Single-photon transport in one-dimensional coupled-resonator waveguide with local and nonlocal coupling to a nanocavity containing a two-level system

Mu-Tian Cheng,* Xiao-San Ma, Meng-Ting Ding, Ya-Qin Luo, and Guang-Xing Zhao
School of Electrical Engineering and Information, Anhui University of Technology, Maanshan 243002, People's Republic of China
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Single-photon scattering properties in a coupled-resonator waveguide (CRW) coupled to a nanocavity embedded with a two-level system are investigated theoretically. Two cases are considered: when the nanocavity is locally coupled to one resonator and when it is nonlocally coupled to two resonators of the CRW. The transmission and reflection amplitudes are obtained for the two cases, respectively. The results show that the position of perfect transmission remains unchanged, while the position of perfect reflection is shifted due to the nonlocal coupling. An asymmetric Fano resonance appears in the transmission spectrum and can be controlled by adjusting the coupling strengths in the nonlocal coupling case. The effects of the coupling strengths and dissipation on the transport properties are also analyzed for the two cases.

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I. INTRODUCTION

Recently, the photon transport in a low-dimensional waveguide has attracted much attention due to its wide application in quantum-information processing and the realization of photonic devices. Many experimental [1–6] and theoretical [7–42] works reported photon transport properties in different kinds of waveguides, such as metal nanowires [24,25,32,43] and silicon nanowires [44]. Some photonic devices, such as single-photon switching [7,13,16,18,24], routers [4,45], diodes [46,47], and single-photon transistors [27,43], have been proposed. Many quantum effects, such as Fano [48,49] and Dicke-type transmission [50], resonance fluorescence [51], a photon blockade [52], and generating nonclassical light sources [53], have been investigated. The coupled-resonator waveguide (CRW) is an important physical model, which can be realized by photonic crystals [54,55] or superconductor transmission line resonators [56–58]. The photon transport properties in the CRW embedded with a two-level or three-level atom have also been widely explored [15–22]. In this context, most of the coupling between the atom and the resonator of the CRW is taken to be local. Recently, Zhou *et al*. considered the nonlocal coupling between the atom and the CRW and explained the destructive interference phenomenon of the transmission spectra according to the effect of which-way detection [59]. In addition, the photon transport in a one-dimensional discrete system locally and nonlocally coupled to a defect has been investigated recently [60–62]. The nonlinear Fano resonance [60] and the nonlinear Fano-Feshbach resonances [61] have been discussed based on the nonlocal coupling between the defect and the one-dimensional discrete system.

In this paper, we consider the photon scattering in the CRW coupled to a nanocavity embedded with a two-level system. This model is useful in quantum-information and quantum optical devices. First, the two-level system is a qubit, which plays important roles in quantum information. Second, the nanocavity can enhance the interaction between the two-level system and the photon in the waveguide. Many atomic cavity quantum electrodynamics experiments use the cavity to enhance the interaction between the two-level system and the photon in the waveguide. For example, Aoki *et al*. reported realization of single-photon routing by using a fiber-coupled microtoroidal cavity interacting with individual cesium atoms [4]. Since the CRW is an important physical model, it is natural to ask what will happen for photon transport in the CRW which couples to a nanocavity interacting with a two-level system. The purpose of this paper is to try to answer this question. Also, the dispersion relation of the photon in the CRW is cosine. If the incident photon is in a high-energy regime, the dispersion relation can be approximately linear. And if the incident photon is in a low-energy regime, the dispersion relation can be approximately quadratic in form [16,28]. So this model may be used to explain more experimental results (such as the waveguide with linear or quadratic form dispersion relations) involved in nanocavity-enhancing photon-atom interaction in cavity quantum electrodynamics experiments.

Recently, Tan *et al*. discussed entangling two distant nanocavities via the CRW [63]. Based on their model, if one embeds a two-level system in the nanocavity, our model may be realized. Due to the interaction possibly being long range and nonlocal, we consider two cases, one where the nanocavity locally couples to one resonator of the CRW and one where it nonlocally couples to two resonators of the CRW, as shown in Figs. 1(a), and 1(b), respectively. By using the obtained analytical results of the transmission and reflection amplitudes, we show that the photon transport can be modified strongly due to the nonlocal coupling. The results may be useful in designing optical quantum devices.

