Implementation of a nonlocal N-qubit conditional phase gate using the nitrogen–vacancy center and microtoroidal resonator coupled systems*

Cao Cong(曹 聪)[a], Liu Gang(刘 刚)[c], Zhang Ru(张 茹)[a)b)], and Wang Chuan(王 川)[a)b)†]

[a)] *School of Science, Beijing University of Posts and Telecommunications, Beijing* 100876, *China*
[b)] *State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing* 100876, *China*
[c)] *School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing* 100876, *China*

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Implementation of a nonlocal multi-qubit conditional phase gate is an essential requirement in some quantum information processing (QIP) tasks. Recently, a novel solid-state cavity quantum electrodynamics (QED) system, in which the nitrogen–vacancy (NV) center in diamond is coupled to a microtoroidal resonator (MTR), has been proposed as a potential system for hybrid quantum information and computing. By virtue of such systems, we present a scheme to realize a nonlocal N-qubit conditional phase gate directly. Our scheme employs a cavity input–output process and single-photon interference, without the use of any auxiliary entanglement pair or classical communication. Considering the currently available technologies, our scheme might be quite useful among different nodes in quantum networks for large-scaled QIP.

Keywords: N-qubit conditional phase gate, nitrogen–vacancy center, microtoroidal resonator

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1. Introduction

Quantum logic gates play a significant role in quantum information processing (QIP).[1] It is well known that any unitary operation can be decomposed into two kinds of elementary gates.[2] Two-qubit conditional gates together with some single-qubit rotations are sufficient for universal quantum computing. The implementation of local and nonlocal two-qubit gates has been widely studied in different kinds of quantum systems.[3–5] However, the decomposition of N-qubit gates becomes more and more complicated with the increment of qubit number N, especially for nonlocal gates among different nodes in quantum networks. For example, for nonlocal N-party controlled-unitary gates, it requires $2(N-1)$ bits of classical communication and $N-1$ additional shared ebits, if auxiliary entanglement pairs, local operations, and classical communication are permitted.[6] Thus, it is still an open question to seek a more simple and universal scheme to realize a nonlocal multi-qubit gate directly. The implementation of an N-qubit conditional phase gate is of vital importance as it is the most basic multi-qubit gate and is frequently needed in some QIP tasks, such as quantum Gover searches,[7] quantum error corrections,[8] quantum entanglement preparation,[9] and so on. Nonlocal N-qubit conditional phase gates can further be used for entanglement distribution among different nodes in quantum networks, which enables the experimental realization of distributed QIP.

In previous works, cavity quantum electrodynamics (QED) systems with atoms confined in a quantized optical microcavity become one of the most promising platforms for investigating QIP because of the strong coupling of qubits and the short interaction time.[10–16] By using cavity-assisted photon scattering,[17] several schemes concerning the direct realization of multi-qubit conditional phase gates have been proposed.[18–20] A similar idea has also been generalized to encode qubits in decoherence-free subspace (DFS).[21] Recently, a novel solid-state cavity QED system has been introduced, in which the nitrogen–vacancy (NV) centers in diamond are coupled to a microresonator with a quantized whispering-gallery mode (WGM). The NV center consists of the nearest-neighbor pair of a nitrogen atom substituted for a carbon atom and a lattice vacancy in diamond. The electron spin relaxation time and the dephasing time of NV centers are demonstrated to be ∼ms at room temperature and ∼s at low temperature.[22–24] Meanwhile, the electron spin states can be efficiently controlled by an electromagnetic field or optical pulse.[25] By coupling to the photonic crystal cavity, the resonant zero phonon line (ZPL) relevant to the emitted photon from a single NV center can be significantly enhanced.[26] Moreover, the quantum nondemolition (QND) measurement on the electron spin states of NV centers can be performed with high fidelity and low error rate.[27,28] Based on these unique properties, the NV centers in diamond have attracted much interest, and much theoretical

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†Corresponding author. E-mail: wangchuan82@gmail.com

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and experimental effort has been devoted to QIP using the NV centers and microresonator coupled systems.

