Simultaneous Turbulence Mitigation and Mode Demultiplexing using one MPLC in a Two-Mode 200-Gbit/s Free-Space OAM-Multiplexed Link

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Abstract: We experimentally utilize a multi-plane light convertor (MPLC) for simultaneous orbital-angular-momentum (OAM) mode demultiplexing and turbulence-induced crosstalk mitigation. Results show up to 15-dB reduction of crosstalk in a two-mode 200-Gbit/s OAM-multiplexed link.

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

1. Introduction

There is growing interest in increasing the capacity of free-space optical communication links [1]. One approach is to use mode-division-multiplexing (MDM), which is a type of space-division-multiplexing (SDM) [2]. In a typical MDM link, multiple independent data-carrying beams are each structured to be located on a different spatial mode. If these modes are mutually orthogonal, then the beams can be multiplexed at the transmitter aperture, spatially co-propagate, and be demultiplexed at the receiver aperture – all with little inherent crosstalk [3].

One example of such a modal set are orbital-angular-momentum (OAM) beams, which are a subset of Laguerre Gaussian (LG) beams [4]. OAM beams are characterized by a phasefront that "twists" in a helical fashion as it propagates, such that the mode value l represents the number of 2π phase changes in the azimuthal direction [5]. Moreover, the intensity profile forms a ring with a central null [6].

There are two challenges when operating an OAM-based MDM link in a turbulent atmosphere. First, turbulence can cause power coupling among modes that can lead to system crosstalk [7]. Second, it is desirable to efficiently demultiplex the various data channels at the receiver into their original launched modes [8].

In terms of turbulence mitigation, there are several approaches including: (i) using spatial-light-modulators (SLM) or digital-micro-mirror-device for enabling adaptive optics [9,10] and (ii) electronic-based digital-signal-processing (DSP) using MIMO-based algorithms [11,12]. In terms of modal demultiplexing, especially for OAM beams, published techniques have included various types of optical transformations [8,13-16]. One particular approach for demultiplexing is the use of a multi-plane light converter (MPLC), which is composed of multiple phase plates and has been shown to demultiplex multiple modes from HG or LG modal sets [15,16].

In this paper, we experimentally utilize multi-plane light convertor to simultaneously demultiplex mode and reduce turbulence-induced crosstalk by up to 15 dB in a two-mode 200-Gbit/s orbital-angular-momentum-multiplexed link. Without using wavefront sensor or MIMO DSP processing, we use one MPLC consisting of 6-plane phase patterns to simultaneously (i) demultiplex two OAM modes, and (ii)mitigate turbulence-induced crosstalk by using wavefront matching method [16] and genetic algorithm [13]. Crosstalk improvement of >9.3dB and >6.4 dB for channel 1 ($\ell = 0$) and channel 2 ($\ell = +1$), respectively, is achieved under 6 realizations of turbulence (distortion strength $D/r_0 = 1.4$). Bit error rate (BER) performance is measured for both channels with crosstalk mitigation, in which power penalty of ~0.2dB and ~2dB is achieved at 3.8e-3 forward error correction limit for channel 1 and channel 2, respectively.

2. Concept and experimental setup

The concept of simultaneously mitigating turbulence-induced crosstalk and demultiplexing OAM modes using one MPLC is shown in Figure 1a. Atmospheric turbulence introduces distortion to the wavefront of OAM beams, which will induce power coupling between neighboring modes and crosstalk in the OAM-multiplexed link. After propagation, the beam with distorted wavefront evolves into distorted intensity profile as shown in Figure 1b. At the receiver, the wavefront of distorted beams will be spatially manipulated when propagating through the 6 consecutive phase patterns in the MPLC. The generation of such phase patterns consists of two steps, (i) applying wavefront matching method to generate initial phase patterns which could demultiplex undistorted OAM beams, and (ii) iteratively updating phase patterns using genetic algorithm to reduce the turbulence-induced modal crosstalk. The genetic algorithm could iteratively search for the optimized phase patterns utilizing the measured crosstalk from each OAM channel. Utilizing the MPLC at the receiver, the turbulence-induced crosstalk mitigation and demultiplexed could be achieved simultaneously.

