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Scalable quantum information transfer between nitrogen-vacancy-center ensembles

Feng-yang Zhang [a,c,*], Chui-Ping Yang [b], He-Shan Song [c]

[a] School of Physics and Materials Engineering, Dalian Nationalities University, Dalian 116600, China
[b] Department of Physics, Hangzhou Normal University, Hangzhou, Zhejiang 310036, China
[c] School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, China

HIGHLIGHTS

- Quantum information transfer between any two selected NV ensembles is implemented.
- This architecture is robust against the dissipation of the system.
- We explicitly show that for resonant interaction and large detuning cases.

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ABSTRACT

We propose an architecture for realizing quantum information transfer (QIT). In this architecture, a *LC* circuit is used to induce the necessary interaction between flux qubits, each magnetically coupling to a nitrogen-vacancy center ensemble (NVCE). We explicitly show that for resonant interaction and large detuning cases, high-fidelity QIT between two spatially-separated NVCEs can be implemented. Our proposal can be extended to achieve QIT between any two selected NVCEs in a large hybrid system by adjusting system parameters, which is important in large scale quantum information processing.

1. Introduction

Quantum information transfer (QIT) has many applications in communication science [1]. There exist physical systems for realizing QIT, such as, cavity quantum electrodynamics (QED) [2–5], linear

* Corresponding author at: School of Physics and Materials Engineering, Dalian Nationalities University, Dalian 116600, China.
E-mail address: zhangfy1986@gmail.com (F.-y. Zhang).

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optics devices [6], and superconducting qubits [7–11]. In addition, a nitrogen-vacancy center in diamond has been recently considered as one of the most promising candidates for quantum information processing, due to its relatively long coherence time and the possibility of coherent manipulation at room temperature [12]. For instances, the electron spin relaxation time $T_1 = 6$ ms [13] and isotopically pure diamond sample dephasing time $T_2 = 2$ ms [14] have been reported, coherent oscillations in a single electron spin have been observed [15], and coherent time of a nitrogen-vacancy center has been improved very much in the recent years and could reach 1 s [16]. On the other hand, hybrid solid-state devices have attracted tremendous attentions (see [17] and references therein). Theoretically, the physical systems, composed of spin ensembles and superconducting qubits fabricated in a TLR (transmission line resonator), have been proposed [18–21]. Experimentally, a quantum circuit consisting of a superconducting qubit and a nitrogen-vacancy center ensemble (NVCE) has been implemented in Ref. [22]; and a quantum SWAP gate has been realized in this circuit, by employing the strong coupling between a superconducting qubit and a NVCE [22]. In addition, Marcos et al. [23] have proposed a hybrid system, in which the direct coupling between a superconducting flux qubit and a NVCE is much stronger than that between a NVCE and a TLR. For the work on the coupling between a NVCE and a TLR, see Refs. [24,25]. Experimentally, the strong coupling between a superconducting flux qubit and a NVCE has been demonstrated [26]. Moreover, by using the strong coupling, the QIT between a flux qubit and a NVCE has been performed in experiment [27]. Then, the strong coupling between a NVCE and a TLR via a flux qubit used as a data bus was proposed in Ref. [28]. These results provide a platform for using NVCEs as quantum memories, which are essential in quantum information processing.

Motivated by the recent works on the coupling between *LC* circuits and flux qubits [29–32], and the strong coupling hybrid solid quantum system [23,26–28], as well as the QIT with the solid quantum system [33–35], we will propose an architecture for scalable QIT among NVCEs. In this architecture, a *LC* circuit is used to induce the necessary interaction between flux qubits, each magnetically coupling to a NVCE. We explicitly show that for resonant interaction and large detuning cases, high-fidelity QIT between the two spatially-separated NVCEs can be implemented by solving Schrödinger equations. Moreover, this architecture can be extended to scale up multiple flux qubits and NVCEs by using a single *LC* circuit, and the QIT between any two selected NVCEs can be achieved in this large hybrid system. To the best of our knowledge, how to realize QIT between NVCEs in this architecture has not been proposed yet. Note that, Refs. [36,37] reported the QIT between two ensembles which are trapped in spatially separated cavities, respectively. But, the fidelity of the QIT was not calculated and the dissipation of the system was not considered in Refs. [36,37].

2. Model

We propose a QIT hybrid circuit, as shown in Fig. 1, which consists of a *LC* circuit acting as a data bus to induce coupling between two flux qubits. Each flux qubit couples to a NVCE by a magnetic field. Each NVCE is an information memory unit. The electronic ground state of a single nitrogen-vacancy center (NVC) has a spin $\mathbb{S} = 1$, with the levels $m_s = 0$ and $m_s = \pm 1$ separated by zero-field splitting D. For a NVC, the Hamiltonian can be described by (assuming $\hbar = 1$) [38,39]

$$H_{NVC} = D\mathbb{S}_z^2 + E(\mathbb{S}_x^2 - \mathbb{S}_y^2) + g_e\mu_B\vec{B}\cdot\vec{\mathbb{S}}, \tag{1}$$

where zero field splitting $D = 2.88$ GHz, $\vec{\mathbb{S}} = \{\mathbb{S}_x, \mathbb{S}_y, \mathbb{S}_z\}$ is a usual Pauli spin-1 operator, E is the strain-induced splitting coefficient, B is the applied magnetic field, g_e is the Lande factor, and μ_B is the Bohr magneton. When the static magnetic field $\vec{B}$ is applied along the crystalline axis of the diamond, the degeneracy of levels $|m_s = \pm 1\rangle$ can be removed. The quantum information is encoded in sublevels $|m_s = 0\rangle \equiv |0\rangle$ and $|m_s = -1\rangle \equiv |1\rangle$ serving as two logic states of a qubit. For a NVCE with NVCs $(1, 2, \ldots, N)$, the ground state is defined as $|g\rangle = |0_1 \cdots 0_k \cdots 0_N\rangle$ while the excited state is defined as $|e\rangle = S^+|g\rangle = (1/\sqrt{N})\sum_{k=1}^{N}|0_1 \cdots 1_k \cdots 0_N\rangle$ with operator $S^+ = (S^-)^\dagger = (1/\sqrt{N})\sum_k^N |1\rangle_k\langle 0|$, where the subscript k represents the kth NVC. Thus, the Hamiltonian of a NVCE is written as [20] $H_{NVCE} = \frac{1}{2}\Omega S_z$, where $\Omega = D - g_e\mu_B B_z$ is the energy gap between the ground state $|g\rangle$ and the excited state $|e\rangle$, with the operator $S_z = |e\rangle\langle e| - |g\rangle\langle g|$.