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ABSTRACT

We give an overview the progress of our work in silicon photonic programmable circuits, covering the technology stack from the photonic chip over the driver electronics, packaging technologies all the way to the software layers. On the photonic side, we show our recent results in large-scale silicon photonic circuits with different tuning technologies, including heaters, MEMS and liquid crystals, and their respective electronic driving schemes. We look into the scaling potential of these different technologies as the number of tunable elements in a circuit increases. Finally, we elaborate on the software routines for routing and filter synthesis to enable the photonic programmer.

Keywords: Programmable Photonics, Silicon Photonics, Photonic Packaging

1. INTRODUCTION

Photonic integrated circuits (PIC) have grown into an established technology over the past few decades. By combining diverse optical functions (lasers, modulators, detectors, splitters, wavelength filters, etc.) on the surface of a chip, more complex functions can be integrated within a smaller footprint and with lower power consumption and cost compared to traditional bulk-optical components. The integration density of photonic circuits is rapidly growing, and especially silicon photonics, with its large integration density, is rapidly pushing the number of optical components on a chip to the 1 million mark.[1] As a technology platform, photonics is on a similar scaling trajectory as electronics but with a lag of several decades. As we already use optical and photonic technologies in many applications in our society, we can expect that photonic chips will be enablers for innovation, dramatically increasing functionality at a lower cost, just like we witnessed with electronics.

However, if we look at the landscape of photonic chips today, we see a somewhat different picture. Even though photonic technology has demonstrated its capabilities in research demonstrators for spectroscopy, sensors, LiDAR, microwave signal processing, and quantum information processing, we see that commercial use of

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photonic chips is almost exclusively limited to the traditional field of optical communication, which comprises both telecom networks and data centers. It seems that, in stark contrast with the many scientific demonstrations over the past decades, there is a high threshold to adopt photonic chip technology in actual products for new application domains, even though the benefits are clear. Some barriers hinder the use and deployment of this promising technology.

The fact that photonic chip products today are mostly constrained to the communications markets puts a significant economic limitation on the industry. While the transceiver market (especially for data centers) is considered a large-volume market for photonic standards, it is dwarfed by the market of electronic chips. To justify investment in photonic chip fabrication facilities (”foundries”), the photonics market must grow beyond these limits. This is only possible if the technology finds its way into new applications. The current situation for photonic chips could be compared to the hypothetical case where electronics would be limited to simple calculators. Instead, electronics can be found in virtually every device we make and purchase today, and a similar scenario can be imagined for photonics. After all, optics is already widely used for diverse applications in consumer electronics, automotive, and healthcare.

So what is holding photonics back from breaking through into all kinds of sensing and signal-processing products? The chip technology developed in the foundries seems capable of making chips for these applications, as has been demonstrated over the past decades in thousands of publications. So the difficulty lies in translating the first proof-of-concept demonstrations into a product. And indeed, in this process, we can discern some clear bottlenecks with the current photonic chip technologies. When transitioning from an initial proof-of-concept demonstrator of a new device to a product, the photonic chips need to become a reproducible part of an entire system. During a first set of experiments, it is fine if only one or a few chips work sufficiently well. While in a production setting, the circuits need to have a good yield, meaning that a sizeable fraction of the fabricated chips works in various operational conditions (e.g., ambient temperatures). As photonic chip fabrication processes come with inherent variability, and many photonic chip platforms are very sensitive to temperature, the circuits need to be designed for robustness and yield, not just for operation under ideal circumstances. This requires design processes that today are not yet widespread in the photonics community.[2] In electronics, concepts such as *design for manufacturability* and *design for yield* are already established and supported in the design tools. However, photonic circuits and components are typically much more susceptible, and these practices still need proper translation to the photonic domain. Add to this problem that there is much less standardization in photonic design flows than in electronic design flows, and it becomes clear that there is today still a wide chasm to cross before we can speak about *first-time-right design* for PICs.

This means that any innovator who wants to develop a new PIC-based product will have to go through several chip fabrication iterations before a representative prototype can be demonstrated. As photonic fabrication cycles in commercial (silicon) photonics foundries can take as long as a year between design tape-out and testing, it is clear that this imposes a very long runway between an idea and its translation into a minimum viable product.

A second contribution to this long development runway is the lack of flexible photonic chip hardware. Every PIC is essentially a custom-designed circuit, which must be fabricated before testing. Compare this to digital electronics developments, where at least the first iterations can be done in off-the-shelf programmable hardware such as microcontrollers or field-programmable gate arrays (FPGA). These can validate the concept and even make an initial product demonstrator. And only if needed for reasons of cost, performance, or power consumption, the design can then be translated to custom application-specific integrated circuits (ASIC). The introduction of such easily accessible programmable hardware in the 1980s-2000s has pushed electronics way beyond its original application spaces to the point where it can be found in almost every appliance we use today. It also widened the community of developers and innovators to what we now call the maker community.[3]

In other words, for photonic chips to break through as a mainstream technology with sustainable and cost-effective fabrication volumes, general-purpose (or at least multi-purpose) programmable photonic chip platforms are needed to fill the same gap in the photonic ecosystem as FPGAs do in the electronic ecosystem. Like electronic FPGAs, such programmable photonic processors would not be suitable for all applications, but they would allow accelerated product development and ease the transition to custom-designed chips. Their flexibility comes at a cost, of course. These chips are larger (therefore more expensive), accumulate higher optical losses (light has to pass through many more building blocks), and require a lot more electronics to control. So, when application volumes or performance requirements would demand it, custom-designed photonic chips will still be necessary, while for low-volume applications, general-purpose programmable photonics might be a cost-effective solution.[4]

Figure 1 shows a conceptual drawing of such a programmable photonic processor. At the core is a waveguide mesh of optical gates that can be configured to couple the light between two input and two output waveguides. This makes it possible to configure light paths between functional building blocks to define a new photonic circuit.

