Universal quantum gates on electron-spin qubits with quantum dots inside single-side optical microcavities

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We present some compact quantum circuits for a deterministic quantum computing on electron-spin qubits assisted by quantum dots inside single-side optical microcavities, including the CNOT, Toffoli, and Fredkin gates. They are constructed by exploiting the giant optical Faraday rotation induced by a single-electron spin in a quantum dot inside a single-side optical microcavity as a result of cavity quantum electrodynamics. Our universal quantum gates have some advantages. First, all the gates are accomplished with a success probability of 100% in principle. Second, our schemes require no additional electron-spin qubits and they are achieved by some input-output processes of a single photon. Third, our circuits for these gates are simple and economic. Moreover, our devices for these gates work in both the weak coupling and the strong coupling regimes, and they are feasible in experiment.

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I. INTRODUCTION

In quantum computing, a quantum algorithm is usually realized by a sequence of quantum gates [1]. Constructing compact quantum gates is crucial for building a quantum computer. It has been proven that any quantum entangling gate supplementing with single-qubit gates can implement a universal quantum computing [2]. The controlled-not (CNOT) gate is a universal two-qubit gate and it attracts much attention. As for multi-qubit quantum systems, attention was mainly focused on the three-qubit Toffoli and Fredkin gates as they can be used to implement any multi-qubit quantum computing with Hadamard gates [3, 4].

Up to now, many important proposals have been proposed for physically implementing quantum gates [5–7]. For example, in 2001, Knill et al. [8] proposed a probabilistic scheme for implementing a CNOT gate on two photonic qubits by using linear optical elements, additional photons, and postselection. Based on cross-Kerr nonlinearity or charge detection, Nemoto et al. [9], Lin et al. [10], and Beenakker et al. [11] provided some interesting proposals for a deterministic quantum computing. In these schemes, some additional qubits are employed. A strong cross-Kerr nonlinearity is still a big challenge in experiment at present. To achieve a nontrivial nonlinearity between two individual qubits for a deterministic quantum computation with the present experimental techniques, an appealing platform for quantum information processing with an artificial atom and a cavity is proposed [12, 13].

A quantum system combining a cavity and an artificial atom, such as a quantum dot (QD), a superconducting qubit, or a diamond nitrogen-vacancy center, is a perfect platform for quantum information processing because of its long coherence time and its good scalability. By utilizing such a platform, some interesting schemes were proposed for implementing the quantum gates on hybrid photon-matter systems [12, 13]. Based on the QD-cavity platform, a scalable deterministic quantum computation on photonic qubits [14, 15] and a deterministic photonic spatial-polarization hyper-CNOT gate [16] were proposed recently. The quantum circuits for the universal gates on superconducting qubits [17, 18] or diamond nitrogen-vacancy center qubits [19, 20] assisted by optical microcavities were designed as well. Constructing universal quantum gates compactly can reduce the quantum resource needed and their errors.

A QD system is one of the promising candidates for quantum information processing and quantum state storage in solid-state quantum systems. The coherence time of a QD can be extended to µs by using spin echo techniques [21–23]. The single QD spin manipulation which is crucial for the implementation of single-qubit gates, can be achieved by using pulsed magnetic resonance techniques, nanosecond microwave pulses, or picosecond/femtosecond optical pulses [24–26]. Due to the external magnetic field and the short dephasing time, the magnetic resonance techniques are not compatible with our work. In our work, the 90° rotation on the electron-spin qubit around the optical axis can be
achieved by using a single photon, and the 180° rotation can be achieved by using a single photon which interacts with the QD twice \[81].

In this paper, we present some compact quantum circuits for a universal quantum computing on an electron-spin system assisted by the QDs inside single-side optical microcavities. Based on the giant circular birefringence induced by a QD-cavity system as a result of cavity quantum electrodynamics \[12, 13\], we construct the CNOT, Toffoli, and Fredkin gates on a stationary electron-spin system, achieved by some input-output processes of a single photon. Our schemes are simple and economic. They are accomplished with a success probability of 100% in principle and they do not require the additional electron-spin qubits which are employed in \[11\]. Our circuits for implementing the CNOT and Toffoli gates are especially compact. The electron qubits involved in these gates are stationary, which reduces the interaction between the spins and their environments, different from \[11\]. Moreover, our quantum circuits for the Toffoli and Fredkin gates beat their synthesis with two-qubit entangling gates and single-qubit gates largely. With current technology, these universal solid-state quantum gates are feasible.

II. COMPACT QUANTUM CIRCUIT FOR A CNOT GATE ON A STATIONARY ELECTRON-SPIN SYSTEM

A. A singly charged quantum dot in a single-side optical resonant microcavity

Figure \[1\] depicts the single-side QD-cavity system used in our schemes, i.e., a self-assembled In(Ga)As QD or a GaAs interface QD embedded in an optical resonant microcavity with one mirror partially reflective and the another one 100% reflective \[12, 13\]. According to Pauli’s exclusion principle, a negatively charged exciton \((X^−)\) consisting of two electrons bound to one hole can be optically excited when an excess electron is injected into the QD \[19\]. In Fig. 1, \(|\uparrow\rangle\) and \(|\downarrow\rangle\) represent the spins of the excess electron with the angular momentum projections \(J_z = +1/2\) and \(J_z = −1/2\) along the cavity axis, respectively. \(|\uparrow\downarrow\rangle\) and \(|\downarrow\uparrow\rangle\) represent the hole-spin states with \(J_z = +3/2\) and \(J_z = −3/2\), respectively. \(|R⟩\) and \(|L⟩\) present the right-circularly polarized photon and the left-circularly polarized photon, respectively. In 2008, Hu et al. \[12, 13\] showed that the L-polarized photon \(|L⟩\) drives \(|\uparrow⟩\) transform into \(|\uparrow\downarrow⟩\) and the R-polarized photon \(|R⟩\) drives \(|\downarrow⟩\) transform into \(|\downarrow\uparrow⟩\), respectively, due to Pauli’s exclusion principle. The coupled R-polarized \((L\)-polarized\) photon and the uncoupled L-polarized \((R\)-polarized\) photon acquire different phases and amplitudes when they are reflected by the cavity. The reflection coefficient

