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Modulating the single-photon transport periodically with two emitters in two one-dimensional coupled cavity arrays

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ABSTRACT

We theoretically investigate the coherent transport behavior of a single-photon in T-type coupled cavity arrays (CCAs). Firstly, the case two two-level atoms (TLA) located inside two cavities of the incident channel is investigated, with the first TLA fixed at the T node and the second TLA in any position of CCA-a. The results show that the position of the second atom can periodically manipulate the transfer rate, and the single-photon can be completely routed into CCA-b deterministically. Secondly, we consider the two Λ-type three level atom instead of the two-level atom. When the driving field is present, the Fano-resonance can be observed and gradually becomes a double-peak with the increase of the driving field strength. In addition, the Rabi frequency of the first atom can alter the position of the double-peak, while the driving field intensity of the second atom only varies the peak value of the transfer rate, and the maximum probability may be obtained when the Rabi frequencies of the two Λ-type TLA are equal.

1. Introduction

Single photon is considered as important candidate of quantum information in quantum communication and quantum computation due to the fact that it has long coherent time and low dissipation [1–8]. In recent years, the rapid development of quantum networks consisting of quantum nodes and quantum channels has attracted widely attentions [9–13]. Quantum nodes, usually used to connect different quantum channel, are significant part ingredient due to manipulating and storing quantum information [14]. The single photon quantum router is an essential element for quantum network [14–19]. Consequently, Many quantum devices, such as quantum router, switching, single-photon frequency converter [20], transistors and optical diodes, are also demonstrated [21–25], especially in the extensive research of the single-photon quantum router. Quantum router is a main element for controlling the path of quantum signal [26], and the investigation of single-photon routing will have direct application to the implementation of quantum networks for quantum information processing and quantum computation [4]. Since an extensive of theoretical and experimental researches on single-photon quantum router scheme have been proposed in various system [12,15,17,23,26–33]. More recently, Zhou and Lu proposed the schemes of quantum router of the single-photon with three-level atom driven by a classical field with two channels [33,34]. Chen investigated that the nanocavity locally coupled with zeroth resonators of both arrays A and arrays B [26]. Song and Cheng studied the single photon scattering in a pair of coupled-resonator waveguides coupled to a quantum emitter [21,23]. The coherent transport of the single-photon in T-typed coupled cavity arrays (CCAs) has also been proposed by Lu and Cheng [13,25], the result shows that the possibility of the transfer rate routed into another channel does not exceed 0.5 when the single photon is incident from infinite waveguides.

In these configurations mentioned above, the maximum probability of the single photon from incident channel transferred into the another channel is no more than 0.5[26], which limits the development of the quantum router and cannot send full quantum information to the specified port. For more flexible use of quantum router, thus a multi-emitter quantum router, which can route the single-photon into another channel with high probability, is expected. Using atomic cavity which is formed by a pair of atoms not only can be utilized to store information [35,36], but also can enhance the possibility of the single-photon transferred into another channel [10].

Based on the previous theoretical work, we propose a simple model to effectively control the transport of the single-photon in T-shaped CCAs, which is an important device on construction of quantum network with three ports [25]. The proposed model with double-emitter (two- and three-level atoms) in a T-type coupled cavity arrays (CCA), one of the atom is at the node and the other is at any position in the incident CCA-a. It has been found that adjusting the position of the second atom can easily control the path of the single-photon, and the transfer rate can reach maximum 1 with the single-photon incident from CCA-a.

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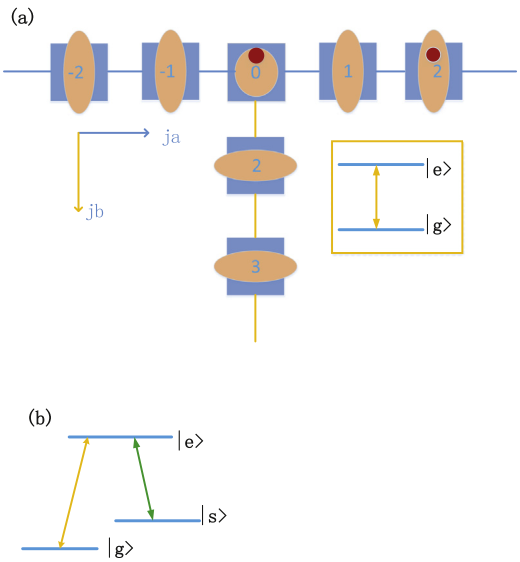

