Electronic feedback control of Mach-Zehnder interferometers for scalable optical computing

Alessandro di Tria[1] [0009-0008-4459-9875], Marcelo Carnica[1], Edoardo Mauri[1], Giorgio Ferrari[2] [0000-0002-2854-8444], Marco Sampietro[1] [0000-0003-4825-9612] and Francesco Zanetto[1] [0000-0002-0242-5016]

[1] Department of Electronics, Information and Bioengineering, Politecnico di Milano, piazza Leonardo da Vinci 32, 20133 Milano, Italy
[2] Department of Physics, Politecnico di Milano, piazza Leonardo da Vinci 32, 20133 Milano, Italy
`francesco.zanetto@polimi.it`

Abstract. We present an electronic technique to control photonic processors based on Mach-Zehnder interferometers. By leveraging transparent photodetectors and local feedback loops, the working point of each interferometer is automatically configured. The concurrency of two control loops per device enables the computation of 2x2 vector-matrix multiplications in the analog domain, enabling scalable optical computing.

Keywords: Optical Computing, Light Sensors, Electronic Control Loop.

1 Introduction

We are witnessing an exponential growth of applications such as machine learning and artificial intelligence [1], all of which require fast and heavy computational networks to operate. In particular, vector-matrix multiplication (VMM) is the fundamental operation that needs to be carried out to run these algorithms, as it represents the linear function of the weighted sum of the neuron inputs. Traditionally, this operation is performed with digital electronic circuits, particularly Graphic Processing Units (GPUs), which allow for highly-parallelized operation. However, the performance demands on these networks are starting to exceed the intrinsic limitations of traditional electronic hardware, which struggles to perform matrix operations at high speed and low energy consumption [1].

A promising alternative is offered by integrated photonic processors. Indeed, photonics allow for the encoding of information with light, which does not dissipate energy when it travels inside an optical waveguide. Moreover, photonic devices are ideal to perform linear operations, meaning that certain photonic architectures can implement matrix transformations directly in the optical domain as light travels through the photonic structure [2]. As a result, VMM can be performed by photonic processors at light-speed and with virtually zero energy consumption.

Among the different architectures, photonic processors based on Mach-Zehnder interferometers (MZIs) are gaining popularity, mainly for the simplicity of working with a single wavelength and the possibility to encode and manipulate light as a complex number. Although MZI-based optical architectures have been already used to accelerate VMM networks, current demonstrations are limited by the difficulty of properly setting the state of each MZI to configure the desired matrix. This is mainly due to fabrication mismatches, which affect the device's transfer function, and thermal variations, which cause drifts and fluctuations of the working point. The former would require an initial calibration to compensate for hardware non-idealities [3], whose duration and complexity scale vertiginously with the matrix size. In addition, this approach can mitigate the effect of process errors, but it is not suitable against thermal drifts and crosstalk, aging and generic environmental changes. All these effects limit the computation precision and the scaling of the processor order.

To overcome these issues, this work proposes an electronic control technique to automatically set a unique MZI working point and implement an arbitrary unitary 2x2 transformation. The technique leverages local feedback loops with integrated actuators and transparent sensors, which allow to monitor the state of the interferometer without introducing additional insertion losses. The approach can be seamlessly extended to processors with multiple interferometers, thus enabling scalable optical computing.

2 Optical core

2.1 Working principle

The core of the vector-matrix multiplication is the Mach-Zehnder interferometer (MZI). Indeed, an MZI with two phase shifters integrated on the input and internal arms (Fig. 1a) implements a programmable 2x2 optical gate, whose complex-valued transfer matrix depends on the phase shifts φ and θ:

$$T_{MZI} = -je^{-j\theta/2}\begin{bmatrix}\sin(\theta/2) & \cos(\theta/2)\,e^{-j\phi} \\ \cos(\theta/2) & -\sin(\theta/2)\,e^{-j\phi}\end{bmatrix} \tag{1}$$

This is a unitary matrix, as the total optical power is preserved assuming negligible propagation losses. Once φ and θ are set, a certain transfer matrix is configured. However, even small imperfections in the fabrication process of the device or environmental variations affect its real transfer function, altering the matrix coefficients in an unpredictable way. Thus, a pre-calibration would be necessary to retrieve the actual matrix, performing optical and electro-optical characterization of each element of the interferometer. While this approach can be feasible for a single MZI, the time and complexity needed to characterize each device increase exponentially in higher-order architectures, which require complex calibration algorithms [4].