\[
r(\omega) = |r(\omega)|e^{i\varphi(\omega)} = 1 - \frac{\kappa[i(\omega_X - \omega) + \frac{\gamma}{2}]}{[i(\omega_X - \omega) + \frac{\gamma}{2}][i(\omega_c - \omega) + \frac{\gamma}{2} + \frac{\kappa^2}{\gamma}]} + g^2
\]

\[1\]
can be obtained by solving the Heisenberg equations of the motion for the cavity mode \(a\) and the dipole operation \(\sigma_-\) driven by the input field \(a_{in}\), and combing the relation between the input field \(a_{in}\) and the output field \(a_{out}\) in the weak excitation approximation \[32\].

\[
\frac{d\hat{a}}{dt} = - \left[ i(\omega_c - \omega) + \frac{\kappa}{2} + \frac{\kappa_s}{2} \right] \hat{a} - g\sigma_- - \sqrt{\kappa} \hat{a}_{in} + \hat{H},
\]

\[
\frac{da_{out}}{dt} = - \left[ i(\omega_X - \omega) + \frac{\gamma}{2} \right] \sigma_- - g\sigma_z \hat{a} + \hat{G},
\]

\[
\hat{a}_{out} = \hat{a}_{in} + \sqrt{\kappa} \hat{a}.
\]

\[2\]

Here \(\omega_c\) and \(\omega\) are the frequencies of the cavity mode and the input single photon, respectively. \(\omega_X^−\) is the frequency of the dipole transition of the negatively charged exciton \(X^−\). \(g\) is the coupling strength between the cavity mode and \(X^−\). \(\kappa/2\) and \(\kappa_s/2\) are the decay rate and the side leakage rate of the cavity field, respectively. \(\gamma/2\) represents the decay rate of \(X^−\). \(\hat{H}\) and \(\hat{G}\) are the noise operators related to the reservoirs.

Hu et al. \[12, 13\] showed that \(|r_0(\omega)| \simeq 1\) for all \(\omega\) if \(\kappa_s \ll \kappa\). If \(\kappa_s \ll \kappa\) and \(g > (\kappa, \gamma)\), one can see that \(|r_h(\omega)| \simeq 1\) when \(|\omega - \omega_c| \ll g\). Here \(r_0(\omega)\) and \(r_h(\omega)\) are given by Eq. \[1\] with \(g = 0\) and \(g \neq 0\), respectively. When \(\kappa_s\) is negligible, the transformations induced by the interaction between the QD and the input single photon can be expressed as follows:

\[
(|R⟩ + |L⟩) |\uparrow⟩ \xrightarrow{\text{cav}} e^{i\phi_0} (|R⟩ + e^{i\phi_h} |L⟩) |\uparrow⟩ = e^{i\phi_0} (|R⟩ + e^{i(\phi_h - \phi_0)} |L⟩) |\uparrow⟩,
\]

\[
(|R⟩ + |L⟩) |\downarrow⟩ \xrightarrow{\text{cav}} e^{i\phi_h} |R⟩ |\downarrow⟩ + e^{i\phi_0} |L⟩ |\downarrow⟩ = e^{i\phi_0} (e^{i(\phi_h - \phi_0)} |R⟩ + |L⟩) |\downarrow⟩.
\]

\[3\]

Here \(\phi_0 = \arg[r_0(\omega)]\) and \(\phi_h = \arg[r_h(\omega)]\). We consider the case that the QD is resonant with the cavity mode and it interacts with the resonant single photon \((i.e., \omega_X = \omega_c = \omega)\) in the conditions \(\kappa_s \ll \kappa\) and \(g > (\kappa, \gamma)\) below. In this
FIG. 1: (a) Schematic diagram of a coupled single-side QD-cavity system. (b) The energy-level structure of a QD-cavity system is driven by the left-circularly polarized photon ($|L\rangle$) and $|\uparrow\rangle \rightarrow |\uparrow\downarrow\uparrow\rangle$ is driven by the right-circularly polarized photon ($|R\rangle$), respectively.

FIG. 2: Compact quantum circuit for deterministically implementing a CNOT gate on two QD electron-spin qubits with a single-photon medium. The polarizing beam splitter PBS ($i = 1, 2, 3, 4$) in the basis \{|$R\rangle$, $|L\rangle$\} transmits the $R$-polarized photon and reflects the $L$-polarized photon. BS is a 50:50 beam splitter. The $\pm$–PBS transmits the photon in the state $|+\rangle = (|R\rangle + |L\rangle)/\sqrt{2}$ and reflects the photon in the state $|−\rangle = (|R\rangle − |L\rangle)/\sqrt{2}$. The half wave plate (HWP) set to 22.5° induces the transformations $|R\rangle \xrightarrow{H_p} (|R\rangle + |L\rangle)/\sqrt{2}$ and $|L\rangle \xrightarrow{H_p} (|R\rangle − |L\rangle)/\sqrt{2}$. $D^+$ and $D^−$ represent two single-photon detectors.

In 2011, Young et al. [33] measured the macroscopic phase shift of the reflected photon from a single-side pillar microcavity induced by a single QD in experiment. In a realistic cavity system, although it is hard to achieve the phase shift $\varphi_h − \varphi_0 = ±\pi$ due to the side leakage and the cavity loss [34], the phase shift $±\pi/2$ can be actually achieved in a QD-single-side-cavity system and it has been demonstrated by Hu’s group [31]. When $\kappa_s < 1.3\kappa$, the phase shift $\pi$ in our schemes can be achieved by a single photon which interacts with the QD twice. The above model works for a general polarization-degenerate cavity mode, including the micropillar [35–37], H1 photonic crystal [38, 39], and fiber-based [40] cavities.

