Optical geometric manipulation of an electron spin in diamond

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Abstract: We report single electron spin quantum gates using spin-state-dependent geometric phase induced by a cyclic rotation in the orbital space with a polarized light. By performing quantum process tomography, we achieved manipulation fidelity over 90% in average.

1. Introduction

Solid-state spin is a stable and scalable quantum medium, promised as a quantum engineering platform, such as quantum information and quantum sensing. As a method of spin manipulation to maintain this scalability, light gives a local field to access individual spins. However, while a spin-orbit interaction mediates between the optical field and the spin, which never interact with each other directly, the orbital instability prevents a practical spin manipulation, in contrast to direct spin manipulation with microwave. Although previous works adiabatically eliminate the orbital exited state by using far-detuned light to reduce the effect of the exited state relaxation [1, 2], the long operation time increases the total effect of the relaxation or other incoherent processes. In contrast, non-adiabatic rotation the orbit state to obtain a spin-state-dependent geometric phase can also rotate the spin state [3].

A nitrogen-vacancy (NV) center in diamond has stable electron spin and spin-orbit interaction for a spin-photon interface, which was demonstrated as spin-photon entanglement generation [4] and measurement [5]. Although this electron spin can be reliably operated with microwaves, it is still a challenging task to faithfully manipulate it arbitrarily with light defined by polarization under a zero field [6].

2. Scheme for non-adiabatic geometric spin rotation

Electron spin states $|m_S = \pm 1\rangle$ of an orbital ground state in a NV center degenerate under a zero magnetic field. Spin-orbit interaction and spin-spin interaction couple the electron spin and orbit exited states $|m_L = \pm 1\rangle$ to make an excited state $|A_2\rangle = |+1\rangle_L|-1\rangle_S + |-1\rangle_L|+1\rangle_S$ under a low temperature. By selecting the driven orbital state depending on the polarization of light, spin-dependent orbital rotation can be achieved. Spin-dependent cyclic evolution of the orbital state obtains a geometric phase, which depends on the state evolution trajectory, to rotate the degenerate spin. Here, we control the trajectory by changing the detuning of light. Hence, an arbitrary single-spin rotation can be achieved by properly choosing the polarization and detuning of light for the rotation axis and angle, respectively. Since the spin coherence prolongs [7] and the spin basis are spatially defined as a polarization of light under a zero magnetic field, the rotation can be practically performed.

3. Experimental results

We performed Pauli-X, Y and Z gate, which consist of 4 ns pulse using horizontal, diagonal and right circular polarized light. Figure 1 shows quantum process tomography using a geometric spin state preparation and readout technique [2]. The achieved fidelity is over 90% in average, which is limited by the exited state relaxation.

4. Conclusion

We demonstrate universal optical geometric manipulation of an electron spin in diamond with practical fidelity. The optical geometric spin rotation under zero field is not only allow quick and local access but also immune to driving and environmental error, thus opening the way to fast quantum random access memories and quantum processors.

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6. References

[1] D. Press, T. D. Ladd, B. Zhang and Y. Yamamoto, Complete quantum control of a single quantum dot spin using ultrafast optical pulses. *Nature* **456**, 218–221 (2008).

[2] B. B. Buckley, G. D. Fuchs, L. C. Bassett and D. D. Awschalom, Spin-Light Coherence for Single-Spin Measurement and Control in Diamond. *Science* **330**, 1212–1215 (2010).

[3] E. Sjöqvist *et al*., Non-adiabatic holonomic quantum computation. *New J. Phys.* **14**, 103035 (2012).

[4] E. Togan *et al.*, Quantum entanglement between an optical photon and a solid-state spin qubit. *Nature* **466**, 730–734 (2010).

[5] H. Kosaka and N. Niikura, Entangled Absorption of a Single Photon with a Single Spin in Diamond. *Phys. Rev. Lett.* **114**, 053603 (2015).

[6] Y. Sekiguchi, N. Niikura, R. Kuroiwa, H. Kano, and H. Kosaka, *Nat. Photon. in press* (2017).

[7] Y. Sekiguchi *et al.*, Geometric spin echo under zero field. *Nat. Commun.* **7**, 11668 (2016).

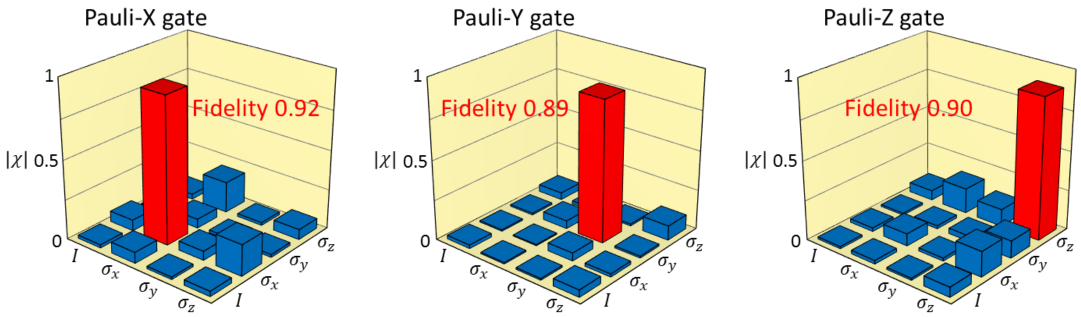

Fig.1. Quantum process tomography for Pauli-X, Y and Z gates.