

400-Gbit/s QPSK free-space optical communication link based on four-fold multiplexing of Hermite-Gaussian or Laguerre-Gaussian modes by varying both of the modal indices

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We experimentally demonstrate the four-fold multiplexing of Hermite-Gaussian (HG_{mn}) or Laguerre-Gaussian (LG_{lp}) modes to achieve a 400-Gbit/s quadrature-phase-shift-keyed (QPSK) free-space optical (FSO) communication link. In this experiment, both of the two modal indices for the HG and LG modes are simultaneously utilized to achieve a larger potential orthogonal modal space. Moreover, we also investigate and compare the effects of aperture size, lateral displacement, and rotation on the system. We measure the degree of performance degradation due to the following: (1) a receiver aperture with a limited size causes power loss and crosstalk for both HG and LG modes; (2) a lateral misalignment between the transmitter and receiver leads to crosstalk for LG modes but might not affect HG_{0n} or HG_{m0} modes due to axial symmetry; and (3) a rotational misalignment between the transmitter and receiver causes crosstalk for the HG modes but tends not to affect the LG modes due to azimuthal symmetry. © 2018 Optical Society of America

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Space-division-multiplexing (SDM) is a potentially significant technique for optical communication systems since multiple independent data-carrying beams can simultaneously propagate over the same spatial medium, thereby increasing aggregate transmission capacity [1]. A subset of SDM is mode-division-multiplexing (MDM), in which each data-carrying beam: (i) occupies a different mode from a larger orthogonal modal basis set, and (ii)

enables efficient beam (de)multiplexing and spatially-overlapping transmission with little inherent crosstalk [2, 3].

In general, the beam properties of a given modal basis can be fully described by two indices, such that these two indices form a two-dimensional set of orthogonal values, e.g., Hermite-Gaussian (HG) beams can be characterized by (m, n) referring to the x and y directions, respectively, and Laguerre-Gaussian (LG) beams can be characterized by (ℓ, p) referring to the azimuthal and radial directions, respectively [4-9]. The different mode-multiplexed beams can be chosen from the different orthogonal values of the modal basis sets.

There have been several reported demonstrations using MDM to achieve higher capacity in free-space optical (FSO) data communication links [10-14]. The modal basis sets used for the FSO transmission of multiple multiplexed data-carrying beams have included LG modes and vector modes; we note that orbital-angular-momentum (OAM) modes are a subset of the LG modal group [15-17]. To the best of our knowledge, there have been few FSO reports of MDM for data transmission that: (i) use multiple multiplexed HG modes, or (ii) simultaneously utilize and vary both of the two modal indices for any modal group, which could potentially provide a larger 2-dimensional modal space of orthogonal data carrying channels and increase the transmission capacity for a communication link.

In this letter, we experimentally demonstrate the four-fold multiplexing of HG or LG modes to achieve a 400-Gbit/s QPSK FSO communication link. By simultaneously utilizing both two modal indices for the HG or LG modes, we transmit four channels, achieving power penalties of <4 dB for all channels. Moreover, we also show the performance degradation dependent on aperture size, as well as the lateral and rotational misalignment between the transmitter/receiver apertures. This experimental analysis

