

PROGRAMMABLE INTEGRATED PHOTONICS: A NEW PARADIGM FOR LOW COST MULTIFUNCTIONAL OPTICS

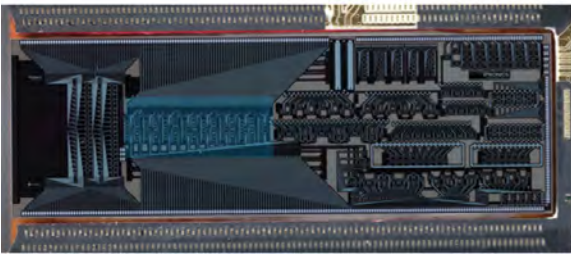
José CAPMANY^{1,2,*}, Daniel PEREZ-LOPEZ²

¹ Photonics Research labs, Universitat Politècnica de València, Valencia, Spain.

² iPronics, Programmable Photonics, València, Spain

* jose.capmany@ipronics.com

10x32 mm



This article presents the rationale, basic principles of operation, technology stack, and areas of application of a new technology approach called programmable integrated photonic. In essence, it is based on the same high-level concepts that inspired several decades ago the birth of programmable integrated electronic devices such as the microprocessor, the field programmable gate array, and the digital signal processor. We provide a final discussion on its current limiting challenges.

<https://doi.org/10.1051/photon/202412534>

Integrated photonics is a technology with a clear objective, the research, development, fabrication, and testing of devices, circuits, and subsystems capable of generating, processing, controlling, and detecting guided-wave lightwave signals carrying useful information. It is an enabling technology that can support a myriad of applications that include telecommunications (optical networks, IoT, and 5G), switching and interconnections (cloud and edge data centers), computing (artificial intelligence and neuromorphic), sensing (lidar, bio, civil infrastructures), robotics and aerospace to cite a few.

From the *technology point of view*, integrated photonics shares common features with microelectronics

as both are semiconductor technologies and, for certain materials, both can leverage from CMOS fabrication processes. There are also important differences. First of all, while Silicon reigns in microelectronics this is not the case in photonics. Silicon is an indirect gap material and thus not suitable for implementing active devices such as laser sources and amplifiers. These and others such as detectors and high-performance modulators are currently being implemented in other material platforms such as III-V InP or Lithium Niobate. While it is true that silicon on insulator (SOI) and silicon nitride (SiN) are predominant in the area of passive devices and circuits, no material platform can integrate monolithically all the required

components. To overcome this limitation both hybrid and heterogeneous integration approaches are being pursued. In the first case, different chips implementing active and passive components are physically interfaced through input/output waveguide ports, while in the second active components are either flip-chip bonded or transfer printed on top of a passive silicon chip. From the *operational point of view* microelectronics is mainly digital, work with electrons, which can be stopped and stored and it is highly nonlinear thanks to the switching operation enabled by transistors. Photonics is on the contrary linear and analog, and works with photons, which neither can be stopped or easily stored, can provide huge bandwidths

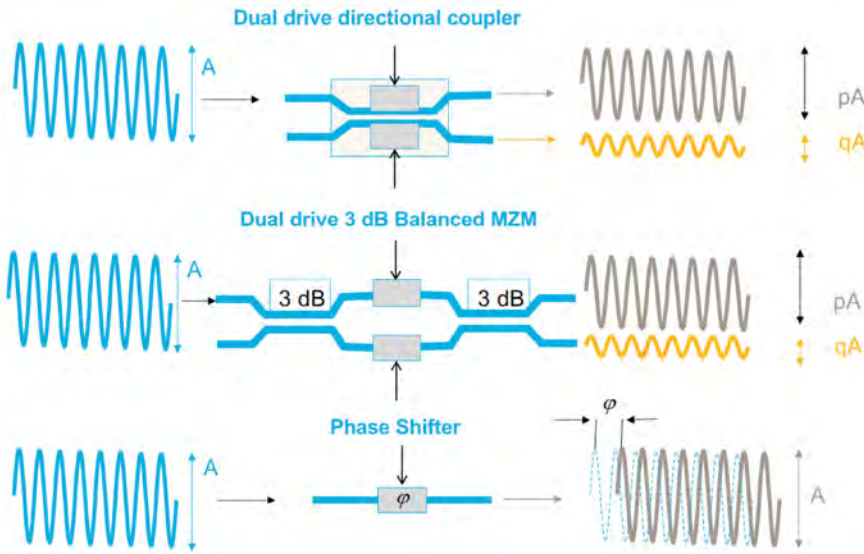


Figure 1. Basic building blocks in programmable photonics.