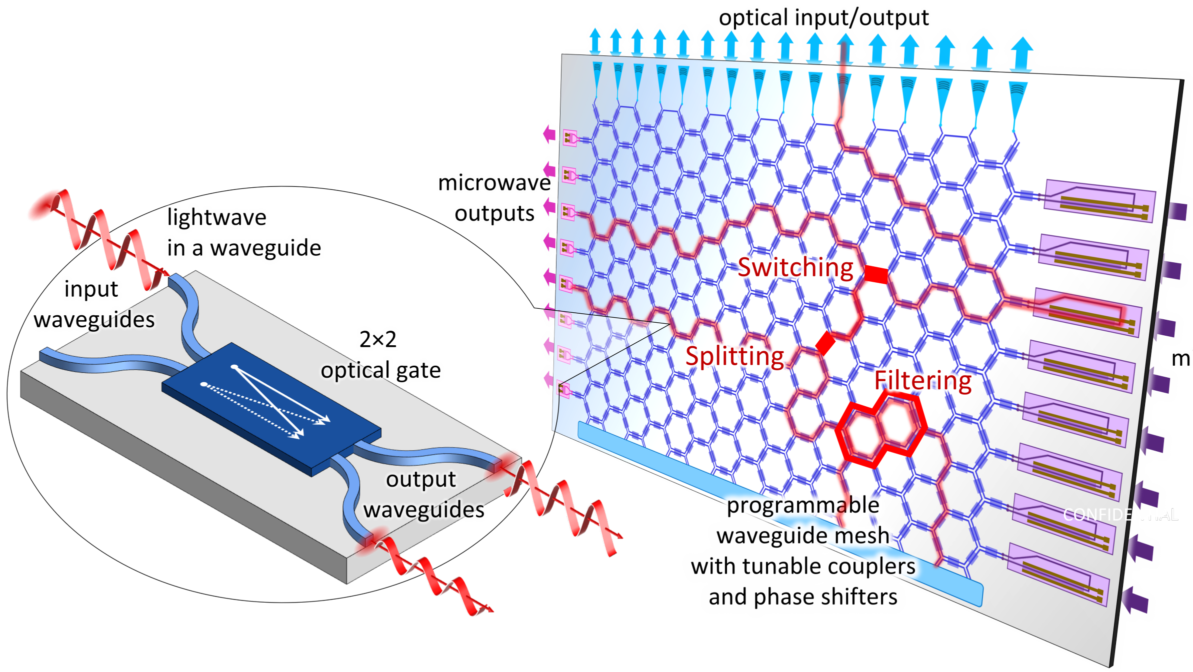

Figure 1. General-purpose programmable photonic processor: A waveguide mesh consisting of optical gates (containing phase shifters and/or tunable couplers) connects functional building blocks and waveguide ports. Optical signals can be routed, distributed, or filtered by tuning the coupling and phase delay in the optical gates. High-speed microwave signals can be converted into optical signals through modulators and back into microwave signals through high-speed photodetectors.

Realizing this future for programmable photonics takes more than just building such a photonic chip. As already mentioned, the reconfigurability requires tight integration with driver and readout electronics and software routines to calibrate, configure and control light paths on the chip. This requires a technology stack that comprises photonic and electronic chip technologies, co-packaging techniques, and multiple layers of software, all the way up to software development kits (SDK) for innovators and educators.

In this paper, we will discuss the scaling challenges for these programmable photonic chips and our work toward realizing a general-purpose programmable photonic processor. It covers the work of multiple research projects that contribute to the multiple layers of the technology stack. In the PhotonicSWARM project of the European Research Council, the basic architectures and strategies for programmable photonics have been explored. The European project MORPHIC focused on an implementation for programmable photonic chips where the electro-optic configuration is implemented using low-power MEMS actuators in silicon photonics, which come with their own set of challenges for circuit integration and electronic driving. The work of MORPHIC is continued in the project PHORMIC where we also integrate optical amplifiers, which can be used to offset some of the losses in the larger programmable circuits but could also enable new functionality for programmable light sources or non-linear functions. The projects GRAPHSPAY and MALEPHICENT look into the software routines for designing, modeling, and programming configurations into programmable photonics.

We will start with a quick overview of programmable photonic architectures in section 2, followed in section 3 by a quick exploration of the different approaches to implement the key photonic building block in a programmable photonic circuit: the phase shifter. Section 4 discusses the circuit scaling challenges, focusing on the integration of photonics and electronics. Then the programming layers are discussed in Section 6. We end in Section 7 with a discussion of the overall ecosystem for programmable photonics.

2. PROGRAMMABLE PHOTONICS

Making a photonic circuit programmable means you need an electronic way to control the flow of light on a chip. This can be done using electro-optic switches, tunable couplers, and phase shifters that form optical gates, usually with two input ports and two output ports, allowing control of the coupling between two signals and tuning their relative phase delay, essentially making the output waves a programmable 2×2 linear combination of the input waves. By organizing such optical gates in a mesh connected by waveguides, optical signals can be routed and distributed between different points in the mesh. As the function of the individual gates can be described by a linear operation, the behavior of the full mesh is also linear.[5]

Today, we can identify two main classes of such waveguide meshes that we call *forward only* or *recirculating*.[6] They are illustrated in Fig. 2. In a forward-only waveguide mesh, light flows in one direction from a set of input ports to a set of output ports.[7,8] This effectively implements a linear transformation between a vector of input waves and a vector of output waves. Therefore, the propagation of light through the mesh is equivalent to an analog matrix-vector multiplication, also called a multiply-accumulate (MAC) operation. These can be used as fundamental computation operations in pattern recognition algorithms and machine learning. Likewise, when used with single photons, these linear transformations can be used as quantum gates. It is therefore not surprising that most demonstrations of such forward-only circuits are geared towards neuromorphic computing[9–11] or quantum information processing.[12–14]

