Simultaneous Orthogonalizing and Shaping of Multiple LG Beams to Mitigate Crosstalk and Power Loss by Transmitting Each of Four Data Channels on Multiple Modes in a 400-Gbit/s Free-Space Link

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Abstract: We experimentally utilize orthogonal combinations of multiple Laguerre-Gaussian modes in a 400-Gbit/s free-space link with limited-size aperture or misalignment. Power loss and crosstalk could be reduced by up to ~15 dB and ~40 dB, respectively.

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1. Introduction

The ability to simultaneously transmit multiple independent data-carrying beams can increase the total capacity of a free-space optical link, and this is called space-division-multiplexing (SDM) [1]. A form of SDM is to make each of the beams mutually orthogonal, such that little inherent crosstalk is induced when multiplexing at the transmitter aperture, spatially co-propagating, and demultiplexing at the receiver aperture [2]. One type of this system of orthogonal beams and channels is the use of modes in a modal basis set. For example, mode-division-multiplexing (MDM) would entail the transmission of each beam on a different orthogonal spatial mode [3].

MDM links can be accomplished in many ways. For example, Laguerre-Gaussian (LG) beams form a 2-dimensional set of orthogonal modes, in which: (i) l represents the number of 2π phase shifts in azimuthal direction of the phasefront, and (ii) $p+1$ represents the number of radial intensity nodes (rings/spot) [4]. We note orbital-angular-momentum (OAM) modes are considered as a subset of the full LG modal set for which many LG modes do carry OAM [5]. An MDM free-space link can be formed by multiplexing many orthogonal LG beams [6-8].

Unfortunately, there are many problems that can arise in a free-space link that could cause coupling of power among other modes, thereby reducing orthogonality and increasing system crosstalk among data channels. Moreover, some of these problems can also cause channel power loss since transmitted power is no longer recovered in the right mode or at all. Specifically, problems causing crosstalk and channel power loss include: (a) limited-size aperture, (b) misalignment between the transmitter and receiver apertures, and (c) atmospheric turbulence [9-11].

Previous reports have shown various approaches for mitigating the above issues, including adaptive optics for and channel equalization by multiple-input-multiple-output-digital-signal-processing (MIMO-DSP), but these typically require more hardware and may not mitigate both crosstalk and power loss [12,13].

In this paper, we simultaneously orthogonalize and shape the combination of multiple LG modes to mitigate crosstalk and power loss by transmitting each of four data channels on the combination of multiple LG beams in a 400-Gbit/s quadrature phase shift keying (QPSK) free-space optical (FSO) link. At the transmitter side, four orthogonal mode combinations are generated and multiplexed. Each of the combinations consists of multiple LG modes with designed weights, which could be calculated based on the singular value decomposition (SVD) of the transmission matrix for a given link. Therefore, the transmitted mode combinations could still be mutually orthogonal after propagating through a link with a limited-size aperture or misalignment. Experimental results show that with a limited-size aperture, the power loss and the crosstalk could be respectively reduced by up to ~8 dB and ~23 dB when using these mode combinations. In addition, with a displacement, the power loss and crosstalk could be respectively reduced by up to ~15 dB and ~40 dB when using these mode combinations.

2. Concept and experimental setup

Figure 1(a1) shows a four-channel MDM link in which each channel is transmitted on a single LG mode. In such a link, when the receiver aperture size is limited or there is a misalignment between the transmitter and the receiver, as shown in Fig. 1(b2) and 1(b3), power on the desired LG mode would couple into other LG modes, causing crosstalk and power loss. The concept of transmitting each channel on a combination of multiple LG modes to mitigate the effect of the limited-size aperture or misalignment in an MDM link is shown in Fig. 1(a2). Generally, the mode coupling between a set of LG modes in a given link can be described as a complex transmission matrix: $\mathbf{H}$ [x]. The $\mathbf{H}$ can be factorized by SVD and written as $\mathbf{H} = \mathbf{U} \cdot \sum \cdot \mathbf{V}^*$.At the transmitter side, the orthogonal combinations of a set of LG modes are generated based on the columns of the **V**. After passing through the limited-size aperture or being affected by the misalignment, the transmitted mode combinations for different channels are still orthogonal to each other. As a result, the orthogonal mode combinations could be demultiplexed with little crosstalk based on the rows of the inverse of the **U** matrix. Besides the orthogonalization, intensity profiles of the transmitted mode combinations would also be shaped, which might simultaneously reduce the power loss.

