E-2-01 (Invited) Extended Abstracts of the 2021 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2021, pp271-272

Programmable Silicon Photonics

Wim Bogaerts, Lukas Van Iseghem, Mi Wang, Hong Deng, Iman Zand,
Xiangfeng Chen, K.P. Nagarjun, Umar Khan
Ghent University - IMEC, Photonic Research Group, Department of Information Technology, Gent, Belgium
Center for Nano-and Biophotonics (NB-Photonics), Ghent University, Gent, Belgium
wim.bogaerts@ugent.be

***Abstract*—We present the new field of programmable photonic circuits. We introduce the evolution from specialized photonic circuits to general-purpose photonic processors, and describe the layers in the technology stack and their challenges.**

I. Introduction

Silicon Photonics is rapidly maturing from a specialty academic research field to an industrial technology platform. Its popularity can be attributed to two key features: Compatibility with large-volume CMOS manufacturing processes, and the high refractive index contrast. The high contrast makes it possible to reduce the waveguides to submicrometer dimensions and integrate thousands of optical elements on the same chip. Today, the industrial push for silicon photonics is mostly driven by fiber-optic communication markets (telecom, datacom), but silicon photonics is finding its ways in other applications domains, such as sensors and biomedical instruments.

The potential for large-scale integration is also powering a growth in circuit complexity. As the number of photonic components on a chip increases, we also see an increasing need to combine photonics with electronics, either on the same chip or in multi-chip solutions. Larger chips need more electronic control for the optical functions: Wavelength filters need to be configured, or the effect of fabrication variation needs to be compensated. Active control is becoming more and more an integral part of the photonic integrated circuit.

The new field of *programmable photonics* takes this a step further, going from a tunable photonic circuit to a reconfigurable photonic circuit that can perform more than one function [1]. This again increases circuit complexity,and the need for more control channels. A second evolution that we see with programmable photonics is the emergence of generic chip layouts where the function is defined by the electronics.

Silicon photonics is a key platform to enable this. Multi-functional or general-purpose circuits contain many more components than specialized single-function circuits. Silicon's high integration density makes this possible. Also, many efficient tuning elements are needed. Heaters are still the most commonly used tuning technique, and in silicon these are both compact and fairly power efficient.

Even though silicon photonics technology is already available on multiple industrial platforms, programmable photonics is still in an early phase. The massive scale of the circuits creates new challenges for driver electronics, control algorithms and packaging. And the programmability requires a new layer of software to give users access to the functionality.

Today, we see that most of the effort in programmable photonics is focused on large-scale multi-path interferometers [2], that project light from a set of input ports to a set of output ports. These *forward-only* circuits are especially useful in quantum-optic applications and machine-learning accelerators [3]. A second class of circuits uses *recirculating* waveguide meshes [4], that can also configure delay lines and resonators to implement wavelength filters. These circuits, which are more complex and difficult to control, can act as true general-purpose photonic processors, and are often called photonic FPGAs, like the electronic *field-programmable gate arrays*.

In this paper we will discuss the state of programmable photonics, and it will become clear that the photonic chip is just one element in a technology stack that brings together photonics, electronics, microwave technology, packaging, control routines and software engineering. Without these elements, the technology cannot fulfill its potential of becoming a generic platform, as an equivalent to programmable electronics.

Programmable photonics pushes the boundaries of various engineering domains to assemble the entire technology stack. While the photonic chip guides the actual photons, its configuration needs to be controlled by electronics and software layers, and all elements need to be brought together.

A. Photonics: Actuators and Monitors

Programmable photonic circuits take tunability of a photonic circuits to an entirely new level: rather than defining the connectivity of waveguides in the chip design phase, this is done at the time of operation. The core of programmable photonic chip is a mesh of waveguides coupled together with tunable couplers and phase shifters. Light is routed by tuning these gates to *bar*, *cross* or *partial* coupling state. A waveguide mesh can scale to hundreds or thousands of gates, and all of these need to be tuned. This requires electrically actuated tuners that are compact, have a short optical length, and above all consume as little power as possible. Heaters in silicon photonics are efficient, but when thousands are needed at the same time, this can lead to thermal management problems and crosstalk. That is why there is a drive towards lower-power solutions such as MEMS devices [5].

This work is supported by the European Union grants 780283 (MORPHIC) and 725555 (PhotonicSWARM), and by the Flemish Research Foundation (FWO-Vlaanderen) through grant G020421N (GRAPHSPAY)

