Automatic setting of multiple FSO orthogonal communication channels between photonic chips

SeyedMohammad SeyedinNavadeh[1], Maziyar Milanizadeh[2], Francesco Zanetto[1], Vittorio Grimaldi[1], Christian De Vita[1], Giorgio Ferrari[1], David A.B. Miller[3], Andrea Melloni[1], Francesco Morichetti[1*]

[1]*Department of Electronics, Information and Bioengineering, Politecnico di Milano, via Ponzio 34/5, 20133, Milano, Italy*
[2]*Advanced Electronics and Photonics Research Centre, National Research Council Canada, M-50, 1200 Montreal Rd. Ottawa, ON, Canada, K1A0R6*
[3]*Ginzton Laboratory, Stanford University, Spilker Building, Stanford, CA 94305, USA*
*corresponding author e-mail: francesco.morichetti@polimi.it

Abstract: Multiple orthogonal free-space optical (FSO) communication channels are automatically established between photonic chips hosting programmable integrated processors. All-optical channel demultiplexing is achieved with a crosstalk < -30 dB even after co-propagation though arbitrary mode mixers.

1. Introduction

Transmission of spatially multiplexed channels, or spatial modes, has been considered for years as a strategy to increase the capacity of Free-Space Optical (FSO) links [1]. However, in free-space, mode orthogonality can be impaired by the presence of obstacles as well as by the inherent time varying nature of environment (e.g., turbulence). As a result, it can be difficult, or even impossible, to identify a-priori the mode sets to be used at the transmitter side that are more robust against mode mixing effects and can provide minimum crosstalk after demultiplexing [2,3].

In this work, we experimentally show that a pair of self-configuring programmable photonic processors, used respectively at the transmitter (Tx) and receiver (Rx) side of an FSO link, can be used to establish multiple orthogonal channels between two photonic chips, according to the scheme theoretically presented in [4]. The system automatically finds the best FSO communication channels, that are the ones providing the highest power transmission, by iteratively optimizing the configuration of two photonic circuits. Pairs of spatially overlapped orthogonal FSO beams, not belonging to any conventional FSO mode set (Hermite-Gauss, Laguerre-Gauss, etc.), can be demultiplexed with less than -30 dB mutual crosstalk even after co-propagation through a variety of unknown scatterers (amplitude and/or phase masks with different patterns) introduced in the free-space path.

2. Reconfigurable Spatial MUX/DEMUX

The core of the proposed system is a pair of programmable silicon photonic processor, labelled as reconfigurable spatial MUX and DEMUX in Fig. 1(a), which are made of meshes of integrated Mach-Zehnder Interferometers (MZI). Each circuit has two "rows" of MZIs (8 and 7 diagonally cascaded MZIs), where each row is used to perform (de)multiplexing of an FSO spatial mode. Both MUX and DEMUX terminate at one side with 9 vertically radiating grating couples, arranged in a 3x3 square array, which are used as a 2D optical antenna array to couple the light into free space or vice versa. At the other end of the circuit, two input/output waveguides, labelled as IN/OUT$_i$, i = {1,2}, are used for fiber coupling. Figure 1(b) shows the micrograph of the photonic chip that is fabricated in a

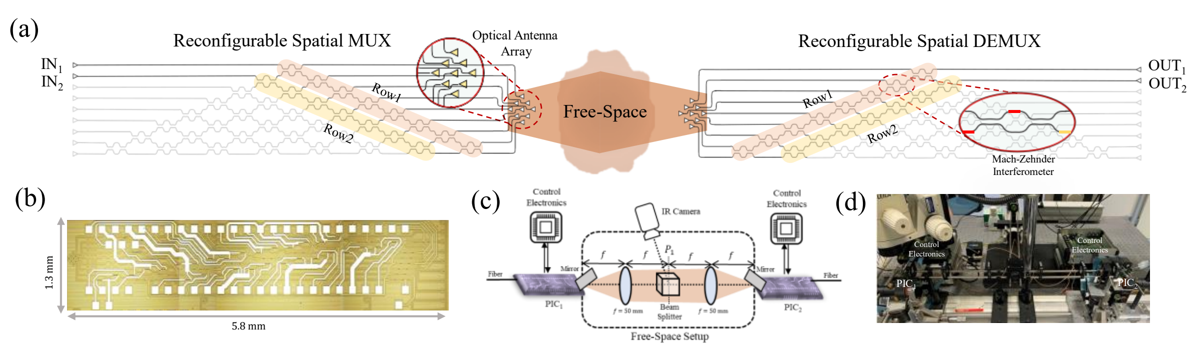

Figure 1. (a) Schematic of the proposed system for spatial MUX and DEMUX, (b) Micrograph of the realized photonic chip, (c) schematic of the free-space optical setup, (d) picture of the setup