Fig. 1. (Color online) (a) Schematic diagram of the single photon router in T-shaped CCAs composed of one infinite CCA-a and a semi-infinite CCA-b. Two two-level atom, described by $|g\rangle$ and $|e\rangle$, are separately placed at different cavities in coupled cavity arrays, with the first atom at $j_a = 0$th and the second atom at $j_a = n$th. The first atom couples to CCA-a and CCA-b via $|g\rangle \leftrightarrow |e\rangle$ with strengths g_a and g_b respectively, and the second atom is only coupled to CCA-a field with strength g_n. (b) The position of two Λ-type three-level atoms which is characterized by $|g\rangle_l$, $|s\rangle_l$, $|e\rangle_l$ $(l = 1,2)$. The transition $|e\rangle_l \leftrightarrow |s\rangle_l$ is completed by the classical field with Rabi frequency Ω_l $(l = 1,2)$

Controlling other parameters can also effectively improve the quantum routing capability of the single-photon.

This paper is organized as follows. In Section 2, the theoretical model, with two atoms separately embedded in any two cavities of CCA-a in T-type CCAs, is proposed, and the transmission, reflection, and transfer rate amplitudes are derived by employing the discrete-coordinate scattering approach. In Section 3, we study the routing capability of the single photon by adjusting the parameters. In Section 4, in place of two-level atoms, two Λ-type three level atoms are placed in different cavities are investigated. The calculation results are the same except for energy-dependent potentials and effective coupling strength. In Section 5, we study the effect of the classical fields on single-photon transport properties. Finally, conclusions are presented In Section 6.

2. The theoretical model

As schematically shown in Fig. 1, two two-level atoms are embedded separately in two different cavities of T-typed coupled cavity arrays (CCAs), which is made up of one infinite and a semi-infinite CCAs, labeled as CCA-a and CCA-b respectively. For simplicity, the two atoms, whose ground state $|g\rangle_l$ and excited state $|e\rangle_l$ $(l = 1,2)$, are located in any cavities at $j_a = 0$th and $j_a = n$th correspondingly.

Once a photon is inside one cavity of the CCAs, it will spread along the CCAs and can be scattered by the atoms. The Hamiltonian for the CCAs are given by

$$\begin{aligned}H_C = &\sum_{j_a}[\omega_a a^\dagger_{j_a} a_{j_a} - \xi_a(a^\dagger_{j_a+1} a_{j_a} + a^\dagger_{j_a} a_{j_a+1})]\\ &+ \sum_{j_b}[\omega_b b^\dagger_{j_b} b_{j_b} - \xi_b(b^\dagger_{j_b+1} b_{j_b} + b^\dagger_{j_b} b_{j_b+1})],\end{aligned} \tag{1}$$

where a_{j_a} (b_{j_b}) is the annihilation operator of the j_ath (j_bth) single-mode cavity with frequency ω_a (ω_b), $j_a = -\infty, \dots, \infty$ and $j_b = 1, \dots, \infty$. Taking CCA-a as example, the coupling constant ξ_a, which is confirmed by the coupling between neighbor cavities, represents the photon hopping from one cavity into another. For simplicity, here it is assumed that all the cavities have same frequency ω_a and same hopping energy ξ_a between any two nearest-neighbor cavities. $a^\dagger_{j_a+1} a_{j_a+1}$ means that the photon is created in the $j_a + 1$th cavity and is annihilated in the j_ath cavity in CCA-a. The Hamiltonian in H_C is a typical tight-binding boson model. By introducing the Fourier transformation $a_{k_a} = \frac{1}{\sqrt{2\pi}}\int dj_a a_{j_a} e^{ik_a j_a}$ and $b_{k_b} = \sqrt{\frac{2}{\pi}}\int dj_b b_{j_b} \sin k_b j_b$ for the CCA-a and CCA-b accordingly [13]. The dispersion relation are $E^a_k = \omega_a - 2\xi_a \cos k_a d_0$ and $E^b_k = \omega_b - 2\xi_b \cos k_b d_0$, which indicate that CCA-a (CCA-b) has an energy band. Here, for brevity, the distance d_0 between any two neighbor-cavities is set to unity. The distance between two atoms is labeled as $D = nd_0$, which is determined by the nth cavity where the second atom is located. In general, D equals to n due to the distance d_0 is regarded as unity.

