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All-optical router at single-photon level by interference

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Abstract – The realization of the all-optical router with multiple input ports and output ports will have direct application to achieve the quantum network. We present a scheme of all-optical routing of coherent-state photons in a waveguide-cavity coupled system. Our router has four input ports and four output ports. The routing of photons is based on the interference. The outcomes show that the transport of the coherent-state photons injected through any input port can be controlled by the phases of the coherent-state photons injected through other input ports. This control can be realized at the single-photon level and requires no additional control fields. Therefore, the all-optical routing at single-photon level can be achieved.

Introduction. – The routing capability of information is a requisite in quantum network [1]. Photons are considered as the ideal carrier of information. Therefore, the investigation of routing of photons will have direct application to realize quantum network for optical quantum information and quantum computation. The routing of photons has been studied extensively in various systems [2–10]. However, most of the routers have only one input port and rely on the system parameters or a strong pulse containing many photons. Recently, a scheme to achieve all-optical routing of single photons with two input ports and two output ports has been successfully demonstrated [11]. In this scheme, the control single photons and routed single photons are connected by an intermediate three-level atom. By coupling two different atomic transitions respectively to the routed and control photons, the routed single photons can be controlled through injecting the control single photons. It will be of interest to realize the all-optical routing of photons at single-photon level by other physical mechanisms. Moreover, the all-optical routing with more than two input and output ports, which is essential for the quantum network, still needs to be explored.

For these purposes, we propose a scheme to study the all-optical routing of coherent-state photons with four input ports and four output ports by other coherent-state photons. It is significant that the all-optical routing of photons is realized by the interference depending on the phase differences between the routed and the control photons. Our scheme is based on the waveguide QED system [12–30], in which the strong coupling between the waveguide photons and the emitters coupled to the waveguide is realized. The routed photons and control photons are connected by an intermediate single-mode cavity. When the photons in the coherent state are injected into any of the input ports, the photon transport does not depend on the phase of the photons. However, when more than one input port is injected with coherent-state photons, the photon transport can be controlled by the phase differences between the photons injected into different ports. Our router can be realized at the single-photon level. Under certain conditions, our scheme is a router with two input ports and two output ports. Compared to [11], the intermediate single-mode cavity is coupled to

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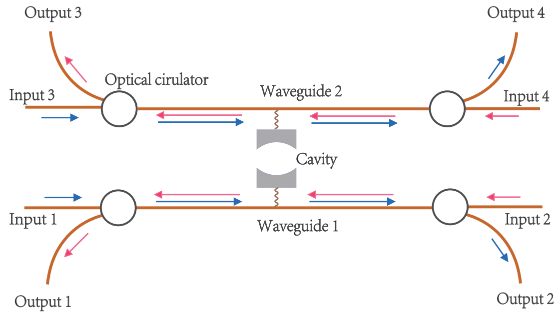

Fig. 1: (Color online) Schematic configuration of the all-optical routing of single photons with four input ports and four output ports.

both the routed and control photons in our scheme. This may avoid the cross-contamination of matching different atomic transitions, respectively, to the routed and control photons.

Model and results. – The system under consideration is depicted in fig. 1. The cavity is strongly side-coupled to lossless waveguides 1 and 2. The output ports are separated from the input ports by optical circulators. The system Hamiltonian in the rotating-wave approximation is written as ($\hbar = 1$)

$$\begin{aligned} H &= \sum_{j=1,2}\left(\int \mathrm{d}\omega\omega r_{j\omega}^{\dagger} r_{j\omega} + \int \mathrm{d}\omega\omega l_{j\omega}^{\dagger} l_{j\omega}\right) \\ &+ \omega_c c^{\dagger} c + \sum_{j=1,2}\int \mathrm{d}\omega g_j c^{\dagger}(r_{j\omega} e^{i\omega z_c/v_g} \\ &+ l_{j\omega} e^{-i\omega z_c/v_g}) + \text{h.c.}, \end{aligned} \tag{1}$$

