Block-free optical quantum Banyan network based on quantum state fusion and fission*

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Optical switch fabric plays an important role in building multiple-user optical quantum communication networks. Owing to its self-routing property and low complexity, a banyan network is widely used for building switch fabric. While, there is no efficient way to remove internal blocking in a banyan network in a classical way, quantum state fusion, by which the two-dimensional internal quantum states of two photons could be combined into a four-dimensional internal state of a single photon, makes it possible to solve this problem. In this paper, we convert the output mode of quantum state fusion from spatial-polarization mode into time-polarization mode. By combining modified quantum state fusion and quantum state fission with quantum Fredkin gate, we propose a practical scheme to build an optical quantum switch unit which is block free. The scheme can be extended to building more complex units, four of which are shown in this paper.

Keywords: optical switch fabric, quantum state fusion, quantum Fredkin gate, linear optics

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1. Introduction

Based on the principle of quantum mechanism and unique quantum mechanical effects (e.g. quantum entanglement), quantum information technology can enhance the transmission, processing and storage of information, and has been developing quickly. A single photon, owing to its low decoherence rate and easier manipulation, has been widely used in quantum information technology (e.g. quantum key distribution[1]) and quantum computing (e.g. quantum logical gate[2,3]). With the development of the photon-based quantum key distribution system, several experimental multiple-user quantum communication networks were built.[4–8] In these networks, trusted relays were used to implement long distance quantum key distribution. The key factor is that the relay should be trusted. In a short distance quantum key distribution system, an untrusted optical switch can be used to build a multiple-user network.[4,7]

In a classical communication network, switch-based topology is widely applied. In an optical fiber communication network, an optical switch is used to build an optical cross connection (OXC) by which different devices can be connected. For optical quantum, the OXC can also be used to build an end-to-end quantum channel for two quantum communication terminals. Various switch fabrics were proposed for OXC, e.g. crossbar network, banyan network, Beneš network, Clos network, *et al.*[9] A higher performance OXC should be lower in block rate, smaller in insert loss and shorter in processing delay. The banyan network has self-routing property since a qubit can be routed by only knowing its input and output addresses as shown in Fig. 1. Each 2×2 switch can be either in a cross state or in a through state. A qubit is routed to the lower output of a switch at the i-th stage if the i-th most significant bit is '1' and to the upper output if it is '0'. Although the banyan network has a simple structure and short processing delay, it also has a shortcoming in that a block exists. In a classical optical network, it is a difficult problem except for adopting a more complex structure, while, there exists an efficient method to overcome the block in the banyan network by quantum characteristics, e.g. quantum superposition.[10] Several quantum switch schemes were proposed,[11–14] but a practical optical quantum circuit has not been proposed. Quantum state fusion and quantum state fission combining with quantum Fredkin gate may be one of the efficient ways to remove the block.

Quantum state fusion and quantum state fission are two processes proposed by Vitelli *et al.*[15] Quantum state fusion is defined as the physical process by which the internal quantum states of two particles (e.g. photons) are combined into a four-dimensional internal state of a single particle (photon).[15] For photons, the input photons may be in the two-dimensional polarization mode, the output photon may be in the four-dimensional spatial-polarization mode.

An inverse process, quantum state fission, is defined as the physical process by which a higher-dimensional quantum state of a particle is split into two (or more) particles. By the quantum state fusion process, the blocking in Fig. 1 can be ef-

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ficiently removed. In the output of the second stage, a state fusion process could be used to implement the information fusion. Then in the third stage, a state fission process should be used to split them again. Although this is a good solution, the spatial-polarization mode still needs two output physical channels. We design a state conversion circuit to convert the spatial-polarization mode into the time-polarization mode. The base states in time mode appear at a time instant or another time instant which is separated from the first one by a constant interval. This time interval is larger than the width of the optical pulse and dead time of the single photon detector.

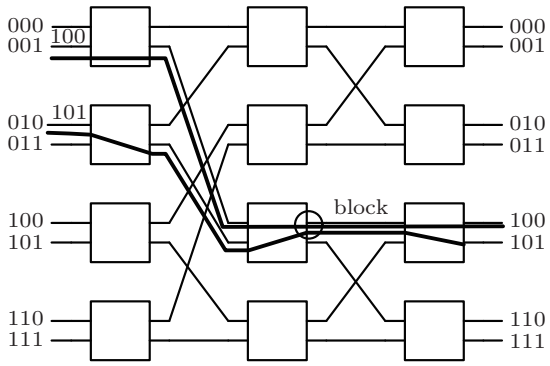


Fig. 1. Block in banyan network.

