

Mitigation of Atmospheric Turbulence in an Optical Free Space Link with an Integrated Photonic Processor

F. Morichetti[1], G. Cavicchioli[1], A. Martinez[1], S. Seyedinnavadeh[1], F. Zanetto[1], C. Mazzucco[2], M. Re[2], M. Mattivi[2], F. Morandi[1], A. D'Acierno[2], U. Spagnolini[1], A. Melloni[1]
[1] *Dipartimento di elettronica informazione e bioingegneria, Politecnico di Milano, Milano, Italy*
[2] *Huawei Technologies Italia srl, Segrate, Italy*
Corresponding author: andrea.melloni@polimi.it

Abstract: Mitigation of turbulence in a Free Space Optical communication link is demonstrated using an integrated programmable optical processor. 10Gbit/s OOK signals are successfully transmitted on an indoor setup emulating hundreds of meters link. ©2022 The authors

1. Introduction

In a Free Space Optics (FSO) link, there are several phenomena that can affect and degrade the performance of the channel. Among them, atmospheric turbulence plays a relevant role and today is the main obstacle in the implementation of high bitrates reliable FSO communication systems [1]. The effect of turbulence on optical beams can be described as a random phase and amplitude modulation which results in a beam profile affected by scintillation. This random modulation reduces the coupling efficiency with the receiver and causes deep fading in the signal after the photodetector [2]. These effects can be mitigated using a multi-aperture receiver; the distorted wavefront is sampled in several points where each portion of the optical signal has its own amplitude and phase. By increasing the number of apertures, the fading probability reduces. The sampled optical signals originating from each aperture have random and uncorrelated amplitude and phase and they must be recombined coherently, but their phase randomly change in time because of turbulence, with a bandwidth several hundreds of Hz [1].

In this work, the incoming optical beam is sampled by an integrated optical phased array antenna with 16 elements and each sample is coherently combined by means of a Programmable Optical Processor (POP). The dynamic adaptive control layer can compensate the fluctuations of the incoming phase front and stabilize the link at 10 Gbit/s. The experiments are conducted indoor emulating the atmospheric turbulence with realistic intensities. The results demonstrate the effectiveness of the approach in terms of performance and footprint compared with other solutions.

2. System implementation

The proposed FSO receiver (Rx) has been designed to receive optical beams with a diameter about 40 mm and compensate for turbulence effects giving a scintillation index up to $\sigma_\mathrm{I} = 10^{-2}$, corresponding to an outdoor link of hundreds of meters length. A schematic of the prototype is shown in Fig. 1(a). The first stage is composed by a lens system which takes the incoming beam and reduces its size to match the dimension of the integrated Optical Phase Array (OPA). The POP is composed by a self-configuring binary mesh of integrated Mach-Zehnder Interferometers (MZIs). The 16 optical antennas of the OPA are connected to a distinct input optical waveguide of the POP. The POP is connected to a custom electronic board which is responsible for the self-configuration of the device. To couple a gaussian beam with a waist of 42.6 mm to an OPA with a 180 µm-diameter, an optical system consisting of a biconcave lens with a focus length of 500 mm and diameter of 50.8 mm, and a dielectric mirror has been realized. The lens focuses the beam, while the mirror is placed 45° with respect to the optical axis such that the light is reflected vertically and illuminates the OPA.

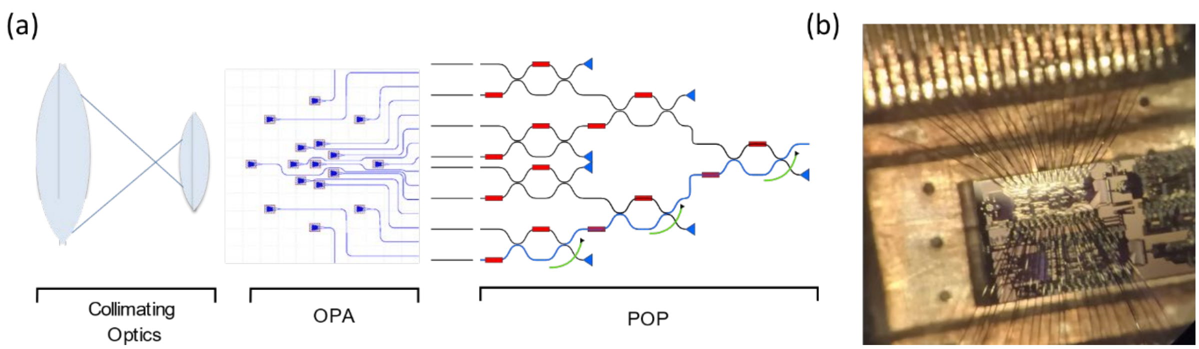

Fig. 1. (a) Scheme of the multi-aperture receiver. (b) Photo of the silicon photonic PIC with OPA and POP.