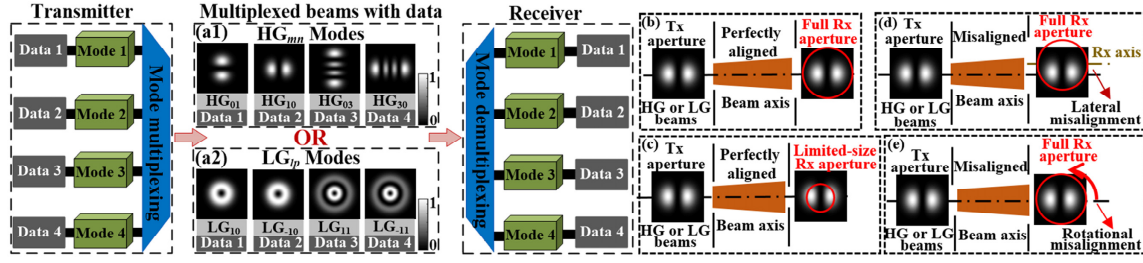


Fig. 1. Conceptual diagram using four HG modes or LG modes for mode-division-multiplexing (MDM) free-space optical (FSO) communication links. The simulated intensity (a1) HG beams (HG₀₁, HG₁₀, HG₀₃, and HG₃₀); (a2) LG beams (LG₁₀, LG₋₁₀, LG₁₁, and LG₋₁₁). Illustration of an MDM FSO communication link with (b) perfect alignment and a full Rx aperture, (c) perfect alignment and a limited-size aperture, (d) lateral misalignment and (e) rotational misalignment between the Tx and Rx. Tx: transmitter; Rx: receiver.

may help in providing more insights into system design, such as minimizing channel crosstalk in systems with limited aperture size; many of these insights can also be determined by analyzing mode profile. We measure various system effects, including: (1) power loss and crosstalk for both HG and LG modes caused by a limited-size aperture, (2) crosstalk increase for LG modes but small crosstalk increase for HG₀₁ or HG₁₀ modes under lateral misalignment between the transmitter and receiver, and (3) crosstalk increase for HG modes but small crosstalk increase for LG modes under a rotational misalignment between the transmitter and receiver.

Fig. 1 shows the concept of a MDM FSO link using four orthogonal modes. HG_{mn} modes (HG₀₁, HG₁₀, HG₀₃, and HG₃₀) or LG_{lp} modes (LG₁₀, LG₋₁₀, LG₁₁, and LG₋₁₁) are selected as examples of the simultaneous utilization of both indices. Specifically, we choose these modes due to their pairwise symmetry, which help reduce the mode dependent penalty (e.g., HG₀₁/HG₁₀, HG₀₃/HG₃₀, LG₁₀/LG₋₁₀, LG₁₁/LG₋₁₁). In the process, independent data-carrying beams with different indices are multiplexed at the transmitter and then co-propagate in free space. At the receiver, the received HG or LG beams are demultiplexed and demodulated.

In an ideal case, the receiver could receive the whole transmitted beams and be perfectly aligned with the transmitter, as shown in Fig. 1(b). For a non-ideal case, there might be misalignment between them, which may cause increased system degradation, when simultaneously utilizing both modal indices for HG or LG sets [18-20]. Moreover, the receiver might have a limited aperture size, which would produce power loss and crosstalk, as shown in Fig. 1(c) [18-20]. The lateral and rotational misalignment between the transmitter and receiver are shown in Figs. 1(d) and 1(e), respectively. These issues might have different effects on HG as opposed to LG modes due to these modes' different 2-dimensional structural characteristics [18-20].

Figure 2(a) illustrates the experimental setup. First, a 100-Gbits/s signal is generated by a bit pattern generator and it is modulated on the beam from an external laser source at 1550 nm by a QPSK transmitter. In the transmitter, the incoming beam is split into two branches, then modulated by Mach-Zehnder interferometer based modulators at 50 Gbaud, and finally combined for output. Subsequently, the signal is amplified by a 15-dB gain EDFA. Then the signal is split into four branches by a ~2-dB excess

loss coupler. Each branch is sent into a collimator that generates a collimated Gaussian beam with a diameter of 3 mm at which the intensity values fall to 1/e² of their axial values. The resulting Gaussian beams are sent to two spatial light modulators (SLMs). The designed phase holograms on each half of the screens are used to generate the four different HG or four different LG by tailoring the amplitude and phase profile of the incoming beam. The loss induced by SLMs for HG and LG mode generation is ~8 dB. These four outputs are multiplexed using three beam splitters. After a coaxial free-space propagation of ~1 m with minimum excess loss in the lab (without additional turbulence effects), the multiplexed beams are directed to SLM-3 at the receiver side, which loads the conjugate phase profile of the desired mode. The experimental intensity profiles and the receiver phase patterns loaded on the SLM-3 for the corresponding HG or LG beams are also shown in Figs. 2(b) and 2(c), respectively. Such phase patterns have circular aperture shapes, whose size are defined as aperture size in our experiment. The loss of SLM-3 is ~2 dB, and the conversion efficiency is ~1 dB for the four LG modes, HG₀₁ and HG₁₀, and ~2 dB for HG₀₃ and HG₃₀. Finally, the resulting beam is coupled into a SMF for coherent detection and bit error rate (BER) measurements.

