Long-distance quantum information transfer with strong coupling hybrid solid system

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In this paper, we demonstrate how information can be transferred among the long-distance memory units in a hybrid solid architecture, which consists the nitrogen-vacancy (NV) ensemble acting as the memory unit, the LC circuit acting as the transmitter (receiver), and the flux qubit acting as the interface. Numerical simulation demonstrates that the high-fidelity quantum information transfer between memory unit and transmitter (receiver) can be implemented, and this process is robust to both the LC circuit decay and NV ensemble spontaneous emission.

Quantum information transfer (QIT) and long-distance quantum communication (LDQC) play an important role in the field of the quantum information1. They can transmit quantum information between distant sites. How to realize QIT and LDQC is still an open question. Generally speaking, a good physical system should satisfy two conditions for the QIT and LDQC. First, the system has sufficiently long coherence time, i.e., QIT and LDQC should be achieved before the decoherence happens. Second, the system has a robust channel to avoid the loss of information. As far as we know, there are many proposals for the QIT and LDQC. For example, (i) several optical cavities (microsphere cavities) were linked by fibers (superconducting qubits), and atoms (atomic ensembles, quantum dots, ions, or ionic ensembles) acting as qubits were trapped in each cavity, the deterministic QIT and LDQC were realized with separated qubits2–8. (ii) QIT and LDQC were implemented with separated qubits via the virtual excitation of the data bus to induce the coupling9–12. (iii) Using linear optics devices, the QIT and LDQC were achieved by one photon of an entangled pair in free-space13, and so on. Due to optical absorption and channel's noise, the successful probabilities of the QIT and LDQC will reduce with the increase of the distance. In this paper, we propose a different scheme, which is a good candidate for realizing QIT and LDQC.

On the other hand, among various kinds of solids, the nitrogen vacancy (NV) in diamond has a long coherence time at room temperature14 and large capacity of information storage15. It is a promising candidate for the storage of the quantum information. In this physical system, the recent experiments have implemented two-qubit conditional quantum gate16 and Deutsch-Jozsa algorithm17. Another solid system, the superconducting qubits have advantages in design flexibility, large-scale integration, and compatibility to conventional electronics18,19. And they have shown the superiority in quantum simulation20 and generating of the quantum entanglement21, etc. Thus, the hybrid solid system devices have attracted tremendous attentions, which consist of respect advantages of various physical systems (see22 and references therein). Recently, ref. 23 has proposed the magnetic coupling between a superconducting flux qubit and a single NV center can be about 3 orders of magnitude stronger than that associated with stripline resonators. Then, the coherent coupling and information transferred between a flux qubit and a NV ensemble have been implemented24,25, respectively. In addition, the coupling between single NV center and a superconducting cavity by a flux qubit has been suggested26, the strong coupling between a NV ensemble and a transmission-line resonator by a flux qubit was presented27, and the short-distance QIT between NV ensembles was proposed28.

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are defined in terms of the classical current where \( \Delta \) with the magnetic field and \( |s| \) serving as qubit. For the NV ensemble, the ground state is defined as \( S(1) \). The information is encoded in sublevels \( SnVE \) and \( SnVE \), with operator \( \sigma \), where \( \sigma = \sigma|a| + |a\rangle \langle b| \) are defined in terms of the classical current \( \Phi_\alpha \) and \( \Phi_\beta \) respectively.

Motivated by the recent papers\(^{23-28}\), here, we elaborate a different proposal to realize QIT and LDQC with simple physical set-ups. As shown in Fig. 1, Alice and Bob have a same device, respectively, which consists of a NV ensemble, a flux qubit, and a LC circuit. The NV ensemble acts as the information memory unit, the flux qubit acts as the interface, and the LC circuit is a transmitter (receiver) of information. In the large detuning regime, the degrees of freedom of the flux qubit can be eliminated, and we obtain the effective coupling between the NV ensemble and the LC circuit. And the entanglement of the two subsystems is induced by a flux qubit. Initially, the information is stored in the memory unit of Alice. Then, the information is transferred to transmitter by means of evolution of the system. Through the antenna radiation of the LC circuit, the information is transferred in free-space. At distant sites, the information is received by the receiver of Bob, then stored in the memory unit. So, the LDQC between two spatially-distant memory units has been achieved.