where $r_{j\omega}^{\dagger}$ ($l_{j\omega}^{\dagger}$) creates a right (left) propagating photon with frequency ω in the waveguide j, $c^{\dagger}$ creates a photon in the cavity, ω_c is the cavity resonance frequency, g_j is the coupling strength of the cavity to the waveguide j, z_c is the position of the cavity, and v_g is the group velocity of the photons. Here, we have assumed that g_j is frequency independent, which is equivalent to the Markovian approximation. The waveguides are considered with the linear dispersion relation, *i.e.* $\omega = v_g|k|$, with k wave number [13]. We will take z_c zero and extend the frequency integration to $\pm\infty$ below.

We study the photon scattering with input-output formalism [31]. The input and output operators are defined as $o_j^{(in)}(t) = \frac{1}{\sqrt{2\pi}}\int \mathrm{d}\omega o_{j\omega}(t_0)e^{-i\omega(t-t_0)}$ ($o = r, l$) and $o_j^{(out)}(t) = \frac{1}{\sqrt{2\pi}}\int \mathrm{d}\omega o_{j\omega}(t_1)e^{-i\omega(t-t_1)}$, respectively. The operators $o_{j\omega}^{(in)}$ and $o_{j\omega}^{(out)}$ in the scattering theory are related to the input and output operators through $o_j^{(in)}(t) = \frac{1}{\sqrt{2\pi}}\int \mathrm{d}\omega o_{j\omega}^{(in)} e^{-i\omega t}$ and $o_j^{(out)}(t) = \frac{1}{\sqrt{2\pi}}\int \mathrm{d}\omega o_{j\omega}^{(\mathrm{out})} e^{-i\omega t}$ [24], respectively. In our scheme, initially, the cavity is in the vacuum state and the injected photons are in the coherent states. For the coherent input state, $o_j^{(in)}(t)|\Psi_0\rangle = \frac{1}{\sqrt{2\pi}}\int \mathrm{d}\omega\alpha_\omega e^{-i\omega t}|\Psi_0\rangle$, with $|\Psi_0\rangle$ the system ground state, and α_ω a complex number. The mean number of the coherent-state photons is represented by $\int \mathrm{d}\omega\,|\alpha_\omega|^2$.

We first consider the case in which the photons with frequency ω in a coherent state with mean photon number $|\alpha|^2$ are injected into input port 1. After calculations, we obtain $o_j^{(out)}(t)|\Psi_0\rangle = f(\gamma_1, \gamma_2, \alpha, \omega_c, \omega)e^{-i\omega t}|\Psi_0\rangle$. Therefore, the output photons have the same frequency with the input photons due to the energy conversation. The mean numbers of the photons outputting from each ports are

$$\begin{aligned} N_{r1}^{(out)} &= \frac{\delta_\omega^2 + \gamma_2^2}{\delta_\omega^2 + (\gamma_1+\gamma_2)^2}|\alpha|^2, \\ N_{l1}^{(out)} &= \frac{\gamma_1^2}{\delta_\omega^2 + (\gamma_1+\gamma_2)^2}|\alpha|^2, \\ N_{r2}^{(out)} &= N_{l2}^{(out)} = \frac{\gamma_1\gamma_2}{\delta_\omega^2 + (\gamma_1+\gamma_2)^2}|\alpha|^2, \end{aligned} \tag{2}$$