II. LOCAL COUPLING

We consider a simple model first, where the nanocavity is locally coupled to only one resonator (labeled the 0th resonator) of the CRW, as seen in Fig. 1(a). A two-level system, whose ground state and excited state are denoted as $|g\rangle$, and $|e\rangle$, respectively, is placed in the nanocavity. The total Hamiltonian can be written as [16,23]

$$H = H_p + H_c + H_a + H_i, \tag{1}$$

*mtcheng@ahut.edu.cn

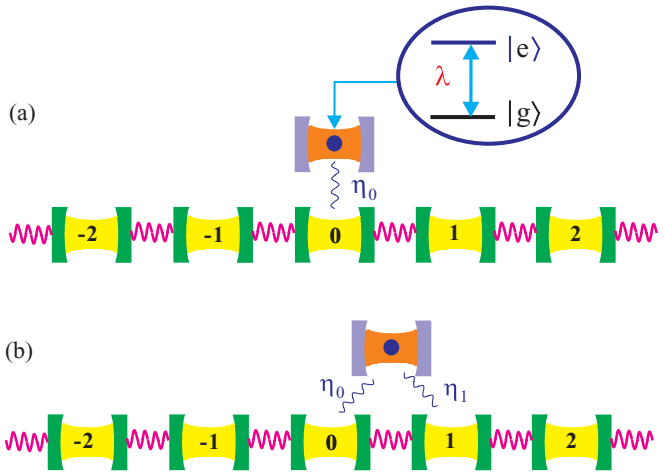

FIG. 1. (Color online) (a) Schematic configuration for the hybrid system of a one-dimensional CRW locally coupling with a nanocavity interacting with a two-level system with excited state $|e\rangle$ and ground state $|g\rangle$. (b) Schematic view of the nanocavity nonlocally coupling with two resonators of the one-dimensional CRW.

where H_w, H_c, H_a, and H_i describe the propagation of the single photon in the CRW, the nanocavity, the atom, and the interaction, respectively. The four terms are given as

$$H_w = \omega_c \sum_j C_j^\dagger C_j - \xi \sum_j (C_{j+1}^\dagger C_j + C_j^\dagger C_{j+1}), \quad (2a)$$

$$H_c = \omega_a a^\dagger a, \quad (2b)$$

$$H_a = \omega_e |e\rangle\langle e|, \quad (2c)$$

$$H_i = -\eta_0 (C_0^\dagger a + a^\dagger C_0) + \lambda (a^\dagger |g\rangle\langle e| + a|e\rangle\langle g|), \quad (2d)$$

where ω_c is the resonance frequency of the resonator mode and ξ is the hopping coefficient. Here, we have supposed that all the resonators of the CRW have the same frequency. $C_j^\dagger$ is the creation operator of photon at site j of the CRW. $a^\dagger$ (a) denotes the creation (annihilation) operator of the photon in the nanocavity, and ω_a is the resonance frequency of the nanocavity mode. ω_e represents the frequency of state $|e\rangle$ of the atom. We have set the energy scale such that the energy of level $|g\rangle$ is zero. $|m\rangle\langle n|(m,n = e,g)$ is the dipole transition operator between $|m\rangle$ and $|n\rangle$. η_0 is the coupling strength between the 0th resonator and the nanocavity. λ is the coupling strength between the atom and the nanocavity.

Since the number of excitations is conserved in this hybrid system, for the one-excitation subspace, the eigenstate of the system has the form [16,23]

$$|E_k\rangle = \sum_j u_k(j) C_j^\dagger |0\rangle_w |0\rangle_c |g\rangle_a + u_c |0\rangle_w |1\rangle_c |g\rangle_a + u_e |0\rangle_w |0\rangle_c |e\rangle_a. \quad (3)$$

Here, $u_k(j)$ are the amplitudes of single-photon states in the jth resonator. $|0\rangle_w |0\rangle_c |g\rangle_a$ ($|0\rangle_w |0\rangle_c |e\rangle_a$) denotes that no photon is in the resonator or the nanocavity, and the two-level system is in the ground (excited) state. $|0\rangle_w |1\rangle_c |g\rangle_a$ represents that the photon is in the nanocavity. u_c and u_e are the corresponding amplitudes, respectively.

