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Programmable photonics for atmospheric turbulence compensation in free space optics communications

A. Martinez[1], S. Seyedinnavadeh[1], F. Zanetto[1], F. Morandi[1], A. Milani[2], A. D'Acierno[2], L. Resteghini[2] , F. Morichetti[1], and A. Melloni[1]

1. DEIB, Politecnico di Milano, via Ponzio 34/5, 20133, Milan, Italy
2. Huawei Technologies Italia Srl, Centro Direzionale Milano 2 SNC, 20054 Segrate, Italy
**andresivan.martinez@polimi.it*

***Abstract*— An integrated programmable optical processor is used to mitigate turbulence-induced scintillation effects in Free Space Optical communications. The proposed adaptive transceiver is tested using 5 Gbit/s OOK signals transmitted through an indoor setup that emulates an FSO link of hundreds of meters.**

***Keywords*— Free space optics, programmable photonics, optical processor, silicon photonics**

I. INTRODUCTION

Atmospheric turbulence is a major obstacle for high-bitrate, reliable Free Space Optics (FSO) communication systems [1]. It causes random phase and amplitude perturbations in optical beams, reducing transceiver coupling efficiency and causing deep signal fading after the photodetector [2]. This effect can be mitigated using an adaptive optical transceiver that samples (spatially) the incoming beam and then coherently combines these samples faster than the channel's coherence time to recover beam spatial coherence.

In this paper, we present an adaptive optical receiver comprising an optical antenna array (OAA) and a programmable optical processor (POP). Our self-adaptive control scheme automatically mitigates scintillation without requiring knowledge of the medium or pre-calibration of the mesh elements. Experimental results demonstrate the effectiveness of this approach with intensity-modulated optical signals at a data rate of 5 Gbit/s transmitted through an indoor setup that emulates an FSO link of hundreds of meters.

II. INTEGRATED FSO TRANSCEIVER

The integrated FSO transceiver is designed to generate and receive optical beams using an optical antenna array (OAA). The scheme of the transceiver PIC is shown in Fig. 1(a). The OAA comprises 16 surface grating couplers (GCs) arranged in two concentric rings with one central GC. The programmable optical processor (POP) is a 16x1 binary mesh implemented on a commercially available Silicon Photonics (SiPh) platform [see Fig. 1(b)]. It comprises 15 balanced Mach-Zehnder interferometers (MZIs), each equipped with two thermal shifters as actuators and an integrated germanium photodetector (PD) positioned in one of the output ports. This architecture allows the coherent recombination of the two optical signals at the input of each MZI [3]. A lock-in control system was implemented in each actuator using the dithering technique. This scheme allows one to control each MZI independently and simultaneously (and, therefore, each GC) [4], thus allowing the modification of the shape of the radiated beam. Finally, the coherently recombined signal from the last MZI of the mesh is extracted using a vertically aligned single-mode fiber.

III. EXPERIMENTAL RESULTS

To validate turbulence-induced scintillation mitigation, we constructed an indoor FSO link emulator [Fig. 2(a)]. An SMF collimator assessed transceiver PIC reception (Tx forward) and transmission (Tx backward) capabilities under turbulent conditions. Turbulence emulation utilized a spatial light modulator (SLM) introducing a phase screen (PS) in the beam's

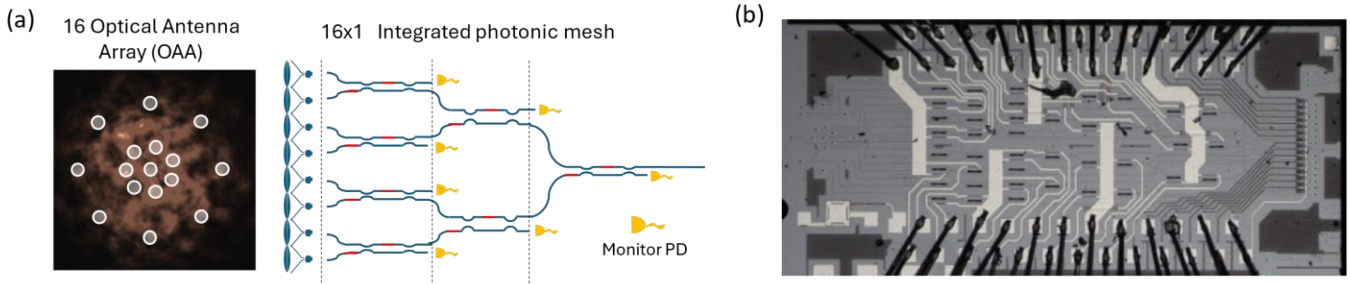

Fig. 1: (a) Schematic of the programmable photonic processor implemented with an 16x1 integrated photonic mesh. An array of 16 optical antennas (grating couplers) is used to sample the incoming turbulent beams in 16 spots. (b) Photograph of the PIC fabricated in a silicon photonic platform.

