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Automatic mitigation of tilt and phase-front distortions in multichannel chip-to-chip free-space optical links

(Student paper)

SeyedMohammad SeyedinNavadeh[1], Maziyar Milanizadeh[1], Francesco Zanetto[1], Marc Sorel[2,3], Giorgio Ferrari[1], David A.B. Miller[4], Andrea Melloni[1], Francesco Morichetti[1]

[1] Department of Electronics, Information and Bioengineering, Politecnico di Milano, via Ponzio 34/5, 20133, Milano, Italy
[2] School of Engineering University of Glasgow, Glasgow, G12 8QQ, UK
[3] TeCIP Institute, Scuola Superiore Sant'Anna, 56124 Pisa, Italy
[4] Ginzton Laboratory, Stanford University, Spilker Building, Stanford, CA 94305, USA
[*]corresponding author e-mail: francesco.morichetti@polimi.it

We demonstrate automatic compensation of tilt and phase front distortions in a multichannel chip-to-chip free-space optical (FSO) link. The system exploits a pair of integrated photonic processors made of self-configuring meshes of Mach-Zehnder Interferometers (MZIs) that automatically find the best orthogonal communication channels with more than 30 dB mutual isolation.

Keywords: *Programmable Photonic Circuits, Free-Space Optics, Orthogonal Communication Channels, Silicon Photonics*

INTRODUCTION

Free-space optics (FSO) communication links are subjected to several challenges, including pointing errors and scintillation due to turbulent atmosphere [1]. A solution to mitigate these impairments makes use of adaptive optical systems that can be dynamically controlled to compensate for time-varying conditions of the link [2]. Integrated programmable photonic processors consisting of generic reconfigurable architectures are a promising approach to implement adaptive optics on a chip. Recently, we demonstrated that a silicon photonic mesh of Mach-Zehnder Interferometers (MZIs) controlling an array of optical antennas can be used both as an adaptive transmitter (Tx) to automatically shape and steer FSO beams [3] and as a receiver (Rx) to separate multiple spatially overlapped FSO beams [4]. A pair of self-configuring MZI meshes can automatically establish chip-to-chip FSO links on multiple beams by finding the best orthogonal communication channels [5].

In this work, we report on a chip-to-chip system that can provide automatic compensation of tilt and phase front distortions in multichannel FSO links. Tilt-tolerant and phase-distortion robust communication is demonstrated in a two-mode FSO system with more than 30 dB mutual isolation even in the presence of realistic impairments.

MULTI-CHANNEL CHIP-TO-CHIP FREE SPACE OPTICAL LINK

Figure 1(a) shows a microphotograph of the photonic integrated circuit (PIC) employed in this work. It is realized in a standard Si-Photonics platform (AMF foundry) with 220-nm-wide waveguides and is designed to work around a wavelength of $\lambda = 1.55\ \mu\text{m}$. It consists of a waveguide mesh of thermally tuneable MZIs with a 9x2 diagonal architecture [6], implementing a programmable photonic processor. At one end of the photonic processor (left side shown in Fig. 1a), 9 single-mode waveguides are connected to a 9-element optical antenna array, configured in a 3x3 square with spacing of $d = 50\ \mu\text{m}$ (Fig. 1a$_3$). The elements of the array are realized by surface grating couplers (GCs) with $\approx 9° \times 5°$ beamwidth and $10°$ of tilt of the out-of-plane radiated light. At the other end of the chip (right side), 2 single-mode waveguides, denoted with IO_j , $j = \{1,2\}$, are used for input/output fiber coupling.

A pair of photonic chips are employed as transmitter (Tx) and receiver (Rx), respectively, as shown in Fig. 1(b). For deflecting the vertically emitting beam of the array of GCs, a tilted mirror is placed on top of both chips (not shown in the schematic). The setup includes two biconvex lenses in Fourier configuration for collimation/focusing of the beam from the PICs. A spatial light modulator (SLM) is inserted in the path between the two chips, which is used to introduce arbitrary distortions of the phase front of the FSO beams to dynamically emulate pointing errors and time-varying obstacles in the link. A photograph of the FSO chip-to-chip link implemented in the lab setup is shown in Fig. 1(c), with a zoom of the SLM in the inset of the figure. Each photonic chip is mounted on a printed circuit board and a custom-designed electronic board is used for automatically controlling the working point of each photonic chip through integrated thermal tuners. The self-configuring algorithm is based on the maximization of the optical power at IO_j ports and is implemented by using different dithering frequencies for each MZI [6].

