Reconfigurable Silicon-Photonic Beam Regenerator for Free-Space Optical Links

SeyedMohammad SeyedinNavadeh, Alessandro di Tria, Flavio Novelli, Francesco Zanetto, Giorgio Ferrari, Marco Sampietro, Andrea Melloni, and Francesco Morichetti

Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano, Via Ponzio 34/5, 20133 Milan, Italy
francesco.morichetti@polimi.it

2024 IEEE Photonics Conference (IPC) | 979-8-3503-6195-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/IPC60965.2024.10799873

***Abstract*— A reconfigurable photonic integrated circuit is used to regenerate free space optical beams affected by atmospheric turbulence. Signal regeneration is demonstrated using data transmission experiments at 5 Gbps.**

Keywords—Integrated Photonics, Programmable Photonic Circuits, Mach-Zehnder Interferometer Mesh, Free-Space Optical Communications

I. Introduction

In free-space optical communications, the quality of transmitted signals is degraded by the inherently dynamic nature of the channel, because of the effects of atmospheric turbulence. [1] Turbulence induces a progressive reduction of the spatial coherence of the beams, which results in a fracturing of the intensity and phase profile of the beam front, which is also know as scintillation. Since the effects of turblence increases with the propagation length, it would be useful to have optical devices capable of restoring the original shape of the beam along the link.

In this work, we report on a reconfigurable photonic integrated circuit that can be used to regenerate free space optical beams affected by atmospheric turbulence. The circuit, whcih is made of a pair of silicon photonic meshes of tuneable Mach-Zehnder interferometers (MZIs), can couple arbitrary FSO beams perturbed by atmospheric turbulence and regenerate them at the output ports [2,3]. Reported experiments show the effectivenss of the proposed FSO beam regenerator on signals modulated at 5 Gbps (OOK-NRZ).

II. Reconfigurable Silicon-Photonic Beam Regenerator

The beam regeneration concept is shown in Fig. 1(a). The free-space optical link consisting of a transmitter (Tx) and receiver (Rx) is established through sending modulated optical beams into the free-space. The perturbation present in the channel causes amplitude and phase manipulation of the wavefront which causes degradation in the received modulated signal at Rx side. A reconfigurable beam regenerator is thus advantageous for coupling the perturbed beam into a photonic chip and then regenerating another beam based on the channel condition.

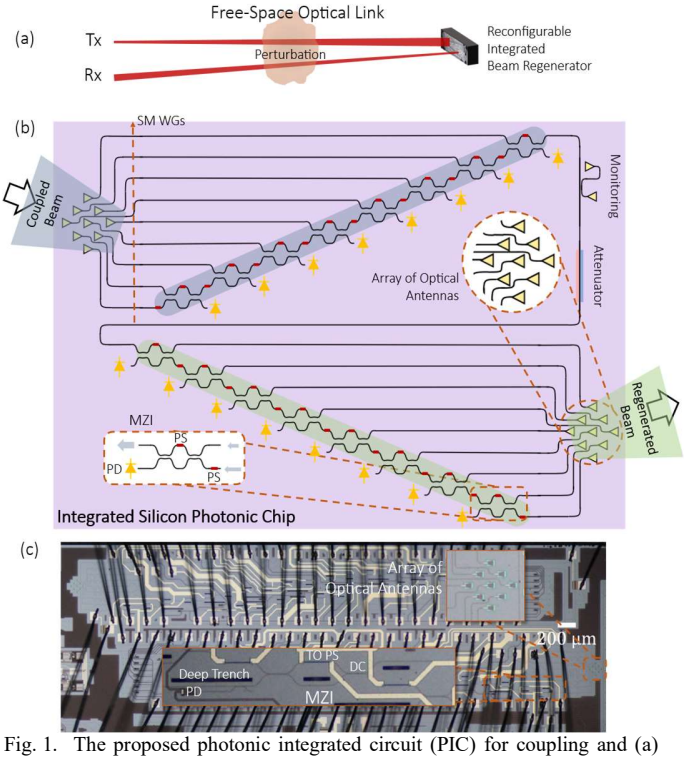

Fig. 1. The proposed photonic integrated circuit (PIC) for coupling and (a) Beam regeneration concept in free-space optical links, (b) Schematic of the integrated beam regenerator circuit consisting of two arrays of optical antennas and meshes of MZIs for beam coupling and regeneration, (c) A micro-photograph of the realized Silicon-photonic chip at a commercial foundry.