In this paper, we use this modified quantum state fusion scheme, quantum state fission scheme and quantum Fredkin gate to build block-free optical quantum switch units. The rest of the paper is organized as follows. In Section 2, a heralded linear optical quantum Fredkin gate is presented. In Section 3, a quantum state fusion scheme with time-polarization mode as output is given. A quantum state fission scheme with state conversion circuit is also given. In Section 4, a block free optical quantum switch unit with two two-dimensional polarization states as inputs is proposed. Four types of switch fabric units are also proposed for four different scenarios with fused state (or states) as input. Finally, in Section 5, we draw some conclusions from the present studies.

2. Heralded linear optical quantum Fredkin gate

The quantum Fredkin gate is also named controlled swap gate, that is, if the control bit is in state $|1\rangle$, then the two target qubits swap their states and otherwise, they remain in their initial states if the control bit is in state $|0\rangle$. The quantum Fredkin gate can be built by three CNOT gates.[16] There are two types of optical methods to implement the quantum Fredkin gate. One is the linear optical method by which the Fredkin gate is built by linear optical components;[17] the other is a nonlinear optical method by which the nonlinear effect of optical components is used.[18,19] In linear optical quantum information processing, the qubit could be implemented by the photon with special polarization direction. The schemes and experiments with linear optical method are developed quickly. Gong *et al*. constructed a heralded Fredkin gate by using four CNOT gates and linear optical components;[17] they also simplified the methods into post-selection ones which operate in the coincidence basis and require ancillary photons in the maximally entangled state.

Here, the state $|0\rangle$ is prepared by a photon with horizontal polarization, denoted by $|H\rangle$, and the state $|1\rangle$ is prepared by a photon with vertical polarization, denoted by $|V\rangle$. The operation for the optical quantum bit is converted into the operation of polarization of the photon. For a Fredkin gate, the two input quantum bits are $|\psi\rangle_{a_1} = \beta_{1h}|H\rangle_{a_1} + \beta_{1v}|V\rangle_{a_1}$ and $|\psi\rangle_{a_2} = \beta_{2h}|H\rangle_{a_2} + \beta_{2v}|V\rangle_{a_2}$, where β_{1h}, β_{1v}, β_{2h}, and β_{2v} are arbitrary complexes, and $|\beta_{1h}|^2 + |\beta_{1v}|^2 = 1$, $|\beta_{2h}|^2 + |\beta_{2v}|^2 = 1$, a_1 and a_2 denote different space modes as shown in Fig. 2.[17] So the joint state of the two input photons is

$$\begin{aligned} |\psi_{\text{in}}\rangle &= |\psi\rangle_{a_1}|\psi\rangle_{a_2} \\ &= \beta_{1h}\beta_{2h}|H\rangle_{a_1}|H\rangle_{a_2} + \beta_{1h}\beta_{2v}|H\rangle_{a_1}|V\rangle_{a_2} \\ &\quad + \beta_{1v}\beta_{2h}|V\rangle_{a_1}|H\rangle_{a_2} + \beta_{1v}\beta_{2v}|V\rangle_{a_1}|V\rangle_{a_2}. \end{aligned} \quad (1)$$

The quantum Fredkin gate shown in Fig. 2 can be in "Cross" state or "Through" state controlled by the control qubit $|c\rangle_{\text{in}}$. In "Cross" state the two input qubits are swapped, the qubit $|\psi\rangle_{b_1} = |\psi\rangle_{a_2}$ and the qubit $|\psi\rangle_{b_2} = |\psi\rangle_{a_1}$. In "Through" state the two input qubits pass through directly, the qubit $|\psi\rangle_{b_1} = |\psi\rangle_{a_1}$ and the qubit $|\psi\rangle_{b_2} = |\psi\rangle_{a_2}$. In Fig. 2, D_1 and D_2 are two single photon detectors (SPDs). The CNOT gate can make the polarization direction of the photon rotate 90°. HWP_1 and HWP_3 are 22.5°-tilted half-wave plates (HWPs), which act as Hadamard gates ($|H\rangle \to (|H\rangle + |V\rangle)/\sqrt{2}$, $|V\rangle \to (|H\rangle - |V\rangle)/\sqrt{2}$). HWP_2 and HWP_4 are 67.5°-tilted half-wave plates which perform the transformation: $|H\rangle \to (|V\rangle - |H\rangle)/\sqrt{2}$ and $|V\rangle \to (|H\rangle + |V\rangle)/\sqrt{2}$. The polarization beamsplitter (PBS) works as follows: the horizontally polarized photon passes through, while the vertically polarized photon is reflected. If $|c\rangle_{\text{in}} = |1\rangle = |V\rangle$, and no photon arrives at D_1 and D_2, the output state is

$$\begin{aligned} |\psi_{\text{out}}\rangle &= \beta_{1h}\beta_{2h}|H\rangle_{b_2}|H\rangle_{b_1} + \beta_{1h}\beta_{2v}|H\rangle_{b_2}|V\rangle_{b_1} \\ &\quad + \beta_{1v}\beta_{2h}|V\rangle_{b_2}|H\rangle_{b_1} + \beta_{1v}\beta_{2v}|V\rangle_{b_2}|V\rangle_{b_1}. \end{aligned} \quad (2)$$

