Flexible Platform for Feeding Photonic Integrated Processors

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***Abstract* — Enhanced Photonic Integrated Circuits (PIC) are required for the current demand of flexibility and reconfigurability in telecommunications networks. Thus, an extensive characterization and testing is necessary to provide an accurate prediction of the PIC performance. The use of Spatial Light Modulator (SLM) as a diffractive device to reconstruct images from Computer Generated Holograms (CGH) allows to modulate the wave form of a light beam. In this study, we proposed the use of the SLM technology as a flexible platform for feeding photonic integrated processors. Preliminary results were obtained, to produce a multiplexing/demultiplexing CGH to be applied into an optical chip for data compression based on Haar wavelet transform.**

Keywords - Photonic Integrated Circuits (PIC); Integrated Optics; Spatial Light Modulator (SLM); Computer Generated Holography (CGH).

I. INTRODUCTION

In the recent years, we have witnessed a huge increase in the data traffic which the traditional copper based electronic mediums fail to carry [1] [2]. The subsequent evolution in optical communications has led to the emergence of Photonic Integrated Circuits (PIC). PIC-based optical communication offers an efficient and cost-effective alternative to data transmission driving to a significant growth in the segment [1]. It is expected an annual growth rate of 25.2% during the estimate period of 2015 to 2022 [2]. Furthermore, PIC increasing demand can also be attributed to innovative applications in bio-photonics [1].

PIC can be characterized as a multiport device composed by an integrated system of optical elements embedded onto a single chip using a waveguide architecture [3]. The testing of optical components is more difficult than testing electrical components and for an accurate prediction of the PIC performance, an extensive characterization and testing is required [4]. Moreover, optical components testing is difficult and time-consuming, e.g., due to the tight 3D alignment tolerances for accurate coupling of light [4].

The SLM capability to dynamically reconfigure the light makes it an attractive technology to excite cores and/or modes [5], [6], as it allows the arbitrary addition or removal of channels by the software and it is anticipated that it can improve channel compensation. This feature can then be explored to feed/receive optical signal from the PIC.

SLM is an electrically programmable device that modulates light according to a spatial (pixel) pattern [7]. This device can control incident light in amplitude-only, phase-only or the combination phase-amplitude [7], [8]. However, common methods of hologram generation cannot arbitrarily modulate the amplitude and phase of a beam simultaneously [9], [10]. It is not then possible to simply address the inverse Fourier Transform of the desired pattern into the far-field and replicate the resulting distribution of amplitude and phase directly on the SLM [9]. Thus, it is necessary to apply optimization algorithms to calculate the best hologram possible within the constraints of the device [9].

The SLM based on nematic Liquid Crystal on Silicon (LCoS) technology is an electrically addressed reflection type phase-only spatial light modulator in which the liquid crystal is controlled by a direct and accurate voltage and can modulate the wave front of a light beam [8], [11]. It is used as a diffractive device to reconstruct images from Computer Generated Holography (CGH) [12]. This optical signal processing can be produced with different techniques, e.g., linear Fourier transform (i.e., linear phase mask) [13], Iterative Fourier Transform Algorithm (IFTA) [14], [15], Gerchberg-Saxton algorithm [16] and simulated annealing [17]. The use of a SLM as a diffractive device to reconstruct images from CGH allows to modulate the wave front of a light beam.

In this study, we proposed the use of the SLM technology as a flexible platform for feeding photonic integrated processors, i.e., to feed/receive optical signal from the PIC. Preliminary results were obtained, to produce an expected CGH to be applied into an optical chip for data compression based on Haar wavelet transform. The paper is organized in four sections. Section II describes the methodology applied. Subsection II-A presents the design of the PIC for data compression; subsection II-B presents the generation and optimization of the CGH; and subsection II-C presents the SLM setup. Section III and IV presents the obtained results and its discussion, respectively. Section V concludes the study and presents future work.

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II. METHODOLOGY

The methodology is divided into three subsections: A) the design of the optical chip for data compression based in Haar wavelet transform; B) the algorithms used for the generation and optimization of the CGH; and C) the implementation of the SLM setup to acquire the CGH.

A. PIC for data compression based on Haar wavelet transform

The design of the new data compression chip based on Haar Transform (HT) is presented in Figure 1 [3].

