Integrated Photonic Processors for Optical Free-Space Links
[Invited Paper]

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Abstract: Programmable photonic integrated processors offer a large potential for the generation, manipulation, and detection of free-space optical beams (FSO). Applications are shown on the automated setting of optimal orthogonal MIMO channels and transmission through time varying FSO links.

1. Introduction

As the data rate of communication and computing architectures increases, analog processing in the optical domain is emerging as a good candidate for supporting digital electronics. Integrated photonic processors have been recently proposed in many different areas, including mathematical accelerators for machine learning and artificial neural networks, cognitive radio and compressive sensing, intelligent signal processing in fiber optic communication, and optical quantum key distribution [1]. In free-space optics (FSO), optical beams need to be shaped and steered according to the specific application (communication, sensing, positioning, or ranging) and based on the real-time properties of the link, which can change substantially due to for example atmospheric conditions, presence of obstacles and relative displacement of transmitter and receiver. These effects are particularly critical in multiple-input multiple-output (MIMO) FSO systems where the use of spatially multiplexed optical beams can increase the capacity of the link, but at the same time mode orthogonality can be affected by such variability of the system conditions [2].

Here we show how photonic integrated processors made from programmable integrated meshes of thermally tuneable Mach-Zehnder Interferometers (MZIs) can be effectively used to generate, manipulate, and detect FSO beams with optimized shapes [3,4]. For instance, we demonstrate the automated determination of best orthogonal MIMO communication channels through arbitrary unknown media and active real-time compensation of spatial decorrelation effects due to atmospheric turbulence by means of a photonic processor-assisted receiver.

2. Integrated photonic processors for FSO links

Several MZI mesh topologies can be used for the implementation of integrated photonic processors, which include for example triangular meshes (Fig. 1a_1) and binary tree meshes (Fig. 1a_2). For operation at a wavelength of 1550 nm, the photonic chips are fabricated using a standard 220-nm silicon photonic platform, which enables

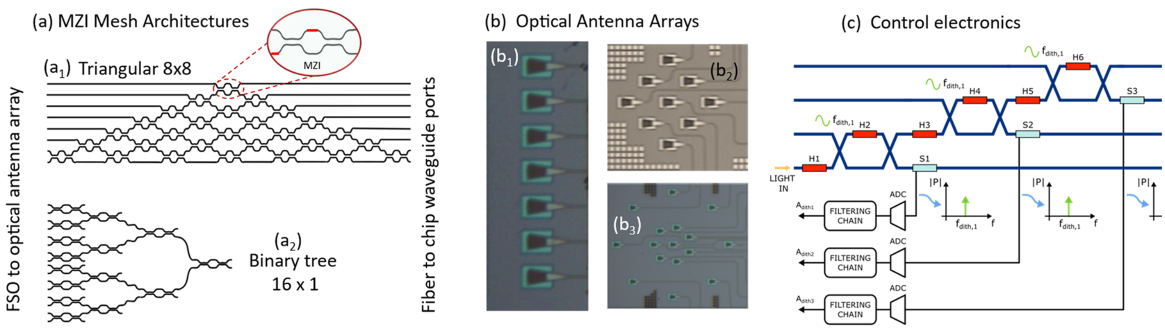

Figure 1. (a) Schematic of the MZI-based photonic processors with triangular and binary-tree topologies. (b) Top view photograph of on-chip optical antenna made of 1D linear (b_1), 2D square (b_2) and 2D circular array (b_3) of GCs; (c) Scheme of the control electronics for automated configuration and stabilization of the cascaded MZIs of the integrated photonic processors.

