An integrated programmable quantum photonic processor for linear optics

Jacob Mower[1,#], Nicholas C. Harris[1,#], Greg Steinbrecher[1], Yoav Lahini[2], and Dirk Englund[1,*]

1 Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
2 Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

 # equal contribution,
**correspondence: englund@mit.edu*

Abstract: We introduce a reconfigurable silicon quantum photonic network for implementing general linear optics transformations in the spatial mode basis. This network enables implementation of a range of quantum algorithms; we discuss the phase estimation algorithm.
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1. Introduction

There is growing interest in implementing quantum information processing (QIP) algorithms using linear optics; tasks including quantum simulation [1], quantum walks [2] and boson sampling [3] have been demonstrated experimentally (e.g., [4]). However, these experiments were performed in single-purpose architectures in which only a small subset of linear optics transformations could be implemented. We introduce a programmable quantum photonic processor (QPP) that enables the implementation of any unitary possible with linear optics using a network of dynamically tunable Mach-Zehnder interferometers (MZI) on a silicon PIC. We anticipate that the ability to rapidly implement an arbitrary unitary optical transformation on a large set of spatial modes can greatly accelerate the development, optimization, and verification of linear optics quantum algorithms.

2. Implementing quantum logic gates: the 6-mode CNOT gate and iterative phase estimation algorithm

Fig. 1 shows the QPP. We represent the MZI as a two-input, two-output box. Circuits such as the six-mode CNOT can be embedded in large arrays [Fig. 1(a)]. Fig. 1(b) shows the CNOT gate implemented previously based on a proposal by Ralph *et al.* [5] and Fig. 1(c) shows the corresponding QPP implementation. The upper number in each box gives the intensity reflectivity, η, of the MZI, which is given by the internal phase setting, and the lower number corresponds to the output phase setting. Fig 1(d) shows the decomposition of the unit cell into photonic integrated circuit components: two directional couplers followed by thermo-optic modulators. More complex circuits than the CNOT gate, such as the iterative phase estimation algorithm (IPEA), can also be programmed into the QPP. Fig. 2(a) shows the layout of the IPEA for a particular unitary operator using a controlled phase gate and single qubit rotations.

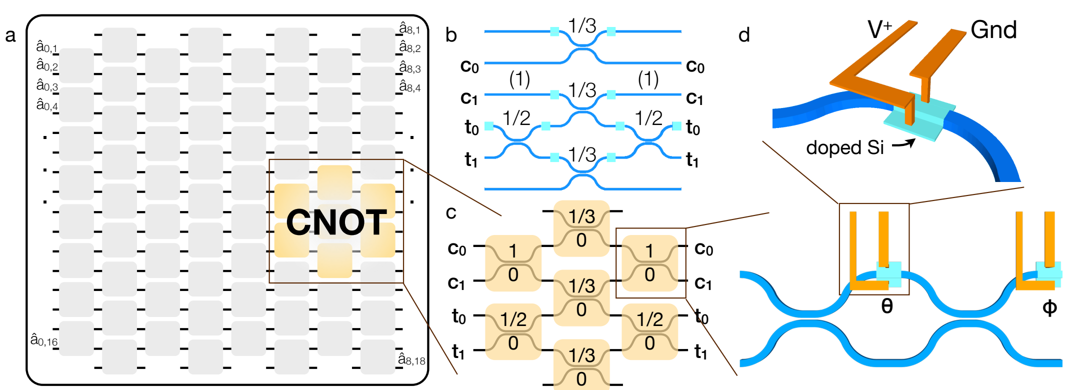

Fig. 1. (a) Schematic representation of the MZI array, (b) the six-mode CNOT gate, (c) The CNOT gate implemented in MZIs with the numbers shown representing splitting ratio and external phase settings of the MZI, (d) Rendering of the MZI unit cell composed of two directional couplers and two phase shifters.

To implement this scheme, we fabricated photonic networks on silicon-on-insulator (SOI) wafers. This takes advantage of advanced fabrication processes, high-quality single photon sources [6], single-photon detectors [7], and potential integration with CMOS. To quantify the performance of the quantum logic gates, we separately experimentally characterized the constituents of the networks: the phase shifters and directional couplers [8]. The thermo-optic modulators showed a loss of 0.23 +/- 0.13 dB and the directional couplers had a splitting ratio of 50.9% +/-1.9% at 1560 nm. We use these results to simulate the IPEA, quantifying performance using the normalized matrix difference between real and actual restricted multi-particle unitaries [3]. Considering imperfections in the directional couplers and heaters, the performance of the IPEA is still very close to one; the orange curve in Fig. 2(b) shows the performance of a circuit programmed into specific elements of the MZI array. The yellow curve shows the performance of the same system where the phase settings were optimized using a nonlinear algorithm given known imperfections in the circuit. The optimized circuits demonstrate the ability of these reconfigurable circuits to route around defects.

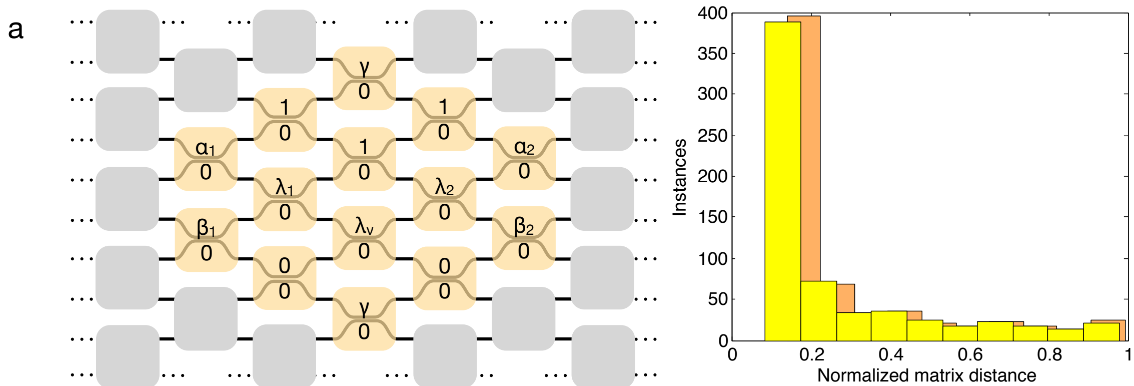

Fig. 2. (a) MZI settings to implement the IPEA. Greyed MZIs are not used. In (b), we show histograms of the circuit performance – quantified by the normalized matrix difference – for realistic randomness due to fabrication. In orange, we show the un-optimized performance, and in yellow, the optimized performance.

3. Outlook

The QPP also offers a unique opportunity to study quantum random walks (QRW), which have recently been studied as an alternative approach to QIP [2]. An inherent difficulty in the study of quantum dynamics in disordered systems [9] is that a single realization of disorder offers very little information and can contain extreme arrangements leading to artifacts. With current integrated photonics technology, multiple iterations of disorder usually require the manufacturing of many separate samples or non-trivial processing of a single sample. By contrast, the QPP proposed in this paper is amenable to such studies, as the same device can be used to probe many different realizations of any disordered configuration by only modifying the voltage applied across thermo-optic modulators.

Strong investment in silicon photonics for classical information processing [10] suggests that the performance of silicon-based QPPs will continue to improve. But the path toward implementing extremely large and unit-fidelity gates lies in designing more fabrication-tolerant MZIs, e.g., by making all mode couplers tunable *in situ* using MZIs to achieve precisely $\eta = 0.50$. Such systems can be combined with on-chip detectors [7], sources [6], and high-performance CMOS logic [10].

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