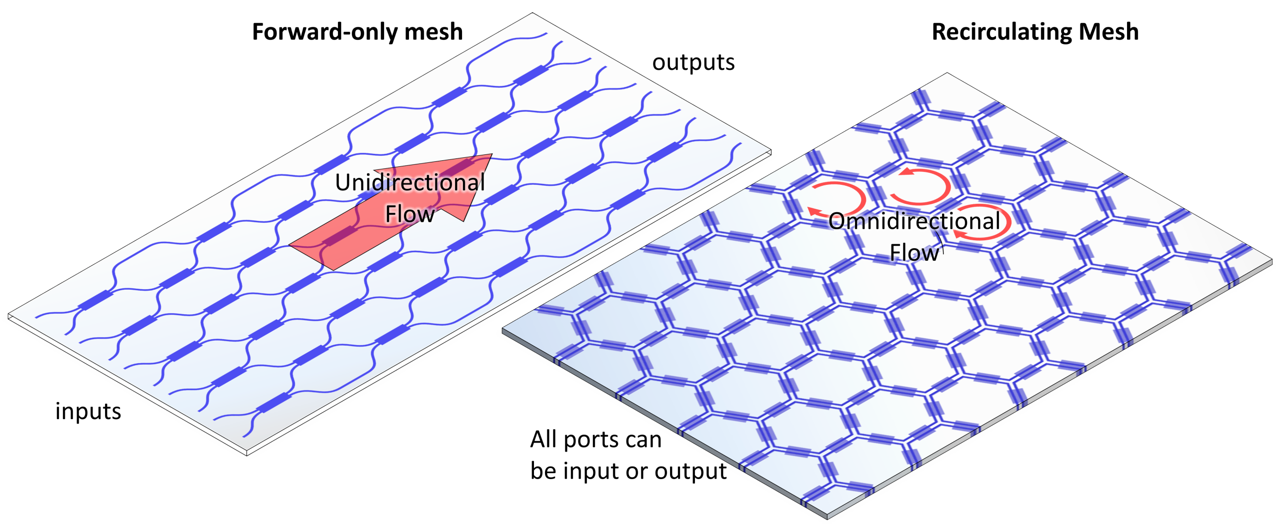

Figure 2. Waveguide mesh architectures. Left: a forward-only mesh, where light flows in one direction from a set of input ports to a set of output ports. Right: a recirculating mesh, where light is coupled from one unit cell to the next and can travel between any pair of ports.

The other class of architectures is the *recirculating* waveguide mesh. It makes use of the same optical gates but now arranged in waveguide loops. The coupling between these loops can be controlled, making it possible to route the light in all directions through the mesh.[15,16] Such architectures, which can have triangular, rectangular, or hexagonal unit cells, are more generic than the forward-only waveguide meshes, as all ports can now be used as either inputs or outputs. Also, forward-only meshes are usually constructed with balanced paths, making their response more or less wavelength independent. Recirculating meshes, on the other hand, can be used to construct both balanced and imbalanced paths, allowing the construction of interferometric wavelength filters. As the light can also be routed in a loop, it is possible to implement resonant filters.[17] When active photonic elements, such as amplifiers, modulators, and photodetectors, are attached to such a recirculating mesh, they can be connected into arbitrary photonic circuits. Therefore, this class of programmable photonic circuits is a good candidate to take up the role of general-purpose photonic processors.[6,18]

While there have been several demonstrations of forward-only and recirculating programmable photonic circuits, the technology still faces significant challenges. Many of those have to do with scaling: With all the programmable elements, these circuits are typically much larger and more complex than application-specific circuits, scaling to 1000s of individually controllable electro-optic actuators, such as tunable couplers and phase shifters. As light has to pass through many actuators on its path, these actuators should have excellent optical performance. In the following section, we discuss the need for the perfect electro-optical actuator for programmable photonics and different approaches that are being explored today.

The many controllable elements also present challenges to the system integration schemes. All actuators need to be electrically addressable, which requires large-scale multi-channel driver electronics and packaging/assembly techniques to connect the photonics and the electronics. If the programmable photonic chips also need to process high-speed modulated signals, the chip would require specialized RF amplifiers and packaging. This tight integration of photonics and electronics could also present thermal constraints to the packaging strategy.

It needs a reminder that these photonic chips are inherently analog signal processors. Unlike digital systems, where snapping to the discrete zero/one levels act as a correction mechanism, analog signals will accumulate errors due to the imperfect behavior of the waveguides and optical gates, which will translate into unwanted noise and crosstalk.[19,20] Some of these effects can be compensated by proper calibration and configuration algorithms,[19,21] or using active optimization and feedback control using photodetectors inside the mesh or on the periphery.[22]

Programmability implies software control. Therefore programmable photonic circuits need software libraries that both govern the low-level behavior of the chip (e.g., feedback routines for each optical gate) and the high-level functionality (configuring waveguide routing and wavelength filters). Some of these tasks can be mathematical problems that cannot be solved in polynomial time and therefore require heuristic search algorithms once the circuits scale beyond a certain size. This software stack should be accessible to users and developers to implement their own functionality.

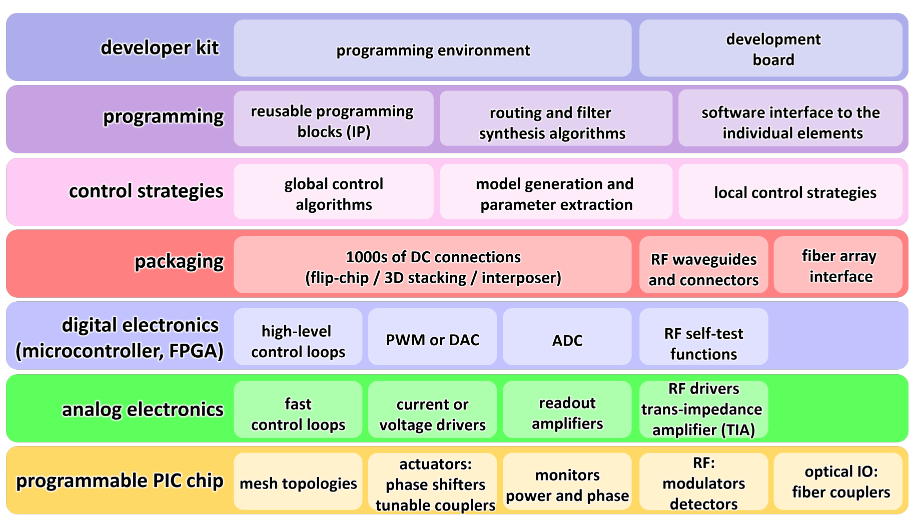

Figure 3. Technology stack for programmable photonics.[4,6] To realize a programmable photonics system, one needs to combine the photonic chip with analog and digital driver electronics and software layers.

