This article has been accepted for publication in IEEE Summer Topicals Meeting Series 2024 (paper MB3.3)

Optical Fi-Wi-Fi Bridge with 32-Port Focal Plane Fiber Array for Robust Waveguide Coupling

Bernhard Schrenk
Center for Digital Safety and Security
AIT Austrian Institute of Technology
Vienna, Austria
bernhard.schrenk@ait.ac.at

ABSTRACT

An all-fiber focal plane beamformer with 32 fine-pitched antenna elements and 1×32 switch is employed for robust coupling of light between two optical single-mode waveguides over a free-space link. The penalty in bit error ratio due to an angular receiver misalignment can be fully mitigated.

I. INTRODUCTION

Optical wireless communication is recognized as a natural extension of the fiber continuum when it comes to transmission capacity and spectral bandwidth [1]. It can deliver a vastly superior performance compared to radio-based wireless systems, but is also constrained by its line-of-sight requirement and poor alignment tolerances when establishing a free-space optical bridge between two fiber-based channels. While opto-mechanic pointing and tracking systems [2] are well suited to correct large initial alignment errors in free-space optical links while further expanding the field-of-view for its demarcation points [3], their bulky and costly nature and the arguably slow response might render them as sub-optimal when it comes to highly directed point-to-point beams with non-moving targets. Various schemes have been proposed to address this implementation challenge: Fast 2D detector arrays can ensure an alignment-tolerant reception [4]. Optical beamformers can additionally retain a transparent rather than a translucent configuration by supporting the coupling of light to a receiving waveguide. This is accomplished by integrating a large number of antenna elements to shape the response of the receiving optical head. Demonstrations for such works include phased-array configurations [5], wavelength-assisted beam deflection [6] and wavelength-agnostic focal plane arrays (FPA) [7]. Although PIC-based beamformers bear the potential to scale up in near future, they are often subject to complex tuning and calibration mechanisms, optical loss and an increased assembly burden when being interfaced with single-mode fiber access.

This work introduces a wavelength-agnostic fiber-based beamformer with 32 antenna elements, which will be employed to eliminate an angular pointing error for the receiver-side termination point of a wireless bridge between two fiber ports.

II. ALL-FIBER FOCAL PLANE ARRAY

The FPA concept employs an array of antenna elements at the focus of the optical telescope system that acts as demarcation point between a fiber-based waveguide and a free-space optical link. These antenna elements can be detectors if a direct translation to the electrical domain is desired, but can instead support a more transparent flavor for the fiber-to-air interface when a waveguide is used as the antenna element. If the FPA is applied to the transmitting telescope, the waveguide that is fed within the array will determine the offset for the illumination of the telescope lens with respect to its center, and hence the angle at which the light is emitted – without physically moving the telescope. Vice versa, if the FPA concept is applied to the receiving telescope, a certain waveguide within the array will sink the incoming light, depending on its angle of incidence. Proven optical switching technology can then be applied to select the corresponding array waveguide in either scenario.

Here, an all-fiber FPA concept will support the receiving terminal of a Fi-Wi-Fi bridge (Fig. 1). A collimated beam is emitted by the transmitter telescope, which is subject to a single-element feed. The robustness of the receiver to a misalignment in its pointing angle α between the center of its field-of-view (FoV) and the incident beam is supported by a FPA with fine-pitched fiber array so that the fiber continuum within a high-capacity single-mode infrastructure is retained while minimal trade-offs have to be made for the antenna element spacing.

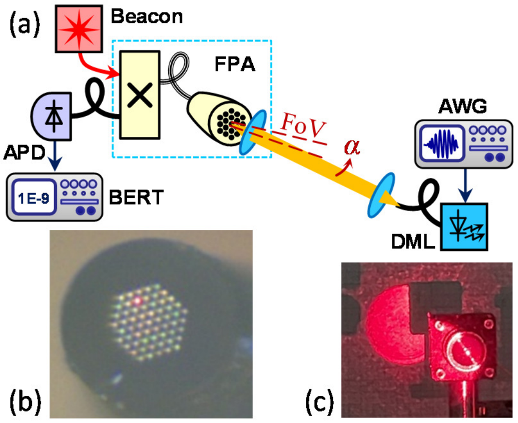

Fig. 1. (a) Optical wireless bridge terminator assisted by focal plane array to ensure robust air-to-fiber coupling. (b) fine-pitched fiber array of the FPA with port 21 illuminated in red. (c) tracking of the angular alignment error for the receiving telescope through red beacon laser at the transmitter telescope.

