Transfer and teleportation of quantum states encoded in decoherence-free subspace

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Quantum state transfer and teleportation, with qubits encoded in internal states of atoms in cavities, among spatially separated nodes of a quantum network in a decoherence-free subspace are proposed, based on a cavity-assisted interaction with single-photon pulses. We show in detail the implementation of a logic-qubit Hadamard gate and a two-logic-qubit conditional gate, and discuss the experimental feasibility of our scheme.

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Quantum state transfer and teleportation are significant components in quantum-information processing, especially for quantum networks. As the confined atoms in cavity QED systems are well suited for storing qubits in long-lived internal states, spatially separated cavities could be used to build a quantum network assisted by photons [1–7]. On the other hand, decoherence due to the inevitable interaction with the environment destroys quantum coherence. So decoherence-free subspaces (DFSs) of the Hilbert space have been introduced to protect against some errors due to environmental coupling with a certain symmetry [8–10]. For example, Ref. [10] utilized two atoms to encode a single logic qubit, i.e., $|\tilde{0}\rangle \equiv |1\rangle_1|0\rangle_2 = |10\rangle$, $|\tilde{1}\rangle \equiv |0\rangle_1|1\rangle_2 = |01\rangle$, which are robust to collective dephasing errors caused by ambient magnetic fluctuation.

In this Brief Report, for the quantum state encoded in a DFS mentioned above, we present the implementation of a single-logic-qubit Hadamard gate and a two-logic-qubit conditional gate based on cavity-assisted interaction with single-photon pulses. Based on these gates, we will carry out quantum state transfer and teleportation between two spatially separated nodes in a quantum network. Compared with previous related works, our proposal does not rely on synchronous optical lattices [4] in implementation of the single-logic-qubit Hadamard gate. In addition, auxiliary entangled photon pairs, as employed in [5], are unnecessary in our two-logic-qubit conditional gate. Moreover, for quantum state transfer, neither entangled photon pairs [11] nor a special time-symmetric wave packet of the photons [1] is necessary in our scheme. So our scheme could not only protect quantum information from some decoherence, but also reduce the experimental difficulty compared to previous schemes [1,4,5,11]. Furthermore, in our scheme, each node of the quantum network in the DFS has an individual input port for photons to complete the necessary operations, and different operational results can be distinguished by detecting the output photons.

The main idea, using cavity-assisted photon scattering to realize a controlled phase flip (CPF) between two atoms [3–6], is sketched below. Suppose that two identical atoms, each of which has a three-level configuration, are located in a high-finesse cavity. The levels $|0\rangle$ and $|e\rangle$ of the atom are resonantly coupled to the bare cavity mode with h polarization or by the h component of an input photon, while level $|1\rangle$ is decoupled because of the large detuning, as shown in Fig. 1. If the duration of the input photon pulse T is sufficiently long and the atom-cavity coupling is much stronger than both the cavity decay and spontaneous emission of the atomic state, the pulse in resonance with the bare cavity mode, i.e., the two atoms in the state $|1\rangle_1|1\rangle_2$, will yield a pulse shape almost unchanged but with a π phase added when reflected by the cavity. On the contrary, if either of the two atoms is in the state $|0\rangle$, as the cavity mode is shifted by the resonance with the atom, the pulse will be reflected by the cavity with both its shape and phase unchanged [3]. Therefore, by reflecting a single-photon pulse with h polarization, the two-atom controlled phase gate $U_{\mathrm{CPF}} = \exp(i\pi|1\rangle_{11}\langle 1| \otimes |1\rangle_{22}\langle 1|)$ is available.

