

# Simultaneous Pre-and Post-Turbulence Compensation of Multiple Orbital-Angular-Momentum 100-Gbit/s Data Channels in a Bidirectional Link Using a Single Adaptive-Optics System

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**Abstract:** The simultaneous pre-and post-turbulence compensation of multiple orbital-angular-momentum (OAM) modes propagating through turbulent channel is experimentally demonstrated in a bidirectional free-space optical (FSO) link by using a single adaptive-optics system. ©2013 Optical Society of America

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## 1. Introduction

Orbital angular momentum (OAM) has gained much interest recently due to its potential for efficiently multiplexing many independent data streams in a space-division-multiplexing (SDM) communication system [1, 2]. Light beams carrying OAM can be described in the spatial phase form of  $\exp(i\ell\varphi)$  ( $\ell=0, \pm 1, \pm 2, \dots$ ), in which  $\varphi$  refers to the azimuth angle and  $\ell$  determined the OAM value [1, 3]. One key characteristic of beams carrying OAM is that they have a helical phase-front and “doughnut” intensity shape when  $\ell \neq 0$ , and they lie within by an unbounded mode space (i.e.,  $\ell$  can take any integer value) with each of them orthogonal to all of the others [2, 3]. The orthogonality enables the efficient multiplexing and demultiplexing of the spatially overlapping multiple OAM beams in SDM-based free space optical (FSO) links.

Experimental reports have demonstrated 2.56-Tbit/s on a single wavelength with 32 modes [2] and 100-Tbit/s on 42 wavelengths each with 24 modes [4]. However, a key challenge in OAM multiplexed FSO links is the ability to compensate for atmospheric turbulence, given that the turbulence distortions will significantly degrade OAM beams and cause crosstalk among adjacent channels [5-7]. Recently, it has been experimentally shown that turbulence compensation of multiple OAM beams can be achieved in an unidirectional link by using a new adaptive optics (AO) compensation scheme at the receiver [8]. Meanwhile, the reciprocity of the atmospheric turbulence [9] implied that this AO system could potentially be employed to pre-distort the outgoing beams emitted from the receiver simultaneously, significantly simplifying the system complexity [10, 11].

In this paper, we demonstrate that by using a single AO system, the pre-and post-turbulence compensation of multiple OAM beams could be achieved simultaneously in a bidirectional FSO link, in which the AO system is located at only one end of the system such that one direction experiences pre-compensation and the other direction experiences post-compensation. Rotatable phase screen plate with phase distribution obeying Kolmogorov spectrum statistics [12] is used to emulate atmospheric turbulence. The experimental results suggests the link with post-compensation will achieve better performance than the pre-compensated link by about >1 dB depending on the mode-spacing  $\Delta$  of the transmitted modes (>7 dB when  $\Delta = 2$ ).

## 2. Concept and Experimental Setup

The concept of simultaneous pre-and post-compensation of the OAM-based bidirectional FSO link is illustrated in Fig. 1. Two groups of multiplexed data-carrying OAM beams (at TX-1 and TX-2) propagate through the atmospheric turbulence with opposite directions. A recently-proposed AO system for OAM beams [8] is placed at one end of the system (TX-2), which is used to compensate the received OAM beams from TX-1 and pre-distort the outgoing beams from TX-2 simultaneously.

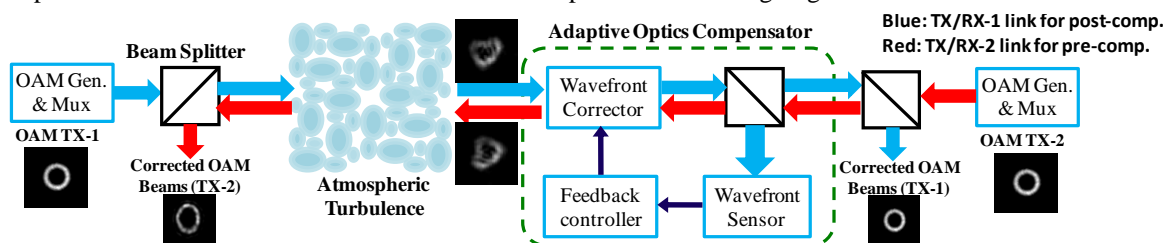


Fig. 1. Concept diagram of the bidirectional link. The multiplexed beams from TX-1 and TX-2 experience post- and pre compensation respectively.