Utilizing the optical circular birefringence induced by cavity quantum electrodynamics, the QD-cavity platform has been used to generate the maximally entangled states [12, 13, 31, 41–43], construct the conditional phase gate on hybrid photon-QD systems [12, 13], and design the hyper-CNOT gate on photonic qubits [19]. Based on the double-side one [41], some universal quantum gates on photonic qubits [16, 17] and hybrid photon-QD systems [15] have been proposed. In 2011, Wang et al. [44] proposed a scheme for implementing a quantum repeater, resorting to the QDs in double-side cavities. In the following, we discuss the implementation of a deterministic quantum computing with QD-single-side-cavity systems, shown in Fig. 1. The QD-double-side-cavity system is robust to the transmission and the reflection coefficients, while the side leakage rate of the QD-single-side-cavity system is lower than the double-side one.
B. Compact circuit for a CNOT gate on a stationary electron-spin system

The principle for implementing a CNOT gate on the two stationary electron-spin qubits in the QDs confined in single-side resonant optical microcavities is shown in Fig. 2. It flips the state of the target qubit when the control qubit is in the state $|\downarrow\rangle$. Suppose the input state of the quantum system composed of the control and the target qubits (confined in the cavities 1 and 2, respectively) are initially prepared as

$$|\psi\rangle_{in} = |\uparrow\rangle_c (\alpha_1 |\uparrow\rangle_t + \alpha_2 |\downarrow\rangle_t) + |\downarrow\rangle_c (\alpha_3 |\uparrow\rangle_t + \alpha_4 |\downarrow\rangle_t).$$

Here $\sum_{i=1}^{4} |\alpha_i|^2 = 1$. The input single photon is prepared in the equal polarization superposition state $|\psi\rangle' = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$.

Let us introduce the principle of our deterministic CNOT gate on two stationary electron-spin qubits. As depicted in Fig. 2 a single photon is injected into the input port $in$, and its $R$-polarized component is transmitted to the spatial model 1 by the polarizing beam splitter PBS$_1$ and then arrives at PBS$_2$ directly, while its $L$-polarized component is reflected to the spatial model 2 for interacting with the QD inside the cavity 1. After the photon emitting from the spatial models 1 and 3 arrives at PBS$_2$ simultaneously, a Hadamard operation $H_p$ is performed on it. That is, we let the photon pass through the half-wave plate (HWP) oriented at 22.5°, which results in the transformations as follows:

$$|R\rangle \xrightarrow{H_p} \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle), \quad |L\rangle \xrightarrow{H_p} \frac{1}{\sqrt{2}}(|R\rangle - |L\rangle).$$

Before and after the photon passes through the block composed of PBS$_3$, the QD inside the cavity 2, and PBS$_4$, a Hadamard operation $H_e$ is performed on the electron spin in the QD inside the cavity 2, respectively. Here $H_e$ completes the transformations as follows:

$$|\uparrow\rangle \xrightarrow{H_e} \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle), \quad |\downarrow\rangle \xrightarrow{H_e} \frac{1}{\sqrt{2}}(|\uparrow\rangle - |\downarrow\rangle).$$

The evolution of the whole system composed of a single-photon medium and the QDs inside the cavities 1 and 2 induced by the above operations ($PBS_1 \rightarrow$ cavity 1 $\rightarrow$ PBS$_2$ $\rightarrow$ HWP $\rightarrow$ H$_e$ $\rightarrow$ PBS$_3$ $\rightarrow$ cavity 2 $\rightarrow$ PBS$_4$ $\rightarrow$ H$_e$) can be described as follows:

$$|\psi\rangle' \otimes |\psi\rangle_{in} \rightarrow |R\rangle_9 |\uparrow\rangle_c (\alpha_1 |\uparrow\rangle_t + \alpha_2 |\downarrow\rangle_t) + |L\rangle_9 |\downarrow\rangle_c (\alpha_3 |\uparrow\rangle_t + \alpha_4 |\downarrow\rangle_t).$$

Here and below, we use $|R\rangle_i$ ($|L\rangle_i$) to denote the photon in the state $|R\rangle$ ($|L\rangle$) emitting from the spatial mode $i$ and use $H_{ei}$ to denote a Hadamard operation performed on the $i$-th QD-spin qubit.

Next, the single photon is measured in the basis $\{ |\pm\rangle = (|R\rangle \pm |L\rangle)/\sqrt{2} \}$ by the detectors $D^+$ and $D^-$. From Eq. (8), one can see that the response of the detector $D^+$ indicates that the CNOT gate on the two electron-spin qubits succeeds; if the detector $D^-$ is clicked, after we perform a classical feed-forward operation $\sigma_c = |\uparrow\rangle\langle\downarrow| + |\downarrow\rangle\langle\uparrow|$ on the control qubit, the CNOT gate is accomplished as well. That is, the output state of the system composed of the control and the target qubits confined in the cavities 1 and 2 becomes

$$|\psi\rangle_{in} \xrightarrow{\text{CNOT}} |\psi\rangle_{out} = \alpha_1 |\uparrow\rangle_c |\uparrow\rangle_t + \alpha_2 |\uparrow\rangle_c |\downarrow\rangle_t + \alpha_3 |\downarrow\rangle_c |\downarrow\rangle_t + \alpha_4 |\downarrow\rangle_c |\uparrow\rangle_t.$$

The quantum circuit shown in Fig. 2 can be used to implement a CNOT gate on the two-qubit electron-spin system in a deterministic way, which implements a not operation on the target qubit if and only if (iff) the control qubit is in the state $|\downarrow\rangle$.