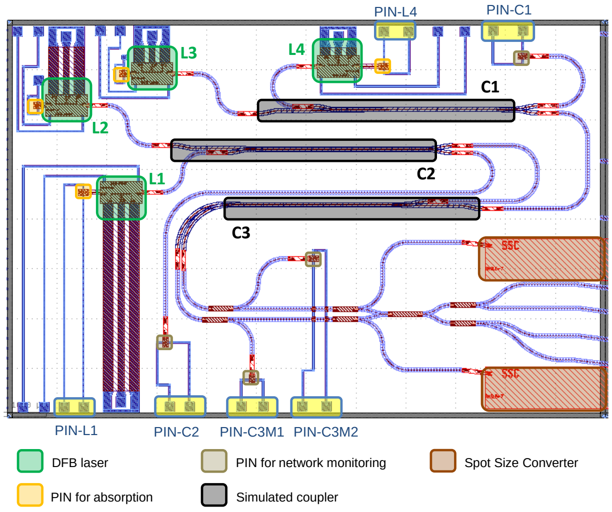

Figure 1. Design of an optical chip for data compression based on HT.

The chip is composed by four Distributed Feedback (DFB) lasers (L1-L4), three asymmetric couplers (C1-C3), six PIN photodiodes for network monitoring (PIN: L1, L4, C1, C2, C3M1, C3M2) two spot size converters, six multimode interferometers (MMI) 1x2 and one MMI 2x2.

The HT operations include Low-pass (L) and High-pass (H) filters applied over one dimension at a time. This filtering operation corresponds to the calculation of the average between two neighbors' pixels values (low-pass) or the difference between them (high-pass) [18]. The HT is implemented with a 3 asymmetric couplers (2x2) network, which reproduces the required operations, i.e., the average (sum) and the difference (subtraction) between the optical input pair [3]. The proposed asymmetric couplers were designed and simulated in the OptoDesigner from Phoenix Software [19].

The 2D HT can be decomposed in 4 sub-bands, LL, LH, HL and HH [18]. The LL gives the data compressed. In the chip these 4 sub-bands can be extrapolated from the 4 output waveguides (WG) at the end of the 3 asymmetric couplers network, see Figure 2. The measurements of the distance between the 4 WG at the end of the 3 asymmetric coupler network (represented as d1, d2 and d3 in Figure 2) have an order of magnitude of 200 μm. Measurements were performed with a Leica microscope (DM 750M; 1CC50 HD) and an objective of 20x (HI Plan EPI, 20x/0.40) [20].

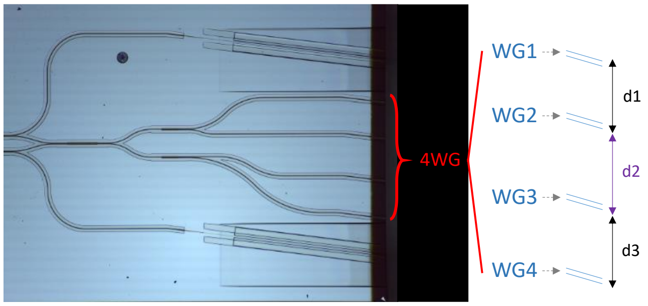

Figure 2. Measurements of the distance between the 4 waveguides (WG) at the end of the 3 asymmetric coupler network.

Further description of the design and characterization of the optical chip can be found in this study [3].

B. Generation of the CGH

The CGH produces a phase mask or diffractive optical element to apply to the SLM [13]. The information to be transformed (in the Fourier domain) is introduced into the optical system by the SLM, with a phase mask that is appropriate to the input function of interest [21]. The following calculus applied for the generation of the CGH were based in the Fourier optical principles presented in [21].

The CGH was obtained with a linear phase mask calculated in the frequency domain (1), where cx and cy are the horizontal and vertical tilt parameters, respectively; and fx and fy are the spatial frequency matrix arrays corresponding to the image to be generated in the X and Y axis, respectively.

$$Mask_{linear} = -2\pi(cx\,fx + cy\,fy) \tag{1}$$

The mask transfer function to be sent to the SLM, is given by $H_{mask} = \angle\big(\exp(iMask_{linear})\big)$, ensuring that the phase values are set in the range of $[-\pi, \pi]$.