In 2008, Dayan *et al.*[29] experimentally demonstrated the single-photon input–output process from a microtoroidal resonator (MTR) coupling to an atom. Although the MTR is intrinsically required to be of a high Q factor, the Q factor can be surely degraded when the MTR couples to an optical fiber, which enables the efficient input–output process of flying photons. The experiment also indicates that the single atom within the resonator can dynamically control the cavity output. Thus, the MTR-like devices can be used for entanglement generation[30] and realizing quantum gates[31] between distant atoms. In 2011, Chen *et al.*[32] proposed a potentially practical scheme to deterministically entangle separate NV centers fixed on the exterior surface of MTRs in a scalable fashion. They argued that the NV center and MTR coupled system can serve as an efficient node and connecting the nodes with optical fiber may pioneer a new route for constructing a quantum network on a large scale. In addition, deterministic entanglement generation and quantum state transfer,[33,34] quantum entanglement purification,[35] and concentration[36] have also been presented using such coupled systems.

In this paper, we focus our attention on how to realize a nonlocal N-qubit conditional phase gate using the NV center and MTR coupled systems, assisted by the cavity input–output process and single-photon interference.[37] Compared with previous works, our new proposed scheme does not require any auxiliary entanglement pair or classical communication. Meanwhile, our gate can work nonlocally among spatially separated nodes in a quantum network, which is more appropriate for large-scaled QIP. Due to the direct implementation rather than resorting to two-qubit nonlocal gates, the physical realization can be greatly simplified.

2. Model and method

The configuration of the basic model of our scheme is schematically shown in Fig. 1(a), in which a negatively charged NV center is fixed close to the exterior surface of an MTR with coupled optical fiber.[32] The relevant electron level structure of the NV center is shown in Fig. 1(b). In realistic applications, the information can be encoded in the electron spin ground states as $\left|{}^3A, m_s=-1\right\rangle = |0\rangle$ and $\left|{}^3A, m_s=+1\right\rangle = |1\rangle$, which facilitates the quantum information storage and further applications. The excited state sub-level $\left|{}^3E, A_2\right\rangle = |e\rangle$ can be adopted as the ancillary state.[32,38] Here the level transition between $|0\rangle$ ($|1\rangle$) and $|e\rangle$ is resonantly coupled to the $|L\rangle$ ($|R\rangle$) circularly polarized photon. When we introduce a single-photon pulse with frequency ω_p to input the MTR (see Fig. 1(a)), under the assumption of weak excitation limit when the NV center is initially prepared in the ground state, we can

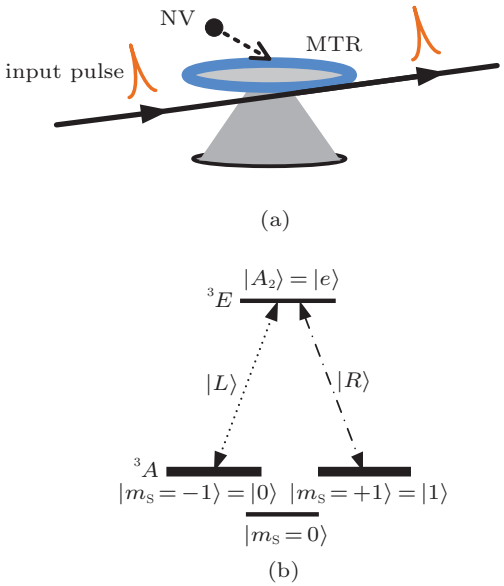


Fig. 1. (color online) Diagrammatic illustration of the basic model of our scheme. (a) An NV center is fixed on the exterior surface of an MTR and a single-photon pulse is introduced to interact with the NV center via the cavity input–output process. (b) The relevant electron energy level structure of the NV center and the relevant transition coupling with the input polarized photon. The sophisticated level splitting of the excited states is not shown.