From the Schrödinger equation $H|E_k\rangle = E_k|E_k\rangle$, we obtain

$$(E_k - \omega_c) u_k(j) = -u_c \eta_0 \delta_{j,0} - \xi [u_k(j-1) + u_k(j+1)], \quad (4a)$$

$$(E_k - \omega_a) u_c + \eta_0 u_k(0) - \lambda u_e = 0, \quad (4b)$$

$$(E_k - \omega_e) u_e - \lambda u_c = 0. \quad (4c)$$

By eliminating the amplitudes u_e and u_c, we obtain the discrete-scattering equation for the single excitation,

$$(E_k - \omega_c + V) u_k(j) = -\xi [u_k(j+1) + u_k(j-1)], \quad (5)$$

where the effective potential

$$V(j) \equiv \frac{\eta_0^2 (E_k - \omega_e)}{\lambda^2 - (E_k - \omega_a)(E_k - \omega_e)}. \quad (6)$$

For the nanocavity local coupling to the 0th resonator, the $u_k(j)$ has the solution

$$u_k(j) = \begin{cases} e^{ikj} + re^{-ikj}, & j < 0, \\ te^{ikj}, & j > 0, \end{cases} \quad (7)$$

where t and r are the transmission and reflection amplitudes, respectively. In the CRW, E_k is characterized by

$$E_k = \omega_c - 2\xi \cos k. \quad (8)$$

By using Eqs. (5)–(8), together with the continuous condition $u_k(0^+) = u_k(0^-)$, we obtain the transmission amplitude

$$t = \frac{\xi(e^{ik} - e^{-ik})}{\xi(e^{ik} - e^{-ik}) + V} = \frac{\xi(e^{ik} - e^{-ik})(\lambda^2 - \Delta_e \Delta_a)}{\xi(e^{ik} - e^{-ik})(\lambda^2 - \Delta_e \Delta_a) + \eta_0^2 \Delta_e}, \quad (9)$$

and the reflection amplitude

$$r = \frac{-V}{\xi(e^{ik} - e^{-ik}) + V} = \frac{-\eta_0^2 \Delta_e}{\xi(e^{ik} - e^{-ik})(\lambda^2 - \Delta_e \Delta_a) + \eta_0^2 \Delta_e}, \quad (10)$$

where $\Delta_e \equiv E_k - \omega_e$ and $\Delta_a \equiv E_k - \omega_a$, which are also dependent on k.

The transmission amplitude can also be rewritten as $t = \sqrt{T} e^{i\phi}$, where $T \equiv |t|^2$ is the transmission probability of the incident photon and ϕ is the phase shift imposed on the transmitted photon. Equation (9) indicates that the transmission vanishes and the reflection reaches the maximum 1 at the band edges with $k = 0, \pi$ for the local coupling case. The transmission also vanishes, and the reflection reaches the maximum at $E_k^{T=0} = [(\omega_e + \omega_a) \pm \sqrt{(\omega_e - \omega_a)^2 + 4\lambda^2}]/2$, which is independent of η_0 due to the destructive interference [see Fig. 2(a)]. Figure 2(b) shows ϕ as a function of $E_k - \omega_e$. The phase of the scattering photon experiences π jump at $E_k^{T=0}$, leading to the total destructive interference.

From Eqs. (9) and (10), one can find that there is a perfect transmission at $E_K^{T=1} = \omega_e$ due to the constructive interference, which is different from the case of a dip in the previous studies where the two-level system was directly

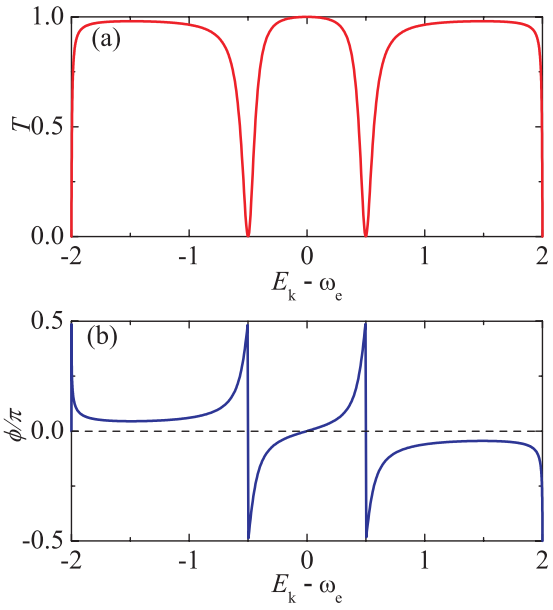

FIG. 2. (Color online) (a) Transmission probability T and (b) phase shift ϕ as a function of $E_k - \omega_e$. In the calculation, $\omega_c = \omega_e = \omega_a = 2$. $\lambda = \eta_0 = 0.5$. All parameters are in units of ξ.