with $\gamma_j = 2\pi g_j^2$ being the decay rates from the cavity to the waveguide j, and $\delta_\omega = \omega_c - \omega$ the detuning. $N_{rj}^{(out)}$ ($N_{lj}^{(out)}$) is the mean number of the right(left)-moving photons in the waveguide j after scattering. Hence, $N_{r1}^{(out)}$, $N_{l1}^{(out)}$, $N_{r2}^{(out)}$ and $N_{l2}^{(out)}$ correspond to the mean numbers of the photons outputting from ports 2, 1, 4 and 3, respectively. It is easy to verify the conservation relation $\sum_{o,j} N_{oj}^{(out)} = |\alpha|^2$. When the input photons resonantly interact with the cavity and the coupling strengths of the cavity to the two waveguides are equal, *i.e.* $\delta_\omega = 0$ and $\gamma_1 = \gamma_2$, the photons are redirected into the four output ports equally. When $\delta_\omega \gg \gamma_1$ or $\gamma_2 \gg \gamma_1$, the waveguide 1 is almost decoupled to the cavity and we find $N_{r1}^{(out)} \to |\alpha|^2$. When the cavity is decoupled to the waveguide 2 and the input photons resonantly interact with the cavity, the photons are completely reflected and redirected into the output port 1.

The photons injected into different ports arrive at the position z_c simultaneously and then interact with the intermediate cavity. We proceed to study the routing of the photons by photons in two cases. One case is the routing of photons by photons injected into another input port, the other case is by photons injected into other two input ports. In the two-input case, when the photons in the coherent states are injected into ports 1 and 2, the mean numbers of the output photons are obtained as

$$\begin{aligned} N_{r1}^{(out)} &= [1 - 2\frac{(1+\cos\phi)\gamma_1\gamma_2 + \gamma_1\delta_\omega\sin\phi}{\delta_\omega^2 + (\gamma_1+\gamma_2)^2}]\,|\alpha|^2, \\ N_{l1}^{(out)} &= [1 - 2\frac{(1+\cos\phi)\gamma_1\gamma_2 - \gamma_1\delta_\omega\sin\phi}{\delta_\omega^2 + (\gamma_1+\gamma_2)^2}]\,|\alpha|^2, \\ N_{r2}^{(out)} &= N_{l2}^{(out)} = \frac{2(1+\cos\phi)\gamma_1\gamma_2}{\delta_\omega^2 + (\gamma_1+\gamma_2)^2}|\alpha|^2, \end{aligned} \tag{3}$$

with ϕ being the phase difference between the photons injected into input ports 2 and 1. Here we have considered that the photons injected into the two input ports have the same photon mean number $|\alpha|^2$ and the same frequency ω.

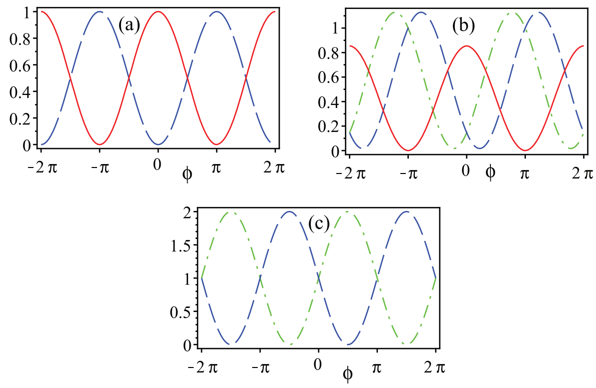

Fig. 2: (Color online) The mean photon numbers $N_{oj}^{(out)}$ against the phase differences in the two-input case. The blue dashed lines are $N_{r1}^{(out)}$, the green dash-dotted lines are $N_{l1}^{(out)}$, the red solid lines are $N_{r2}^{(out)} = N_{l2}^{(out)}$. We take $\delta_\omega = 0$, $\gamma_2 = \gamma_1$ in (a), $\delta_\omega = 0.5\gamma_1$, $\gamma_2 = 0.6\gamma_1$, in (b), and $\delta_\omega = \gamma_1$, $\gamma_2 = 0$ in (c). The other parameter is $|\alpha|^2 = 1$.