adiabatically solve the quantum Langevin equations and get the reflection coefficient of the input pulse as[30]

$$r_{L,R}(\omega_p) = \frac{\left[\mathrm{i}(\omega_c-\omega_p)-\frac{\kappa}{2}\right]\left[\mathrm{i}(\omega_0-\omega_p)+\frac{\gamma}{2}\right]+g^2}{\left[\mathrm{i}(\omega_c-\omega_p)+\frac{\kappa}{2}\right]\left[\mathrm{i}(\omega_0-\omega_p)+\frac{\gamma}{2}\right]+g^2}, \quad (1)$$

here ω_c is the MTR mode frequency, ω_0 is the transition frequency between the energy level $|0\rangle$ ($|1\rangle$) and $|e\rangle$. κ and γ are the cavity decay rate and NV center dipole decay rate, respectively. g is the coupling strength of the hybrid interaction. The absolute value of $r_{L,R}(\omega_p)$ is verified to be close to unity, which implies the photon experiences a very weak absorption, and the output pulse only obtains a pure state-dependent phase shift as $r_{L,R}(\omega_p) = \mathrm{e}^{\mathrm{i}\phi}$. On the other hand, considering the coupling strength $g=0$ when the input photon pulse encounters an NV center in a mismatched level, the reflection coefficient could get back to the textbook result for an empty cavity[39]

$$r^0_{L,R}(\omega_p) = \frac{\mathrm{i}(\omega_c-\omega_p)-\kappa/2}{\mathrm{i}(\omega_c-\omega_p)+\kappa/2}, \quad (2)$$

the relative phase can be rewritten as $r^0_{L,R}(\omega_p) = \mathrm{e}^{\mathrm{i}\phi_0}$. If the parameters of the hybrid interaction satisfy the resonant condition $\omega_0=\omega_c=\omega_p$, and $g \geq 5\sqrt{\kappa\gamma}$,[32] we have $\phi=0$ and $\phi_0=\pi$, and the evolution of the composite system can be described as

$$\begin{aligned} &|L\rangle|0\rangle \to |L\rangle|0\rangle, \quad |R\rangle|0\rangle \to -|R\rangle|0\rangle, \\ &|L\rangle|1\rangle \to -|L\rangle|1\rangle, \quad |R\rangle|1\rangle \to |R\rangle|1\rangle. \end{aligned} \quad (3)$$

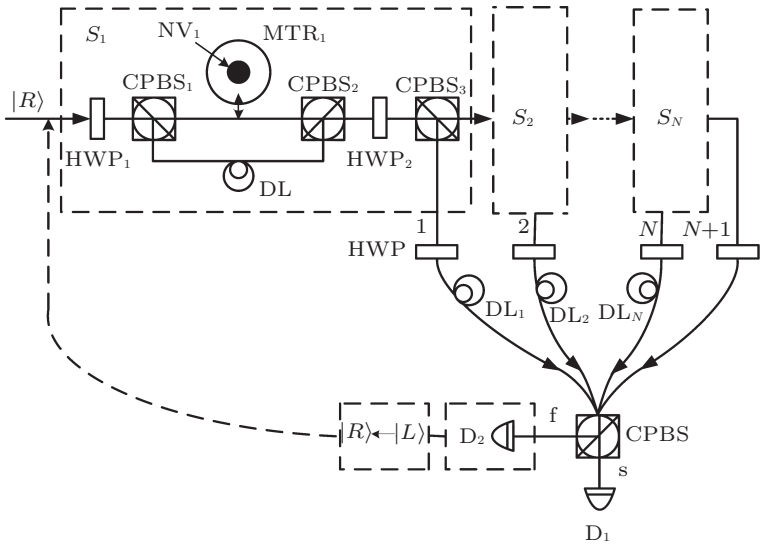


Fig. 2. Schematic setup for implementing the nonlocal N-qubit conditional phase gate, where HWPs are half-wave plates, CPBSs are circular polarization beam splitters, DLs are delay lines. The optical length of all the possible optical paths $1 \to N+1$ should be well designed to have good interference at CPBS. The detector D_2 can be replaced by a polarization-flip operation and an optical path directed to the photon input port.