First, to evaluate the effect of aperture size on the system performance, we measure the received total power and the power on each of the four HG modes or four LG modes with various aperture sizes while only one is transmitted, as

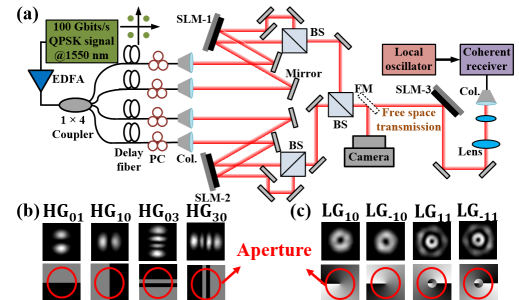


Fig. 2. (a) Experimental setup of an MDM free-space optical communication system multiplexing orthogonal HG or LG modes. QPSK: quadratic phase-shift-keying; EDFA: erbium-doped fiber amplifier; PC: polarization controller; Col: collimator; SLM: spatial light modulator; BS: beam splitter; FM: flip mirror; experimental intensity profiles and receiver phase patterns of (b) four HG and (c) LG beams;

shown in Fig. 3. In all cases, the power values are normalized to the received total power of the desired modes. Such total power is tuned to be almost the same value when the aperture diameter is 4 mm. The received power of the desired mode decreases when decreasing the aperture size of the pattern on SLM-3, because the received beam is too large to be fully captured. We find that an aperture diameter of 4 mm is large enough to avoid obvious power loss for all these modes. Moreover, we observe a power coupling for both the HG and LG modal bases, from the desired mode to other modes when aperture size is smaller than the beam diameter of 3 mm. For example, when transmitting HG₀₁ mode and reducing the aperture size, a power coupling and crosstalk occur from HG₀₁ into HG₀₃, as shown in Fig. 3(a1). Here, we only choose two HG and two LG modes, and it is expected that the other modes (HG₁₀ & HG₃₀ and LG₋₁₀ & LG₋₁₁) would show similar trends.

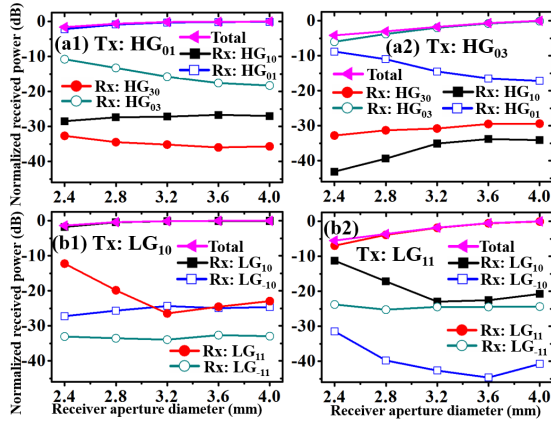


Fig. 3. Normalized received total power and power distribution among the four HG modes when transmitting (a1) HG₀₁ and (a2) HG₀₃ with the aperture diameter. Normalized received total power and power distribution among the four LG modes when transmitting (b1) LG₁₀ and (b2) LG₁₁ with the aperture diameter.

Lateral displacement of the receiver from the optimal line of sight is studied in Fig. 4, where only one HG or LG mode is transmitted with various horizontal displacements emulated by horizontally moving the receiver pattern on SLM-3. The receiver aperture diameter is 4 mm, and the beam spot size is < 4 mm. Figure 4(a) shows that when transmitting the HG₀₁ or HG₀₃ beams, the power on the desired modes does not change too much with the horizontal displacement. This might be caused by the invariance of the receiver phase patterns with the horizontal displacement due to their axial symmetry [19]. However, when transmitting HG₁₀ or HG₃₀ beams, we observe modal coupling occurs from the desired modes to other modes with the horizontal displacement, which would affect their crosstalk behaviors. Figure 4(b) shows the cases of LG beams with the lateral displacement. The results show that as the horizontal displacement increases, it could affect the power coupled into other modes, while the power on the desired mode decreases.

