Single-Photon Scattering in a Waveguide Coupled to a Nanocavity

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Abstract. When a one dimensional coupled-resonator waveguide is coupled to a nanocavity with a three-level atom embedded in it, the transmission and reflection coefficients of a single photon with different polarizations are symmetric as a function of the detuning for local coupling while they are asymmetric for nonlocal coupling. The effects of dissipation on the scattering properties are also analyzed.

Keywords: Nanocavity, Coupled-Resonator Waveguide, Local Coupling, Nonlocal Coupling, Dissipation

1 Introduction

Since photons travel at the speed of light in vacuum and are robust against various sources of decoherence, they are very promising in quantum information processing (QIP). In investigations of controlling a single photon, the coupled-resonator waveguide (CRW) is regarded as an alternative system to realize single photon transfer. In experiments, a CRW can be realized by using coupled-cavity array [1], coupled superconducting transmission line resonators [2], or defect resonators in photonic crystals [3]. It is important to control the coherent transport of a scattered single photon by tuning the parameters of the system. It has potential applications for building a quantum switch using photons in quantum network. Since the polarization degree of freedom is widely used in QIP [4, 5, 6], it is necessary to investigate the effects of different polarizations of photons on photon scattering.

In this paper, the photon scattering process induced by a Λ-type three-level atom is investigated. As shown in Figs. 1(a) and 1(b), the CRW is constructed by an array of coupled resonators labeled with $-N, -N+1, \ldots, N$, through which a photon with polarization H incidents from the left. The atom initially at one of its ground state $|H\rangle$ is embedded in a nanocavity. The nanocavity is coupled to the CRW. The effects of different coupling forms and the dissipation on the photon scattering are discussed.

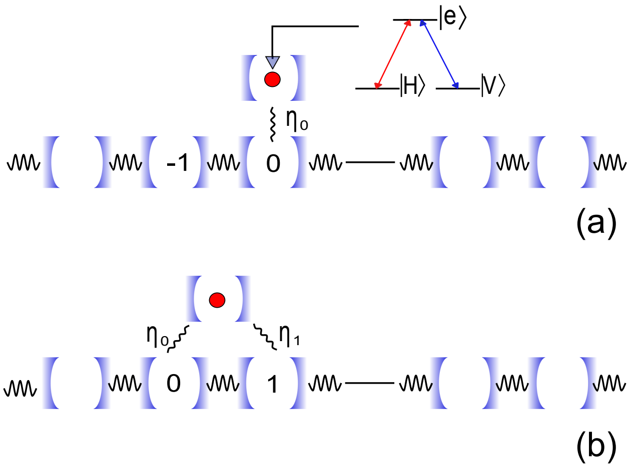

Figure 1: Schematic setup of the coupling. The ground states of the atom is degenerated with states $|H\rangle$ and $|V\rangle$, the excited state is $|e\rangle$. (a) Local coupling. (b) Nonlocal coupling.

2 Transmission and Reflection with Dissipation

For an ideal case, there is no dissipation in the system. For local coupling, the transmission and reflection coefficients of a single photon with different polarizations are plotted as a function of the detuning $E_k - \omega_e$ in Fig. 2. From Fig. 2, it is shown that the transmission and reflection spectrum of the single photon is symmetric about the resonance due to the local coupling between the nanocavity and CRW. In Figs. 2(a) and 2(c), the curve of the transmission coefficient T_H falls dramatically to zero near the edge while the reflection coefficient R_H increases quickly to 1. The minimum of T_H is the maximum of R_H. That is, the transmission and reflection probability of the photon with polarization H are mutually compensated. From Figs. 2(b) and 2(d), it is shown that the generated V polarized photons emerge near the region of zero detuning with $E_k - \omega_e \epsilon [-1, 1]$. While in the region $E_k - \omega_e \epsilon [-2, -1] \cup [1, 2]$, almost no photons with V polarization appear. In Fig. 2(e), the sum of the total spectrum is a straight line. That is, the total transmission and the reflection probability is conserved since there is no dissipation in the system. Due to the interaction between photons and the atom, the photon with one kind polarization can be converted to another kind polarization.

In real physical systems, the atomic decay and the intrinsic loss of coupled resonator are inevitable. In calculation of the transmission and reflection spectrum, the imaginary parts $-i\gamma_e$ and $-i\gamma_a$ can be added to the three-level atom transition frequency ω_e and the nanocavity frequency ω_a.

