

Article

Multi-Actuator Lens Systems for Turbulence Correction in Free-Space Optical Communications

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Abstract

The implementation of efficient free-space channels is fundamental for both classical and quantum free-space optical (FSO) communication. This can be challenging for fiber-coupled receivers, due to the time variant inhomogeneity of the refractive index that can cause strong fluctuations in the power coupled into the single-mode fiber (SMF), and requires the use of adaptive optics (AO) systems to correct the atmospheric-induced aberrations. In this work, we present two adaptive optic systems, one using a fast-steering prism (FSP) for the correction of tip-tilt and a second one based on a multi-actuator deformable lens (MAL), capable of correcting up to the third order of Zernike's polynomials. We test both systems at telecom wavelength both with artificial turbulence in the laboratory and on a free-space channel, demonstrating their effectiveness in increasing the fiber coupling efficiency.

Keywords: adaptive optics; deformable lens; free-space optical communication

1. Introduction

Free-space optical (FSO) communication presents some undeniable advantages with respect to radio frequency (RF) links for the implementation of point-to-point communication, in terms of both transmission efficiency and security. The high frequency of optical beams leads to high speed modulation, allowing higher data rates and low beam divergence, which maximizes the power intercepted by the legitimate receiver, increasing both transmission efficiency and security. The use of optical frequencies can also be exploited for the use of quantum key distribution (QKD), which allows the exchange of secret keys with unconditional security [1].

The importance of high-speed communication justifies the effort spent on the development of new devices and techniques for pushing the communication towards its fundamental limits [2]. This research is mainly focused on fiber systems, which means that the best-performing communication devices are based on single-mode fiber (SMF) technology and work at the telecom wavelength. For the cases where the installation of optical fibers is not possible, for geographic or economic reasons, FSO communication represents a good alternative [3]. However, the free-space channel is affected by atmospheric turbulence, which severely decreases the coupling efficiency (CE) into the SMF. This requires the use of adaptive optics (AO) for partially compensating the effects of the turbulence and increasing the amount of light coupled into the fiber [4–10].



Received: 27 May 2025

Revised: 7 August 2025

Accepted: 18 August 2025

Published: 29 August 2025

Citation: Schiavon, M.; Vanzo, A.; Campaci, K.; Marulanda Acosta, V.; Bonora, S. Multi-Actuator Lens Systems for Turbulence Correction in Free-Space Optical Communications. *Photonics* **2025**, *12*, 870. <https://doi.org/10.3390/photonics12090870>

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The working principle of AO systems consists in measuring wavefront aberrations and correcting it using active optical elements [11]. The typical AO system works using reflecting elements, such as a fast-steering mirror (FSM) for the correction of the first order of the turbulence (tip–tilt) and a deformable mirror (DM) for the correction of higher orders. The use of transmitting elements, on the other hand, could open the way to more compact systems, which represents a very promising feature for FSO systems. The use of a multi-actuator deformable lens (MAL) for coupling into an SMF has already been demonstrated at visible wavelengths [12]. However, the use of such devices for FSO communication requires a study of its performance at telecom wavelength, in which high-speed telecommunication devices work.

In this article, we investigate the performance of two different AO systems, based on transmitting devices, which work at telecom wavelength. The first system is based on a fast-steering prism (FSP) and can correct the first order of the turbulence (tip–tilt). The second system uses a MAL, which is capable of correcting up to the fourth order of the turbulence. Both systems are tested using induced atmospheric turbulence in the laboratory, and the performance of the second one is also assessed on a 100 m ground-to-ground free-space channel.

2. Materials and Methods

2.1. The Fast-Steering Prism

The optical setup used to test the performance of the FSP is shown in Figure 1.