To carry out a quantum transfer and a teleportation in the DFS, we need to construct a Hadamard operation $\tilde{H}$ on the single-logic qubit and a conditional gate operation on the two-logic qubit. The $\tilde{H}$ operation is shown in Fig. 2 for the logic qubit at an arbitrary node i (or, say, cavity i). The half-wave plate 1 (HWP1), with its axis at 45° to the horizontal direction, rotates the photon polarization as $|h\rangle \leftrightarrow |v\rangle$. P_{45} is a 45° polarizer projecting the polarization $(|h\rangle + |v\rangle)/\sqrt{2}$. TR is a device which can be controlled exactly as needed to transmit or reflect a photon [11], and the switching-time sequences of TR1 and TR2 are also given in Fig. 2.

Assume that the state of the logic qubit in the cavity i is $|\tilde{1}\rangle$. The $\tilde{H}$ operation can be performed by following four steps. (1) A single-photon pulse in state $(1/\sqrt{2})(|h\rangle + |v\rangle)$ is imported from port i. It passes through TR1 and C, and then

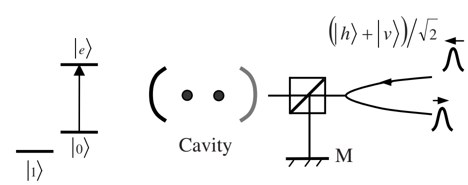

FIG. 1. Left: Level configuration of an atom in a cavity. Right: Schematic setup to implement a two-atom controlled phase gate by cavity-assisted polarized-photon scattering.

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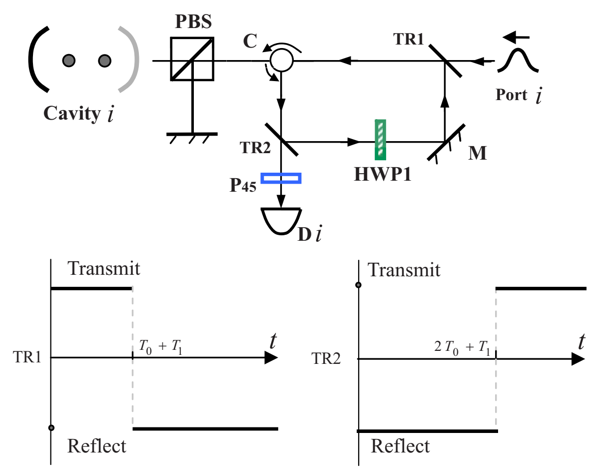

FIG. 2. (Color online) Schematic setup for a single-logic-qubit operation $\widetilde{H}$ and time control sequence of TR1 and TR2. Di is a detector, C is a circulator. HWP1 rotates the photon polarization as $|h\rangle \leftrightarrow |v\rangle$. TR can be controlled exactly as needed to transmit or reflect a photon. The single-photon pulse's path for $\widetilde{H}$ is port i–TR1-C-PBS-cavity-PBS-C-TR2-HWP1-M-TR1-C-PBS- cavity-PBS-C-TR2-P_{45}-Di. The states of TR1 and TR2 can be controlled accurately by computer. T_0 is the time for the single-photon pulse process TR1-C-PBS-cavity-PBS-C-TR2, while T_1 is the time for TR2-HWP1-M-TR1.

reaches the polarizing beamsplitter (PBS) and the cavity i. Meanwhile, we perform a flip operation on the logic qubit inside the cavity i, i.e., $\widetilde{X}=C^{2,1}_{\rm NOT}H_2U_{\rm CPF}H_2C^{2,1}_{\rm NOT}$, whose function is to flip the logic qubit $|\widetilde{0}\rangle \leftrightarrow |\widetilde{1}\rangle$ [6], and thereby the state becomes $(1/\sqrt{2})(|h\rangle|\widetilde{0}\rangle+|v\rangle|\widetilde{1}\rangle)$ after the photon pulse comes back from the cavity i and the PBS. (2) Reflected by TR2, the photon pulse goes through HWP1, yielding the state $(1/\sqrt{2})(|v\rangle|\widetilde{0}\rangle+|h\rangle|\widetilde{1}\rangle)$. (3) After being reflected by M and TR1, the single-photon pulse arrives at PBS again. We need two NOT operations on atom 1, one before and another after the photon pulse is reflected by the cavity, i.e., the operation sequence $\sigma_x^1 U_{\rm CFP}\sigma_x^1$. So we get to the state $(1/\sqrt{2}) \times(|v\rangle|\widetilde{0}\rangle-|h\rangle|\widetilde{1}\rangle)$. (4) Finally, when the single-photon pulse passes TR2 and P_{45}, the photon is detected by Di, and thereby the logic qubit inside the cavity i is left in the state $(1/\sqrt{2})(|\widetilde{0}\rangle-|\widetilde{1}\rangle)$. The operation process above can be shown more specifically as follows:

$$\frac{|h\rangle+|v\rangle}{\sqrt{2}}|\widetilde{1}\rangle \xrightarrow{\widetilde{X}} \frac{1}{\sqrt{2}}(|h\rangle|\widetilde{0}\rangle+|v\rangle|\widetilde{1}\rangle) \xrightarrow{\rm HWP1} \frac{1}{\sqrt{2}}(|v\rangle|\widetilde{0}\rangle+|h\rangle \times|\widetilde{1}\rangle) \xrightarrow{\sigma_x^1 U_{\rm CFP}\sigma_x^1} \frac{1}{\sqrt{2}}(|v\rangle|\widetilde{0}\rangle-|h\rangle|\widetilde{1}\rangle) \xrightarrow{P_{45}} \frac{|h\rangle+|v\rangle}{\sqrt{2}}\frac{1}{\sqrt{2}}(|\widetilde{0}\rangle-|\widetilde{1}\rangle). \quad (1)$$

So a click of Di means the success of the Hadamard gate on the logic qubit. Otherwise, we have to repeat the above steps from the very beginning with single-photon input and initial

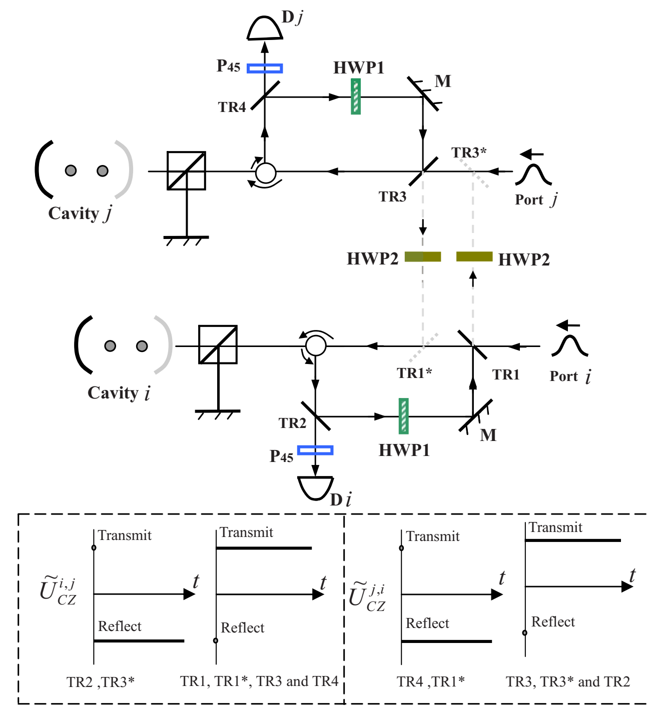

FIG. 3. (Color online) Schematic setup for two-logic-qubit conditional phase gate $\widetilde{U}^{i,j}_{\rm CZ}$ ($\widetilde{U}^{j,i}_{\rm CZ}$) which uses the additional channel shown by dashed gray lines. HWP2 performs a Hadamard gate on the photon polarization states. The single-photon pulse's path for $\widetilde{U}^{i,j}_{\rm CZ}$ ($\widetilde{U}^{j,i}_{\rm CZ}$) is port i–TR1-TR1*-C-PBS–cavity i–PBS-C-TR2-HWP1-M-TR1-HWP2-TR3*-TR3-C-PBS–cavity j–PBS-C-TR4-P_{45}-Dj (port j–TR3*-TR3-C-PBS–cavity j–PBS-C-TR4-HWP1-M-TR3-HWP2-TR1*-C-PBS–cavity i–PBS-C-TR2-P_{45}-Di). Unlike $\widetilde{H}$, the TRs remain unchanged during the conditional phase gating.