In this case, the quantum Fredkin gate is in "Cross" state. Otherwise, if $|c\rangle_{\text{in}} = |0\rangle = |H\rangle$ and no photon arrives at D_1 and D_2, the quantum Fredkin gate is in "Through" state. If the quantum efficiency η of SPD is 100% and the dark count is not taken into account, the success rate of the quantum Fredkin gate is 0.25.

A simple model of the quantum Fredkin gate is shown in Fig. 2(b) in which only the inputs and outputs are given.

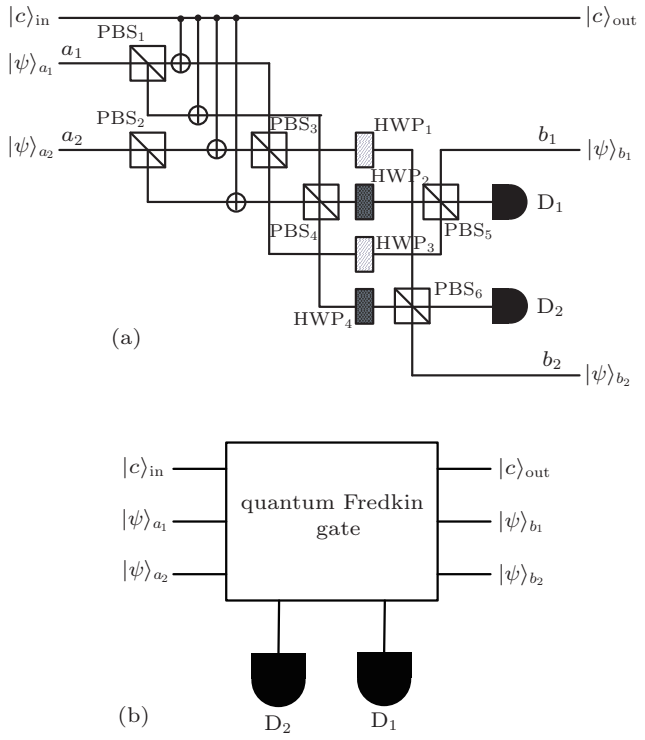


Fig. 2. A linear optical implementation of quantum Fredkin gate.[17] Panel (a) shows a quantum circuit, and panel (b) a simple model in which only inputs and outputs are given.

3. Quantum state fusion and fission

In this section, we introduce the schemes of quantum state fusion and state fission proposed by Vitelli *et al.*[15] and our modification for applying them to the optical quantum switch unit.

3.1. Scheme of quantum state fusion

Vitelli *et al.* proposed a schematic of quantum state fusion,[15] in which the two-dimensional quantum qubits of two input photons can be combined into a single output photon within a four-dimensional quantum space. According to this scheme, we add a state conversion circuit and a control qubit $|c\rangle_{d_{\rm in}}$ as shown in Fig. 3. In Fig. 3, the half wave plates are all oriented at 22.5° with respect to the H direction except for HWP$_6$ which is oriented at −22.5°. Let $|\psi\rangle_{a_3} = \beta_{3h}|H\rangle_{a_3} + \beta_{3v}|V\rangle_{a_3}$ and $|\psi\rangle_{a_4} = \beta_{4h}|H\rangle_{a_4} + \beta_{4v}|V\rangle_{a_4}$ denote two input states, where β_{3h}, β_{3v}, β_{4h}, and β_{4v} are arbitrary complexes, $|\beta_{3h}|^2 + |\beta_{3v}|^2 = 1$, and $|\beta_{4h}|^2 + |\beta_{4v}|^2 = 1$. The ancillary photon enters into the setup in $|H\rangle$ state, that is, $|a\rangle = |H\rangle$. So the joint input state is

$$\begin{aligned}|\psi\rangle_{\rm in} = {} & (\beta_{3h}\beta_{4h}|H\rangle_{a_3}|H\rangle_{a_4} + \beta_{3h}\beta_{4v}|H\rangle_{a_3}|V\rangle_{a_4} \\ & + \beta_{3v}\beta_{4h}|V\rangle_{a_3}|H\rangle_{a_4} \\ & + \beta_{3v}\beta_{4v}|V\rangle_{a_3}|V\rangle_{a_4})|H\rangle_a|c\rangle_{d_{\rm in}}. \end{aligned} \tag{3}$$

