Experimental Demonstration of 400-Gbit/s Free-Space Mode-Division-Multiplexing by Varying Both Indices when using Four Laguerre-Gaussian Modes or Four Hermite-Gaussian Modes

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Abstract:
We experimentally demonstrate a 400-Gbit/s mode-division-multiplexed free-space-optical communication link using four Laguerre-Gaussian modes or four Hermite-Gaussian modes, achieving a power penalty < 4 dB. The influence of displacement and rotation on system performance is investigated.

OCIS codes: (060.2605) Free-space optical communications; (060.4230) Multiplexing;

1. Introduction
Free-space optical (FSO) communications have received interest due to the potential increase in total data capacity and decrease in probability of intercept when compared to radio-based communications [1,2]. One method of further increasing the total data capacity of FSO is to use space division multiplexing (SDM), in which multiple independent data-carrying beams simultaneously propagate over the same medium [3]. A subset of SDM is to use mode division multiplexing (MDM), in which each beam is transmitted on an orthogonal mode from a modal basis set [4]. The orthogonality helps to ensure that the different beams can be multiplexed, transmitted, and demultiplexed with little inherent crosstalk [5].

Previous reports of FSO communication links that transmit data using MDM have used Laguerre-Gaussian (LG) modes. LG modes can be characterized by an azimuthal index ($l$) and a radial index ($p$) (i.e., LG$_{lp}$). Many reported the transmission of data on multiple data-carrying beams using multiple $l$ values but keeping $p = 0$ [6,7]. This is typically referred to as multiplexing of beams carrying orbital angular momentum (OAM). Other reports have shown MDM using two data-carrying beams in which there were different $p$ values but the same $l$ value [8].

Importantly, MDM can be implemented with other types of orthogonal modal basis sets, including Hermite-Gaussian (HG) modes [9], which can also be defined by two different indices ($m, n$) (i.e., HG$_{mn}$) [10]. However, different modal sets may have different systems limitations due to the specific beam structures and transmitter/receiver apparatus [11].

In this paper, we experimentally demonstrate 400-Gbit/s FSO MDM communications using four LG modes or four HG modes. In both cases, we simultaneously transmit multiple modes by varying both indices, ($l, p$) for LG modes and ($m, n$) for HG modes. Power penalties of < 4 dB is achieved for all channels. Moreover, we also investigate the effect of displacement and rotation of receiver apertures on the system performance when using LG modes or HG modes. Experimental results indicate that with a larger lateral displacement, the crosstalk between channels will be higher for LG modes while it can stay in the same level for certain HG modes due to their axial symmetry; in contrast, with a larger rotation, the crosstalk will be higher for HG modes while it can stay in the same level for LG modes due to their circular symmetry.

2. Concept and Scheme

Figure 1. (a) Concept of a MDM optical communication link using four LG modes or HG modes. (b) Experimental setup. EDFA: Erbium-doped fiber amplifier; PC: polarization controller; Col.: collimator; SLM: spatial light modulator; BS: beam splitter; FM: flip mirror; IR: infrared.

Figure 1(a) illustrates the concept of a MDM FSO communication link using four orthogonal LG$_{lp}$ modes (LG$_{10}$, LG$_{-10}$, LG$_{11}$, LG$_{-11}$) or four HG$_{mn}$ modes (HG$_{10}$, HG$_{01}$, HG$_{30}$, HG$_{03}$). All data streams can be efficiently multiplexed and demultiplexed due to the orthogonality of LG or HG modes. The experimental setup is shown in Fig. 1(b). First, a 50-Gbaud quadrature phase-shift-keying (QPSK) signal at 1550 nm is generated, amplified and split into four branches. Each of the branches is relatively delayed by a single mode fiber (SMF) with different lengths for signal decorrelation. The four branches are then sent into collimators, each generating a collimated Gaussian beam with a beam diameter of 3 mm. The four beams are launched onto two programmable spatial light modulators (SLMs) loaded with different phase holograms on each half of the screen to create different LG beams (LG$_{10}$, LG$_{-10}$, LG$_{11}$, LG$_{-11}$) or HG beams (HG$_{10}$, HG$_{01}$, HG$_{30}$, HG$_{03}$). These generated LG or HG beams are spatially combined by three beam splitters in two steps and then coaxially propagate in free space over ~1 m. At the receiver, the beams are sent to the SLM-3 loaded with a specific demultiplexing phase pattern for a particular beam to be converted to a Gaussian-like beam and finally coupled into SMF for coherent detection and bit error rate (BER) measurement.
3. Experimental results and discussions

