

Entanglement of Nanophotonic Quantum Memory Nodes Via 35 km of Deployed Fiber

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Abstract: We generate remote entanglement between spatially separate color-center based nanophotonic quantum network nodes. In addition, we demonstrate remote entanglement distribution across a 35 km long fiber loop deployed in the Boston urban area. © 2024 The Author(s)

1. Introduction

Distributing quantum entanglement between quantum memory nodes separated by extended distances is a critical element for the realization of quantum networks, enabling potential applications ranging from quantum repeaters and long-distance secure communication to distributed quantum computing and distributed quantum sensing and metrology [1–4]. Here, we demonstrate remote entanglement generation in a two-node quantum network utilizing the silicon-vacancy (SiV) color center in diamond coupled to nanophotonic cavities [5]. 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 [6]. In this work, we extend those results and generate heralded entanglement between SiV centers spatially separated by ≈ 20 m 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 (737 nm) to the O-band (1350 nm) and demonstrate entanglement through 35 km of deployed fiber in the Boston urban area. This serves as a crucial step towards realizing practical quantum networking technology.

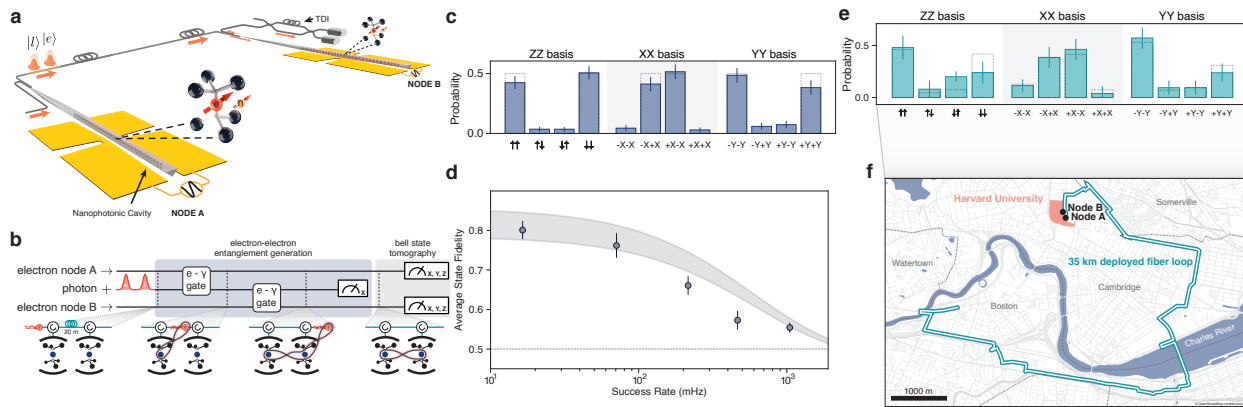


Fig. 1: Two node quantum network. a. Experimental setup. Each SiV is localized in a nanophotonic cavity within a cryostat in two separate laboratories. b. Entanglement generation sequence. A photonic qubit is entangled with the electron spin in node A using the spin-photon ($e-\gamma$) gate. A second $e-\gamma$ 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. c. Measurement results of electronic Bell state tomography. d. 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. e. Measurement results of nuclear Bell state tomography of $|\Phi\rangle$ state created through a 35 km long deployed fiber link shown in f., resulting in a fidelity of $\mathcal{F} = 0.69(7)$. f. 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.

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 (Figure 1 a). The SiVs are formed using the ^{29}Si isotope of silicon. The electron spin acts as a communication qubits strongly interacting with light, while the auxiliary ^{29}Si nucleus acts as a memory qubit. Microwave (MW) pulses are used to perform rotations on the electron and nuclear degrees of freedom [7]. The nanophotonic cavity enhances the interactions between light and electron spin, enabling strong coupling (cooperativity node A (node B) $C = 12.4(1.5)$) 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 (Figure 1 b). 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 the electrons in the 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.

3. A Two-Node Quantum Network

To demonstrate the basic principles of network operation, the nodes are initially directly connected via $\approx 20\text{ m}$ 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 $\mu = 0.017$. Correlations are measured to estimate the resulting Bell state fidelity (Figure 1 c). We measure a Bell state fidelity of $\mathcal{F} = 0.86(3)$, 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 Figure 1 d, where we show we can operate at success rates beyond 1 Hz while maintaining entanglement.

To build large-scale quantum networks, generation of quantum entanglement across metropolitan scale fiber networks is required. Light at the SiV's resonance wavelength (737 nm) experiences a prohibitively large in-fiber loss of $> 4\text{ dB km}^{-1}$, which limits the practical range of remote entanglement distribution. To overcome this, we employ bidirectional QFC to the telecom O-band (1350 nm). After the photonic qubit at 737 nm 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.

We combine QFC with entanglement generation of SiV's 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 40 km in length with minimal additional infidelity. To highlight the compatibility of this system with conventional fiber infrastructure, we generate entanglement through a 35 km loop of telecom fiber deployed in the Boston area urban environment with an insertion loss of 17 dB (Figure 1 e/f). Using this deployed link, we generate entanglement with a fidelity of $\mathcal{F} = 0.69(7)$, demonstrating a functioning quantum network link in a realistic fiber environment.

4. 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. Combining these advances with the potential ability to create a large number of cavity-QED systems fabricated on a chip, this approach can eventually result in large-scale, deployable quantum networking systems.

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