Experimental Demonstration of Adaptive-Optics-Based Turbulence Mitigation in a Mode-Multiplexed Free-Space Optical Link by Using both Radial and Azimuthal Spatial Indices

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Abstract: We experimentally demonstrate turbulence mitigation by adaptive optics for a 400-Gbit/s free-space link multiplexing four Laguerre Gaussian modes using both radial and azimuthal indices. The turbulence-induced power loss and crosstalk are reduced by ~10 dB and ~18 dB, respectively.

OCIS codes: (060.2605) Free-space optical communications; (050.4865) Optical vortices; (010.1330) Atmospheric turbulence.

1. Introduction

Space-division-multiplexing (SDM) can increase the total capacity of an optical communications link by simultaneously transmitting multiple independent data streams each on a spatially distinct beam [1, 2]. A subset of SDM is mode-division-multiplexing (MDM), in which each beam is located on a different orthogonal spatial mode from a modal basis set. We note that modal sets typically have two spatial indices to define the specific modal value and amplitude/phase distribution; for example, Laguerre Gaussian (LG) beams have the azimuthal and radial values of ℓ and p, respectively [3, 4]. For free-space optical (FSO) communication systems, MDM has been demonstrated in which: (a) one index is fixed and multiple channels are each transmitted on a different value of the other index (*e.g.*, fixing p and varying ℓ) such that the channels are in a 1-dimensional (1-D) set [2, 5], and (b) both indices are varied (*e.g.*, varying both ℓ and p) such that a larger 2-D modal set can be used [6, 7].

Generally, atmospheric turbulence is a key limitation in FSO communication systems [8]. Turbulence can cause beam distortion in amplitude and phase, power loss, scintillation, and beam wandering. The critical issue for an MDM link is that a data beam going through turbulence will have power coupled from its transmitted spatial mode into other modes, potentially causing severe degradation due to crosstalk [9, 10].

Previous reports have shown various techniques (e.g., adaptive optics (AO) and multiple-input-multiple-output DSP) to mitigate turbulence effects in 1-D MDM FSO systems [11-14]. One example of adaptive-optics-based turbulence mitigation in a 1-D MDM link is using a spatial light modulator (SLM) at the receiver to introduce an inverse transfer function to partially undo the modal coupling [11, 12]. However, there has been little reported on experimentally demonstrating turbulence mitigation in a 2-D MDM FSO system that considers both modal indices.

In this paper, we experimentally demonstrate a 400-Gbit/s FSO MDM communication link through emulated turbulence using four LG modes with both transmitted radial and azimuthal indices being varied (LG_{10}, LG_{11}, LG_{-10}, LG_{-11}), each carrying a 50-Gbaud quadrature-phase-shift-keyed (QPSK) signal. An AO system is implemented at the receiver to mitigate the turbulence effect by utilizing a spatial light modulator (SLM) for wavefront correction and a wavefront sensor (WFS) for wavefront sensing. A Gaussian beam at a separate wavelength is used as the probe beam. With the scheme, the power loss and crosstalk could be reduced by ~10 dB and ~18 dB, respectively.

2. Concept and experimental setup

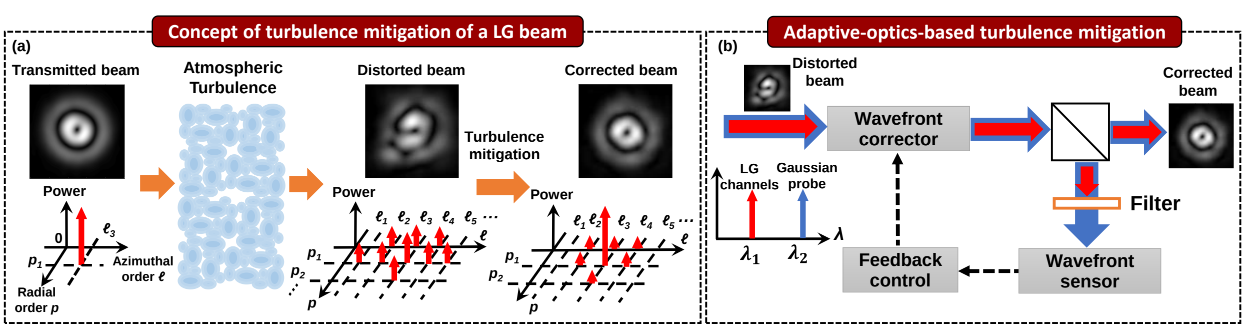

Figure 1. (a) Concept of turbulence-induced power loss and modal coupling on LG beams. (b) Concept of adaptive-optics-based turbulence mitigation for multiplexed LG beams. A Gaussian beam at a separate wavelength is used for wavefront distortion probing.