Figure 2. (a) Relative power loss for LG10, LG11, HG10 and HG30 under various receiver aperture diameters. The channel crosstalk for each channel of (b) LG modes or (c) HG modes when all the four channels are demultiplexed at the receiver with various lateral displacement. (d) The channel crosstalk of LG10, LG11, HG10 and HG30 when all the four LG or HG channels are demultiplexed at the receiver with various rotation angles. The receiver aperture has a circular shape and a diameter of 4.0 mm. Tx and Rx: LG10, LG11 is transmitted and received; Rx: LG11 all other three modes are transmitted and LG10 is received. Figure 2(a) shows the measured power loss for LG10, LG11, HG10 and HG30 as a function of aperture diameter at the receiver side. As expected, the power loss decreases with the aperture diameter. When the aperture diameter is 4.0 mm, power loss for all the four modes is almost 0, so for the following BER and crosstalk analysis, the aperture with a diameter of 4.0 mm is chosen. The receiver aperture shape here is round, and a different aperture shape such as rectangle might give different results.

Figures 2(b) and 2(c) respectively present crosstalk for each channel of LG modes or HG modes when all the four channels are demultiplexed at the receiver with a lateral displacement. Here, the crosstalk for a certain LG or HG mode is the power coupled from the other three modes over the power of the desired mode. It is observed that for all four LG modes, crosstalk increases with the displacement. However, for HG10 and HG30 the crosstalk change is very small as the displacement varies, which is due to the invariance of the receiver pattern to not-too-large horizontal displacements. We also note that for HG30, there is a crosstalk peak for a displacement of 0.3 mm. This is due to the entire mismatch between the receiver pattern and HG30 mode, which causes high power loss for the HG30 beam. After this point, the receiver pattern starts to convert part of the HG30 beam to the Gaussian beam that could be coupled into an SMF, thus increasing the power of HG0 beam. Figure 2(d) illustrates the crosstalk for LG10, LG11, HG10 and HG30 when the receiver aperture has a rotation. We see that for the LG modes, due to the rotational symmetry property, crosstalk varies little with rotation angle, while for HG10 and HG30, crosstalk changes rapidly with rotation angle.

Figure 3. (a) Experimental bit error rate of (a) LG modes or (b) HG modes as a function of OSNR when all the four LG or HG beams are transmitted. (c) BER measurements for HG10, HG11, LG10 and LG11, with and without displacement. (d) BER measurements for HG10, HG11, LG10 and LG11, with and without rotation. B2B : back to back; Disp.: displacement; FEC: forward error correction; OSNR: optical signal-to-noise ratio. The aperture diameter is 4.0 mm. In the BER measurements, all the four LG or four HG beams are transmitted, each carries a 100-Gbit/s QPSK signal. Figure 3(a) and 3(b) show the BERs for every LG mode or HG mode as a function of optical signal-to-noise ratio (OSNR) as well as the back-to-back case. We observe that for LG modes, the power penalties of all four channels are <2dB, while for HG modes, HG10 and HG30 have higher power penalties than HG10 and HG30, probably caused by the higher crosstalk. BERs for two HG modes and LG modes under a given receiver displacement (0.2 mm) or rotation (10°) are shown in Figs. 3(c) and 3(d). The better crosstalk behavior of HG10 over HG10, in Fig. 2(c), is also reflected in the lower BER power penalty of this mode. Again, in correlation with Fig. 2(b), the BER power penalties of LG10 and LG11 change little. When adding a 10° rotation, the power penalties of LG modes remain relatively unchanged due to the circular symmetry of their receiver patterns while for HG modes, this rotation causes higher power penalties due to the increased crosstalk.

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