III. COMPACT QUANTUM CIRCUIT FOR A TOFFOLI GATE ON THREE ELECTRON-SPIN QUBITS IN QDS

The principle for implementing a Toffoli gate on a three-qubit electron-spin system is shown in Fig. 3. It is used to flip the state of the target qubit iff both the two control qubits are in the state $|\downarrow\rangle$. Suppose the quantum system, which is composed of the three independent excess electrons inside the cavities 1, 2, and 3 that act as the first control qubit, the second control qubit, and the target qubit, respectively, is initially prepared in an arbitrary state

$$|\Xi\rangle_{in} = |\uparrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_1 |\uparrow\rangle_t + \alpha_2 |\downarrow\rangle_t) + |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_3 |\uparrow\rangle_t + \alpha_4 |\downarrow\rangle_t) + |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_5 |\uparrow\rangle_t + \alpha_6 |\downarrow\rangle_t) + |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_7 |\uparrow\rangle_t + \alpha_8 |\downarrow\rangle_t).$$

Here $\sum_{i=1}^{8} |\alpha_i|^2 = 1$. The input single photon is prepared in the equal polarization superposition state $|\psi\rangle' = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$.
Here \( \sum_{i=1}^{8} |\alpha_i|^2 = 1 \).

Next, we will specify the evolution of the system from the input state to the output state for characterizing the performance of our Toffoli gate. As illustrated in Fig. 3, our scheme for a Toffoli gate on a three-qubit electron-spin system can be achieved with four steps.

First, an input single photon in the state \( |\Xi^p\rangle = \frac{1}{\sqrt{2}}(|R\rangle - |L\rangle) \) goes through the block composed of PBS\(_2\), the QD inside the cavity 2, and PBS\(_1\), and then an \( H_p \) is performed on it (i.e., let the photon go through HWP\(_1\)). Based on the argument as made in Sec. 11B one can see that the above operations (PBS\(_2\) \rightarrow cavity 1 \rightarrow PBS\(_2\) \rightarrow HWP\(_1\)) transform the state of the complicated system composed of the single photon and the three QD-spin qubits from \( |\Xi_0\rangle \) into \( |\Xi_1\rangle \). Here

\[
|\Xi_0\rangle = |\Xi^p\rangle \otimes |\Xi^\text{in}\rangle,
|\Xi_1\rangle = (|L\rangle_5 |\uparrow\rangle_{c_1} |\uparrow\rangle_{c_2} (|\alpha_1\rangle |\uparrow\rangle_t + |\alpha_2\rangle |\downarrow\rangle_t) + |L\rangle_5 |\uparrow\rangle_{c_1} |\downarrow\rangle_{c_2} (|\alpha_3\rangle |\uparrow\rangle_t + |\alpha_4\rangle |\downarrow\rangle_t) + |R\rangle_5 |\downarrow\rangle_{c_1} |\uparrow\rangle_{c_2} (|\alpha_5\rangle |\uparrow\rangle_t + |\alpha_6\rangle |\downarrow\rangle_t) + |R\rangle_5 |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (|\alpha_7\rangle |\uparrow\rangle_t + |\alpha_8\rangle |\downarrow\rangle_t). \tag{11}
\]

Second, PBS\(_3\) transforms \( |R\rangle_5 \) and \( |L\rangle_5 \) into \( |R\rangle_6 \) and \( |L\rangle_7 \), respectively. Before and after the component \( |R\rangle_6 \) (\( |L\rangle_7 \)) of the photon goes through the block composed of PBS\(_4\), the QD inside the cavity 2, and PBS\(_6\) (PBS\(_5\), the QD inside the cavity 2, and PBS\(_7\)), an \( H_p \) is performed on it with HWP\(_2\) and HWP\(_4\) (HWP\(_3\) and HWP\(_5\)). The operations (HWP\(_2\) \rightarrow PBS\(_4\) \rightarrow cavity 2 \rightarrow PBS\(_6\) \rightarrow HWP\(_4\) and HWP\(_3\) \rightarrow PBS\(_5\) \rightarrow cavity 2 \rightarrow PBS\(_7\) \rightarrow HWP\(_5\)) transform the state of the complicated system into

\[
\rightarrow |\Xi_2\rangle = |L\rangle_{18} |\uparrow\rangle_{c_1} |\uparrow\rangle_{c_2} (|\alpha_1\rangle |\uparrow\rangle_t + |\alpha_2\rangle |\downarrow\rangle_t) + |R\rangle_{18} |\uparrow\rangle_{c_1} |\downarrow\rangle_{c_2} (|\alpha_3\rangle |\uparrow\rangle_t + |\alpha_4\rangle |\downarrow\rangle_t) + |R\rangle_{19} |\downarrow\rangle_{c_1} |\uparrow\rangle_{c_2} (|\alpha_5\rangle |\uparrow\rangle_t + |\alpha_6\rangle |\downarrow\rangle_t) + |L\rangle_{19} |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (|\alpha_7\rangle |\uparrow\rangle_t + |\alpha_8\rangle |\downarrow\rangle_t). \tag{12}
\]

Third, before and after the photon goes through the block composed of PBS\(_8\), the QD inside the cavity 3, and PBS\(_9\) when it emits from the spatial model 19, an \( H_e \) is performed on the electron spin in the QD inside the cavity 3, respectively. These operations (\( H_{e_3} \rightarrow PBS\_8 \rightarrow cavity 3 \rightarrow PBS\_9 \rightarrow H_{e_3} \)) complete the transformation

\[
\rightarrow |\Xi_3\rangle = |L\rangle_{18} |\uparrow\rangle_{c_1} |\uparrow\rangle_{c_2} (|\alpha_1\rangle |\uparrow\rangle_t + |\alpha_2\rangle |\downarrow\rangle_t) + |R\rangle_{18} |\uparrow\rangle_{c_1} |\downarrow\rangle_{c_2} (|\alpha_3\rangle |\uparrow\rangle_t + |\alpha_4\rangle |\downarrow\rangle_t) + |R\rangle_{23} |\downarrow\rangle_{c_1} |\uparrow\rangle_{c_2} (|\alpha_5\rangle |\uparrow\rangle_t + |\alpha_6\rangle |\downarrow\rangle_t) + |L\rangle_{23} |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (|\alpha_7\rangle |\uparrow\rangle_t + |\alpha_8\rangle |\downarrow\rangle_t). \tag{13}
\]

Subsequently, the wave packet emitting from the spatial model 23 arrives at the 50:50 beam splitter (BS) with the wave packet emitting from the spatial model 18 simultaneously.

