E-1-04

Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp215-216

Selective quantum teleportation transfer of a photon polarization state into a carbon nuclear spin state in an NV center in diamond

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Abstract

We demonstrate reliable quantum state transfer of a photon into one of carbon isotopes coupled to a nitrogen-vacancy center in diamond based on the principle of quantum teleportation. The selected carbon is first entangled with the electron, which is then permitted to absorb a photon into a spin-orbit correlated eigenstate. Detection of the electron after relaxation into the spin ground state allows post-selected transfer of arbitrary photon polarization into the carbon memory. The quantum teleportation transfer allows arbitrary addressing of integrated quantum memories to realize scalable quantum repeaters for long-haul quantum communications and distributed quantum computers for large-scale quantum computation and metrology.

1. Introduction

Quantum teleportation is a widely used principle for quantum information technologies including quantum communication and quantum computing. Long-haul quantum communication requires quantum repeaters based on quantum teleportation to transfer a quantum bit or qubit into a distant site without revealing the qubit state. On the other hand, quantum computation also requires quantum teleportation not only for one-way quantum computing but also for quantum blind computing to securely transfer input and output data via quantum communication. Finally, quantum teleportation is also in demand for the quantum storage of highly confidential data, such as DNA data, that are securely transferred by photons into quantum memories.

We have recently demonstrated the transfer of photon polarization into a nitrogen nuclear spin in a single nitrogen-vacancy (NV) center in diamond [1]. However, the stored information is limited to only one nuclear spin per one NV center, which is a big obstacle for scaling up the memory size. On the other hand, there exist a large number of carbon isotopes (^{13}C), which also have nuclear spins, within the reach of a nitrogen-vacancy center via a hyperfine interaction even in diamond with a natural abundance of ^{13}C (1.1%), and the number can be increased by isotope enrichment technology. The stored qubits in carbon nuclear spins must be independent of each other and individually addressable. We have also recently demonstrated that the quantum state of isolated carbon nuclear spins weakly coupled to the NV center's electron can be ideally maintained by the geometric spin echo based on time reversal under a zero magnetic field [2]. However, it is hard to initialize and manipulate a spin-half carbon nuclear spin under a zero magnetic field, in contrast to the spin-1 nitrogen, which has a zero-field split state to allow manipulation by a resonant microwave.

In the previous work [3], we have successfully initialized and manipulated a carbon nuclear spin using a nitrogen as a nanomagnet to lift the degeneracy of the electron while maintaining a magnetic field of zero at the carbon nuclear spin, then transfer the polarization state of photons into the spin quantum state of the thus-prepared carbon nuclear spin. We have experimentally demonstrated that the state transfer process shows quantum nature and thus the transfer fidelity exceeds the classical limit, based on the quantum process tomography technique. However, it was difficult in the previous scheme to select one carbon nuclear spin out of many carbon nuclear spins in the environment. If multiple carbon nucleons in the vicinity of the NV center can be used as multi-quantum memory and photons can be received, the scalability of entangled communication can be expected. In this work, we enable selective quantum teleportation transfer into one carbon by simplifying the sequence of entanglement generation through initialization into superposition state in the NV system with two carbons isotopes coupled to the electron spin in an NV center. Two carbon hyperfine frequencies of 0.9 MHz and 0.4 MHz are observed by ODMR in this demonstration.

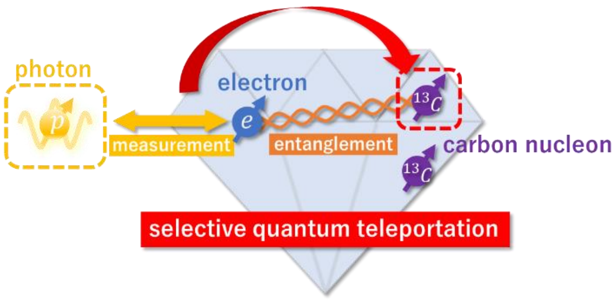

Fig. 1 Schematics of the selective quantum state transfer. We first prepare an entanglement between electron spin (e) and selected carbon nuclear spin (^{13}C) (twisted line), and then measure photon polarization (p) and electron spin in the Bell basis by photon absorption [4] (bidirectional arrow), which announces the success of the quantum state transfer from the photon into the carbon (curved arrow).