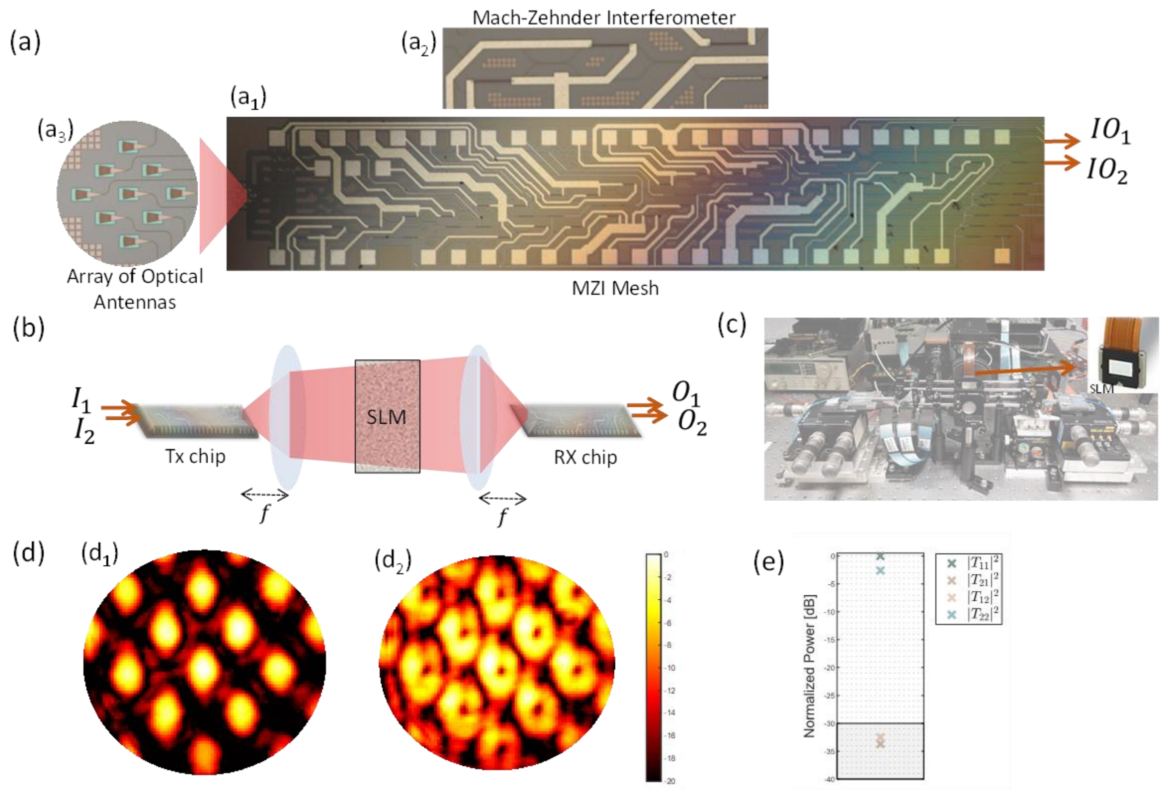

Fig. 1. Photograph of the photonic chip integrating a programmable processor made of a two-diagonal mesh of thermally tuneable MZIs (a_2) connected to an 3x3 array of optical antennas (grating couplers, a_3); (b) Schematic and (c) photograph of the chip-to-chip experimental setup integrating an SLM for arbitrary manipulation of FSO beams; (d) Camera-view measurement of the shape of the 1st and 2nd modes that are automatically obtained by tuning the 1st and 2nd rows of the two processors (SLM off, no intentional phase perturbation). (e) Received power (normalized to the 1st channel) of the 1st and 2nd mode, together with the mutual residual crosstalk.

The photonic processor at the Tx/Rx side can self-configure to find the pair of most strongly-coupled FSO channels. To this aim, the MZIs of each diagonal of the mesh are sequentially tuned to coherently combine the contributions of the beam sampled by the array of GCs [4] in such a way that the Tx and Rx meshes can adapt to the status of the link for finding two orthogonal channels. Figures 1(d_1) and (d_2) shows the shape of the beams that are automatically obtained for the 1st and 2nd modes, when no intentional phase perturbation is introduced in the link (SLM off) [7]. The multiple replicas in the pattern are due to the fact that the spacing between array elements is larger than half wavelength. The diagram in Fig. 1(e) shows the normalized power for the two channels ($|T_{11}|^2$, $|T_{22}|^2$) as well as the crosstalk between them ($|T_{21}|^2$, $|T_{12}|^2$) (power levels are normalized to that of the 1st channel). The coupling efficiency of the 2nd channel is slightly lower, but the mutual crosstalk between two channels is less than < -30 dB.