These technological layers are visualized in Fig. 3. To realize the potential of general-purpose programmable chips, it is important that all essential blocks in this technology stack are available, from the basic photonic chip technology to a Software development kit (SDK) for the user. And, of course, this only makes sense if all elements can be fabricated in a cost-effective manner and in sufficient volumes. After all, one of the key benefits of a generic technology is that it can be produced in large quantities to serve a variety of applications.[4] This requires a complete ecosystem of chip designers, foundries (photonic and electronic), packaging techniques, and software providers.

3. LOOKING FOR THE IDEAL PHASE SHIFTER

The actuators in the optical gates already present us with a first set of challenges: they must have extremely high performance. As light propagates through long chains of phase shifters and tunable couplers, they must have very low optical insertion losses. They should take up a small chip footprint, and have a short optical length to allow granular control of optical delay lines. Preferably, their response is broadband to enable functionality over a wide wavelength band. Also, their electrical power consumption should be low, and preferably they can be voltage-actuated with CMOS-compatible voltages ($< 5\,\mathrm{V}$). They should be compatible with existing photonics platforms or at least with the integration of active building blocks such as modulators, detectors, and optical amplifiers. In the next few paragraphs, we will mostly focus on phase shifters, as these form the most basic electro-optic actuator; after all, switches and tunable couplers can also be implemented using phase shifters.[8] Figure 4 shows several different mechanisms that can be used to implement an electro-optic phase shifter.

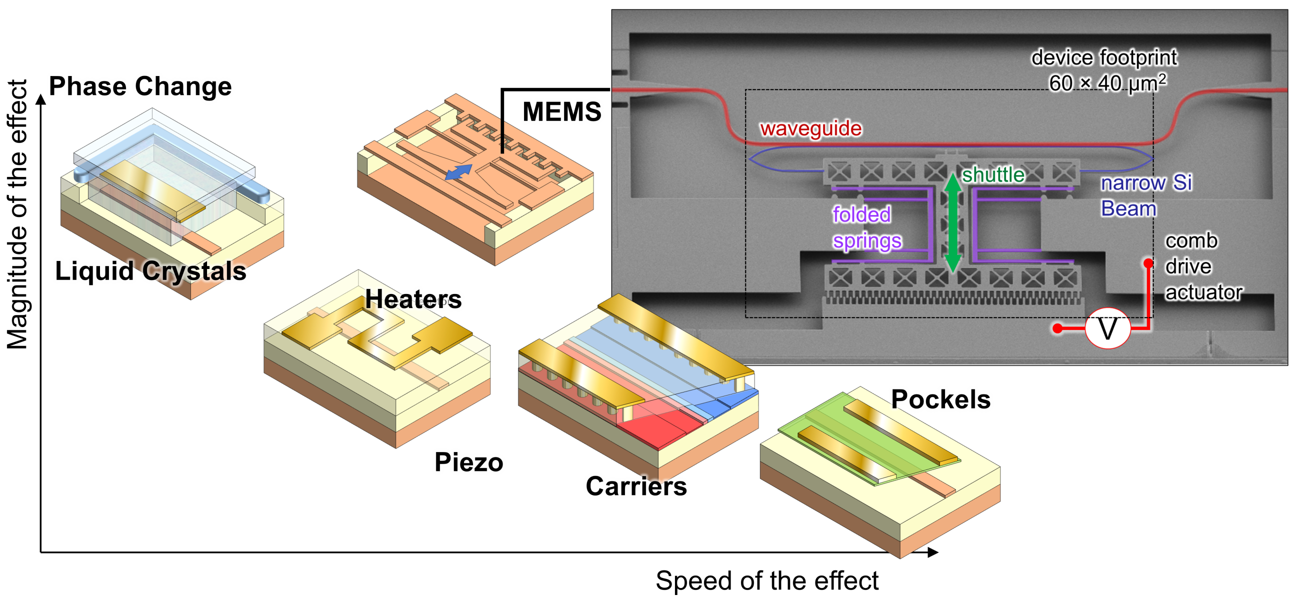

Figure 4. Electro-optic actuation mechanisms, classified by the speed of the effect and the magnitude. The stronger the effect, the shorter and more compact the phase shifter can be implemented. Inset: A MEMS Phase shifter developed in the MORPHIC project.[23]

Today, the most prominent technique to implement an electro-optic phase shifter, in multiple PIC platforms, is a heater.[24] It relies on the principle that the refractive index of most optical materials is dependent on temperature. And a heater is very easy to implement in most platforms in the form of an electrical resistor. If the resistor is kept sufficiently far away from the optical waveguide, it does not introduce any excess optical losses, and in many cases, the resistor can be dimensioned to operate at a voltage that is convenient for the driver electronics. Heaters come at a significant cost though: they require continuous power consumption to maintain the elevated temperature. The thermal tuning efficiency (usually expressed as P_π, i.e., the electrical power required to induce a π phase shift in the optical wave, depends on the thermo-optic coefficient of the materials, as well as the volume that needs to be heated and the thermal insulation of heater-waveguide combination. As silicon has a high thermo-optic coefficient and very compact waveguides, silicon photonic heaters can be very efficient, with $P_\pi \approx 15 - 20\,\mathrm{mW}$ for regular heaters and $P_\pi \approx 1 - 5\,\mathrm{mW}$ when local substrate removal is applied to better insulate the heater and waveguide.[24,25] It is clear that, even with these efficient heaters, it will be challenging to scale up the power dissipation to circuits with thousands of active elements, and this does not even address the difficulties of tackling thermal crosstalk.[26]