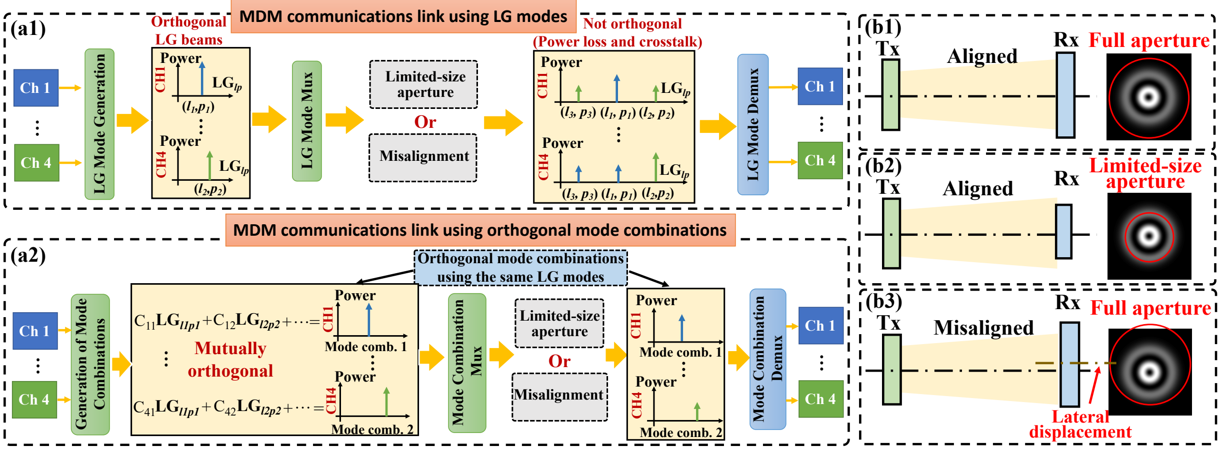

Figure 1: Concept diagram of a four-channel MDM link in which each data channel is transmitted on (a1) a single LG mode or (a2) a combination of multiple LG modes to mitigate the effect of the limited-size aperture and misalignment. The illustration of an FSO link with (b1) full receiver aperture and perfectly alignment, (b2) limited-size receiver aperture and perfectly alignment, and (b3) full receiver aperture and lateral displacement. Ch: Channel; Comb.: combination; Tx: Transmitter; Rx: Receiver.

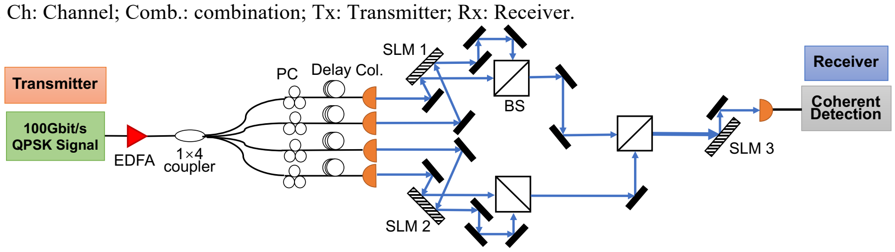

Figure 2. Experimental setup of a four-channel MDM FSO communication system multiplexing four LG modes or four orthogonal mode combinations. QPSK: quadrature phase-shift keying; EDFA: erbium-doped fiber amplifier; PC: polarization controller; Col.: collimator; SLM: spatial light modulator; BS: beam splitter.