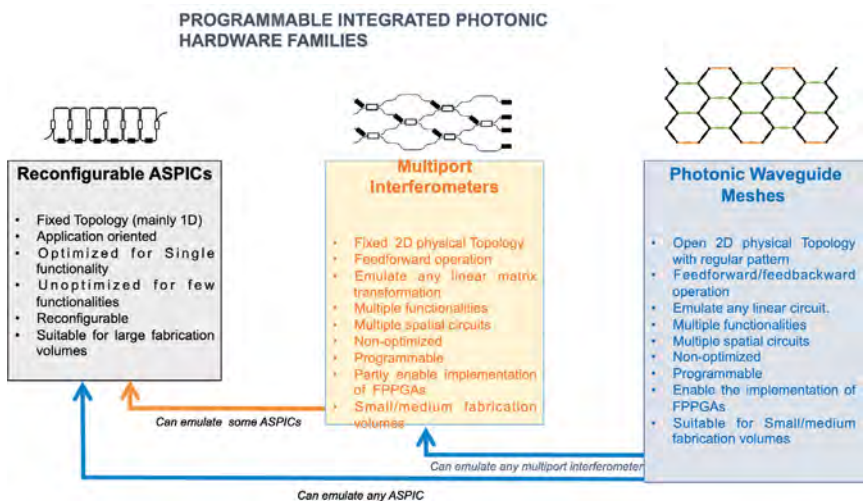
and low power consumption when moving data. It is clear therefore that both technologies are complementary, and the question is how and whether it makes sense to leverage this complementarity.

It turns out that the surge of applications requiring ever-increasing processing speed, bandwidth, and reduced power consumption is exerting considerable pressure on microelectronics, which is jeopardized by the saturation of its main scaling laws (Moore, Dennard, and Amdahal). This context opens a window of opportunity for integrated photonics especially for photonic integrated

circuits (PICs). However, integrated photonics is a much less mature technology and still requires long development and fabrication cycles for application-specific circuits (ASPICs) with considerable impact as well on costs.

A way to overcome this limitation is to resort to programmability [1], [2], an approach that leverages on the fabrication of a single hardware that can be dynamically reconfigured *via* software to implement and emulate different circuits and subsystems enabling multiple applications with the same product. This approach leads to ●●●

Figure 2. The three families of Programmable Photonics Hardware.



Fiber Optic Hermetic Feedthroughs

Screw-in type



10⁻¹¹mbar.l/s hermeticity
1000 bars pressure

CF or KF flange type



10⁻¹¹mbar.l/s hermeticity
UHV applications

Phone - 33 (0)1 69 36 64 32
Mail - contact@sedi-ati.com
Web - sedi-ati.com



Scan me!

The expert in
extreme
environments

substantial cost savings by leveraging economies of scale and reduces non-recurrent (NRE) engineering costs. Programmability has been instrumental for the success of electronics (where microprocessors, digital signal processors, field programmable gate arrays, GPUs and CPUs account for more than a 50% of the world market) and we believe that it will have a similar impact in integrated photonics. In this short article we provide an introduction to the principles, applications and future prospects of programmable integrated photonics.

PRINCIPLES OF PROGRAMMABLE INTEGRATED PHOTONICS

Programmable photonics is a broadband analog technology that enables the programming of signal processing tasks based on the ability of photonic circuits to manage multiple optical interference [1-3]. In essence, this entails the independent setting of amplitude and phase characteristics of the multiple interfering signals. For the first task, it employs either tunable couplers or Mach-Zehnder interferometers, while for the second a phase shifter is needed (see Figure 1).

