Graduate Research Statement

Introduction:

The laws of quantum mechanics enable certain technologies that are 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 have the capability to 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 the properties of novel materials[5]. While research efforts across the globe are seeking to realize such technologies in a range of physical systems, I will pursue the photonics approach in graduate school. Light is the ideal candidate not only for quantum simulation but also for long-distance communication, which will be necessary for developing large-scale processors and quantum communication protocols.

Photonic integrated circuits (PIC) offer a robust and scalable platform for implementing large-scale quantum computing (LSQC). It has been demonstrated that simple optical elements such as beam splitters and phase shifters can be used to efficiently encode qubits[6], realize high-fidelity quantum gates[7], and perform non-deterministic quantum computations[6], features that are unachievable with classical 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 in the Electrical Engineering department at the Massachusetts Institute of Technology, where I plan to do my graduate training, 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 PIC-based Mach Zehnder interferometers (MZIs) with internal and external phase shifters (Fig.1) could enable high-fidelity quantum simulation (HFQS)[7]. Fidelity describes how close an operation is to the ideal quantum operation; to a good approximation, LSQC requires quantum-gate fidelities above a certain threshold[8]. Due to advanced fabrication processes and the optimization of gate settings that the Quantum Photonics group has developed, the QPP should offer a path towards achieving these error rates on a PIC.

General Approach:

The initial step to HFQS consists of preparing single photons from a source such as a time-multiplexed spontaneous parametric down-conversion element[9]. Then, the QPP evolves the state of these photons, implementing the required unitary transformations. Finally, the readout is accomplished by measuring the photons with superconducting nanowire single photon detectors[10], which determine whether one or more photons are present.

I joined the Quantum Photonics 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 system mitigated static errors in the drivers that could affect the QPP optimization. Furthermore, we observed that, in addition to static errors, the drivers exhibit correlated errors that appear when a channel is set to constant level while all other channels vary and vice versa. Overcoming both static and correlated errors should enable the optimization of the QPP parameters for HFQS. Given the opportunity, I would join the Quantum Photonics group at MIT to verify this prediction. As a starting point, I would implement the schemes suggested by Rebentrost *et al* [11]. The optimization of phase settings demonstrated by Mower & Harris, *et al*[7], along with the proposed protocol will enable determining the QPP's fidelity. Achieving the expected error rates would also enable testing fault-tolerant schemes such as those suggested by Knill[8], which would evaluate the success of the proposed plan.

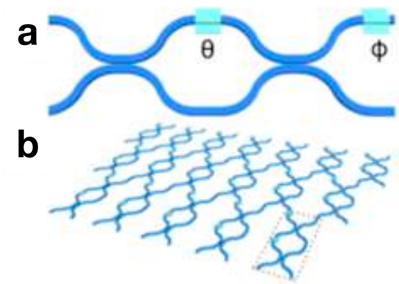

Figure 1: A MZI implements unitaries with an internal and external variable phase shifter as shown in Fig. 1(a). To evolve the state of photons, MZIs are tiled to form lattices, such as that in Fig. 1(b) [7].

Intellectual Merit:

Band structure calculations account for up to 30% of the computation time used at supercomputer centers[12]. 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 atoms constituting the material[12]. A conventional computer might not converge to the quantum state of all possible atomic states, making quantum chemistry problems hard to simulate. The QPP, however, can implement any linear optics unitary transformation for state evolution. That is, quantum chemistry simulations in the QPP will not only converge to accurate solutions, but they will converge in a significantly reduced time.

Broader Impact:

The proposed work will enable using the QPP not only to design novel materials, but also for the simulation of interesting problems in quantum chemistry, biology and solid-state physics; testing of QKD protocols; implementation of quantum machine learning algorithms[11]; optical routing in telecommunication networks[13]; and for accelerating classical circuit operations. These are all important applications not only for scientific purposes, but also for national security and future economic competitiveness. This project will 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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