**Results**

**System and Model.** The model as shown in Fig. 1. The flux qubit can be described as a two-level system\(^{29,30}\), the Hamiltonian is (setting \( \hbar = 1 \)) \( H_j = \frac{1}{2} (\varepsilon \sigma_z + \Delta \sigma_x) \), where \( \varepsilon(\Phi) = 2I_0(\Phi - 0.5\Phi_0) \) is the energy spacing of the two classical current states, \( I_0 \) is persistent current of the flux qubit, \( \Phi_0 = h/2e \) is the magnetic-flux quantum, \( \Phi = \Phi_\alpha/2 + \Phi_\beta \) is the external magnetic flux applied in the qubit; \( \Delta \) is the energy gap between the two states at the degeneracy point; Pauli matrices \( \sigma_z = |b\rangle \langle b| - |a\rangle \langle a| \) and \( \sigma_x = |b\rangle \langle a| + |a\rangle \langle b| \) are defined in terms of the classical current where \( |a\rangle = |\Omega\rangle \) and \( |b\rangle = |\bar{\Omega}\rangle \) denote the states with clockwise and counterclockwise currents in the loop. After transformation to the eigenbasis of the flux qubit, the Hamiltonian can be rewritten as \( H_q = \frac{1}{2} \omega_q \sigma_z \) with \( \hbar \omega_q = \sqrt{\varepsilon^2 + \Delta^2} \) the energy level separation of the flux qubit.

A NV has an electron spin \( S = 1 \), with zero-field splitting \( D = 2.88 \text{ GHz} \) between the levels \( m_s = 0 \) and \( m_s = \pm 1 \). By applying a static magnetic field along to the crystalline axis of diamond, the degeneracy of levels \( |m_s = \pm 1\rangle \) can be removed. The information is encoded in sublevels \( |m_s = 0\rangle \equiv |0\rangle \) and \( |m_s = -1\rangle \equiv |1\rangle \) serving as qubit. For the NV ensemble, the ground state is defined as \( |g\rangle = |0_1\cdots 0_N\rangle \) and the excited state is \( |e\rangle = S^+|g\rangle = (1/\sqrt{N}) \sum_{k=1}^{N} |1_1\cdots 1_k\cdots 0_N\rangle \) with operator \( S^+ = (S^-)^\dagger = (1/\sqrt{N}) \sum_{k=1}^{N} |1_k\cdots 0_N\rangle \langle 0| \). Under the large \( N \) and low excitations conditions, the operators \( S^+ \) and \( S^- \) satisfy the bosonic commutation relation, i.e., \([S^+, S^-] \approx 1\). Thus, the Hamiltonian of NV ensemble is written as \( H_{NV} = \frac{1}{2} \Omega S^+ S^- \), where \( \Omega = D - g_e \mu_B B_z \) is the energy gap between the ground state sublevels \( |0\rangle \) and \( |1\rangle \) with the magnetic field \( B_z \) and \( g_e \) and \( \mu_B \) are the Lande factor and the Bohr magneton, respectively.

The NV ensemble couples to the flux qubit via the magnetic field created. The Hamiltonian for flux qubit coupled to a NV ensemble can be represented by \( J(S^+ + S^-)\sigma_z \) with the coupling strength

![Figure 1.](http://example.com/figure1.png)
\[ J = (\sum_k |I_k|^2)^{1/2} \], here \( I_k \) is the coupling strength between the flux qubit and NV centers. After a trivial change of basis on the flux qubit and we make a rotating wave approximation, the direct interaction Hamiltonian of the flux qubit and the NV ensemble is \( J(\sigma^+ + \sigma^-)^\ast \).

The LC circuit is described by a simple harmonic oscillator Hamiltonian \( \omega a^\dagger a \) with resonance frequency \( \omega = 1/\sqrt{LC} \), where \( a^\dagger \) and \( a \) are the plasmon creation and annihilation operators, respectively. In addition, since the interaction between a flux qubit and an LC circuit via the mutual inductance \( M \) has been experimentally realized\(^{34}\), the physical features have been widely studied both in theory\(^{35}\) and in experiments\(^{36,37}\). The interaction Hamiltonian is \( g'(a^\dagger + a)\sigma \), with coupling strength \( g' = MI_0\sqrt{\omega/2L} \). At the eigenbasis of the flux qubit, neglecting the small diagonal terms, the interaction Hamiltonian can be written \( g(\sigma^+ + \sigma^-) \) with effective coupling constant \( g = g'(\Delta/\epsilon^2 + \Delta^2) \) under the rotating-wave approximation and the condition that \( \Delta > \epsilon \) is satisfied.