2. Principle

Quantum teleportation consists of the preparation of an entanglement and the measurement in the Bell basis, resulting in post-selective transfer of the quantum state [1, 3]. In this demonstration, we first prepare an entanglement between electron spin and carbon nuclear spin, and then measure photon polarization and electron spin in the Bell basis by photon absorption [4] to transfer the photon polarization state into the carbon nuclear spin state. In the practical protocol of the one-way quantum repeater system with an NV center at each node, the photon is emitted from one node, leaving an electron entangled with the emitted photon. The success of the photon storage in the other node establishes the entanglement between two adjacent nodes.

3. Sample and experimental setup

A negatively charged NV center in diamond consists of a nitrogen impurity (^{14}N) and an adjacent vacancy (V), where the triplet state electron (e) is localized. Both the electron and the nitrogen nucleus show a spin 1 property constituting a V-type three-level system with two degenerate $m_{s,I} = \pm 1$ states (denoted $|\pm 1\rangle_{e,N}$), which constitute a logical qubit called a geometric spin qubit [5-7], and an $m_{s,I} = 0$ state (denoted $|0\rangle_{e,N}$), which constitute an ancilla. These are split by a zero-field splitting of around 2.87 GHz for the electron and a nuclear quadrupole splitting of around 4.95 MHz for the nitrogen. On the other hand, a carbon nuclear spin (^{13}C), weakly coupled to the electron via a hyperfine interaction (0.9 MHz in this demonstration), shows a spin half property constituting a two-level system with two degenerate $m_I = \pm 1/2$ states (denoted $|\uparrow\rangle_C, |\downarrow\rangle_C$) under a zero magnetic field. We utilize the nitrogen as a nanomagnet localized at the vacancy. The electron and nuclear spins are manipulated by microwave and radio waves, and electron orbital is manipulated by a green laser in the wavelength of 532 nm and red lasers in wavelength of 637 nm.

4. Result

We selectively initialize one of carbons, which couple with the electron by 0.9 MHz, into $|\uparrow\rangle + |\downarrow\rangle$ state to simplify the gate sequence of entanglement generation. The initialization consists of a π-pulse of the nuclear spin with radio wave and a coherent population trapping of electron spin synchronized to the precession of the nuclear spin with red laser. The obtained fidelity is about 80%. The entanglement between the electron and nuclear spins is generated by the same scheme as Ref. 3, and then an incoming photon absorption projects the polarization state of the photon and the spin state of the electron into one of the Bell states [4]. In order to demonstrate the quantum state transfer, after preparing the polarization state of photon in the superposition state of right and left polarizations, we post-select the absorbed events to readout the nuclear spin state. Figure 2 shows that the nuclear spin states $|\uparrow\rangle \pm |\downarrow\rangle$ change depending on the superposition phase ϕ_p of the photon polarization, indicating that the quantum state transfer is successful. The overall fidelity including initialization, transfer and readout is about 70%.

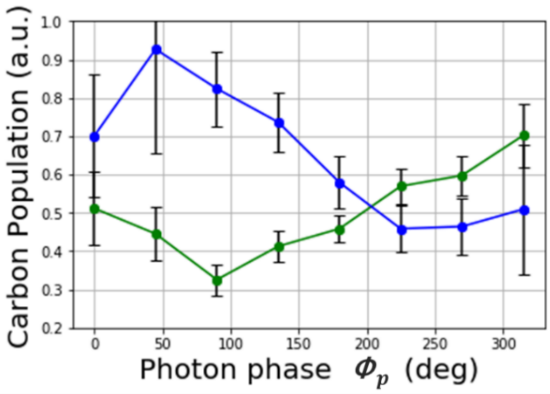

Fig. 2 Experimental demonstration of the quantum state transfer. The horizontal axis of the graph represents the phase of the superposition of the incoming photon, and the blue and the green line respectively indicate the carbon nuclear spin population measured by $|\uparrow\rangle + |\downarrow\rangle$ and $|\uparrow\rangle - |\downarrow\rangle$. Oscillation is observed as expected, indicating the quantum nature of the transfer.

5. Conclusions

We succeeded in quantum teleportation transfer from a photon selectively to one carbon nuclear spin with a fidelity of about 70% in NV degenerate system with two weakly coupled carbons. This demonstration indicates that carbon nuclear spins can be applied to multi-quantum memories.

Acknowledgements

This work was supported by Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (nos. 16H06326, 16H01052, 16K13818); by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) as an "Exploratory Challenge on Post-K computer" (Frontiers of Basic Science: Challenging the Limits); by the Research Foundation for Opto-Science and Technology; and by a Japan Science and Technology Agency (JST) CREST Grant (no. JPMJCR1773).

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