The scheme for realizing a nonlocal N-qubit conditional phase gate is schematically shown in Fig. 2, in which the elementary unit S_i ($i = 1, 2, ..., N$) surrounded by the dashed line has the identical structure as S_1 for the i-th MTR with NV center qubit inside, both satisfying $\omega_0 = \omega_c = \omega_p$ and $g \geq 5\sqrt{\kappa\gamma}$ in the hybrid interaction with the input single-photon pulse in principle. The half-wave plate (HWP) is used to perform a Hadamard operation on the photon states. The circular polarization beam splitter (CPBS) is exploited to transmit the $|R\rangle$ circularly polarized photon and reflect the $|L\rangle$ photon. For simplicity, we only take $N = 3$ as an example. Suppose the input single-photon pulse is initially in the state $|R\rangle$ and the three nonlocal NV centers are in an arbitrary state:

$$\begin{aligned}\sum_{i=1}^{8}\alpha_i|jkl\rangle \;=\; & \alpha_1|000\rangle+\alpha_2|001\rangle+\alpha_3|010\rangle+\alpha_4|011\rangle\\ & +\alpha_5|100\rangle+\alpha_6|101\rangle\\ & +\alpha_7|110\rangle+\alpha_8|111\rangle, \end{aligned} \tag{4}$$

here the probability amplitude α_i satisfies the relations $\sum_{i=1}^{8}|\alpha_i|^2 = 1$, and $|jkl\rangle$ denotes the state of NV center 1 to NV center 3 with j, k, l being equal to 0 or 1, respectively. So after the photon passes through S_1, the state of the whole system will become

$$\begin{aligned}|\chi\rangle \;=\; & |R\rangle\otimes(\alpha_5|100\rangle+\alpha_6|101\rangle+\alpha_7|110\rangle+\alpha_8|111\rangle)\\ & -|L\rangle\otimes(\alpha_1|000\rangle+\alpha_2|001\rangle\\ & +\alpha_3|010\rangle+\alpha_4|011\rangle). \end{aligned} \tag{5}$$

That is, the structure S_1 is designed to decide whether to transmit or reflect the photon depending on the state of NV center 1. If NV center 1 is initially in the state $|1\rangle$, the input photon $|R\rangle$ will pass through $CPBS_3$ and be transmitted to S_2 without any change, otherwise the input photon will be transformed into the state $|L\rangle$ and be reflected by $CPBS_3$. We then let the transmitted $|R\rangle$ photon transmitted or reflected by S_2 or S_3 depending on the state of the NV center 2 or NV center 3, respectively. During the whole process, the input photon may take one of four possible optical paths 1, 2, 3, and 4 from the input port to arrive at CPBS, all experiencing a Hadamard operation before arriving at it. As the optical length of all the optical paths are equal, based on the single-photon interference effect,[37] the state of the whole system will evolve as:

$$\begin{aligned}& \to \alpha_8|R\rangle_4|111\rangle-\alpha_7|L\rangle_3|110\rangle\\ & -|L\rangle_2(\alpha_5|100\rangle+\alpha_6|101\rangle)\\ & -|L\rangle_1(\alpha_1|000\rangle+\alpha_2|001\rangle+\alpha_3|010\rangle+\alpha_4|011\rangle)\\ & \to \frac{1}{\sqrt{2}}|L\rangle_f\otimes(\alpha_1|000\rangle+\alpha_2|001\rangle+\alpha_3|010\rangle\\ & +\alpha_4|011\rangle+\alpha_5|100\rangle+\alpha_6|101\rangle+\alpha_7|110\rangle+\alpha_8|111\rangle)\\ & -\frac{1}{\sqrt{2}}|R\rangle_s\otimes(\alpha_1|000\rangle+\alpha_2|001\rangle+\alpha_3|010\rangle\\ & +\alpha_4|011\rangle+\alpha_5|100\rangle+\alpha_6|101\rangle+\alpha_7|110\rangle-\alpha_8|111\rangle), \end{aligned} \tag{6}$$