The Hamiltonian of the two atoms is given by

$$H_A = \omega_{1e}|e\rangle_1\langle e| + \omega_{2e}|e\rangle_2\langle e|, \tag{2}$$

here we have set energy scales of the $|g\rangle_1$ and $|g\rangle_2$ are zero. ω_{1e} and ω_{2e} are the energy spacing of the two atoms. The interaction between two atoms with CCA-a and CCA-b can be written as

$$H_I = g_a(\sigma^1_{eg} a_0 + H.c.) + g_b(\sigma^1_{eg} b_1 + H.c.) + g_n(\sigma^2_{eg} a_n + H.c.), \tag{3}$$

$\sigma^l_{eg} = |e\rangle\langle g|_l$ $(l = 1,2)$ are the ladder operator of the TLAs. At the intersection point $j_a = 0$ $(j_b = 1)$, the transition between $|g\rangle_1 \leftrightarrow |e\rangle_1$ couples to the cavity modes a_0 and b_1 with coupling strengths g_a and g_b, respectively. While the transition between $|g\rangle_2 \leftrightarrow |e\rangle_2$ of the second atom is only coupled to the cavity mode a_n with coupling strength g_n.

The total Hamiltonian of the hybrid system reads

$$H = H_C + H_A + H_I, \tag{4}$$

For studying the single-photon scattering in the single-excitation subspace, the eigenstate of the full system $|\Psi\rangle$ is supposed to be

$$|\psi\rangle = \sum_{j_a}\alpha(j_a)a^\dagger_{j_a}|0gg\rangle + \sum_{j_b}\beta(j_b)b^\dagger_{j_b}|0gg\rangle + U_{1e}|0eg\rangle + U_{2e}|0ge\rangle, \tag{5}$$

where $|0\rangle = |0_a 0_b\rangle$ means there are no photon both in CCA-a and CCA-b, $\alpha(j_a)$ and $\beta(j_b)$ are the probability amplitudes of the single-photon states in the j_ath cavity of CCA-a and j_bth cavity of CCA-b respectively. The parameter U_{le} $(l = 1,2)$ is the probability amplitude of the lth TLA in excited state while the other TLA is in the ground state.

Based on the Schrödinger equation $H|\Psi\rangle = E|\Psi\rangle$, we get the following equation

$$(E - \omega_{1e})U_{1e} = g_a\alpha(0) + g_b\beta(1), \tag{6a}$$

$$(E - \omega_{2e})U_{2e} = g_n\alpha(n), \tag{6b}$$

$$(E - \omega_a)\alpha(j_a) = -\xi_a[\alpha(j_a + 1) + \alpha(j_a - 1)] + g_a U_{1e}\delta_{j_a 0} + g_n U_{2e}\delta_{j_a n}, \tag{6c}$$

$$(E - \omega_b)\beta(j_b) = -\xi_b[\beta(j_b + 1) + \beta(j_b - 1)] + g_b U_{1e}\delta_{j_b 1}, \tag{6d}$$

Removing the atomic amplitudes in Eqs. (6a)–(6b), the discrete scattering equations of the single-photon can be read as

$$\begin{aligned}(E - \omega_a)\alpha(j_a) = &- \xi_a[\alpha(j_a + 1) + \alpha(j_a - 1)] + V_a(E)\alpha(j_a)\delta_{j_a 0}\\ &+ G(E)\beta(1)\delta_{j_a 0} + V_n(E)\alpha(j_a)\delta_{j_a n},\end{aligned} \tag{7a}$$

$$(E - \omega_b)\beta(j_b) = -\xi_b[\beta(j_b+1) + \beta(j_b-1)] + V_b(E)\beta(j_b)\delta_{j_b 1} + G(E)\alpha(0)\delta_{j_b 1}, \tag{7b}$$

For convenience, we introduce the energy-dependent delta potentials and the effective dispersive coupling strength correspondingly

$$V_d(E) \equiv \frac{g_d^2}{E - \omega_{1e}} (d = a, b), \tag{8a}$$

$$V_n(E) \equiv \frac{g_n^2}{E - \omega_{2e}}, \tag{8b}$$