The quantum state fusion is successful if there is one and only one photon in each H-channel of PBS$_{11}$ and PBS$_{12}$, no photon at each V-channel of PBS$_{11}$ and PBS$_{12}$, one and only one photon at b_3' and b_4'. The detailed working process of quantum state fusion is shown in Ref. [15] and its supplementary materials. After quantum state fusion, the spatial-polarization state at b_3' and b_4' is

$$\begin{aligned}|\psi\rangle_{b_{43}'} = {} & \beta_{4h}\beta_{3h}|H\rangle_{b_4'} + \beta_{4h}\beta_{3v}|V\rangle_{b_4'} \\ & + \beta_{4v}\beta_{3h}|H\rangle_{b_3'} + \beta_{4v}\beta_{3v}|V\rangle_{b_3'}. \end{aligned} \tag{4}$$

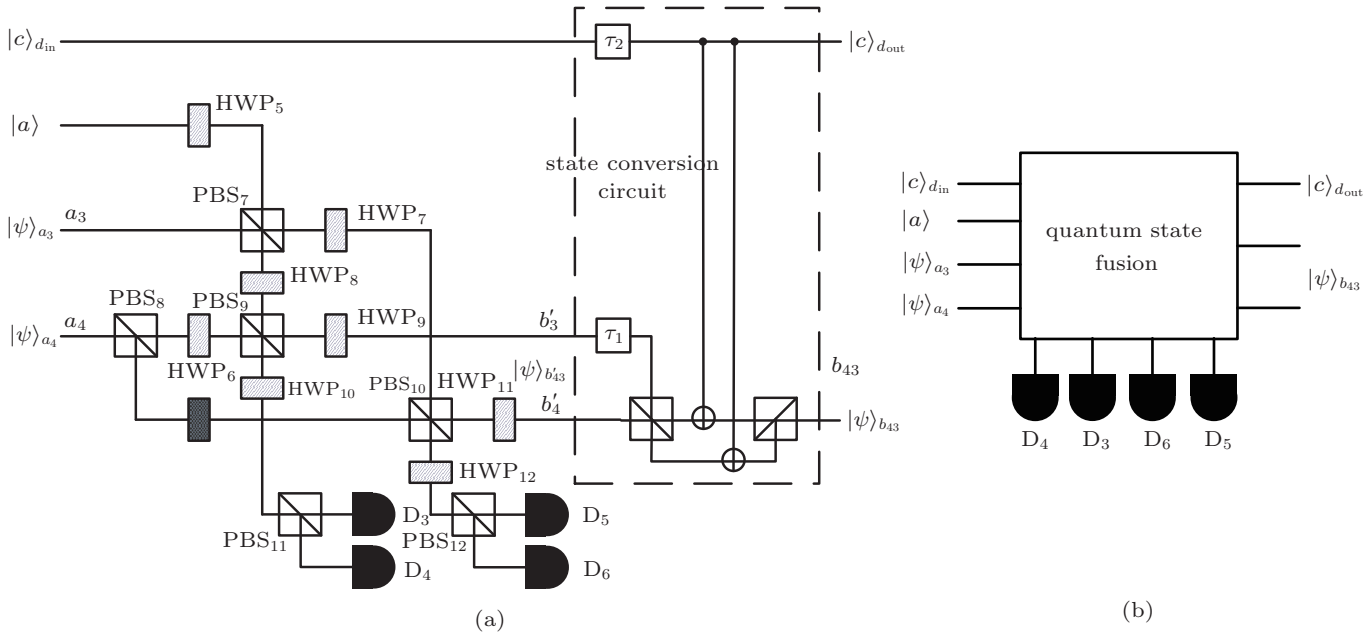


Fig. 3. Quantum state fusion. Panel (a) shows a quantum circuit and panel (b) a simple model in which only inputs and outputs are given.

In Fig. 3(a), the state conversion circuit aims at converting the spatial-polarization mode into a time-polarization mode. Here the state of a photon is in a four-dimensional Hilbert space obtained by time-polarization mode, which means that the photon may occur at one of the two time instants and may be in one of the two polarization directions. There are two time delay components with delay τ_1 and τ_2, two CNOT gates and two PBS components in the conversion circuit. The spatial modes at b_3' and b_4' are combined into one path (spatial) mode at b_{43} based on the two CNOT gates which perform NOT operation only on the photons from b_3' by adjusting the values of τ_1 and τ_2 properly.

A simple model is shown in Fig. 3(b) in which only the inputs and outputs are given.