Fourth, the balanced BS, which completes the transformations

\[
|R\rangle_{18} \rightarrow |\sqrt{2} (|R\rangle_{24} + |R\rangle_{25}) \rangle, \quad |L\rangle_{18} \rightarrow |\sqrt{2} (|L\rangle_{24} + |L\rangle_{25}) \rangle, \quad |R\rangle_{23} \rightarrow |\sqrt{2} (|R\rangle_{24} - |R\rangle_{25}) \rangle, \quad |L\rangle_{23} \rightarrow |\sqrt{2} (|L\rangle_{24} - |L\rangle_{25}) \rangle. \tag{14}
\]
transforms $|\Xi_3\rangle$ into the state

$$
\begin{align*}
\text{BS} & \frac{1}{\sqrt{2}} |\Xi_4\rangle = |\uparrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_1 |\uparrow\rangle_t + \alpha_2 |\downarrow\rangle_t) + |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_3 |\uparrow\rangle_t + \alpha_4 |\downarrow\rangle_t) \\
& + |\downarrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_5 |\uparrow\rangle_t + \alpha_6 |\downarrow\rangle_t) + |\uparrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_7 |\downarrow\rangle_t + \alpha_8 |\uparrow\rangle_t) \\
& + \frac{1}{\sqrt{2}} [ |\uparrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_1 |\uparrow\rangle_t + \alpha_2 |\downarrow\rangle_t) + |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_3 |\uparrow\rangle_t + \alpha_4 |\downarrow\rangle_t) \\
& + |\downarrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_5 |\uparrow\rangle_t + \alpha_6 |\downarrow\rangle_t) - |\uparrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_7 |\downarrow\rangle_t + \alpha_8 |\uparrow\rangle_t) \\
& + \frac{1}{\sqrt{2}} [ |\uparrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_1 |\uparrow\rangle_t + \alpha_2 |\downarrow\rangle_t) + |\downarrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_3 |\uparrow\rangle_t + \alpha_4 |\downarrow\rangle_t) \\
& + |\downarrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_5 |\uparrow\rangle_t + \alpha_6 |\downarrow\rangle_t) - |\uparrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_7 |\downarrow\rangle_t + \alpha_8 |\uparrow\rangle_t)]
\end{align*}
$$

(15)

According to the outcomes of the measurement on the single photon in the basis $\{|\pm\rangle\}$, we perform the appropriate single-qubit operations on the qubits shown in Table I, and then the state of the solid-state quantum system composed of the three electron-spin qubits becomes

$$
|\Xi\rangle_{\text{out}}^c = |\uparrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_1 |\uparrow\rangle_t + \alpha_2 |\downarrow\rangle_t) + |\uparrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_3 |\uparrow\rangle_t + \alpha_4 |\downarrow\rangle_t) \\
+ |\downarrow\rangle_{c_1} |\uparrow\rangle_{c_2} (\alpha_5 |\uparrow\rangle_t + \alpha_6 |\downarrow\rangle_t) + |\uparrow\rangle_{c_1} |\downarrow\rangle_{c_2} (\alpha_7 |\downarrow\rangle_t + \alpha_8 |\uparrow\rangle_t).
$$

(16)

From Eqs. (11) and (16), one can see that the evolution $|\Xi\rangle_{\text{in}}^\text{ToF}loli \rightarrow |\Xi\rangle_{\text{out}}^c$ is accomplished. That is, the quantum circuit shown in Fig. 3 implements a Toffoli gate on the three stationary electron-spin qubits in QDs, and it flips the state of the target qubit inside the cavity 3 if both the two control qubits inside the cavities 1 and 2, respectively, are in the state $|\downarrow\rangle$ with a successful probability of 100% in principle.

### TABLE I: The relations between the measurement outcomes of the single photon and the classical feed-forward operations for implementing the Toffoli gate on the three stationary electron-spin qubits.

| photon | qubit $c_1$ | qubit $c_2$ | qubit $t$ |
|--------|-------------|-------------|-------------|
| $D^+_1(|\uparrow\rangle_{20})$ | $I_2$ | $I_2$ | $I_2$ |
| $D^-_1(|\downarrow\rangle_{27})$ | $-\sigma_z$ | $\sigma_z$ | $I_2$ |
| $D^+_2(|\uparrow\rangle_{28})$ | $\sigma_z$ | $I_2$ | $I_2$ |
| $D^-_2(|\downarrow\rangle_{29})$ | $I_2$ | $-\sigma_z$ | $I_2$ |