These are the basic building blocks, which can be programmed by the action of external electronic signals (which will be described in the next section). The combination and interconnection of these basic building blocks allows the implementation of programmable photonic circuits featuring various degrees of complexity and functionality, which can be grouped into three hardware families shown in Figure 2 and which we now briefly explain.

The most basic configuration for Programmable PICs, the reconfigurable ASPIC [2] is shown in the left part of Figure 2. It retains most of the main features of fixed designs but brings some degree of reconfigurability whereby the operation and bias points governing the circuit response can be programmed but the overall functionality of the chip is not changed. A second family, shown in the center block of Figure 2 is formed by multipoint interferometers [3]. These are based on two-dimensional (2D) fixed topologies built from tunable interferometers and can be programmed to emulate any linear feedforward arbitrary unitary matrix transformation. Finally, photonic waveguide meshes [4], based on balanced tunable interferometers assembled to form 2D topologies following regular geometric patterns are capable of emulating any reconfigurable ASPIC and multipoint interferometer while in addition can implement any feedforward and feed backward transformation. The upper right part of Figure 2 shows, as an example, a hexagonal waveguide mesh but other 2D patterns (triangular, square) are possible.

THE TECHNOLOGY STACK

Implementing and operating a programmable integrated photonic processor involves the design and coordination of several layers that implement different tasks. This layered structure is known as the technology stack [5-6] and is shown in Figure 3.

Figure 3(a) shows a particular implementation where the different physical

Figure 3. The technology stack of a general-purpose integrated photonics processor.





Figure 4. Some examples of application fields for programmable integrated photonics.

elements, input and output ports, and control elements are displayed for reference. The technology stack architecture is displayed in Figure 3(b). It basically consists of three different layers. The photonic layer includes the optical programmable waveguide mesh chip with several surrounding high-performance blocks (an example is shown as an inset in Figure 3(a) and the photonic input and output ports. The electronic layer includes all the elements required to monitor, control, and drive the photonic elements using electronic signals. It can also include radiofrequency ports and devices if

required by the particular application. Finally, the software layer [7] is composed of two different sublayers. The top one is the programming environment for the specific application which allows the external user to easily program the system and circuit configurations to be implemented and/or emulated by the processor without needing to have a specific knowledge of the hardware configuration. The lower sublayer takes care of implementing and coordinating all the necessary operations to analyze, optimize, and implement self-healing actions if a failure is produced in the optical hardware or

if, for example, a set of restrictions related to different performance metrics such as delays, energy consumption, number of hops are imposed on the available resources. Its action is transparent to the high-level user. It is the correct orchestration of the available resources that is pursued by the swift interaction of all the layers in the architectural pile and where in the last term resides much of the added value of a programmable photonic circuit.

APPLICATIONS OF PROGRAMMABLE INTEGRATED PHOTONICS

Programmable photonics is a transversal enabling technology approach and as such, can find applications in a myriad of areas. Figure 4 shows some of these areas, which we briefly describe in the following lines.

a) *Telecommunications and data centers* (Interconnection, routing, and switching). In this area of application, programmable photonic processor products can help to develop new generations of flexible and programmable intelligent optical transceivers, high-capacity routers, switches, and multiplexer/demultiplexers. A special area of interest is intra-data center interconnections, where ●●●

SPECTROGON

State of the art products

Interference filters

- 200 to 15000 nm
- Bandpass
- Longwave-pass
- Shortwave-pass
- Broad-bandpass
- Neutral density
- Web stock items

Holographic gratings

- 150 to 2000 nm
- Pulse compression
- Telecom
- Laser tuning
- Monochromator
- Spectroscopy
- Web stock items

UK: sales.uk@spectrogon.com • Tel +44 1592770000
 Sweden (headquarters): sales.se@spectrogon.com • Tel +46 86382800
 US: sales.us@spectrogon.com • Tel +1 9733311191

www.spectrogon.com

there is a need for the so-called elephant traffic of broadband, flexible and low power consumption circuit switching solutions.

