Towards Large-Scale Silicon Photonic Programmable Optical Processors for Machine Learning and Optical Quantum Computing

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***Abstract*— We discuss the progress made towards large-scale programmable optical processors on Silicon Photonics for ultrafast and energy efficient computing.**

***Keywords*—Optical computing, programmable optical processors, Silicon photonics.**

I. Introduction

Programmable optical processors are promising structures for ultrafast and energy efficient computation in classic and quantum photonics. These processors efficiently perform the vector-matrix multiplication extensively used in artificial intelligence and machine learning tasks. Due to the inherent parallelism presents in optics in contrast with sequential operations in electronics, optical processors are faster offering better energy efficiency compared to their electronic counterparts [1]. Today, deep learning is facing growing computational demand limiting its development if we continue using conventional electronic processors [2]. Energy efficient computational accelerators fabricated in silicon photonic (SiPh) are candidates to meet the computational demands of future machine learning and deep learning tasks.

Programmable optical processors also pave the way for integrated optical quantum computing [3]. Single photons are excellent candidates for quantum computing due to their noise and decoherence-free nature. One can generate optical qubits by encoding single photons in one degree of freedom such as polarization or path. Optical integrated quantum computing requires quantum logic gates to manipulate these qubits. Quantum logic gates are represented by unitary matrices, such that a $2^n \times 2^n$ unitary matrix multiplication is identical to an n-qubit gate. Therefore, a programmable optical processor capable of performing unitary matrix multiplication on single photons works as an arbitrary optical integrated quantum gate.

II. Progress Towards Large-Scale Programmable Optical Processors on Silicon Photonics

SiPh is the technology of choice for programmable optical processor leveraging complementary metal oxide semiconductor (CMOS) technology's large investment since the '60s. Small-scale programmable optical processors have been demonstrated on SiPh with a limited number of optical input/outputs [1]. Scaling the programmable optical processors is, however, challenged by the insertion loss of building blocks mainly Mach-Zehnder interferometers (MZIs), phase error in the phase shifters, and difficulties related to the calibration and programming. Different mesh topologies are presented to improve the processor performance in the presence of loss and phase error [4]. Hybrid integration of active gain blocks in SiPh platform, already developed for SiPh switches, is a viable solution to compensate for the insertion loss and improve the optical processor performance [5]. Also, silicon nitride technology platform offering lower propagation loss than silicon-on-insulator contributes to decreasing the insertion loss. The coupling and on-chip insertion loss become even more crucial when we use the optical processor as a quantum gate [3].

Large scale programmable optical processors should be fully reconfigurable by software after the fabrication similar to what is offered by the electronics field-programmable gate arrays (FPGAs). However, there are two main challenges to address. Firstly, programmable optical processors, unlike electronic FPGAs, are based on analogue building blocks sensitive to the fabrication variations. Hardware error correction schemes can address this issue. Secondly, calibration and programming optical processors require sensing both the optical power and optical phase. Although sensing the optical power is straightforward in SiPh using on-chip photodetectors, sensing the optical phase requires elaborate hardware or novel optical on-chip phase measurement techniques.

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