A variety of alternatives to heaters are being explored. The linear electro-optic effect or Pockels effect can provide a phase shift when an electric field is applied without static power consumption. One such material, Lithium Niobate, is already widely used for high-speed modulators. In the past few years thin-film Lithium Niobate on insulator (LNOI) also scaled down waveguide dimensions, enabling larger circuits.[27] But even with these reduced dimensions, the phase shifters are still several 100 µm long. An alternative is to extend silicon photonics with new electro-optic materials, such as Barium Titanate (BTO) or polymers.[28] Those material integration strategies show great promise but require further development before they can be considered sufficiently mature for large-scale circuits.

Another class of materials that can provide a strong optical phase shift in a waveguide is phase-change materials (PCM). These are materials that can be induced to assume different (meta)stable states (usually crystalline and amorphous) by using controlled heating/cooling cycles.[29] The two states can have very different refractive indices. By applying such a PCM as a waveguide cladding, a local heater can switch its state, only consuming power during the transition. This is a very useful mechanism for circuits that only need infrequent reconfiguration. The drawback is that most PCMs have high optical losses on one of the two states, and only recently first explorations of transparent PCMs are showing some promise to overcome this drawback[30]

Yet another family of electro-optic materials is liquid crystals (LC), which consist of highly anisotropic molecules that can be reoriented using an external electric field. While it might seem counterintuitive to integrate liquids on a chip, using liquid crystal on silicon (LCOS) for microdisplays is an established technology.[31] The use of LC to tune silicon photonic waveguides has already been explored for two decades,[32,33] but the main challenge has always been to find an efficient method to locally integrate the liquid on the chip, and to bring the electrodes close enough to the waveguide. Recently we demonstrated a solution to this problem, using an inkjet-printing technique to rapidly deposit precise quantities of liquid crystals onto waveguides in a full silicon photonics platform.[34] Using a local side electrode close to the waveguide, we can fully reorient the liquid crystal with only 5 V actuation, resulting in a 2π phase shifter with a length of less than 100 µm. The liquid crystal molecules do cause some optical scattering, so the phase shifters cannot be considered lossless.

Stress in a waveguide can also be used as an actuation mechanism. While this is potentially lossless, the effect is very weak, requiring very long phase shifters.[35–37] The stress can be induced using piezo-electric materials that only require electrostatic actuation, making this a low-power technique.

Micro-electromechanical systems (MEMS) present another attractive tuning mechanism based on electrostatic actuation. MEMS are on-chip movable elements that are micromachined in silicon using selective and local removal of supporting layers.[38] MEMS has become a well-established technology, and the fact that it also uses silicon processing makes it an interesting candidate to combine with silicon photonics. In the past decade, there have been multiple development tracks that have led to demonstrations of large-scale integration of MEMS actuators with optical waveguide structures.[39] The effects of MEMS can be very strong: after all, by moving a high-index material such as silicon, you can induce a very strong change in the local refractive index. In the project MORPHIC we have tackled the key challenge of integrating MEMS into an existing silicon photonics platform without compromising the existing functionality of high-speed modulators, and photodetectors.[40] This resulted in compact phase shifter and tunable couplers that are controlled using electrostatic comb drives.[23,41,42] For instance, we have demonstrated a phase shifter (Fig. 4) that induces a 2π phase shift with a length of only 50 µm, using a 20 V actuation. The main drawback of MEMS devices is that they need to be suspended in air. Not only does this increase scattering losses (due to the higher index contrast on the interfaces), but it also makes the exposed waveguide device fragile. That is why we have also developed a wafer-level sealing technique to protect them from outside effects.[43]

There is, today, no perfect technology for the perfect low-loss, low-power electro-optic phase shifter that we would need to really scale up these configurable photonic circuits. There are workable solutions that have been used to demonstrate small-scale and medium-scale programmable circuits, and this is driving the field forward, enabling the development of the higher-up layers in the technology stack.

4. LARGE-SCALE PHOTONIC-ELECTRONIC INTEGRATION

When we integrate thousands of phase shifters on a photonic circuit, we also need to connect these to their driver electronics. This presents a major wiring challenge as the circuits scale up. If the photonics and their electronic drivers can be combined into a single chip process (monolithic integration), the drivers can be close to the actuator and be directly controlled through a digital bus. This is by far the most elegant solution, but it requires a monolithic photonic-electronic silicon photonics platform. Such platforms are already available, but the combined photonic and electronic capabilities make them very expensive.[25] Also, while simple actuators such as heaters are available, it is not yet clear if these can also be expanded to accommodate more efficient phase shifter concepts and materials needed for realizing large-scale photonic systems.

If the photonics and electronics cannot be combined in the same chip, a packaging or assembly approach will be needed to interface the actuators with their drivers. When scaling up to more than a few 100 electrical connections, the chip edge no longer provides sufficient room for wire bonding, and area-based approaches are needed, such as flip-chipping, 3-D stacking, or interposers to break out the many electrical connections. Confronted with this challenge, the MORPHIC consortium worked on a high-density ceramic interposer to interface > 3000 electrical connections to the MEMS (or other) actuators[40] to a printed circuit board. For maximum flexibility, the bond pad layout on the chip was standardized so the interposer can be used with multiple iterations of silicon photonic circuits. Interposers can also be used to directly integrate the photonic and electronic chips, like this large-scale optical phased array (OPA) demonstration with > 8192 heaters.[44] An alternative is to reduce the number of electrical pads, for instance, by multiplexing the electronic control. This can be done using multiplexing techniques such as row-column addressing,[45] which can be used to control $M \times N$ phase shifters through $M + N$ pads. But this requires that the actuators are sufficiently slow, as they need to maintain their state while the driver circuit is being multiplexed.