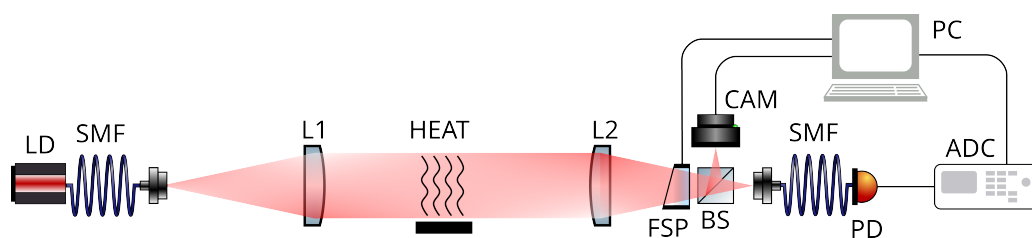


Figure 1. Optical setup used for the test of the FSP in the laboratory.

A laser diode (LD) at telecom wavelength $\lambda = 1550$ nm (MMC-GASFP-V Mini Media Converter, FS.COM GmbH, Karlsfeld, Germany), coupled to an SMF of numerical aperture $NA = 0.14$ and mode field diameter $MFD = 10.4$ μm , is collimated into a beam of diameter 50.8 mm (Rayleigh length $z_R > 1.6$ km) using a lens with a focal length of 300 mm (L1). The beam is propagated on the optical bench for a distance of around 2 m, with an electric heater (HEAT) placed in the middle of the path to generate the turbulence. More details about the turbulence generation and characterization are given in Section 3.1. The beam is collected by the receiving telescope, consisting of a lens of diameter 50.8 mm and focal length 300 mm, which focuses it into an SMF ($NA = 0.14$; $MFD = 10.4$ μm). The FSP is placed between the lens L2 and the fiber, before an unbalanced beam splitter (BS) that sends 70% of the light to the fiber and 30% to a short-wave infrared (SWIR) camera (CAM). The camera (FirstLight C-RED 3) has a full-frame rate of 600 FPS and is linked to the control computer (PC) using a USB 3.0 connection. The images are processed using the PhotonLoop software 2.2.3 by Dynamic Optics [13], which determines the centroid position through a weighted center of gravity algorithm. This position serves as an error signal for computing the voltage to be applied to the FSP via a piezo stack driver (Dynamic Optics srl, Padova, Italy). A proportional–integral control system is employed in this process. The FSP, developed at the CNR-IFN laboratory [14], is composed of two glass windows with a dielectric gel in between. The glass surfaces are uncoated for a total transmittance of about 85%. The first window is fixed, while the second one can be tilted by 3 amplified

piezoelectric actuators. The prism has a clear aperture of diameter 23 mm and it can reach up to ± 2.2 mrad of optical tilt. It presents a response time of about 400 μ s and a minimum resonance frequency at about 400 Hz; see a photo and schematic of the FSP in Figure 2. The head of the fiber is mounted on a manual x-y stage and its position along the optical axis is controlled by a motorized translation stage. The power collected by the fiber is measured by a photodiode (DET01CFC InGaAs Biased Detector, Thorlabs Inc., Thorlabs GmbH, Bergkirchen, Germany), whose output, on a 100 k Ω load, is read using a USB-6009 DAQ (National Instruments) analog-to-digital converter (ADC). The CE is measured as the ratio between the power read by the photodiode and the power before the fiber, measured using a powermeter.

