Controlled phase gates based on two nonidentical quantum dots trapped in separate cavities*

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We propose a scheme for realizing two-qubit controlled phase gates on two nonidentical quantum dots trapped in separate cavities. In our scheme, each dot simultaneously interacts with one highly detuned cavity mode and two strong driven classical fields. During the gate operation, the quantum dots undergo no transition, while the system can acquire different phases conditional on different states of the quantum dots. With the application of the single-qubit operations, two-qubit controlled phase gates can be realized.

Keywords: entanglement, quantum information, quantum dot

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1. Introduction

Recently, much attention in experiment and in theory has been paid to quantum information processing (QIP) devices.[1] Since cavity quantum electrodynamics (CQED) systems can manipulate qubits efficiently,[2,3] they are appropriate candidates for quantum information processing (QIP) and quantum computation. Photonic crystal (PC) cavities have smaller mode volumes and higher quality factors,[4,5] so the light can be confined in the cavity effectively. For this reason, PC cavities can become another kind of ideal candidate for quantum information processing.[6] Although qubits in the CQED can be atoms,[3,7,8] ions[9−12] or quantum dots (QDs),[13] demonstrations of such a basic building of the quantum on-chip network have relied on the atomic systems.[14−16] As is known, the solid-state implementation of those pioneering approaches has opened a door to make the network into a practical and useful QIP system.[1] Among the proposed schemes for solid physical systems, the system of the self-assembled QD embedded in a PC nanocavity has become a very promising system, since a strong QD–cavity interaction can be realized in that kind of system.[17−19]

However, there are two main challenges for the systems of self-assembled QDs. One is the large variation in the emission frequency of the self-assembled QDs,[20] the other is that the interaction between the QDs is difficult to control.[21] So far, there are several methods that have been used to bring the nonidentical QDs into resonance, such as using Stark shift tuning[22,23] and voltage tuning.[24] There are also several solutions that can be used to control the interaction between the QDs, for example, the coherent manipulation of coupled QDs[21] and the control of coupled QDs by using the Kondo effect.[25] Although, in experiment, the tuning of individual QD frequency is achieved mainly by using two closely spaced QDs in a PC cavity,[25] there are a few schemes to acquire the controlled interaction and the controlled gate with two nonidentical QDs trapped in distant cavities connected by a single-mode optical fiber.

In this paper, we propose a scheme for realizing two-qubit controlled phase gates with two nonidentical quantum dots embedded in separate cavities. During the gate operation, none of the QDs, the cavity mode or the fiber mode is excited. The system can acquire different phases conditional on the state of the QDs. With the application of the single-qubit operations, controlled phase gates can be realized. Our scheme has the following advantages. Firstly, the model can be controlled by using external light fields, so the system is controllable. Secondly, as it can be realized

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with nonidentical QDs, it is more practical. Thirdly, there are no QDs, cavity modes or fiber modes in the excited state during the gate operation, thus the scheme is insensitive to spontaneous emission of the QDs, cavity decay and fiber loss.

The rest of this paper is organized as follows. In Section 2, we give the model of the system and derive the effective Hamiltonian; in Section 3, the quantum phase gate is presented; in Section 4, we give a brief discussion and conclusion.

2. Model and Hamiltonian

As shown in Fig. 1, we consider two nonidentical QDs trapped in two distant PC cavities, which are coupled with a fiber. Each dot has two ground states ($|g\rangle = |\uparrow\rangle$, $|f\rangle = |\downarrow\rangle$) and two excited states ($|e\rangle = |\uparrow\downarrow\Uparrow\rangle$, $|d\rangle = |\downarrow\uparrow\Downarrow\rangle$), where ($|\uparrow\rangle$, $|\downarrow\rangle$) and ($|\Uparrow\rangle$, $|\Downarrow\rangle$) denote the spin up and the spin down for electron and hole, respectively. At zero magnetic field, the electron spin ground states are twofold degenerate. Only the dipole allowed transitions $|g\rangle \leftrightarrow |e\rangle$ and $|f\rangle \leftrightarrow |d\rangle$ are coupled correspondingly with σ^+ and σ^- polarization light.[24,26] Choosing the field in the σ^+ polarization, transition $|g\rangle \leftrightarrow |e\rangle$ is coupled to the cavity mode and the classical laser fields with detunings $\Delta_j^{\rm C}$, Δ_j, and δ_j' ($\Delta_j^{\rm C} = \Delta_j + \delta$). During the interaction, state $|f\rangle$ is not affected. Here, the information in our proposed scheme can be stored in states $|g\rangle$ and $|f\rangle$. In the rotating-wave approximation, the Hamiltonian describing the interaction between the QDs and the fields is