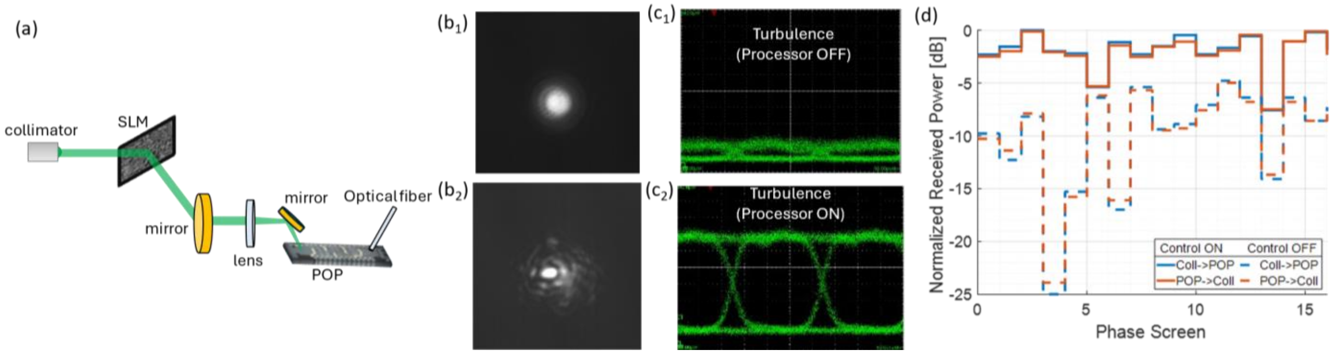

Fig. 2: (a) Schematic of the experimental setup used for the emulation of turbulence-induced scintillation on FSO beams. (b) Photograph of the transmitted beam from the collimator (b_1) before and (b_2) after the SLM. Eye diagrams of the received 5 Gbps NRZ modulated signal at the POP when the control is (c_1) OFF and (c_2) ON. (d) Normalized received optical power for Tx from the collimator to the POP (blue) and vice versa (orange) when the control is ON (solid line) and OFF (dashed line).

propagation path. PSs simulated turbulence strength at various propagation distances with C_n^2 parameter within 10^{-13} and 10^{-9} $[m^{-2/3}]$. An IR camera captured SLM effects on the beam [Fig. 2(b)]. Panel (b_1) displays the Gaussian beam (Tx forward) pre-SLM, while panel (b_2) illustrates the phase screen's impact on the Gaussian beam, distorting its shape, size, and centroid.

First, system-level measurements were conducted under various FSO link conditions using an intensity-modulated 5 Gbps OOK NRZ signal. Fig. 2(c) illustrates the received eye diagram. With the control OFF [Fig. 2(c_1)], the eye diagram closes significantly. However, when the POP is active, it compensates for relative phase differences between the signals by minimizing the received power at each integrated photodetector, thereby maximizing the output power. This compensation significantly reduces intensity fading at the photonic chip's output, resulting in the wide-open eye shown in Fig. 2(c_2).

Finally, we validated the capability of the POP to be used as a transceiver that compensates for atmospheric turbulence. Fig. 2(d) shows the normalized received power for Tx from the collimator to the mesh (blue line) and Tx from the POP to the collimator (orange line) with the control ON (solid line) and OFF (dashed line) across 16 different phase screens introduced by the SLM. With the control OFF, the average power is -15 dBm with a standard deviation of 5.28 dB. With the control ON, the average power improves to -6.1 dBm with a standard deviation of 1.77 dB. The slight residual fading is due to variations in power received by different GCs under different turbulence conditions (SLM configurations). The received power is nearly identical for both link configurations. The phase shifts applied to the MZIs to compensate for power fading were consistent across all phase screens, indicating that when used as a transceiver, the POP automatically pre-compensates for transmission by adjusting the received beam, thus eliminating the need for a return channel.

IV. CONCLUSION

In conclusion, we used a programmable photonic processor to implement an adaptive transceiver, which can be used to mitigate scintillation effects caused by atmospheric turbulence in an FSO link. The results show a significant reduction in intensity fading from beam scintillation when the transceiver is used on either the Tx or Rx side. Our experiments simulated scintillation levels comparable to those expected in outdoor links of several hundred meters. The transceiver's performance could be enhanced by increasing the number of optical antennas in the OPA and using a more complex POP, potentially enabling compensation for higher turbulence levels and extending the FSO link to several kilometers.

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