atomic state preparation. It is easy to check that Fig. 1 also works when $|\widetilde{0}\rangle$ is $(1/\sqrt{2})(|\widetilde{0}\rangle+|\widetilde{1}\rangle)$. Compared with the previous operation of a single-logical-qubit Hadamard gate [4], our proposal needs neither an ancilla system to store information nor optical lattices to transfer atoms synchronously across the cavity.

To ensure the success of these operations, we require the switching-time sequences of TR to be implemented accurately [11]. Actually, in addition to the time control sequences of TR1 and TR2 designed in Fig. 2, we have an alternative. Take TR1 for instance: Once the single-photon pulse from port i has gone through TR1, we change the transmitting state of the TR1 into the reflecting state without waiting for the time T_0+T_1. The switching-time sequence designed for $\widetilde{H}$ is general for arbitrary states of the single-logic qubit.

A two-node controlled phase gate for logic qubits encoded in a DFS, without using entangled photon pairs as in [5], can be implemented with the aid of an additional channel shown by the dashed gray lines in Fig. 3. HWP2, at an angle of 22.5° to the horizontal direction, performs a Hadamard gate on the photon polarization states, i.e., $|h\rangle \rightarrow (1/\sqrt{2})(|h\rangle+|v\rangle)$, $|v\rangle \rightarrow (1/\sqrt{2})(|h\rangle-|v\rangle)$. $\widetilde{U}^{i,j}_{\rm CZ}$ is a controlled-Z (CZ) phase-flip gate with the subscripts i and j indicating the control and target logic qubits in cavities i and j, respectively. Assume that the two logic qubits are in a superposition state $a|\tilde{0}\rangle_i|\tilde{0}\rangle_j+b|\tilde{0}\rangle_i|\tilde{1}\rangle_j+c|\tilde{1}\rangle_i|\tilde{0}\rangle_j+d|\tilde{1}\rangle_i|\tilde{1}\rangle_j$, where a, b, c, and d are normalized constants. The $\tilde{U}_{\mathrm{CZ}}^{i,j}$ operation is completed by following three steps. (1) A single-photon pulse in state $(1/\sqrt{2})(|h\rangle+|v\rangle)$ is input from the port i, passes through the PBS, and reaches the cavity i. We need to perform the operation $\sigma_{x,i}^2 U_{\mathrm{CPF}}\sigma_{x,i}^2$, i.e., the σ_x operation, on atom 2 in cavity i before and after the single-photon pulse is reflected by the cavity i. (2) Due to reflection of TR2, the single-photon pulse passes through HWP1 and goes into the additional channel connected to the node j. (3) After going through HWP2 and being reflected by TR3*, the single-photon pulse arrives at the PBS and then the cavity j. As previously, we have to perform $\sigma_{x,j}^1 U_{\mathrm{CPF}}\sigma_{x,j}^1$, i.e., the σ_x operation, on atom 1 in cavity j before and after the single-photon pulse is reflected by the cavity j. Then the single-photon pulse goes through P_{45} and is detected by Dj. The $\tilde{U}_{\mathrm{CZ}}^{i,j}$ operation process above can be shown step by step as