$$\hat{H}_{\rm QD-Fields} = \sum_{j={\rm A,B}} (g_j a_j \, {\rm e}^{{\rm i}\,\Delta_j^{\rm C} t} + \Omega_j e^{i\Delta_j t} + \Omega_j' \, {\rm e}^{-{\rm i}\,\delta_j' t})\sigma_j^+ + {\rm H.c.}, \quad (1)$$

where a_j is the annihilation operator for the j-th cavity mode, $a_j^\dagger$ is the creation operator, $\sigma_j^+ = |e\rangle_j\langle g|$, with g_j being the coupling constant between single mode cavity j and QD j, Ω_j and Ω_j' are the Rabi frequencies for dot j.

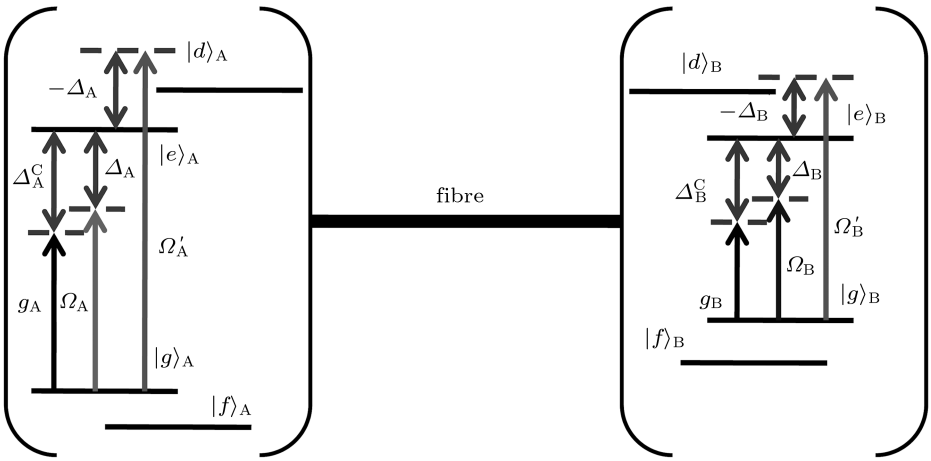


Fig. 1. Sketch of our model, which includes the configuration of the QD level structure and the relevant transitions. Two distant QDs are trapped in separate cavities connected by an optical fiber, the two cavity modes are coupled to the fiber mode with coupling strength ν, each of the QDs is driven with two classical fields and one quantum field. Note that the electron spin ground states are twofold degenerate at zero magnetic field.

The coupling between the cavity modes and the fiber is given by the interaction Hamiltonian

$$\hat{H}_{\rm cavity-fiber} = \nu b(a_{\rm A}^+ + {\rm e}^{{\rm i}\,\varphi} a_{\rm B}^+) + \nu b^+(a_{\rm A} + {\rm e}^{-{\rm i}\,\varphi} a_{\rm B}), \quad (2)$$

where b is the annihilation operator for the fiber mode, ν is the cavity–fiber coupling strength, and φ is the phase due to the propagation of the field through the fiber. It is worthwhile to point out that these two cavities have the same frequencies.

With the choice of

$$\begin{cases} a_1 = \dfrac{1}{2}(c_1 + c_2 + \sqrt{2}c_0), \\ a_2 = \dfrac{1}{2}(c_1 + c_2 - \sqrt{2}c_0)\,{\rm e}^{{\rm i}\,\varphi}, \\ b = \dfrac{c_1 - c_2}{\sqrt{2}}, \end{cases} \quad (3)$$

where c_1, c_2, and c_0 are the annihilation operators for three new bosonic modes, there are linear relations between the new bosonic modes and the modes of the cavity and the fiber. The precondition for Eq. (3) is that there is a coupling between the cavity and the fiber ($\nu > 0$). Then we can rewrite the whole Hamiltonian for our model including Eqs. (1) and (2) as

