Building Large-Scale Programmable Photonic Circuits Using Silicon Photonic MEMS

Wim Bogaerts[a], Pierre Edinger[c], Alain Yuji Takabayashi[b], Iman Zand[a], Xiangfeng Chen[a], Xiaojing Wang[c], Hamed Sattari[b], Peter Verheyen[g], Moises A. Jezzini[d], Giuseppe Talli[d], Saurav Kumar[f], Marco Garcia Porcel[e], Antonio Ribeiro[a], Gaehun Jo[c], Niels Quack[b], Kristinn B. Gylfason[c], Frank Niklaus[c], Umar Khan[a]

[a] *Ghent University - IMEC, Photonics Research Group, Department of Information Technology, Belgium*
[b] *École Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland*
[c] *KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden*
[d] *Tyndall National Institute, Lee Maltings Complex Dyke Parade, T12 R5CP Cork, Ireland*
[e] *VLC Photonics S.L., Ed. 9B, D2, UPV, Camino de vera sn, 46022 Valencia, Spain*
[f] *Commscope Connectivity Belgium, Diestsesteenweg 692, 3010 Kessel LO, Belgium*
[g] *imec vzw. 3DSIP Department, Si Photonics Group, Kapeldreef 75, 3001 Leuven, Belgium*

wim.bogaerts@ugent.be

Abstract: Programmable photonic circuits electronically reconfigure the flow of light on a chip. This requires hundreds or thousands of phase shifters and tunable couplers. Silicon photonic MEMS offer both high integration density and low power consumption. © 2020 The Author(s)

1. Introduction

Silicon Photonics makes it possible to integrate complex photonic circuits with thousands of components on a chip. This is leading us to programmable photonics: photonic circuits where light is controlled through electronics and software, using meshes of phase shifters and tunable couplers connected by waveguides [1]. Depending on their shape, these meshes can perform generic linear operations such as matrix-vector multiplications [2], single-value decomposition, or they can be configured as filter circuits for microwave signals [1].

In such generic circuits, the number of electro-optic actuators roughly scales with the square of the number of ports, rapidly growing into the hundreds or thousands. That means that compact and power-efficient tunable couplers and phase shifters are needed, as the current approach of waveguide heaters will not effectively scale up. In the European MORPHIC project, we develop an approach based on micro-electromechanical systems (MEMS), using electrostatic actuation to induce a phase shift in silicon waveguides, and combine this with the necessary electronics, packaging schemes and software algorithms to create a generic programmable photonic circuit.

2. Silicon Photonic MEMS

MEMS are an effective way of electrically changing the optical properties of a waveguide: by electrically moving material, a large change in refractive index can be induced [4]. However, integrating MEMS with optical waveguides requires that the waveguides become suspended. We developed a process to post-process the MEMS on the existing silicon photonics platform of IMEC, which already contains high-speed modulators and germanium photodetectors [3, 5]. For this, the silicon waveguides are locally exposed and underetched using vapor-phase hydrofluoric acid. This results in compact phase shifters and tunable waveguide couplers [3, 5].
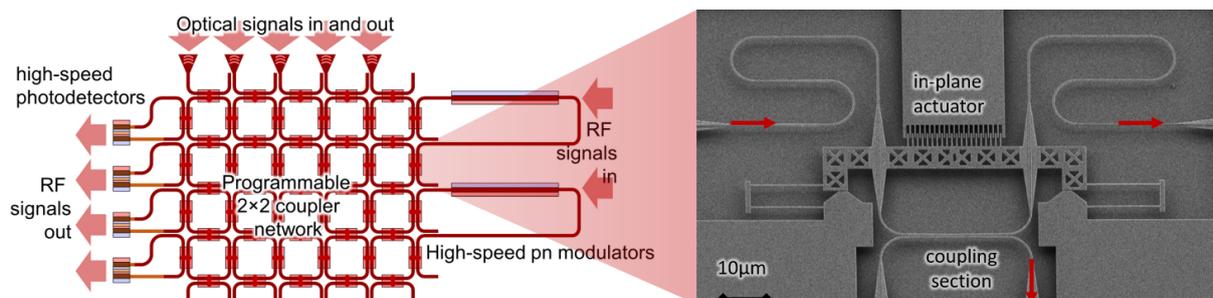
Fig. 1. A programmable PIC circuit schematic with a MEMS tunable coupler [3]

