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Universal photonic processors fabricated by femtosecond laser writing

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ABSTRACT

Photonic integrated circuits (PICs) are steadily becoming an established technology with a wide range of applications in communications, analog signal processing and sensing. Considerable research interest is currently focused on universal photonic processors (UPPs), i.e. reconfigurable PICs which are able to implement any arbitrary unitary transformation on a given input photonic state. The basic building block of a UPP is a (often thermo-optically) reconfigurable Mach-Zehnder interferometer (MZI). UPPs with various topologies and number of modes have been reported in multiple photonic platforms such as silicon nitride, silica on silicon and glass-based femtosecond laser writing (FLW). FLW is a versatile technology that allows for rapid and cost-effective fabrication of three-dimensional waveguide geometries with low propagation losses ($<0.3\,\mathrm{dB\,cm^{-1}}$) from the infrared to the whole visible range. Recently, an efficient implementation of reconfigurable MZIs in this platform was developed featuring thermal isolation structures (i.e. deep trenches and bridge waveguides) and thermal phase shifters, allowing for a dramatic reduction in dissipated power (down to 25 mW for full reconfiguration in air at 785 nm wavelength) and in thermal crosstalk (down to 10 % of the induced phase). Performance of these interferometers is especially advantageous in vacuum, with 0.9 mW dissipation and 0.5 % crosstalk at 2.5×10^{-3} mbar. To demonstrate the potential of this technology we fabricated and characterized a 6-mode FLW-UPP with thermal isolation trenches in a rectangular MZI mesh layout with a total of 30 thermal phase shifters.

Keywords: Femtosecond Laser Micromachining, Photonic Integrated Circuits, Thermo-optic Phase Shifters, Universal Linear Optics, Thermal Crosstalk

1. INTRODUCTION

When compared to bulk optics, integrated photonics provides significant advantages in many aspects such as stability, miniaturization and scalability of devices. Due to this, photonic integrated circuits (PICs) have become an enabling technology in a diverse range of applications including broadband optical communications and quantum information processing.[1,2] One of the most important features of PICs is reconfigurability, which is achieved by shifting the relative optical phase between two signals. This feature allows one to fabricate optical circuits that can be reconfigured actively to perform multiple transformations on the input signal, unlike application-specific circuits. Phase shifting can be implemented through multiple physical effects,[3–5] amongst them one of the most simple yet effective ones is the thermo-optic effect. Thanks to the temperature dependence of the refractive index, a localized tuning of the waveguide temperature can be obtained through a resistive microheater which heats up the substrate as it dissipates electrical power by the Joule effect. These devices display excellent stability and do not introduce additional losses; they are commonly referred to as thermal shifters.

Recently there has been a growing research interest in reconfigurable PICs, in particular circuits with 'universal' reconfigurability known as universal photonic processors (UPPs). These processors are universal in the sense that they can implement arbitrary unitary transformations on an input photonic state. The main building block of UPPs is a reconfigurable Mach-Zehnder interferometer, consisting of two balanced couplers and two

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thermal phase shifters. It has been demonstrated that with this basic unit cell a UPP can be constructed with either a triangular[6] or a rectangular[7] interferometric mesh.

UPPs have been demonstrated in various integrated photonics platforms such as silica-on-silicon,[8] silicon nitride[9,10] and femtosecond laser writing[11] (FLW). Among these platforms, FLW of glass-based materials is a fabrication technique that allows for rapid and cost-effective prototyping of waveguide circuits with low propagation losses in the visible range (<0.3 dB cm^{-1}) and low birefringence.[12] Moreover FLW allows for micro-structuring of the substrate through laser ablation, which can be exploited in combination with thermal shifters to greatly reduce both power dissipation and thermal crosstalk by increasing the thermal isolation of the target waveguide through the addition of trench structures.[13]

With 300 µm deep isolation trenches, a full reconfiguration can be achieved on a MZI with a total power dissipation of tens of milliwatts and ∼20 % phase induced on an adjacent device due to thermal crosstalk, and an even greater improvement can be obtained with vacuum operation. In this work we exploit this significant improvement in thermal isolation to demonstrate a 6-mode rectangular mesh FLW-UPP featuring 15 MZIs and 30 thermal shifters with a total of 60 deep isolation trenches.