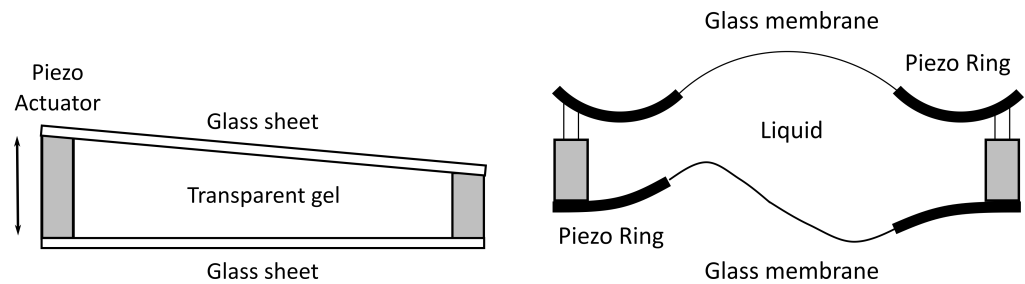


Figure 2. (Left) Schematic representation of the FSP. The device consists of two glass sheets with a transparent gel in between. The refractive index of the gel matches that of the glass. One of the glass membranes is fixed while the other is tilted by using amplified piezoelectric actuators. (Right) Schematic representation of the MAL. The device is composed by two glass thin membranes with a transparent liquid in between. Two rings of piezoelectric actuators can deform the membranes, allowing for the reproduction/correction of up to the 4th order of Zernike polynomials.

2.2. The Multi-Actuator Lens

The MAL was tested using the optical setup shown in Figure 3.

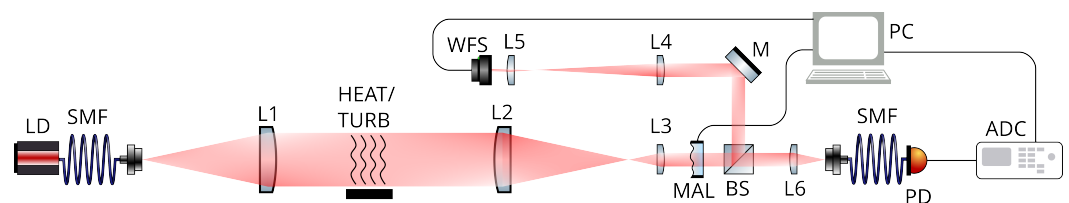


Figure 3. Optical setup used for the test of the MAL in the laboratory.

The transmitting system used for testing the performance of the MAL is the same as that described in Section 2.1, producing a collimated beam of diameter 50.8 mm that propagates on top of an electric heater. See Section 3.1 for further details on the characterization of the generated turbulence. The receiving system is a Keplerian telescope, composed of a first lens of diameter 50.8 mm and focal length 300 mm (L2) and a second lens of focal length 60 mm (L3) that reduces the diameter of the beam to 10.2 mm. The MAL is positioned at the point conjugate to L2, 74 mm behind L3. After the MAL, an unbalanced beam splitter sends 10% of the light towards the wave-front sensor (WFS) and 90% of the light towards the SMF. The WFS is a Shack–Hartmann built using a SWIR camera (FirstLight C-RED 3, Oxford Instruments) with a full-frame rate of 600 FPS, and an array of 6 by 6 microlenses with a focal length of about 5.6 mm and a pitch of 250 μ m. The WFS is placed after a second Keplerian telescope with lenses of focal length 300 mm (L4) and 40 mm (L5), in the point conjugated with the MAL. The beam is focused into the SMF with a lens of focal length 70 mm (L6). Similarly to the system described in Section 2.1, the head of the fiber is mounted on a manual x-y stage and the position on the optical axis is controlled by a

motorized stage. The measurement of the coupled power and the calculation of the CE is performed as described in Section 2.1.

The MAL [15], produced by Dynamic Optics, consists of two thin glass windows, each 150 μm thick, with a piezoelectric actuator ring attached to each. The space between the windows is filled with a transparent gel. Each piezo ring is divided into 9 independently actuated sectors and is bonded to its respective glass window, forming a bimorph structure that causes the glass to bend when voltage is applied. One of the glass windows is fixed at the edges to the surrounding structure, while the other is free to move. As a result, the actuators on the two rings deform the glass differently—one set pushes outward while the other pushes more inward (see schematic in Figure 2). The first window is used to generate defocus and astigmatism while the second one generates coma and secondary astigmatism. The clear aperture of the MAL is 10 mm and the response time is lower than 2.5 ms. The actuators are controlled by a high-voltage driver (Dynamic Optics PZTMini) that can provide up to 125 V; see the schematic of the MAL in Figure 2. The driver is controlled by the Dynamic Optics PhotonLoop software, which analyzes the wavefront images read by the WFS at a rate of 600 FPS and calculates the output voltages that are sent to the MAL [13].