### IV. COMPACT QUANTUM CIRCUIT FOR A FREDKIN GATE ON A THREE-QUBIT ELECTRON-SPIN SYSTEM

Figure 4 depicts the principle of our scheme for implementing a Fredkin gate on a three-qubit electron-spin system assisted by the QDs inside single-side optical microcavities, which swaps the states of the two target qubits iff the control qubit is in the state $|\downarrow\rangle$. Suppose the input state of the system composed of the control qubit, the first target qubit, and the second target qubit inside the cavities 1, 2, and 3, respectively, is initially prepared as

$$
|\Pi\rangle_{\text{in}}^c = |\uparrow\rangle_{c_1} |\uparrow\rangle_{t_1} (\alpha_1 |\uparrow\rangle_{t_2} + \alpha_2 |\downarrow\rangle_{t_2}) + |\uparrow\rangle_{c_1} |\downarrow\rangle_{t_1} (\alpha_3 |\uparrow\rangle_{t_2} + \alpha_4 |\downarrow\rangle_{t_2}) \\
+ |\downarrow\rangle_{c_1} |\uparrow\rangle_{t_1} (\alpha_5 |\uparrow\rangle_{t_2} + \alpha_6 |\downarrow\rangle_{t_2}) + |\downarrow\rangle_{c_1} |\downarrow\rangle_{t_1} (\alpha_7 |\uparrow\rangle_{t_2} + \alpha_8 |\downarrow\rangle_{t_2}).
$$

(17)

Here $\sum_{i=1}^8 |\alpha_i|^2 = 1$. The input single photon is prepared in the state $|\Pi\rangle^p = \frac{1}{\sqrt{2}} (|R\rangle - |L\rangle)$.

Let us now describe the principle of our scheme for implementing a Fredkin gate on the three stationary electron-spin qubits in QDs in detail.
First, based on the argument as made in Sec. III after the input photon goes through the block composed of PBS$_1$, the QD inside the cavity 1, and PBS$_2$, an $H_p$ (i.e., let it go through HWP$_1$) is performed on it, and then the state of the whole system composed of the single photon and the three electron-spin qubits in the QDs confined in the cavities 1, 2, and 3 is transformed from $|\Pi_0\rangle$ into $|\Pi_1\rangle$ by the above operations (PBS$_1$ → cavity 1 → PBS$_2$ → HWP$_1$). Here

$$|\Pi_0\rangle = |\Pi\rangle^p \otimes |\Pi\rangle^n,$$

$$|\Pi_1\rangle = |L\rangle_5 |\uparrow\rangle |\downarrow\rangle |\Pi\rangle_t_1 (\alpha_1 |\uparrow\rangle |\downarrow\rangle + \alpha_2 |\downarrow\rangle |\uparrow\rangle + \alpha_3 |\downarrow\rangle |\downarrow\rangle + \alpha_4 |\downarrow\rangle |\downarrow\rangle) + |R\rangle_5 |\downarrow\rangle |\uparrow\rangle |\Pi\rangle_t_1 (\alpha_3 |\downarrow\rangle |\downarrow\rangle + \alpha_4 |\downarrow\rangle |\downarrow\rangle + \alpha_5 |\downarrow\rangle |\downarrow\rangle).$$ (18)

Second, PBS$_3$ transforms $|R\rangle_6$ and $|L\rangle_7$ into $|R\rangle_6$ and $|L\rangle_7$, respectively. When the photon is in the state $|L\rangle_7$, before and after it goes through the block composed of PBS$_3$, the QDs inside the cavities 2 and 3, and PBS$_7$, an $H_p$ is performed on it with HWP$_3$ and HWP$_5$, respectively, and then it arrives at the balanced BS directly. When the photon is in the state $|R\rangle_6$, after an $H_p$ is performed on it with HWP$_2$, the optical switch $S$ leads it to the block composed of PBS$_4$, the QDs inside the cavities 2 and 3, and PBS$_6$, following with an $H_p$ which is performed on the photon with a wave plate (WP) and a mirror. Here $|R\rangle_20 \xrightarrow{\text{WP mirror WP}} (|R\rangle_20 + |L\rangle_20)/\sqrt{2}$ and $|L\rangle_20 \xrightarrow{\text{WP mirror WP}} (|R\rangle_20 - |L\rangle_20)/\sqrt{2}$. These operations (HWP$_3$ → PBS$_5$ → cavity 2 → cavity 3 → PBS$_7$ → HWP$_5$ and HWP$_2$ → S → PBS$_4$ → cavity 2 → cavity 3 → PBS$_6$ → WP → mirror → WP) complete the transformation

$$\rightarrow |\Xi_2\rangle = |\uparrow\rangle |\uparrow\rangle (\alpha_1 |L\rangle_22 |\uparrow\rangle |\down\rangle + \alpha_2 |R\rangle_22 |\down\rangle |\up\rangle + \alpha_3 |L\rangle_22 |\down\rangle |\down\rangle + \alpha_4 |R\rangle_22 |\down\rangle |\down\rangle) + |\down\rangle |\down\rangle (\alpha_3 |L\rangle_22 |\up\rangle |\down\rangle + \alpha_4 |R\rangle_22 |\down\rangle |\up\rangle).$$ (19)

Third, the photon emitting from the spatial model 20 is injected into the block composed of PBS$_6$, the QDs inside the cavities 2 and 3, and PBS$_4$ again, and before and after the photon interacts with the QDs inside the cavities 3 and 2, an $H_e$ is performed on the QDs inside the cavities 3 and 2, respectively. The optical switch $S$ leads the wave packet to the spatial model 21 for interfering with the wave packet emitting from the spatial model 22. The above operations ($H_e2, H_e3 \rightarrow$ PBS$_6$ → cavity 3 → cavity 2 → PBS$_4$ → $H_e2, H_e3 \rightarrow$ S) complete the transformation

$$\rightarrow |\Xi_3\rangle = |\up\rangle |\up\rangle (\alpha_1 |L\rangle_22 |\up\rangle |\down\rangle + \alpha_2 |R\rangle_22 |\down\rangle |\up\rangle + \alpha_3 |L\rangle_22 |\down\rangle |\down\rangle + \alpha_4 |R\rangle_22 |\down\rangle |\down\rangle) + |\down\rangle |\down\rangle (\alpha_3 |L\rangle_22 |\up\rangle |\down\rangle + \alpha_4 |R\rangle_22 |\down\rangle |\up\rangle).$$ (20)