2. FABRICATION PROCESS

The waveguides of the 6-mode UPP are inscribed in Corning EAGLE XG alumino-borosilicate glass at a depth $d = 30$ µm and optimized for single-mode operation at $\lambda = 785$ nm. The inter-waveguide pitch is set at $p = 80$ µm, the interferometer arms are $L = 1.5$ mm long and the bending radius is $r = 30$ mm. These values are comparable to the current state of the art for FLW circuits.[11,13]

Thermal isolation trenches are fabricated on either side of the top interferometer arm of each MZI by Water Assisted Laser Ablation[14] with a depth of 300 µm and width of 60 µm. Trenches are removed from the substrate by ablating their side walls and subsequently their base with rectangular irradiation patterns. During ablation the sample is suspended upside down in water with the laser light shining from the bottom surface of the sample. Finally, a thin 100 nm layer of gold is deposited on the substrate along with a 2 nm adhesion layer of chromium via thermal evaporation. After a thermal annealing step, the gold film is ablated by a femtosecond laser to delineate thin resistors between trenches and wide contact pads in order to minimize series resistance. The dimensions of the resistors are 1.5 mm in length and 10 µm in width.

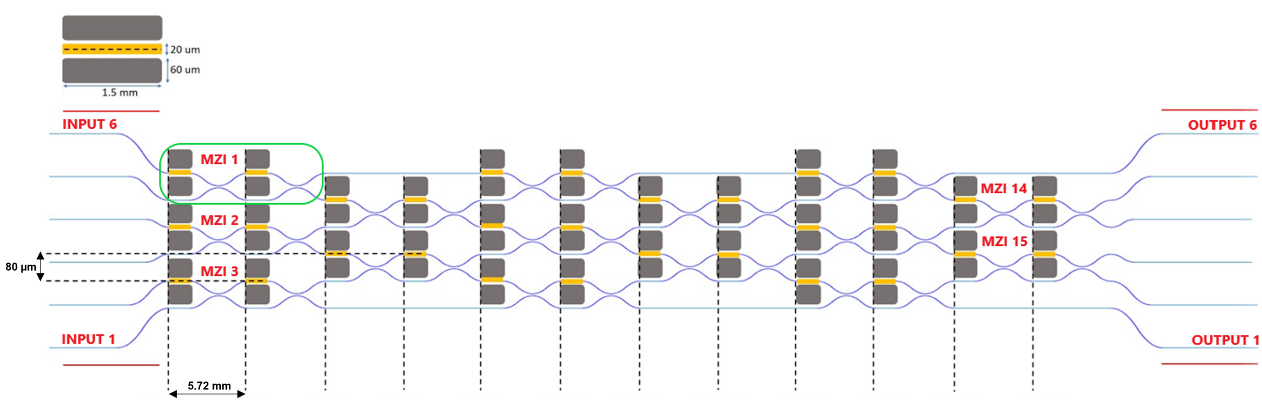
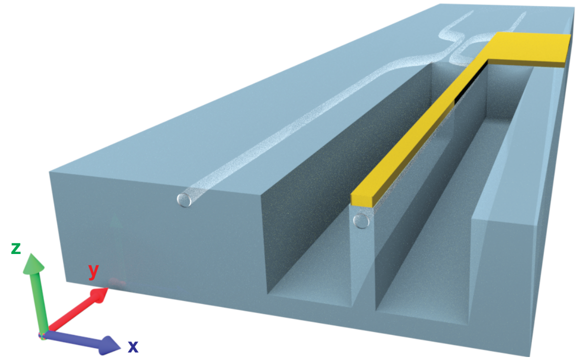
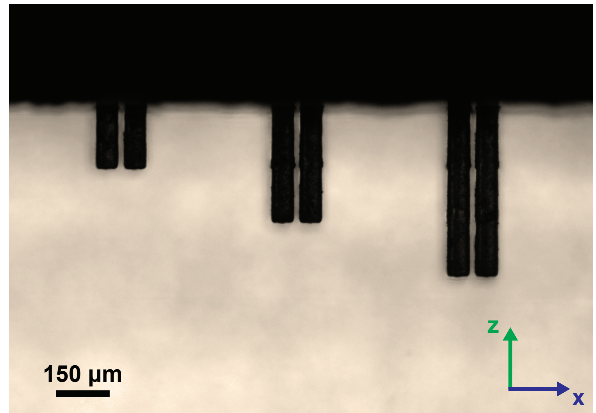