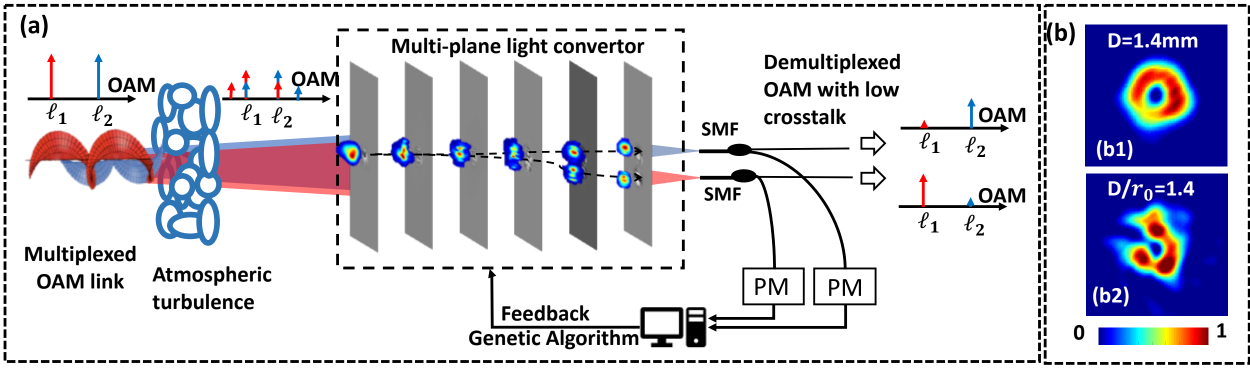

Fig. 1. (a) Concept diagram of simultaneously mitigating turbulence-induced crosstalk and demultiplexing OAM modes using one MPLC. (b) Normalized intensity profile of OAM $\ell = +1$ (b1) without and (b2) with turbulence distortion (D/r_0=1.4, beam diameter D = 1.4mm, fried parameter r_0 = 1mm). SMF: single mode fiber. PM: power meter.

The experimental setup is shown in Fig. 2. At the transmitter side, the 100-Gbit/s QPSK signal at 1550nm is amplified by EDFA. Then the signal is equally split by a 50/50 coupler. Two copies of signal are decorrelated by going through fiber of different path length. Then the polarization of two copies of signals are controlled by polarization controller (PC) independently to achieve largest modulation efficiency at polarization-sensitive spatial light modulator (SLM). The two fiber branches are fed into two input ports of a custom-designed OAM generator/multiplexer, generating two multiplexed OAM beams ($\ell = 0$ and $+1$) [15]. At a distance of ~1-m, the OAM beams are normally incident on the emulated turbulence plate with effective fried parameter r_0 = 1mm. Then the distorted beams are projected onto the first plane of SLM. The beams are bounced between mirror and the same SLM to go through six different phase patterns with neighboring spacing of 31.5mm. After passing through the 6-plane MPLC, the two beams will be separated spatially and tilted with different angles. Then the two beams will be coupled into different ports of fiber array with spacing of 127μm using a single collimator (NA=0.35). After power collection of both ports, a feedback loop is designed to monitor the crosstalk between the two channels. Given the crosstalk at each measurement, a genetic algorithm (GA, MATLAB global optimization toolbox) is applied to update the patterns of first two planes to correct the wavefront of the distorted beam. To measure the crosstalk matrix between two channels, the mode at the transmitter side will be switched between $\ell = 0$ and $+1$. After optimizing the MPLC pattern, the signals carried by the two transmitted OAM beams will be received and detected with lower crosstalk.