The MAL was also tested on the 100 m ground-to-ground channel shown in Figure 4. Both the transmitter and the receiver used the setup shown in Figure 3.

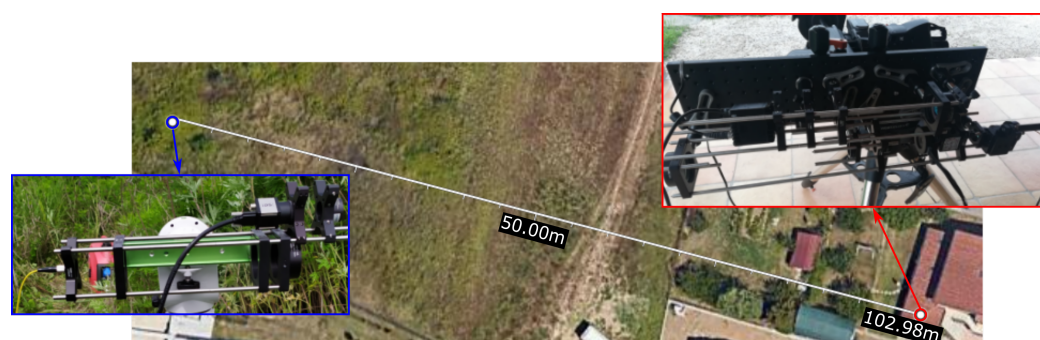


Figure 4. The ground-to-ground channel on which the MAL was tested, with a photo of the transmitting (left) and of the receiving (right) system.

The transmitter is mounted on a motorized tripod (SUNGT Solar Altazimuth Mount, Sky-Watcher), and a camera (UI-3060CP-M-GL, IDS, OnOptics!, Lentate sul Seveso (MB), Italy), combined with an achromatic lens with a focal length of 100 mm, is used to provide a coarse pointing system towards the receiver, which is also mounted on a motorized tripod (CGX equatorial mount and tripod, Celestron).

3. Results

3.1. Turbulence Characterization

The heater is used at three power settings to generate turbulence with different statistics. Values of D/r_0 are obtained by fitting the RMS error of Zernike coefficient distribution with the expected distribution assuming Kolmogorov turbulence and following Noll's results [16]. The experimental RMS errors do not follow Kolmogorov distribution, as the tilt is significantly lower than expected by the model. However, by fitting only the RMS errors of the orders higher than tilt, it is possible to estimate an approximated value of the D/r_0 parameter. This discrepancy is anticipated, as the link is horizontal, whereas the theoretical model is based on Kolmogorov turbulence theory, which applies to vertical laser propagation through the atmosphere. As such, some divergence from the theoretical predictions is to be expected. Low-to-medium turbulence (power 2/5) corresponds to $D/r_0 = 1.14 \pm 0.05$, medium turbulence (power 3/5) corresponds to $D/r_0 = 4.9 \pm 0.3$ and

high turbulence to full strength (power 5/5) corresponds to $D/r_0 = 6.2 \pm 0.3$. Estimation of D/r_0 is also carried out for field acquisitions under daytime turbulence and with a fire source located below the beam. The resulting fits are shown in Figure 5. The power spectral densities (PSDs) of both the total RMS phase error and the Zernike modes of turbulence are analyzed to assess the temporal characteristics of the turbulence, both for the generated and the on-field cases. The results are presented in Figure 6. Across all acquisitions, the PSD of the total phase error does not exhibit the expected behavior predicted assuming Kolmogorov turbulence theory — namely, a $\sim f^{-2/3}$ trend at low frequencies (where tilt dominates) and a $\sim f^{-8/3}$ trend at higher frequencies [17]. Furthermore, the Zernike tilt PSD deviates from the expected $\sim f^{-17/3}$ trend, as described in [18]. As a result, estimating the knee-frequency of the power spectrum and thus the corresponding apparent wind velocity is neither feasible nor meaningful. This analysis indicates that neither the generated turbulence nor the turbulence from the horizontal on-field link conforms to the temporal model assuming Kolmogorov theory.

