2226

Large-scale Programmable Silicon Photonics

(Invited paper)

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ABSTRACT

In the past few years, new concepts for general-purpose, programmable photonic integrated circuits have been proposed. These stand in contrast to custom-designed, *application-specific photonic integrated circuits* (ASPIC), in a similar way as electronic *field-programmable gate arrays* (FPGA) and microcontrollers stand in contrast with *application-specific integrated circuits* (ASIC). Several programmable PIC concepts have already been experimentally demonstrated on a modest scale, reproducing functionality in programming that was hitherto limited to custom-designed hardware. The PhotonicSWARM project looks into the scaling potential of such programmable PICs, combining distributed optical paths with distributed control algorithms to keep larger circuits manageable. We will discuss these concepts and the recent results in this project, implemented using silicon photonics technology.

Keywords: Programmable Photonics, Photonic Integrated Circuits.

1. INTRODUCTION

Photonic Integrated Circuit (PIC) technology today has reached a point where large-scale integration has become a technological possibility. Especially with silicon photonics, chips with >10000 optical elements can be fabricated with acceptable quality. This has resulted in demonstrations of large-scale switches, or optical phased array components, but most photonic circuit demonstrations remain much smaller in scale. They are typically designed to perform a single function with best efficiency, similar to electronic ASICs. In contrast, new photonic circuit concepts have emerged in the past years that have the ambition to be more generic in applicability, and reconfigurable to perform a multitude of different optical functions [1]–[4]. Such *programmable PICs* bear a resemblance with electronic FPGAs. These new programmable PICS, or photonic processors, consist of regular arrangements of optical waveguides and couplers to realize arbitrary connectivity and distribution of light on the chip. Combined with active functionality such as modulation, detection and gain, they can perform different operations in incoming light and/or electrical of *radio-frequency* (RF) signals. A conceptual schematic of such a generic programmable PIC is shown in Figure 1. Optical inputs/outputs are connected to a reconfigurable linear circuit. This circuit provides connectivity to active optical elements such as electro-optic modulators or high-speed photodetectors (which provide the inputs and outputs for RF signals).

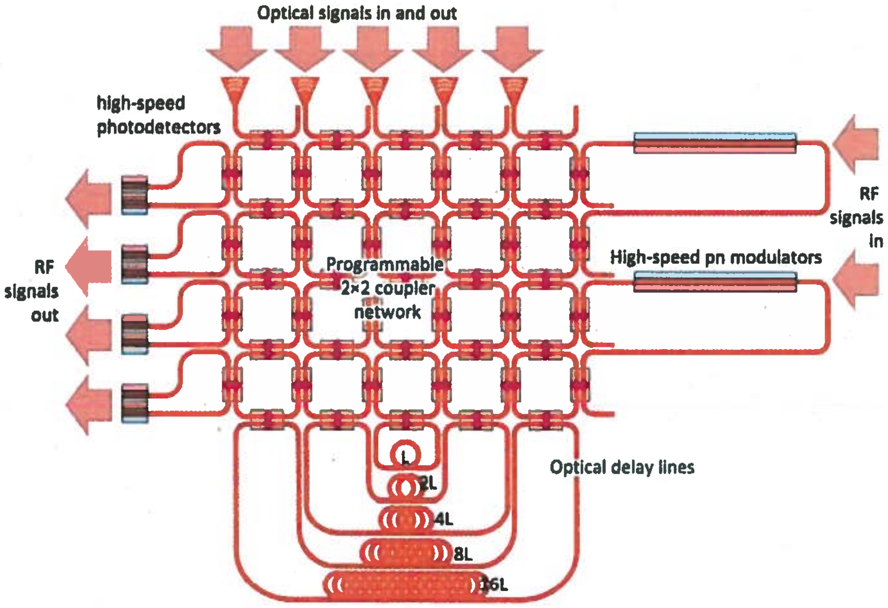

Figure 1: Conceptual schematic of a programmable photonic IC. A programmable linear circuit connects optical input/outputs with RF modulators and photodetectors. The linear circuit can perform arbitrary linear transformations between its input/output ports and perform wavelength filtering functions, either using the 'edge' delay lines, or by configuring a path in the mesh.