3. Scaling to larger circuits

These MEMS actuators are combined into large-scale circuits, forming a waveguide mesh that can be electrically controlled. Different mesh topologies are possible, from forward-only meshes for linear computations, to generic recirculating meshes for programmable filters. Because the MEMS waveguides require transitions between suspended waveguides and oxide-clad waveguides, the choice of mesh topology is important to reduce excess transition losses and backreflections. Also, when scaling up to larger meshes, partitioning strategies become important to break up excessively long optical paths. These form a new class of optical placement and routing problems that require custom algorithms to design and program these new photonic circuits [6].

4. Integration

A programmable photonic circuit is more than the photonic chip. The many actuators need to be electrically controlled, which requires close integration with electronics. In the case of MEMS, this requires driving voltages in the range of 20-50V, which imposes additional constraints on the packaging. Also, some applications require high-speed microwave in/outputs, so it becomes clear that integration strategies based on flip-chipping, 3D stacking or 2.5D interposers are required. To protect the MEMS devices, which are sensitive e.g. to particles and humidity, a hermetic wafer-level sealing process is applied [7] before the connection with the electronics. To use a programmable circuit through the electronics stack, software control layers are needed, from simple feedback loops and parasitic control [8] to high-level programming schemes such as routing [6] or filter synthesis [1].

5. Applications

Programmable PICs can be deployed in two likely scenarios. The linear optical circuits are exceptionally useful for applications which require matrix algebra, such as artificial neural networks [2], optical qubit processing, or beamforming. This requires the integration of waveguide meshes in custom-designed application-specific PICs. However, programmable PICs can also be designed to perform a multitude of functions, limited only by the software-defined connectivity. The use-case, and the ecosystem for such general-purpose PICs, resembles that of electronic FPGAs [9]. Like FPGAs, they could be purchased off the shelf and programmed for a variety of scenarios, such as switching applications or microwave processing for sensing or wireless communication.

6. Summary

Large-scale programmable photonics presents an opportunity for silicon photonics to address a wide variety of applications. However, the technology stack for these new chips imposes significant requirements on the packaging, electronics and software algorithms. We develop a silicon photonics process with integrated MEMS to scale up to large circuits with lower power consumption.

Acknowledgements

References

1. D. Pérez *et al.*, "Programmable multifunctional integrated nanophotonics - Review Article," Nanophotonics 2018 **7**, 1351–1371 (2018).
2. N. C. Harris *et al.*, "Linear programmable nanophotonic processors," Optica **5**, 1623 (2018).
3. W. Bogaerts *et al.*, "MORPHIC : Programmable photonic circuits enabled by silicon photonic MEMS," Proc. SPIE **11285**, 11285–1 (2020).
4. C. Errando-Herranz *et al.*, "MEMS for Photonic Integrated Circuits," IEEE J. Sel. Top. Quantum Electron. **26**, 1–1 (2019).
5. N. Quack *et al.*, "MEMS-enabled Silicon Photonic Integrated Devices and Circuits," IEEE J. Quantum Electron. **56**, 8400210 (2020).
6. X. Chen *et al.*, "Graph Representations for Programmable Photonic Circuits," J. Light. Technol. **38** (2020).
7. X. Wang *et al.*, "Wafer-level vacuum sealing by transfer bonding of silicon caps for small footprint and ultra-thin MEMS packages," J. Microelectromechanical Syst. **28**, 460–471 (2019).
8. I. Zand *et al.*, "Effects of Coupling and Phase Imperfections in Programmable Photonic Hexagonal Waveguide Meshes," Photonics Res. **8** (2019).
9. W. Bogaerts *et al.*, "Programmable Photonics: An Opportunity for an Accessible Large-Volume PIC Ecosystem," IEEE J. Sel. Top. Quantum Electron. **26** (20).