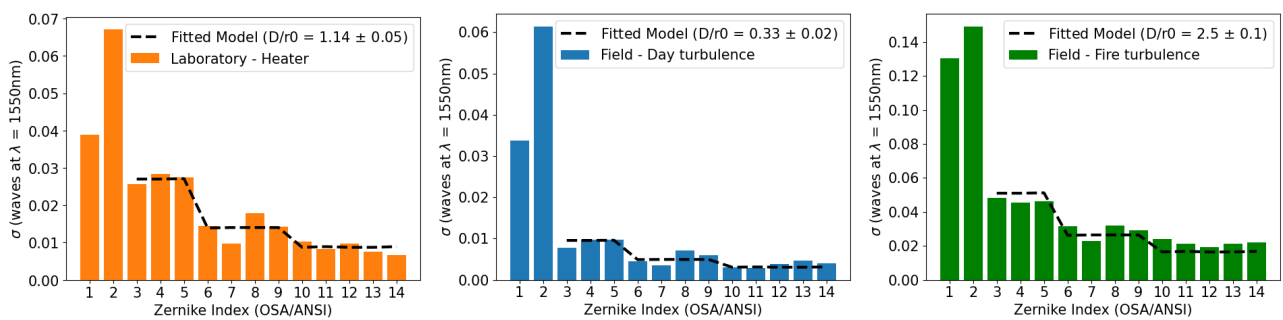


Figure 5. Standard deviations of the Zernike modes and fit results using the Kolmogorov turbulence model (excluding the tilt RMS error) for (left) the laboratory experiment with the heater at a strength of 2/5, (center) the free-space experiment, and (right) the free-space experiment with a fire under the optical link.

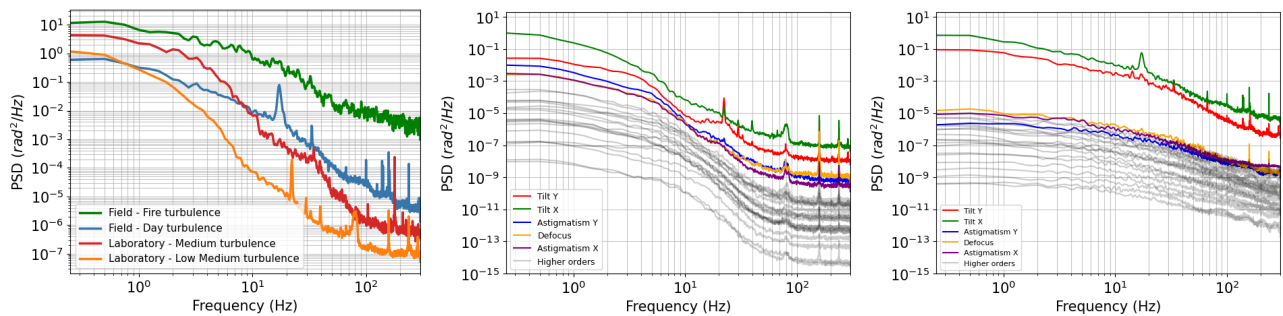


Figure 6. (Left) PSDs of the mean squared error of phase for different acquisitions; (center) PSDs of the Zernike modes with low-to-medium turbulence generated with the heater; (right) PSDs of the Zernike modes of the on-field acquisition with day turbulence.