An alternative approach is to control the working point of each interferometer with local feedbacks, leveraging the use of integrated photodetectors to monitor the state of the device and acting on the phase shifters in a closed-loop way. The strategy proposed in this paper is based on two concurrent local feedback loops: one acting on phase shifter φ by monitoring the optical power in the internal arm of the MZI and one linking θ to the optical power at the output of the interferometer.

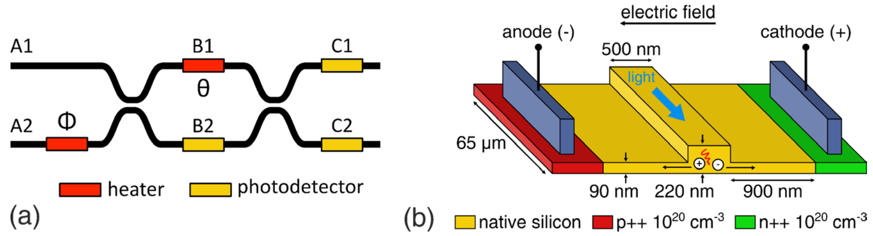

Fig. 1. (a) Schematic of a Mach-Zehnder interferometer, with two phase shifters (heaters) φ and θ integrated at the input and internal arms, respectively. The sections have been named A for the input, B for the internal arms and C for the output, with a number indicating the branch. (b) Cross-section of a transparent photodetector.

By naming the two input powers A_1 and A_2 and their relative phase difference χ_A, we can determine the relation between the optical power percentage after the first coupler $B_{2\%}$ and the phase shift φ as:

$$\mathrm{B}_{2\%} = \frac{1}{2} + \frac{\sqrt{\mathrm{A}_1\,\mathrm{A}_2}}{\mathrm{A}_1 + \mathrm{A}_2} \cdot \sin(\chi_A + \varphi) = \frac{1}{2} + \frac{\sqrt{\mathrm{A}_1\,\mathrm{A}_2}}{\mathrm{P}_{\mathrm{tot}}} \cdot \sin(\chi_A + \varphi) \qquad (2)$$

where $\mathrm{P}_{\mathrm{tot}} = A_1 + A_2$ is the total optical power at the input of the MZI. Therefore, once the input signal is well-known in power and phase, the phase shift φ is uniquely set when the measured value of $B_{2\%}$ matches the desired target. The same approach can be used to set phase shifter θ, using the output of the first coupler to compute the target $C_{1\%}$. Assuming negligible propagation losses, $\mathrm{P}_{\mathrm{tot}} = A_1 + A_2 = B_1 + B_2 = C_1 + C_2$ can be measured in a single position, for example at the output of the gate.

2.2 Transparent photodetectors

In order to implement the proposed control strategy, light needs to be measured in multiple points of the interferometer. This measurement has to be very linear, ensuring a good precision in the computation of the power percentages, and minimally invasive, avoiding excessive insertion losses that would affect the scalability of the system. These requirements led to the choice of transparent photodiodes [5], which are lateral p-i-n diodes, with the waveguide core in the middle (see Fig. 1b), that extract the electron-hole pairs naturally generated by the propagation losses of light in the guide. Therefore, they allow us to measure light without introducing additional losses and are suitable for our control system.

2.3 Electronic control loop

The control feedback law (Fig. 2a) is realized in the electronic domain by a modular system made of two boards (Fig. 2b), specifically designed for operating large-scale photonic circuits. For a generic phase shifter-coupler section X, the output optical power is readout and converted into the digital domain, where the power percentage in one of the branches $X_{1\%}$ is computed. The target $X_{1\%}$ is then subtracted from the measured value and the result is fed to an integral controller, whose output, re-converted in the analog domain, is the signal driving the phase shifter and closing the loop. The whole loop converges when the error signal $X_{1\%\,meas} - X_{1\%\,target}$ is zeroed, effectively implementing the desired phase shift. The control algorithm has been implemented with an FPGA for maximum flexibility in the experimental validation, but its simplicity allows for easy integration into an electronic chip if footprint and power consumption of the electronic controller are of concern.