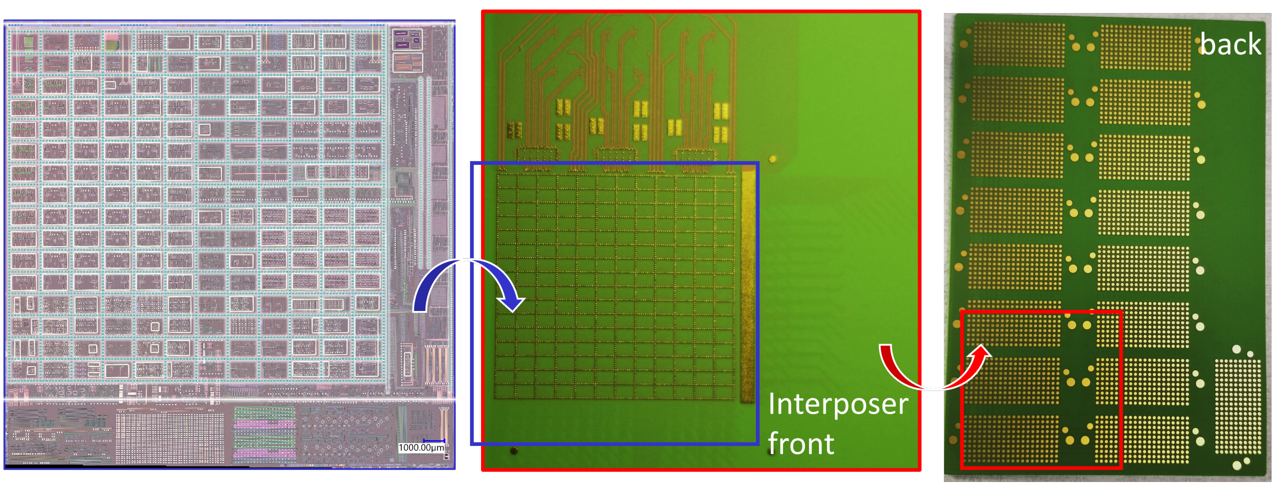

Figure 5. Interposer technology developed in the MORPHIC project.[46] The silicon photonics chip can have up to 3305 electrical connections on a fixed grid. A ceramic interposer breaks out these bond pads to a much wider pitch compatible with standard printed circuit board technology. The interposer also supports up to 24 high-speed connections for modulators and photodetectors.

Every actuator requires an electronic driver circuit, and monitor detectors will require readout electronics. These need to be optimized for the specific phase shifter technology. For instance, heaters are preferably controlled using a current drive, and the electronics need to be able to supply sufficient power. MEMS, Pockels-effect materials, and piezo actuators are voltage driven but require typically a high voltage 20-100 V.[37,47] Liquid crystals respond to the absolute value of the voltage but require an alternating-current (AC) drive to suppress the migration of ions in the liquid.

While small-scale demonstrations of programmable circuits can make use of lab equipment, larger circuits require dedicated multi-channel drivers. For instance, the aforementioned OPA demonstration used eight custom-designed driver chips, each with 1024 digital-to-analog converters (DAC), to control the photonic chip. And in the MORPHIC project, a modular 64-channel driver board has been developed specifically for high-voltage MEMS actuators.

5. VARIABILITY, IMPERFECTIONS AND LOSSES

One of the major challenges in large-scale photonic circuits is the sensitivity of on-chip waveguides to small variations in the fabricated geometry.[48] Even nanometer-scale deviations of the waveguide width and thickness can give rise to unacceptable behavior of the circuit, and this problem becomes more prominent as the circuits become larger. Programmable circuits can actually help in addressing this because the built-in electro-optic actuators can be used to compensate for many of the fabrication variations. For instance, phase errors in a waveguide can easily be tuned out by a phase shifter. It is also possible to circumvent small imperfections by adding additional degrees of freedom in a waveguide circuit. One particular example to illustrate this is the typical Mach-Zehnder interferometer (MZI) that can be used as a 2×2 optical gate. The MZI consists of a 50:50 splitter, two waveguides with a phase shifter, and a 50:50 combiner. Small deviations in the optical length of the waveguides can be compensated by the phase shifters, but if the couplers do not have a perfect 50:50 splitting ratio, it becomes impossible to tune over the full range of 0-100% coupling. This solution is to use a two-stage or three-stage MZI circuit,[49,50] using three or four 50:50 splitters, respectively. the additional tunability now makes it possible to tune the circuit over the full coupling range, even when the 50:50 splitters are as bad as 25:75 (for the two-stage case) or 15:85 (for the three-stage circuit).[49,50] This comes of course at a cost: the new gate requires $2 - 3\times$ the number of actuators, with the accompanying larger footprint, power consumption, optical length, and the need for extra driver electronics. Also, the control and configuration of these more complex gate circuits become more difficult.

This concept can be generalized to larger waveguide meshes: By making a mesh somewhat larger than strictly necessary for the desired functionality, imperfections can be compensated using the additional optical gates. This requires careful characterization and calibration of all the gates and a configuration algorithm that takes into account these additional degrees of freedom.[19,21]

Depending on the waveguide mesh architecture, imperfections will have different effects. In forward-only meshes errors in phases and coupling coefficients can give rise to crosstalk or errors in the actual transmission coefficients. In recirculating meshes, small deviations in coupling coefficients can inject light into paths of different lengths, resulting in strong wavelength-dependent behavior. This can already become a problem with coupling errors of 1% or less. Even worse, the loops in the mesh could form parasitic ring resonators, giving rise to sharp resonance peaks in the transmission spectrum.[20] Compensating these effects is not straightforward, even when additional degrees of freedom are incorporated in the mesh.

