Remote Entanglement of Quantum Memories over a Metropolitan Network

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Abstract: We generate remote entanglement between spatially separate color-center based quantum nodes at rates up to 1 Hz. In addition, we demonstrate remote entanglement across a deployed 35km long fiber loop in the Boston urban area.

1. Introduction

Generating quantum entanglement between remote quantum memory nodes is an enabling functionality to realize quantum networks for applications ranging from secure quantum communication to quantum enhanced sensing [1].

We demonstrate remote entanglement generation in a two-node quantum network utilizing the silicon-vacancy (SiV) color center in diamond coupled to nanophotonic cavities. The SiV has emerged as a promising quantum networking platform which, when integrated in high quality-factor nanophotonic resonators, has enabled high-efficiency spin-photon gates and memory enhanced quantum communication [2]. Here we extend those results and generate heralded entanglement between SiV centers spatially separated by ~20m with rates up to 1 Hz. Furthermore, to highlight the compatibility of this technology with pre-existing fiber networks, we implement nonlinear-optical based quantum frequency conversion (QFC) to convert photonic qubits at SiV wavelengths (737nm) to the O-band (1350nm) and demonstrate entanglement through 35km of deployed fiber in the Boston urban area. This thus serves as a crucial step towards realizing practical quantum networking technology.

2. Setup

Our quantum network nodes consist of SiV centers formed in nanophotonic diamond cavity resonators which reside in individually operated dilution refrigerator setups in separate laboratories. The SiVs are formed using the ^{29}Si isotope of silicon so that one electron spin and one nuclear spin are available for manipulation and storage. Microwave (MW) pulses are used to perform rotations on the electron and nuclear degrees of freedom [3]. The nanophotonic cavity serves to enhance interactions between light and electron spin, enabling strong coupling (C = 12.4/1.5) and an electron spin-dependent cavity reflection. Through combining this spin-dependent cavity reflection with an incident weak coherent state (WCS) based photonic time-bin qubit and MW control of the electron spin, the incoming time-bin photon and the electron-spin become entangled.

We utilize a serial configuration to generate remote entanglement between the electron spins in node A and B mediated by a time-bin photonic qubit (Fig 1a). The incident photon is first entangled with node A utilizing the reflection-based spin-photon gate. It is then transmitted via optical fiber to node B, whereby it undergoes a second spin-photon gate, leading to a 3 qubit Greenberger-Horne-Zeilinger (GHZ) state between the photon and two nodes. The time-bin photon is then measured in the X basis using a time-delay interferometer (TDI) to herald the generation of a distributed Bell state $|\Phi \pm\rangle$ between the electron spins of node A and B.

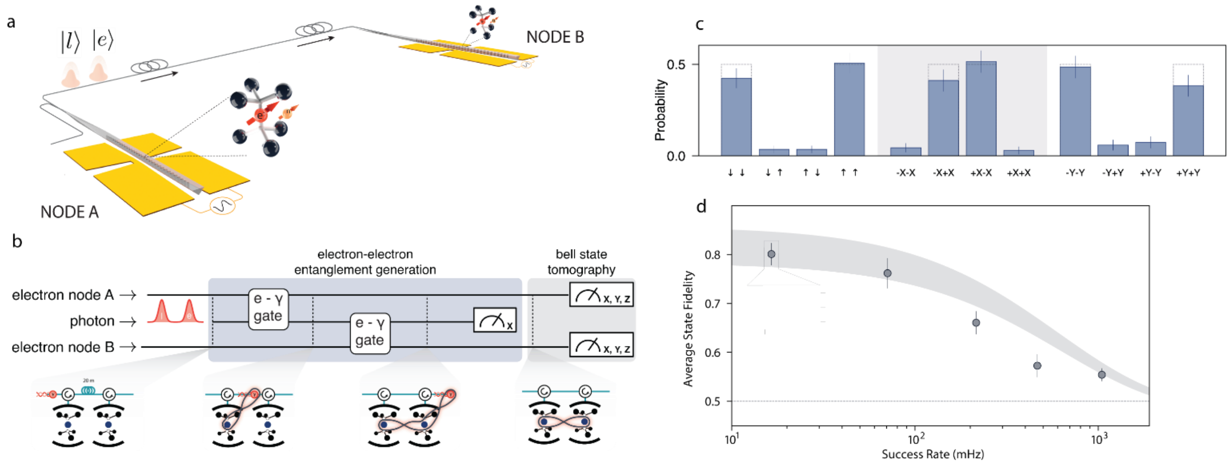

Fig. 1. Two node quantum network. a. Experimental setup. Each SiV is localized in a nanophotonic cavity within a cryostat in two separate laboratories. The quantum network nodes are connected via a ≈ 20 m long optical fiber. b. Entanglement generation sequence. A photonic qubit is entangled with the electron spin in node A using the spin-photon (e – γ) gate. A second e − γ gate entangles the photonic qubit with node B, generating a GHZ state among the two electronic qubits and the photonic qubit. A measurement of the photonic qubit in the X basis heralds the generation of an electronic Bell state. b. Measurement results of Bell state tomography. Measured correlations in the ZZ, XX, and YY bases of the electronic spin corresponding to a Bell state fidelity of 0.86. c. Sweep of mean photon number of the photonic qubit. Entanglement is shown to persist above the classical limit (dashed line) for success rates up to 1 Hz.