III. EXPERIMENTAL FI-WI-FI BRIDGE

The experimental setup is included in Fig. 1. A fiber-coupled directly modulated laser (DML) at 1553.73 nm is used as transmitter for a 10 Gb/s on-off keyed data signal. A collimated beam with a waist diameter of 7 mm is formed to transmit the data over a free-space lab link with a length of 3 m. The FPA front-end at the receiver is comprised of the 32-port fiber array and a coupling lens, centered to port 1 of the array. The fine-pitched multi-port configuration features a hexagonal lattice for packing fibers over its cross-section, as shown in Fig. 1(b). The fiber cores are compatible with ITU-G.652B single-mode fiber and the cladding of the fibers has been thinned to allow for a reduced core-to-core spacing of 37 µm. An optical 1×32 switch based on micro-electro-mechanic system (MEMS) technology completes the FPA. It chooses the optimal antenna element for signal reception based on the photocurrent of the avalanche photodetector (APD) which receives the signal for a bit error ratio (BER) measurement. A red beacon laser has been counter-injected into the optical wireless link to assist the tracking of the angular alignment error for the receiving telescope.

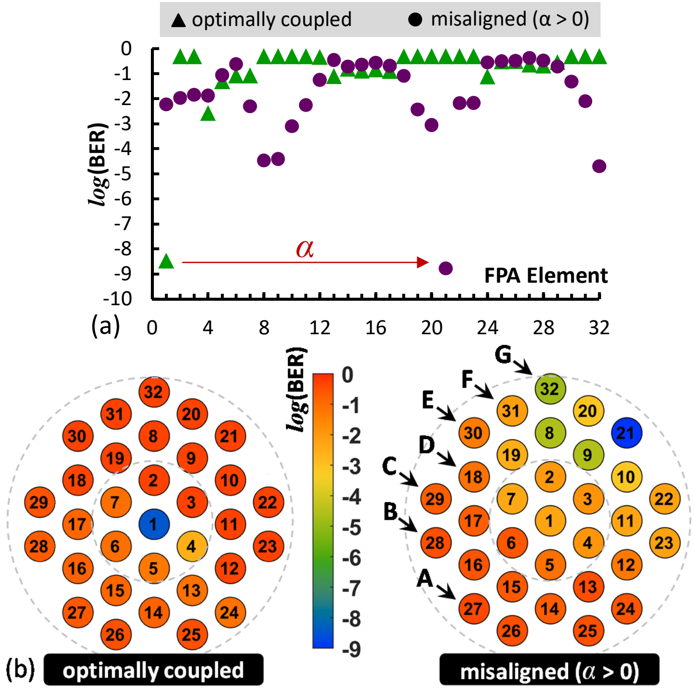

Fig. 2. (a) BER performance for all FPA antenna elements under perfectly aligned and misaligned optical receiver head. (b) BER distribution over cross-section of receiver-side FPA under condition of misalignment and corresponding eye diagrams for all antenna elements.

IV. RESULTS AND DISCUSSION

Figure 2(a) presents the BER for all FPA antenna elements when transmitter and receiver are aligned to each other (▲) and for the case that the receiver is misaligned by $\alpha = 2$ deg (●). This error in angle causes an offset in the receiver's field-of-view, as can be seen in Fig. 1(c) through the misaligned reverse pointing beam of the red beacon emitted by the receiver-side FPA.

For a perfect alignment the center element (port **1**) shows the best coupling and thus the lowest BER of 3.4×10^{-9} (▲). All other ports have a considerably higher BER. When introducing an angle error α in the alignment of the receiver, the received beam is focused away from the center and the BER increases to 5.9×10^{-3}. However, it is possible to recover a similarly good reception condition when retrieving the signal from an antenna element farther from the center – without necessitating a mechanical adjustment of the optical receiver head. For the set angle error α, port **21** collects the data signal for reception at a BER of 1.7×10^{-9} (●), which means that no penalty is incurred.