coupled to the waveguide. Unlike $E_k^{T=0}$, $E_k^{T=1}$ is independent of ω_a. The phase of the scattering photon is zero, leading to the constructive interference, as shown in Fig. 2(a).

The coupling strengths are important parameters in this system. We show T as a function of $E_k - \omega_e$ with different λ and η in Fig. 3 to show the influence of the coupling strengths on the transmission properties. In Fig. 3(a), $\lambda = 0$, which means that the two-level system is decoupled from the nanocavity. A dip appears at $E_k = \omega_a = \omega_e$ in the transmission spectrum. For the case of $E_k = \omega_a = \omega_e$, the incident photon and nanocavity are resonant. Only the nanocavity is excited while the two-level system is not excited due to $\lambda = 0$, so the single photon is completely reflected ($r = -1$) at $E_k = \omega_a$. When $\lambda \neq 0$,

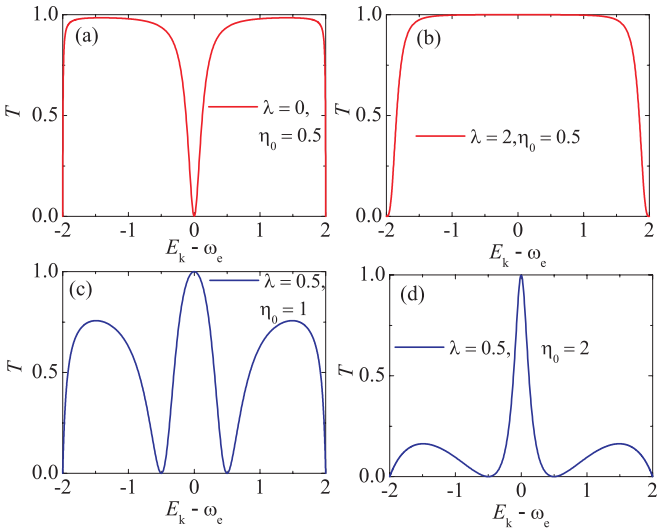

FIG. 3. (Color online) T as a function of $E_k - \omega_e$ with different coupling strengths (shown in the plots). In the calculation, $\omega_c = \omega_e = \omega_a = 2$. All parameters are in units of ξ.

both the nanocavity and the two-level system are excited. The transmission reaches the maximum at $E_k^{T=1}$ and the minimum at $E_k^{T=0}$, as shown in Fig. 2(a). The width between the maximum and the minimum $\Delta E = |E_k^{T=1} - E_k^{T=0}| = |\omega_e - \omega_a \pm \sqrt{(\omega_e - \omega_a)^2 + 4\lambda^2}|/2$. Particularly, when $\omega_e = \omega_a$, $\Delta E = \lambda$. So the width ΔE can be extremely small if λ is very small. However, if λ increases to $\lambda = 2\xi$, the two dips at $E_k^{T=0}$ are superposed in $E_k - \omega_2 = \pm 2$. The peak still exists in the transmission spectrum due to the constructive interference, as shown in Fig. 3(b). In addition, if the coupling λ further increases such that $\lambda \gg \eta_0$, the incident photon can be almost completely transmitted except $k = 0, \pi$. The system becomes nearly transparent. ΔE is independent of η_0, but the influence of η_0 on the transmission spectrum is obvious. The peak at $E_k^{T=1}$ becomes narrow as η_0 increases. Also, the two side peaks are strongly suppressed, as shown in Fig. 3(d). If $\eta_0 \gg \lambda$, the two side peaks are almost completely suppressed, and only a very narrow peak at $E_k^{T=1}$ exists. Further calculations reveal that the width of the peak at $E_k^{T=1}$ decreases with decreasing λ. We also note that the transmission spectrum is symmetric if $\omega_e = \omega_a$. These transport properties may have an application in designing optical filters.

