Demonstration of an Air-Water Communication Link Through Dynamic Aerosol and Water Curvature when Considering the 2-D Modal Coupling of a Spatially Structured Beam

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Abstract: We experimentally investigate the 2-D modal power coupling of LG_{11} and HG_{11} beams under dynamic aerosol and water curvature, and demonstrate a 1-Gbit/s LG_{11}FSO link, having a penalty of ~3-dB compared with no-effect cases.

OCIS codes: (060.2605) Free-space optical communication; (010.7340) Water; (050.4865) Optical vortices

1. Introduction

Free-space optical (FSO) communications has the potential for higher capacity and directionality as compared to radio systems [1]. Even more so, underwater optical communications can have significantly higher capacity when compared to its key communications competitor, that being acoustic waves [2]. There have been reports of underwater optical links in the blue-green wavelength range, and various effects can occur in the underwater environment [2-4].

Importantly, there are scenarios in which the optical data beam experiences a complex and dynamic environment, potentially raising additional challenges. One example is when a platform above the water is communicating at a high data rate with a platform below the water, and vice-versa [5]. In this case, the beam passes through the dynamic aerosol above the water and the dynamically changing water surface curvature at the air-water interface [5-8]. A common fundamental Gaussian beam will experience beam distortion and beam wandering, thereby degrading the link performance [6-8].

This scenario can be even more challenging when the beam is sent on a specific spatial mode and the detector needs to recover and identify the spatial amplitude and phase of the beam. This is the case for mode-division multiplexing (MDM) links, in which multiple data beams are transmitted on many different orthogonal modes [9]. Specifically, the structured beam transmitted through a dynamic air/water interface may experience significant power coupling to neighboring spatial modes, thus degrading the link and causing deleterious crosstalk [10]. These effects and link degradation have been reported for the case of Laguerre Gaussian (LG) beams with only the azimuthal value l being examined for a radial value of p=0 [10,11]. However, degrading modal coupling might occur for both azimuthal and radial components or horizontal and vertical components of a structured beam when considering both aerosol and water surface curvature.

In this paper, we experimentally investigate the 2-D modal coupling of a spatially structured beam that passes through dynamic aerosol and water surface curvature and demonstrate a 1-Gbit/s air-to-water FSO communication link using an LG_{11} beam. The aerosol and water curvature could induce various degradations to a structured beam (e.g., beams carrying LG or Hermite Gaussian (HG) modes), inducing power loss of the transmitted mode and power coupling to the neighboring modes. Experimental results show that: (i) with the temporal frequency of the "sine-shaped" water curvature increase to 8 Hz (~25 mm period for the "sine-shape"), the modal power loss of LG_{11} and HG_{11} beams increase by >4 dB, and their modal coupling to adjacent modes increase by up to 15 dB; (ii) Under 8 Hz curvature, the modal power coupling of an HG_{11} beam is sensitive to the beam rotation angle and that of the LG_{11} beam is less sensitive; (iii) the aerosol with an attenuation of 3-5 dB could increase modal power coupling to adjacent modes by up to 16 dB; (iv) the combination of both effects could further degrade the beam as compared with the single-effect case. We also demonstrate a 1-Gbit/s on-off-keying (OOK) FSO link at 532 nm through the dynamic aerosol and water curvature using a LG_{11} beam, and observe a 3-dB power penalty for a bit-error-rate (BER) at the 7% forward error correction (FEC) limit (3.8×10^{-3}), as compared with the no-effect case.

2. Concept and experimental setup

Fig.1 (a) shows the concept of an FSO link through a dynamic air-water interface using a structured beam. At the transmitter, the data channel is carried by a spatially structured beam, which could be an HG beam (characterized by indices m and n, referring to the horizontal and vertical structures, respectively [12]) or an LG beam (characterized by indices l and p, referring to the azimuthal and radial structures, respectively [12]). When such structured beams are transmitted through the dynamic aerosol and water surface curvature, there could be various degradations suffered by the beam, such as wavefront distortion, beam wandering, scattering, and absorption. Those degradations could affect the amplitude and phase profiles of the received beams, resulting in time-varying modal power loss and power coupling, as shown in Fig. 1 (b). Specifically, the power loss of the transmitted mode would reduce the signal-to-noise ratio (SNR) of the recovered signal; the modal power coupling would result in channel crosstalk when multiple modal channels are multiplexed and transmitted.