3.2. Scheme of quantum state fission

Vitelli *et al*. also proposed an inverse process of quantum state fusion, i.e., quantum state fission, in which the four-dimensional quantum state of a single photon is split into two two-dimensional states of two photons, each carrying a qubit.[15] We add a state conversion circuit to their scheme as shown in Fig. 4. There are four input states: one fused state $|\psi\rangle_{a_{56}}$, one control state $|c\rangle_{d_{\rm in}}$ under which state conversion circuit performs, and two ancillary states $|a\rangle$ and $|b\rangle$ which are in $|H\rangle$ at the inputs. In Fig. 4, the half wave plates are all oriented at 22.5° with respect to the H direction, acting as Hadamard gates, except for $\rm HWP_{23}$ and $\rm HWP_{24}$ which are oriented at 45° so as to be equivalent to the NOT gate swapping states $|H\rangle$ and $|V\rangle$.

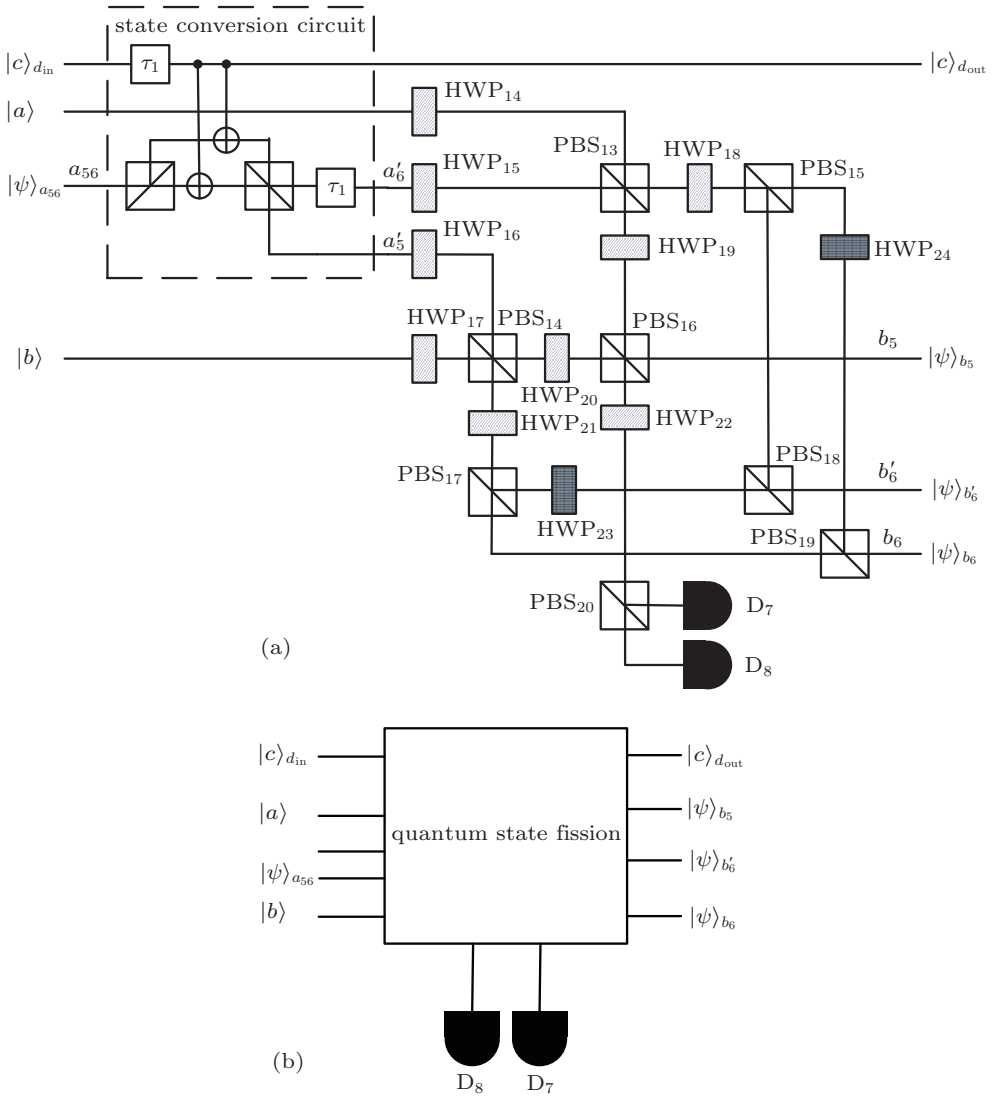


Fig. 4. Quantum state fission. Panel (a) shows a quantum circuit, and panel (b) a simple model in which only inputs and outputs are given.