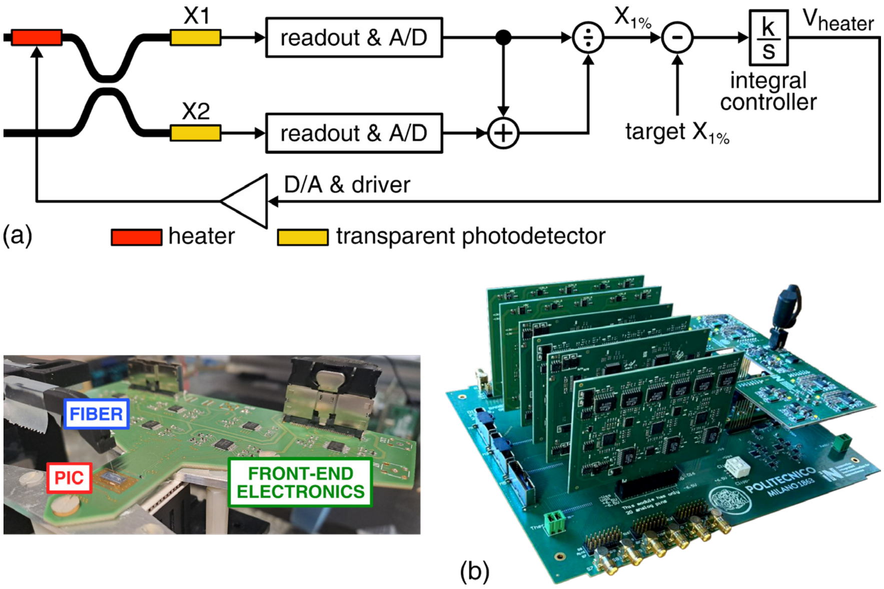

Fig. 2. (a) Schematic of the electronic control loop implemented to automatically configure the MZIs. (b) Photographs of the custom-designed electronic control system.

3 Experimental results

We designed a photonic integrated circuit (PIC) to test the electronic control strategy. It is realized in silicon photonics technology and designed to work with $\lambda =$

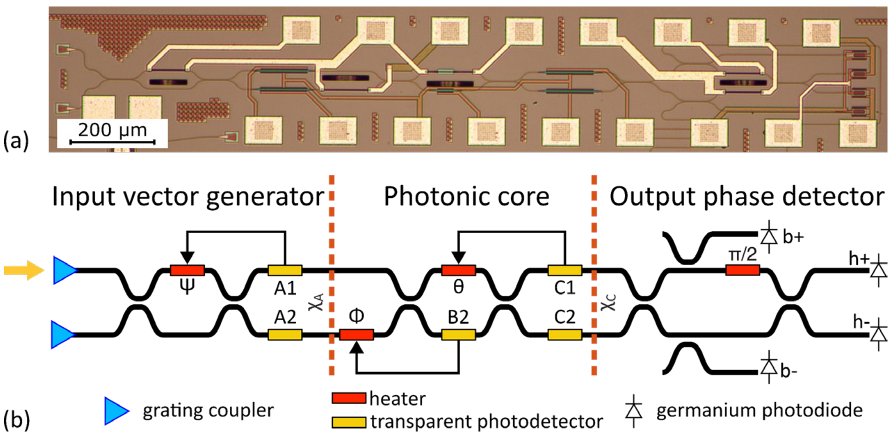

Fig. 3. Microphotograph (a) and schematic (b) of the photonic integrated circuit realized to test the control strategy.

$1550\ nm$. It features heaters as phase actuators and transparent photodiodes to measure light without introducing optical losses. The PIC is conceptually divided into three sections (Fig. 3): an input vector generator; a 2x2 photonic core performing vector-matrix multiplications; an output phase detector used to validate the correct result of the operation. The custom electronic system has been used to implement 3 electronic control loops: one to set the input, and two for the implementation of the 2x2 matrix in the optical gate. The result of the multiplication is computed in power using photodetectors C_1 and C_2 and in relative phase χ_C using the coherent detector in the last stage, with the formula [6]:

$$\chi_C = \tan^{-1}\left(\frac{g_+ - g_-}{h_+ - h_-}\right) \tag{3}$$

The strategy has been first used to generate the input vector $[A_1\ A_2]$. The laser light has been injected into the chip through the top grating coupler, achieving an on-chip optical power of 0 dBm. The input vector has been chosen by controlling the first MZI with heater ψ to set the power percentage $A_{1\%}$. In order to evaluate the accuracy of the control loop, the target power $A_{1\%}$ has been swept from 0 to 100% with incremental steps of 0.1%. The measurement shown in Fig. 4a confirms the ability of the control to set any target optical power, with a standard deviation in the error of only 0.05% (see Fig. 4b), corresponding to a resolution of $\log_2 1/\sigma = 11$ bits.