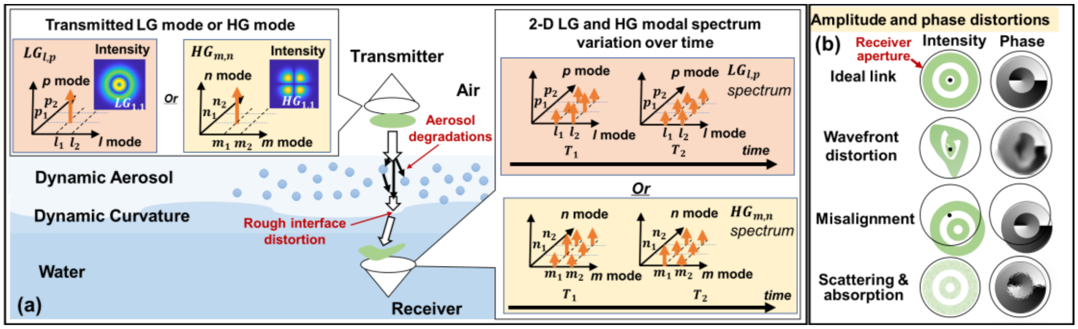

Fig. 1 (a) The concept of the dynamic air-water interface effects on the LG and HG beam propagation. The aerosol and interface curvatures could induce degradations to the transmitted beams, thereby inducing dynamic modal power loss and power coupling. (b) The degradation of amplitude and phase profiles due to wavefront distortion, misalignment, and scattering & absorption. The amplitude and phase profiles of LG_{11} are shown as an example.

Fig. 2 (a) shows the experimental setup. The l-Gbit/s OOK signal carried by 1064-nm laser is coupled into free space through a collimator and then converted to a 532-nm wavelength (green light) Gaussian beam through second-harmonic-generation in PPLN. The light is subsequently split into two branches. One is used as the reference beam, and the other is converted to a designated mode (LG_{11} or HG_{11} with a diameter of ~2 mm) by an SLM. After combining the LG or HG beam with a beacon Gaussian beam (for tracking) at 520 nm, the beams are transmitted through the dynamic air-water interface. The aerosol is generated by an ultrasonic-based aerosol generator, and the "sine-shaped" curvature is induced by a ripple generator. The resulting beam is processed by a tracking system (response speed of ~1 kHz). To measure the LG and HG modal power coupling of the distorted beam, we combine the incoming beam with the reference beam with a tilt angle and measure their interference using a camera (off-axis holography) [13], and the spatial amplitude & phase of the distorted beam as well as the modal spectrum could be subsequently recovered. To measure the BER performance, the incoming beam (e.g., LG_{11}) is spatially transformed back to a Gaussian beam using SLM and coupled into a single-mode-fiber-based receiver. Fig. 2 (b) shows the variation of beam center (i.e., the blue dots) over ~10 s with and without tracking. The results show that the effects of the air-water interface could induce beam wandering, and it is partially mitigated by the tracking system.

