Establishing Multiple Chip-to-Chip Orthogonal Free-Space Optical Channels using Programmable Silicon Photonics Meshes

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Two silicon photonics programmable meshes of Mach-Zehnder interferometers are used to automatically establish chip-to-chip orthogonal free-space communication links. Optimum channels with mutual isolation of more than 30dB are found even in case of a misaligned link or in presence of an obstacle in the path.

Keywords—Programmable photonic circuits, free-space optics, orthogonal communication channels, silicon photonics

I. INTRODUCTION

Programmable Photonic Integrated Circuits (PPICs) are emerging as versatile chip-scale platforms for applications in many different fields including microwave photonics, quantum and neural networks, mode manipulation in fiber-optic communications and sensing [1]. Due to the large scale of integration and the possibility of integrating both power-efficient tuning elements and on-chip monitor photodetectors, silicon photonics (SiP) appears as a good candidate for implementation of PPICs. Recently, we demonstrated that a programmable silicon photonic mesh of Mach-Zehnder Interferometers (MZIs) has a wide potential in the manipulation of free-space optical (FSO) beams, as it can generate perfectly-shaped FSO beams even when using an array of imperfect optical antennas and it can image field patterns with a desired shape through obstacles [2].

In this work, we use a pair of MZI meshes, respectively at the transmitter and receiver side of a FSO link, to establish chip-to-chip FSO communication on multiple orthogonal beams. The first conceptualization of this system was given in [3] and finds here its first experimental validation. Optimum communication channels are found by iterative self-optimization of each MZI mesh. Orthogonal FSO channels can be separated with more than 30 dB of mutual isolation without any excess loss, even in presence of a partial obstruction in the free-space path.

II. PROGRAMMABLE PHOTONIC MESH CIRCUIT

The programmable photonic meshes used in this work are realized on a standard 220 nm silicon photonic platform (AMF foundry, Singapore) and are designed to work at a wavelength of 1.55 µm. The mesh topology is "bi-diagonal", employing two "rows" of integrated waveguide MZIs in each mesh, consisting of 8 and 7 MZIs, respectively (Fig.1a). Therefore, each mesh has 9 input/output ports, which are realized using vertically-emitting grating couplers, and can support 2 orthogonal channels, one for each row. The 9 ports at one end are arranged as a 3x3 square array for coupling between free-space beams and the single-mode waveguides of the meshes. The total size of the square aperture is much larger than a wavelength, which leads to presence of higher diffraction orders in the resulting output pattern. At the other end of the mesh, 2 output ports indicated with $WG_i, i = \{1,2\}$, are used for coupling into an optical fiber. Each integrated MZI block of the mesh consists of two 3-dB directional couplers, and two thermo-optic phase shifters (one on a waveguide just outside the MZI and one on internal arm) are fabricated on top of the waveguides for controlling the relative phase shift of the MZI inputs and the MZI split ratio. The two meshes are set up as shown in Fig. 1(a) to face each other, making use of an optical setup in between (not shown here) consisting of two turning mirrors on top of the chips and two fixed lenses to reflect and converge radiated beams from and to the 3x3 coupler arrays, which are separated by 70 cm. Fig. 1b₁ shows this simplified schematic with the square "apertures" of 9 grating couplers or "pixels" , but omitting the mirrors and lenses that route the light between them.

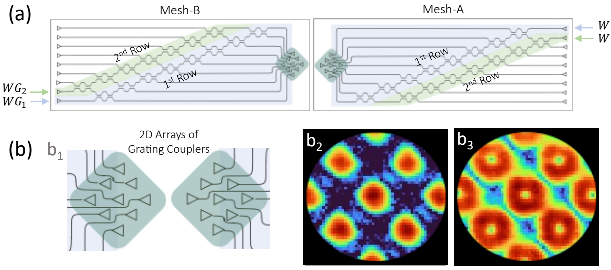

Figure 1: Two programmable photonic circuits with two diagonal rows of MZIs are used to establish two orthogonal free-space communication channels. (a) Schematic of the meshes with fiber-coupled input/output ports indicated with WG_i , and free-space ports, shown in the middle, with 3x3 coupler arrays; the 1st row is color-coded with blue and the 2nd row with green in both meshes. (b) Schematic of the radiating apertures of two meshes each consisting of 3×3 grating couplers (b_1), along with the radiated far-field beam of the 1st and 2nd mode pairs in (b_2) and (b_3), respectively. (Fixed free-space mirror and lens optics between the arrays is omitted here.)

