Graduate Research Statement

Introduction:
The rules of quantum mechanics enable technologies that are inherently more powerful than their classical counterparts. For example, quantum key distribution (QKD) enables the transmission of data with absolute, unconditional security[1]; quantum simulation protocols could solve many-body problems such as high temperature superconductivity[2], which in turn could revolutionize the way nations produce and transmit energy around the globe[3]; and quantum metrology techniques push the boundaries of precision measurement[4]. I am particularly intrigued by the possibility of using quantum computers to solve currently intractable problems such as band structures calculations in quantum chemistry to accurately predict novel materials[5]. While research efforts across the globe are seeking to realize such technologies in a range of physical systems, in graduate school, I would like to pursue the photonics approach.

Quantum effects are particularly easy to observe in optical systems. Photonic integrated circuits (PIC), in particular, offer a robust and scalable platform for implementing linear optics quantum computing (LOQC). It has been demonstrated that linear optics can be used to efficiently encode qubits[6], realize high-fidelity quantum gates[7], and to perform non-deterministic quantum computations[6], a feature that is unachievable with classical deterministic or probabilistic computation schemes. However, experiments in photon-based quantum information processing to date have been limited by three major obstacles: inefficient production of single, and entangled photons; the difficulty of fabricating the complex PICs required for state evolution and tomography; and the inefficiency of single-photon detectors. The Quantum Photonics group at the Massachusetts Institute of Technology is currently working to radically improve all three problem-areas by developing a programmable quantum photonic processor (QPP) with integrated sources and integrated high-performance state tomography.

Hypothesis:
It has been shown that the QPP, which consists of a network of waveguide-based Mach Zehnder interferometers (MZIs) with internal and external phase shifters (Fig.1), could enable high-fidelity quantum simulation[7]. However, this PIC has not yet been used to experimentally test high-fidelity quantum computation (HFQC) schemes in the context of LOQC. Fidelity describes how close an operation is to the ideal quantum operation. HFQC is only possible if quantum-gate error probabilities are below some threshold[8]. Due to advanced fabrication processes and the optimization of gate settings that the Quantum Photonics group has developed, the QPP offers a path towards achieving these error rates on a PIC.

General Approach:
The initial step consists of preparing single photons from a source such as a time-multiplexed spontaneous parametric down-conversion element[9]. ~~This~~ The source sets the state of any given mode to a single-photon state. An optical mode is simply the distribution of photons in a waveguide. Then, the QPP evolves the state of these photons, implementing the required unitary transformations, and preserving the total photon number. Finally, the readout is accomplished by measuring an optical mode with superconducting nanowire single photon detectors[10], which determine whether one or more photons are present in that mode.

I joined the group for the summer of 2014 as part of the MIT Summer Research Program. During this time, I built a calibration and characterization system for the network of multi-channel, tunable phase shifter drivers that control the QPP. The goal was to mitigate static errors in the drivers that could potentially affect the optimization of phase settings of the QPP. This

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Comment [IU3]: Good. Shows you know the gaps in the research field.

Comment [IU4]: I haven't read that MIT is where you are pursing graduate school. You need to clearly state this because I think you document implies this but you don't clearly state it.

Comment [IU5]: Good.

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Comment [IU7]: Specify group name again.

optimization could compensate for fabrication defects, which in turn would dramatically improve the fidelity of quantum gates[7]. Furthermore, it was observed that, in addition to static errors, the drivers exhibit dynamic correlations that appear when a channel is set to constant level while all other channels vary and vice versa. Although it is generally difficult to calibrate the drivers to eliminate dynamic fluctuations, the errors that they could introduce to the QPP could be overcome by implementing a HFQC scheme. Given the opportunity, I would join the Quantum Photonics group at MIT to contribute to the experimental investigation of the QPP. As a starting point, I would implement the scheme suggested by Knill[6]. The optimization of phase settings demonstrated by Mower & Harris, *et al*[7], along with the proposed protocol would enable performing quantum simulations, compensating for fabrication errors, photon loss, detector inefficiency, and phase decoherence.

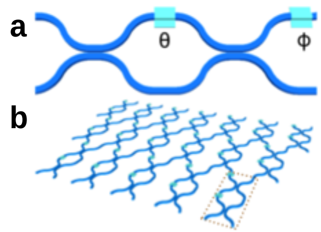

Figure 1: A MZI implements unitaries with an internal and external variable phase shifter as shown in Fig. 1(a). To evolve the state of photons, MZIs are tiled to form lattices, such as that in Fig. 1(b) [7].

Comment [IU8]: I think you should say this earlier. It is not clear until this point and that is a little confusin. You can restate it here bc you are specifying the exact research within the group.

Comment [IU9]: What are your general hypotheses? How will these methods help you answer those questions? How will your work be different from these? What are your anticipated results?

Intellectual Merit:

Band structure calculations account for up to 30% of the computation time used at supercomputer centers[11]. Although conventional computers can be used to predict material properties, these are mere approximations. The exact solution to the Schrödinger equation within a given numerical basis scales exponentially with the number of basis functions[11]. A conventional computer might not converge to the quantum state of all possible molecular states, making quantum chemistry problems hard to simulate. The QPP, however, can implement any unitary transformation for state evolution. That is, quantum chemistry simulations would not only converge to accurate solutions, but would also do it in a significantly reduced time.

Broader Impact:

The proposed work would enable using the QPP not only to design novel materials, but also for the simulation of interesting problems in quantum biology, solid-state physics, and testing of QKD protocols. These are all important applications not only for scientific purposes, but also for national security and future economic competitiveness. Lastly, this project would both, prepare me for a career in a national laboratory or government agency, and allow me to mentor and motivate other students to pursue STEM fields through outreach activities and publications.

References:

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