The concept of the atmospheric turbulence effect on LG beams and turbulence mitigation is illustrated in Fig. 1(a). The atmospheric turbulence can induce amplitude and phase distortion on the transmitted LG beams [8-10]. Such distortion can induce power loss, scintillation, and beam wandering for an FSO communication system [8-10]. For an LG multiplexed system, the distortion along both azimuthal and radial directions leads to a modal mismatch between the transmitted and received LG beams. As a result, there would be modal coupling from the transmitted mode to both azimuthal and radial modes (neighboring ℓ and p modes), resulting in inter-channel crosstalk in an LG-multiplexed link. By utilizing a turbulence mitigation approach (*e.g.*, AO), the wavefront of the distorted LG beam could be recovered and subsequently, the turbulence-induced modal coupling could be compensated.

An AO system is implemented for turbulence mitigation in an LG-multiplexed link, as shown in Fig. 1(b). Multiplexed LG data channels at λ_1 are combined, and then propagate coaxially with a Gaussian beam at λ_2. At the receiver, this Gaussian beam is separated by a bandpass filter, and functions as a probe beam for distortion estimations and wavefront sensing using a WFS. A feedback controller is used to calculate the required correction pattern on wave-front correctors (*e.g.*, SLM) to compensate for the phase front distortion of both the Gaussian probe and the distorted LG beams.

Figure 2(a) represents the experimental setup. At the transmitter, a 50-Gbaud QPSK signal is generated and amplified at 1550 nm. The generated data channel is split into four branches and delayed by single-mode fibers with different lengths for data decorrelation. Each data branch is converted to an LG mode with different ℓ and p indices (*i.e.*, LG_{10}, LG_{11}, LG_{-10}, LG_{-11}) by using SLMs 1 and 2 [6], and the intensity profiles of the generated beams are shown in Fig. 2(b). The generated $\mathrm{LG}_{\pm 10}$ and $\mathrm{LG}_{\pm 11}$ modes have the beam size D ~3.2 mm and ~4.4 mm, respectively. A Gaussian beam at 1560 nm is expanded to a similar size of the LG_{11} beam, and then combined with the multiplexed LG beams. The multiplexed beams subsequently propagate through a turbulence emulator (*i.e.*, rotating phase plate) fabricated following Kolmogorov spectrum statistics with a Fried parameter r_0 of 1 mm. The ratio D/r_0 is thus ~3.2 and ~4.4 for $\mathrm{LG}_{\pm 10}$ and $\mathrm{LG}_{\pm 11}$ modes, respectively, which can be used to estimate the turbulence strength. At Rx, an AO system is designed to mitigate turbulence-induced power loss and modal coupling. In the AO module, SLM 3 serves as a wavefront corrector, and a WFS is used for wavefront sensing. The Gaussian probe beam is first filtered out by a free-space bandpass filter centered at 1560 nm and then directed to the wavefront sensor. Measured wavefront distortion of the Gaussian probe is used to generate the wavefront correction pattern on the SLM 3. The SLM 3 is imaged with the WFS by a 4-f system, thus the beam at the SLM 3 is conjugated with the beam at the WFS. The corrected multiplexed beams are down-converted back into Gaussian beams by SLM 4 and received by the coherent receiver for signal processing. In the setup, an off-axis holography system is used to measure the intensity and phase profiles of the beams.