3.2. Laboratory Experiments

The coupling efficiency with the FSP was measured with different levels of turbulence, with medium turbulence corresponding to half strength of the heater ($D/r_0 \approx 4.9$) and high turbulence to full strength ($D/r_0 \approx 6.2$). Figure 7 shows the most significant results: the FSP is able to reduce the X and Y average tilt coefficient to less than 10^{-5} waves (center plot) and their standard deviations to less than 0.1 waves (right plot) for both tested turbulence strengths. However, as evident from the left histogram of Figure 7, this translates to an improvement in the probability distribution of the coupling efficiency only for the medium turbulence, while for the high turbulence both the non-corrected and corrected case have an exponential probability distribution, with a higher average value in the latter. This is

due to the presence of higher-order aberrations that the FSP is not able to compensate, especially in the high-turbulence case.

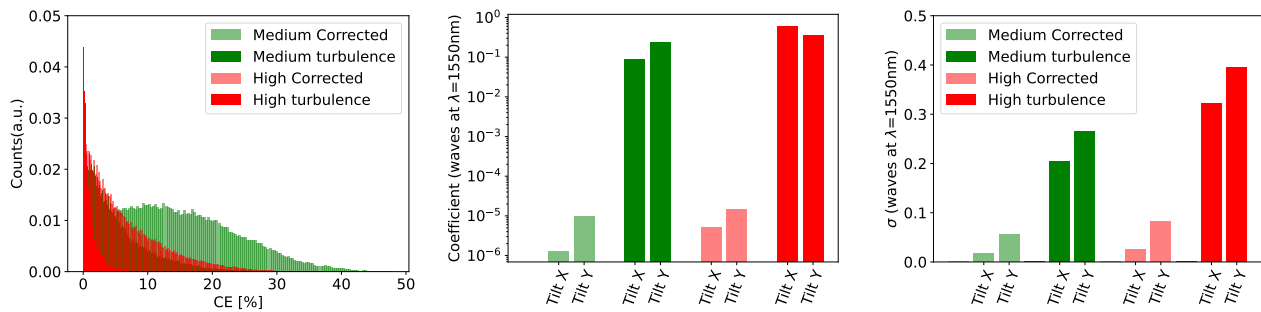


Figure 7. (Left) Coupling efficiency measured with the system with FSP. Different coupling efficiencies refer to acquisitions with different level of turbulence: medium turbulence, not corrected (0.05 ± 0.05); medium turbulence, corrected (0.15 ± 0.09); high turbulence, not corrected (0.01 ± 0.01); high turbulence, corrected (0.07 ± 0.06). (Center) Mean tilt values of the acquisitions. Y-axis is logarithmic. (Right) Standard deviations of the tilt of the acquisitions.

The coupling efficiency with the MAL correction was measured with different levels of correction: tip and tilt modes, modes up to the first order, modes up to the third order. Figure 8 shows the results of the experiment for a low-to-medium turbulence level, corresponding to a little less than half strength of the heater ($2/5$, correspondent to $D/r_0 = 1.14 \pm 0.05$). As expected, the coupling efficiency increases with the order of modes corrected, while the root mean square error of the phase and the standard deviation of the Zernike modes that describe the phase at the receiver decrease. The results show that the correction of aberrations with the MAL increases the fiber coupling efficiency of single-mode fiber injection from about 5% in the absence of correction to more than 20%.

