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Quantum information transfer between photonic and quantum-dot spin qubits

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We propose schemes for the efficient information transfer between a propagating photon and a quantum-dot (QD) spin qubit in an optical microcavity that have no auxiliary particles required. With these methods, the information transfer between two photons or two QD spins can also be achieved. All of our proposals can work with high fidelity, even with a high leakage rate. What is more, each information transfer process above can also be seen as a controlled-NOT (CNOT) operation. It is found that the information transfer can be equivalent to a CNOT gate. These proposals will promote more efficient quantum information networks and quantum computation.

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The faithful transfer of quantum information and logical operation between a propagating photon and a stationary qubit plays a significant role in quantum information science such as quantum networks\(^2\), quantum repeaters\(^2\), and optics quantum computing\(^{12}\), since photons are the perfect candidates for fast and reliable long-distance communication, while stationary qubits are suitable for processor and local storage. Some schemes for the interaction between photonic and stationary qubits, for example atomic qubits\(^{22}\), have been reported. In recent years, semiconductor quantum dots (QDs) have attracted extensive attention. As promising solid-state qubits, single spin confined in QD has a long coherence time\(^{22}\) and a potential for integration on a chip\(^{22}\). Moreover, QD manipulation has had significant progress\(^{1-17}\). Many quantum communication and quantum computation schemes have been proposed based on QD spins combined with optical microcavities such as entanglement measurements\(^{14-16}\), quantum logic gates\(^{15-17}\), entanglement generators\(^{20}\), and quantum repeaters\(^{21}\). In 2013, Gao et al. experimentally demonstrated the transfer of quantum information carried by a photonic qubit to a QD spin qubit using quantum teleportation\(^{22}\). They generated an entangled spin-photon state in a QD and interfered the photon with a single photon in a superposition state of two colors, i.e., a photonic qubit in a Hong–Ou–Mandel setup. A coincidence detection at the output of the interferometer heralds a successful teleportation. The demonstration of successful quantum teleportation of photonic and QD spin qubits could promote the realization of on-chip quantum networks based on semiconductor nanostructures.

The interaction between a circularly polarized beam of light and a QD-cavity system is introduced first. Then, we propose information transfer between a photon and a QD spin in an optical microcavity, with no auxiliary particle required. The information transfer between two photons or two QD spins is proposed with a QD spin or a photon as auxiliary photon. All of the information transfer processes above can be achieved deterministically and can be seen as controlled-NOT (CNOT) gates for quantum computation.

Considering a singly charged QD in an optical microcavity shown in Fig. 1, if the injected excess electron spin is in the state \(|↑⟩\), the QD-cavity system resonantly absorbs a left-handed circularly polarized beam of light \(|L⟩\) and creates a negatively charged exciton in the state \(|↓⇑⟩\). If the injected excess electron spin is in the state \(|↓⟩\), the QD-cavity system resonantly absorbs a right-handed circularly polarized beam of light \(|R⟩\) and creates a negatively charged exciton in the state \(|↓⇓⟩\). Here, \(|⇑⟩\) and \(|⇓⟩\) represent the heavy-hole spin states \(|+\frac{3}{2}⟩\) and \(|−\frac{3}{2}⟩\), respectively. Due to this spin selection rule, the \(L\) and \(R\)-light encounter different phase shifts after reflection from the cavity system.

The Heisenberg equations for the cavity field operator \(a\) and the QD dipole \((X−)\) operator \(\hat{σ}_s\) in the interaction picture, and the input-output equation are given by\(^{22}\)

\[
\dot{a}_\text{in} = a_\text{out} + \hat{σ}_s \text{ victim } a_\text{out}
\]

Fig. 1. Spin-dependent transitions for negatively charged exciton \(X−\). (a) A charged QD inside a micropillar microcavity with circular cross section. (b) The spin selection rule for optical transitions of negatively charged exciton \(X−\) due to the Pauli’s exclusion principle. \(L\) and \(R\) represent the left- and the right-hand circularly polarized lights, respectively.
\[
\frac{d\hat{a}}{dt} = -\left[i(\omega_c - \omega) + \frac{\kappa}{2} + \frac{\kappa^\prime}{2}\right] \hat{a} - g\hat{\sigma}_- - \sqrt{\kappa}\hat{a}_{in}, \quad \frac{d\hat{\sigma}_-}{dt} = \left[i(\omega_X - \omega) + \frac{\gamma}{2}\right] \hat{\sigma}_- - g\hat{\sigma}_z \hat{a}.
\]

(1)

where \(\omega, \omega_c,\) and \(\omega_X\) are the frequencies of the input probe light, cavity mode, and \(X^-\) transition, respectively, \(g\) is the coupling strength between \(X^-\) and the cavity mode, \(\gamma/2\) and \(\kappa/2\) are the decay rates of \(X^-\) and the cavity field, and \(\kappa^\prime/2\) is the side leakage rate of the cavity.