Figure 1: Schematic of the 6-mode UPP. Dark rectangles represent 300 µm deep isolation trenches. Yellow rectangles represent the 30 microheaters. The unit cell of the circuit is highlighted by the green line, it is composed of two balanced directional couplers and two phase shifters. The overall circuit features 15 MZIs arranged in a rectangular mesh[7] with fan-in and fan-out for compatibility with 127 µm fiber arrays.



(a)



(b)

Figure 2: a) 3D model of a reconfigurable MZI featuring deep isolation trenches. b) Microscope image of isolation trenches respectively 150 , 300 and 450 µm deep. Note: the distance between two adjacent trenches is 20 µm, while the resistor width is 10 µm

2.1 Preliminary Optical Characterization

After fabrication of the device a preliminary optical characterization has been performed. The final device features a total 2.7 dB insertion losses.

We have characterized also the two rightmost MZIs (MZI14 and 15 in Fig. 1) in both air and vacuum to evaluate the phase shifting performance. Results are shown in Table 1. The power dissipation to obtain a 2π phase shift is in the order of 30 mW in standard conditions, while crosstalk is in any case lower than 25 %. When the device is placed in a vacuum at 2.5×10^{-3} mbar the power dissipation drops by 60 % down to 11 mW and crosstalk decreases to 2 % on the nearest neighboring MZI.

To fully calibrate the UPP means to determine experimentally the values of both the power dissipation and the initial phase shift of each thermal shifter (i.e. the phase shift when no power is applied), which are randomly determined by the fabrication process. The complete characterization process is adapted from the literature.[7,8] It is divided in two steps; the first step consists in characterizing all of the internal phase shifters, namely the ones between the directional couplers of the MZIs, so that the transmission of each interferometer can be independently tuned. The second step consists in the characterization of the external phase shifters placed before the first coupler of each MZI. Here we report on the first step of the characterization process.

3. UNIVERSAL 6 MODE PROCESSOR

The final circuit, as shown in Fig. 1, consists of 15 such MZIs in a rectangular mesh with added fan-in and fan-out for coupling to 127 µm fiber arrays. To characterize the circuit, we start by modeling the (normalised) optical power at the cross output of an ideal MZI as:

$$\mathcal{P}_{\text{out}} = \frac{1 + \cos(\phi + \phi_0)}{2}, \tag{1}$$

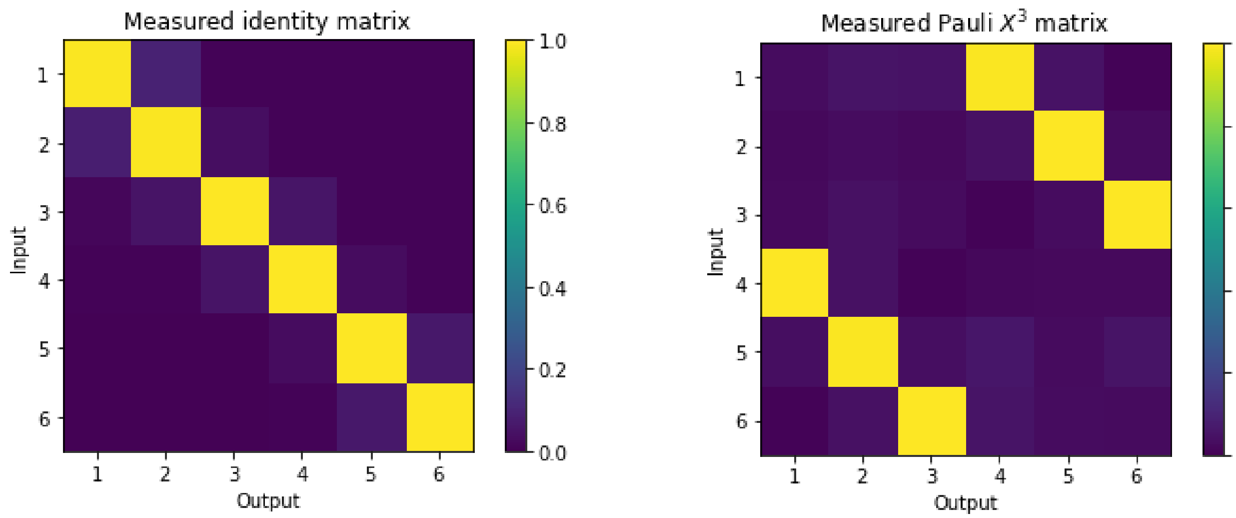
where $\mathcal{P}_{\text{out}}$ is the optical power measured at one of the two outputs of the MZI, ϕ is the phase shift induced by the internal phase shifter and ϕ_0 is the initial phase of the phase shifter. The phase ϕ is related to the electrical power dissipated on the microheater according to $\phi = \alpha P$.