standard 220-nm silicon photonic platform (AMF foundry) and is designed to work around a wavelength of 1550 nm. Each MZI is controlled independently by actuating on two thermo-optic phase shifters (heaters) integrated on top of the internal and external arms, and a transparent photodetector (PD) at the output [5]. Two identical photonic chips are placed in the FSO setup illustrated in Fig. 1(c). Two biconvex lenses with focal length $f = 50$ mm are used in a Fourier transforming configuration to give a collimated far field at plane P_1, and then to transform the beam back to the aperture of the 2nd chip. The far-field beam shapes are acquired using an IR camera focused on plane P_1, making use of a beam splitter. Two turning mirrors on top of the photonic chips reflect the light beam, vertically emitted by the grating couplers, to horizontal propagation. A picture of the optical setup is shown in Fig. 1(d).

3. Demultiplexing Two Orthogonal Channels

We first examine the operation of the spatial DEMUX when pairs of orthogonal beams are arriving at the receiver. As shown in Fig. 2(a), in this experiment two spatially overlapped Hermite-Gaussian-like modes (HG_{00} and HG_{01}), sharing the same wavelength, polarization (TE) and direction of arrival impinge on the optical antenna array of the DEMUX chip. The 1st and 2nd MZI rows of the mesh are configured to extract the power of the two beams at different output waveguides OUT_1 and OUT_2, respectively, using a simple local feedback loop for zeroing the bottom output of each single MZI [5]. Figure 2(b) shows that the two channels are separated with more than 30 dB of rejection. The quality of the demultiplexed channels is demonstrated using a transmission experiment in which the two FSO beams are modulated at 10 Gbit/s OOK. Figures 2(c_1)-(c_2) show clearly open eyes with no evidence of coherent crosstalk. To quantify the effect of the residual interfering channel, we measured the Bit Error Rate (BER) versus optical SNR at the receiver for both signals (modes) sorted at different output ports (Fig. 2d). As a reference curve, we measured the BER for the two individual modes HG_{00} only (blue) and HG_{01} only (red) – that is, when the interfering mode is turned OFF. After demultiplexing with the interfering mode ON, no degradation of the BER is observed (yellow and purple curves), demonstrating the good separation of the two channels.

4. Establishing Two Orthogonal Communication Channels Automatically

Two meshes of MZIs can be used to establish FSO communication channels through automatically optimized orthogonal spatial modes. As discussed in [4], the optimization process consists of injecting the light iteratively back and forward on both sides and reconfiguring the rows of MZIs in the receiving mesh. Figure 3(b_1) shows the shape of the beam that is obtained after reconfiguring the 1st row of MZIs in both meshes. This is the beam for most strongly coupled mode (1st mode), since with this optimization method, the system automatically performs a physical implementation of multiple-channel Singular Value Decomposition (SVD) between the source and receiver spaces [4]. Running the same process for the 2nd row of MZIs in both meshes, the 2nd most strongly coupled mode is found, which is shown in Fig. 3(b_2). As shown in Fig. 3(b_3), the 2nd mode is extracted with a (slightly) lower power, while the mutual isolation is more than 30 dB, demonstrating the orthogonality between the channels automatically established.

