Large-scale Programmable Integrated Photonic Circuits: From Microwave Photonics to Optical Computing

Daniel Pérez-López
ITEAM Research Institute, Universitat Politècnica de Valéncia, Spain,
iPronics programmable photonics S.L., Valencia, Spain
dperez@iteam.upv.es

Abstract: Multipurpose programmable circuits promise to achieve arbitrary functionality and dynamic system operation as an alternative to custom fixed design. This work reviews the fundaments, programming methods, and performance of its application to microwave-photonics and computing. © 2022 The Author(s)

1. Introduction

During the last decade, the maturity of integrated photonics processes has enabled the incorporation of hundreds of on-chip phase actuators. This technological progress has permitted the development of complex reconfigurable circuits with more degrees of freedom and versatility, leading to the advent of a new class of devices called multipurpose programmable photonic circuits [1-2].

Programmable photonic circuits can tailor their performance by setting their control signals. Although most of the works have focused on the early-day demonstrations of small and medium scale circuits, applying the technology to practical demonstrations is one of the key pending challenges. In this work, we review the fundaments of the technology (hardware and software layer) and analyze the challenges to be addressed, with particular focus on the application of programmable photonic circuits to microwave photonics and computing.

1.1 The photonic circuit architecture and workflow.

Multipurpose programmable photonic ICs [1-2] rely on the large-scale integration of optical beam splitters and optical phase actuators into a central core, to which one can append a selection of high-performance building blocks to synthesize optical and electro-optical circuits on demand. The basic building block, the programmable unit cells, can be defined by a 4-port photonic unit cell that can perform either as a cross/bar switch, a tunable coupler, or as a phase shifter. Unlike conventional circuits, programmable photonic circuits are programmed after fabrication to implement multiple applications. Fig. 1(a) shows the system architecture. For its configuration, early-day manual implementations had been substituted by automated routines [1-2]. Fig. 1(b) and (c) illustrate the resulting mapping of coupling factor configurations after the automated programming of a 1x8 optical beam splitter block and the spectral power response, respectively.

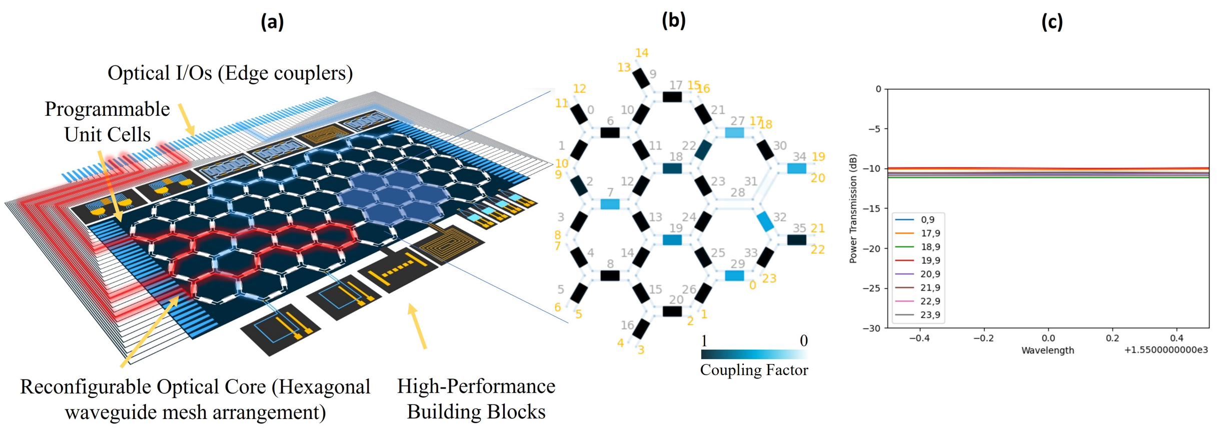

Fig. 1. (a) Scheme of the multipurpose programmable photonic integrated circuit. (b) extraction of the optical core and reconfiguration parameters computed to program a 1x8 optical beam splitter, (c) resulting optical power spectrum after the automated configuration process.

2. Applications focus: Microwave photonics

Radiofrequency (RF) or Microwave photonics (MWP) [3], brings together the worlds of RF engineering and optoelectronics interfacing these highly dissimilar media. It is the best positioned technology to provide a flexible, adaptive, and future-proof physical layer with unrivaled characteristics by enabling the realization of key functionalities in microwave systems, which are either complex or even not directly possible within the RF domain. Despite its tremendous potential, the widespread use and application of MWP is currently limited by the high cost, time-consuming development, and complex nature of its systems, both in their discrete system or integrated circuit versions.

The integration of optoelectronic systems as high-performance blocks in general-purpose programmable photonic circuits generates a potential multipurpose MWP signal processor architecture [4]. Table 1 illustrates the microwave photonic functionalities that can be achieved together with the employed on-chip blocks and the configuration of the waveguide mesh arrangement.

To enable competitive and practical photonic-assisted applications like 5G, 6G communications, radar, base station processing, radio-over-fiber, and RF-photonic systems in general, the processor requires the achievement of critical figures of merit. First, the bandwidth of the optoelectronic components needs to achieve at least 35 GHz. This metric is well reached through Multi-Project Wafer run services. Next, the overall RF gain is typically limited by the low conversion efficiencies of the optoelectronic blocks and on-chip loss. Integrating on-chip amplifiers as high-performance blocks is essential to compensate and boost the RF gain [5]. In addition, signal integrity needs to be granted through noise filtering and advanced linearization techniques [6].

Finally, the software layer governing the configuration process of the different elements mainly requires the automation of arbitrary optical filters, multiport interferometers, and the driving of the electro-optic blocks.

