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# Scalable Integration of Solid State Quantum Memories into a Photonic Network

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**Abstract:** Single nitrogen vacancy centers in nanostructured diamond form high quality nodes integrated into low-loss photonic circuitry, enabling on-chip detection and signal manipulation. Pre-selection provides near-unity yield. Long coherence times are demonstrated in integrated nodes.

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## 1. Introduction

A scalable quantum network with distinct quantum memory nodes connected via photonic channels would enable quantum information systems such as quantum computers and repeaters [1]. There are four requirements that must be met to achieve scalability: 1) quantum memory nodes with state coherence much longer than the time to generate entanglement, 2) photonic circuitry with modifiable connections and low information loss, 3) high-fidelity state transfer between node and channel quantum states, and 4) near-unity yields of nodes, channels, interfaces, and detection. Our proposed network architecture consists of quantum nodes - single negatively charged nitrogen vacancy centers (NVs) in nano-structured diamond - connected via a photonic integrated circuit (PIC). Here, we report advances towards achieving the four requirements of a scalable quantum network.

## 2. Experiment and Results

The NV center has emerged as a promising solid-state quantum bit (qubit) with an accessible highly coherent nuclear spin state, and an electronic spin state that can be initialized, manipulated, and measured optically for high-fidelity computations. Various quantum protocols based on the unique properties of NVs have been proposed [3, 4], and quantum entanglement and state teleportation between two nodes has been demonstrated [2]. However, the achieved entanglement time is much longer than the spin coherence time of the NV, and NV creation is stochastic so yield is extremely low.

Near-unity quantum node yield can be achieved through pre-selection. We fabricated arrays of diamond nodes and characterized the nodes confocally. We then selected nodes with single, well-positioned NVs with good spin and spectral properties and integrated them into the pre-built photonic backbone.

The gap between entanglement creation and storage time can be reduced by increasing NV emission into the narrow zero phonon line (ZPL) by modification of the local density of photonic states, e.g. with a cavity [5], and by maximizing the coupling of the NV emission into the PIC. We have shown that high coupling efficiency (up to 82% of ZPL emission) can be achieved with a simple coupling region - a single mode diamond waveguide with tapered ends placed over an air gap in a single mode waveguide, as illustrated in Figure 1a [8].

To demonstrate the experimental efficiency of this simple coupling structure, as well as the achievable high yield, we integrated four diamond waveguides - each pre-selected to contain one NV center near the center of the waveguide - into a silicon nitride (SiN) PIC. Once integrated, each node was excited via a confocal microscope at 532 nm. A cross correlation measurement on one of the NVs between signal collected via the confocal setup and signal collected through the waveguide shows the preservation of single photon character (Figure 1c). Saturation measurements corrected for detection inefficiencies and background show high collection efficiency with over 1.4 million NV photons per second collected into the single mode optical waveguide at infinite excitation, 3.8× more than is collected

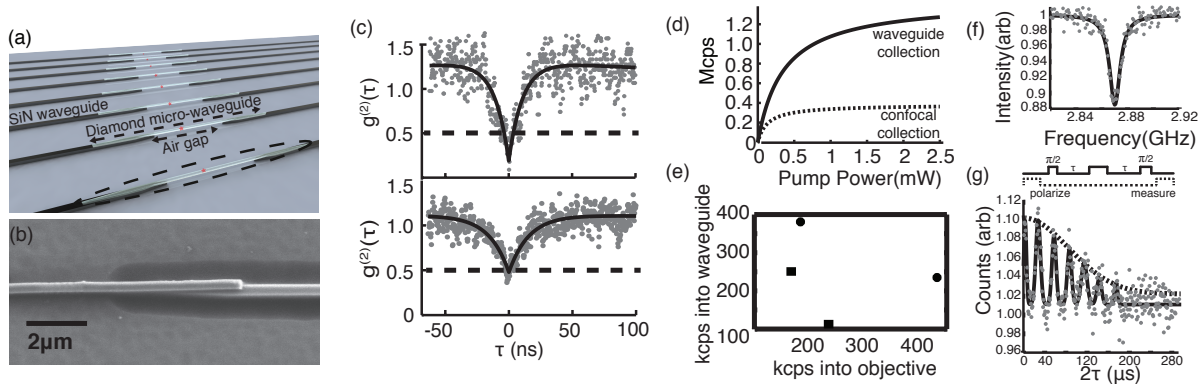


Fig. 1. Demonstration of a PIC with NV emission efficiently collected into a SiN waveguide a) Schematic of a PIC with multiple integrated quantum memory nodes. b) Scanning electron micrograph of a diamond waveguide placed over a gap in a SiN waveguide. c) normalized auto-correlation via confocal collection (top) and normalized cross-correlation (bottom) measurements of one integrated quantum node confirming single photon emission into the waveguide. d) Saturation measurements corrected for background and collection losses. e) Counts collected into a free space objective vs. counts collected into the single mode SiN waveguide for 4 integrated NV centers at 125uW of excitation. Circles are calculated from saturation curves, and squares are measured. f) ODMR of an integrated NV under no magnetic field with waveguide collection. g) A Hahn-Echo measurement to decouple the NV from the surrounding spin bath and measure  $T_2 > 120 \mu\text{s}$ .

through the confocal setup (Figure 1d). Moreover, all four nodes that we integrated into the PIC show high collection efficiency with  $> 1 \times 10^5$  NV photons per second collected into the single mode waveguide at 125  $\mu\text{W}$  of excitation (Figure 1e) [8].

Finally, we measured the spin properties of our integrated quantum nodes. Optically detected magnetic resonance collected through the waveguide shows high contrast of 12% (Figure 1f), and a  $T_2$  measurement shows that our quantum nodes retain the long coherence times typical of NVs during the fabrication and integration process (Figure 1g) [8].

In conclusion, we have integrated multiple high-quality quantum nodes into a low-loss PIC in a way that allows near-unity yield and high coupling efficiency between the quantum node and quantum channel. Future work towards a scalable quantum network will increase efficiency with single-photon detectors integrated into the PIC [9], and modulators used to route light through a PIC with increased complexity.

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