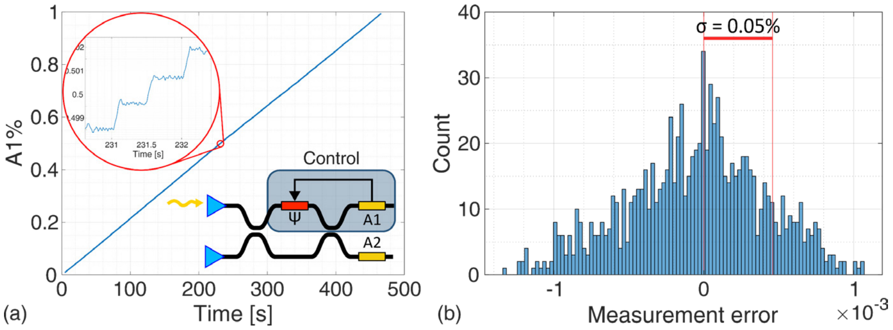

Fig. 4. (a) Sweep of the controlled $A_{1\%}$ power from 0 to 100% with incremental 0.1% steps. (b) Histogram of the control error, computed as $A_{1\%\,meas} - A_{1\%\,target}$.

Then, by selecting an input vector of in-phase optical beams of equal power with $A_{1\%} = 50\%$, an arbitrary matrix has been implemented with the optical gate by choosing $\phi = 1.8\pi$ and $\theta = 0.15\pi$, automatically set by two feedback loops targeting the correct values of $B_{2\%}$ and $C_{1\%}$. After configuration, the control on the optical gate has been paused to keep the matrix fixed and the input has been changed using the input generator, in order to perform 9 vector-matrix multiplications. Fig. 5 shows the results in a polar plot, where the radius is the power percentage $C_{1\%}$ measured by the output light sensors and the angle is the phase difference χ_C measured by the output phase detector. All results are very accurate, showing a root mean square error in the measured $C_{1\%}$ power below 1% and in the measured χ_C phase of only 29 mrad, corresponding to an equivalent resolution of 8 bits. These figures of merit are better than those retrieved by other approaches operated without feedback [4,7], proving that the proposed control strategy is effective in setting a precise target matrix without any pre-calibration.

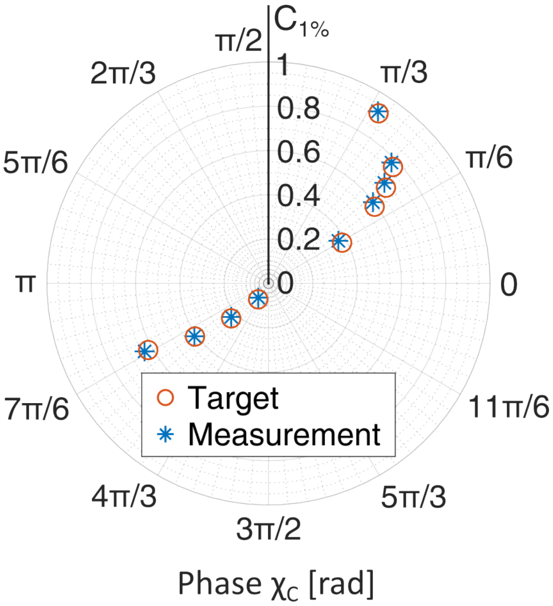

Fig. 5. Polar plot of the result of the VMM, using a matrix with $\phi = 1.8\pi$, $\theta = 0.15\pi$ and 9 different inputs. The measurements in blue stars match the theoretical values in red circles.

4 Conclusions

We successfully demonstrated a novel technique to control the working point of Mach-Zehnder interferometers. By employing local feedback loops with integrated transparent photodetectors, we managed to control the optical power in any point of the interferometer with very high precision (11 bits) and no prior calibration. The concurrency of two feedback loops allows to set a specific 2x2 unitary matrix that can be leveraged to perform vector-matrix multiplication in the optical domain. We tested the implementation of a matrix and performed several computations, obtaining a result with a 1% precision in power and 29 mrad in phase difference.

The technique can be seamlessly extended to higher-order MZI-based photonic processors [8], thanks to the low losses ensured by transparent photodetectors and the independent local feedbacks which reduce the complexity of configuring the processor. This would allow us to perform generic NxN vector-matrix multiplication in the optical domain, overcoming the scaling issues and boosting the potential of optical computing.

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