Characterization and ENOB Analysis of a Reconfigurable Linear Optical Processor

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Abstract: The characterization of a broadband low-loss 4 × 4 MZI-based reconfigurable linear optical processor is reported. The impact of MZI extinction ratio on the effective number of bits (ENOB) at the device output is also investigated.

1. Introduction

Photonic integrated circuits (PIC) have emerged as a powerful tool to bring the large bandwidth of optics in the sub-mm scale. In particular, the silicon photonics platform has made significant progress over the years, leveraging the mature CMOS process. Today, programmable PICs are particularly promising because they can perform precise light processing even in the presence of fabrication inaccuracies [1] and they can be exploited in various fields [2] such as optical filtering, quantum information processing [3], reconfigurable true-time optical delay lines [4], and machine learning accelerators [5]. In this paper we demonstrate a broadband low-loss reconfigurable linear optical processor (RLOP) operating in the C-Band based on 2 × 2 Mach-Zehnder interferometer (MZI) elements and realized within a multi-project wafer run (MPW) by ANT [6]. With the aim of exploiting these devices in the real world, we also evaluate the impact of the finite MZI extinction ratio (ER) over the reduction of the effective number of bits (ENOB) at the device output.

2. Linear Optical Processor

2.1. Operation Principle and Device Design

The basic element of the RLOP is a 2 × 2 reconfigurable MZI consisting of two connected 3-dB 2 × 2 multimode interferometers (MMI) with a thermp-optic phase shifter on one of the internal arms (θ) and an another at one of the outputs (ϕ). A single MZI can thus perform any rotation in the special unitary group of degree two (i.e., $SU(2)$) and can be programmed by applying the appropriate bias voltage to its two phase shifters. An $N \times N$ device with N inputs and outputs, performing any rotation of a special unitary group of degree N (i.e., $SU(N)$) [7], can be created by combining $N(N-1)/2$ MZI. The realized device, depicted in Fig. 1, is a 4×4 structure able to perform any $SU(4)$, followed by a diagonal matrix multiplication section for controlling the output powers or extending the processor to a larger structure [4]. The device with four optical inputs and four optical outputs (shown on the left-hand side of Fig. 1) has been designed for fabrication in a silicon photonic e-beam MPW by ANT [6]. The design objective is to achieve small footprint, low loss and broadband operation in the C-band to minimize the filtering effect, detrimental in large structures where many MZI are cascaded. The device has $12+8$ thermo-optic phase shifters (connected to electrical pads on the PIC perimeter), the former for the the $SU(4)$ matrix and the latter for the diagonal one.

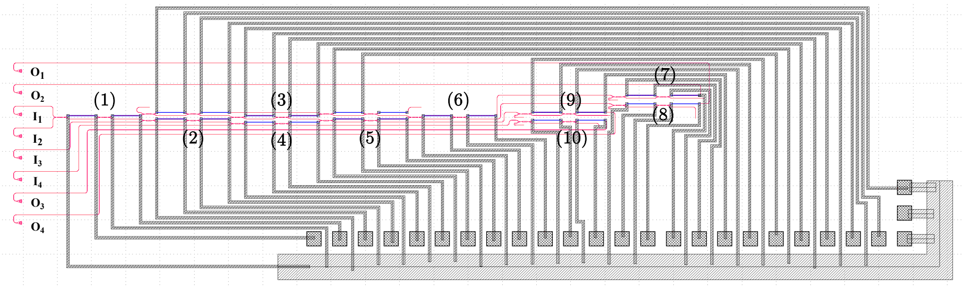

Fig. 1: 4 × 4 Reconfigurable Linear Optical Processor (RLOP). Size: 5×1.5 mm^2.

2.2. Measurements

Every phase shifter of the RLOP has been characterised according to the procedure in [4] to determine the phase-voltage relation accounting for process variations. Each MZI exhibits an insertion loss (IL) of approximately 0.7 dB and an average extinction ratio (ER) of 26.8 dB at 1550 nm, while the average V_π and P_π are 3.9 V and 55 mW, respectively. Fig. 2 reports the single MZI bandwidth normalized to the GC response (3-dB bandwidth, i.e., B_{3dB} = 35 nm) and the normalized transmission at 1550 nm of MZI 6 in cross state and MZI 9 in bar state, i.e., the best and worst one from the ER standpoint (42.5 dB and 22.9 dB, respectively).

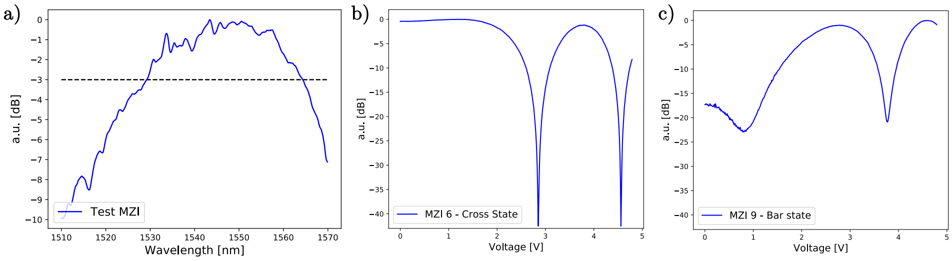

Fig. 2: Test MZI bandwidth (a); normalized transmission of MZI 6 in cross state (b) and MZI 9 in bar state (c).