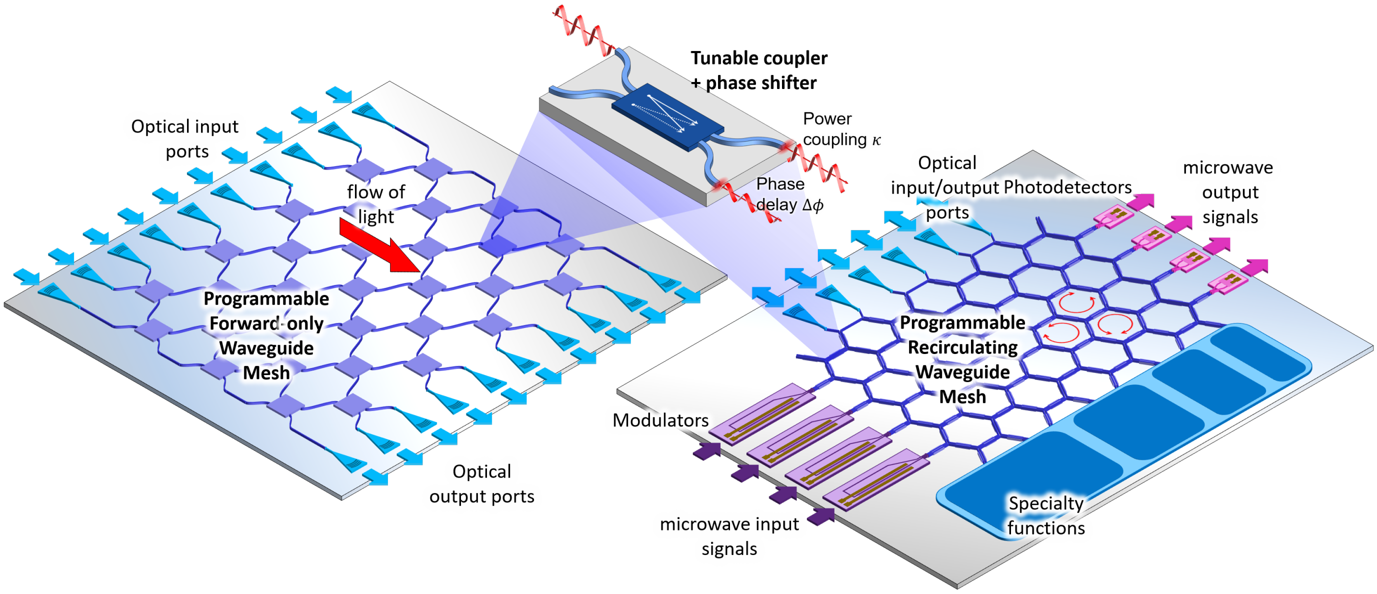

Fig. 1. Programmable Photonic Circuits. Left: Forward-only circuit. Right: recirculating mesh.

B. Electronics

Each electro-optic tuner needs to be electrically controlled, so we see a similar challenge with the driver electronics: we need many channels, and they need to be compact and power efficient. Also, the electronics need to read out any photodetectors in the circuit, and implement control loops.

C. Packaging

The many tuners and many drivers need to be brought together. Unless electronics and photonics are implemented on the same chip (this is possible but not trivial), this translates into a packaging challenge to implement thousands of electrical interfaces. On top of that, the chip set needs to be thermally stabilized, and interfaces to the outside world (optical fibers, microwave connectors) need to be accommodated.

D. Control

Controlling a large-scale programmable photonic chip is a new challenge. In essence, the circuit is a gigantic multi-path interferometer, fabricated in a technology which is notoriously sensitive to minute variations in fabrication and environmental conditions. Small errors in the tunable couplers or phase shifters can give rise to strong parasitic responses, which will also be wavelength dependent. As a result, the high-dimensional control landscape has many local minima and maxima. In forward-only meshes, the unidirectional flow of light makes control manageable, but recirculating meshes rely mostly on calibration and open-loop set points [6]. Control can be facilitated by incorporating monitors in the photonic mesh, but these also consume space, introduce additional optical losses, and require additional readout electronics and electrical connections. So they should be used judiciously.

E. Programming

To make this photonic-electronic system truly programmable, it needs a programming interface. At the lowest level, it needs to give users access to the individual optical elements on the chip. But to become practical, higher-level functional routines are needed to route light or configure functions such as wavelength filters. As the operation of a photonic circuit is very different than that of an electronic circuits, new programming formalisms are needed, starting from a photonic *hardware description language* (HDL).

II. Summary

Programmable photonics is still an emerging field, and there are many challenges that need to be addressed to complete the technology stack. But the potential for these circuits is huge, and they can bring about a revolution in the adoption of photonic chip technology.

References

[1] W. Bogaerts, D. Pérez, J. Capmany, D. A. Miller, J. Poon, D. Englund, F. Morichetti, and A. Melloni, “Programmable photonic circuits,” *Nature*, vol. 586, no. 7828, pp. 207–216, 2020.

[2] D. A. B. Miller, “Self-configuring universal linear optical component [Invited],” *Photonics Research*, vol. 1, no. 1, p. 1, 2013.

[3] N. C. Harris, J. Carolan, D. Bunandar, M. Prabhu, M. Hochberg, T. Baehr-Jones, M. L. Fanto, A. M. Smith, C. C. Tison, P. M. Alsing, and D. Englund, “Linear programmable nanophotonic processors,” *Optica*, vol. 5, no. 12, pp. 1623–1631, 2018.

[4] J. Capmany, I. Gasulla, and D. Pérez, “Microwave photonics: The programmable processor,” *Nature Photonics*, vol. 10, no. 1, pp. 6–8, 2016.

[5] C. Errando-Herranz, A. Y. Takabayashi, P. Edinger, H. Sattari, K. B. Gylfason, and N. Quack, “MEMS for Photonic Integrated Circuits,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 26, no. 2, pp. 1–1, 2019.

[6] D. Pérez-López, A. López, P. DasMahapatra, and J. Capmany, “Multipurpose self-configuration of programmable photonic circuits,” *Nature Communications*, vol. 11, no. 1, p. 6359, 12 2020.