III. ESTABLISHING OPTIMUM ORTHOGONAL COMMUNICATION CHANNELS AUTOMATICALLY

The two meshes of MZIs can be configured automatically to establish optimum FSO communication channels through two orthogonal pairs of modes. The optimization process follows this procedure: referring to Fig. 1(a), we first shine the light into "input" WG_1 of Mesh-A (on the right) with arbitrary settings of the MZIs in the 1st row; in this way an arbitrary beam radiates from the free-space ports of the mesh, propagates in the free-space and is coupled to the input aperture (2D array of gratings) of Mesh-B (on the left). Then, we configure each MZI in the 1st row of Mesh-B by acting on the phase-shifters and minimizing the power in the upper output port of each MZI. Following this procedure, the FSO beam that is sampled and coupled to the free-space ports can be summed up coherently and extracted at the output WG_1 of Mesh-B. As the next step, we run the same procedure but reversing direction of the light propagation, i.e., the light is injected from WG_1 of Mesh-B, it propagates (as a phase-conjugate beam) in free space and is received by the grating array of Mesh-A, and the optimization process is done on the 1st row of Mesh-A by minimizing the power in the lower output port of each MZI. By iterating this process in the forward and backward direction, the most strongly coupled channel can be found and established automatically. This is because that this procedure performs a physical implementation of singular value decomposition (SVD) of the wave coupling operator between source and receiver spaces [4]. Once the 1st rows of both meshes are configured, the same optimization process can be carried out for the 2nd rows on both sides to obtain the orthogonal mode with the second-strongest coupling strength. In the following, we examine this concept for different conditions of the source and receiver as well as in the presence of an obstacle in the free-space path, and we evaluate the mutual isolation between the automatically established channels.

a) *Reference condition*. First, we establish two channels only in presence of the external mirror and lens optics between the chips, i.e., with neither misalignments nor obstacles in the free-space path. The far-field radiated beam shapes of the 1st and 2nd mode are captured using an IR camera and shown in Figs. 1(b_2) and (b_3), respectively (which are in this case the same beam shapes shining from either Mesh-A or Mesh-B). A high mutual rejection of more than 35 dB is obtained between the modes extracted at output waveguides of the receiving mesh upon execution of the optimization process.

b) *Tilted apertures.* If we intentionally tilt the turning mirrors positioned on top of the grating arrays of the meshes, which is equivalent to slightly rotating the plane of pixels (Fig. 2a_1), the physical channel in between and, therefore, the coupling operator, is changed. If we let the MZI meshes automatically find their optimum configuration, we obtain a new set of orthogonal channels, which has the beam shapes as in Figs. 2($b_{2\text{-}3}$) for the 1st and 2nd mode, respectively. Also, in this case the mutual isolation is 35 dB.

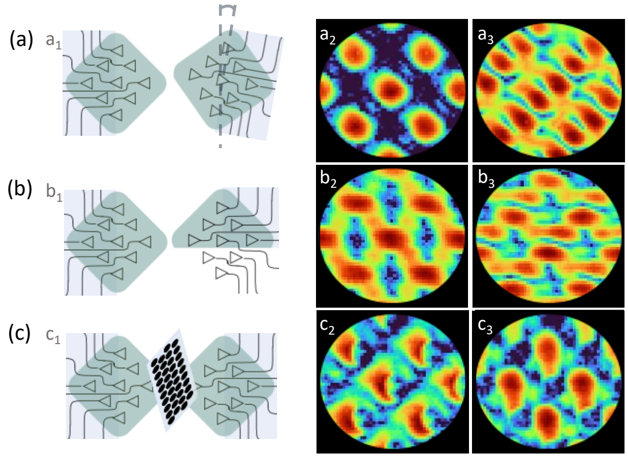

Figure 2: Automatic establishment of two orthogonal channels in different conditions. (a) Tilt of the pixels in the aperture (a_1); the corresponding beam shapes of the 1st and 2nd MZI row of Mesh-A are illustrated in (a_2) and (a_3), respectively. (b) Turning off some of the pixels in Mesh-A (b_1), along with the beam shapes for the 1st (b_2) and 2nd (b_3) row, when injecting the light in the input waveguides of Mesh-A. (c) Inserting an obstacle in between two meshes (c_1) and capturing the beam shapes for the 1st and 2nd row as in (c_2) and (c_3), respectively, after proceeding with optimization of the rows.

c) Asymmetric transmitter-receiver apertures. In this case, we intentionally configure some of the MZIs of Mesh-A in a way that some of the grating couplers of the array are always switched off, as shown in Fig. 2(b_1). This explicitly means that the source/receiving wave function space of Mesh-A has lower dimension with respect to that of Mesh-B. Even though the system is now asymmetric, after performing the optimization process, a new pair of orthogonal channels is found, with 30 dB of isolation and a slight decrease (~3 dB) in the extracted mode powers. Figures 2($b_{2\text{-}3}$) show the beam shapes of the 1st and 2nd mode (from Mesh-A), respectively.

d) Obstacle in the free-space path. As a further experiment, we introduced an obstacle in the free-space path that partially obstructs the link between the two chips. As shown in Fig. 2c_1 the obstacle consists of a periodic mask, which is patterned by opaque spots of size ~ 75% of the spot size of the main beam and the same period as the diffraction pattern. Upon optimizing the two MZI meshes, the beam shapes of Figs. 2($c_{2\text{-}3}$) are found for the 1st and 2nd mode. We record a slight decrease in the extracted powers of the modes (~4 dB), while still having a mutual isolation of 33 dB.

The high mutual rejection observed in all these experiments means that mutually orthogonal beam pairs are found in each case, even though now these beams do not belong to any conventional family of FSO beams.

IV. CONCLUSIONS

Employing two programmable photonic integrated circuits based on MZI meshes, we demonstrated experimentally the establishment of chip-to-chip FSO communications on pairs of orthogonal modes. Optimum orthogonal channels are automatically found by self-configuration of MZI stages, with neither knowledge of the transmission matrix nor calculation of eigenmodes of the channel, and even when the chips are misaligned or the beams are partially obstructed. Loss-less separation of orthogonal modes is achieved with more than 30 dB of rejection. The approach is readily scalable to more than two orthogonal channels if architectures with more MZI rows are used.

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