Fourth, the single photon is detected by the detectors $D^\pm_1$ in the basis \{±\} after the 50:50 BS transforms $|\Xi_3\rangle$.
into $|\Xi_4\rangle$. Here
\[
|\Xi_4\rangle = \frac{1}{2} \left[ |\uparrow\rangle_4 |\uparrow\rangle_1 (\uparrow_2 + \downarrow_2) + |\uparrow\rangle_4 |\downarrow\rangle_1 (\uparrow_2 - \downarrow_2) + |\downarrow\rangle_4 |\downarrow\rangle_1 (\uparrow_2 + \downarrow_2) + |\downarrow\rangle_4 |\uparrow\rangle_1 (\uparrow_2 - \downarrow_2) \right]
+ \frac{1}{2} \left[ |\uparrow\rangle_4 |\downarrow\rangle_1 (\uparrow_2 - \downarrow_2) + |\downarrow\rangle_4 |\uparrow\rangle_1 (\uparrow_2 + \downarrow_2) \right].
\] (21)

Fifth, according to the outcomes of the measurement on the output single photon, we perform some appropriate classical feed-forward single-qubit operations, shown in Table II, on the electron-spin qubits to make the state of the system composed of the three electrons inside the cavities 1, 2, and 3 to be
\[
|\Pi\rangle_{\text{out}} = |\uparrow\rangle_4 |\uparrow\rangle_1 |\uparrow\rangle_2 + |\uparrow\rangle_4 |\downarrow\rangle_1 |\downarrow\rangle_2 + |\downarrow\rangle_4 |\downarrow\rangle_1 |\uparrow\rangle_2 + |\downarrow\rangle_4 |\uparrow\rangle_1 |\downarrow\rangle_2 \rangle.
\] (22)

From Eqs. (18) and (22), one can see that the evolution $|\Pi\rangle_{\text{in}}$ Fredkin $|\Pi\rangle_{\text{out}}$ is completed. That is, the quantum circuit shown in Fig. 4 implements a Fredkin gate on the three-qubit electron-spin system in a deterministic way, which swaps the states of the two target qubits iff the state of the control qubit is in the state $|\downarrow\rangle$.

|TABLE II: The relations between the measurement outcomes of the photon and the feed-forward operations for achieving a Fredkin gate on the three-qubit electron-spin system.|
|---|---|---|---|
|Parent qubit $c$| qubit $t_1$| qubit $t_2$|
|Feed-forward| photon $\uparrow$| photon $\downarrow$| photon $\downarrow$|
|$D_1^+ (|\uparrow\rangle_{25})$| $I_2$| $I_2$| $I_2$|
|$D_1^- (|\downarrow\rangle_{26})$| $-\sigma_z$| $\sigma_z$| $\sigma_z$|
|$D_2^+ (|\uparrow\rangle_{27})$| $\sigma_z$| $I_2$| $I_2$|
|$D_2^- (|\downarrow\rangle_{28})$| $I_2$| $\sigma_z$| $\sigma_z$

\section{V. THE FEASIBILITIES AND EFFICIENCIES OF OUR SCHEMES}

So far, all the procedures in our schemes for the three universal quantum gates are described in the case that the side leakage rate $k_s$ is negligible. To present our ideas more realistically, $k_s$ should be taken into account. In this time, the rules of the input states changing under the interaction of the photon and the cavity become
\[
|\uparrow\rangle \xrightarrow{\text{cav}} -|r_0\rangle |\uparrow\rangle, \quad |\downarrow\rangle \xrightarrow{\text{cav}} |r_h\rangle |\downarrow\rangle,
\]
\[
|\uparrow\rangle \xrightarrow{\text{cav}} |r_h\rangle |\uparrow\rangle, \quad |\downarrow\rangle \xrightarrow{\text{cav}} -|r_0\rangle |\downarrow\rangle.
\] (23)

The fidelities and efficiencies of the universal quantum gates are sensitive to $k_s$ as $k_s$ influences the amplitudes of the reflected photon (see Eq. (11)). Here the fidelity of a quantum gate is defined as
\[
F = \langle |\Psi_{\text{real}}\rangle |\Psi_{\text{ideal}}\rangle^2,
\] (24)

where $|\Psi_{\text{ideal}}\rangle$ is the output state of the system composed of the QD-spin qubits involved in the gate and a single-photon medium in the ideal case (that is, the photon escapes through the input-output mode). $|\Psi_{\text{real}}\rangle$ is the output
state of the complicated system in the realistic case (that is, the cavities are imperfect and the side leakage $\kappa_s$ is taken into account). The efficiency of the gate is considered as

$$\eta = \frac{n_{\text{out}}}{n_{\text{in}}}.\quad (25)$$

Here $n_{\text{in}}$ and $n_{\text{out}}$ are the numbers of the input photons and the output photons, respectively.

For perfect cavities, the fidelities of our universal quantum gates can reach unity. By considering the side leakage and combining the specific processes of the construction for the universal quantum gates discussed above, the fidelities of our CNOT gate $F_C$, Toffoli gate $F_T$, and Fredkin gate $F_F$, and their efficiencies $\eta_C$, $\eta_T$, and $\eta_F$ can be calculated as follows:

$$F_C = \frac{1}{2} \times \frac{(1+2|r_h| + |r_0||r_h|) / [(1+|r_h|)^2 + (1-|r_0|^2 + |r_h|^2(1-|r_h|^2)]}{128},$$

$$F_T = \frac{1}{2} \times \frac{(3 + 2|r_0| + |r_h|[5 + |r_h| + |r_0|(4 + |r_0|)] / [(1 + |r_h|)^4 + 2(|r_h|^2 - 1)^2 + 2(|r_h| - 1)^2 + (|r_0| - 1)^4 + 2(|r_0|^2 - 1)^2}}{128},$$

$$F_F = \frac{1}{2} \times \frac{(4 + 2|r_h| + |r_0|)(3 + 2|r_0| + |r_h|)[5 + |r_h| + |r_0|(4 + |r_0|)] / [(1 + |r_h|)^2 + (|r_h|^2 - 1)^2 + 2(|r_h| - 1)^2 + (|r_0|^2 - 2) + 4(|r_0|^2 - 1)^2}}{512}.\quad (27)$$

$$\eta_C = \frac{(2 + |r_h|^2 + |r_0|^2)^2}{16},$$

$$\eta_T = \frac{(2 + |r_h|^2 + |r_0|^2)^2(6 + |r_h|^2 + |r_0|^2)}{128},$$

$$\eta_F = \frac{(2 + |r_h|^2 + |r_0|^2)^2[4 + (|r_h|^2 + |r_0|^2)^2][12 -(|r_h|^2 + |r_0|^2)]}{512}.\quad (31)$$

