A photonic controlled-phase gate by passive use of a Λ system

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Photonic systems are promising for realizing quantum information processing because of their long coherence times. However, due to the weak interaction between photons, implementation of photonic gates has been difficult. One way to overcome this problem is to exchange the photonic and atomic qubits and to enhance the effective photon-photon interaction. For this purpose, the cavity-QED or waveguide-QED systems are suitable [1-3], where the spatial modes of the input photon and the radiation from the atom match in a one-dimensional field and strongly interfere with each other. A pioneering work in this direction is Duan-Kimble scheme [1,4], which achieves a photon-photon controlled-NOT gate with active control of the atom such as initialization, single-qubit rotation, and measurements. Recently, we showed that deterministic swapping of photonic polarization and atomic qubits is possible by using a Λ-type atom and proposed a scheme for photon-photon $\sqrt{\mathrm{SWAP}}$ gate [2]. An advantage of this scheme is that the atom is used totally passively, that is, active control by auxiliary fields is unnecessary throughout the gate operations. However, the scheme requires photonic qubits with different frequencies, which would require a complicated optical circuit.

In this work, we propose a scheme for implementing a photonic controlled-phase gate using a Λ-type atom. In this scheme, all photonic polarization qubits are of the same frequency and the atom is used totally passively. Moreover, the infidelity due to incomplete atom-photon swapping is automatically filtered out, which substantially improves the gate fidelity when the decay rates of the Λ system are unbalanced ($\Gamma_H \neq \Gamma_V$). The proposed scheme is also applicable to the photonic qubits encoded in frequency; this is advantageous practically since the two transition frequencies of a Λ system are different in general.

The proposed photon-photon gate operates with three steps. (i) We swap the photonic and atomic qubits [2] and store the first photonic qubit in the atom. (ii) We then apply a photon-atom controlled-phase gate between the second photonic qubit and the atom. (iii) Finally, we swap the photonic and atomic qubits again and retrieve the first photonic qubit from the atom. These three steps complete the photon-photon controlled-phase gate. Below, we discuss step (ii). As drawn in Fig. 1, the second photonic qubit is split into two paths depending on its polarization, horizontal or vertical. Only the vertical component is forwarded to the atom and is swapped with the atom. This means that the first photonic qubit stored in the atom is retrieved only when the second photonic qubit is polarized vertically. Then, a single-qubit phase gate is applied to the retrieved first photonic qubit with a half-wave plate. The retrieved first photonic qubit is swapped with the atom again, then the first photonic qubit is fully stored in atom again and the vertical component of the second photonic qubit is retrieved. The horizontal polarization component of the second photon is applied a delay line and a wave form corrector (WFC) for the compensation of the deformation of the vertical wave packet. After that, the vertical and horizontal components are combined again. Thus, in the controlled-phase operation, the photon-atom state vector evolves as follows:

$$\begin{aligned}
&\alpha|H\rangle|0\rangle + \beta|H\rangle|1\rangle + \gamma|V\rangle|0\rangle + \delta|V\rangle|1\rangle \\
&= |H\rangle(\alpha|0\rangle + \beta|1\rangle) + |V\rangle(\gamma|0\rangle + \delta|1\rangle) \\
(\mathrm{SWAP1}) &\rightarrow |H\rangle(\alpha|0\rangle + \beta|1\rangle) + (-\gamma|H\rangle + \delta|V\rangle)|1\rangle \\
(\mathrm{Phase}) &\rightarrow |H\rangle(\alpha|0\rangle + \beta|1\rangle) + (-\gamma|H\rangle - \delta|V\rangle)|1\rangle \\
(\mathrm{SWAP2}) &\rightarrow |H\rangle(\alpha|0\rangle + \beta|1\rangle) + |V\rangle(\gamma|0\rangle - \delta|1\rangle).
\end{aligned}$$

Here, another merit of our scheme is that the main imperfection coming from the atom-photon interaction due to the discrepancy of the decay rates between Γ_H and Γ_V is automatically filtered out by the PBS. This turns the infidelity of the output state into a heralded loss, which is advantageous in quantum information processing (Fig.2).

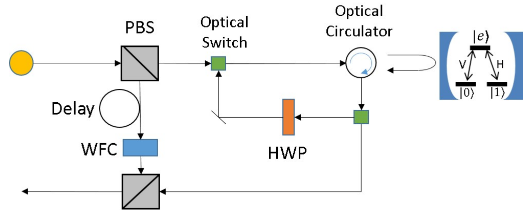

FIG. 1. Schematic of the photon-atom controlled-phase gate.

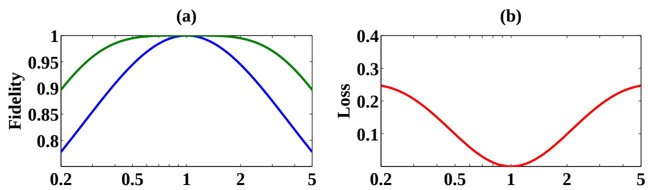

FIG. 2. (a) Fidelity before filtering (Blue). Fidelity after filtering (Green). (b) Loss rate caused by the filtering (Red). Here, x-axis shows Γ_V/Γ_H and the long pulse limit ($\gg$ atomic lifetime) is assumed.

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