regeneration of such beams is shown schematically in Fig. 1(b). Two array of optical antennas, here realized using grating couplers, are present in the circuit; one for coupling and the other for regeneration. Input single-mode waveguides (SM WGs) of the grating couplers are connected to a mesh of Mach-Zehnder Interferometers (MZIs) which are configured in a diagonal [3]. Each MZI is realized using 50:50 directional couplers (DCs) and two phase shifters (PSs) and a photodiode is used for configuring the working point of the MZI; i.e., the output port of the MZI that is needed to be nulled is read via PD signal and a simple control feedback loop is used to tune the PSs [4]. Each contribution of the sampled coupled input beam into the SM \

979-8-3503-6195-7/24/$31.00 ©2024 IEEE
Authorized licensed use limited to: Politecnico di Milano. Downloaded on January 07,2026 at 14:04:48 UTC from IEEE Xplore. Restrictions apply.

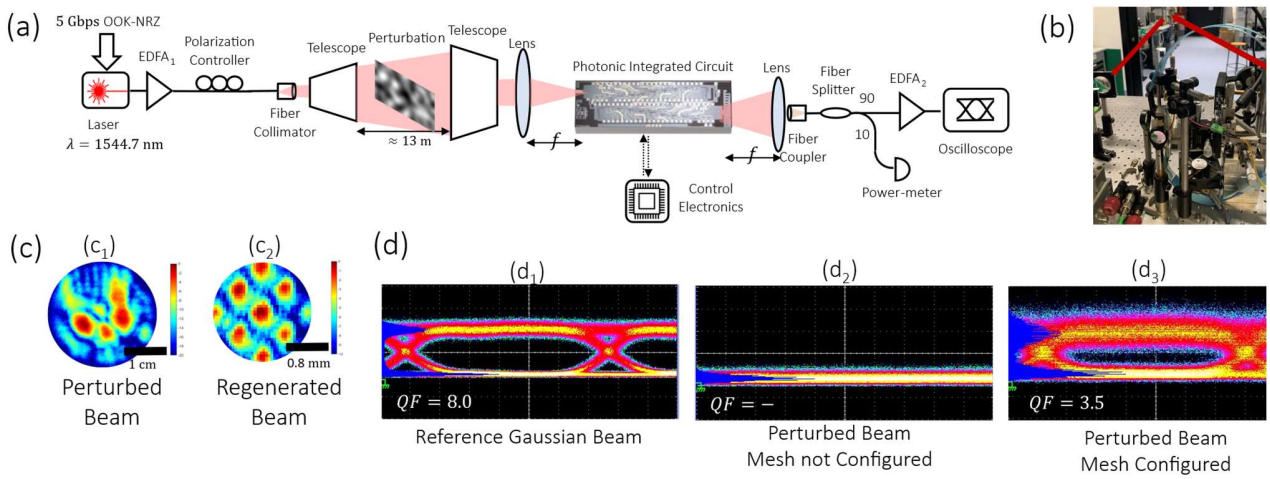

Fig. 2. (a) Schematic of the indoor optical setup for free-space link, (b) photograph of the setup in laboratory, (c) Examples of the input perturbed beams and the regenerated beams, (d) eye diagrams of 5 Gbps OOK-NRZ modulated signals in case of the reference beam (d_1), perturbed beam without configuring

WGs is therefore can coherently be summed up by tuning the MZIs in a diagonal. The circuit is mirrored and therefore another diagonal of MZI and array of optical antennas are connected to the first one and are used for regeneration of the output beam. In between two diagonals, an attenuator and S-like tapped couplers are used for monitoring reasons.