If the QD couples to the cavity, we call it a hot cavity; if the QD does not couple to the cavity, we call it a cold cavity. In the weak approximation, the reflection coefficient in the steady state for hot cavity can be obtained as follows:

\[
r_b(\omega) = 1 - \frac{\kappa\left[i(\omega_X - \omega) + \frac{\kappa^\prime}{2}\right]}{\left[i(\omega_X - \omega) + \frac{\kappa}{2}\right] + \frac{\gamma}{2} + \frac{\kappa^\prime}{2} + g^2}.
\]

(2)

If the \(X^-\) and the cavity mode are uncoupled (a cold cavity), the coupling strength is \(g = 0\) and the reflection coefficient is

\[
r_0(\omega) = \frac{i(\omega_c - \omega) + \frac{\kappa}{2} + \frac{\kappa^\prime}{2}}{i(\omega_c - \omega) + \frac{\gamma}{2} + \frac{\kappa^\prime}{2}}.
\]

(3)

If the single excess electron lies in the spin state \(|\uparrow\rangle\), the L photon feels a hot cavity and gets a phase shift of \(\phi_b(\omega)\) after reflection, whereas the R photon feels a cold cavity and gets a phase shift of \(\phi_b(\omega)\). Conversely, if the electron lies in the spin state \(|\downarrow\rangle\), the R photon feels a hot cavity and gets a phase shift of \(\phi_b(\omega)\) after reflection, whereas the L photon feels the cold cavity and gets a phase shift of \(\phi_b(\omega)\). The side leakage can be neglected in ideal conditions. For the hot cavity where \(X^-\) strongly couples to the cavity, \(g/\gamma, k\). So \(|r_3(\omega)| \approx 1\) when \(|\omega - \omega_c| < g\). For the cold cavity, \(g = 0\). We can obtain \(r_0(\omega) \approx 1\). With the initial states of an electron spin and a circularly polarized photon in states \((|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}\) and \((|\uparrow\rangle - |\downarrow\rangle)/\sqrt{2}\), after being reflected, the light-spin state evolves as

\[
\frac{1}{2}(|R\rangle + |L\rangle) \Theta (|\uparrow\rangle + |\downarrow\rangle),
\]

\[
\rightarrow \frac{1}{2}e^{i\phi}\left[\left(\frac{1}{2}e^{i\Delta \phi}|L\rangle\right)\uparrow + (e^{i\Delta \phi}|R\rangle + |L\rangle)|\downarrow\right],
\]

(4)

where \(\Delta \phi = \phi_b - \phi_0,\) where \(\phi_0 = \arg[r_0(\omega)],\) and \(\phi_b = \arg[r_b(\omega)],\) \(\theta^\prime = (\phi_b - \phi_0)/2 = -\theta^\prime\) is the Faraday rotation angle. When the frequency \(\omega - \omega_c \approx \kappa/2\), the phase-shift difference between the left-hand circular polarization light and the right-hand circular polarization light will be \(\Delta \phi = \pi/2\).

Suppose that a photon is in a superposition state \(|\Psi\rangle_a = a|R\rangle_a + \beta|L\rangle_a\) \((|a|^2 + |\beta|^2 = 1)\), which is the state transferred to a solid-state qubit. The setup of information transfer from a photon to a solid-state qubit is shown in Fig. 2. The spin state of QDs is generated in \(|\Psi\rangle_s = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)\). After the photon passing through the half-wave plate (HWP) and phase shift P, the state of the photon is

\[
\frac{1}{\sqrt{2}}[(\alpha + \beta)|R\rangle_a + i(\alpha - \beta)|L\rangle_a].
\]

(5)

Then the photon interacts with the QD. The state of the system of the photon and the QD will be

\[
\frac{1}{\sqrt{2}}[(\alpha + \beta)|R\rangle_a|\uparrow\rangle + i(\alpha - \beta)|L\rangle_a|\downarrow\rangle,\]

\[
\rightarrow \frac{1}{\sqrt{2}}[(\alpha|\uparrow\rangle + i\beta|\downarrow\rangle)|R\rangle_a + (\alpha|\downarrow\rangle + i\beta|\uparrow\rangle)|L\rangle_a].
\]

(6)

Because of the second HWP, the state will be converted to

\[
\frac{1}{\sqrt{2}}[(\beta|\uparrow\rangle + i\alpha|\downarrow\rangle)|R\rangle_a + (\alpha|\downarrow\rangle + i\beta|\uparrow\rangle)|L\rangle_a].
\]

