Large scale programmable photonic circuits using silicon photonic MEMS

Umar Khan[1], Iman Zand[1], Pierre Edinger[2], Gaehun Jo[2], Simon J. Bleiker[2], Alain Yuji Takabayashi[3], Cleitus Antony[4], Junsu Lee[4], Arun Kumar Malik [4], Peter Verheyen[5], Cristina Lerma Arce [6], Tigers Jonuzi[7], Jan Watte[6], Niels Quack[3], Frank Niklaus[2], Kristinn B. Gylfason[2], and Wim Bogaerts[1]

[1]*Ghent University - IMEC, Photonics Research Group, Department of Information Technology, Belgium;*
[2]*KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden;*
[3]*Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland;*
[4]*Tyndall National Institute, Lee Maltings Complex Dyke parade, T12 R5CP Cork, Ireland;*
[5]*imec vzw, 3DSIP Department, Si Photonics Group, Kapeldreef 75, 30001 Leuven, Belgium;*
[6]*Commscope Connectivity Belgium, Diestsesteenweg 692, 3010 Kessel Lo, Belgium;*
[7]*VLC Photonics S.L., Ed. 9B, D2, UPV, Camino de vera sn, 46022 Valencia, Spain*

umar.khan@ugent.be

Abstract: We demonstrate low-power and non-volatile MEMS actuators on an industrially established silicon photonics platform. The compact electrostatically actuated phase shifters and tunable couplers enable large-scale programmable photonic integrated circuits.

Of the many available photonics platforms, silicon photonics has emerged as one of the most prominent and industrially scalable technology for *photonic integrated circuits* (PIC), by taking advantage of the established *complementary metal oxide semiconductor* (CMOS) manufacturing infrastructure. Thanks to the high refractive index contrast between the device layer (silicon) and the cladding (oxide) of the *silicon-on-insulator* (SOI) wafers, high integration density has become one of the key selling points for this platform. Still, silicon photonic manufacturing volumes are quite low, which reduces the advantage of the CMOS infrastructure in terms of scaling and cost reduction. As a result, developing a new photonic chip, even on a standard platform, is costly and time-consuming.

One of the reasons for this high cost is that most photonic chips are application specific, and validation of even the simplest circuit requires a full cycle of design, fabrication and testing. This slows down prototyping, and the development of a new chip is only viable if the eventual fabrication volumes are large. In photonics, there are currently no rapid prototyping platforms corresponding to the *field-programmable gate arrays* (FPGA) familiar from electronics. This highlights the need for a generic photonic chip that can be programmed to rapidly validate a new design [1], which can then lead to an application specific chip that can be fabricated in high volumes. Such a prototyping cycle will not only shorten the design validation period but will also reduce the involved fabrication cost because programmable chips, if sufficiently generic, can be fabricated in large volumes resulting in smaller costs.

A general-purpose programmable photonic chip requires many tunable elements that can be electronically controlled. These tuners are usually analog phase shifters or tunable beam couplers, and sometimes digital switches. Integrating thousands of such tuners on a chip presents a challenge, because today the most common tuning mechanism for silicon photonics is a local heater, which consumes significant power (5-30 mW), has a response time in the millisecond range, and needs sufficient spacing to avoid thermal cross-talk. For large-scale photonic circuits, a more power-efficient (low power consumption, low insertion loss, small footprint etc.) tuning mechanism is needed that can also be integrated directly with the other functional building blocks of the silicon photonics platform. Different tunable components based on the thermal, carrier-based, liquid crystal, and Pockels effects have already been investigated but a constant application of current/voltage is required to keep the components in a particular state.

In this manuscript, we present a *micro-electromechanical system* (MEMS) enhancement for IMEC's established silicon photonics platform, scalable to large-scale general-purpose programmable photonic integrated circuits which consume little power. This is complemented by matching multi-channel driver electronics meeting the high-voltage requirements, and a packaging flow to integrate the photonics, electronics and optical/electrical interfaces. A software framework for programming of these circuits is being developed, to make it user-friendly.