In reality we control these devices by setting a current instead of the electrical power. For this reason we have to make some considerations. Firstly, while the difference in optical path lengths ϕ of the individual MZI is indeed proportional to the electrical power dissipated by the microheater by a linear factor α, the electrical power is in turn related to the current flowing through the microheater by RI^2. The resistance R is, however, dependent itself on the current. Hence we include a higher-order term in the dissipated electrical power:[15]

$$P = R_0 I^2 + \beta I^4, \tag{2}$$

Table 1: Results of characterization of MZ14 and MZ15 at atmospheric pressure and in vacuum. $P_{2\pi}$ is the electrical power required to achieve a 2π phase shift on the MZI. Crosstalk is defined as the phase induced on the adjacent device divided by the phase shift of the powered MZI.

Pressure	Measure	MZ14	MZ15
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



(a) (b)

Figure 3: Identity and Pauli X^3 gate implemented in the 6-mode processor.

where R_0 is the resistance of the microheater at room temperature, I is the current passing through it and β is a non-linear factor which accounts for the dependence of R on I. Secondly, due to thermal cross-talk we adopt a linear combination of electrical powers; then, the difference in optical paths ϕ_i of the i-th MZI depends on the powers P_j of all the others by:

$$\phi_i - \phi_{0,i} = \sum_j \alpha_{ij} P_j, \tag{3}$$

and for each power P_j the same expansion to fourth order in the current is applied. In general, the matrix α_{ij} could have the same size as the number of MZIs on the chip; however, in the absence of horizontal cross-talk, the matrix is block diagonal where each block corresponds to a vertical column of MZIs. This significantly improves the computational overhead and reduces the number of measurements needed.

In practical applications we wish to know the vector of powers needed to achieve a specific configuration of the ϕ_i. This is not as easy as inverting the matrix α_{ij}, as this does not guarantee that each P_j is a positive real number. To this end we can leverage the fact that for an MZI, ϕ_i and $\phi_i + 2\pi$ induce the same effect. In other words, we have:

$$\phi_i - \phi_{0,i} + 2\pi n_i = \sum_j \alpha_{ij} P_j, \tag{4}$$

where n_i is an integer. This translates the problem from a linear algebra one to a minimization one.

So far all of the 15 internal phase shifters have been characterized. By controlling them, we can implement a subset of unitary matrices such as switching, Pauli X gates and random permutations. As a preliminary measurement we implemented and measured two unitaries: identity and Pauli X^3 gate. The results are shown in Fig. 3. The fidelities, calculated as $\mathcal{F}(M_{exp}, M) = 1/6\,\mathrm{Tr}\big(M_{exp}^{\dagger} M\big)$, are equal to 0.9968 and 0.9967 respectively.

4. CONCLUSION

In this work we have demonstrated the largest UPP in the FLW platform to date, with 6 optical modes, 30 thermal phase shifters and 60 deep isolation trenches allowing for an efficient reconfiguration of the device with a significant reduction in both power dissipation and thermal crosstalk. We have performed a preliminary characterization of the device and implemented two unitaries as a first benchmark of its performance. The implementation of these unitaries demonstrates the quality of the device, indicating how valuable can be the role of the FLW platform for the realization of high fidelity integrated UPPs.

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