An estimation of the output signal is given by (2).

$$S_{out} = ifft\big(H(fft(S_{in}))\big) \tag{2}$$

S_{in} describes the signal of the input beam (3), where $(x0, y0)$ provides the horizontal and vertical position and (wx, wy) the width and the height of the beam, respectively, see Figure 3.

$$S_{in} = \exp\left(-\left(2\frac{x - x0}{wx\,log(\sqrt{2})}\right)^2 - \left(2\frac{y - y0}{wy\,log(\sqrt{2})}\right)^2\right) \tag{3}$$

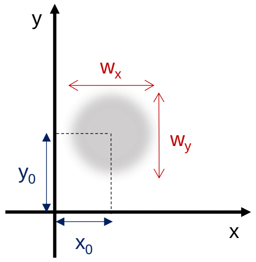

Figure 3. Diagram in Cartesian coordinate system describing the parameters $(x0, y0)$ and (wx, wy) used for the estimation of the Input beam S_{in}.

1) *Optimization of the CGH*

To obtain a hologram that replicates the output of the 4 WG of the optical chip (see Figure 2), the linear transformations in the Fourier domain presented in (4), (5) were applied.

$$H = \angle\left(e^{iH_1} + e^{iH_2} + e^{iH_3} + e^{iH_4}\right) \qquad (4)$$

$$H_1 = \exp\left(i * \left(2\pi(cx_1 * fx + cy_1 * fy)\right)\right) \qquad (5)$$

A phase-only SLM does not allow to simply address the inverse Fourier of the desired pattern into the far-field and replicate the resulting distribution of amplitude and phase directly on the SLM [9], thus it is challenging to spatially modulate the light with the expected resolution and accuracy.

To overcome this difficulty, an iterative algorithm to obtain the desired hologram with an error factor $\delta \leq 5\%$ was implemented. The main steps of the algorithm can be described as: i) generate a 1st linear phase mask to produce the expected initial field (I_{exp}), based on (4); ii) initially set the four values a_{1-4} to 1, from $H = \angle\left(a_1 e^{iH_1} + a_2 e^{iH_2} + a_3 e^{iH_3} + a_4 e^{iH_4}\right)$; iii) acquire the hologram generated by SLM (I_{SLM}) with a camera and feed this data to the algorithm; iv) calculate the difference between the hologram generated and the initial field expected, defined as error factor: $\delta = abs(I_{SLM} - I_1) \leq 0.05$; iv) if the condition $\delta \leq 0.05$ is not satisfied repeat steps (ii-iv) by iteratively adjusting the values of a_{1-4} to compensate the error factor. The algorithm was developed in Matlab [22], which was able to control both SLM and camera hardware. The block diagram of the algorithm is presented in Figure 4.

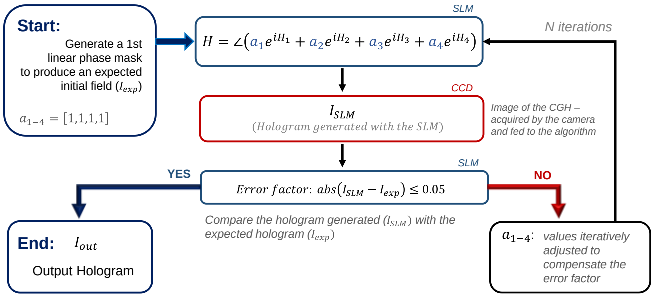

Figure 4. Block diagram of the algorithm applied for the optimization of the CGH.

The error factor (δ) reproduces the deviation of the generated hologram when compared with the expected output of the optical chip, i.e., the dimensions of the 4 WG.

C. *Setup to generate the CGH*

A reflective LCoS phase only SLM, model PLUTO-TELCO-012, with a wavelength range of 1400-1700 nm, an active area of 15.36 mm × 8.64 mm, a pixel pitch of 8.0 µm, a fill factor of 92% and reflectivity of 80% [8] was used to generate the hologram. The setup was composed by: a laser (1550nm wavelength); a polarization controller; two lenses (AC254-050-C-ML, AR coating 1050-1620nm) L1 and L2 with a focal length of 75mm and 250mm, respectively; a Near-Infrared (IR) (1460-1600nm) camera (sensing area: 6.4×4.8, resolution: 752×582, pixel size: 8.6×8.3) to capture the hologram produced; and a neutral density to avoid saturation in the camera acquisition, see Figure 5.