$$\begin{aligned}
\hat{H} &= \hat{H}_0 + \hat{H}_{\rm i}, && (4)\\
\hat{H}_0 &= \sqrt{2}\nu(c_1^+ c_1 - c_2^+ c_2), && (5)\\
\hat{H}_{\rm i} &= \Big[\frac{1}{2}g_{\rm A}(c_1 + c_2 + \sqrt{2}c_0)\,{\rm e}^{{\rm i}(\Delta_1+\delta)t} \\
&\quad + \Omega_{\rm A}\,{\rm e}^{{\rm i}\,\Delta_1 t} + \Omega'_{\rm B}\,{\rm e}^{-{\rm i}\,\Delta_1 t}\Big]\sigma_1^+ \\
&\quad + \Big[\frac{1}{2}g_{\rm B}(c_1 + c_2 - \sqrt{2}c_0)\,{\rm e}^{{\rm i}\,\varphi}\,{\rm e}^{{\rm i}(\Delta_2+\delta)t} \\
&\quad + \Omega_{\rm B}\,{\rm e}^{{\rm i}\,\Delta_2 t} + \Omega'_{\rm B}\,{\rm e}^{-{\rm i}\,\Delta_2 t}\Big]\sigma_2^+ + {\rm H.c.} && (6)
\end{aligned}$$

We now perform unitary transformation $\exp(-{\rm i}\,H_0 t)$. The Hamiltonian can be rewritten as

$$\begin{aligned}
\hat{H}_{\rm I} &= \Big\{\frac{1}{2}g_{\rm A}[c_1\,{\rm e}^{{\rm i}(\Delta_1+\delta-\sqrt{2}\nu)t} + c_2\,{\rm e}^{{\rm i}(\Delta_1+\delta+\sqrt{2}\nu)t} \\
&\quad + \sqrt{2}c_0\,{\rm e}^{{\rm i}(\Delta_1+\delta)t}] + \Omega_{\rm A}\,{\rm e}^{{\rm i}\,\Delta_1 t} + \Omega'_{\rm A}\,{\rm e}^{-{\rm i}\,\Delta_1 t}\Big\}\sigma_1^+ \\
&\quad + \Big\{\frac{1}{2}g_{\rm B}[c_1\,{\rm e}^{{\rm i}(\Delta_2+\delta-\sqrt{2}\nu)t} + c_2\,{\rm e}^{{\rm i}(\Delta_2+\delta+\sqrt{2}\nu)t} \\
&\quad - \sqrt{2}c_0\,{\rm e}^{{\rm i}(\Delta_2+\delta)t}]\,{\rm e}^{{\rm i}\,\varphi} + \Omega_{\rm B}\,{\rm e}^{{\rm i}\,\Delta_2 t} \\
&\quad + \Omega'_{\rm B}\,{\rm e}^{-{\rm i}\,\Delta_2 t}\Big\}\sigma_2^+ + {\rm H.c.} \qquad (7)
\end{aligned}$$

We can cancel free Hamiltonian H_0 in this way.

The method proposed in Refs. [27]–[29] is used to derive the effective Hamiltonian of the system under the following conditions: (i) $\Delta_j = -\delta'_j$ and $|\Omega_j| = |\Omega'_j|$ for the transition between states $|g\rangle_j$ and $|e\rangle_j$; (ii) the large detuning condition ($|\Delta_j|, |\delta'_j| \gg |g_j|, |\Omega_j|, |\Omega'_j|$); (iii) $|\Omega_j| \gg |g_j|$. The first condition can completely cancel the Stark shift and the relevant terms caused by the external light fields. As the quantum information is initially encoded in the QD ground states, under the large detuning condition, the probability for QD absorbing photons from the light field or being excited is negligible. So the QD excited state will not be populated and can be adiabatically eliminated. Moreover, the second and the third conditions ensure that the terms proportional to $|g_j|^2/\Delta_j$, $|g_j|^2/\delta'_j$, and $|g_{\rm A}g_{\rm B}|/2(1/\Delta_{\rm A} + 1/\Delta_{\rm B})$ can be neglected. Thus, we can obtain the effective Hamiltonian as

$$\begin{aligned}
\hat{H}_{\rm eff} = -\sum_{\substack{m=0,1,2\\ j=A,B}} &(\lambda_{j,m} c_m\,{\rm e}^{{\rm i}\,\Delta_m t} \\
&+ \lambda^*_{j,m} c_m^+\,{\rm e}^{-{\rm i}\,\Delta_m t})|g\rangle_j\langle g|, \qquad (8)
\end{aligned}$$