2. LINEAR PHOTONIC PROCESSORS

The linear circuit (or linear processor) is the heart of the programmable PIC. It is essentially a N-port linear circuit of which the scatter matrix (S-matrix) can be reconfigured to perform connectivity functions, but also wavelength filtering operations between the different ports. This is done by a cascade of tunable optical couplers and tunable optical phase shifters. Simple switchings is not sufficient, as the multiple inputs can interfere and control of both amplitude and phase in the circuit is essential to obtain the desired coupling ratios between inputs and outputs. The most straightforward implementation of such a circuit was already proposed in 1994 [5]: It consists of a cascade of tunable balanced *Mach-Zehnder interferometers* (MZI) and phase shifters. In 2013, this concept was extended to include simple control algorithms that allow the circuit to configure itself to certain functions [4]. Experimental demonstrations show that these circuits can be used to demonstrate adaptive beam coupling [3] and different linear transformations [2], [6].

By incorporating optical delays in such a linear circuit, programmable wavelength filters can be constructed. The delays can be simple waveguides, but a lot more flexibility is gained by creating programmable loops in the circuits, effectively creating a mesh of coupled ring resonators. Such meshes can have different topologies, based on square or hexagonal unit cells [7], [8].

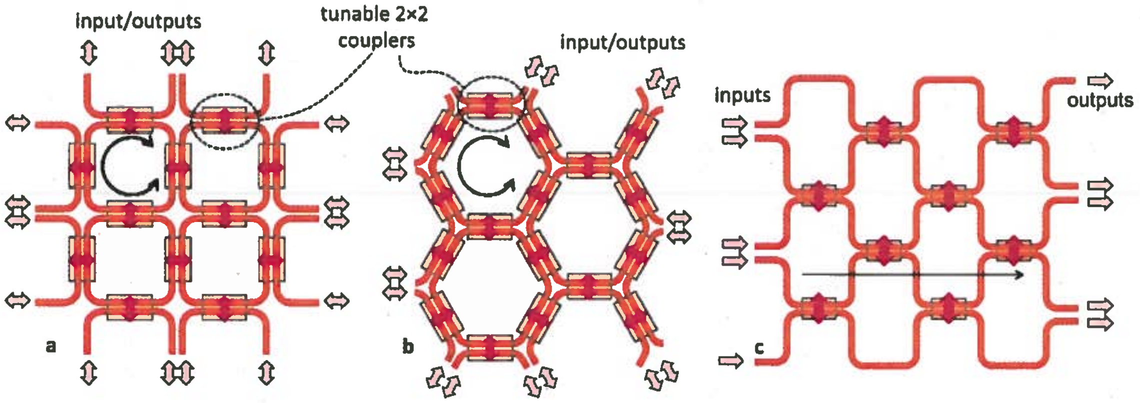

Figure 2: Different architectures for linear photonic processors. (a) Rectangular meshes form a network of ring resonators [7] *(b) Hexagonal lattices offer richer connectivity and clockwise/counterclockwise coupling* [8]. *(c) Unidirectional Mach Zehnder interferometer networks map inputs to a different set of outputs* [5], [9] .

3. A NEW FIELD WITH NEW CHALLENGES

The field of programmable photonic circuits is only just taking off. The first demonstrations show the potential of the technology and the concept, but with these new concepts come new challenges. The reconfigurability implies that the circuits are much larger than non-reconfigurable circuits that should perform similar optical tasks: they contain an order of magnitude more building blocks. This imposes requirements on the technology in terms of integration density and the performance of the individual building blocks. Imperfections and parasitic effects (e.g. loss, backscattering) will accumulate much faster in a programmable circuit. Also, as any function in such a circuit needs actuation, there is a constant power consumption. All implementations of programmable photonic circuits today use thermal tuners, with a tuning efficiency of 10-50mW per π phase shift. Scaling up to thousands of tuners becomes impractical in terms of power consumption. Alternative low-power tuning methods, such as photonic MEMS are not yet available on large-scale integration platforms, but are actively studied, for instance in the European project MORPHIC.