(7)

Then we implement a \(-\pi/2\) phase shift on \(|\downarrow\rangle\). The state will be

\[
\frac{1}{\sqrt{2}}[(\alpha|\uparrow\rangle + \beta|\downarrow\rangle)|R\rangle_a + (\alpha|\downarrow\rangle + \beta|\uparrow\rangle)|L\rangle_a].
\]

(8)

It can be seen that, if \(D_2\) is clicked, the spin state of the QD will be \(|\Psi\rangle_{s2} = \alpha|\uparrow\rangle + \beta|\downarrow\rangle\). Obviously, the information of the photon is transferred to the solid-state QD spin qubit. If \(D_1\) is clicked, the spin state of the QD will be \(|\Psi\rangle_{s1} = \alpha|\downarrow\rangle + \beta|\uparrow\rangle\), which can be converted to \(|\Psi\rangle_{s2}\) by a single-qubit operation. So the information transfer from a photon to a solid-state QD spin qubit is deterministic.

What’s more, the setup above implements the transformation as follows:

\[
|\Psi\rangle_a|\Psi\rangle_s = (\alpha|R\rangle_a + \beta|L\rangle_a) \Theta \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle),
\]

\[
\rightarrow \frac{1}{\sqrt{2}}(|\alpha|\uparrow\rangle + \beta|R\rangle_a|\uparrow\rangle + (\alpha|R\rangle_a + \beta|L\rangle_a)|\downarrow\rangle].
\]

(9)

Obviously, it is a CNOT operation with the QD spin as the control qubit and the photon as the target qubit. When the spin state is \(|\downarrow\rangle\), the photon state will be inverted. Otherwise, the photon state will remain unchanged.

Next, we consider the inverse case, which is the information transfer from a solid-state qubit to a photon shown in Fig. 3. Suppose that the spin state of the QD is \(|\Psi\rangle_s' = \alpha|\uparrow\rangle + \beta|\downarrow\rangle\) and the state of photon is \(|\Psi\rangle_a' = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)\). Before the interaction between the photon and the QD, an operation in \(||\uparrow\rangle\rangle_s, |\downarrow\rangle\rangle_s\rangle\) basis vectors as follows is implemented on the spin state of QD utilizing a pulse.
Recently, the information of the solid-state QD spin qubit is transferred to a photon. The modulation of the spin state of the QD will be implemented two times before ($\hat{U}_1$) and after ($\hat{U}_2$) the photon passes through the QD.

$$\hat{U}_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ i & -i \end{pmatrix}. \quad (10)$$

Then, the spin state of the QD is $\frac{1}{\sqrt{2}}[(\alpha + \beta)|\uparrow\rangle_s + i(\alpha - \beta)|\downarrow\rangle_s]$. Because of the interaction between the photon and the QD, the state of the whole system is

$$\frac{1}{2}[(\alpha + \beta)|R\rangle_a + i(\alpha - \beta)|L\rangle_a]|\uparrow\rangle_s + i(\alpha + \beta)|L\rangle_a + i(\alpha - \beta)|R\rangle_a]|\downarrow\rangle_s]. \quad (11)$$

Then, the operation

$$\hat{U}_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad (12)$$

is implemented on the spin state of the QD. The state of the system will be

$$\frac{1}{\sqrt{2}}[(\beta|R\rangle_a + i\alpha|L\rangle_a)|\uparrow\rangle_s + (\alpha|R\rangle_a + i\beta|L\rangle_a)|\downarrow\rangle_s]. \quad (13)$$

which can be converted to the following state by a $-\pi/2$ phase shift on $|L\rangle$:

$$\frac{1}{\sqrt{2}}[(\beta|R\rangle_a + \alpha|L\rangle_a)|\uparrow\rangle_s + (\alpha|R\rangle_a + \beta|L\rangle_a)|\downarrow\rangle_s]. \quad (14)$$

After that, a measurement will be implemented on the spin state of QD. If $|\uparrow\rangle$ is obtained, the state of the photon will be $|\Psi\rangle_a = \beta|R\rangle_a + \alpha|L\rangle_a$, which can be converted to $|\Psi\rangle_a = \alpha|R\rangle_a + \beta|L\rangle_a$ by a single-photon operation. Obviously, the information of the solid-state QD spin qubit is transferred to the photon. If $|\downarrow\rangle$ is obtained, the state of the photon will be $|\Psi\rangle_a = \alpha|R\rangle_a + \beta|L\rangle_a$. So the information transfer from the solid-state QD spin qubit to the photon is also deterministic.