here the subscript of the photon state represents that the photon takes the m-th ($m = 1, 2, 3, 4$) optical path. At the final output ports s and f, we can make a measurement on the output photon with detectors D_1 and D_2. If D_1 is triggered (with a 50% success probability), a conditional phase gate $U_{CP}^3 = \exp(i\pi|111\rangle\langle 111|)$ between the three nonlocal NV center qubits has been realized. If D_2 clicks, nothing has happened to the three NV centers.

Based on the basic scheme, a nonlocal N-qubit conditional phase gate $U_{CP}^N = \exp(i\pi|11\cdots1\rangle\langle 11\cdots1|)$ with $N > 3$

can be directly generalized. Furthermore, we can also replace the detector D_2 with a polarization-flip operation and an optical path directed to the input port (see Fig. 2), so the output $|L\rangle$ photon can be tuned into state $|R\rangle$ and be automatically fed back to restart the setup. In this way, all we need to do is to wait for a photon detection at D_1, heralding the accomplishment of the gate operation and that the whole process is in an ideal one-step-implementation method.

3. Discussion

The key point of our scheme is the single-photon input–output process regarding the MTRs with each coupling to an NV center. Behind which, the physics is the giant optical Faraday rotation near the resonance regime. The hybrid interaction between the single-photon pulse and the coupled system is generalized by the basic Jaynes–Cummings (JC) model with respect to a Λ-type atom. Numerical simulation about the reflection coefficient of the input pulse and the phase shift induced on the output pulse after considering the effect of parameters variation has been performed in Refs. [32] and [33] in detail. According to the results, under the resonant condition $\omega_0 = \omega_c = \omega_p$, the reflectance $r_{L,R}(\omega_p) \approx 0.95$ can be achieved with the coupling strength $g \geq 3\sqrt{\kappa\gamma}$ even when $g < 0.1\kappa$, which implies the coupled systems do not essentially need to work in the stringent strong coupling and high-Q conditions. The decay rate γ_{total} approach to $2\pi \times 15$ MHz because of the dipolar transitions.[38] The rate γ within the ZPL range is 3%–4% of γ_{total}.[40] Provided the Q factor of the MTRs $Q = c/\lambda\kappa \sim 10^4$ with c denoting the speed of light and the transition wavelength $\lambda = 637$ nm between the states $|0\rangle$ ($|1\rangle$) and $|e\rangle$,[38] in order to reach $r_{L,R}(\omega_p) \simeq 1$, the coupling strength g should be on the order of hundreds of megahertz, which is not a difficult experimental requirement. In our scheme, the basic unit is the structure S_i. If we simply suppose every linear optics operations are perfectly carried out, we can numerically calculate the fidelity F of the hybrid interaction between the single-photon pulse and the coupled system under the resonant condition in each S_i; the results against g/κ for different γ are shown in Fig. 3. We can further roughly estimate the fidelity of our proposed nonlocal N-qubit conditional phase gate in one trial to be F^N. The results for different qubit number N when $\gamma = 1.5 \times 10^{-5}\kappa$ can be found in Fig. 4. Considering a set of efficient parameters $[g, \kappa, \gamma_{total}, \gamma_{ZPL}] = [0.3, 26, 0.013, 0.0004] \times 2\pi$ GHz,[41] we have $g \approx 3\sqrt{\kappa\gamma}$ and $F > 0.95$ under the resonant condition.