Figure 2(b) maps the logarithmic BER over the cross-section of the FPA. Results are presented for the optimally coupled and the misaligned receiver scenarios. The movement of the focal point towards the rows **F** and **G** upon misalignment can be noticed, as it is also evidently confirmed through the 32 eye diagrams collected over all FPA antenna elements (Fig. 3).

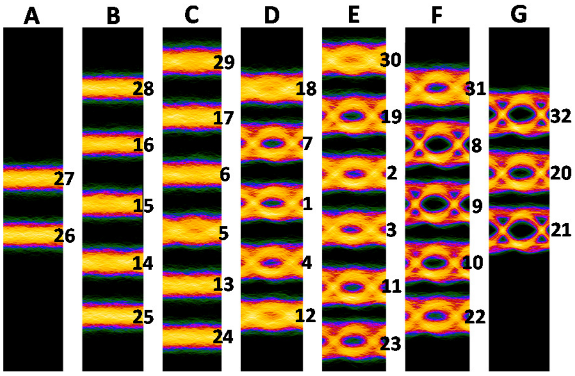

Fig. 3. Eye diagrams retrieved at all 32 FPA elements for misaligned case.

V. CONCLUSION

A simple fiber-based FPA with 32 fine-pitched (37 µm) antenna elements has been demonstrated to mitigate an alignment penalty in a fiber-to-fiber optical wireless bridge serving 10 Gb/s data transmission. Besides the use of a colorless optical MEMS switch, the concept relies on no more than passive fiber components and thus permits wideband operation. Scaling towards a larger FPA dimension and the use of multiple antenna elements for the simultaneous shaping of co-existing pencil- (waveguide-to-waveguide) and wide- (waveguide to free-space detector) beams are left for future work.

REFERENCES

[1] M.Z. Chowdhury, M.T. Hossan, A. Islam, and Y.M. Jang, "A Comparative Survey of Optical Wireless Technologies: Architectures and Applications," *IEEE Access*, vol. 6, pp. 9819-9840, Jan. 2018.

[2] Y. Kaymak, R. Rojas-Cessa, J. Feng, N. Ansari, M.C. Zhou, and T. Zhang, "A Survey on Acquisition, Tracking, and Pointing Mechanisms for Mobile Free-Space Optical Communications," *IEEE Comm. Surveys & Tutorials*, vol. 20, no. 2, pp. 1104-, 2018.

[3] A. Bekkali, H. Fujita, and M. Hattori, "New Generation Free-Space Optical Communication Systems With Advanced Optical Beam Stabilizer," *J. Lightwave Technol.*, vol. 40, no. 5, pp. 1509-1518, Mar. 2022.

[4] T. Umezawa *et al.*, "FSO Receiver With High Optical Alignment Robustness Using High-Speed 2D-PDA and Space Diversity Technique," *J. Lightwave Technol.*, vol. 39, no. 4, pp. 1040-1047, Feb. 2021.

[5] M.C. Shin *et al.*, "Chip-scale blue light phased array," *Opt. Lett.*, vol. 45, no. 7, pp. 1934-1937, Apr. 2020.

[6] T. Koonen, F. Gomez-Agis, F. Huijskens, K.A. Mekonnen, Z. Cao, and E. Tangdiongga, "High-Capacity Optical Wireless Communication Using Two-Dimensional IR Beam Steering," *J. Lightwave Technol.*, vol. 36, no. 19, pp. 4486-4493, Oct. 2018.

[7] L. Ciu *et al.*, "Two-dimensional scanning of silicon-based focal plane array with field-of-view splicing technology," *Opt. Expr.*, vol. 31, no. 2, pp. 1464-1474, Jan 2023.

ACKNOWLEDGEMENT

This work has received funding from the SNS JU under the EU's Horizon Europe research and innovation programme (Grant Agreement No. 101139182).