$$\begin{aligned}&\frac{1}{\sqrt{2}}(|h\rangle+|v\rangle)\otimes(a|\tilde{0}\rangle_i|\tilde{0}\rangle_j+b|\tilde{0}\rangle_i|\tilde{1}\rangle_j+c|\tilde{1}\rangle_i|\tilde{0}\rangle_j\\&\quad+d|\tilde{1}\rangle_i|\tilde{1}\rangle_j)\xrightarrow{\sigma_{x,i}^2U_{\mathrm{CFP}}\sigma_{x,i}^2}\frac{1}{\sqrt{2}}[a(-|h\rangle+|v\rangle)|\tilde{0}\rangle_i|\tilde{0}\rangle_j+b(-|h\rangle\\&\quad+|v\rangle)|\tilde{0}\rangle_i|\tilde{1}\rangle_j+c(|h\rangle+|v\rangle)|\tilde{1}\rangle_i|\tilde{0}\rangle_j+d(|h\rangle+|v\rangle)\\&\quad\times|\tilde{1}\rangle_i|\tilde{1}\rangle_j]\xrightarrow{\mathrm{HWP1,HWP2}}a|v\rangle|\tilde{0}\rangle_i|\tilde{0}\rangle_j+b|v\rangle|\tilde{0}\rangle_i|\tilde{1}\rangle_j+c|h\rangle\\&\quad\times|\tilde{1}\rangle_i|\tilde{0}\rangle_j+d|h\rangle|\tilde{1}\rangle_i|\tilde{1}\rangle_j\xrightarrow{\sigma_{x,j}^1U_{\mathrm{CFP}}\sigma_{x,j}^1,\mathrm{P}45}\frac{1}{\sqrt{2}}(|h\rangle+|v\rangle)\\&\quad\otimes(a|\tilde{0}\rangle_i|\tilde{0}\rangle_j+b|\tilde{0}\rangle_i|\tilde{1}\rangle_j+c|\tilde{1}\rangle_i|\tilde{0}\rangle_j-d|\tilde{1}\rangle_i|\tilde{1}\rangle_j).\end{aligned}\tag{2}$$

If we get a click of Dj, the $\tilde{U}_{\mathrm{CZ}}^{i,j}$ operation succeeds. The silence of Dj means failure and we must repeat the above steps from the very beginning. Considering the symmetric operation for the two-qubit gate, the $\tilde{U}_{\mathrm{CZ}}^{j,i}$ operation can be done by a similar process to Eq. (2), where the single-photon pulse is input from port j, as shown in Fig. 3. The corresponding controlled-NOT (CNOT) operation for the logic qubits in a DFS is given by $\tilde{C}_{\mathrm{NOT}}^{i,j}=\tilde{H}_j\otimes\tilde{U}_{\mathrm{CZ}}^{i,j}\otimes\tilde{H}_j$ and $\tilde{C}_{\mathrm{NOT}}^{j,i}=\tilde{H}_i\otimes\tilde{U}_{\mathrm{CZ}}^{j,i}\otimes\tilde{H}_i$. It should be mentioned that the TR1* (or TR3* for node j), whose function is to connect spatially separated nodes, has no action during the single-logic-qubit Hadamard operation. So we can keep them always on, in the transmitting state, while the $\tilde{H}$ operation is carried out in individual nodes.

The transfer of information in a quantum network is an important subject for quantum-information processing [1,2]. Based on the operations investigated above, we show below the information exchange between the ith logic qubit $\alpha_i|\tilde{0}\rangle+\beta_i|\tilde{1}\rangle$ and the jth logic qubit $\alpha_j|\tilde{0}\rangle+\beta_j|\tilde{1}\rangle$, using the following single-photon pulse sequence:

$$\tilde{U}_{\mathrm{SWAP}}^{i,j}=\tilde{C}_{\mathrm{NOT}}^{i,j}\tilde{C}_{\mathrm{NOT}}^{j,i}\tilde{C}_{\mathrm{NOT}}^{i,j}.\tag{3}$$

TABLE I. Bob's corresponding operations on the logic qubit $|\tilde{\Psi}\rangle_k$ after he has learned the measurement outcomes from Alice by a classical communication channel. $\sigma_{x,k}^1$ means the σ_x operation on atom 1 in cavity k. The $\tilde{X}$ operation has been given in the text.