The OPA consists of a 2D array of grating couplers (GCs). The number of GCs, their distribution, and their separation distance has been set by analyzing the power coupling efficiency P_R of different geometries. When the diameter of the receiver d_R approaches the coherence radius r_0, the coupled intensity reaches a relatively high value while maintaining a low standard deviation. For larger values of d_R, signal fading increases considerably without a significant increase of P_R. Similarly, reducing d_R below r_0 is not acceptable because, even if the fading probability is low, the coupling efficiency falls rapidly. The best option is to choose an aperture whose dimension is comparable with r_0. In such conditions, the sampled optical field does not show uncorrelated phase contributions that are detrimental for the overall system performance. The OPA has been designed based on simulation results for $C_n^2 = 10^{-13}$ and $r_0 = 4$ cm. It is composed of 16 identical GCs arranged in two rings with a radius 60 μm and 180 μm respectively (Fig. 1(a)). Each CG is about 48 μm-long and 23 μm-wide, with a 24 μm-long taper and a transmittance of 60 %. The elevation angle θ is 3°, the azimuth angle ϕ is 0°, and the divergence (Phi-Theta) is 5.6°×9.8°.

The POP is a 16x1 binary mesh realized in the Silicon Photonics (SiPh) platform. It is composed by 15 MZI. Each one is endowed with two thermal shifters and one of the outputs of each MZI is connected to an integrated photodiode (PD). The POP is connected through wire bonding to a custom electronic board that reads the signal of the PDs and change the working point of the actuators. This board implements a control loop which minimizes the signal read by the PDs. In this way, the optical signals entering a MZI are coherently recombined at the output. Finally, at the output of the last MZI, the recombined signal is coupled vertically to a single-mode fiber.

3. Experimental Results

The indoor FSO link emulator, used to validate the mitigation of the turbulence effects, was built using a beam expander and a thermal gun. The beam expander generates a beam with a diameter around 5 cm. The thermal gun is used to emulate the turbulence indoor. Fig. 2(a) shows a photo of the beam in absence of turbulence and Fig. 2(b) when the gun is on. By changing the position of the gun, we were able to vary the C_n^2 from 10^{-14} to 10^{-10}. Fig. 2(c) shows the frequency spectrum of the optical signal received by an aperture of 3 m. The harmonics generated by atmospheric turbulence extend up to a frequency range of about 500 Hz, which is even more than typical values reported in the literature (300 Hz) [1].

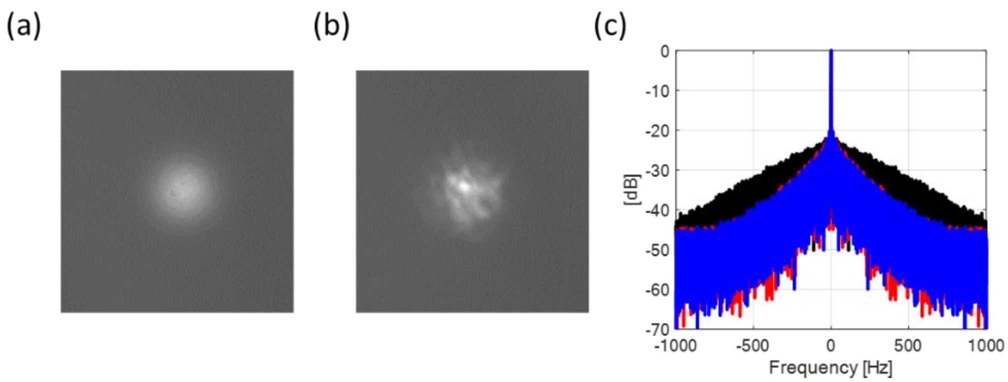

Fig. 2. Gaussian beam generated indoor (a) without turbulence and (b) with artificial turbulence. (c) power spectral density of the optical signal received by an aperture of 3 mm close to the Tx (black), after 1 m (red), after 2 m (blue).

Fig. 3.(a) shows the schematic of the employed experimental setup. To mitigate the turbulence effects, the control board applies a bias voltage to the thermal actuators placed on top of each MZI in order to minimize one of the MZI output ports. The optimization is performed using the dithering technique, that makes possible to minimize the power at a specific port of the mesh without computing its transfer function [3]. The control board performs a lock-in measurement that is selective in frequency and phase, allowing the use of a single dithering frequency for various actuators and therefore, allowing a larger control bandwidth [4]. The results shown in this section were obtained by placing the gun to emulate a turbulence with C_n^2 in the order of 10^{-12}. Due to the size of the beam and short length of the link, the wander effect was negligible.