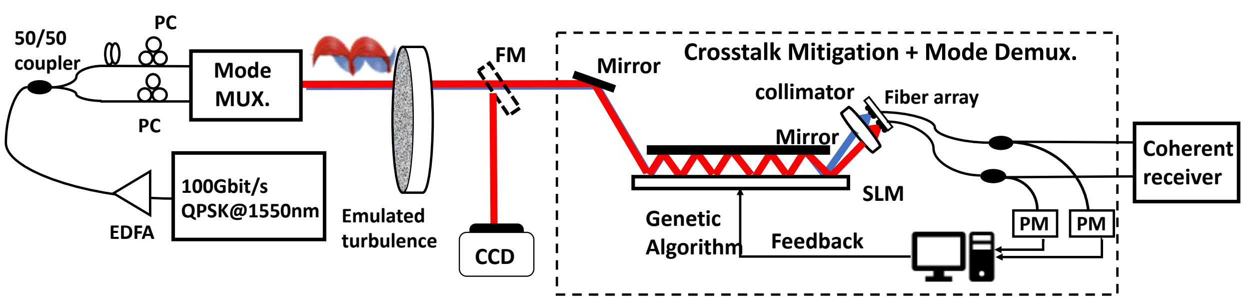

Fig. 2. Experimental setup of using MPLC for turbulence-induced crosstalk mitigation and mode demultiplexing in an OAM-multiplexed link. QPSK: quadrature phase-shift keying; EDFA: erbium-doped fiber amplifier; PC: polarization controller; MUX: multiplexer; SLM: spatial light modulator; FM: flip mirror; PM: power meter.

3. Experimental results and discussion

Figure 3(a1) shows the received power for different transmitted OAM modes when the MPLC pattern is designed for demultiplexing OAM modes ($\ell = 0$ and $+1$) using wavefront matching method without turbulence. The crosstalk of <-20dB for both channels is achieved. Limited by the reflection rate and modulation efficiency of the SLM, the received power of for channel 1 ($\ell = 0$) and channel 2 ($\ell = +1$) is around -29.9dBm and -29.19dBm, respectively. Figure 3(a2) shows that the MPLC could also demultiplex the OAM modes ($\ell = -1$ and $+1$) by updated MPLC pattern using the same method. The received power of channel 1 ($\ell = -1$) and channel 2 ($\ell = +1$) is around -29.31dBm and -29.88dBm. The crosstalk for both channels is <-16dB.

To illustrate the optimization process of turbulence-induced crosstalk mitigation, the crosstalk at different measurements of genetic algorithm is shown in Fig. 3b. The crosstalk starts to randomly change after the genetic algorithm is applied. We stop the measurement after the threshold (<-18 dB crosstalk between two channels) is achieved or upper limit number of measurements (180 measurements) is reached. SLM patterns after such optimization process is shown in Fig. 3c as an example. Two mitigation patterns are applied to the round-shape working region of first two planes, respectively. Each mitigation pattern is composed of 10×10 elements where each element consists of 30×30 SLM pixels and each SLM pixel has a size of 9.2 μm. Limited by the modulation efficiency of the SLM, gratings of different angles are applied to the working region and background. Figure 4(d1-d2) shows the received power of channel 1 and channel 2, respectively, under the three cases where there is (i) no turbulence(left bar), (ii) only demultiplexing patterns on the MPLC under turbulence(middle bar) and (iii) updated mitigation patterns added to demultiplexing patterns under turbulence(right bar).