The influence of receiver rotation on system performance is also explored. Figure 5(a) presents the received power on the four HG modes when HG₁₀ or HG₃₀ is transmitted, in which the rotation is emulated by rotating the receiver

patterns. We observe that power of the desired mode decreases gradually with the rotational angle. Moreover, a larger rotation angle could also cause a higher power coupling into some other modes. However, for LG₁₀ modes, the results show that the power change on the four LG modes is negligible when the receiver rotates, which might be due to the rotational symmetry property of LG modes. Furthermore, we could expect the performance trends would be similar when transmitting other LG modes.

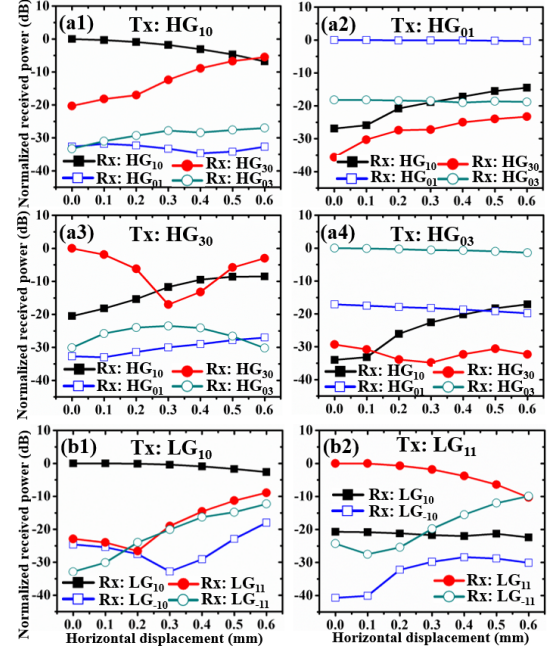


Fig. 4. (a1-a4) Normalized received power among the four HG modes when only one HG mode is transmitted with various lateral displacements. Normalized received power among the four LG modes when transmitting (b1) LG₁₀ or (b2) LG₁₁ with various receiver lateral displacements. The displacement refers to the distance between the beam center and the receiver in horizontal direction.

For the BER measurements, we transmit all four HG or all four LG modes simultaneously, each mode carrying a 100-Gbit/s QPSK signal. First, we measure the crosstalk for all the HG or LG modes with horizontal displacement and rotation angle, as shown in Figs. 6(a1-a3). Here, the crosstalk for a certain mode refers to the power coupled from all the other three modes over the power on the desired mode. We note that for all the four LG modes, the crosstalk increases with the displacement. However, for HG₀₁ and HG₀₃, the crosstalk does not change very much with horizontal displacement due to the relative invariance of their receiver phase patterns with the lateral displacement [19]. In addition, we observe that there is a crosstalk peak for HG₃₀ at the displacement of 0.3 mm. This might be caused by the largest mismatch between the HG₃₀ beam and the receiver phase pattern, which causes a lower received power for the HG₃₀ beam. Furthermore, when the receiver rotation angle increases, the crosstalk for LG modes remains relatively unchanged, whereas the crosstalk increases rapidly for the HG modes.

Figures 6(b1) and (b2) show the measured BERs of all four HG modes or four LG modes as a function of optical

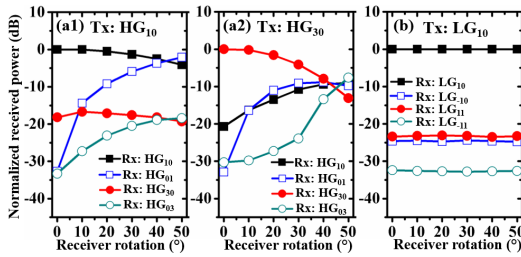


Fig. 5. Normalized received power among the four HG modes or four LG modes when transmitting (a1) HG₁₀, (a2) HG₃₀, and (b) LG₁₀ with various receiver rotation angles. The receiver aperture is circular, with a diameter of 4 mm.