Similarly to the single-input case, the output photons have the same frequency as the input photons. It is interesting that the expressions of the mean output-photon numbers are periodic functions of ϕ with period 2π. Therefore, the routing of photons can be achieved by the phase of other photons injected into another input port. When $\phi = 2\pi$, $\delta_\omega = 0$ and $\gamma_1 = \gamma_2$, the photons are completely redirected into output ports 3 and 4 due to the constructive interference. However, when $\phi = \pi$, the photons are completely redirected into output ports 1 and 2 due to the destructive interference. We plot the mean photon numbers in eqs. (3) against the phase difference in fig. 2. Therefore, the routing of the coherent-state photons injected into the input port 1 can be achieved by the phase of the coherent-state photons injected into the input port 2. This routing is based on the interference determined by the phase difference. The interference cannot be obtained when the input photons are in Fock states [25]. This is because the coherent state is the eigenstate of the annihilation operator.

When the cavity is decoupled to the waveguide 2, *i.e.* $\gamma_2 = 0$, our scheme becomes a router with two input ports and two output ports. The mean numbers of the photons outputting from either port are obtained as $N_{r1}^{(out)} = \frac{\delta_\omega^2+\gamma_1^2-2\gamma_1\sin\phi\delta_\omega}{\delta_\omega^2+\gamma_1^2}|\alpha|^2$, and $N_{l1}^{(out)} = \frac{\delta_\omega^2+\gamma_1^2+2\gamma_1\sin\phi\delta_\omega}{\delta_\omega^2+\gamma_1^2}|\alpha|^2$. It is interesting that when $\delta_\omega^2 = \gamma_1^2$, the expectation value $N_{o1}^{(out)}$ can be from 0 to $2|\alpha|^2$ by adjusting the phase ϕ. The details are shown in fig. 2(c).

When the photons in coherent states are injected into input ports 1 and 3, the outcomes have the forms similar to the outcomes in eqs. (3) except for γ_j. Hence, it is not necessary to study the details of this situation.

In the three-input case, it is enough to study the situation in which the coherent-state photons with frequency ω are injected into input ports 1, 3 and 4. In this situation, the output photons have the frequency ω and the mean numbers of the output photons are obtained as

$$\begin{aligned} N_{r1}^{(out)} &= \frac{A}{\delta_\omega^2+(\gamma_1+\gamma_2)^2}|\alpha|^2, \\ N_{l1}^{(out)} &= \frac{B}{\delta_\omega^2+(\gamma_1+\gamma_2)^2}|\alpha|^2, \\ N_{r2}^{(out)} &= \frac{C}{\delta_\omega^2+(\gamma_1+\gamma_2)^2}|\alpha|^2, \\ N_{l2}^{(out)} &= \frac{D}{\delta_\omega^2+(\gamma_1+\gamma_2)^2}|\alpha|^2. \end{aligned} \tag{4}$$

The expressions of phase-dependent A, B, C, and D are $A = \delta_\omega^2 + \gamma_2^2 + 2\gamma_1\gamma_2 - 2\delta_\omega\sqrt{\gamma_1\gamma_2}(\sin\theta + \sin\theta') - 2\sqrt{\gamma_1\gamma_2}\gamma_2(\cos\theta + \cos\theta') + 2\cos(\theta - \theta')\gamma_1\gamma_2$, $B = \gamma_1^2 + 2[1 + \cos(\theta - \theta')]\gamma_1\gamma_2 + 2(\cos\theta + \cos\theta')\gamma_1\sqrt{\gamma_1\gamma_2}$, $C = \delta_\omega^2 + (\gamma_1+\gamma_2)^2 - \gamma_2\gamma_1 + 2\sin\theta\sqrt{\gamma_1\gamma_2}\delta_\omega + 2\sin(\theta-\theta')\gamma_2\delta_\omega - 2\cos\theta\gamma_1\sqrt{\gamma_1\gamma_2} + 2\cos\theta'\gamma_2\sqrt{\gamma_1\gamma_2} - 2\cos(\theta' - \theta)\gamma_1\gamma_2$, $D = \delta_\omega^2 + (\gamma_1 + \gamma_2)^2 - \gamma_2\gamma_1 + 2\delta_\omega[\sin\theta'\sqrt{\gamma_1\gamma_2} + \sin(\theta' - \theta)\gamma_2] - 2\cos(\theta - \theta')\gamma_2\gamma_1 - 2\cos\theta'\gamma_1\sqrt{\gamma_1\gamma_2} + 2\cos\theta\gamma_2\sqrt{\gamma_1\gamma_2}$, with θ (θ') the phase difference between the photons injected into input ports 3 (4) and 1. The photons injected into each of the three ports have the same mean photon number $|\alpha|^2$. The mean numbers of output photons in eqs. (5) against the phase differences are plotted in fig. 3. It shows that the routing of the photons by other photons can be achieved in the three-input case.