Figure 2 shows the experimental setup of a four-channel MDM FSO communication system multiplexing four LG modes or four orthogonal mode combinations. At the transmitter side, a 100-Gbit/s QPSK signal at 1550 nm is amplified by an erbium-doped fiber amplifier (EDFA) and then equally split into four branches by a 1×4 coupler. After decorrelation by single mode fibers with different lengths, each branch is sent into a collimator that generates a collimated Gaussian beam with a diameter of 3 mm. The Gaussian beams are sent to two spatial light modulators (SLMs) loaded with different phase holograms on each half of the screen to create different single LG beams or mode combinations. These four outputs are multiplexed and then coaxially propagate in free space over ~1 m. At the receiver side, SLM 3 is loaded with a specific phase pattern for the incoming beam to be converted to a Gaussian-like beam. The specific phase patterns for mode combinations at both transmitter and receiver are determined by the SVD of **H**, which could be obtained by transmitting a probe beam in one channel at the transmitter. Finally, the Gaussian-like beam is coupled to an SMF for coherent detection and bit error rate (BER) measurements.

3. Experimental results and discussion

Figure 3(a1) and (a2) respectively show the aperture-induced power loss and channel crosstalk with the aperture radius when each channel is transmitted on a single LG mode or a mode combination. Three different LG modes with different *p* values but the same *l* value (LG_{10}, LG_{11} and LG_{12}) are used to design the mode combinations. As expected, the power loss decreases with the aperture radius. However, by using the designed mode combinations, the power loss for both channels could be reduced compared to the single LG modes with an aperture radius of 1.0-1.6 mm. Moreover, the crosstalk for single LG_{10} and LG_{11} modes increases when the aperture size decreases. This is because the limited-size aperture blocks a part of the LG modes, and thus degrading the orthogonality between LG modes with different *p* values. However, by using the designed mode combinations, the crosstalk between the two channels could be reduced because the orthogonality between different mode combinations would not be degraded by the limited-size aperture. We also see that when the aperture radius is less than 0.8 mm, the crosstalk for mode combination 2 increases, which is mainly due to its large power loss. Figure 3(b1) and (b2) respectively show the displacement-induced power loss and channel crosstalk with the horizontal displacement. Here two different LG modes with different p values but the same l value (LG_{10} and LG_{11}) are used to design the mode combinations. It's observed that for single LG modes, both of the power loss and crosstalk would become larger with the horizontal displacement. However, for the mode combinations, the power loss for both the mode combinations could be reduced compared with the single LG modes when the displacement is from 0.4 to 0.7 mm. In addition, the crosstalk for both of the two combinations could stay at a relatively low level (<-27 dB) with the displacement.

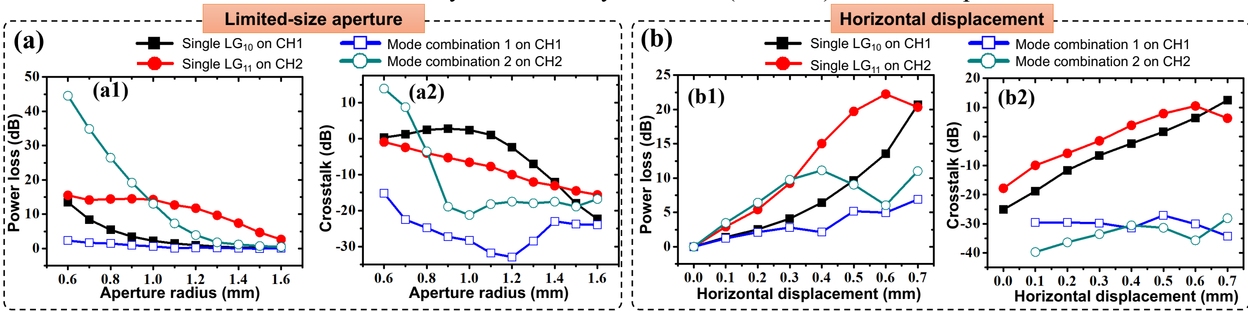

Figure 3. (a1) Aperture-induced power loss and (a2) channel crosstalk under various aperture radiuses for single LG modes or designed mode combinations when LG_{10}, LG_{11} and LG_{12} modes are utilized. (b1) Displacement-induced power loss and (b2) channel crosstalk under various displacements for single LG modes or designed mode combinations, when LG_{10} and LG_{11} modes are utilized. Here, the crosstalk for a certain channel is the power coupled from the other channel over the power of the desired channel. We note that the mode combinations are designed for each given link, such that the designed weights in each combination are different under different aperture radiuses or displacements.

