Research Statement: Scalable Solid State Quantum Information Processing

1 Introduction

Quantum computation and communication systems leverage the advantages of quantum information to surpass their classical counterparts in certain applications. Theoretical work promises secure communication networks and computational speed-ups for problems that are classically intractable. However, while proof-of-principle experimental demonstrations have been performed, these are limited to a handful of nodes with limited - and often immutable - connectivity between nodes. My research focuses on investigating and demonstrating solid-state quantum information processing architectures that can reach the scalability requirements for general-purpose quantum computing.

2 Current Work

I am interested in quantum information architectures in which stationary isolated quantum memories are connected via photonic channels. In particular, I am interested in solid state quantum memories connected via photonic integrated circuits (PICs). This promises to be a compact, phase-stable, and scalable architecture for small quantum computation networks or for intermediate quantum repeater nodes in a larger quantum communication network. One promising solid-state quantum memory is the negatively charged nitrogen-vacancy center in diamond which provides millisecond electron spin coherence times [1]. Moreover, the state of the electron spin can be transferred to the state of an emitted photon which can be used to mediate multi-qubit interactions. Recent work demonstrated the high fidelity entanglement of two spatially separated NVs [2], but the entanglement rate remains well below the decoherence rate, limiting the network size to two.

During the first year of my PhD I helped demonstrate many of the necessary photonic components fabricated directly into bulk diamond [3]. However, patterning in diamond is challenging and the production of high quality quantum nodes is inherently low yield due to the stochastic process of NV creation. Thus, I pioneered a hybrid approach in which the diamond nodes are fabricated in arrays and pre-characterized with only the best integrated into a separate high-quality PIC [4] that provides all photonic routing, photonic detection, and on-chip microwave control for single qubit rotations.

Although a simple diamond waveguide can be used to guide a majority of the light into an underlying PIC [4], the rate of photons coherent with the electron spin state is limited by phonon interactions with the lattice. To increase the collection rate beyond this bound it is necessary to resonantly enhance the transition of interest. To this end, I developed a process for fabricating nanobeam photonic crystal cavities with rectangular cross-sections that are loaded into a waveguide mode for high coupling into the underlying PIC. This new fabrication technique provides consistent fabrication across the full chip and cavities with resonances with record high quality factors at the optical transition coherent with the spin state [5]. I also developed a novel hybrid cavity structure that allows for the stable and reversible post-fabrication tuning of the resonance position to account for any fabrication imperfections [6].

3 Future Directions

With a scalable hybrid architecture interfacing high quality diamond nodes with an underlying active PIC it is now necessary to show an on-chip entanglement rate much faster than the decoherence rate, beginning with an increased rate of photons entangled with the electron spin. To achieve this, I am working with collaborators to investigate the sources of decoherence and mitigate them with a combination novel nanostructure design, careful nanofabrication, and post-fabrication surface treatments. Furthermore, I am currently pursuing theory on optimal quantum computing architectures that make best use of our new experimental capabilities.

For instance, an on-chip platform provides a phase stability that is difficult to achieve in free space, fast active components for circuit reconfigurability, and multimode interferometer geometries made possible by nanofabrication. Looking forward, I will continue investigating and demonstrating all of the components necessary for a scalable quantum information platform - from single qubit control, to optimal multi-qubit gate implementations, to the necessary classical control.

References

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