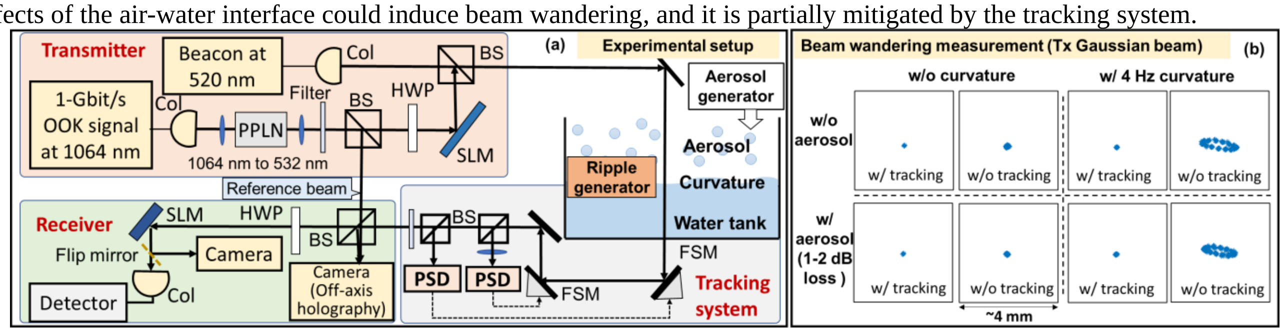

Fig. 2 (a) The experimental setup. Col: collimator; PPLN: periodically poled lithium niobite; SLM: spatial light modulator; HWP: half-wave plate; BS: beam splitter; PSD: position-sensitive detector; FSM: fast steering mirror; The dashed lines are electrical cables. The reference beam is blocked during BER measurements. (b) The recorded beam center positions under various air-water interface effects with and without tracking. The tracking system is always applied for all the modal power coupling, beam profile, and BER measurements.

3. Experimental results

In this experiment, we characterize the "sine-shaped" curvature by its temporal frequency, and the height of the water curvature is ~0.5 mm. We note that the 4 Hz and 8 Hz curvatures have wavelengths (the period of "sine shape") of ~ 75 and ~25 mm, respectively. Moreover, we characterize the aerosol by its attenuation towards a Gaussian beam in free space, and the attenuation is 1-2 dB and 3-5 dB for the two aerosol cases, respectively. We note that the aerosol particle size is ~ 5 μm.

Fig. 3 shows the received power on each LG and HG mode under various aerosol and curvature conditions when LG_{11} and HG_{11} beams are transmitted, respectively. Aerosol cases with attenuations of 1-2 and 3-5 dB could increase the power coupling to the adjacent modes ([$LG_{01}, LG_{10}, LG_{02}, LG_{20}$] for LG_{11} and [$HG_{01}, HG_{10}, HG_{02}, HG_{20}$] for HG_{11}) by up to ~13 and ~16 dB, respectively. This could be because the aerosol induces spatial-dependent absorption and scattering, resulting in amplitude and phase distortions of received beams. Moreover, the curvature with a frequency of 4 and 8 Hz increases the modal power coupling to adjacent modes by up to ~8 and ~15 dB, respectively. This could be due to the amplitude and phase of the received beam being affected by: (i) the curvature-induced wavefront distortion [8], and (ii) the beam-wandering-induced residual misalignment between the beam and the receiver [6]. With the combination of both effects, the modal power coupling and/or modal power loss are further increased as compared with the single-effect cases.

Fig. 4 (a) shows the example amplitude and phase profiles of the received LG_{11} beam under aerosol and curvature effects. Such distortion of the beam amplitude and phase profiles could be the reason for the modal power coupling shown in Fig. 3. Moreover, we can observe from Fig. 3 that the modal power coupling of HG_{11} is mainly along the direction of *n* modes under 8 Hz curvature, which might be due to that the curvature is mainly along the direction of *n* modes. To investigate the sensitivity of LG_{11} and HG_{11} beams to curvature direction, we rotate the beams and investigate the variation of their modal power coupling (example images of beams are shown in Fig. 4 (b2-b5)). As shown in Fig. 4 (b), under the 8 Hz curvature effect, the modal power coupling and modal power loss of the LG_{11} beam remains similar under different beam rotation angles, which could be due to that the LG_{11} beam is azimuthally symmetric. On the other hand, the modal power coupling of HG_{11} varies with beam rotation angles, due to its azimuthal asymmetry, thereby being sensitive to the direction of curvature.

