show essentially different behavior when the classical field is replaced by the b-mode cavity field. For example, when the b-mode cavity does not contain photons, the three-level Λ-type atom cannot act as a two-level system because the atomic transition driven by the b-mode photon still participates in the dynamic process. Therefore, our single-photon-level control cannot be well achieved when the three-level Λ-type atom is coupled to a waveguide.

IV. DRESSED-STATE REPRESENTATION

We can consider that the coupling between the b-mode photons and the atomic transition $|2\rangle \leftrightarrow |3\rangle$ leads to dressed states. The expression of the dressed states can be obtained as

$$|\Psi_\pm\rangle = A_\pm|2,n\rangle + B_\pm|3,n-1\rangle, \tag{6}$$

with the corresponding energies

$$\omega_\pm = \omega_2 + n\omega_b + \frac{\delta_b \pm \sqrt{\delta_b^2 + 4g_b^2 n}}{2}. \tag{7}$$

Here

$$A_\pm = \frac{-\delta_b \pm \sqrt{\delta_b^2 + 4g_b^2 n}}{\sqrt{2\sqrt{\delta_b^2 + 4g_b^2 n}\left(\sqrt{\delta_b^2 + 4g_b^2 n} \mp \delta_b\right)}}$$

and

$$B_\pm = \frac{2g_b\sqrt{n}}{\sqrt{2\sqrt{\delta_b^2 + 4g_b^2 n}\left(\sqrt{\delta_b^2 + 4g_b^2 n} \mp \delta_b\right)}}.$$

Thus, our scheme can be considered as a waveguide coupled to a V-type system in the dressed-state representation, as shown in Fig. 4. The effective coupling strength of the a_0-mode photon to the transition $|1,n\rangle \leftrightarrow |\Psi_\pm\rangle$ can be derived as $g_\pm = g_a A_\pm$. Hence, the Hamiltonian represented in the dressed-state representation has the form

$$H' = \sum_{i=\pm} \omega_i \sigma^{ii} + \sum_j \omega_a a_j^\dagger a_j - \xi \sum_j (a_{j+1}^\dagger a_j + \text{H.c.}) + \sum_{i=\pm} (g_i a_0 |\Psi_i\rangle\langle 1,n| + \text{H.c.}).$$

In particular, when $n = 0$, the effective V-type system becomes a two-level system.

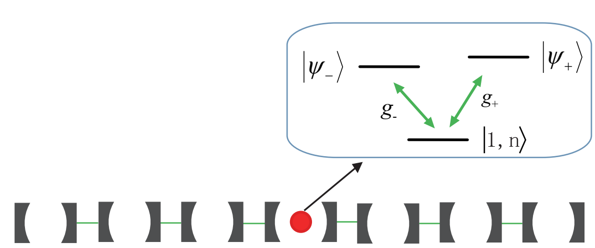

FIG. 4. (Color online) In the dressed-state representation, the scheme shown in Fig. 1 can be considered as a 1D waveguide coupled to an effective V-type atom with effective coupling strengths $g_\pm$.

It is necessary to bring in two parameters

$$\delta_\pm = \delta_a + \frac{\delta_b \pm \sqrt{\delta_b^2 + 4g_b^2 n}}{2}$$

to represent the detunings between the transition energy $|1,n\rangle \leftrightarrow |\Psi_\pm\rangle$ and the energy Ω_k of the incident photon. When one of the two detunings $\delta_\pm$ is zero, we can find the potential $V \to \infty$ and the amplitude $t = 0$. Therefore, for single-photon transport in a coupled-cavity waveguide coupled to a V-type system, once one of the atomic transitions resonantly matches the photon, the input photon will be completely reflected. We note that the condition $\delta_\pm = 0$ is equivalent to the condition $\delta_a(\delta_a + \delta_b) = g_b^2 n$ derived in the bare-state representation.

When $\delta_- g_+^2 + \delta_+ g_-^2 = 0$ we can find $\delta_a + \delta_b = 0$. As mentioned above, the full transmission can be obtained in this case. Therefore, the full transmission of the injected single photon can be achieved when $\delta_- g_+^2 + \delta_+ g_-^2 = 0$ in a coupled-cavity waveguide coupled to a V-type atom. All these outcomes can also be verified by obtaining the single-photon transport property of a waveguide with a nonlinear dispersion relation coupled to a V-type atom as we have done in the bare-state representation. These behaviors are similar to the single-photon transport in a linear waveguide coupled to a V-type atom [23].

The effective energies $\omega_\pm$ of the dressed state relate to the number of b-mode photons. When the value of n is large enough, the detunings $\delta_\pm$ become much larger than the effective coupling strengths $g_\pm$. In this case, the single-photon transmission efficient is approximately unity because the V-type system is nearly decoupled to the input single photon.

V. CONCLUSION

The transport of the injected single photon in a 1D waveguide coupled to a three-level emitter with a cascade configuration has been investigated. The atomic transition from $|2\rangle$ to $|3\rangle$ is driven by b-mode photons. When the emitter is in the ground state initially, whether the b-mode cavity contains photons determines the effective configuration of the emitter. Consequently, the single-photon transport property depends on whether the b-mode cavity contains a photon or not. The single-photon transport can also be controlled by the parameters of the b-mode cavity. We also studied the dressed-state representation. All the outcomes were obtained in the strong-coupling regime. Our scheme represents an all-optical device operated at the single-photon level.

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