In Fig. 3, the effects of dissipation on single photon scattering is plotted for nonlocal coupling. The transmission spectrum, reflection spectrum, and photon flux of photons with different polarizations are not symmetric about the zero detuning. In Fig. 3(a), the positions of the two peaks and three troughs near zero detuning in T_H are shifted to large values of detuning $E_k - \omega_e$. The

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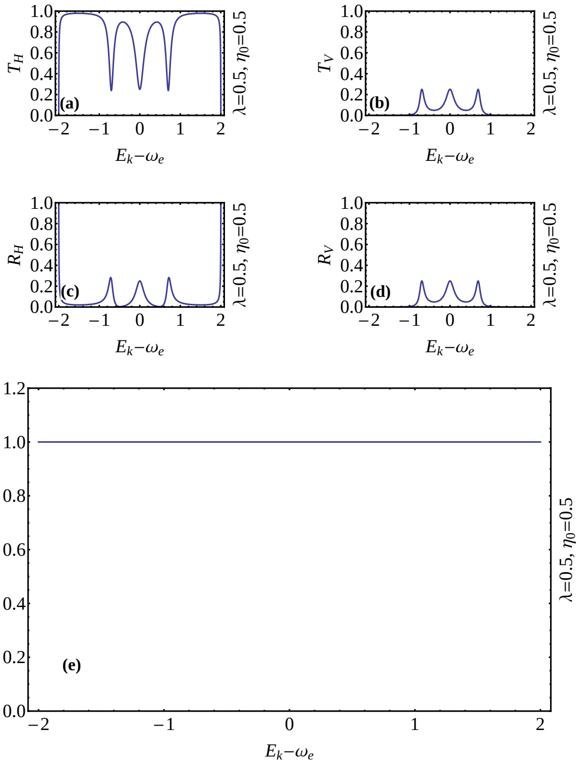

Figure 2: The transmission, reflection and total spectrum of different polarized photons are plotted as a function of the detuning when the nanocavity locally couples with the CRW and without dissipation.

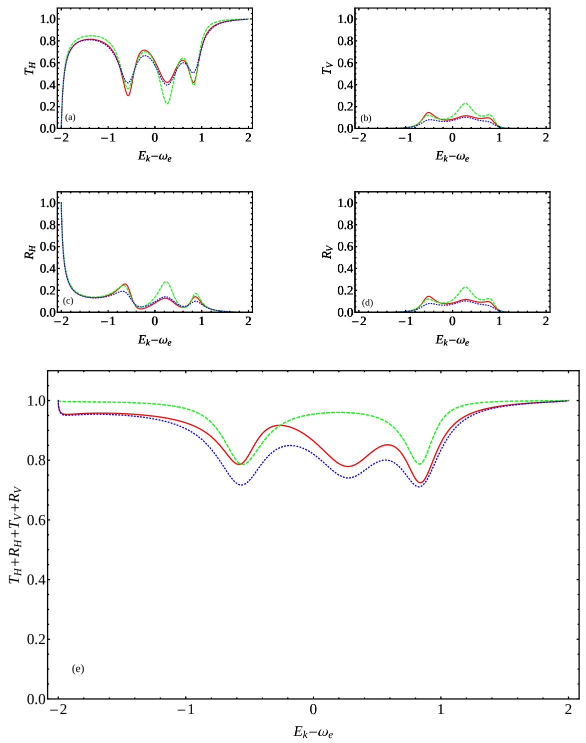

Figure 3: The transmission, reflection and total spectrum of different polarized photons are plotted as a function of the detuning when the nanocavity nonlocally couples with the CRW and dissipation is considered.

area surrounded by the green dashed line is smaller than those surrounded by the other two lines while it becomes larger than others in Figs. 3(b)-3(d). In Fig. 3(e), the area surrounded by the green dashed line is larger than the others. This indicates that improving the quality of the nanocavity and reducing the nanocavity decay rate will play important role in reducing the losses of photons.

3 Conclusion

The control of a single photon in a coupled-resonator waveguide coupled to a nanocavity with a three-level atom embedded in it is investigated. The photon scattering process induced by a three-level atom shows that the transmission of H polarized photons oscillates around zero detuning. For local coupling, the transmission spectrum of H polarized incident photons is symmetric about zero detuning. Though the single photon is more likely to transport through the CRW other than to be reflected back or to be converted into photons with other polarization, there are always some values of detuning at which photons can be reflected back or converted to other polarization with noticeable probabilities. For nonlocal coupling, the transmission of H polarized photons approaches and saturates to one when the detuning is greater than 0.9. If the dissipation is considered, the decay of nanocavity plays an important role in the transmission of photons. Reducing the decay rate of nanocavity can greatly reduce the loss of photons.

Acknowledgements

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