Losses form another obstacle when we scale up the photonic circuits. Even if we further develop the phase shifter technology, most high-density waveguide platforms still have propagation losses of 1 dB/cm. As the circuits become larger, these losses will accumulate. If programmable photonic circuits need to become a viable technology to develop new applications, a solution for reducing these losses is needed. One approach is the integration of optical amplification to offset the losses. Apart from III-V semiconductor technologies, most PIC technology platforms do not have built-in optical gain. However, it is possible to heterogeneously integrate III-V semiconductor optical amplifiers (SOA) on other waveguide platforms, in particular, silicon or silicon nitride photonics.[51] Using either die-to-wafer bonding or micro-transfer printing, working amplifiers and laser sources have been demonstrated in full silicon photonics platforms.[52] The micro-transfer printing approach is now being extended in the project PHORMIC to co-integrate with the MEMS actuators developed for IMEC's iSiPP50G platform.

SOAs could make a big difference in the scaling of larger programmable photonic circuits, but they also come with drawbacks. They can be quite large and long, and they consume a lot of electrical power, which translates into significant local heating of the photonic chip. Incorporating SOAs inside a waveguide mesh might, therefore, not be the most straightforward approach, and instead, they can be placed on the periphery or in local islands inside the mesh. Note that the combination of amplifiers and waveguide loops in a recirculating mesh could give rise to unwanted lasing. And of course, amplification might help us along the way in compensating for the attenuation induced by optical losses. Still, it will not help in any way to reduce the noise induced by the optical loss. In the most extreme case of quantum optic circuits, the amplifiers will not help at all with the loss of single photons.

6. PROGRAMMING AND CONTROL

Unlike most application-specific photonic circuits, programmable photonic circuits are not functional out of the box. The states of the various optical elements need to be configured first for the chip to perform a useful function. The main configurable functionality is the linear transformation of the waveguide mesh (either feed-forward or recirculating). We can discern two main types of functions: those where the phase and/or wavelength of the optical signals is relevant, and those where we only care about intensity, and which we will call phase-agnostic.

Examples of phase-agnostic functions is connecting pairs of input/output ports with the sole intent of transporting the signal between functional building blocks. This is a very common use case in optical switching, or when one wants to compose a circuit by connecting building blocks on the periphery of the waveguide mesh. Routing in a waveguide mesh corresponds to a pathfinding algorithhm. It is possible to use existing algorithms developed for network and logistics optimizations, by translating the optical waveguide mesh into a graph.[53–55] Finding individual routes is a fairly trivial problem, but the complexity scales once multiple routes need to be established and the waveguide mesh becomes crowded. In this case, congestion avoidance heuristics are needed,[53,56] as the problem rapidly scales to become impractical to handle with deterministic methods. Other phase-agnostic functions include $1 : N$ power splitting or distribution, or $M : N$ distribution of M signals on different wavelengths to N waveguide ports.

Phase-dependent configurations can be more difficult: here the light is split over multiple paths that can be recombined to form interferometers. The two most common examples are the aforementioned matrix-vector multiplication in forward-only meshes (although these can also be configured in recirculating meshes), and wavelength filters in recirculating meshes. In both cases, accurate control of path lengths and phase delays is needed. It can be a lot more difficult to calculate such configurations, as interferometric devices with many phase tuners give rise to an optimization landscape with a large number of local peaks and valleys, and the optimization can be different for each wavelength channel. Local optimization techniques based on the steepest descent can quickly find a good local solution,[57] but it is not guaranteed that they will find the best global solution. However, in special cases, such as certain forward-only waveguide meshes, a transformation between the input and output ports can be constructed with iterative methods.[5,50,58] For filter functions, it is often more efficient to define a filter topology consisting or delay lines and ring resonator loops, and then optimize the settings within this configuration. This makes it possible to use some existing filter synthesis algorithms as a starting point, and it limits the degrees of freedom for the optimization routines. The filter configuration then becomes very similar to the configuration of custom-designed filters.[59,60]

Beyond the programming of linear functionality, one can also use the configurability of the circuit to configure more advanced active functions. For instance, by embedding one or more standard silicon modulators in a larger configurable circuit, some of the imperfections of the phase modulators can be suppressed, and the modulation format can even be made configurable, switching from pure intensity modulation to pure phase modulation.[61]

These programming routines can interact with the hardware in different ways. The most basic method would be offline programming: a configuration is calculated based on a model of the hardware, after which all the actuators are set to their desired state. This requires precise knowledge of the behavior of all actuators, which can be collected through an initial calibration step.[19,55] This can work well if the system is stable and does not suffer from excessive drift or crosstalk. In some cases, it is possible to even compensate for crosstalk, if the effects can be captured in a linear transformation.[26]

Alternatively, the programming can rely on feedback routines that involve the actual hardware. This requires the placement of monitor detectors inside or on the edge of the waveguide mesh. Multiple actuators can be configured using a single monitor.[8,62] This multiplexing can even be scaled up through the use of dithering or pilot tones, which makes it possible to separate the effect of each individual actuator on the output signal,[22,63] Most detectors only detect the intensity of light directly, so if phase configurations are needed, the monitor must be embedded in an interferometric structure to translate phase delay into amplitude variation.[64]

To make these programming routines useful, they must be integrated into a development environment that makes it possible for the user to try out new configurations, and experiment in both simulation and actual hardware. In the MORPHIC and PhotonicSWARM project we have built such a software environment that allows us to design, simulate, and program configurable waveguide meshes, and also directly interact with the hardware to experimentally configure the circuits.[65]

7. THE ECOSYSTEM

The name *Programmable photonics* covers a broad range of technologies. In the broadest sense, it describes every photonic chip that has some form of a software interface, even if that is only used to tune or optimize the single functionality of the circuit. Actually, most photonic transceiver circuits today would fall into this category. More narrowly, one can identify the circuits which are still designed for a specific type of function, but that function needs active configuration to be actually useful. Matrix-vector multipliers, neuromorphic circuits, or quantum information processors would fall into this category. They require significant programming, but the chips are still designed for a single function. Programmable microwave photonic filters are another example.[66]

The narrowest class of programmable photonic chips are the general-purpose photonic processors that we described at the beginning of this paper. These photonic chips have no predefined function; just a collection of functional building blocks that can be arbitrarily connected and configured. As we discussed, these circuits would fill a very important gap in the photonic chip ecosystem today.