To realize large scale programmable circuits, we are using low-power MEMS actuated tunable components (phase shifters [2], and tunable couplers [3]) which can also be latched to a particular state for non-volatile operation. In contrast to the conventional silicon photonic circuits, the MEMS structures need to be freestanding, so the buried oxide underneath the waveguides needs to be locally removed to facilitate the movement. For this, we have developed a wafer level post-processing flow based on vapor-phase *hydrofluoric acid* (HF) etching that releases the MEMS structures. The open cavities with free-standing MEMS waveguides are then hermetically sealed in order to protect the MEMS structures from environmental influence and contamination during operation [4].

Both general-purpose and application-specific programmable circuits have been designed using the MEMS actuated tuning components to demonstrate the working of large-scale programmable circuits. Optical gates consisting of tunable couplers and phase shifters are connected with waveguides to form a hexagonal mesh as shown in Fig. 1(a). Integrated photo-detectors are embedded inside the circuits to monitor the configured state and condition of the circuits. The chip supports up to 3300 electrical connections which need to be accessible to the outside world. Thus, a matching packaging scheme has been devised to take care of the optical and electrical (including high-speed) interfaces, using a multi-layer ceramic interposer and passive *printed circuit boards* (PCBs) to fan-out the electrical interfaces from the photonic chip. The sealed photonic chip is flip-chipped on to the interposer as shown in Fig. 1 (b), and a 72-channel fiber array is attached to the photonic chip to access the optical ports.

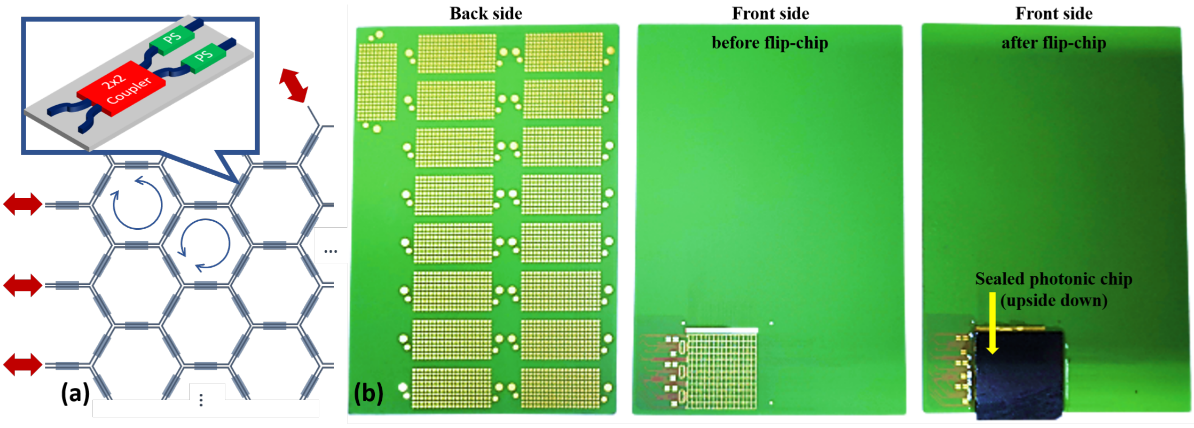

Fig. 1. (a) Schematic of the hexagonal mesh. Dark blue rectangles represent optical gates consisting of 2x2 tunable coupler and phase shifters. Red and blue arrows represent the optical ports and light circulation in a cell respectively. (b) Pictures of the front and the back sides of the multilayer (20 signal layers) ceramic interposer. Sealed photonic chip is flip-chipped on the front side of the interposer.

Finally, there is a need for electronics not only to actuate the many tuners but also to read-out the monitors from the circuits. A multi-channel *electronic interfacing and control* (EIC) board has been designed for this very purpose, using a modular approach where multiple boards can be combined to control larger circuits. On top of that, a programming framework facilitates the configuration by mapping the electrical connections to the circuit schematic and visualizing the configured circuit and the current state of gates in the circuit.

To summarize, we have developed a MEMS enhanced silicon photonics platform that is suitable for high volume production of large scale programmable photonic integrated circuits.

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