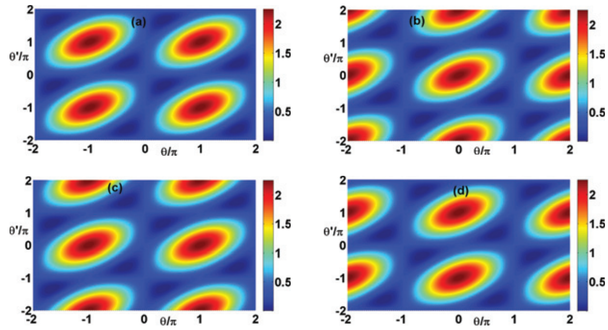

Fig. 3: (Color online) The mean photon numbers against the phase differences in the three-input case. Panels (a), (b), (c) and (d) denote $N_{rl}^{(out)}$, $N_{l1}^{(out)}$, $N_{r2}^{(out)}$ and $N_{l2}^{(out)}$, respectively. For all the plots, the parameters are $\delta_\omega = 0$, $\gamma_2 = \gamma_1$, and $|\alpha|^2 = 1$.

From the expressions of eqs. (3) and (4), the routing properties do not depend on $|\alpha|^2$. Hence, the routing can be achieved at the single-photon level. We have considered that all the photons injected into different ports have equal frequencies and mean photon numbers. To obtain the phase-dependent interference, the condition of equal frequencies is necessary, whereas the condition of equal mean photon numbers is not necessary. However, the degree of interference depends on the difference between the mean numbers of the photons injected into different input ports. To achieve a good interference effect, we have considered that the mean photon numbers are equal.

We have studied the routing of photons when the input photons are in single-mode coherent states, without

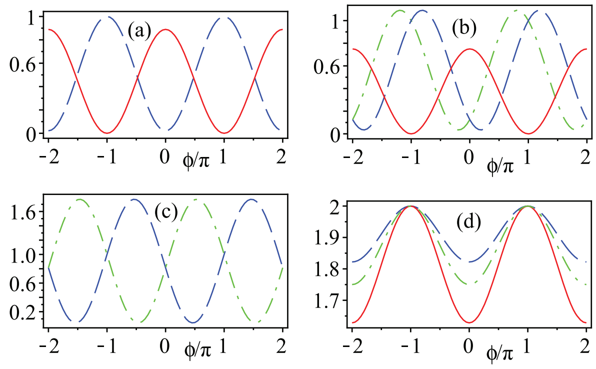

Fig. 4: (Color online) The mean numbers of the output photons against the phase differences in the two-input case. The input photons are in coherent states prepared in Gaussian-type wave packets and the cavity decay has been considered. For all the plots, we take $\Omega = 0.3\gamma_1$ and $\gamma_c = 0.1\gamma_1$. In (a), (b) and (c), the blue dashed lines are $N_{r1}^{(out)}$, the green dash-dotted lines are $N_{l1}^{(out)}$, the red solid lines are $N_{r2}^{(out)} = N_{l2}^{(out)}$. The other parameters in (a), (b) and (c) are the same as the parameters in figs. 2(a), (b) and (c), respectively. Panel (d) shows the sum of the mean numbers of the photons outputting from all output ports $N^{(out)}$. The blue dashed line, green dash-dotted line, and red solid lines in (d) correspond to the situations as shown in (a), (b) and (c), respectively.

