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Low-power programmable integrated photonic circuits fabricated by femtosecond laser micromachining

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Summary. — Photonic integrated circuits (PICs) are steadily becoming an established technology with a wide range of applications in communications, sensing and analog signal processing. PICs manipulate light signals using waveguides, directional couplers and phase shifters as building blocks. Recently, there has been growing interest in fully reconfigurable PICs, which can be programmed to perform any linear transformation on the input signal. Femtosecond Laser Micromachining (FLM) is a versatile fabrication technology that allows rapid and cost-effective fabrication of PICs. Reconfigurability in FLM PICs is implemented by means of thermal phase shifters, which provide optical signal modulation without added signal loss. Until recently only few thermal shifters could be fabricated on the same chip due to their high power dissipation and thermal crosstalk. This limitation can be overcome with the introduction of isolation structures fabricated via FLM, which provide a more than ten-fold reduction in dissipated power and crosstalk, allowing us to fabricate fully programmable PICs with tens of thermal shifters integrated into the same device.

1. – Introduction

Photonic integrated circuits (PICs) have enabled a diverse range of applications thanks to their many advantages over bulk optics. One of the most important features of PICs is their reconfigurability. Phase shifts can be induced between optical signals by exploiting various physical effects [1-3], among them the thermo-optic effect results in a simple yet effective implementation. A localized increase in temperature is achieved by heating microheaters via Joule effect, resulting in a localized refractive index change. These devices are known as thermo-optic shifters, or thermal shifters.

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Fully reconfigurable PICs are attracting growing interest in the fields of optical communications and quantum information processing [4, 5]. In particular, circuits that can be "universally" reconfigured to implement arbitrary unitary transformations are known as universal photonic processors (UPPs). A UPP can be obtained with an interferometric mesh composed of many reconfigurable Mach-Zehnder interferometers (MZIs) arranged in either a triangular or rectangular geometry [6, 7]. A single MZI representing the unit cell of such a circuit is composed of two thermal shifters and two balanced directional couplers. Many integrated photonics platforms have been employed for the realization of UPPs, such as silicon nitride [8, 9], silica-on-silicon [10] and femtosecond laser micromachining [11] (FLM). The latter is a versatile technique for the fabrication of waveguides in glass substrates which allows for fast and cost-efficient prototyping of circuits featuring low propagation losses in the visible and NIR range (lower than 0.3 dBcm^{-1}) along with low birefringence [12]. Another key advantage of FLM is the ability to ablate the substrate to obtain microstructures, which has been exploited in conjunction with thermal shifters to fabricate trench structures that greatly improve the thermal performance of these devices [13]. In the following we present the design and fabrication of a 6-mode UPP in the FLM platform in a rectangular mesh geometry, along with a partial calibration of half of its 30 phase shifters and preliminary results for its application as an optical switch.

2. – Basic building blocks

2˙1. *Fabrication process.* – The waveguides for this circuit are inscribed at a depth of 30 μm in Corning EAGLE XG alumino-borosilicate glass and are optimized for single mode operation at a wavelength of 785 nm. The distance between two waveguides (*i.e.*, the inter-waveguide pitch) is 80 μm and the bending radius is 30 mm. With 1.5 mm long thermal shifters and these parameters a single MZI is 11.4 mm long. These values chosen for pitch, inscription depth and bending radius are comparable to the state of the art for this platform [11,13]. After waveguide fabrication, 300 μm deep, 60 μm wide and 1.5 mm long thermal isolation trenches are fabricated by water-assisted laser ablation [14]. The microheaters are formed by ablating a 100 nm thick gold layer with a femtosecond laser, delineating 10 μm thin resistive strips and large conductive contact pads.

2˙2. *Optical characterization.* – The characterization of the phase shifting performance of the reconfigurable MZIs consists in the evaluation of two parameters: power dissipation and thermal crosstalk. Power dissipation is described as the electrical power dissipated on a single thermal shifter to obtain a given phase shift, in particular we are interested in power $P_{2\pi}$ required to obtain a full 2π phase shift on the MZI. Thermal crosstalk is caused by unwanted heating of MZIs neighboring the operated microheater, and can be

Table I. – *Results of characterization of two neighboring MZIs in air and in vacuum.*

Pressure	Measure	MZI1	MZI2
ATM	$P_{2\pi}$ (mW)	36	28
ATM	Crosstalk (%)	22.3	13.4
2.5×10^{-3} mbar	$P_{2\pi}$ (mW)	11.5	11
2.5×10^{-3} mbar	Crosstalk (%)	2.5	1.9