III. NONLOCAL COUPLING

In a realistic physical system such as photonic-crystal waveguide coupled to a nanocavity, the interaction may be long range and nonlocal. In this section, we will consider the nonlocal coupling regime. The analytical expressions of the transmission coefficients are deduced.

The schematic configuration for the nanocavity nonlocally coupling to two resonators is shown in Fig. 1(b). We suppose the nanocavity nonlocally couples to the 0th and the 1th resonator with coupling strengths η_0 and η_1, respectively. The Hamiltonian H_i in Eq. (1) should be changed to

$$H_i = -\sum_{p=0,1} \eta_p (C_p^\dagger a + a^\dagger C_p) + \lambda (a^\dagger |g\rangle\langle e| + a|e\rangle\langle g|). \tag{11}$$

With the modified H_i, from the Schrödinger equation, we obtain

$$(E_k - \omega_c) u_k(j) = -u_c \sum_{p=0,1} \eta_p \delta_{j,p} - \xi [u_k(j-1) + u_k(j+1)], \tag{12a}$$

$$(E_k - \omega_a) u_c + \sum_{p=0,1} \eta_p u_k(p) - \lambda u_e = 0, \tag{12b}$$

$$(E_k - \omega_e) u_e - \lambda u_c = 0. \tag{12c}$$

We also modify $u_k(j)$:

$$u_k(j) = \begin{cases} e^{ikj} + re^{-ikj}, & j < 0, \\ te^{ikj}, & j > 1. \end{cases} \tag{13}$$

By solving Eqs. (12a)–(12c) and using Eq. (13), we obtain

$$t = \frac{(e^{ik} - e^{-ik})(\Delta_e\eta_0\eta_1 - \Delta_a\Delta_e\xi + \lambda^2\xi)}{(e^{ik} - e^{-ik})(\Delta_e\eta_0\eta_1 - \Delta_a\Delta_e\xi + \lambda^2\xi) + \Delta_e\eta_0\eta_1(e^{ik} + e^{-ik}) + \Delta_e\left(\eta_0^2 + \eta_1^2\right)}, \tag{14a}$$

$$r = \frac{-\Delta_e(\eta_0 + e^{ik}\eta_1)^2}{(e^{ik} - e^{-ik})(\Delta_e\eta_0\eta_1 - \Delta_a\Delta_e\xi + \lambda^2\xi) + \Delta_e\eta_0\eta_1(e^{ik} + e^{-ik}) + \Delta_e\left(\eta_0^2 + \eta_1^2\right)}. \tag{14b}$$

The transmission and reflection coefficients become cumbersome compared with the results for the case where the nanocavity locally couples to only one resonator. It is easy to check that $|t|^2 + |r|^2 = 1$. From Eqs. (14a) and (14b), one can obtain the conditions for perfect transmission,

$$E_k^{T=0} = \frac{\omega_a + \frac{\eta_0\eta_1}{\xi} + \omega_e \pm \sqrt{\left(\omega_a + \frac{\eta_0\eta_1}{\xi} - \omega_e\right)^2 + 4\lambda^2}}{2}, \tag{15}$$

and perfect reflection

$$E_k^{T=1} = \omega_e. \tag{16}$$

Equation (15) shows that, in the case where the nanocavity is nonlocally coupled to two resonators, the position of the perfect reflection is shifted. However, the point of perfect transmission still occurs at ω_e, remaining unchanged, as seen from Eq. (16). This property allows us to vary the width $|E_k^{T=1} - E_k^{T=0}|$ by changing the coupling strength between the nanocavity and the CRW, as shown in Fig. 4(a). The transmission shows strong asymmetric Fano resonance, which can be adjusted with the coupling strength between the nanocavity and the CRW. The situation results from the appearance of a bound state in the continuum [64]. The width between the two dips in the transmission spectrum is $\sqrt{(\omega_a + \eta_0\eta_1/\xi - \omega_e)^2 + 4\lambda^2}$, which increases with increasing λ, as shown in Fig. 4(b).