Alice's measurements	Bob's operations
$\lvert\tilde{0}\rangle_i\lvert\tilde{0}\rangle_j$	Nothing
$\lvert\tilde{0}\rangle_i\lvert\tilde{1}\rangle_j$	$\tilde{X}$
$\lvert\tilde{1}\rangle_i\lvert\tilde{0}\rangle_j$	$\tilde{Z}=\sigma_{x,k}^1 U_{\mathrm{CPF}}\sigma_{x,k}^1$
$\lvert\tilde{1}\rangle_i\lvert\tilde{1}\rangle_j$	$\tilde{Z}\tilde{X}$

The corresponding process reads $(\alpha_i|\tilde{0}\rangle+\beta_i|\tilde{1}\rangle)(\alpha_j|\tilde{0}\rangle+\beta_j|\tilde{1}\rangle)\rightarrow(\alpha_j|\tilde{0}\rangle+\beta_j|\tilde{1}\rangle)(\alpha_i|\tilde{0}\rangle+\beta_i|\tilde{1}\rangle)$. Compared with previous work [1], we do not need special laser pulses with time-dependent Rabi frequency and laser phases to excite a time-symmetric wave packet of the photon from the sending node to the receiving node. In addition, we do not require a transfer channel made using auxiliary entangled photon pairs [11]. More importantly, compared to [1,11], our logic qubits are encoded in a DFS which is robust to collective dephasing error.

Now we turn to a proposal for quantum state teleportation [12] for the logic qubits described above. Assume that we have three logic qubits in states $|\tilde{\Psi}\rangle_i$, $|\tilde{\Psi}\rangle_j$, and $|\tilde{\Psi}\rangle_k$, respectively, with the former two belonging to Alice and the third to Bob. $|\tilde{\Psi}\rangle_i=\alpha|\tilde{0}\rangle+\beta|\tilde{1}\rangle$ is an unknown state and will be teleported to Bob. First, teleportation needs entanglement between Alice's second qubit $|\tilde{\Psi}\rangle_j$ and Bob's qubit $|\tilde{\Psi}\rangle_k$ in a Bell state. We take $|\tilde{\Psi}\tilde{\Psi}\rangle_{jk}=(1/\sqrt{2})(|\tilde{0}\rangle_j|\tilde{0}\rangle_k+|\tilde{1}\rangle_j|\tilde{1}\rangle_k)$ as an example. The Bell-style entanglement can be implemented by an $\tilde{H}$ and $\tilde{C}_{\mathrm{NOT}}$ operation for the initial state $|\tilde{0}\rangle_j|\tilde{0}\rangle_k$, i.e.,

$$|\tilde{0}\rangle_j|\tilde{0}\rangle_k\xrightarrow{\tilde{H}_j}\frac{1}{\sqrt{2}}(|\tilde{0}\rangle_j+|\tilde{1}\rangle_j)|\tilde{0}\rangle_k\xrightarrow{\tilde{C}_{\mathrm{NOT}}^{j,k}}\frac{1}{\sqrt{2}}(|\tilde{0}\rangle_j|\tilde{0}\rangle_k+|\tilde{1}\rangle_j|\tilde{1}\rangle_k).\tag{4}$$