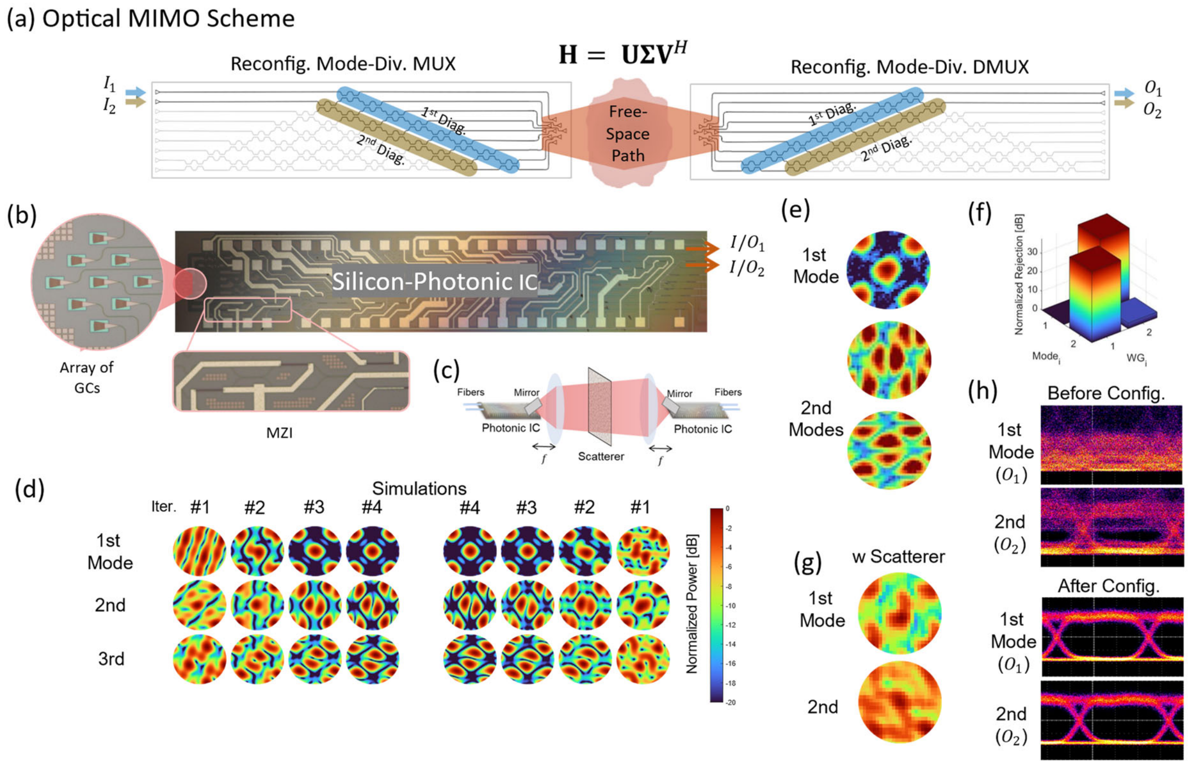

Figure 2. Photonic integrated processors for MIMO FSO links: (a) Schematic of the two-processor system determining best communication channels in an arbitrary medium; (b) Photo of the silicon photonic chip; (c) Use of the proposed system in the presence of an obstacle (scatterer) in the link; (d) Simulated evolution of the far-fields radiated by the two processors during the automated configuration process and final shape at convergence (after 4 iterations); (e) Measured field shapes at convergence and (f) Mutual isolation confirming

the integration of meshes with tens of MZIs in a footprint of a few mm^2. In order to couple an FSO beam to the MZI mesh, arrays of optical antennas are integrated into the photonic chip as input ports. Such optical antennas can be efficiently realized by means of surface grating couplers (GCs), which can be arranged in different configurations. As examples, Fig. 1b shows a 1D array of 4 GCs (b_1), a square 2D array of 9 GCs (b_2), and a circular 2D array of 16 GCs (b_3). The output waveguide ports are used to collect the light beams that are processed by MZI mesh and couple each of them to an optical fiber. Each MZI has two thermal phase shifters (in one of the outer and inner arms) and performs a 2x2 unitary transformation on pairs of optical input fields. Such integrated photonic processors are automatically configured and real-time stabilized by means of local feedback loops that monitor individually each MZI (Fig. 1c); the MZIs are monitored by means of integrated or off-chip photodetectors and dithering signals are applied to the phase shifters to identify the MZI working point and maximize the optical output power. Pilot tones are applied to the input FSO beams to handle simultaneously different beams with the same circuit. By using these control strategies photonic processors with tens of MZIs can be configured in less than 50 ms [4].

