Tutorial: Programmable Photonic Circuits

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***Abstract*—In this tutorial, we will discuss the fundamentals of programmable photonics: the technological underpinnings, the hardware architectures and algorithms for configuration and control. How will this impact the use of photonic chips in the future?**

***Index Terms*—silicon photonics, programmable photonics, photonic integrated circuits**

I. Introduction

Photonic integrated circuits (PICs) are becoming increasingly complex, with more and more optical functions integrated on the same chip. As photonic circuits are inherently analog circuits, the larger integration scale also increases the accumulation of imperfections. That is why, as the circuits increase in size, more and more tunable elements are being incorporated. This allows the fine-tuning of the functionality or performance, but increasingly the tuning elements are also used to reconfigure the optical pathways on the PICs, effectively redefining the optical functionality, or ”programming” the photonic circuit.

PICs are made to process optical signals. These can be simple digital bitstreams for high-speed optical interconnects, but also analog sensor readouts, high-speed analog microwave signals, or quantum signals (qubits). As the signal processing tasks become more diverse, programmability of the photonic chips becomes more important.

II. Information processing in photonic circuits

Light can encode information in various properties: intensity, phase, spatial field profile, polarization, and wavelength. When we move from generalized optics to photonic circuits, some of these aspects are abstracted. When we describe an *optical circuit*, we introduce certain assumptions: light is processed in discrete circuit building blocks, which are connected by waveguides to transport the optical signals into one or more guided waveguide modes. The propagation of light can be simplified this way, removing the need to solve Maxwell’s equations, and instead relying on the description of scattering signals in the building blocks.

In a photonic circuit, the information is now encoded in a set of complex-valued amplitudes (magnitude and phase) of light propagating in the discrete eigenmode. This can still be done for different wavelengths on the spectrum. On these optical signals, different processing tasks can be performed: generation or amplification, modulating an electrical signal, wavelength conversion, wavelength filtering (this also applied a filtering on the modulated signals), phase-to-amplitude conversion (e.g. using interferometers) and optical-to-electrical conversion (using photodetectors). Combining these different functions not only allows optical signal processing, but also processing of high-speed microwave signals encoded on the optical carrier wavelengths [1].

For example, in [2] we report a signal processor chip that combines lasers, modulators, tunable filters and detectors to perform a variety of optical and microwave signal processing functions, including optical and microwave filtering, conversion between domains, frequency doubling, and optical/microwave signal generation (oscillator). However, while this chip can be reconfigured to perform different functions, the flow of light is mostly predefined, which limits the functionality of the chip to the functions that have been preconceived during its design. True programmable photonics breaks that mold.

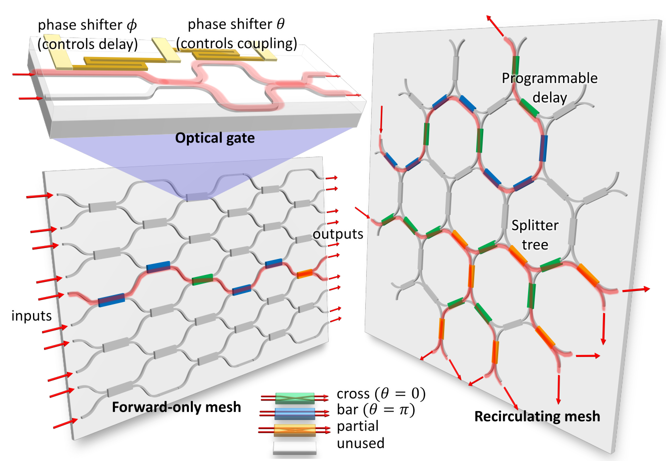

Fig. 1. Programmable waveguide meshes based on 2×2 optical gates

III. Making circuits programmable

What is needed to make photonic chips truly programmable? First of all, it should be possible to redefine the flow of light through the circuit [3]. On a photonic circuit, this implies that connectivity between building blocks can be redefined. The common approach to this is through a *waveguide mesh*: a network of waveguides connected by *optical gates* that

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couple the waveguides together with a configurable coupling ratio, and at the same time can control the relative phase delay between the waveguides. This way, such optical gates can fully manipulate the complex amplitude of the lightwaves. When the gates are lossless, the relation between the inputs and outputs is described by a unitary 2×2 transfer matrix. Primitive optical gates only require two input waveguides and two output waveguides. Gates with larger number of N input/output ports can be constructed from these primitive gates by cascading them into a circuit. Again, if the gates are lossless, this larger circuit will also be described by an $N \times N$ unitary matrix. We can identify two classes of waveguide meshes: *forward-only* and *recirculating*. The former supports a unidirectional flow of light, physically separating inputs and outputs. This simplification makes it possible to implement certain signal processing operations very efficiently. In particular, when using the amplitudes at the input and output to represent a vector of complex numbers, the circuit can perform a matrix-vector multiplication in real time. This makes the circuits particularly interesting for accelerators in neural networks or for linear quantum processing [4]. Recirculating meshes allow coupling between all ports; it is more flexible, but also more difficult to configure. They are a more likely candidate to implement a truly general-purpose programmable photonic circuit. Because the light can propagate through the circuit in all directions, it is possible to define interferometers with delays, resonators and loop mirrors [5], [6]. When combining these programmable linear circuits with active functions (amplifiers, modulators, detector), arbitrary circuits can be constructed.

IV. Current developments

Programmable photonics are still in an early phase, and demonstrations are still limited in scale and functionality. Still, there are many interesting developments ongoing.

A. Better building blocks

The performance of the complete circuit is largely determined by the capabilities of the individual optical gate: its optical loss, power consumption, path delay, response time, etc. Today, most demonstrations are based on heaters, but this will not scale to very large circuits. Therefore, developments on better building blocks based on other mechanisms (e.g. MEMS, liquid crystals) are ongoing [7], [8]

B. Large-scale electronic driver integration

As these circuits increase in size, the electronic driver integration should follow: every optical gate needs its driver circuits, and monitors distributed in the circuit need to be read out. All these drivers also need packaging, which is typically a serious challenge, as the system assembly combines optical, electrical, RF, mechanical and thermal considerations.

C. Calibration, Configuration and Control

In these large circuits, everything is tunable, but that also means that everything needs to be controlled at all times. As all functions are analog, there no strong self-correcting mechanisms and therefore every element needs careful calibration and control routines. this is far from trivial, as the state of each optical gate cannot be directly observed, but only indirectly (through the transmission of light). Effects such as thermal crosstalk need to be addressed in the overall control routines [9].

To implement functionality in the circuit, configuration routines are needed to figure out the desired state of each gate, which combines its coupling strength and its phase. Depending on the mesh topology, configuration can be done without much prior knowledge or calibration of the gates (so-called *self-configuration* [10]), or with the help of pre-calibration, with algorithms to identify optimum path through the system [11] or distributed paths to realize an interferometric filter function [12].

V. Building an ecosystem

Programmable photonics introduces a new way to interact with light, directly through a software interface. This low-threshold access can do for photonic chips what spatial light modulators have done for free-space optics. It allows to experiment with new functionality in a more interactive way, iterating faster than in a traditional design-fabricate-test cycle. This can give a boost to the adoption of photonics, and to innovations based on PICs.

VI. Summary

In this tutorial, we will cover the technological underpinnings of programmable photonics, look at the different element in the technology stack, and how today's implementations are paving the way for new applications of photonic chips.

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