Quantum information transfer with nitrogen-vacancy centers coupled to a whispering-gallery microresonator

Peng-Bo Li* and Fu-Li Li

MOE Key Laboratory for Nonequilibrium Synthesis and Modulation of Condensed Matter, Department of Applied Physics, Xi'an Jiaotong University, Xi'an 710049, China

We propose an efficient scheme for the realization of quantum information transfer and entanglement with nitrogen-vacancy (NV) centers coupled to a high-Q microspherical resonator. We show that, based on the effective dipole-dipole interaction between the NV centers mediated by the whispering-gallery mode (WGM), quantum information can be transferred between the NV centers through Raman transitions combined with laser fields. This protocol may open up promising possibilities for quantum communications with the solid state cavity QED system.

PACS numbers: 03.67.Hk, 42.50.Pq, 78.67.-n

Cavity quantum electrodynamics (cavity QED) [1] that studies the coherent interaction of matter with quantized fields has been a central paradigm for quantum information and processing [2]. Most recently the solid-state counterpart of cavity QED system has attracted great interests, which circumvents the complexity of trapping single atoms and can potentially enable scalable device fabrications. Among various solid-state cavity QED systems, the composite system in which NV centers in diamond nanocrystals are coupled to a WGM microresonator has emerged as one of the most promising candidates [4–6]. This composite nanocrystal-microresonator system takes the advantage of both sides of NV centers and WGM microresonators, i.e., the exceptional spin properties of nitrogen vacancy centers [7, 8] and the ultrahigh quality factor and small mode volume of WGM microresonators [3, 9]. The application of this solid state cavity QED system in quantum information and processing is of great interests [10, 11].

In this work, we present an experimentally feasible scheme for the implementation of quantum information transfer and entanglement between distant NV centers in diamond nanocrystals coupled to a WGM microresonator. This proposal exploits the effective dipole-dipole interactions between the NV centers mediated by the WGM. The nonlocal interactions combined with lasers are utilized to induce Raman transitions between two centers via the exchange of virtual cavity photons. Quantum information encoded in the spin states of the electronic ground triplet can be transferred from one NV center to the other though coherent control on the evolution of the system. This protocol is very efficient because the excitations of the WGM and the NV centers are suppressed during the transfer process. Experimental realization of this scheme may open up promising possibilities for quantum information and processing with the solid state cavity QED system.

Consider two negatively charged NV centers positioned near the equator of a high-Q microsphere cavity, as shown in Fig.1. NV centers in diamond consist of a

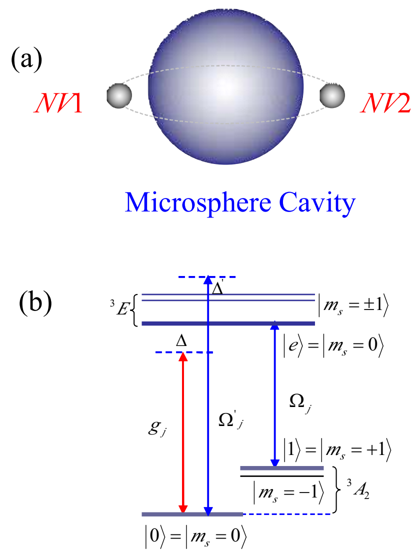

FIG. 1. (Color online) (a) The schematic of two identical NV centers in diamond nanocrystals attached around the equator of a single fused-silica microsphere cavity. (b) Energy level structure with couplings to the cavity mode and driving laser fields. Quantum information is encoded in the spin states $|m_s = 0\rangle$ and $|m_s = +1\rangle$ of the $^3A_2$ triplet, i.e., $|0\rangle = |m_s = 0\rangle$, and $|1\rangle = |m_s = +1\rangle$.

substitutional nitrogen atom and an adjacent vacancy having trapped an additional electron, whose electronic ground state has a spin $S = 1$ and is labeled as $^3A_2$ [7]. We encode the quantum information in the spin states $|m_s = 0\rangle$ and $|m_s = +1\rangle$ of the $^3A_2$ triplet such that $|0\rangle = |m_s = 0\rangle$, and $|1\rangle = |m_s = +1\rangle$. The NV centers can be excited via dipole-allowed transitions to the ^3E triplet states. Correspondingly, the spin state $|m_s = 0\rangle$ of the ^3E triplet is labeled as $|e\rangle = |m_s = 0\rangle$. The modes of spherical resonators can be classified by mode numbers n, l and m, which determine the characteristic radial (n) and angular (l and m) field distribution of the modes.