While photonic chips can be fabricated with the same technology base as standard integrated electronics, the economic considerations are very different. Even with the exploding market for data center communication, the volumes for photonic chips are still much lower than the capacity of a single CMOS fab. To justify the investments in the multiple commercial photonics foundries that have opened up in recent years, the volumes for photonic chips should scale up by many orders of magnitude. This implies that photonic chips should break into other markets, especially high-volume consumer electronics. We already mentioned that this process is slowed down by the lack of mature first-time-right design flows and general-purpose photonic processors.

For this to work, the entire technology stack for programmable photonics should be available. The photonic chips should be "good enough", integrated with electronic drivers, and the essential software layers should be in place. Like with existing electronic FPGAs, photonic processors should be supported by developer boards and an SDK, giving the users low-threshold access to the photonic functions. A company like iPronics has already demonstrated an initial prototype of such a generic photonic engine with its electronic and photonic interface.[67]

Figure 6 sketches the development cycle for a new photonic product based on a custom-designed PIC and compares this to a cycle based on programmable PICs. When these can be purchased off-the-shelf, the long and costly chip design and manufacturing steps can be bypassed. Taking into account that product development would require three or more chip iterations, it is clear how much a general-purpose chip can accelerate this process.

It is of course important that this is available at an affordable cost. The bill of materials for these larger, more complex chips, the packaging, and the driver electronics will, at first sight, be more expensive than that of an optimized application-specific chip (set). But this is only the case if they are manufactured in the same volumes. Generic photonic processors can be fabricated in larger volumes, and the development cost can be spread over a large number of users. Cost calculations show that this can easily offset the premium of a larger chip area, even when including profit margins for resellers.[4] Even for low-to-medium volume markets, the use of these generic chips could be cost-effective compared to a custom-designed chip. Especially when taking into account the time-to-market for current photonic chips, having a programmable chip can dramatically lower development costs.

The fact that programmable photonic chips have a software interface presents another unique advantage. One does not necessarily need in-depth expertise with photonic chips to actually use these photonic circuits. This opens up photonics technology to the much larger community of electronics and software engineers. Given today's shortage of skilled photonics engineers, this larger community is destined to be the motor of a new wave of innovation. They can contribute to the ecosystem with new configuration algorithms and design methodologies, effectively creating a new market of photonic *intellectual property* (IP).

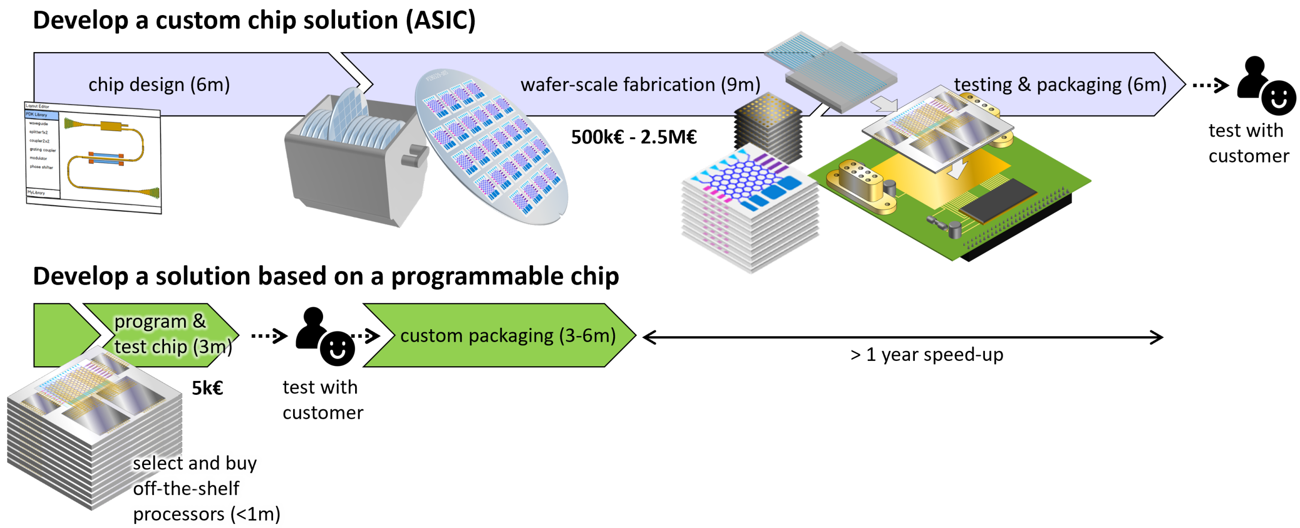

Figure 6. Development cycles for a prototype based on a custom application-specific PIC and based on an off-the-shelf programmable PIC.

8. SUMMARY

The term "scaling" is applicable in many ways to the new technology of programmable photonics. First of all, as these circuits are typically much larger than most application-specific PICs today, they require a technological scaling of the photonic chips, the packaging, and the electronic drivers.

On the other hand, programmable photonics can become an enabler to fundamentally change the scaling of the entire photonic chip ecosystem. To become economically viable, photonic chip fabrication volumes need to be many times larger than they are today, and programmable photonics will lower the thresholds for innovation in photonic chips, effectively opening up new markets and a much larger user community.

To realize this breakthrough, we have been working on the different technological elements needed to build a fully integrated photonic processor. In the work of various projects listed here, we have been developing more efficient electro-optic actuators, packaging technologies, driver electronics, and software layers, essential steps on the road toward a fully functional general-purpose photonic processor.

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