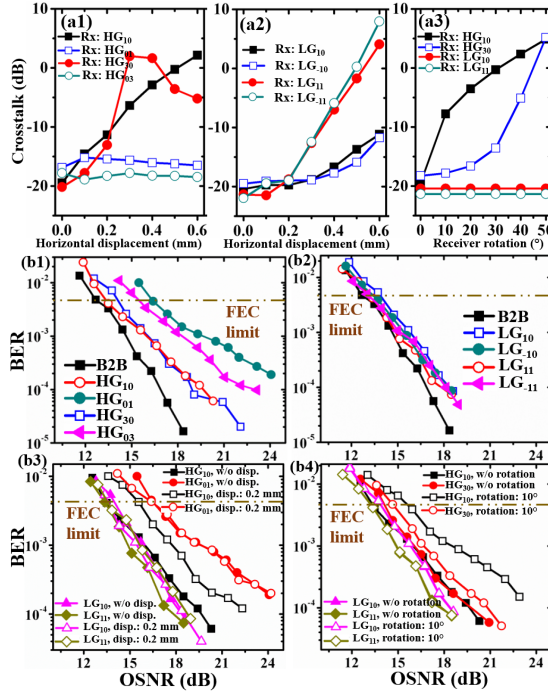


Fig. 6. Crosstalk for each mode when all four HG or LG modes are transmitted with various (a1–a2) receiver lateral displacements or (a3) receiver rotation angles. Measurement of bit error rate (BER) as a function of the optical signal-to-noise ratio (OSNR) for: (b1) all HG modes, (b2) all LG modes with well alignment, HG₁₀, HG₀₁ and LG₁₀, LG₁₁ with and without (b3) a receiver lateral displacement of 0.2 mm, or (b4) HG₁₀, HG₃₀ and LG₁₀, LG₁₁ with and without a receiver rotation angle of 10°. All the four HG or LG beams are transmitted. B2B: back to back; Disp.: displacement.

signal-to-noise ratio (OSNR) with the well-aligned transmitter and receiver, i.e., without lateral or rotational misalignment. The results show at a BER of 3.8×10^{-3} (the 7% overhead forward error correction (FEC) limit), the power penalties of the four LG channels are <2 dB. However, for HG channels, HG₀₁ and HG₀₃ have higher power penalties than HG₁₀ and HG₃₀ due to their higher crosstalk of ~3 and ~2 dB, respectively, which could be caused by the imperfect alignment. This misalignment issue may affect HG and LG modes differently, which could potentially cause the crosstalk difference between HG and LG modes. Figures 6(b3) and (b4) show the measured BERs for two HG modes and two LG modes with a receiver lateral displacement of 0.2 mm and a rotation angle of 10°, respectively. We note that the higher crosstalk for HG₀₁

over HG₀₁ shown in Fig. 6(a1), is reflected in its higher BER power penalty. Again, LG₁₀ and LG₁₁ modes show little BER power penalties, which is also consistent with their crosstalk behaviors in Fig. 6(a2). With a rotation angle of 10°, higher power penalties exist for HG modes due to the higher crosstalk. However, for LG modes, the impact of rotation is relatively small due to the rotational symmetry property. Since HG₁₀ and HG₀₁ behave similarly for a given receiver rotation angle due to their symmetry, we choose non-symmetric HG₁₀ and HG₃₀ for the BER analysis due to their bigger BER performance difference.

Our study uses a circular transmitter/receiver aperture. This was due to that we use circular lenses and fibers. However, a rectangular aperture might be another choice in an MDM FSO link. Although a different shape would likely lead to different results for HG or LG modes, we believe that power loss and crosstalk trends shown in this paper would be similar for rectangular apertures.

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