It is still a big challenge to achieve strong coupling in experiment at present [15]. However, strong coupling has been observed in the QD-cavity systems with the micropillar form [33, 45, 47] and the microdisk form [48, 49], and the QD-nanocavity systems [50] in experiment. In 2004, Reithmaier et al. [14] observed $g/(\kappa + \kappa_s) \approx 0.5$ in a micropillar cavity with a quality factor of $Q = 8800$ [$Q = 40000$]. In 2011, Hu et al. [31] demonstrated $g/(\kappa + \kappa_s) \approx 1.0$ in a micropillar cavity with $\kappa_s/\kappa \approx 0.7$ and $Q \approx 1.7 \times 10^4$. In 2010, Loo et al. [47] reported $g = 16 \mu eV$ and $\kappa = 20.5 \mu eV$ in a $d = 7.3 \mu m$ micropillar with $Q = 65000$.

The fidelities and the efficiencies of our universal quantum gates, which vary with the coupling strength and the side leakage rate, are shown in Figs. 5 and 6, respectively. From these figures, one can see that our schemes are feasible in both the strong coupling regime and the weak coupling regime. $\kappa_s$ can be made rather small by improving the sample growth or the etching process.

A QD system has the discrete atom-like energy levels and a spectrum of the ultra-narrow transition that is tunable with the size of the quantum dot. The growth techniques of QDs produce the size variations of the QDs. The spectral line-width inhomogeneous broadening is caused by the fluctuations in the size and shape of a QD, and it has gained the widespread attention [51]. The spectral inhomogeneity is an important property and it is not necessarily a negative consequence for their applications in quantum information processing. The imperfect QD in a realistic system, i.e., the shape of the sample and the strain field distribution are not symmetric, reduces the fidelities of the gates and it can be decreased by designing the shape and the size of the sample or encoding the qubits on a different type of QDs [13, 31].

The information between the photon medium and the QD spins is transferred by the exciton. That is, the exciton dephasing reduces the fidelities of the gates. The exciton dephasing, including the optical dephasing and the spin...
The efficiency of our CNOT gate (\(F_C\)) is sensitive to the dipole coherence time \(T_d\) and the cavity-photon coherence time \(T\). The exciton dephasing reduces the fidelities of the universal quantum gates less than 10% as it reduces the fidelities by a factor

\[
1 - \exp(-\tau/T_2),
\]

and the ultralong optical coherence time of the dipole \(T_2\) can reach several picoseconds at a low temperature \([52, 53]\), while the cavity-photon coherence time \(\tau\) is around 10 picoseconds in an InGaAs QD. The QD-hole spin coherence time \(T_2\) is long more than 100 nanoseconds \([54]\).

VI. DISCUSSION AND SUMMARY

Quantum logic gates are essential building blocks in quantum computing and quantum information processing \([1]\). CNOT gates are used widely in quantum computing. Directly physical realization of multiqubit gates is a main direction as the optimal length of the unconstructed circuit for a generic \(n\)-qubit gate is \([4^n - 3n - 1]/4\) \([55]\).

Some significant progress has been made in realizing universal quantum gates. Refs. \([14, 15, 23]\) present some interesting schemes for the quantum gates on hybrid light-matter or electron-nuclear qubits. Based on parity-check gates, the CNOT gate on moving electron qubits is proposed in 2004, assisted by an additional electron qubit \([11]\). A Toffoli gate on atom qubits with a success probability of 1/2 is constructed by Wei et al. in 2008 \([57]\). Our CNOT, Toffoli, and Fredkin gates are compact, simple, and economic as the ancilla qubits, employed in \([9, 11]\), are not required, and only a single-photon medium is employed. The proposals for the Toffoli and Fredkin gates beat their synthesis with two-qubit entangling gates and single-qubit gates largely. The optimal synthesis of a three-qubit Toffoli gate requires six CNOT gates \([57]\) and five quantum entangling gates on two individual qubits are required to synthesize a three-qubit Fredkin gate \([58]\). All our schemes are deterministic and the qubits for the gates are stationary. The side leakage rate of a single-side cavity is usually lower than that of a double-side one \([41]\). Moreover, a QD is easier to be confined in a cavity than an atom \([34, 59]\).

In summary, we have proposed some compact schemes for implementing quantum computing on solid-state electron-spin qubits in the QDs assisted by single-side resonant optical microcavities in a deterministic way. Based on the fact
that the $R$-polarized and the $L$-polarized photons reflected by the QD-cavity contribute different phase shifts, the compact quantum circuits for the CNOT, Toffoli, and Fredkin gates on the stationary electron-spin qubits are achieved by some input-output processes of a single-photon medium and some classical feed-forward operations. Our proposals are compact and economic as the additional QD-spin qubits are not required and our schemes for implementing the multiqubit gates beat their synthesis with two-qubit entangling gates and single-qubit gates largely. The success probabilities of our universal quantum gates are 100% in principle. With current technology, our schemes are feasible. Together with single-qubit gates, our universal quantum gates are sufficient for any quantum computing in solid-state QD-spin systems.

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