3. Finding optimal FSO modes automatically

By using a pair of integrated processors, it is possible to realize a multiple input multiple output (MIMO) FSO system that automatically determines the optimal orthogonal communication channels through an arbitrary unknown medium [5]. As shown in Fig. 2a, a two-processor system calculates optically the singular value decomposition (SVD) of the coupling matrix $\mathbf{H}=\mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$ of the MIMO FSO link, where the left and right singular matrices **U** and **V** are implemented by the two processors for the first best-coupled modes (each row of the diagonal mesh is associated to a different mode), and singular values on the diagonal matrix **Σ** provide the end-to-end coupling from input I_i to output O_i. Fig. 2b shows the photo of a 9-input (optical antenna array of Fig. 2b) / 2-output bi-diagonal chip which is used in [4] to find the first two modes of an FSO link (including obstacles and scatterers in the optical path, Fig. 2c). For this system, simulations in Fig. 2(d) show the evolution of the

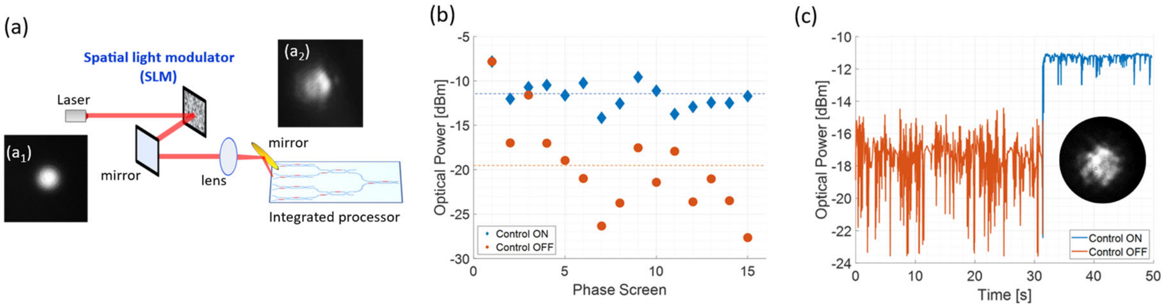

Figure 3. Automated compensation of time-varying FSO channels by using a photonic processor-assisted receiver. (a) Schematic of the experimental setup where an SLM is employed to introduce phase perturbation and spatial decorrelation (scintillation) on a FSO Gaussian beam. (b) Measure optical power collected at the output port of a 16x1 binary-tree photonic processor for different configuration of the SLM when the active control is switched off (red circles) and activated (blue diamonds); (c) Time trace of the measured output power when the perturbation in the link is introduced by a heat gun (instead of by the SLM) that generates fast turbulent components.

beams radiated by the two processors at different iteration steps of the control algorithms, which consist in injecting the light iteratively backward and forward on both sides and reconfiguring the rows of MZIs in the receiving mesh. After only four iterations in this case, the 1st Gaussian-like, the 2nd (horizontally antisymmetric), and 3rd (horizontally antisymmetric) degenerate modes are found. The experimental shape of such modes is shown in panel €, and their mutual orthogonality (> 30 dB rejection at the output ports) is shown in panel (f). The presence of a scattering element in the optical path breaks the orthogonality. This effect is visible in the eye diagrams of two 5 Gbit/s NRZ OOK signals transmitted on these modes, which are substantially closed due to high mutual cross-coupling [panel (f), before configuration]; orthogonality can be recovered by the two-processor system that can determine the pair of new communication modes [shapes in panel (g)], that maintain orthogonality after passing through such obstacle, thus recovering the quality of the received signals [panel (f), after configuration].

4. Automated compensation of time varying FSO channels

To demonstrate the dynamic compensation of time-varying conditions in the FSO link, the experimental setup shown in Fig. 3(a) is used. A Gaussian beam (a_1) generated by an optical collimator impinges on a spatial light modulator (SLM), which introduces a phase modulation of the beam phase front, so as to emulate the effect of atmospheric turbulence. The beam at the receiver side (a_2) is focused on the 2D optical antenna array integrated into the photonic chip. In this experiment, a 16x1 binary-tree architecture with the circular array of Fig. 1(b_3) is employed. Figure 3(b) shows the power at the output port of the photonic processor for different phase screens generated by the SLM when the control of the processor is OFF (red circles) and ON (blue diamonds). Results show that dynamic intensity fading due to the SLM is substantially reduced from more than +/- 10 dB to less than +/- 2 dB. Figure 3(c) shows the time trace of the output power coupled by the receiver when turbulence is introduced by replacing the SLM with a heat gun introducing a much faster (up to 500 Hz) perturbation of the link (perturbed field shape in the inset) [6]. Effective recovery and stabilization of the received power is demonstrated with an increase of 6 dB in the average power and a ten times reduction of the fading standard deviation.

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