where

$$\begin{aligned}
\lambda_{{\rm A},0} &= \frac{\sqrt{2}}{4}g_1\Omega^*_{\rm A}\Big(\frac{1}{\Delta_1+\delta} + \frac{1}{\Delta_1}\Big),\\
\lambda_{{\rm A},1} &= \frac{g_1\Omega^*_{\rm A}}{4}\Big(\frac{1}{\Delta_1+\delta-\sqrt{2}\nu} + \frac{1}{\Delta_1}\Big),\\
\lambda_{{\rm A},2} &= \frac{g_1\Omega^*_{\rm A}}{4}\Big(\frac{1}{\Delta_1+\delta+\sqrt{2}\nu} + \frac{1}{\Delta_1}\Big),\\
\lambda_{{\rm B},0} &= -\frac{\sqrt{2}}{4}g_2\Omega^*_{\rm B}\Big(\frac{1}{\Delta_2+\delta} + \frac{1}{\Delta_2}\Big)c_0\,{\rm e}^{{\rm i}\,\varphi},\\
\lambda_{{\rm B},1} &= \frac{1}{4}g_2\Omega^*_{\rm B}\Big(\frac{1}{\Delta_2+\delta-\sqrt{2}\nu} + \frac{1}{\Delta_2}\Big)\,{\rm e}^{{\rm i}\,\varphi},\\
\lambda_{{\rm B},2} &= \frac{1}{4}g_2\Omega^*_{\rm B}\Big(\frac{1}{\Delta_2+\delta+\sqrt{2}\nu} + \frac{1}{\Delta_2}\Big)\,{\rm e}^{{\rm i}\,\varphi},\\
\Delta_0 &= \delta, \quad \Delta_1 = (\delta - \sqrt{2}\nu),\\
\Delta_2 &= (\delta + \sqrt{2}\nu). \qquad (9)
\end{aligned}$$

In the case $\lambda_{j,m} \ll \Delta_m$, bosonic modes c_0, c_1, and c_2 cannot exchange energy with each other. Thus, the above Hamiltonian transforms into[30,31]

$$\begin{aligned}
\hat{H}_{\rm e} = &\sum_{\substack{m=0,1,2\\ j=A,B}} \frac{|\lambda_{j,m}|^2}{\Delta_m}|g\rangle_j\langle g| \\
&+ 2\frac{|\lambda_{{\rm A},m}\lambda_{{\rm B},m}|}{\Delta_m}\cos\theta_m|g\rangle_{\rm A}\langle g||g\rangle_{\rm B}\langle g|, \qquad (10)
\end{aligned}$$

where θ_m is the argument of $\lambda_{{\rm A},m}\lambda^*_{{\rm B},m}$. The above Hamiltonian describes the Stark shift that depends on the state of the QD. And the Stark shift is caused by the nonresonant coupling between the classical field and the vacuum bosonic mode. Since the Stark shift of the QD is nonlinear with respect to the number of the QDs in the ground state $|g\rangle$, the Hamiltonian in Eq. (10) can be used to construct the controlled phase gate with two nonidentical QDs.

3. Phase gate

Although the Hamiltonian in Eq. (10) is independent of the cavity and the fiber modes, the interaction of the QDs is caused by virtual excited photons in the modes of the cavity and the fiber. For this reason, when the initial state of the new bosonic mode is in the vacuum state, which also corresponds to the vacuum states for the modes of the cavity and the fiber, there will be no cavity or fiber mode being in the excited state during the interaction between the QDs and the fields. In this situation, the evolution of the

logical state under the Hamiltonian given in Eq. (10) is given by

$$\begin{cases} |ff\rangle \rightarrow |ff\rangle, \\ |fg\rangle \rightarrow \mathrm{e}^{\mathrm{i}\,\phi_{fg}t}|fg\rangle, \\ |gf\rangle \rightarrow \mathrm{e}^{\mathrm{i}\,\phi_{gf}t}|gf\rangle, \\ |gg\rangle \rightarrow \mathrm{e}^{\mathrm{i}(\phi_{gf}+\phi_{fg}+\phi_{gg})t}|gg\rangle, \end{cases} \tag{11}$$

with

$$\begin{cases} \phi_{fg} = -\sum\limits_{m=0,1,2} \dfrac{|\lambda_{\mathrm{A},m}|^2}{\Delta_{\mathrm{A},m}}, \\ \phi_{gf} = -\sum\limits_{m=0,1,2} \dfrac{|\lambda_{\mathrm{B},m}|^2}{\Delta_{\mathrm{B},m}}, \\ \phi_{gg} = -2\sum\limits_{m=0,1,2} \dfrac{|\lambda_{\mathrm{A},m}\lambda_{\mathrm{B},m}|}{\Delta_m}\cos\theta_m. \end{cases} \tag{12}$$

