

Programmable Silicon Photonic Integrated Circuits

(Invited Paper)

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Abstract

Programmable photonic circuits offer a new way to explore photonic chips: instead of hardwiring waveguide connections, one programs a mesh of tunable couplers. This requires electronics and software routines to govern the behavior of the chip, making it possible to rapidly develop new photonic applications.

I. INTRODUCTION

Photonic integrated circuits (PIC) are getting more complex as technology is improving. Especially with silicon photonics circuits, thousands of building blocks (couplers, phase shifters, photodetectors and even amplifiers) can be integrated onto a chip [1]. But today, most of these circuits are designed for a single application: they are application-specific PICs, or ASPICs. That means that a new chip needs to be designed for every new need, which slows down deployment in new applications [2].

What if PICs could follow the patterns of programmable electronics? Off-the-shelf available microcontrollers, digital signal processors (DSP) and field-programmable gate arrays (FPGA) can be configured to perform various tasks and make it possible to implement new functions in a matter of days, rather than months to design and fabricate a new chip.

The emerging field of programmable PICs tries to fill this space [3]. Rather than a specialized circuit of functional building blocks for a specific function, a programmable photonic circuit uses a mesh of waveguides with tunable couplers to define the connectivity on the chip at run-time in software through driver electronics. In this conference paper, we will explain the basic principles behind such generic programmable PICs, and where the technological needs differ from today's ASPICs.

II. PROGRAMMABLE WAVEGUIDE MESHES

At the heart of a programmable PIC is a mesh of interconnected waveguides, where the flow of light is controlled using tunable couplers and electro-optic phase shifters. A implementation is with a Mach-Zehnder interferometer with dual phase shifters, which can control the coupling ratio and phase delay independently [6]. It is not trivial to implement tunable couplers that cover a broad wavelength range with a full 0-100% tuning range, but this can be solved by using additional circuit elements and active control [5].

Depending on the connection topology, we can identify two broad classes of meshes: *forward-only* and *recirculating*. In a forward-only mesh, light flows in one direction, and the couplers control the interference between different paths [6]. Such meshes are well suited for input-to-output switching, or for linear transformations between input and output modes, implementing matrix operations for artificial neural networks and quantum-optic circuits [7].

In recirculating meshes, the waveguides are arranged in loops, which are coupled along the edges. This way, light can be coupled back onto itself, forming delay lines and resonators. The delays and loops can form interferometric wavelength filters [4] to select specific optical wavelength bands, or process radio-frequency (RF) signals modulated on an optical carrier.

The reconfigurability of the mesh is only possible with many electrically controlled tunable couplers and phase shifters. These need to be compact and have a low optical loss, because the light passes through many actuators in series. In silicon photonics, the most common phase shifters are based on heaters, but these consume a lot of power, which does not scale well to larger circuits. Less mature alternatives include piezo-electric actuators, liquid crystals and MEMS [8].

III. WHAT IS NEEDED FOR A PROGRAMMABLE PIC?

While the waveguide mesh core is essential to reconfigure the PIC, additional elements are needed for a generic fully programmable PIC. First of all are inputs and outputs for signals: for optical signals, fiber interfaces are most straightforward (surface gratings or edge couplers). But it is also possible to use high-speed electro-optic modulators to translate RF to the optical domain, and (balanced) photodiodes to translate modulated optical signals back to the RF domain.

The programmable PIC needs driver and control electronics, to control the many the phase shifters and tunable couplers independently. This requires with many electrical channels which need to be connected to the chip. We have developed a