Figure 4(a1) and (a2) present the displacement-induced power loss and channel crosstalk with the horizontal displacement for single LG modes or designed mode combinations when LG modes with different l values but the same p values (LG_{10} and LG_{-10}) are utilized in the link. We see that for single LG_{10} or LG_{-10} mode, the power loss and crosstalk increase with the displacement. However, for both of the mode combination 1 and 2, the power loss could be reduced compared with the single LG modes when the displacement is from 0.8 to 1.1 mm. Moreover, the crosstalk for both of the two mode combinations could stay at a relatively low level (<-17 dB) with the displacement. In the BER measurements, four single LG modes (LG_{10}, LG_{11}, LG_{-10} and LG_{-11}) or four orthogonal mode combinations are transmitted, each of which carries a 100-Gbit/s QPSK signal. Here, the aperture radius is 1.0 mm and there is no displacement between transmitter and receiver. Mode combination 1 and 2 are designed using LG_{10}, LG_{11} and LG_{12} modes, while mode combination 3 and 4 are designed using LG_{-10}, LG_{-11} and LG_{-12} modes. We observe that for mode combinations, the power penalties of all four channels are < 2 dB at the forward error correction (FEC) limit. However, for single LG modes, the error vector magnitude (EVM) for all the four channels are >50% when the OSNR is 18.3 dB due to their high crosstalk.

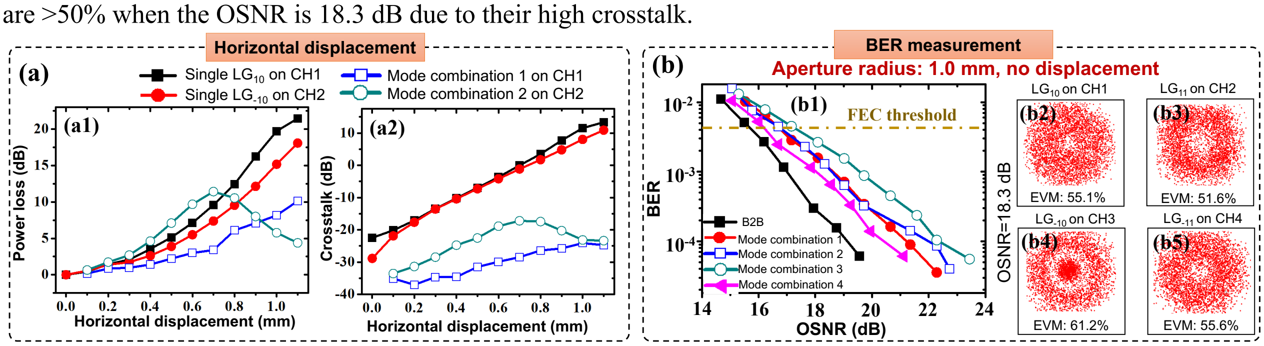

Figure 4. (a1) Displacement-induced power loss and (a2) channel crosstalk under various horizontal displacements for single LG modes or designed mode combinations when LG modes with different l values but the same p value (LG_{10} and LG_{-10} modes) are utilized. (b1) Experimental bit error rate (BER) of the four mode combinations with OSNR when all the four mode combinations are transmitted. Measured constellations for LG_{10}, LG_{11}, LG_{-10}, and LG_{-11} modes when all the four single LG modes are transmitted. B2B: back to back; FEC: forward error correction.

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