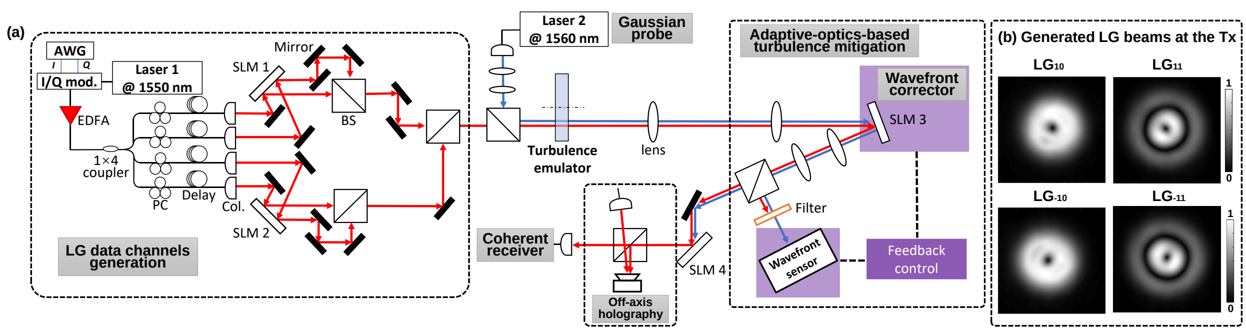

Figure 2. (a) Experimental setup of turbulence mitigation of 4-LG beams with different ℓ and p indices by using a Gaussian probe beam at a separate wavelength; (b) Intensity profiles of generated LG beams (LG_{10}, LG_{11}, LG_{-10}, LG_{-11}) at the Tx. BS: beam-splitter; Col.: Collimator; PC: polarization controller; SLM: spatial light modulator; AWG: Arbitrary Waveform Generator; EDFA: Erbium-Doped Fiber Amplifier.

3. Experimental results and discussion

The intensity and phase profiles of a LG_{-11} beam at 1550 nm under turbulence effect is first characterized by off-axis holography, as shown in Figs. 3(a1, a2). A Gaussian beam generated by a coherent copy of the same laser for LG_{-11} is used for the hologram. The extracted intensity and phase profiles are subsequently used for LG modal decomposition. Figure 3(a3) represents the calculated normalized 2-D LG spectrum. The modal coupling to both neighboring ℓ and p modes is induced as a result of the intensity and phase distortion caused by the atmospheric turbulence. We also measure the LG spectrum of a LG_{-11} beam at the probing wavelength (1560 nm) with the same turbulence realization, as shown in Fig. 3(a4). The similar LG spectrum indicates that the similar wavefront distortion is induced by the turbulence within 10 nm wavelength separation, so that the Gaussian beam at the probing wavelength could be used for wavefront sensing in the AO system. Figures. 3(b1, b2) show the mitigated intensity and phase profiles of the LG_{-11} beam at 1550 nm.

We further measure the crosstalk matrix for four multiplexed LG beams, as shown in Fig. 3(c). The crosstalk between different LG channels is < -18 dB without turbulence. The specific turbulence realization induces ~6-19 dB power loss for different LG channels, and the crosstalk increases by ~18 dB. With the AO mitigation, the power of the desired modes could be mitigated with ~1.5 dB residual power loss. The crosstalk between different LG channels is compensated and the inter-channel crosstalk is reduced to <−18 dB.