3. High-Rate Entanglement

To demonstrate the basic principles of network operation, the nodes are initially directly connected via ≈ 20 m long optical fiber and the above protocol is performed. As a WCS is used as the input photon of the system, the tuning of the mean photon number (μ) of the WCS provides a mechanism to tradeoff the resulting bell-state fidelity for the entanglement generation rate. We initially perform the entanglement generation protocol with a low μ = 0.017. Correlations are measured to estimate the resulting bell state fidelity (Fig 1c). We measure a bell states fidelity of 0.86 unambiguously demonstrating entanglement between the two nodes By increasing μ, the rate of entanglement can be increased at the expense of increased multi-photon events degrading the entanglement fidelity. We explore this tradeoff in Fig 1d, where we show we can operate at success rates beyond 1 Hz while maintaining entanglement.

4. Long-Distance Entanglement

To build large-scale quantum networks, generation of quantum entanglement across metropolitan scale (10+ km) fiber networks is required. Light at the SiVs resonance wavelength (737nm) experiences prohibitively large in-fiber loss > 4dB / km which limits the practical range of remote entanglement distribution. To overcome this, we employ birdirectional QFC to the telecom O-band. After the photonic qubit at 737nm is initially entangled with node A, it is downconverted to the telecom O-band via a periodically poled lithium niobate (PPLN) waveguide pumped with 1623 nm light and transmitted through the fiber network. At node B, the photon is upconverted back to 737 nm via a second PPLN waveguide (Fig 2a)

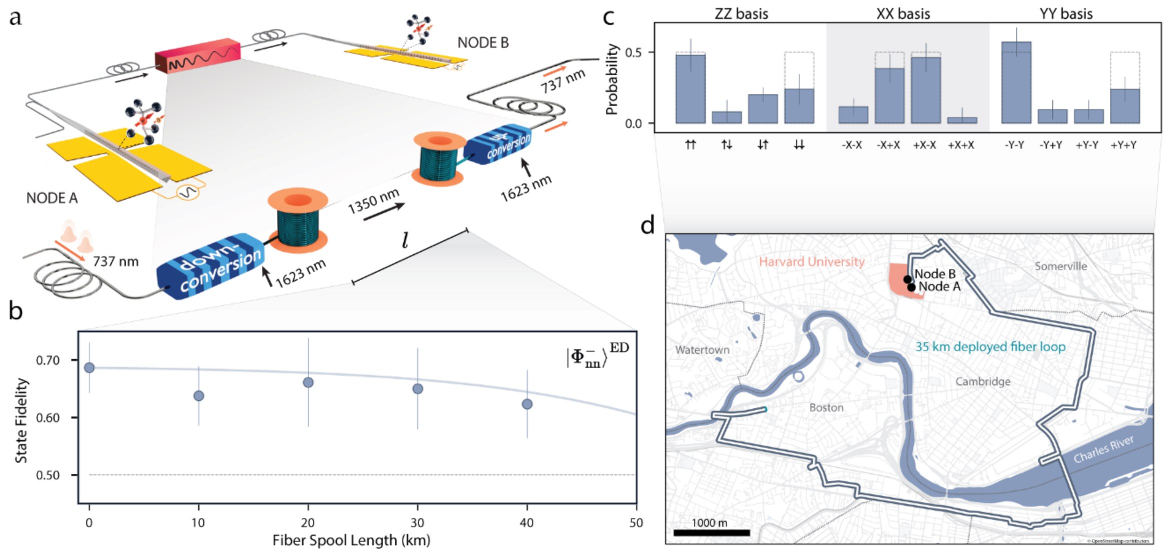

Fig 2. Entanglement generation through 35 km of deployed fiber. a. Schematic of quantum frequency conversion setup. At node A, the photonic qubit is downconverted from 737 nm to 1350 nm, which can propagate with low loss in telecom single mode fibers. At node B, it is upconverted back to 737 nm. b. Bell state fidelities for varying lengths of telecom fiber spools between the two nodes. Entanglement persists for fiber lengths up to 40 km. c. Measurement results of Bell state tomography of $|\Phi\rangle$ state created through a 35 km long deployed fiber link shown in d., resulting in a fidelity of 0.69. d. Route of the deployed fiber link connecting node A and node B. It consists of 35 km deployed telecom fiber routed towards and back from an off-site location, in the greater Boston metropolitan region.

We combine QFC with the previous entanglement generation protocol and the SiVs nuclear spin to demonstrate entanglement over long distances. Initially entanglement is performed through large fiber spools, with entanglement successfully demonstrated with fiber spools up to 40km in length with minimal additional infidelity (Fig 2b).

To highlight the compatibility of this system with conventional fiber infrastructure, we generate entanglement through a 35km loop of telecom fiber deployed in the Boston area urban environment with an insertion loss of 17dB (Fig 2c/d). Using this deployed link, we generate entanglement with a fidelity of 0.69, demonstrating a functioning quantum network link in a realistic fiber environment.

5. Outlook

Our experiments demonstrate the key ingredients for building large-scale deployed networks using the SiV based integrated nanophotonic platform. Through additional optimizations of QFC, utilization of non-classical photonic qubit sources, and optimization of the path architecture, significantly higher entanglement rates can be achieved This combined with the potential ability to create a large number of cavity QED systems fabricated on a single chip can allow the realization of large-scale deployable quantum networks utilizing SiVs.

6. References

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