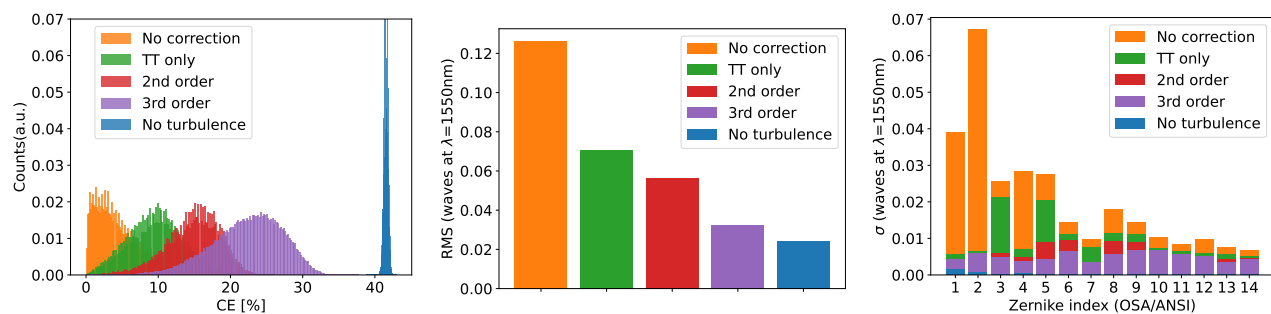


Figure 8. (Left) Coupling efficiency measured with the system with MAL. Different coupling efficiencies refer to acquisitions with different levels of correction: no correction (0.05 ± 0.04), correction of tip–tilt only (0.10 ± 0.04), correction of Zernike modes up to 2nd order (0.15 ± 0.04), correction of modes up to 3rd order (0.22 ± 0.05), and closed loop with no turbulence generated (0.415 ± 0.003). (Center) Mean RMS of the acquisitions. (Right) Standard deviations of the Zernike modes of the acquisitions.

3.3. Field Test

The field test took place on the 18 and 19 May 2023, two cloudy late-spring days characterized by particularly still air. The acquisitions were taken during the late afternoon and were characterized by very mild turbulence, lower than the low-to-medium turbulence level used to test the MAL in the laboratory. For this reason, we introduced artificial turbulence by making a fireplace below the optical path, around 20 m before the receiver. This generated strong turbulence which allowed us to test the operation of the MAL under different turbulence regimes on a real free-space optical channel.

The results in Figure 9 show that the MAL is able to reduce the root mean square error and increase the coupling efficiency in both turbulence configurations. Despite the lower improvement in the coupling efficiency with respect to the laboratory experiment, due to the worse condition for the optimization of the coupling efficiency, it is still possible to see a passage from a long-tail probability distribution to a Gaussian distribution. This effect is less evident for the artificial turbulence generated with the fire below the optical path, since the corresponding turbulence is characterized by a stronger weight of the higher orders that the MAL is not able to correct. However, the MAL is still able to increase the mean coupling efficiency and to strongly reduce the effect of fadings in the optical channel, thus also providing a clear advantage in the case of strong turbulence.

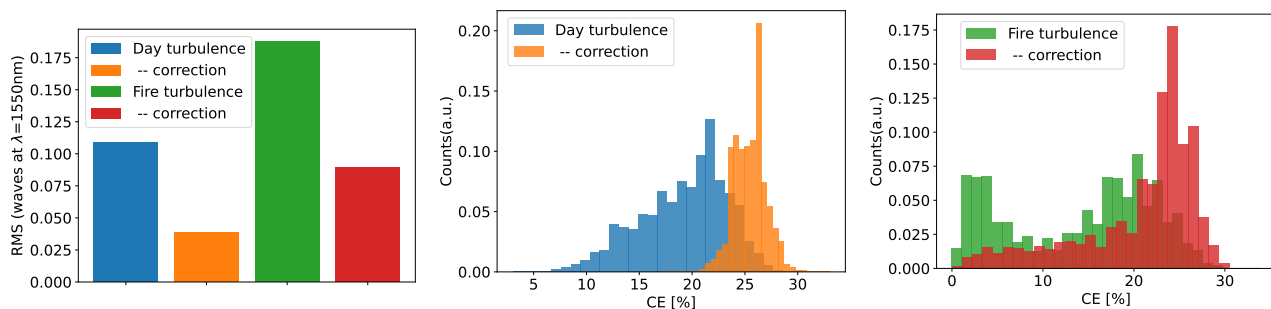


Figure 9. (Left) Mean RMS of the acquisitions with the late-afternoon turbulence (19 May 2023 at 17:55) and with the fire-induced turbulence (19 May 2023 at 18:25). (Center) Coupling efficiency with the late-afternoon turbulence and no correction (0.19 ± 0.04) and correction up to the 3rd order (0.25 ± 0.01). (Right) Coupling efficiency with the fire-induced turbulence and no correction (0.14 ± 0.08) and correction up to the 3rd order (0.21 ± 0.07).