The experimental setup is presented in Fig. 2. Two groups of three OAM-multiplexed beams each carrying 100-Gbit/s QPSK signal are created by using two spatial light modulators (SLM 1-2, the surface of each SLM is divided into two different regions, one region generates one OAM beam, the other region generates two OAM beams by loading a specially-designed spiral phase pattern). A Gaussian beam, which acts as a probe beam for wavefront sensing in the AO system, is expanded by using a 4-f lens system to become as wide as the widest OAM beam along the propagation path and propagates collinearly with OAM beams from TX-1. The multiplexed beams transmitted from TX-1 and TX-2 propagate with opposite directions through the turbulence emulator, which consists of a rotatable stage and a phase screen plate. The phase screen plate with Fried's

parameter  $r_0 = 1\text{mm}$  is used to emulate a 1 km turbulence channel. A closed-loop Shack-Hartmann-based AO system is placed at TX-2 side to compensate the turbulence-distorted OAM from TX-1 and pre-distort the outgoing beam from TX-2 by using the same correction pattern obtained from the Gaussian probe beam. Both the multiplexed beams from TX-1 and TX-2 are then down-converted back into Gaussian beams respectively, which is then coupled into single mode fibers and sent for coherent detections and off-line digital signal processing after passing through both the phase screen plate and the wavefront corrector.

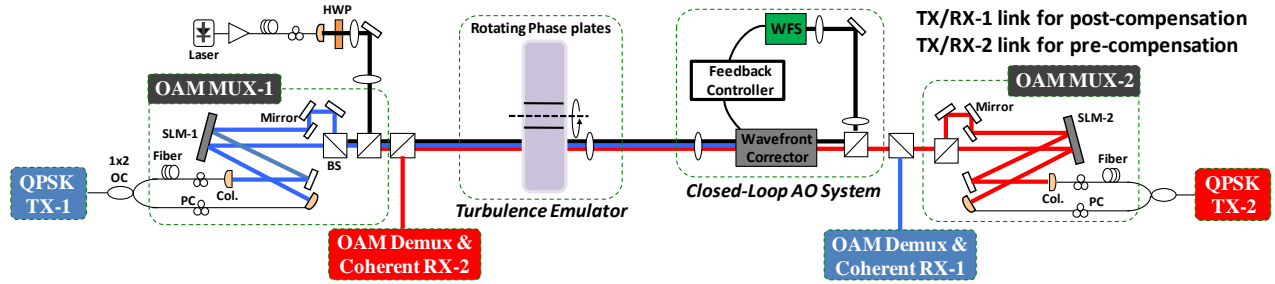


Fig. 2. Experimental setup. AO: adaptive optics, BS: beam-splitter, Col.: Collimator, HWP: half wave plate, OC: optical coupler, PC: polarization controller; SLM: spatial light modulator, WFS: wavefront sensor ( HASO from Imagine optic Inc.).

### 3. Experiment Results and Discussion

Fig. 3 shows the intensity profile and interference pattern of the OAM beams with/without pre- and post-compensation respectively. From the far-field images, one can see that the distorted OAM beams (b1-2, c1-2) are efficiently compensated (b5-6, c5-6) for both TX/RX-1 and TX/RX-2 links. The interference patterns shown in (b7-8, c7-8), in comparison with (b3-4, c3-4) verify that the OAM wavefronts has also been corrected significantly. Note that the post-compensation for TX/RX-1 link get better compensation performance than the pre-compensation experienced by TX/RX-2 link. The received power fluctuations when transmitting OAM  $l=5$  for both links with/without compensation is depicted in Fig. 4(a), indicating that the received power after compensation could remain fairly stable. Fig. 4(b) further illustrates the distribution of power coupled into the fiber over neighboring OAM modes when transmitting OAM  $l=5$  with/without pre- and post-compensation for a specific turbulence realization. One can see that after compensation, the power of transmitted mode  $l=5$  dominates in the power spectrum. The BER performance for channel  $l=5$  with/without compensation under turbulence realization #10 when transmitting 3 multiplexed channels is presented in Fig. 5 (a). The corresponding recovered constellations of 100-Gbit/s QPSK signal are also shown in Fig. 5(b1-8), respectively. Considering that crosstalk is dependent on the separation of the transmitted OAM modes, the performance under different OAM mode-spacings ( $\Delta=2, 4$ ) is also investigated. It is observed that the BERs in the cases without compensation are extremely high (not shown in Fig. 5(a)), and the TX/RX-1 link with post-compensation could achieve better performance than the pre-compensated TX/RX-2 link by  $> 1\text{ dB}$  depending on the mode-spacing.