The detailed working process can be obtained in the supplementary materials of Ref. [15]. The state conversion circuit added here aims at converting time-polarization mode into a spatial-polarization mode. The CNOT gates work only on the photon in the second time mode. After state conversion, the spatial-polarization state at a_5' and a_6' is

$$|\psi\rangle_{a'_{56}} = \beta_{5h}\beta_{6h}|H\rangle_{a'_5} + \beta_{5h}\beta_{6v}|V\rangle_{a'_5} + \beta_{5v}\beta_{6h}|H\rangle_{a'_6} + \beta_{5v}\beta_{6v}|V\rangle_{a'_6}.$$

The quantum fission is successful if there is one and only one photon in the H-channel of PBS_{20}, no photon in the V-channel of PBS_{20}, one and only one photon in b_5, one and only one photon in b_6, no photon in b'_6. A simplified version of the scheme is shown in Fig. 4(b).

4. Block-free optical quantum switch units

According to the heralded quantum Fredkin gate in Section 2, quantum state fusion and quantum state fission in Section 3, we propose an optical quantum switch unit (OQSU) which is block free. Actually, the quantum state fusion schematic in Section 3 can be directly applied to the scenario in which two qubits derived from two different inputs are switched to the same output at the same time. The two qubits can be fused and transmitted in the same quantum channel. Here, we propose a scheme in which the two input states may be fused or not.

4.1. Optical quantum switch unit (OQSU) with block free

The proposed optical quantum switch unit is shown in Fig. 5. There are two input information qubits at a_7 and a_8, $|\psi\rangle_{a_7}$and $|\psi\rangle_{a_8}$, four control qubits $|c\rangle_{f_{\rm in}}$, $|c\rangle_{F_{\rm in}}$, $|c\rangle_{s_{\rm in}}$, and $|c\rangle_{d_{\rm in}}$, and one ancillary qubit $|a\rangle$. Let $|c\rangle_{f_{\rm in}}$ denote the output competition. When $|c\rangle_{f_{\rm in}} = |1\rangle$, it means that an output competition exists and the quantum state fusion works. When $|c\rangle_{f_{\rm in}} = |0\rangle$, it means that there is no output competition and the quantum Fredkin gate works. Let $|c\rangle_{F_{\rm in}}$ denote the operation of quantum Fredkin gate which is in a cross state when $|c\rangle_{F_{\rm in}} = |1\rangle$, in a through state when $|c\rangle_{F_{\rm in}} = |0\rangle$. Let $|c\rangle_{s_{\rm in}}$ denote the output port of the fused state which is b_7 when $|c\rangle_{s_{\rm in}} = |1\rangle$, b_8 when $|c\rangle_{s_{\rm in}} = |0\rangle$. Let $|c\rangle_{d_{\rm in}}$ act as the control qubit of the CNOT gate and be used to combine the two spatial modes after delay of τ_2. Let $|\varphi\rangle$ denote the vacuum state. The input-output relations under different control qubits are shown in the Table 1.

In Fig. 5, the path selection circuit consists of two CNOT gates and two polarization beam splitters. When $|c\rangle_{f_{\rm in}} = |1\rangle$, the two input states $|\psi\rangle_{a_7}$ and $|\psi\rangle_{a_8}$ transmit to the output ports at a''_7 and a''_8. Otherwise, they transmit to the outputs at a'_7 and a'_8. The two states at a'_7 and a'_8 transmit to the quantum Fredkin gate. They are swapped or not under the control of qubit $|c\rangle_{F_{\rm in}}$. The two states at a''_7 and a''_8 are fused into a spatial-polarization mode. Then the spatial-polarization mode is converted into a time-polarization mode by a converting circuit in which the time delays τ_1 and τ_2 are set properly. The output selection circuit is used to transmit the fused state to the expected output under the control of qubit $|c\rangle_{s_{\rm in}}$. So the two output states $|\psi\rangle_{b_7}$ and $|\psi\rangle_{b_8}$ can be a single state or fused state. The operation is performed according the value of the control qubits as shown in Table 1.