The Bell-state measurement in teleportation also uses $\tilde{H}$ and $\tilde{C}_{\mathrm{NOT}}$ operations, i.e., a $\tilde{C}_{\mathrm{NOT}}^{i,j}$ operation between $|\tilde{\Psi}\rangle_i$ and $|\tilde{\Psi}\rangle_j$ and an $\tilde{H}_i$ operation to $|\tilde{\Psi}\rangle_i$. As a result, we get the final state $|\tilde{\Phi}\rangle=\frac{1}{2}[|\tilde{0}\rangle_i|\tilde{0}\rangle_j(\alpha|\tilde{0}\rangle+\beta|\tilde{1}\rangle)_k+|\tilde{0}\rangle_i|\tilde{1}\rangle_j(\alpha|\tilde{1}\rangle+\beta|\tilde{0}\rangle)_k+|\tilde{1}\rangle_i|\tilde{0}\rangle_j(\alpha|\tilde{0}\rangle-\beta|\tilde{1}\rangle)_k+|\tilde{1}\rangle_i|\tilde{1}\rangle_j(\alpha|\tilde{1}\rangle-\beta|\tilde{0}\rangle)_k]$. Following the operations shown in Table I, we finish the teleportation of a quantum state from the logic qubit i to the logic qubit k.

From the schematic setup in Fig. 3 and the operations presented above, we learn that the single-logical-qubit Hadamard operation and the two-logical-qubit conditional operation coexist in our scheme, and could work independently by control of the transmitting or reflecting state of the connecting devices TR1* and TR3*. This is very important for scalability of the quantum network.

Experimentally, the currently achieved technology of deterministic single-photon sources [13] provides potential support for our scheme. As 300 000 high-quality single photons can be generated continuously within 30 s, a fast implementation of our scheme is available. Moreover, to fix two atoms in an optical cavity, we have to confine the atoms in optical lattices embedded in an optical cavity, and this has been achieved experimentally [14]. To confine each atom in a particular lattice, a more advanced technique is needed. Alternatively, we may consider an ion-trap–cavity combined setup with two charged atoms fixed by the trap potential and optically coupled via the cavity mode. A single calcium ion has been successfully trapped in such a device [15]. The experimental extension to two ions satisfying the Purcell condition should in principle be available in the near future.

In our scheme, if the duration T for the photon pulse input in the cavity and the cavity decay rate κ satisfy $\kappa T \gg 1$, the basic operation U_{CPF} is insensitive to both the atom-cavity coupling strength and the Lamb-Dicke localization. According to the numerical simulation [3], if $\kappa T \sim 100$ and the atom-cavity coupling is several times stronger than the dissipative factors in the system, the gate fidelity is almost unity. In terms of the numerical [3] and experimental results [7], U_{CPF} takes $T=3\sim 5$ μs for $\kappa T \gg 1$. With the experimental numbers $\kappa/2\pi \sim 4$ MHz, $g/2\pi \sim 30$ MHz, $\Gamma/2\pi \sim 2.6$ MHz [7,16], we may estimate that the time for the logic-qubit operations $\widetilde{H}$ and $\widetilde{C}_{\mathrm{NOT}}$ is of the order of $10^{-6}-10^{-5}$ s. In realistic experiments, however, we should pay attention to photon loss during the experiment and to the detector inefficiency. Fortunately, as the different operational results in each step are distinguishable in our scheme, (for example, the single-logic-qubit operation $\widetilde{H}_i$ in the ith cavity is associated with a single-photon-pulse input in port i and the detector Di, whereas the two-logic-qubit operation $\widetilde{U}_{\mathrm{CZ}}^{i,j}$ is relevant to the input port i and the response of Dj), successful detections of the single-photon pulses ensure high fidelity of the gate operations. This implies that, as we discard the events without detector clicks, the errors due to photon loss can be completely removed, i.e., this is a repeat-until-success operation [17]. So, for our proposal, high-fidelity quantum gates are possible even in the case of photon loss [18].

In summary, we have proposed the implementation of a single-logic-qubit Hadamard operation and a two-logic-qubit conditional gate, based on which we may carry out quantum state transfer and teleportation between spatially separated nodes of a quantum network in a DFS. As the cavity QED technique is developing very quickly, we hope for more applications of the quantum logic operation in DFSs as in our scheme.

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