*lipengbo@mail.xjtu.edu.cn

Usually the so-called fundamental WGM ($n = 1, l = m$) attracts great interests, whose field is concentrated in the vicinity of the equatorial plane of the sphere. The fundamental WGM of frequency ν_0 dispersively couples the transition $|0\rangle \leftrightarrow |e\rangle$ for each NV center with coupling constant g_j and detuning Δ. The same transition is also driven by a largely detuned π-polarized laser field (frequency ω') with Rabi frequency Ω'_j and detuning Δ' ($\Delta' \gg \Omega'_j$), which is used to eliminate the Stark-shift term of the state $|0\rangle$ induced by the vacuum WGM. Under the condition $\Delta \gg g_j$, we can adiabatically eliminate the photons from the above description [12]. By considering the terms up to second order and dropping the fast oscillating terms, we can obtain the effective Hamiltonian describing the dipole-dipole interaction between the two NV centers. If the WGM is initially in the vacuum state, the Hamiltonian then reduces to (let $\hbar = 1$) $V = \Theta|e\rangle_1\langle 0| \otimes |0\rangle_2\langle e| + \mathrm{H.c.}$, with $\Theta = g_1 g_2/\Delta$.

We now consider in each NV center the transition $|1\rangle \leftrightarrow |e\rangle$ is driven resonantly by a σ^--polarized laser with Rabi frequency Ω_j. Then the entire Hamiltonian is

$$\hat{H} = \sum_{j=1,2} (\Omega_j |e\rangle_j\langle 1| + \Theta|e\rangle_1\langle 0| \otimes |0\rangle_2\langle e| + \mathrm{H.c.}) \quad (1)$$

Assume that NV1 and NV2 are initially prepared in their stable ground states $|1\rangle_1$ and $|0\rangle_2$, respectively. If we assume that $\Theta \gg \{\Omega_1, \Omega_2\}$, then under the interaction of Eq. (1), this configuration corresponds to Raman transitions between these two distant NV centers. To gain more insight into these transitions, we can rewrite the Hamiltonian of Eq. (1) in the subspace of the collective energy levels of the two NV centers, i.e., $\{|10\rangle, |+\rangle, |-\rangle, |01\rangle\}$, with $|ij\rangle = |i\rangle_1|j\rangle_2 (i, j = 0, 1, e)$ and $|\pm\rangle = 1/\sqrt{2}(|e0\rangle \pm |0e\rangle)$. In the new basis, the effective Hamiltonian has the form

$$\begin{aligned}\hat{H} = &\Theta|+\rangle\langle +| - \Theta|-\rangle\langle -| + \Lambda_1|+\rangle\langle 01| \\ &+\Lambda_1|-\rangle\langle 01| + \Lambda_2|+\rangle\langle 10| - \Lambda_2|-\rangle\langle 10| + \mathrm{H.c.} \quad (2)\end{aligned}$$

with $\Lambda_i = \Omega_i/\sqrt{2}$. The schematic diagram of this coupling configuration in this new basis is shown in Fig. 2, from which we see that Hamiltonian (2) describes an effective Λ system. The effective dipole-dipole interaction V induced by the WGM causes splitting of the excited states $|e0\rangle$ and $|0e\rangle$ into symmetric and antisymmetric superpositions $|\pm\rangle$. Under the condition $\Theta \gg \{\Omega_1, \Omega_2\}$, the laser fields excite Raman transitions from the initial states $|10\rangle$ to the final state $|01\rangle$ via the intermediate states $|\pm\rangle$. Through adiabatic elimination of the states $|\pm\rangle$, the effective Hamiltonian describing this case is

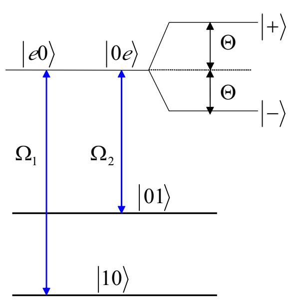

FIG. 2. (Color online) Schematic Raman transitions between two NV centers in dressed state basis

$$\hat{H}_{\mathrm{eff}} = \mathcal{R}|01\rangle\langle 01| + \mathrm{H.c.}, \quad (3)$$

with $\mathcal{R} = \Omega_1\Omega_2/\Theta$. The Hamiltonian (3) describes a two photon Raman transition between two distant NV centers mediated by the WGM.