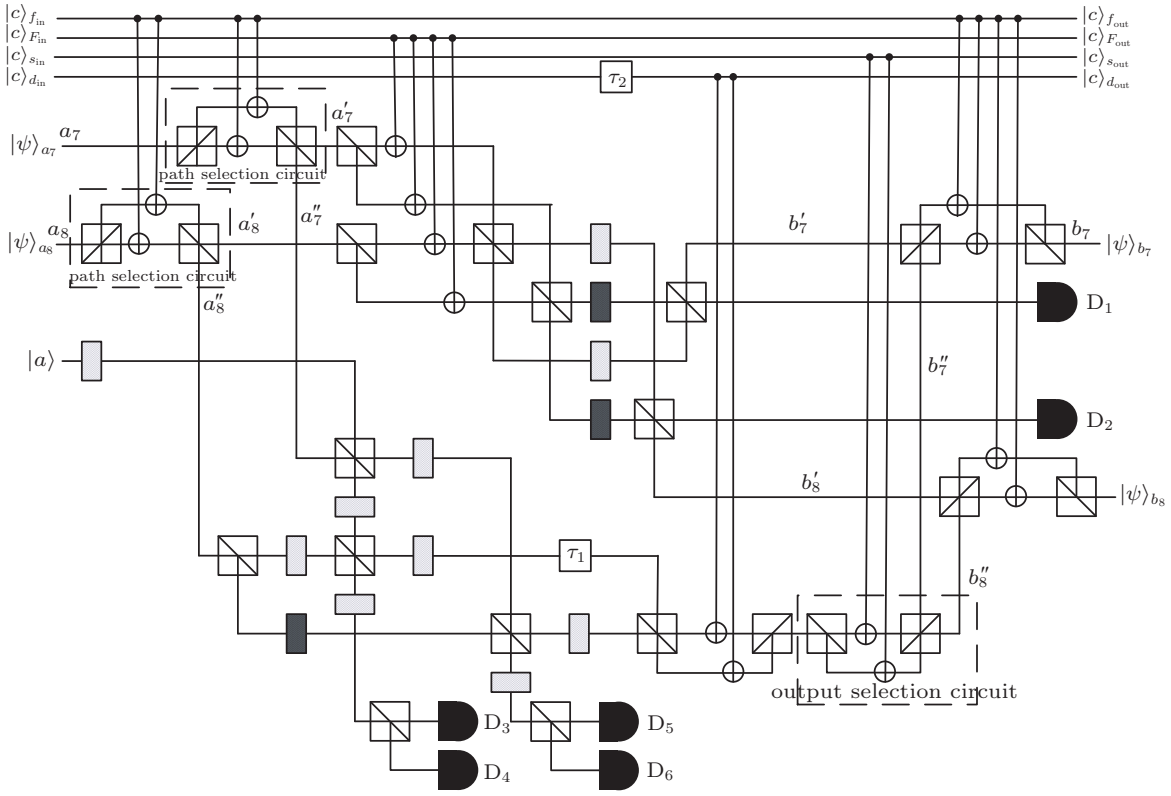


Fig. 5. Optical quantum switch unit with block free.

Table 1. Input–output relations under different control qubits.

$\|c\rangle_{f_{\rm in}}$	$\|c\rangle_{F_{\rm in}}$	$\|c\rangle_{s_{\rm in}}$	$\|\psi\rangle_{b_7}$	$\|\psi\rangle_{b_8}$	Condition
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|\psi\rangle_{a_7}$	$\|\psi\rangle_{a_8}$	Both D_1 and D_2 have no count.
$\|0\rangle$	$\|0\rangle$	$\|1\rangle$	$\|\psi\rangle_{a_7}$	$\|\psi\rangle_{a_8}$	
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|\psi\rangle_{a_8}$	$\|\psi\rangle_{a_7}$	
$\|0\rangle$	$\|1\rangle$	$\|1\rangle$	$\|\psi\rangle_{a_8}$	$\|\psi\rangle_{a_7}$	
$\|1\rangle$	$\|0\rangle$	$\|0\rangle$	$\|\varphi\rangle$	$\|\psi\rangle_f$	Both D_3 and D_5 detect one and only one photon. Both $D_4$and D_6 have no count. There is only one photon in one of the two time modes at b_7 and b_8.
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|\psi\rangle_f$	$\|\varphi\rangle$	
$\|1\rangle$	$\|1\rangle$	$\|0\rangle$	$\|\varphi\rangle$	$\|\psi\rangle_f$	
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|\psi\rangle_f$	$\|\varphi\rangle$	

According to Ref. [15] and its supplementary materials, the state fusion shown in Fig. 3 is successful with a probability of 1/32. By a suitable feed-forward, the success probability can be raised to 1/8. The state fission shown in Fig. 4 is the same as the state fusion. Since the Fredkin gate has a 1/4 success rate under an ideal condition, and assuming the value of the control qubit $|c\rangle_{f_{\rm in}}$ to be $|1\rangle$ or $|0\rangle$ with equal probability, the average success probability of the unit is $1/2\times 1/8+1/2\times 1/4=3/16$.

Since the heralded quantum Fredkin gate, heralded quantum fusion process, and quantum fission process are used in each switch unit, a network will fail if any of the units in the network could not work successfully. In this scenario, the quantum bits should be retransmitted. How to overcome this deficiency will be our further work.

4.2. Optical quantum switch units with different input states

Besides the quantum circuit in Fig. 5, there are other block-free switch units, each of which consists of one or more fusion circuits, one or more Fredkin gates, one or more fission circuits. Here are four examples that are shown in Fig. 6.