The overall RLOP transmittivity is very good, with an a B_{3dB} of 27 nm and an IL of approximately 4.5 dB at 1550 nm for the longest path, excluding the GC effect. To test the RLOP operation, we program the device to implement the $SU(4)$ matrix reported in Fig. 3(a), together with the required phase values and the corresponding voltages of the internal thermo-optic phase shifters, which dominate the power consumption. The average power consumption to run the RLOP is approximately 510 mW. A relative error of 17.5% in the RLOP programming is found, mainly caused by losses in the chip-to-fiber coupling and inter-MZI thermal crosstalk.

2.3. *Influence of finite extinction ratio on output ENOB*

In analog information processing, it is of paramount importance that the effective number of bits (ENOB) at the output is kept as close as possible to the number of bit used at the input. For this reason we investigate, in the absence of other sources of noise and distortion, the impact on the output ENOB of a finite ER in MZI elements of an $N \times N$ RLOP. The ER results as an unwanted crosstalk signal and, in the worst case, is additive for every element in the considered optical structure. Fig. 3(b) represents the ENOB reduction at output as a function of ER and processor depth, i.e., the size N of the implemented matrix. Figure 3(b) highlights that the ENOB reduction is not a concern (i.e., ≤ 0.5) even for moderate-large structures if the ER is > 22 dB, an achievable practical performance with thermo-optic phase shifters. In the reported RLOP implementing a SU(4) matrix, no ER-induced ENOB reduction can be observed since the minimum ER is 22.9 dB, as shown in Fig. 2(c).

a)

$$\mathrm{T}_{\mathrm{SU}(4)} = \begin{bmatrix} -0.3536 - j0.3536 & -0.3536 - j0.3536 & 0.3536 + j0.3536 & -0.3536 - j0.3536 \\ -0.3536 - j0.3536 & -0.3536 - j0.3536 & -0.3536 - j0.3536 & 0.3536 + j0.3536 \\ -0.5000 - j0.5000 & 0.5000 + j0.5000 & 0.3536 + j0.3536 & -0.3536 - j0.3536 \\ 0.0000 + j0.0000 & 0.0000 + j0.0000 & -0.3536 - j0.3536 & 0.3536 + j0.3536 \end{bmatrix}$$

MZI	1	2	3
θ(Rad)	1.5708	6.2832	1.5708
V_θ	2.18 V	3.98 V	2.57 V
MZI	4	5	6
θ(Rad)	1.5708	3.1416	6.2832
V_θ	2.78 V	2.69 V	3.74 V

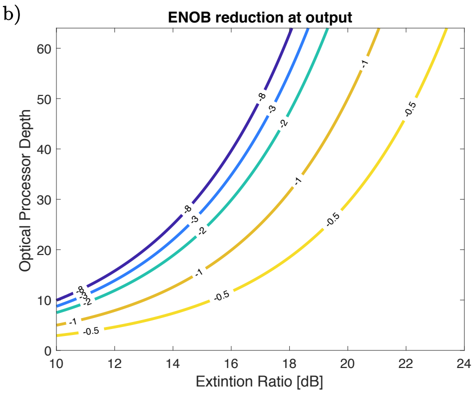

Fig. 3: Implemented $SU(4)$ matrix and corresponding phase/voltage values of the RLOP (a). Output ENOB reduction as a function of the optical processor depth N and ER (b).

3. Conclusions

The design, realization in an e-beam based MPW, and characterization of a 4×4 reconfigurable linear optical processor operating in the C-band is reported. The device exhibits good performance in terms of bandwidth and IL and ER per basic element, making it suitable to scale over higher number of elements (i.e., higher number of inputs), supported also by the investigation on the effect on ENOB of ER for increasing processor depth.

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References

1. D.A.B. Miller, "Perfect optics with imperfect components," Optica 2.8 (2015): 747–750.
2. D. Pérez, *et al.* "Multipurpose silicon photonics signal processor core," Nature Comm. 8.636 (2018).
3. N. Harris, *et al.* "Linear programmable nanophotonic processors," Optica 5.12 (2018): 1623–1631.
4. F. Shokraneh, *et al.* "Theoretical and Experimental Analysis of a 4x4 Reconfigurable MZI-Based Linear Optical Processor," J. Lightw. Technol. (2020).
5. L. De Marinis *et al.* "Photonic neural networks: a survey," *IEEE Access*, 7 (2019): 175827–175841.
6. Applied Nanotools Inc., `https://www.appliednt.com/nanosoi`, accessed on 03/23/2020.
7. M. Reck, *et al.* "Experimental realization of any discrete unitary operator," Phys. Rev. Lett. 73.1 (1994): 58–61.