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Scalability of diamond-based quantum information devices

Kae Nemoto[1,2], Michael Hanks[2,1] . Michael Trupke[3,4], Jörg Schmiedmayer[4], and William J. Munro [5,1]

[1] National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan
Phone: +81-3-4212-2561 E-mail: nemoto@nii.ac.jp
[2] Sokendai, The Graduate University for Advanced Studies,
Shonan Village, Hayama, Kanagawa 240-0193, Japan
[3] Quantum Optics, Nanophysics and Information Group, Faculty of Physics,
University of Vienna, Boltzmanngasse 5, Vienna A-1090, Austria
[4] Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1020 Vienna, Austria
[5] NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi 243-0198, Japan

Abstract

Negatively charged nitrogen vacancy (NV^-) centers are promising candidates for scalable quantum information devices. In this talk, we show how a NV-based quantum information device can be scaled from a single device level implementation to a fully scalable fault-tolerant quantum computer and repeater network.

1. Introduction

Quantum computers have promised a speed-up by exploiting the quantum nature of their states. However, as has been proven in the last two decades, such a quantum computer needs to be excessively large in scale, and it may require an impractically long time to solve computational problems that are not tractable on today's fastest classical computers. Any large-scale quantum computational system requires a fault tolerant implementation to suppress the total error rate below some respective algorithmic threshold. Further, it is well-known that a fault tolerant implementation requires a large overhead in both temporal and spatial resources [1].

Before our technology reaches the point where we can build a large-scale quantum computer, we are likely to be able to construct smaller or specialized quantum information systems, such as quantum simulators or quantum communication based networks. In these systems, the time of operation and/or the states involved in the protocols are limited, and so a fault tolerant implementation may not be necessary. This indicates that it would be preferable that quantum information devices are designed to be adaptive to these different architectural demands. In this talk, we summarize how such a quantum information device can be designed and adapted to different quantum information tasks using an optical cavity and a single negatively charged nitrogen vacancy (NV^-) center.

2. Architecture for quantum information systems

Let us now investigate two different architectures, the first for scalable quantum computation and the second for quantum networks. A scalable quantum computer is fault tolerant and is, for instance, generally assumed to be large enough to run Shor's algorithm on over 700 bits. We employ a 3D-topological quantum computation model, which can be implemented in an array of NV-based quantum information devices with a fixed number of nearest neighbor connections via optical fibers or waveguides. This NV-based quantum information device consists of a single NV center and an optical cavity and is designed to operate so as to conditionally reflect incoming single photons, dependent on the electron spin state, as shown in Fig. 1. This conditional operation creates entanglement between each photon and the electron spin state. The nuclear spins of respective nitrogen 15 atoms are then used to store the resultant entangled states, which are the resources needed for 3D topological quantum computation.

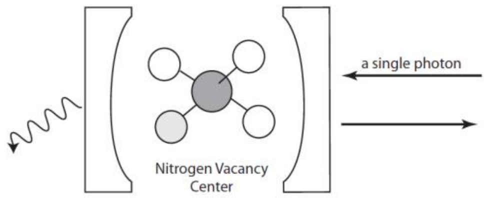

Fig. 1 A schematic illustration of a NV-based quantum information device. The device has two qubits, the first from the electron spin (S=1), and the second from nuclear spin of the ^{15}N atom. With a magnetic field applied, the +1 and 0 states of the electron spin are used to encode a qubit. The cavity is designed to reflect the incoming light when the electron state is 0.

We require the device to satisfy a fault tolerant threshold error rate of 99.27%. The physical parameters, such as the nuclear and electron spin decoherence times and the measurement error rate, can be estimated. It has been shown that all the physical parameters can individually meet this required accuracy [2].

The device is optical, and hence it is readily applicable to quantum communication. The advantages to a quantum communication implementation come from the limited state manipulation and the shallow depth of operation. As the circumference of the earth limits the communication distance, the depth of operation is limited and so a fault tolerant implementation is not necessary.

The NV-based device in the quantum communication scenario must be used slightly different way. The essential task for a quantum communication system is to establish entanglement at distance and so we only need to work with known states and Clifford gates. The fundamental and technological overheads arise from the communication distance. Although the communications distance is limited by the size of the earth, and the speed of light is fixed, the time for quantum and classical signals to propagate can be significant and so the distance is a fundamental element.

For long distances, the system requires some form of error correction code. Though error correction increases the resource overhead of the system, in quantum communication the overhead is much lighter and hence the implementation is much simpler. Suppose we employ the quantum repeater architecture using quantum memories [3]. We can then apply our NV-based quantum information device for the repeater node technology. The NV-based device can distribute entanglement in the same way it does for the quantum computation architecture. Dependent on the distance, the operation order can be optimized. We can further simplify the quantum communication scheme by limiting the task and/or by limiting the distance to less than 500km (which would be beyond current quantum key distribution implementations). In this regime, the repeater system can mainly rely on post selection to maintain the fidelity, and error correction becomes optional for cases requiring high fidelities. There are no changes required to the device itself to shift between these two implementations of quantum repeater systems.

3. Scalable quantum information devices

In these scenarios, the requirement for the gates the device performs is still high (gate error rates less than 0.1%, which is the usual target for fault tolerant implementations). However, in quantum communication systems for shorter distances they may no longer require a fault tolerant implementation, nor error correction. The NV-based quantum information device is scalable from a simple system to a fault-tolerant quantum computer.

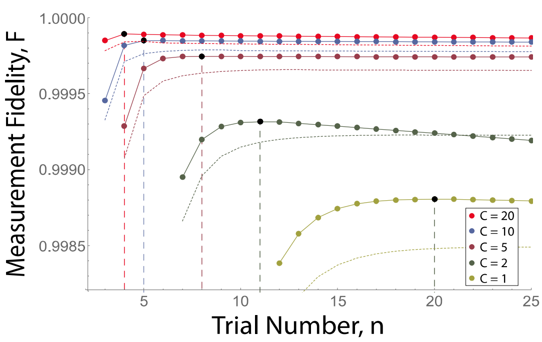

Fig. 2 The measurement fidelity as a function of the number of trials. Each plot indicates a different cavity cooperativity value, ranging from 1 to 20. The dotted lines indicate the performance when the decay to the metastable subspace is 1%.

Now, we can further break the requirements for this scalable device down into the steps required to achieve the desired gate fidelity. To do this, we focus on electron spin measurement with the device. The core of the measurement scheme as well as the entanglement distribution gate is the conditional reflection (dipole induced transparency) and so we evaluate it using the most recent results from NV centers. We show the regime where the device can achieve the fault tolerant threshold. This indicates how we need to prepare the device dependent on the requirements of the tasks at hand. Fig. 2 shows the measurement fidelity for different cavity cooperativities using a majority voting approach [4].

4. Conclusions

As Fig. 2 shows. there is a wide range parameters satisfying the target fidelity. The parameters can be chosen dependent on the task at hand, and the same device design can be adapted to achieve the required fidelity by improving the cavity cooperativity. The use of single photons can also be relaxed to weak coherent pulses. Although these could trigger the photon-induced ionization process, we conclude that weak coherent laser pulses can be used for initial implementations.

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