AUTOMATIC MITIGATION OF TILT AND PHASE FRONT DISTORTION

As a first experiment, the SLM is used to intentionally introduce a tilt to the beam propagating between the two chips (Fig. 2a). This effect is achieved by generating a linear phase change across the SLM to induce a maximum horizontal tilt of 10 mrad, which causes focusing error on the aperture of the Rx chip. The reduction of the coupling efficiency versus the tilt angle is shown by the pink curve ($|T_{11}|^2$) in Fig. 2(a_2) for the fundamental FSO mode (1st channel). A large sensitivity to tiny misalignments is observed and up to 25 dB loss are induced by a tilt angle as low as 2.5 mrad if no active compensation is performed (processors control switched off). The oscillating behaviour of the received power versus the tilt angle is due to the presence of grating lobes in the far field of the beams, which can provide coupling between different diffraction orders. The experiment is then repeated when the electronic controller of the two processors is activated to dynamically compensate for the tilt of the beam. As shown by the green curve ($|\bar{T}_{11}|^2$) in Fig. 2(a_2), active compensation can recover more than > 20 dB power loss due to pointing errors. The residual decrease in the coupling efficiency is due to the limited field of view of the beam which is radiated by the GCs and collimated by the lens system. Figures 2(a_3) and 2(a_4) show the camera view of the measured far-field radiated by the Tx chip compensating for the tilt induced by the SLM.

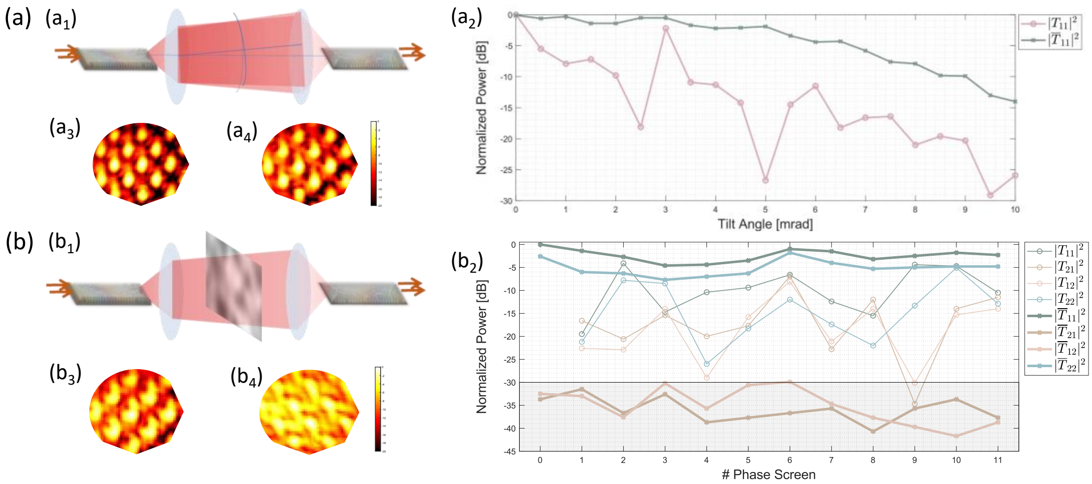

Fig. 2. Automated impairment mitigation in chip-to-chip FSO links. (a_1) Compensation of pointing errors generated by a linear phase profile in the SLM; (a_2) Normalized received power vs. tilt angle when the active control of the photonic processors is OFF (pink curve) and when is activated (green curve); (a_3 - a_4) Measured intensity profiles of the far-field beam radiated by the TX chip compensating for the tilt induced by the SLM; (b_1) Compensation of arbitrary phase front distortions induced by the SLM; (b_2) Normalized received power of the 1st and 2nd mode and mutual crosstalk for eleven different phase front perturbations when active control of the photonic processors is OFF (thin curves) and when is activated (thick curves); (b_3 -b_4) Measured intensity profiles of the far-field (1st mode) radiated by the TX chip compensating for phase distortions induced by the SLM.

Random profiles in the SLM were generated to introduce arbitrary perturbations in the phase front of the FSO beams (Fig. 2b_1). The diagram in Fig. 2(b_2) shows the normalized received power of the 1st and 2nd mode, and the mutual crosstalk between them, for eleven different configurations of the SLM when the photonic processors are off (thin curves, $|T_{ij}|^2, i, j = \{1,2\}$) and when they are activated (thick curves, $|\bar{T}_{ij}|^2, i, j = \{1,2\}$) for compensating phase perturbations. Perturbations in the phase profile of the FSO beams cause both severe losses in the received power of the channels (up to 25 dB) and a strong reduction of the mutual crosstalk. Results show that the dynamic control of the two processors largely recovers the power levels observed in the absence of perturbations [see Fig. 1(e)]. Figures 2(b_3) and 2(b_4) shows some examples of the far field beams radiated by the Tx chip to perform compensation of phase front distortion.

CONCLUSION

We demonstrated automatic compensation of tilt and phase front distortions in a multichannel chip-to-chip communication system emulating realistic conditions of FSO links. The system exploits a pair of programmable processors that self-configure to find the best orthogonal modes and more than 30 dB mutual isolation is achieved on pairs of spatially overlapped channels even in the presence of time-varying impairments. The system can be scaled to a larger number of orthogonal channels by using integrated processors with more MZI rows.

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