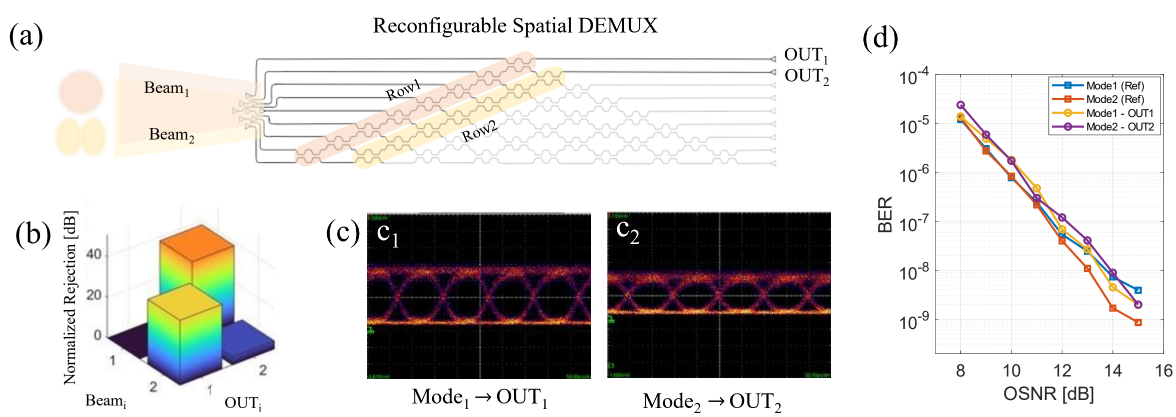

Figure 2. (a) Demultiplexing two orthogonal beams using meshes of MZI, (b) Normalized mode rejection for the extracted beams, (c) Eye diagrams for the 10 Gbit/s received signals at OUT1 (c1) and OUT2 (c2), (d) BER measurements for established channels

By using the pair of reconfigurable spatial MUX/DEMUX, it is also possible to find orthogonal channels though arbitrary scattering media. To this end, we inserted partially obstructing masks in the free-space path between the two chips. In the experiment reported in Fig. 3(a), the mask has a pattern of opaque plus-shaped spots with approximately the same period as the diffraction pattern and is inserted in the far-field (Fourier) plane P_1 of Fig. 1(c). When the mask is aligned to partially obscure the beam spots (Figs. 3c$_1$-c$_2$), both the coupled power and the mutual rejection of the modes are degraded (bar chart of Fig. 3c$_3$). If we perform the optimization process on the MZI rows of both meshes, a new pair of orthogonal channels is found automatically, with almost the same initial mode power extraction and more than 30 dB of rejection, as shown in Fig. 3(d). Notably, these beam shapes, as optimized by the meshes, do not belong to any conventional mode sets, yet they are still orthogonal and represent the best channels of the system.

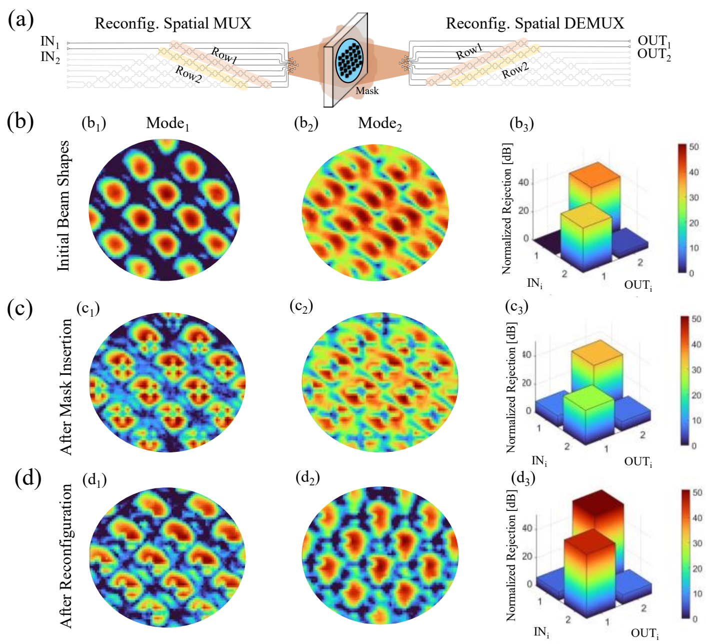

Figure 3. (a) Schematic of the setup for performing (de)multiplexing (b) initial beams shapes and mode rejection automatically obtained before inserting the mask, (c) same after insertion of the mask, (d) the new beam shapes and mutual rejection obtained after reconfiguration.

5. Conclusion

We demonstrated automatic setting of multiple FSO orthogonal communication channels between photonic chips by using a pair of programmable photonic processors. The system automatically finds the best communication modes between transmitter (MUX) and receiver (DEMUX) spaces, with no knowledge of the transmission matrix of the link. Separation of orthogonal modes is achieved without any fundamental excess loss and more than 30 dB rejection, and even after partially obstructing the path with arbitrary scatterers. The approach is readily scalable to more than two orthogonal channels by using architectures with more MZI rows [4].

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