Let us now show how to utilize Hamiltonian (3) to generate entanglement and perform quantum information transfer between two distant NV centers. For the generation of two-particle entangled state, we initially prepare the NV centers in the state $|10\rangle$. Then the state evolution of the system is given by

$$\psi(t) = \cos(\mathcal{R}t)|10\rangle - i\sin(\mathcal{R}t)|01\rangle, \quad (4)$$

which is an entangled state for the two centers. If we choose $\mathcal{R}\tau = \pi/4$, we could obtain the maximally entangled two-particle state

$$\psi(\tau) = \frac{1}{\sqrt{2}}(|10\rangle - i|01\rangle), \quad (5)$$

which is the well-known EPR state. This entangled state is very robust because it only involves the ground states of the two centers. The interaction (3) between the two NV centers can be used to transfer arbitrary quantum information encoded in ground spin states from one center to the other. Suppose that NV1 is prepared in an arbitrary unknown state $\alpha|0\rangle_1 + \beta|1\rangle_1$ initially, and NV2 in the state $|0\rangle_2$. Then under the interaction of Eq. (3), the state vector at the time t is

$$\Psi(t) = \alpha|00\rangle + \beta[\cos(\mathcal{R}t)|10\rangle - i\sin(\mathcal{R}t)|01\rangle]. \quad (6)$$

At the moment $\mathcal{R}t_f = \pi/2$, we turn off the couplings and can get the state

$$\Psi(t_f) = \alpha|00\rangle - i\beta|01\rangle. \quad (7)$$

If we perform a gate operation $U = (1, i)$, we could retrieve the state $\alpha|0\rangle_2 + \beta|1\rangle_2$ for the second NV center:

$$(\alpha|0\rangle_1 + \beta|1\rangle_1)|0\rangle_2 \to (\alpha|0\rangle_2 + \beta|1\rangle_2)|0\rangle_1. \quad (8)$$

This process completes the quantum state transfer from NV1 to NV2, during which the excited states of the total system are never populated.

It is necessary to verify the model and study the performance of this protocol under realistic circumstances through numerical simulations. In the following, we will simulate the dynamics of the system through the Monte Carlo wave function (MCWF) formalism [13]. Two main decoherence processes ought to be taken into consideration, i.e., cavity photon loss (decay rate κ) and decay of the NV centers. For the NV centers, spontaneous emission from the excited state as well as additional decoherence terms should be included in the simulation. In this proposal, we model these decoherence effects through three characteristic decay rates, γ_{e0}, γ_{e1}, and γ_{10}, with $\gamma_{ij}(i,j=0,1,e)$ the decay rate from the state $|i\rangle$ to $|j\rangle$. Then the system is governed by the following master equation

$$\begin{aligned}\dot{\rho} &= -i[\hat{H},\rho] + \kappa(2\hat{a}\rho\hat{a}^\dagger - \hat{a}\hat{a}^\dagger\rho - \rho\hat{a}^\dagger\hat{a}) \\ &+ \sum_{i=1,2}\gamma_{10}[(2\hat{\sigma}^i_{01}\rho\hat{\sigma}^i_{10} - \hat{\sigma}^i_{10}\hat{\sigma}^i_{01}\rho - \rho\hat{\sigma}^i_{10}\hat{\sigma}^i_{01})] \\ &+ \sum_{i=1,2}[\sum_{j=0,1}\gamma_{ej}(2\hat{\sigma}^i_{je}\rho\hat{\sigma}^i_{ej} - \hat{\sigma}^i_{ej}\hat{\sigma}^i_{je}\rho - \rho\hat{\sigma}^i_{ej}\hat{\sigma}^i_{je})](9)\end{aligned}$$

where $\hat{a}$ is the annihilation operator for the cavity mode, and $\hat{\sigma}^i_{\alpha\beta} = |\alpha\rangle_i\langle\beta|$. To solve the master equation numerically, we have used the MCWF formalism from the quantum trajectory method [13]. In the numerical calculations we assume $g_1 \sim g_2 \sim g$, and $\gamma_{e1} \sim \gamma_{e0} \sim 100\gamma_{10} \sim \gamma$ for simplicity.