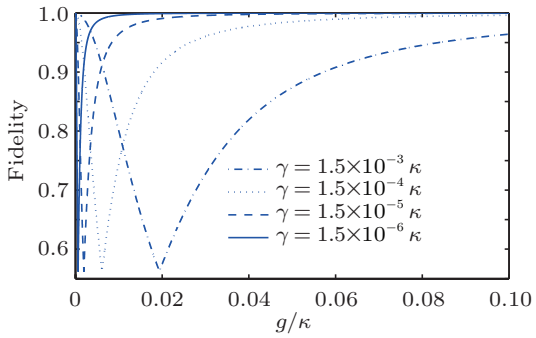


Fig. 3. (color online) Fidelity of the hybrid interaction in each S_i under the resonant condition against g/κ for different γ.

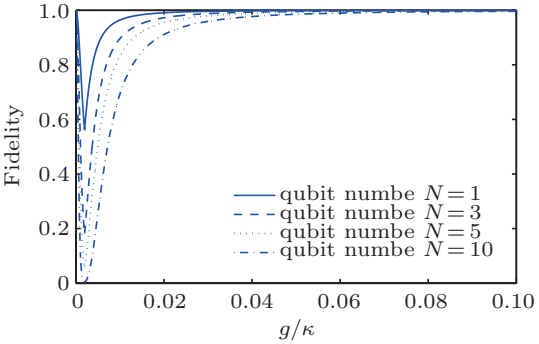


Fig. 4. (color online) Fidelity of the present nonlocal N-qubit conditional phase gate under the resonant condition against g/κ for different qubit number N, here $\gamma = 1.5 \times 10^{-5}\kappa$.

Each of the NV center and MTR coupled system in our scheme can be seen as an efficient node for constructing a quantum network. For this purpose, we may employ NV centers in bulk diamonds,[23,42] which could provide atom-liked optical properties. We can locally adjust the energy levels of different NV centers by an external magnetic field in order to get identical transition frequencies in different nodes. Though the room-temperature coherent manipulation of the electron spin in a single NV center has been proposed to achieve QIP,[43–45] our scheme involving the auxiliary excited state may work well at cryogenic temperatures. Moreover, to make use of the Λ-type scheme, we require the NV centers to be under low strain,[32,38] since high strain would destroy the symmetric properties of the mutually orthogonal circular polarizations. On the other hand, it seems particularly important for the NV centers to be confined in cavities. Based on the recent experimental progress, strong coupling between the NV center and the WGM has been demonstrated using microspheres,[46,47] diamond-GaP microdisks,[41] and SiN photonic crystals,[48] both imply our presented potential scheme may be achievable with current or near-future technologies.

In real experiments, there exist some unavoidable factors leading to photon loss, such as cavity mirror absorption and

scattering, fiber absorption, and detector inefficiency. Fortunately, with photon detectors at the end of the setup, the photon loss events would only decrease the success probability, but not the fidelity of the gate operation. When a highly efficient single-photon source is permitted, that is, 10^4 single-photons/s,[49] our scheme may work in a repeated-until-success fashion,[20] and the gate operation may be expected to be accomplished within a very short period of time. Meanwhile, the weak excitation limit used for obtaining Eq. (1) can be satisfied by a high-quality single-photon source.[49,50] The current fabrication techniques can suppress the photon leakage and make it negligible compared with the main cavity decay into the input–output modes.[51] In addition, as single-photon multipath interference has been utilized, a significant challenge for carrying out our scheme is to maintain phase stability, which requires the optical path lengths to be stable at subwavelength levels.

4. Summary

In summary, we have shown the possibility of realizing a nonlocal N-qubit conditional phase gate using the NV center and MTR coupled systems, assisted by a cavity input–output process and single-photon interference. Without considering the photon loss, our scheme could be implemented in an ideal one-step method with an automatic feedback line added. Even by taking photon loss into consideration, only the success probability rather than the gate fidelity is affected, and our scheme might work in a repeated-until-success fashion with a highly efficient single-photon source. The future technical advances in reducing the photon loss and lowering the experimental imperfection will largely improve the implementation fidelity and the efficiency. Therefore, our scheme might be very useful for constructing a quantum network on a large scale.

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