Similar to the information transfer from a solid-state qubit to a photon, the process above can be seen as the following transformation:

$$|\Psi\rangle_a|\Psi\rangle_a = (\alpha|\uparrow\rangle_s + \beta|\downarrow\rangle_s) \otimes \frac{1}{\sqrt{2}}(|R\rangle_a + |L\rangle_a)$$

$$- \frac{1}{\sqrt{2}}[(\alpha|\downarrow\rangle_s + \beta|\uparrow\rangle_s)|R\rangle_a + (\alpha|\uparrow\rangle_s + \beta|\downarrow\rangle_s)|L\rangle_a]. \quad (15)$$

It is a CNOT operation with the photon as control qubit and the QD spin as the target qubit. When the photon state is $|R\rangle$, the QD spin state will be inverted. Otherwise, the QD spin state will remain unchanged.

With the methods above, we can also achieve the information transfer between QD spins. Now, we explain the principle of information transfer from a QD spin to another QD spin assisted by a photon, which is shown in Fig. 4.

This process can be divided into two steps. 1. Information transfer from a QD spin to a photon. 2. Information transfer from the photon to another QD spin. We assume that the initial states of the excess electron spin in QD1 and QD2 are $|\Phi\rangle_{s_1} = a|\uparrow\rangle_{s_1} + \beta|\downarrow\rangle_{s_1}$ and $|\Phi\rangle_{s_2} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_{s_2} + |\downarrow\rangle_{s_2})$, respectively. The photon is initially generated in state $|\Phi\rangle_a = \frac{1}{\sqrt{2}}(|R\rangle_a + |L\rangle_a)$. So the state of combined system is

$$\frac{1}{2}(a|\uparrow\rangle_{s_1} + \beta|\downarrow\rangle_{s_1}) \otimes (|\uparrow\rangle_{s_2} + |\downarrow\rangle_{s_2}) \otimes (|R\rangle_a + |L\rangle_a). \quad (16)$$

After the red block, the combined state will be

$$\frac{1}{2}(a|\uparrow\rangle_{s_1} + \beta|\downarrow\rangle_{s_1})_a|R\rangle_a + i(a|\downarrow\rangle_{s_1} + \beta|\uparrow\rangle_{s_1})_a|L\rangle_a(|\uparrow\rangle_{s_2} + |\downarrow\rangle_{s_2}). \quad (17)$$

When the photon passes through the green block, the combined state is converted to

$$\frac{1}{2}[i(a|\uparrow\rangle_{s_1} + \beta|\downarrow\rangle_{s_1})_a|R\rangle_a + (a|\downarrow\rangle_{s_1} + \beta|\uparrow\rangle_{s_1})_a|L\rangle_a(|\uparrow\rangle_{s_2} - |\downarrow\rangle_{s_2}) + i(a|\downarrow\rangle_{s_1} + \beta|\uparrow\rangle_{s_1})_a|L\rangle_a(a|\uparrow\rangle_{s_2} - |\downarrow\rangle_{s_2})]. \quad (18)$$

The excess electron spin in QD2 can be in the initial states of the excess electron spin in QD1 by a single-qubit operation according to the measurement results of the states of the electron spin in QD1 and the photon. If $|\uparrow\rangle_{s_1} R\rangle_a$ is obtained, the electron spin state in QD2 is $a|\uparrow\rangle_{s_2} + \beta|\downarrow\rangle_{s_2}$ and no operation is required. If $|\downarrow\rangle_{s_1} R\rangle_a$ is obtained, we can implement a $\hat{\sigma}_X$ operation on QD2 to achieve the information transfer. For $|\uparrow\rangle_{s_1} L\rangle_a$ and $|\downarrow\rangle_{s_1} L\rangle_a$, the operations needed are $\hat{\sigma}_X\hat{\sigma}_Z$ and $\hat{\sigma}_Z$, respectively. This information transfer is also deterministic.
As shown in Fig. 5, photons \( a_1 \) and \( a_2 \) pass through the QD in sequence. After photon \( a_1 \) passes through the QD, the combined state is

\[
\frac{1}{\sqrt{2}} \left( (\Phi)_a = \alpha (|R|)_a + \beta (|L|)_a \right) \otimes \left( (\uparrow) + (\downarrow) \right)_s \tag{20}
\]

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\]
transmission of quantum information, and a QD spin is a stationary qubit used for storage and manipulation. So the information transfer between a photon and a QD spin achieves an interface between a propagating qubit and a stationary qubit for quantum information storage and readout, which plays a central role in quantum communication networks. Given the CNOT gates between these particles, these proposals could also be used as quantum computational primitives.

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References