According to the above mentions, in the Schrödinger picture, the total Hamiltonian of a single device can be written as

\[
H = \omega a^\dagger a + \frac{1}{2}\omega_q \sigma_z + \frac{1}{2}\Omega_0^2 S^− S^+ + J(\sigma^+ + \sigma^-),
\]

(1)

For convenience, the Hamiltonian of the Eq. (1) can be divided into two parts: the free term \( H_0 = \omega a^\dagger a + \frac{1}{2}\omega_q \sigma_z + \frac{1}{2}\Omega_0^2 S^− S^+ \) and the interaction term \( H_I = g(\sigma^+ + \sigma^-) \) and \( J(\sigma^+ + \sigma^-) \). If the conditions \( |\omega_q - \omega| \gg g \) and \( |\omega_q - \Omega| \gg J \) are satisfied (i.e., in the large detuning regime), the effective Hamiltonian of Eq. (1) is obtained by Fröhlich-Nakajima transformation\(^{38,39}\). The expression of the effective Hamiltonian is

\[
H_{\text{eff}} \approx H_0 + \frac{1}{2}[H_I, V],
\]

(2)

where \( V = \frac{J}{\omega_q - \omega}(\sigma^+ - \sigma^-) + \frac{J}{\omega_q - \omega}(\sigma^+ - \sigma^-) \) is an anti-Hermitian operator, which satisfies the relation \( H_I + [H_0, V] = 0 \). The Eq. (2) discards the higher-order terms and only keeps the second-order term.

If the flux qubit is prepared in the ground state \( |a\rangle \) at the initial moment, we can realize the inductive coupling between the LC circuit and the NV ensemble by virtual excitation of the flux qubit. So, with the degrees of freedom of the flux qubit are eliminated, the effective Hamiltonian of the hybrid system can be written as

\[
H_{\text{eff}} = \omega a^\dagger a + \frac{1}{2}\Omega_0^2 S^+ S^- + \lambda (a^\dagger S^- + aS^+),
\]

(3)

where the parameters \( \omega' = \omega - \frac{g^2}{\omega_q - \omega} \) and \( \Omega' = \frac{\Omega}{2} - \frac{g^2}{\omega_q - \omega} \), the last term represents the interaction between the LC circuit and the NV ensemble with the effective coupling strength \( \lambda = \frac{1}{2g^2}\left(\frac{1}{\omega_q - \omega} + \frac{1}{\omega_q - \omega'}\right) \).

Quantum information transfer. For \( n \) Fock states in the LC circuit, the NV ensemble and LC circuit dynamics are completely confined to subspace with basis \( \{|g\rangle |n + 1\rangle, |e\rangle |n\rangle\} \). The Hamiltonian (3) can be solved accurately, the eigenstates can be expressed as

\[
|\Phi_n\rangle = \cos \theta_n |e\rangle |n\rangle + \sin \theta_n |g\rangle |n + 1\rangle,
\]

(4)

\[
|\Psi_n\rangle = -\sin \theta_n |e\rangle |n\rangle + \cos \theta_n |g\rangle |n + 1\rangle,
\]

(5)

with the parameter \( \theta_n = \frac{1}{2}\tan^{-1}\left(2\lambda_n\sqrt{n + 1}/(\Omega' - \omega')\right) \), and corresponding to eigenenergies

\[ E_{\pm} = \left(n + \frac{1}{2}\right)\omega' + \frac{\Omega'}{2} \pm \sqrt{\left(\frac{\Omega'}{2} - \omega' \right)^2 + \lambda^2(n + 1)} \].

Obviously, the Eq. (4) and (5) represent the entangled states between the LC circuit and the NV ensemble. If the information is stored in NV ensemble, we can read out it by measuring quantum states of the LC circuit.

In the interaction picture, the Hamiltonian (3) becomes

\[
H_{\text{eff}} = \lambda (a^\dagger S^- + aS^+),
\]

(6)

with the resonant interaction \( \Omega' = \omega' \). If the information is encoded in the NV ensemble at the initial moment, we can realize the information transfer from NV ensemble (memory unit) to LC circuit (transmitter), that is, \( (\alpha |g\rangle + \beta |e\rangle) |0\rangle \rightarrow |g\rangle (\alpha |0\rangle + \beta |1\rangle) \) with the evolution time \( t_p = (2k + 1)\pi/2\lambda \) \( (k = 0, 1, 2 \ldots) \), where \( \alpha \) and \( \beta \) are the normalized complex numbers. Then, the information of the LC circuit
can be emitted by the antennary radiation. At the distant receiving terminal, the information is received by another LC circuit (receiver), then stored in NV ensemble (memory unit), that is, \(|\Psi\rangle = (\alpha|0\rangle + \beta|1\rangle) \to (\alpha|\Psi\rangle + \beta|\psi\rangle) |0\rangle\). In other word, we realize a LDQC between Alice and Bob without using data bus (fibers, transmission line resonator, or nanomechanical resonator). Moreover, Alice can act as a base station, and Bob can act as a user. We can realize the quantum communication from one base station to many users. The channel of our scheme is electromagnetic wave, which has been widely used in the field of communications. We now discuss the dominant noise of the channel due to microwave photons loss. When the electromagnetic wave transmits in free-space, the signal power of the receiver can be written as

\[ P_r = \frac{P_t G_r G_i}{(4\pi d/\lambda')^2}, \]

where \(P_t\) is the transmitted power, \(G_r\) indicates the gain of antenna-transmitter, \(G_i\) expresses the gain of antenna-receiver, \(d\) is the distance between the transmitter and the receiver, and \(\lambda'\) is the wavelength. In order to avoid the loss of the channel, we should shorten the distance \(d\) between the transmitter and the receiver, or increase the wavelength \(\lambda'\).

