Shape Optimized Photonic Integrated Circuit for Optical Computing Applications

G. Gaullier
Univ. Grenoble Alpes
CEA, LETI
Grenoble, France
gil.gaullier@cea.fr

K. Hassan
Univ. Grenoble Alpes
CEA, LETI
Grenoble, France
karim.hassan@cea.fr

B. Charbonnier
Univ. Grenoble Alpes
CEA, LETI
Grenoble, France
benoit.charbonnier@cea.fr

Y. Thonnart
Univ. Grenoble Alpes
CEA, LIST
Grenoble, France
yvain.thonnart@cea.fr

N. Lebbe*
Univ. Grenoble Alpes
CEA, LETI
Grenoble, France
lebbe.nicolas@gmail.com

A. Glière
Univ. Grenoble Alpes
CEA, LETI
Grenoble, France
alain.gliere@cea.fr

***Abstract*—Shape optimization techniques were quite recently applied to photonic components but to the best of our knowledge, no application to optical computing has been reported yet. Here, we present the design of a photonic integrated circuit, composed of shape optimized passive components, performing a matrix-vector product. A ≈ 2000 times gain on the overall footprint is achieved in comparison with a conventional circuit using classical Mach-Zehnder interferometers.**

Keywords—shape optimization, photonic integrated circuit, optical computing

I. Introduction

We address the issue of performing mathematical calculation using photons, in order to speed up the performances in comparison with usual CMOS computers. Neural Networks constitute an attractive application domain, relying heavily on matrix-vector products, on which we focus in this paper.

Driven by the circuit designs available for modelling a unitary or orthogonal matrix (Section II.) using conventional components [1]-[2], we consider a gain less real matrix. Our goal is to design an optical circuit made up of shape-optimized components. Applying shape optimization in the context of photonic integrated circuits for computing constitutes to the best of our knowledge a pioneering attempt.

Shape optimization (Section III.) allows for the identification of a piecewise constant function representing a shape by looking for the best (in the sense of the local optimization criteria) position of the interface. In photonics, where the optical indices of materials at play need to be recovered, designs and simulation of passive devices have been proposed quite recently using such a technique [3].

The scope of this paper is thus to overcome the classical power transmission problem of a single device and to initiate the possibility to deploy shape optimization techniques in optical computing applications. We include our main present results (Section IV.) showing a considerable reduction of the footprint of the circuit and discuss them (Section V.).

II. Circuit Model

A. Maxwell equations, scattering parameters

For linear, isotropic and non-dispersive dielectric materials with optical index n and time harmonic sources of wavelength λ, the electric field $\boldsymbol{E}$ satisfies the time-harmonic vector wave equation

$$\nabla \times \nabla \times \boldsymbol{E} - k^2 n^2 \boldsymbol{E} = 0, \tag{1}$$

which involves the wavenumber $k = 2\pi/\lambda$. Equation (1) is complemented by boundary conditions allowing for the injection of an optical mode into the input waveguides, and simulating an infinite outer domain on all the other surfaces with perfectly matched layers.

The input modes are linked to the output modes through the so-called S-parameters, which are recovered from the propagating field $\boldsymbol{E}$ for use in our optimization algorithm.

B. The case of orthogonal matrices

Performing the product of a $n \times m$ matrix by a vector consists in finding a circuit with m inputs and n outputs that model the matrix. Since the original paper of Reck *et al.* [1], different topologies of circuits were proposed to represent an orthogonal matrix M using conventional Mach-Zehnder Interferometer (MZI) components. Our approach aims at developing a compact circuit, *i.e.* with reduced depth, by the means of a rectangular topology [2].

The basic principle applied in the previously cited papers is to cancel the upper triangular part of the matrix M with successive multiplications by the transfer matrix S_{MZI} of a MZI with adjusted phase shifters. Finally, a diagonal matrix with coefficients in $\{-1, 1\}$ remains, so that an orthogonal matrix may be decomposed by a product of MZI transfer matrices up to this diagonal matrix.

C. The designed circuit

The singular value decomposition (SVD) of any matrix A makes it possible to represent it as a diagonal matrix with non-negative coefficients, right and left multiplied by two orthogonal matrices.

The diagonal matrix from the SVD may be viewed as a pure attenuation, while the diagonal matrix from the decomposition presented in Section *B.* may be viewed as a pure phase shifter, namely with shift equal to 0 or π. A schematic view is presented in Fig. 1.

A phase control is introduced to guarantee the same relative phase at each column of the circuit by adding phase shifters.

* Currently with Atlantis project-team Inria, CNRS, University of Nice/Sophia Antipolis

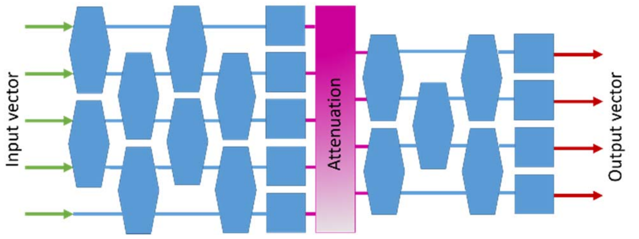

Fig. 1 Schematic view of a circuit relative to a 4 × 5 matrix comprising MZI (blue hexagons), pure phase shifters (blue squares), attenuation (in magenta).

III. SHAPE OPTIMIZATION

Our shape optimization methodology is based on an inverse design process that consists in evolving the boundary of a shape along its outward unit normal to optimize a given figure of merit. The shape is defined by the zero contour of a level-set function. Our approach differs from our previous work [4] in that the real and imaginary parts of the S-parameters are now taken into account.