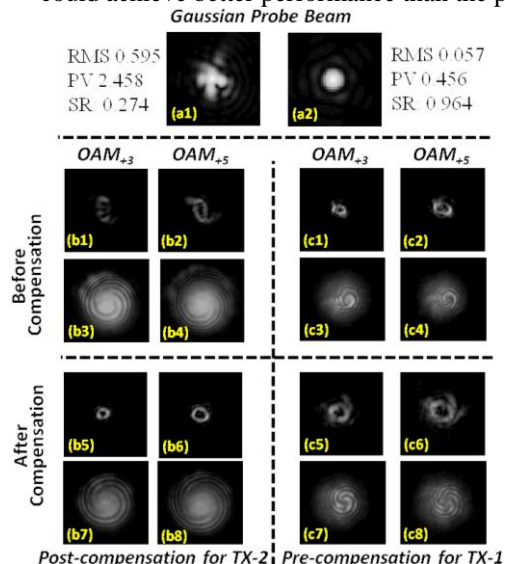


Fig. 3. The far-field intensity and interference images of the OAM beams ( $l=3, 5$ ) before (upper, b1-b4, c1-c4) and after (lower, b5-b8, c5-c8) post- and pre-compensation, respectively. The RMS (root mean square), PV (peak-to-valley) and Strehl ratio of wavefront for the probe beam before/after compensation are also given.

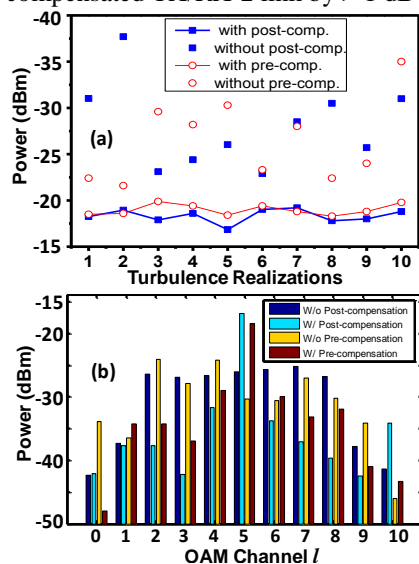


Fig. 4 (a) the power (coupled into fiber) of OAM  $l=5$  under different turbulence realizations, and (b) Power distribution over neighboring OAM modes when transmitting OAM  $l=5$  under a specific turbulence state, with/without pre- and post-compensation.

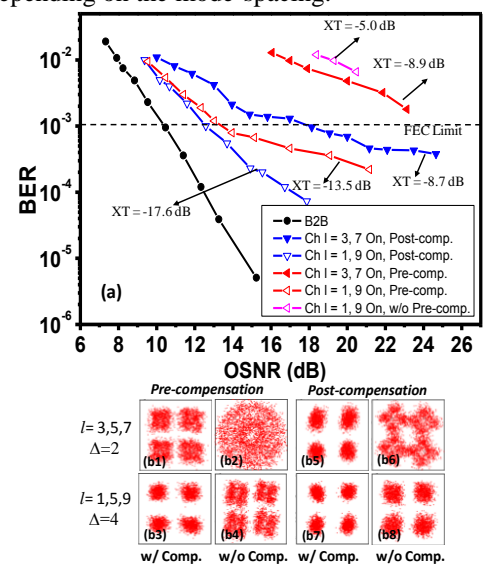


Fig. 5 (a) BER for OAM channel  $l=5$  when transmitting 3 multiplexed channels with different mode spacing ( $l=3, 5, 7$  or  $l=1, 5, 9$ ), under turbulence realization #10, and (b1-b8) The corresponding QPSK constellations recovered for channel  $l=5$ , with/without pre- and post-compensation.

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