Fig.3 displays the time evolution of the system in the presence of the cavity loss and decay of the NV centers. The system starts from the state $\frac{1}{\sqrt{2}}(|0\rangle_1 + |1\rangle_1)|0\rangle_2$. At the moment $t_f = \pi/(2\mathcal{R})$, the first center evolves into its ground state $|0\rangle_1$, while the second center evolves into $\frac{1}{\sqrt{2}}(|0\rangle_2 - i|1\rangle_2)$. Because the WGM cavity is only virtually excited, photon loss can be described by an effective decay rate $\Gamma_C \simeq g^2\kappa/\Delta^2$. The occupation of the excited state $|e\rangle$ can be estimated to be $\langle e\rangle \sim |\Omega_1\Omega_2/\Theta|^2$. Decoherence from the excited state at a rate γ thus leads to the effective decay rate $\Gamma_E \simeq |\Omega_1\Omega_2/\Theta|^2\gamma$. From the figure we find that, provided the condition $\mathcal{R} \geq \{\Gamma_C, \Gamma_E\}$ is fulfilled (Fig. 3(a)-(c)), the transfer process is very efficient. At the end of the process, we can get the target state with a fidelity higher than 99%. When the strong coupling condition $\mathcal{R} \geq \{\Gamma_C, \Gamma_E\}$ is not satisfied (Fig.3 (d)), the transfer process is spoiled. To ensure coherent evolution and efficient quantum information transfer thus requires $\mathcal{R} \geq \{\Gamma_C, \Gamma_E\}$.

In realistic experiments, the above strong coupling condition $\mathcal{R} \geq \{\Gamma_C, \Gamma_E\}$ can be realized with current techniques of the solid state cavity QED system. With the chosen parameters $\Delta = 10g$, $\Omega_1 = \Omega_2 = 0.01g$, we have $\mathcal{R} \sim 10^{-3}g$, $\Gamma_C \sim 10^{-2}\kappa$, and $\Gamma_E \sim 10^{-2}\gamma$. Strong coupling between individual NV center in diamond nanocrystal and the WGM in microsphere or microdisk resonator has been reached [4–6]. The coupling strength between NV centers and the WGM can reach $g/2\pi \sim 0.3 - 1$ GHz. The Q factor of the WGM microresonator can have a value exceeding 10^9, which can leads to a photon loss rate of $\kappa = \omega/Q \sim 2\pi \times 0.5$ MHz for our case. For the NV centers, the electron spin relaxation time T_1 of diamond NV centers ranges from several milliseconds at room temperature to seconds at cryogenic temperature. The dephasing time T_2 induced by the fluctuations in the nuclear spin bath has the value of several microseconds in general, which can be increased to 2 milliseconds in ultrapure diamond [7]. Therefore, the aforementioned strong coupling condition $\mathcal{R} \geq \{\Gamma_C, \Gamma_E\}$ can be satisfied in the solid-state cavity QED experiments, from which we can ensure that the photon loss of the WGM and the decay of the NV centers can have a negligible effect on the quantum information transfer process.