Table 1. Examples of functionalities achieved with a general-purpose programmable photonic processor. HP-MOD: high-speed modulator, HP-PD: high-speed photodetector

<table>
<tr><th>Functionality</th><th>Required High-performance blocks</th><th>Core functionality</th><th>Applications</th></tr>
<tr><td>True-time delay line</td><td>• HP-MOD and HP-PD</td><td>• Optical filter
• Optical delay line</td><td rowspan="10">• 5G and beyond.
• Radar
• Base station processing.
• Radio over fiber
• Fiber to the antenna communications
• RF-photonic systems for security and defense</td></tr>
<tr><td>Self-homodyne filters</td><td>• HP-MOD and HP-PD</td><td>• Optical filter
• Optical interconnect
• Splitter and combiner</td></tr>
<tr><td>RF-multichannel equalization</td><td>• x2 HP-MOD and x2 HP-PD</td><td>• Splitter and combiner
• Optical filter</td></tr>
<tr><td>mm-wave tone generation</td><td>• HP-MOD and HP-PD</td><td>• Optical filter</td></tr>
<tr><td>Opto-electronic oscillators</td><td>• HP-MOD and HP-PD
• RF coupler, RF Amp, RF filter</td><td>• Optical filter (storage)</td></tr>
<tr><td>Arbitrary waveform generation</td><td>• HP-PD</td><td>• Optical filter
• Dispersive system</td></tr>
<tr><td>High-bandwidth Beamforming networks</td><td>• HP-MOD and HP-PD</td><td>• Optical interconnects
• Splitter and combiner</td></tr>
<tr><td>Instantaneous frequency measurement</td><td>• HP-MOD and HP-PD</td><td>• Complementary optical filter</td></tr>
<tr><td>RF-mixing</td><td>• x2 HP-MOD and HP-PD</td><td>• Optical filter</td></tr>
<tr><td>RF- MIMO</td><td>• x4 HP-MOD and x4 HP-PD</td><td>• Interferometric Unit (Matrix generator)</td></tr>
</table>

3. Applications focus: Photonic computing

Another photonic-enabled application that can benefit from the versatile general-purpose processor is photonic computing. The generation of multi-mode linear processing has been demonstrated by integrating feedforward interferometric matrices, showing promising results for implementing matrix linear transformations useful in quantum computing, hardware accelerators for deep-learning applications, and general linear signal processing [7] (See Fig. 2.a). In addition, some works reported this functionality on hexagonal waveguide mesh arrangements (Fig. 2b) [8]. The latter could also be exploited in computing applications benefiting from mixed feedforward and feed backward signal flows, like reservoir computing and future computing protocols.

To enable competitive and practical photonic-assisted applications, the processor demands extensively integrated and non-integrated components for signal preparation, optical monitoring, and electrical driving. Integrating these high-speed optoelectronic interfaces with many RF ports remains a critical challenge in the current photonic integration evolution. Indeed, as illustrated in Fig. 2 (c), implementing a non-discretized 64x64 optical matrix generation requires 4032 and 12096 phase actuators for the feedforward and general-purpose versions, respectively.

On the software side, the scientific and industrial community is focused on efficient automated protocols and fault-tolerant reconfiguration routines. Although current experimental optical neural networks are mostly limited to small- and medium-scale integration proofs-of-concept and real-valued numbers, the evolution to large-scale integration could show the clear advantage of optical networks vs. electrical circuits, specifically in terms of bandwidth, and power consumption, a critical issue faced by electronic neural networks.

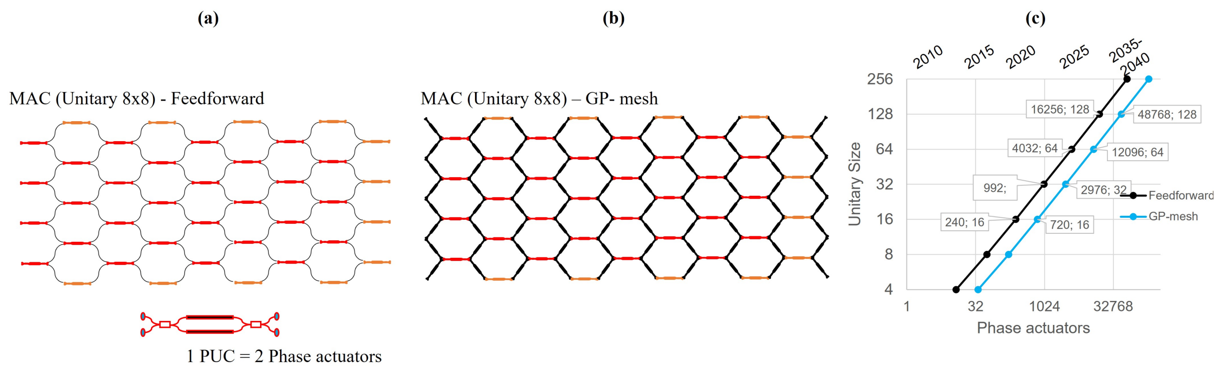

Fig. 3. (a) Schematic of linear interferometer implementing an 8x8 unitary matrix, (b) implementation employing a programmable photonic integrated circuit based on a hexagonal arrangement. (c) evolution of the phase actuators per unitary matrix size.

3. Conclusions

Programmable photonic integrated circuits are a multipurpose technology that employs electrical signals to configure the performance of photonic chips on demand. Especially appealing for applications demanding dynamic and adaptative operations, we reviewed the opportunities in microwave photonics and photonic computing.

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