b) *Flexible microwave photonic interfacing systems for 5/6G wireless communications.* In this strategic area, providing programmable interfaces in terms of functionality and operating band between the fiber optic segment and the radiofrequency segment is instrumental both in base stations and in central office centers. In addition, programmable photonic engines will be able to enable multiband, multi-channel, and multi-input multiple-output transmission and broadcast.

c) *High-performance computing.* Programmable photonics processors are well suited to support a new generation of hardware accelerators essential for parallel computing and interconnection of multi-core processors and disaggregated clusters with remote locations.

d) *Sensors.* Programmable photonic systems will provide the flexibility needed to simultaneously process communication and measurement or remote sensing channels, providing a compact solution in the Internet of Things (IoT), Smart Cities, LIDAR, and autonomous driving application environments.

e) *Artificial intelligence, neurophotonics, and novel approaches for computing.* Incorporating programmable analog photonics adds the possibility of integrating interconnections and very-high-speed matrix-vector multiplication (MVM) operations key in the implementation of hardware systems for deep learning and neural networks. Furthermore, programmable photonics offers unique hardware for the implementation of novel computing paradigms based on linear optic transformations.

f) *Application Specific Photonic Chip Manufacturing.* In this field, programmable photonics helps to accelerate the ASPIC circuit design cycle by allowing the emulation of designs on a hardware platform in a few days, thus avoiding the delay posed by

manufacturing rounds with negative results.

g) *Quantum information systems.* Programmable photonics provides the possibility to emulate linear optical transformers needed to implement quantum logic gates, boson samplers, quantum transport emulators, and numerical operations such as Fourier and Hadamard transformations. On-chip integration of these transformers with specialized single-photon optical sources and detectors will lead to compact and decoherence-free processing systems.

We expect this list to be substantially enlarged as the field of programmable photonics matures.

CONCLUSION

We have briefly reviewed the emerging area of programmable integrated photonics providing, first of all a rationale for its development (i.e., the whys). We have then jumped into describing the basic principles behind the operation of programmable integrated photonic processors, including their basic building blocks and the generations developed so far (i.e. the How). A distinctive feature of these systems as compared to application-specific photonic circuits is that they need a complete layered stack architecture composed of software and hardware layers to operate. We have described the main components of this so-called technology stack. Finally, we have briefly addressed some of the current application fields for programmable integrated photonics, emphasizing that this list will

for sure be enlarged in the forthcoming years. Recent work has been reported on the use of this technology to emulate artificial materials and topological photonics, and work is undergoing in exploiting its features for instance in the implementation of reservoir computing.

We would like to conclude by outlining some of the main challenges that this technology faces towards achieving its goal of global implantation. Scalability, that is the possibility of incorporating a higher component count in the available chip footprint is perhaps the most important limitation. Work is underway to reduce propagation and coupling losses and also to achieve building blocks with reduced insertion losses. The target here is to achieve overall losses in the range of or below 4 dB. In terms of the number of building blocks, the challenge is to jump from the current figure of <1000 to figures around 5000. Power consumption is also another limitation that can hamper scalability. Currently, the activation of photonic building blocks is done using thermo-optic mechanisms that consume a few milliwatts per unit. Lower or negligible power consumption can be achieved using non-volatile tuning mechanisms which are currently being investigated.

If these challenges are solved there is a real good chance that programmable photonics will become as instrumental in the future as microprocessors, FPGAs and digital signal processors (DSPs) have been for electronics. ●

REFERENCES

- [1] W. Bogaerts *et al.*, *Nature* **586**, 207 (2020).
- [2] J. Capmany, D. Perez, *Programmable Integrated Photonics* (Oxford Univ. Press, Oxford, 2020).
- [3] N. C. Harris *et al.*, *Linear programmable nanophotonic processors*, *Optica* **5**, 1623 (2018)
- [4] D. Pérez, *et al.*, *Nat. Commun.* **8**, 636 (2017).
- [5] D. Pérez, I. Gasulla, J. Capmany, *Opt. Express* **26**, 27265 (2018).
- [6] W. Bogaerts, A. Rahim, *IEEE J. Sel. Top. Quantum Electron.* **26**, 1 (2020).
- [7] Pérez-López, D. *et al.*, *Nat. Commun.* **11**, 6359 (2020).