Fig. 3(b) shows the signal acquired at the output of the POP under 3 scenarios: no turbulence induced (yellow), induced turbulence with the POP control on (orange), and induced turbulence with the control off (orange). In absence of turbulence the average received power is -24.2 dBm with a standard deviation std = 0.05 dB. When the control is OFF, the average received power is -25.1 dBm with std = 1.11 dB. The signals of the 16 GCs interact constructively or destructively depending on the random phase fluctuations caused by the turbulence. Also, some GCs may experience blackouts due to the “granularity” of the received beam. Yet, the probability that all GCs undergo some fading or that the signals’ interference led to null power at the output is very low [as seen in Fig. 3(b) and (c)]. When the control is ON, the POP compensates the relative amplitude and phase differences between the signals to maximize the output power, by minimizing the received power at each photodetector. In this case, the average received power is -24.2 dBm with a standard deviation std = 0.31 dB. The probability density function PDF is shown in Fig. 3(c). The POP with the control ON presents a narrower PDF, and also a higher bias.

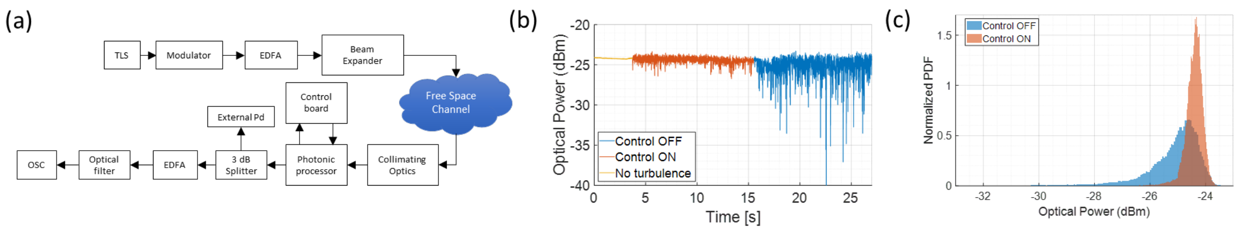

Fig. 3. (a) Schematic of the experimental setup. (b) Output signal intensity of the POP with no turbulence (yellow), with induced turbulence and control on (orange), and control off (blue). (c) PDF of the output signal with control off (blue) and on (orange).

System-level measurements have been performed using a 10GB/s OOK NRZ modulated signal for different conditions of the FSO link. The first characterization has been carried out without the artificial turbulence and without the adaptive control of the POP (Fig. 4(a)). The eye is clearly open and it has a quality factor (QF) of 5.39. When the artificial turbulence is applied to the channel without the adaptive control (Fig. 4(c)), the QF degrades to 3.77 and the eye tends to close because of the fading induced by scintillation. Finally, when the control loop is connected (Fig. 4(b)), the QF is restored to 5.32, a value comparable to the first situation, and the eye opens again. This proves that the POP is able to mitigate scintillation effects and equalizes the channel.

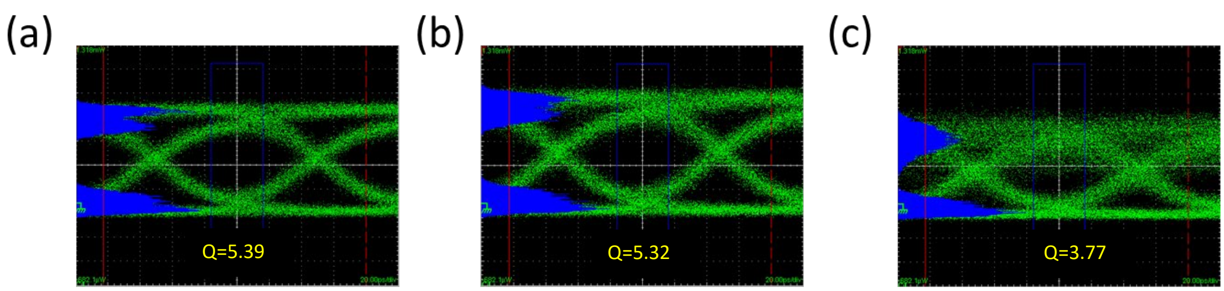

Fig. 4. Eye diagram of the received 10Gb/s signal after FSO propagation in different scenario: (a) reference, (b) presence of turbulence and adaptive control; (c) presence of turbulence without adaptive control.

ACKNOWLEDGEMENT
The research has been carried out in the framework of the Huawei-Politecnico di Milano Joint Research Lab.

References

[1] M. A. Cox, N. Mphuthi, I. Nape, N. Mashaba, L. Cheng and A. Forbes, "Structured Light in Turbulence," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 27, no. 2, pp. 1-21, March-April 2021.
[2] Xiaoming Zhu and J. M. Kahn, "Free-space optical communication through atmospheric turbulence channels," in *IEEE Transactions on Communications*, vol. 50, no. 8, pp. 1293-1300, Aug. 2002.
[3] F. Zanetto, et. al., "Dithering-based real-time control of cascaded silicon photonic devices by means of non-invasive detectors," IET Optoelectronics, vol. 15, p. 111–120, 2021.
[4] D. A. B. Miller, "Self-configuring universal linear optical component," Photonics Research, 1, 2013.