To show how the nonlocal coupling affects the photon transport properties, we plot $E_k^{T=0}$ and $E_k^{T=1}$ as a function of the degree of nonlocality $\rho = \eta_1/\eta_0$ in Fig. 5. It clearly shows that the position of the perfect transmission is fixed, but the positions of the perfect reflection are shifted. When $\rho = 0$, which means the coupling is local, the positions of perfect reflection are symmetric with respect to $E_k = \omega_e$. With increasing ρ, the position of the perfect reflection becomes asymmetric. One of the positions of the perfect reflection closely approaches $E_k^{T=1}$ and another moves far away. So the nonlocal coupling regime can provide narrower $|E_k^{T=1} - E_k^{T=0}|$ than the local coupling regime for a system with the same parameters.

Equation (14b) also shows that the transmission generally vanishes at $k = 0,\pi$. However, if $\eta_0 = \eta_1$, constructive interference can be found at $k = \pi$, as shown by red solid and blue dashed-dotted lines in Fig. 4(a). When $k = \pi$, the probability amplitudes take the expression $u_k(j) = (-1)^j$. For the symmetric coupling case $\eta_0 = \eta_1$, the equation for the nanocavity, Eq. (12b), becomes effectively decoupled from the discrete system, leading to the constructive interference.

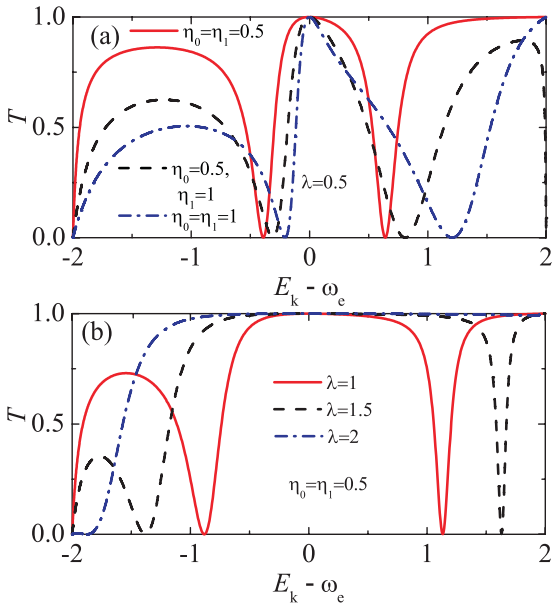

FIG. 4. (Color online) (a) T as a function of $E_k - \omega_e$ with different coupling strengths between the nanocavity and resonator. (b) T as a function of $E_k - \omega_e$ with different coupling strengths between the nanocavity and the atom. In the calculations, $\omega_c = \omega_e = \omega_a = 2$. All parameters are in units of ξ.

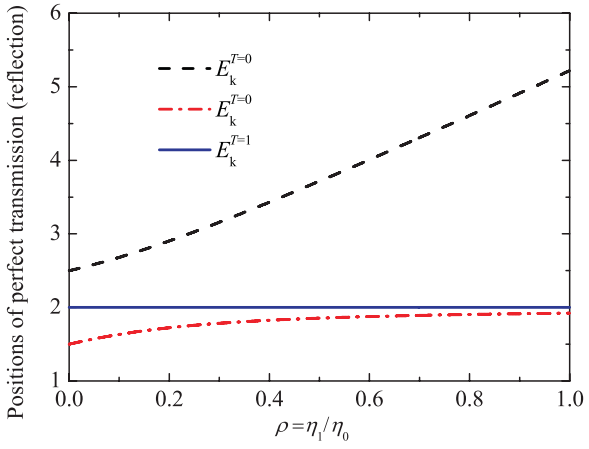

FIG. 5. (Color online) Dependence of the position of the perfect transmission ($T = 1$, blue solid line) and reflection ($T = 0$, black dashed and red dash-dotted lines) as a function of ρ. In the calculation, $\omega_c = \omega_e = \omega_a = 2, \eta_0 = 1, \lambda = 0.5$. All parameters are in units of ξ.

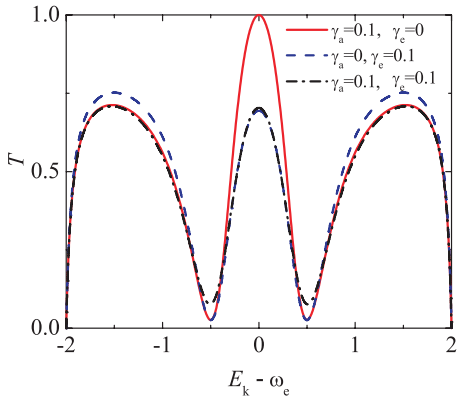

FIG. 6. (Color online) T as a function of $E_k - \omega_e$ with different decay rates for the local coupling case. The parameters are taken as $\omega_c = \omega_a = \omega_e = 2, \lambda = 0.5, \eta_0 = 1$. All parameters are in units of ξ.