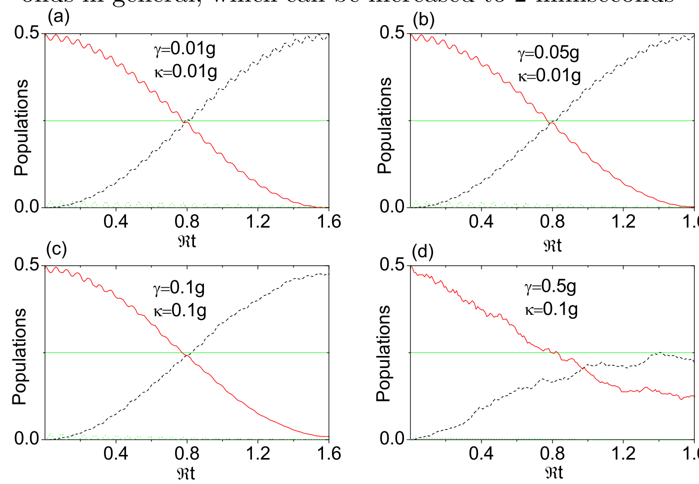

FIG. 3. (Color online) Evolution of the system from the solution of the master equation. In all the figures, red solid line represents the population of $|1\rangle_1|0\rangle_2$, and dark dash line represents the population of $|0\rangle_1|1\rangle_2$. The parameters are chosen as $\Delta = 10g$, $\Omega_1 = \Omega_2 = 0.01g$.

In conclusion, we have presented an experimentally feasible protocol for the implementation of quantum information transfer with NV centers coupled to a WGM microresonator. Relied on the effective dipole-dipole interaction between the NV centers mediated by the WGM, quantum information can be transferred between the NV centers through Raman transitions combined with laser fields. This scheme may represent promising steps towards the realization of quantum communications with the solid state cavity QED system.

This work is supported by the National Key Project of Basic Research Development under Grant No.2010CB923102, and the New Staff Research Support Plan of Xian Jiaotong University under No.08141015.

[1] For a review see,H. J. Kimble, Phys. Scr. **T76**, 127 (1998); H. Mabuchi and A. C. Doherty, Science **298**, 1372 (2002).

[2] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, UK, 2000).

[3] For a review see,K. J. Vahala, Nature (London) **424**, 839 (2003).

[4] Y.-S. Park, A. K. Cook, and H. Wang, Nano. Lett. **6**, 2075 (2006); M. Larsson, K. N. Dinyari, and H. Wang, *ibid.* **9**, 1447 (2009).

[5] S. Schietinger, T. Schroder, and O. Benson, Nano. Lett. **8**, 3911 (2008); S. Schietinger and O. Benson, J. Phys. B **42**, 114001 (2009).

[6] P. E. Barclay, K.-M. C. Fu, C. Santori, and R. G. Beausoleil, Appl. Phys. Lett. **95**, 191115 (2009); C. Santori, P. E. Barclay, K.-M. Fu, R. G. Beausoleil, S. Spillane, and M. Fisch, Nanotechnology **21**, 274008 (2010); P. E. Barclay, C. Santori, K.-M. Fu, R. G. Beausoleil, and O. Painter, Opt. Express. **17**, 8081 (2009).

[7] G. Balasubramanian, P. Neumann, D. Twitchen, M. Markham, R. Kolesov, N. Mizuochi, J. Isoya, J. Achard, J. Beck, J. Tissler, V. Jacques, P. R. Hemmer, F. Jelezko, and J. Wrachtrup, Nature Mater. **8**, 383 (2009).

[8] C. Santori, D. Fattal, S. M. Spillane, M. Fiorentino, R. G. Beausoleil, A. D. Greentree, P. Olivero, M. Draganski, J. R. Rabeau, P. Reichart, B. C. Gibson, S. Rubanov, D. N. Jamieson, and S. Prawer, Opt. Express. **14**, 7986 (2006); T. A. Kennedy, J. S. Colton, J. E. Butler, R. C. Linares, and P. J. Doering, Appl. Phys. Lett. **83**, 4190 (2003).

[9] S. M. Spillane, T. J. Kippenberg, K. J. Vahala, K. W. Goh, E. Wilcut, and H. J. Kimble, Phys. Rev. A **71**, 013817 (2005); Y. Louyer, D. Meschede, and A. Rauschenbeutel, *ibid.* **72**, 013801 (2005).

[10] K.-M. C. Fu, C. Santori, S. Spillane, and R. G. Beausoleil, Proc. SPIE **6903**, 69030M (2008); W. L. Yang, Z. Q. Yin, Z. Y. Xu, M. Feng, and J. F. Du, Appl. Phys. Lett. **96**, 241113 (2010).

[11] T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J. L. OBrien, Nature (London) **464**, 45 (2010); G. Burkard, e-print arXiv:cond-mat/0409626v2 (2004).

[12] D. F. V. James, Fortschr. Phys. **48**, 823 (2000).

[13] R. Schack and T. A. Brun, Comput. Phys. Commun. **102**, 210 (1997).