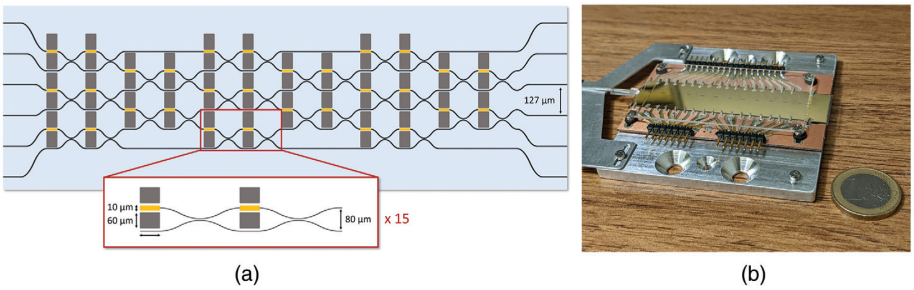

Fig. 1. – (a) Schematic of the 6-mode UPP. Gray rectangles are deep isolation trenches, yellow rectangles are thermal shifters. The unit cell of the circuit is highlighted at the bottom. (b) Picture of the 6-mode reconfigurable circuit complete with electrical packaging and pigtailed fiber array at the input.

evaluated in terms of phase shift induced on a MZI at a given distance from the active shifter as a percentage of the phase induced on the target MZI. Power dissipation and thermal crosstalk were evaluated on two neighboring MZIs, where microheaters are at a distance of 160 μm from each other, in both air and in a vacuum chamber at a pressure of 2.5×10^{-3} mbar. The results are shown in table I. Power dissipation in air is of the order of 30 mW for a full reconfiguration, and decreases to 11 mW in vacuum. Thermal crosstalk is between 10 and 20% in air and drops to 2% in vacuum. The improvement in vacuum operation can be explained by the thermal conductivity of air between trenches, which transports the heat to neighboring waveguides [13].

3. – 6-mode universal processor

The 6-mode universal processor layout is shown in fig. 1(a), it features a total of 15 MZIs in a rectangular mesh and includes fan-in and fan-out for coupling to standard fiber arrays with 127 μm pitch. The circuit is 8 cm long and features a total 2.7 dB insertion losses. A picture of the final device complete with electrical packaging for the control of the 30 thermal phase shifters is shown in fig. 1(b). The calibration of such a mesh is not straightforward, as the static phase between the arms of each MZI is randomly distributed due to intrinsic uncertainties of the fabrication process. We adapted a calibration process from literature [7,10] which is divided into two steps: first the 15 "internal" phases (*i.e.*, those controlled by thermal shifters in the central arms of the MZIs) are

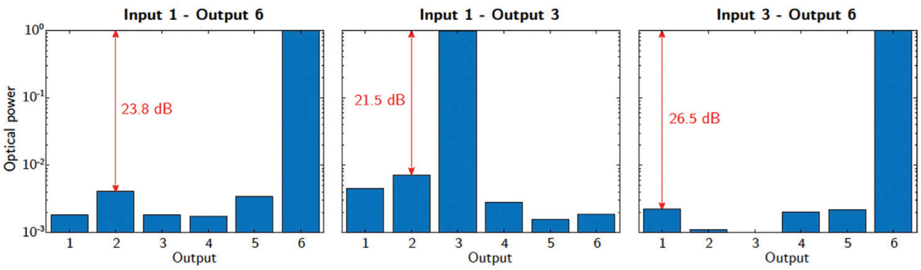

Fig. 2. – Optical power measured at the outputs of the 6-mode UPP while implementing three switching protocols.

characterized by routing light along various paths, then the remaining "external" phases are characterized by forming interferometric rings around them through actuation of the internal shifters. We performed the first step of the calibration process, which allows us to control the transmission of each MZI individually, enabling the implementation of optical switching. We tested the performance of the device by performing three such measurements: switching from input port 1 to output ports 3,6 and from input port 3 to output port 6 in atmospheric pressure. The results are shown in fig. 2; in these three measurements, the device achieves extinction ratios of 23.8, 21.5 and 26.5 dB.

4. – Conclusion

In this work we provide a demonstration of the largest UPP to date in the FLM platform, a rectangular mesh of 15 MZIs with 30 reconfigurable components featuring 60 deep isolation trenches for low power dissipation and thermal crosstalk. A partial calibration of the device has been demonstrated along with switching measurements, which provide a first insight of the performance of this circuit. Despite being very preliminary results, the extinction ratios observed demonstrate already a good performance and indicate how FLM can be a valuable platform for realizing integrated UPPs.

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