considering the cavity decay to other modes but the waveguide modes. The cavity decay can be incorporated by introducing the non-Hermitian Hamiltonian $H_{non} = -i\gamma_c c^\dagger c$, with γ_c the decay rate. The injected coherent state prepared in a Gaussian-type wave packet is defined as $a_\omega^{(in)} |\Psi_0\rangle = \alpha_\omega |\Psi_0\rangle$. The complex number α_k has the form of $\alpha_\omega = \frac{\alpha}{\sqrt[4]{2\pi\Omega^2}} e^{-\frac{(\omega-\omega_0)^2}{4\Omega^2}}$, with 2Ω the bandwidth and ω_0 the center frequency. The mean photon number of the wave packet is $\int \mathrm{d}\omega\, |\alpha_\omega|^2 = |\alpha|^2$. For the Gaussian-type wave packet input, the mean output-photon numbers can be obtained by numerical evaluations. We plot the routing property when the photons in the coherent state prepared in a Gaussian-type wave packet are injected into input ports 1 and 2 in fig. 4. In fig. 4, the cavity decay has been incorporated. In fig. 4(a), the up bound of $N_{r1}^{(out)} = N_{l1}^{(out)}$ is barely affected but the up bound of $N_{r2}^{(out)} = N_{l2}^{(out)}$ decreases evidently compared to fig. 2. In fig. 4(c), both the up bounds $N_{r1}^{(out)}$ and $N_{l1}^{(out)}$ decrease evidently. These are mainly due to the fact that we have considered the wave packet bandwidth, which can be understood as follows. The frequency-dependent condition $\delta_\omega = 0$ is necessary when the value of $N_{r2}^{(out)}$ in fig. 4(a) reaches unit. However, the unit value of $N_{r1}^{(out)}$ in fig. 4(a) only needs the condition $\theta = \pi$, which is frequency independent. In fig. 4(c), we take $\delta_\omega = \gamma_1$, which is frequency dependent. The outcomes obtained under the frequency-dependent condition are affected by the bandwidth. The effect caused by the cavity decay can be studied by the mean number $N^{(out)}$ of all the output photons, with $N^{(out)} = N_{r1}^{(out)} + N_{l1}^{(out)} + N_{r2}^{(out)} + N_{l2}^{(out)}$. As is shown in fig. 4(d), when $\theta = \pi$, the effect of cavity decay can be neglected due to the destructive interference. However, when $\theta = 2\pi$, the cavity decay has an obvious effect due to the constructive interference.

The waveguide can be achieved by a line defect in a 2D photonic crystal slab, and the cavity can be achieved by a point defect or a modulated line defect in a 2D photonic crystal slab. The line defect waveguide can be coupled to the photonic crystal cavity in a chip [32,33]. The coupling efficiency of photonic crystal linear three-hole defect cavities to photonic crystal waveguides can reach 90% [34], which may lead to the case close to the one plotted in fig. 4. Here we have assumed that the waveguide is lossless. Theoretically, the line defect waveguide in a photonic crystal slab may have guided modes without radiation loss [32]. In reality, the waveguide loss, which is caused by finite disorder in fabricated samples, can be reduced to as low as few dB/cm [35]. The waveguide with length on the order of 100 lattice constants should work well. Considering that the lattice constant is on the order of 100 nm, the length of the waveguide is on the order of 10 μm. Therefore, the effect caused by the waveguide loss can be neglected in our scheme.

Conclusions. – In conclusion, we have presented a detailed investigation on the all-optical routing at single-photon level with multiple input and output ports. The routing is achieved by the interference related to the phase differences between the coherent-state photons. Quantum information and quantum computation with optical coherent states are investigated in refs. [36–38]. Besides, the authors in ref. [39] demonstrate that, rather unexpectedly, there exist noisy quantum channels or that the optimal classical information transmission rate is achieved only by signaling alphabets consisting of nonorthogonal quantum states.

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