Programmable Nanophotonic Processor for Arbitrary High Fidelity Optical Transformations

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Abstract: We present an architecture for programmable nanophotonic processors capable of arbitrary discrete transformations for quantum and classical applications. A method to combat fabrication imperfections with high fidelity is discussed along with initial experimental results.

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1. Introduction

Generation of high-dimensional optical transformations is a primary application of photonic integrated circuits in both the quantum and classical regimes. Examples include linear optics quantum gates, one-to-many power splitters, and mixers for optical transceivers. However, these systems are typically custom-built for each application and, in general, cannot be tuned in situ to combat fabrication errors. We have proposed an architecture that allows us to overcome these issues; in particular, we showed in [1] how our architecture can overcome fabrication imperfections to generate arbitrary linear optical quantum gates with high fidelity.

Here, we discuss the methods underlying our previous work and show how this system can be extended to the generation of arbitrary linear optical transformations with high fidelity. This positions our architecture as a general programmable nanophotonic processor (PNP) with myriad applications in both quantum and classical photonics.

2. The PNP Architecture

The building block of our PNP is a reconfigurable beamsplitter whose phase and splitting ratio can be controlled arbitrarily. This is most readily implemented in integrated photonic systems with a Mach-Zehnder interferometer (MZI) composed of directional couplers and phase shifters. Tuning the internal and external phase differences controls, respectively, the splting ratio and differential output phase, allowing any beamsplitter (i.e. any 2×2 unitary) to be implemented. We tile these building blocks in a hexagonal lattice for a full PNP (see Fig. 1 and Ref. [1] for details).

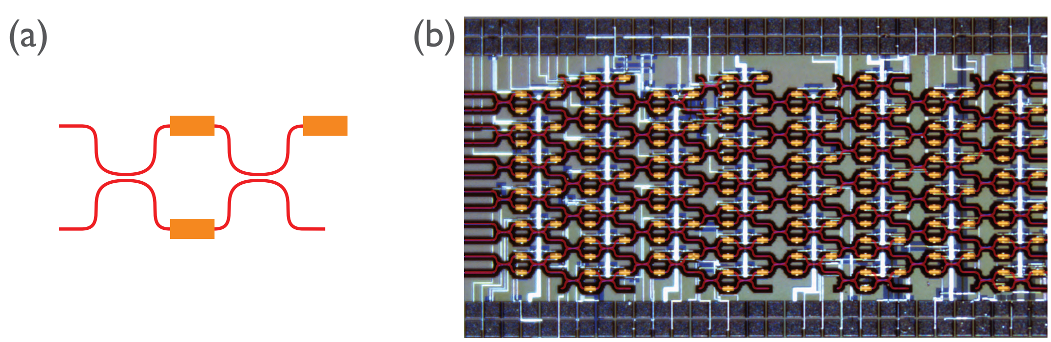

Fig. 1. (a) Single Mach-Zehnder unit cell with internal and external phase shifters. (b) Optical micrograph of one fabricated PNP system (colors adjusted) overlaid with system diagram. In (a) and (b), waveguides are red and thermo-optic phase shifters are orange.

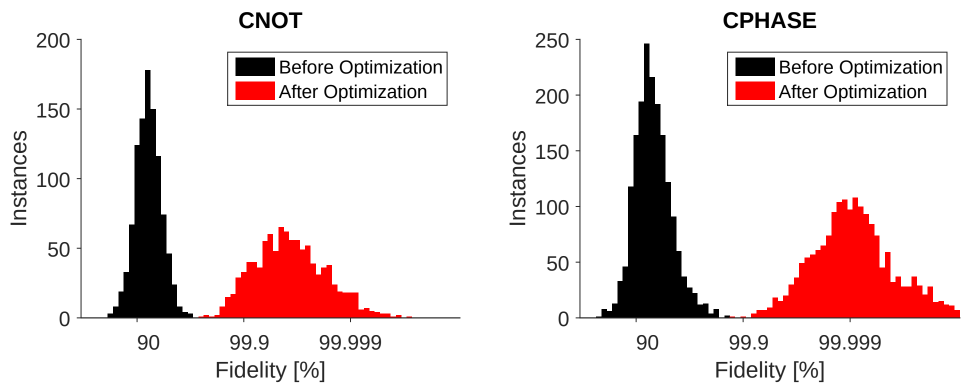

Fig. 2. We simulated fabrication imperfections in each PNP using a Monte Carlo technique with distributions drawn from full-wafer data [2,3] and programmed two different linear optical quantum gates: CNOT [4] and CPHASE [5]. The CNOT gate was optimized for 1000 different instances of imperfections, the CPHASE for 300 at six different phase settings.

3. Realistic System Operation

In an ideal system, the directional coupler is a symmetric 50/50 beamsplitter, the waveguides are all identical, and nothing has loss (or, at minimum, loss is evenly distributed). However, in a realistic system, the directional couplers are not perfectly symmetric [2], the phase shifters have some loss that varies statistically [3] and, due to microscopic variations in waveguide index, there is some static differential phase between the arms of the interferometer.

These effects compound quickly throughout the PNP; without compensation, the system cannot scale to even moderate sizes. To combat this, we have devised an efficient method to characterize each MZI. Once this characterization is performed, we have developed computational techniques that can optimize the applied phases to generate desired transformations with high fidelity. See Fig. 2 for an example of this, applied to linear optical quantum gates.

4. Experimental Realization

We have fabricated a large PNP in the silicon on insulator process (see Fig. 1(b)) and are actively developing the control and characterization architecture to support it. We will discuss the experimental challenges this has presented along with initial results.

5. Discussion

We have shown a nanophotonic processor architecture that can be programmed for arbitrary linear transformations. Taking into account realistic fabrication errors, we have developed a scheme to characterize a given system and tune it to perform arbitrary, high fidelity operations. These operations, which can be as complex as quantum gates or as simple as a one-to-many power splitter, can all be performed in a single system with only electronic reconfiguration. This system has the potential to enhance the performance of integrated photonics systems in a wide variety of applications.

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