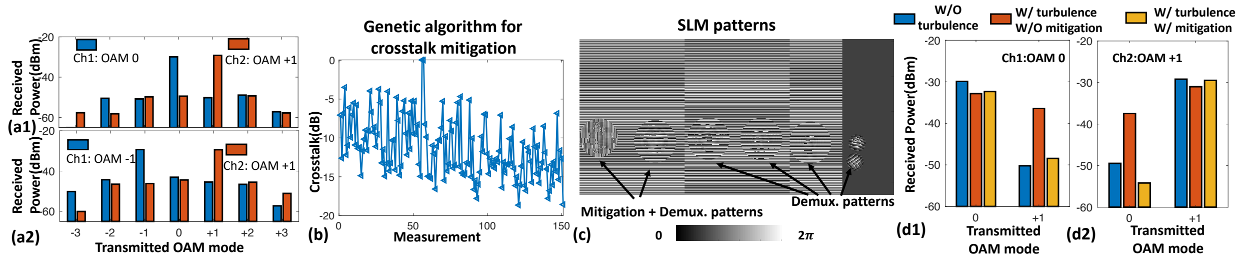

Fig. 3. (a1-a2) Received power of MPLC for (a1) OAM $\ell = 0$ and $+1$ demultiplexing and (a2) OAM $\ell = -1$ and $+1$ demultiplexing without turbulence. (b) Crosstalk under 150 measurements of genetic algorithm for crosstalk mitigation with turbulence. (c) 6-plane SLM pattern for simultaneous crosstalk mitigation and OAM mode ($\ell = 0$ and $+1$) demultiplexing. (d) Received power of MPLC for back-to-back OAM mode ($\ell = 0$ and $+1$) demultiplexing and with/without crosstalk mitigation under turbulence.

Figure 4a shows that crosstalk improvement after MPLC crosstalk mitigation is applied for different realizations of turbulence. Without mitigation under these realizations of turbulence distortion, the crosstalk of channel 1 and channel 2 varies from -1.2 dB to -11.67 dB and from -0.94 dB to -9.28 dB, respectively. After utilizing the propose mitigation method, the crosstalk for channel 1 and channel 2 is decreased by > 9.3 dB and > 6.4 dB, respectively. Under 6 realizations of turbulence, up to 15 dB crosstalk reduction could be achieved.

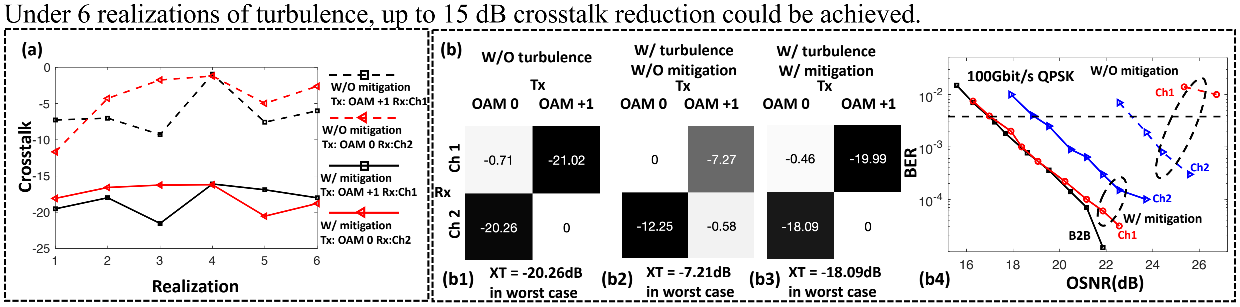

Fig. 4. (a) Crosstalk for two OAM modes ($\ell = 0$ and $+1$) with and without MPLC crosstalk mitigation under different realization of turbulence. (b1-b3) crosstalk matrix of OAM mode ($\ell = 0$ and $+1$) demultiplexing and with/without crosstalk mitigation under turbulence. (b4) Measured bit error rates (BERs) as functions of optical signal-to-noise ratio (OSNR) for two OAM-multiplexed ($\ell = 0$ and $+1$) channels with and without MPLC crosstalk mitigation. XT: crosstalk. B2B: back-to-back.

The crosstalk matrix and measured bit error rates (BERs) performance with turbulence (realization 1) are shown in Fig. 4(b1-b4). As shown in Fig. 4(b1-b2), for the case with turbulence and without using turbulence-induced crosstalk mitigation, the crosstalk is 13.25dB worse compared with that for the case without turbulence. After applying turbulence-induced crosstalk mitigation, the crosstalk for channel 1($\ell = 0$) and channel 2 ($\ell = +1$) is improved by 11.26dB and 6.42dB as shown in Fig. 4(b3). As shown in Fig.4(b4), without using turbulence-induced crosstalk mitigation, channel 1($\ell = 0$) cannot achieve below 3.8e-3 FEC limit and channel 2 ($\ell = +1$) has ~6dB power penalty at the 3.8e-3 FEC limit in BER performance. Using turbulence-induced crosstalk mitigation, there are ~0.2dB and ~2dB power penalty for channel 1 and channel 2, respectively.

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