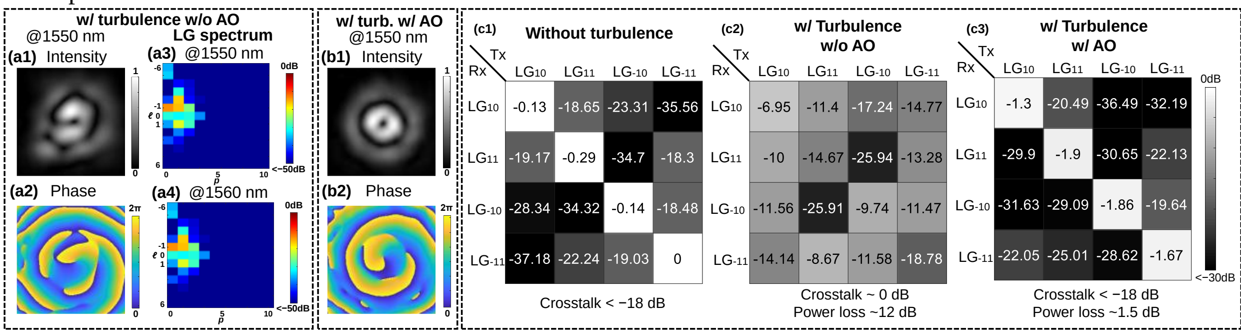

Figure 3. (a1) Intensity and (a2) phase profiles for turbulence-distorted LG_{-11} beam. LG spectrum of turbulence-distorted LG_{-11} beam at (a3) 1550 nm and (a4) 1560 nm. (b1) Intensity and (b2) phase profiles for LG_{-11} beam with turbulence effect with AO mitigation. Normalized channel crosstalk matrix for four multiplexed LG channels (c1) without turbulence, (c2) with turbulence without AO mitigation, and (c3) with turbulence with AO mitigation.

Experimental results of the data transmission through turbulence are shown in Fig. 4. Figure 4(a) shows the bit error rate (BER) performance with and without AO-based turbulence mitigation when four LG data channels are transmitted. A 400-Gbit/s QPSK FSO link can be achieved below the 7% forward error correction (FEC) limit with turbulence mitigation by AO. The corresponding constellations and measured error vector magnitude (EVM) for with and without AO cases at the same transmitted power are shown in Figs. 4(b, c). The optical signal-to-noise ratio (OSNR) of the data channels is reduced from ~18 dB to ~15 dB when the AO module is turned off, which could be due to the turbulence-induced power loss. The EVM is >50% and the data channels cannot be recovered without AO in this particular turbulence realization. Figure 4(c) shows measured BER in different scenarios for the LG_{-11} channel as an example. The B2B case is characterized by fiber transmission only. Compared with the B2B case, there is a ~1 dB OSNR penalty at the FEC threshold by transmitting a single LG_{-11} mode in the free space. ~2 dB more OSNR penalties will be induced by transmitting four multiplexed-LG beams without the turbulence due to the inter-modal crosstalk. The experimental results show that, with AO mitigation, the BER performance with the turbulence effect is similar to that without the turbulence effect. This could be explained by the fact that after AO mitigation, although there would be ~1.5 dB residual power loss, the crosstalk between four LG channels could be minimized. Figure 4(e) shows the BER with and without compensation under various turbulence realizations. It could be seen that the BERs are all below the FEC limit after AO-based mitigation.

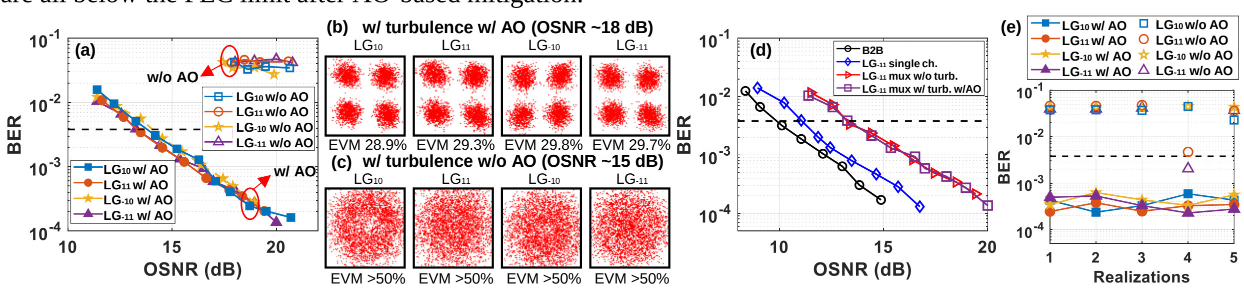

Figure 4. (a) Measured BER as a function of OSNR for four multiplexed LG channels with turbulence effect with and without AO. Constellations and EVM of four LG channels with turbulence effect (b) with and (c) without AO mitigation. (d) Measured BER as a function of OSNR for LG_{-11} in different scenarios. (d) Measured BER for four LG channels with and without AO mitigation with different turbulence realizations.

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