In order to ease the shape optimization of a single MZI, our strategy is to decompose this component into two parts, namely a 50:50 coupler and a phase shifter. Regarding the optimization of the 50:50 coupler, the real and imaginary parts of the S-parameters associated to each output are maximized to reach the values $1/\sqrt{2}$ and $i/\sqrt{2}$ (with $i^2 = -1$).

A gradient descent algorithm, where the gradient is computed by direct and adjoint calculations carried out by the FDTD commercial software RSOFT Photonics (Synopsys, Mountain View, U.S.A.) performs the shape optimization. The overall algorithm is implemented in MATLAB (The MathWorks Inc., Natick, U.S.A.).

IV. RESULTS

The semiconductor platform used as a basis for our design work is composed of a silicon layer deposited on a silica substrate, surrounded with air. This platform is dedicated to the 1.55 µm wavelength for telecom applications. The 0.4 µm wide waveguides are designed to support a single TE mode.

For the 50:50 coupler, around 44 % of the power is transmitted, which corresponds to an insertion loss of -0.6 dB. The phase shift in the bottom arm (Fig. 2) is about 95°. For the shape optimized 90° phase shifters, insertion losses are less than 0.01 % and the error on the phase shift is less than 0.1°.

A small but significant prototype circuit corresponding to a 8 × 8 matrix is considered. The arbitrarily chosen matrix is defined in order to limit the number of phase shifters to design, each one being a multiple of π/10.

For further fabrication of photonic integrated circuits, the layout of the shape-optimized circuit is built, as well as its conventional counterpart using classical MZI for comparison. We reproduce a part of the layout on Fig. 3: two different non-conventional MZI obtained by concatenating elementary shape optimized components are presented. The top (resp. bottom) MZI comprises two 50:50 couplers between a top 90° (resp. 81°) phase shifter and a bottom null phase shifter.

Our approach leads to much more compact components in comparison with the conventional design. A footprint of 135 µm × 20 µm is expected *versus* 9000 µm × 600 µm for the conventional circuit, that is a ≈ 2000 times saving on the chip surface.

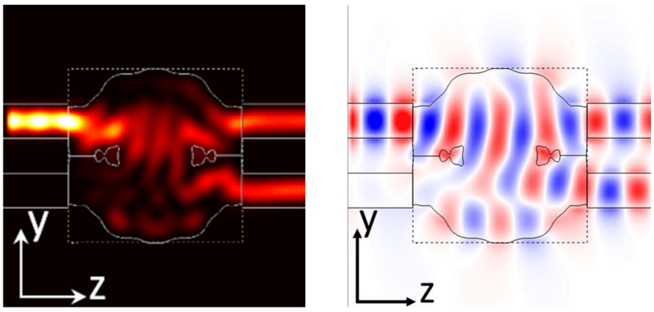

Fig. 2 Energy (left) and electric field $\boldsymbol{E}_x$ (right) inside the shape-optimized coupler when a single TE mode is injected. The shape optimization domain (dashed square) measures 2 µm × 2 µm.

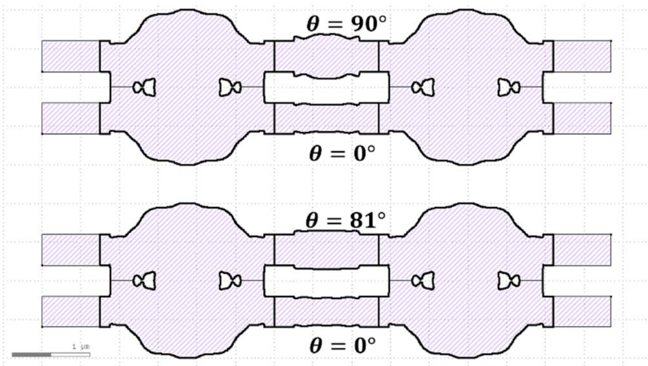

Fig. 3 Shape-optimized MZI with 90°, 0°, 81°, 0° phase shifters from top to bottom, respectively.

V. DISCUSSION AND FUTURE WORK

In this paper, our methodology, dedicated to photonic circuit designed by shape optimization, has been summarized. Our prototype example leads to a footprint reduction by a factor of ≈ 2000 in comparison to a conventional MZI based circuit. The drawback being the insertion loss of -1.2 dB per shape optimized component *versus* less than -0.5 dB for a conventional one.

In the near future, a robust design, improved to tolerate fabrication uncertainties will be created. Then, both shape optimized and conventional circuits will be fabricated and characterized in the CEA-LETI facilities.

REFERENCES

[1] M. Reck, A. Zeilinger, H. J. Bernstein, et P. Bertani, « Experimental realization of any discrete unitary operator », *Phys. Rev. Lett.*, vol. 73, nº 1, p. 58□61, juill. 1994.

[2] W. R. Clements, P. C. Humphreys, B. J. Metcalf, W. S. Kolthammer, et I. A. Walmsley, « An Optimal Design for Universal Multiport Interferometers », *Optica*, vol. 3,n° 12, p. 1460-1465 (2016)

[3] J. S. Jensen and O. Sigmund, “Topology optimization for nano-photonics,” *Laser Photonics Rev.*, vol. 5, no. 2, pp. 308–321, Mar. 2011.

[4] N. Lebbe, C. Dapogny, E. Oudet, K. Hassan, et A. Gliere, « Robust shape and topology optimization of nanophotonic devices using the level set method », *J. Comput. Phys.*, vol. 395, p. 710□746, oct. 2019.