IV. THE CASE WITH DISSIPATION

The energy relaxations and dephasing are unavoidable in realistic physical devices. In this section, we discuss the influence of dissipation on the photon transport by phenomenologically introducing two additional decay rates, γ_a and γ_e, for the nanocavity and the two-level system, respectively. To derive the transmission and reflection amplitudes of photon transport with γ_a and γ_e, the frequencies ω_a and ω_e are substituted by $\omega_a - i\gamma_a$ and $\omega_e - i\gamma_e$, respectively [17,23]. Replacing $\Delta_e = E_k - \omega_e + i\gamma_e$ and $\Delta_a = E_k - \omega_a + i\gamma_a$ in Eqs. (9), (10), (14a), and (14b), one can get the transmission and reflection amplitudes for both the local and nonlocal coupling systems with dissipation.

Figure 6 shows T for the local coupling with dissipation. Obviously, the perfect transmission at $E_k = \omega_e$ is independent of the nanocavity dissipation, as shown by the red solid line in Fig. 6. In this case, the two-level system is excited, whereas the nanocavity is not excited. So the dissipation of the two-level system can influence perfect transmission strongly. T at $E_k = \omega_e$ decreases quickly with increasing γ_e, as shown by the blue dashed line in Fig. 6. Comparing with Fig. 3(c), one can also find that the two side peaks decrease with increasing dissipation of the nanocavity.

Figure 7 shows T for the nonlocal coupling with dissipation. The influences of dissipation on the photon transport for the local and nonlocal cases are similar. The perfect transmission at $E_k = \omega_e$ is destroyed by γ_e, independent of γ_a. However, when $\eta_0 = \eta_1$, the nanocavity is decoupled from the CRW, so the perfect transmission at $k = \pi$ is independent of γ_e and γ_a, as shown in Fig. 7(b).

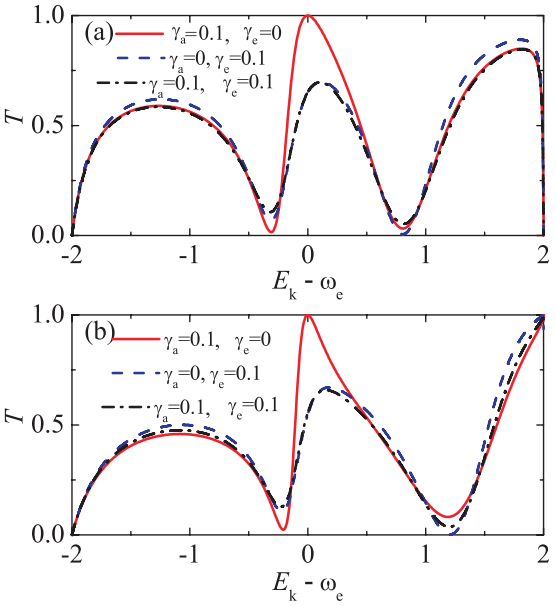

FIG. 7. (Color online) T as a function of $E_k - \omega_e$ with different decay rates for the nonlocal coupling case. (a) $\eta_0 = 1, \eta_1 = 0.5$, (b) $\eta_0 = \eta_1 = 1$. The other parameters are taken as $\omega_c = \omega_a = \omega_e = 2, \lambda = 0.5$. All parameters are in units of ξ.

V. CONCLUSION

In summary, the single-photon transport properties in the CRW locally and nonlocally coupled with a nanocavity containing a two-level system are investigated. The position of the perfect transmission is determined from the transition energy of the two-level system, independent of the nanocavity, and the coupling strength between the nanocavity and the CRW. However, the position of perfect reflection is shifted due to the nonlocal coupling. The perfect transmission at the band edge $k = \pi$, and a tunable asymmetric Fano resonance can appear in the nonlocal coupling case. In addition, the effect of the dissipation of the nanocavity and the atom on the photon transport properties is also explored. These results may have an application in designing photonic devices and controlling photon-matter interactions based on waveguide and nanocavity.

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