III. RESULTS

The hologram was generated in 1st order of diffraction where the polarization was occurring.

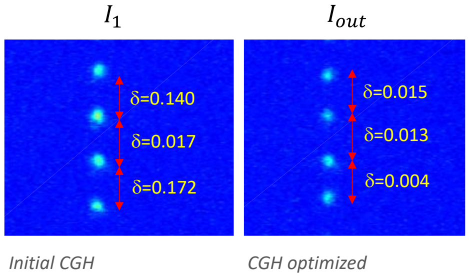

Figure 5. Hologram acquired by the IR camera, left: initial CGH; right: CGH optimized.

Figure 6 presents the holograms acquired by the IR camera, i.e., the initial hologram fed to the optimization algorithm with an obtained error factor $\delta \leq 17\%$ (left figure) and the final optimized CGH, with an error factor $\delta < 2\%$ (right figure).

IV. DISCUSSION

A significant improvement in the generated hologram is achieved with CGH optimization, i.e., a reduction of the error factor (δ) by 15%. Nevertheless, optical artefacts associated with the diffraction of light were not completely eliminated, i.e., additional 2 spots (with less intensity) are generated. This diffraction artefact can cause a reduction of signal expected at the 4 output WG of the optical chip.

The phase mask that replicates the expected output of the optical chip can be used to multiplex/demultiplex the obtained result. Furthermore, a phase mask which addresses the HT operations can also be applied to invert the compression induced by the HT (optically implemented in the chip with the 3 asymmetric couplers network).

The use of the SLM will then allow to provide a proof of concept of the PIC operation.

V. CONCLUSION AND FUTURE WORK

An extensive PIC characterization and testing is essential to provide an accurate prediction of its performance. To complement the PIC characterization process is proposed in this study a concept to use the SLM as a flexible platform for feeding photonic integrated processors. The capacity of the SLM to dynamically reconfigure light allows to feed and/or receive information to the PIC. This data can be used to provide a proof of concept of the operation performed by the optical chip, e.g., 2D HT. A first preliminary result was obtained, i.e., a phase mask that can be used to feed/receive

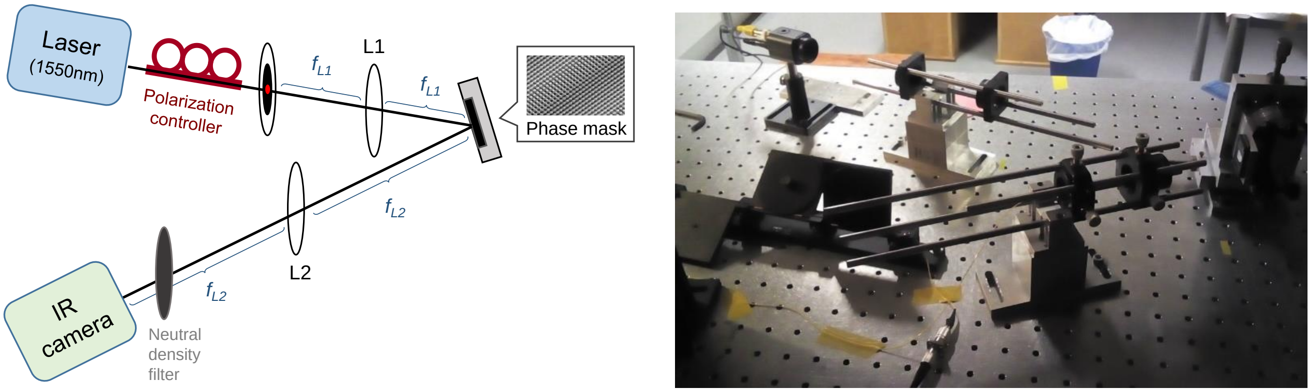

Figure 6. Left figure: Scheme of the hologram reconstruction system, using a laser of 1550nm, a polarization controller, lens L1, a LCoS-SLM, lens L2 and a IR camera. Right figure: Photography of the setup presented in the left figure.

the output of an optical chip for data compression based in the HT.

Further developments will be conducted to implement the HT in the phase mask applied to the SLM and tested with the optical chip, to quantitatively prove the proposed approach.

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