4. Discussion

The measurements presented in the previous section show that both the FSP and the MAL are effective in reducing the effect of the free-space channel turbulence and consequently increasing the coupling efficiency into the SMF of an optical beam at telecom wavelength.

The FSP is effective for correcting the average tip-tilt fluctuations of the optical wave-front for a large range of turbulence. This, however, brings an improvement in the coupling efficiency only for moderate turbulence levels, due to the presence of higher orders of turbulence that the prism is not able to correct.

This problem is mitigated by the MAL, which can correct the turbulence up to the 3rd order of Zernike. This system brings a considerable improvement in the coupling efficiency for moderate turbulence levels both in the laboratory and in a real free-space channel. A further confirmation of its potentiality comes from its test in a real free-space channel with fire-generated turbulence, where the slight improvement in the coupling efficiency is accompanied by a drastic reduction in channel fadings.

Figure 5 shows the characterization of the channel used for testing the devices through the measurement of the standard deviation of the Zernike modes. The turbulence is highly anisotropic, as shown by the different standard deviations of the tip and tilt coefficients. In the laboratory experiment, the anisotropy is due to the strong temperature difference between the surface of the heater, placed just below the optical channel, and the rest of the room, causing a strong vertical air current. The free-space experiment took place in a channel located a few meters above grassy ground, during a warm cloudy day with slight rain around noon. These conditions are a possible explanation of the observed anisotropy, due to the vertical air flow caused by the evaporation of the humidity in the grass, combined with an absence of horizontal winds. The figure also shows how the presence of a source of

heat just below the optical channel is accompanied by a strong influence of the higher-order Zernike modes. Since these channels might not be representative of all the configurations in which such devices might be of interest, a more complete study of their performance would require the implementation of controlled turbulence levels using a fully characterized turbulence simulator [19]. We nevertheless attempted to estimate the D/r_0 parameter by fitting the data using the Kolmogorov turbulence model, although it was originally developed to describe turbulence in vertical links or observations rather than in horizontal links (see Figure 5). Reflective devices like FSMs and DMs, that are well established in astronomical and free-space optics applications, offer high precision, wide dynamic range, and higher-order aberration correction. However, they often require complex relay optics and occupy larger volumes. In contrast, our system, based on transmitting elements (FSP and MAL), provides a significantly more compact and integrated solution, which is especially advantageous in applications with strict space or weight constraints. While the correction performance of the MAL is currently limited to lower-order Zernike modes compared to high-actuator-count DMs, the simplicity, alignment tolerance, and ease of integration of transmissive AO systems make them attractive for fiber coupling tasks in short- to medium-range FSO links.

5. Conclusions

In this work, we show that transmissive elements can be employed for the construction of very compact receiving systems for small-aperture telescopes at telecom wavelengths. The FSP has proven to be the most interesting choice if simplicity is required, at the expense of a lower coupling efficiency, especially for strong turbulence. The MAL, on the other hand, has shown good performance in both the laboratory and the free-space channel, with a consistent increase in the coupling efficiency in the case of moderate turbulence and a reduction in the fadings for high turbulence. This article shows that both devices represent convenient solutions for the implementation of optical communication on short free-space channels. Their use on longer ground-to-ground channels or for satellite communication requires further investigation and is left for future work.

Author Contributions: Conceptualization, M.S., A.V., K.C. and S.B.; Methodology, M.S., A.V., K.C., V.M.A. and S.B.; Investigation, M.S., A.V., K.C., V.M.A. and S.B.; Writing—original draft, M.S., A.V. and V.M.A.; Writing—review & editing, S.B.; Supervision, S.B.; Funding acquisition, M.S. and S.B. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results has received funding from the European Union Horizon 2020 under Grant Agreement n°825051. M. S. acknowledges funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 101082596 (project QUDICE).

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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