In Fig. 6(a), the input state is a fused state, which can be split into two single qubits by quantum state fission operation. Then a quantum Fredkin gate follows. This network can be used in a scenario in which a multiplexed optical quantum signal is demultiplexed and the two resulting separate qubits can be sent to two outputs as they require. In Fig. 6(b), the input states are a fused state and a single state, one of the states after fission is fused with the input single state. This network can be used in a scenario in which a multiplexed optical quantum signal is demultiplexed into two separate qubits, in which one qubit transmits to the output directly and the other is multiplexed with the input single photon signal. In Fig. 6(c), the input are one fused state and one single state. A vacuum state is inserted into the input state at the next time slot in order to perform Fredkin operation. This network can be used in a scenario in which one multiplexed quantum signal is swapped with a single qubit or not. In Fig. 6(d), the input states are two fused states. They fiss and fuse again. This network can be used in a scenario in which two multiplexed quantum signals are demultiplexed and mutilplexed again after exchanging one of the two qubits. In these four scenarios, the switch units are successful if the counts of the detectors in the quantum circuits meet the conditions shown in Section 3 and there is one and only one photon in each output for non-fused state and one and only one photon in each time instant for fused state. Note that some scenarios are not taken into account, e.g. a fused state might compete with another input state for the same output port. These scenarios should be further discussed.

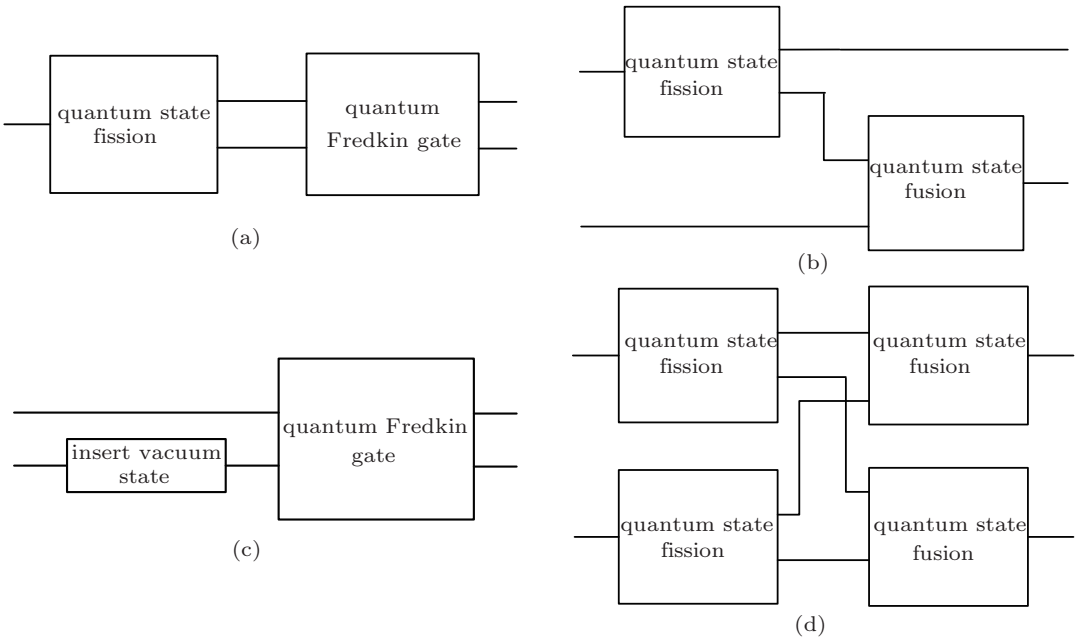


Fig. 6. Basic switch units based on the combinations of quantum state fusion, fission, and Fredkin gate: (a) one fission and one Fredkin gate, (b) one fission and one fusion, (c) one Fredkin gate, (d) two fissions and two fusions.

5. Conclusion

In this paper, we propose an optical quantum switch fabric with block free by using modified quantum state fusion, quantum state fission, and quantum Fredkin gate. This switch fabric can be used to build a banyan network with self-routing. We also propose schemes to build four types of block-free switch fabrics. Since the photon loss in the quantum circuit may reduce the fidelity of the switch fabric, we can improve its performance by using low-loss components and quantum nondemolition (QND) detectors.

Although none of quantum Fredkin gate, quantum fusion and fission processes can be implemented with a success probability of 100%, the switch fabric proposed in this paper can be implemented without the assistance of classical control information and can be used to build an all-optical quantum information network. So, the side information leakage can be avoided.

With the development of integrated optics, a large-scale optical quantum circuit or optical quantum computer may be built.[20,21] Our further work is to make an experiment and discuss how to implement it by integrated optics technology.

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