**Discussion**

For a really physical system, we should take account of decoherence effects. As Alice and Bob have the same dissipation mechanism, here, we only discuss the decoherence effects of Alice. The flux qubit worked in large detuning regime and prepared in the ground state. The decoherence effective of the flux qubit is omitted. Thus, we only consider the decay of LC circuit, the dephasing and relaxation of NV ensemble. Following the standard quantum theory of the damping, the Markovian master equation is

\[ \dot{\rho} = -i [H_{\text{eff}}, \rho] + \mathcal{L}(\rho), \]

where the Lindblad term \(\mathcal{L}(\rho)\) presents the decay of the LC circuit and the decoherence of the NV ensemble, and the detailed expression is \(\mathcal{L}(\rho) = \frac{\gamma}{2}(2\alpha a^{\dagger} a^{\dagger} - a^{\dagger}a^{\dagger} - a^{\dagger}a - a a^{\dagger}) + \frac{\gamma}{2}(S_x \rho S_z - \rho) + \frac{\gamma}{2}(2S^- \rho S^+ - S^+ S^- \rho - \rho S^+ S^-)\) with the decay rate \(\gamma\) of the LC circuit, and the dephasing rate \(\gamma_c\) and the relaxation rate \(\gamma\) of the NV ensemble. Fidelity is a direct measure to characterize how accurate the information transfer from NV ensemble to LC circuit, and its expression is \(F = \langle \hat{\Psi}|\rho|\hat{\Psi}\rangle\), where \(|\hat{\Psi}\rangle = (\alpha|0\rangle + \beta|1\rangle)\) is a target state to be stored in the LC circuit. In Fig. 2, we plot the fidelity \(F\) as a function of the dimensionless time \(\lambda t\) with the different decay rate \(\kappa\), the dephasing rate \(\gamma_c\) and the relaxation rate \(\gamma\). This figure shows that the high-fidelity QIT could be achieved in the weak decoherence case.

The experiment has reported that the coupling strength between flux qubit and NV ensemble is \(J = 70\) MHz, the Lande factor is \(g_e = 2\), the Bohr magneton is \(\mu_B = 14\) MHz/mT, and the magnetic field is \(B_z = 2.6\) mT. Besides, the strong coupling of a LC circuit and a flux qubit has been implemented. In this experiment, the coupling strength between the flux qubit and the LC circuit is \(g = 119\) MHz, the frequency of the LC circuit is \(\omega = 2.723\) GHz, and the decay rate of the LC circuit is \(\kappa = 0.45\) MHz. Through adjusting the frequency \(\omega_f\) of the flux qubit, the large-detuning between the flux qubit and the LC circuit (NV ensemble) can be well satisfied. Also, the resonant condition \(\Omega' = \omega'\) is satisfied at the proper frequency \(\omega_g\), see in Fig. 3. According to the above value of parameters, we can estimate the effective coupling strength between NV ensemble and LC circuit \(\lambda \sim 10\) MHz. Thus, the strong coupling between NV ensemble and LC circuit is realized.
ensemble and $LC$ circuit is realized. So, we can estimate the time $t_p \sim 0.16 \mu s$, which is shorter than the decoherence time of the NV ensemble approaching $1 s^{40}$ and the flux qubits coherence time $T_2 \approx 20 \mu s^{41}$.

In summary, we have proposed a hybrid solid architecture, which can realize the strong coupling between a NV ensemble and a $LC$ circuit by a flux qubit. We have also shown the high-fidelity quantum information transfer between the NV ensemble and the $LC$ circuit. In addition, the LDQC can be implemented using this architecture by the antenna radiation. The proposed architecture opens a way for quantum communication from one base station to many users.

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**Acknowledgements**

FYZ and HSS were supported by the National Science Foundation of China under Grant No. 11175033. ZFY was supported by the National Science Foundation of China under Grant Nos. [11505024, 11447135 and 11447134], and the Fundamental Research Funds for the Central Universities No. DC201502080407.

**Author Contributions**

F.Y.Z. proposed the model and carried out research while X.Y.C. and C.L. provide the technology advices. F.Y.Z. and H.S.S. analyzed the results. F.Y.Z. wrote the paper.

**Additional Information**

**Competing financial interests:** The authors declare no competing financial interests.

**How to cite this article:** Zhang, F.-Y. *et al.* Long-distance quantum information transfer with strong coupling hybrid solid system. *Sci. Rep.* **5**, 17025; doi: 10.1038/srep17025 (2015).