All these tuners need to be controlled, which imposes strong requirements on the electronics. As the number of elements grows beyond the scale of traditional lab equipment, custom driver circuits based on ASICs or FPGAs are needed. The precision of this control is not straightforward: small imperfections can lead to parasitic coupling and interferences that can significantly alter the circuit's function. Therefore the control also requires monitoring of the circuits, and different architectures are possible, inserting monitors either inside the circuit or on the edge. In any case, monitors should induce a minimum of optical losses. Non-invasive techniques such as CLIPP probes [10] can help. Finally, how the control reconfigures and stabilizes the operation of the circuit determines the functionalities that the circuit can accomplish. For instance, an adaptive beam coupler is fairly easy to configure and control [3], [4]. Arbitrary transformations between inputs and outputs require more complicated setup algorithms [9]. Because these circuits are interferometric, small changes in the control can induce large changes in a monitoring response. Control algorithms should therefore be carefully tuned to maintain stability. This can be done either on a global scale for the entire circuit, or on a local scale where only neighbouring circuit elements are taken into consideration. The choice of control algorithm goes hand in hand with the waveguide architectures and the connectivity of the mesh. These considerations are studied in the PhotonicSWARM project.

4. A NEW ECOSYSTEM AROUND PROGRAMMABLE PHOTONIC CHIPS

Programmable photonic chips have the potential to radically change the use of photonic integrated circuits. This is similar to the adoption of FPGAs in electronics. Today, the cost of entering the world of photonic integration is prohibitively high. While the cost of multi-project-wafer runs is still acceptable, the time from design start to packaged chip is usually larger than one year. This stifles development. Programmable PICs, on the other hand, can be available off the shelve and supplied (including standard packages) in a matter of days or weeks. With such chips, the intellectual effort shifts from chip design to programming the functionality. This higher level of abstraction presents new opportunities for innovation. Because programmable PICs can be used in a variety of applications, they can also be fabricated in higher volumes, which will offset the higher cost of the chip (because of its larger complexity and footprint). Like FPGAs and ASICs in electronics, programmable chips will not replace dedicated photonic ICs, which will always have a better performance.

Programmable PICs can find their applications in many domains. Notable are the fields of microwave photonics, where photonic circuits can process RF signals much more efficiently, or quantum optics, where linear processors can perform operations on entangled qubits. But essentially every application field that currently uses dedicated photonic chips or discrete optics could benefit from readily available programmable PICs.

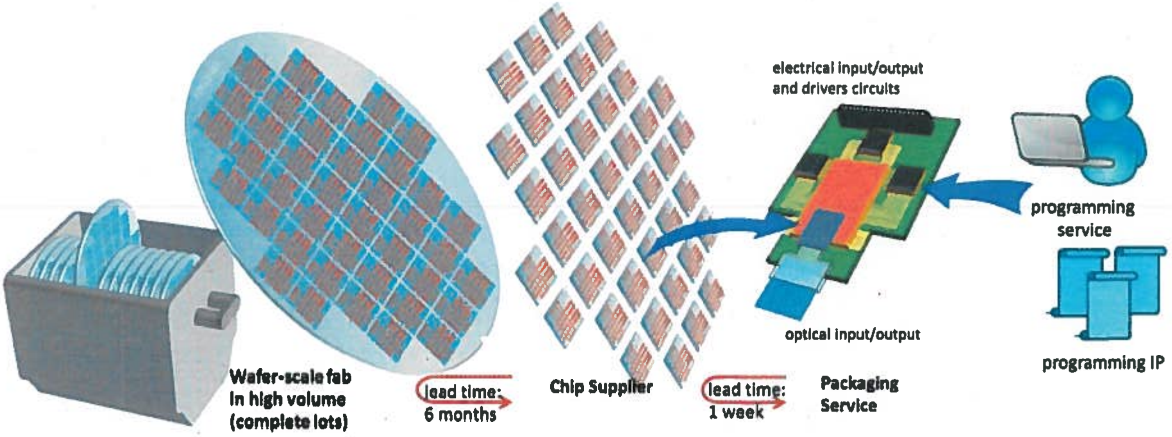

Figure 3: Generic programmable photonics can seed a different ecosystem, providing fabs with regular, homogeneous large-volume manufacturing, while giving end-users customized functionality and a short lead time.

5. SUMMARY

The field of programmable photonic circuits in only just taking off, but there have already been a number of convincing demonstrations. The flexibility of these chips can dramatically lower the barrier of entry in integrated photonics, and create a new ecosystem around the software-defined functionality.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 780283 (MORPHIC – www.h2020morphic.eu) and the European Research Council under grant agreement No 725555 (PhotonicSWARM).

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