General-Purpose Programmable Photonic Circuits

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***Abstract*—Programmable photonic circuits bring much-needed flexibility to the world of integrated optics, making it possible to engineer more diverse functions on a single chip, and accelerate prototyping photonics for new applications. We will discuss recent progress in general-purpose programmable chip technology and the surrounding ecosystem.**

***Index Terms*—silicon photonics, programmable photonics**

I. Introduction

Photonic integrated circuits (PIC) can combine a large number of photonic functions on the same chip, connecting them by waveguides. Over the past decades, the density of components on a PIC has steadily increased [1], driven by increasing maturity of silicon photonic technology platforms [2]. The introduction of new materials is boosting the efficiency of the on-chip active elements (phase tuners, modulators, detectors, light sources) and tighter integration with electronics is going to enable more sophisticated functions [3].

Today, PIC technology development is mainly driven by a single application domain: fiber-optic communication, both for long-distance telecom, and (increasingly) for datacom, especially in datacenters which are seeing a massive growth with the introduction of AI technologies. While this market has provided a great driver for photonic chips, the total market for this application is very small when compared to the aggregate market of electronic chips. This creates a risk that, unless volumes grow substantially, the various photonics foundries might not be economically viable in the long run.

It is not that photonics is not useful for other applications. There have been countless demonstrations of photonic chips for a variety of applications, from sensing, biomedical instrumentation, LiDAR and information processing (both classical analog computations as well as quantum information). However, many of these are confined to the lab, or struggle to gain maturity. The number of products containing a photonic chip not related to optical communication is very small.

What is holding back the penetration of PICs into these more diverse markets? Today, the PIC ecosystem is not yet sufficiently mature to allow a startup company to rapidly build new chip-based applications. Rapid development tools that we take for granted in electronics do not exist for photonics. First-time-right chip design is not yet a reality (even though design tools are improving), and there are no programmable photonics to rapid-prototype new functionality without going through a costly chip design-fabrication-test cycle, in the same way that digital electronics can be prototyped using field-programmable gate arrays (FPGA).

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II. Programmable Photonics

Programmable photonics is the field of photonic chips whose functionality can be altered in software, usually through a layer of electronics. In its most elementary form, these are custom-designed chips with built-in tuners (e.g. heaters) to adjust for fabrication imperfections or slightly alter the chip response (e.g. tune a filter wavelength). However, the term is more commonly used for larger networks of on-chip waveguides where the paths of light can be rearranged, using tunable couplers to adjust splitting ratios and phase shifters to tune the relative phase delays [4]. One particular class of such circuits are so-called recirculating meshes [5]. These organize waveguides in loops, connected by optical gates that control the coupling and phase delay. Through this, any point in the mesh are connected to each other. It is possible to define direct links between input and output ports, distribution networks, and even wavelength filters like Mach-Zehnder interferometers or ring resonators. When compared with additional functional building blocks (modulators, detectors, sources), any photonic circuit can be wired together on the fly.

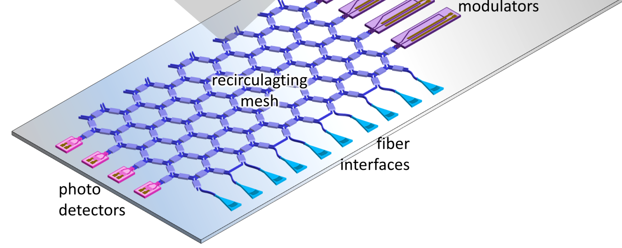

Fig. 1. A programmable photonic chip with a recirculating waveguide mesh.

III. The Technology Bottlenecks

Such large-scale photonic circuits are not so easy to realize. First of all, they are much larger than the typical custom-designed photonic circuits, and the light has to pass through many more individual building blocks (i.e. the optical gates with tunable couplers and phase shifters). That implies that that these gates should be very good in their function, exhibiting low optical loss, low power consumption, low crosstalk. Moreover, they should be compact and have a short optical length, to make the construction of wavelength filters feasible [6]. While the standard workhorse for tunable photonic elements is still the heater, alternatives are being explored, such as MEMS [7] and liquid crystals [8]. However, these are still immature solutions, and need further development. Today's programmable photonic circuits are mostly based on heaters [9], [10].

Each element on a programmable photonic chip also needs its electronics to make it programmable. This defines a need for compact driver electronics, and the photonic-electronic integration techniques to bring the two together. Around that, a software layer needs to be written that makes it possible for the user to calibrate, configure and control the functions on the chip.

Especially in this software stack there is still a massive unexplored territory: The programming routines of today's photonic chips are not much more than machine code or assembly language, addressing the individual states of the optical gates directly. Slightly higher-level functions can already compute single or multiple routes through the chip [11], [12]. Higher-level programming paradigms, including specialized languages that can capture the functional description of photonics, do not really exist.

IV. General-Purpose Programmable Photonics

How do we go from today's world of application-specific PICs to an ecosystem where innovators can source off-the-shelf programmable chips for prototyping or even integrate them directly in their products. The use model is not unlike that of FPGAs. These are commonly found in a variety of products, especially where flexibility (or upgradability) is essential or where the volume or time-to-market requirements are not in favor of taping out a dedicated chip. Similar use cases can be imagined for programmable photonics: if they are fabricated in sufficient volumes, they could have a cost advantage compared to dedicated chips, even if the programmable PICs are larger and require more complex driver electronics [13]. Of course, their performance should be adequate, which imposed strong pressure on the development of better optical gates.

The larger question is: what would be the specifications for a general-purpose chip, i.e. a chip that could be suitable to prototype most commonly imagined photonic use cases? This is not an easy question to answer, given the variety of applications once we go beyond optical communications? Different applications operate in different wavelength ranges, and some require active functions while others don't. It quickly becomes clear that there is probably not a single 'general-purpose' chip, but rather a class of such chips. In itself this is not a problem: with FPGAs we see a similar diversity of devices. But of course, there should be a minimum market to make the photonic chips viable, and more diversity can also mean more dilution. This is very much an unanswered question today.

V. Conclusion

General-purpose programmable photonic chips carry a lot of promise: with their flexibility they could herald a new age for photonics, paving the way for PICs in more diverse application spaces and lowering the barriers for innovation. With a software interface to manipulate light, they make photonic technology more accessible, opening it up to a much wider community.

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