Figure 1(c) shows a micro-photograph of the realized Silicon-photonic chip which is fabricated in a commercial foundry. PSs are metallic heaters and deep trenches are used to reduce the thermal crosstalk effect.

III. Experimental Results and Indoor Demonstration

The realized Silicon-photonic chip is used for an indoor demonstration using the setup shown in Fig. 2(a). The laser is modulated at 5 Gbps (OOK-NRZ) and the signal is amplified and then sent to a fiber collimator. A polarization controller is used to adjust the state of the polarization of the beam which should be adapted to the Spatial Light Modulator (SLM) and also grating couplers. The free-space link is a folded path in the laboratory using a mirror which is about 13-m long as shown in Fig. 2(b). Two telescopes are designed and assembled to adjust the divergence of the beam at Tx and Rx sides. An SLM is used to perturb the beam propagating in the free-space. The beam sizes are adjusted to the two apertures of the PIC, i.e., antenna arrays, using two convex lenses in Fourier-transforming configuration. The regenerated beam is then coupled to another fiber coupler (collimator), and the received signal is amplified again and directed to an optical oscilloscope.

Figure 2(c_1) shows an example of the perturbed beam at the Rx telescope. The perturbation is engineered in this case to have considerable power loss (>20 dB) at the Rx power-meter (Fig. 2b). The regenerated beam is instead shown in Fig. 2(c_2). The output mesh is tuned to couple a Gaussian beam; this can be done by back propagating the beam to the aperture of the chip and tune the MZI diagonal. The far-field beam shape consists of several diffraction orders since the spacing between grating couplers of the antenna array is several wavelengths (50 µm).

Once the input mesh is configured for a reference gaussian beam (without perturbation) that is propagated through free space link, the eye diagram captured for the modulated signal is shown in Fig. 2(d_1). After perturbing the beam using the SLM, the power is lost by > 20 dB, which causes closure of the eye diagram [Fig. 2(d_1)]. If the output mesh for regeneration is kept fixed, once the input mesh is tuned for coupling the perturbed beam, the eye diagram is again retrieved as shown in Fig. 2(d_3). The loss penalty (5-8 dB) causes degradation in the quality of the signal, however the advantage of the beam regenerator chip is evident in coupling and reconstructing the output beam.

The concept of beam generator can be extended to circuits that can handle multiple modes using more MZI diagonals and applied to identify and regenerate optimal modes in FSO systems exploting spatial mode multiplexing [5].

Acknowledgment

Authors acknowledge support from the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on “Telecommunications of the Future” (PE00000001 - program “RESTART”, Structural Project “Rigoletto" and Focused Project “HePIC"). Part of this work was carried out at Polifab, the micro- and nanofabrication facility of Politecnico di Milano(https://www.polifab.polimi.it/).

References

[1] X. Zhu and J. Kahn. “Free-space optical communication through atmospheric turbulence channels”. IEEE Transactions on Communications 50, 1293 – 1300 (2002).

[2] D. A. B. Miller, “Self-aligning universal beam coupler”, Optics Express, vol. 21, no. 5, p. 6360, Mar. 11, 2013, ISSN: 1094-4087.

[3] D. A. B. Miller, “Reconfigurable add-drop multiplexer for spatial modes”, Optics Express, vol. 21, no. 17, p. 20 220, Aug. 26, 2013, ISSN: 1094-4087. DOI: 10.1364/OE.21. 020220.

[4] F. Zanetto, V. Grimaldi, F. Toso, et al., “Dithering-based real-time control of cascaded silicon photonic devices by means of non-invasive detectors”, IET Opto-electronics, vol. 15, no. 2, pp. 111–120, 2021,

[5] S. SeyedinNavadeh, et al., “Determining the optimal communication channels of arbitrary optical systems using integrated photonic processors”, Nature Photonics, Nov. 23, 2023, ISSN: 1749-4893

Authorized licensed use limited to: Politecnico di Milano. Downloaded on January 07,2026 at 14:04:48 UTC from IEEE Xplore. Restrictions apply.