With the application of the one-qubit operation

$$\begin{cases} |g_{\mathrm{A}}\rangle \rightarrow \mathrm{e}^{-\mathrm{i}\,\phi_{fg}t}|g_{\mathrm{A}}\rangle, \\ |g_{\mathrm{B}}\rangle \rightarrow \mathrm{e}^{-\mathrm{i}\,\phi_{gf}t}|g_{\mathrm{B}}\rangle, \end{cases} \tag{13}$$

equation (12) reduces to

$$\begin{cases} |ff\rangle \rightarrow |ff\rangle, \\ |fg\rangle \rightarrow |fg\rangle, \\ |gf\rangle \rightarrow |gf\rangle, \\ |gg\rangle \rightarrow \mathrm{e}^{-\mathrm{i}\,\phi_{gg}t}|gg\rangle. \end{cases} \tag{14}$$

It is clear that the transformation corresponds to the quantum phase gate operation, in which if and only if both the controlling and the controlled bits are both in state $|g\rangle$, there will be an additional phase $\phi_{gg}t$ in the system. With the choice of $\phi_{gg}t = \pi$, equation (14) is just a two-qubit controlled phase π gate, which is also named the controlled-Z gate.

4. Discussion and conclusion

In the following, we discuss the realizability of the experiment first. According to Refs. [26] and [32]–[34], in a system of QDs placed in PC cavities, the coupling constant is about 0.1 meV, the lifetime of exciton is $T_\gamma = 5$ ns, and the decay time of the cavity is $T_\tau = 1.3$ ns. With the choices of $g_{\mathrm{A}} = 0.1$ meV, $g_{\mathrm{B}} = 0.08$ meV, $\Omega_{\mathrm{A}} = 10$ meV, $\Omega_{\mathrm{B}} = 13.75$ meV, $\Delta_{\mathrm{A}} = 200$ meV, $\Delta_{\mathrm{B}} = 200$ meV, $\delta = 2g_{\mathrm{A}}$, and $\sqrt{2}\nu = 2$ meV, we can obtain $\max\{\lambda_{j,m}\} \sim 0.004$ meV, which satisfies the conditions mentioned above. The calculations show that (i) the occupation probability of the excited state is $P_{\mathrm{e}} \sim 0.005$ ($\simeq \max[\Omega_j^2/\Delta_j^2]$), thus, the effective energy relaxation time is $t_r \sim 1000$ ns ($\simeq T_\gamma/P_{\mathrm{e}}$); (ii) the max-occupation probability of the photon is $P_{\mathrm{c}} \sim 0.002$ ($\simeq \max[\lambda_{j,m}^2]/\delta^2$), thus, the effective decay time for the cavity is $t_{\mathrm{c}} \sim 2500$ ns ($\simeq T_\tau/P_{\mathrm{c}}$); (iii) the required effective interaction time for the two-qubit controlled-Z gate is $t \sim 63$ ns ($\simeq \pi/(2\phi_{gg})$). Therefore, it is possible to perform several two-qubit controlled-Z gates within the decoherence time of $\min[t_r, t_{\mathrm{c}}] = 1000$ ns. Here, we should point out that, according to Eq. (3), since the new bosinic modes are linear with respect to the modes of the cavity and the fiber, our scheme can be realized in the regime of $\nu > 0$.

In conclusion, we show that a system of two nonresonant QDs trapped in separate cavities connected by an optical fiber can be used to construct two-qubit phase gates by using the tuned lasers. During the gate operation, none of the QDs, the cavity modes or the fiber mode is excited. The distinct advantages of the proposed scheme are as follows. Firstly, the evolution of the system is dependent on the laser fields. Secondly, during the gate operation, none of the QDs, the cavity modes or the fiber mode is in the excited state. Thirdly, the QDs are nonresonant, so the scheme is feasible in experiment.

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