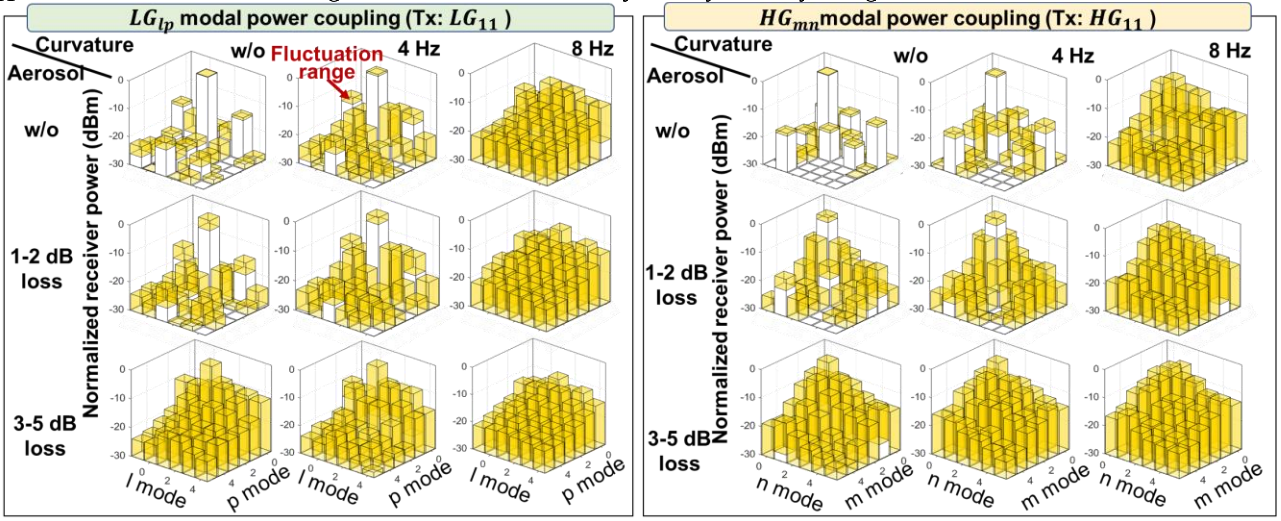

Fig. 3 The fluctuation range (i.e., the yellow bar) of received power on the LG and HG modes under various curvature and aerosol conditions. The total time for measurement is ~10 s. The measurement of each sample takes ~0.1 ms, and the sample rate is 15 Hz. The curvatures have "sine-shapes", and their spatial periods are ~75 and ~ 25 mm for the 4 Hz and 8 Hz curvatures, respectively. The modal power is normalized by the total received power of the beam.

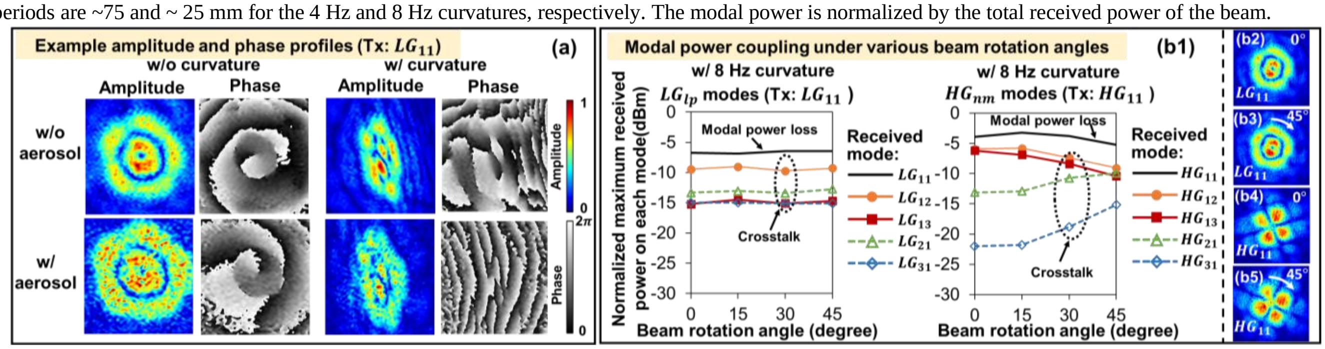

Fig. 4 (a) The example amplitude and phase profiles of a distorted LG_{11} beam under curvature and aerosol effects. (b1) The modal power loss and power coupling for LG_{11} and HG_{11} beams under various beam rotation angles. (b2-b5) Example beam amplitude profiles under different rotation angles.

We analyze the performance of an FSO link using a single LG_{11} beam as an example to show the potential degradations. Fig. 5 (a) shows the modal power loss and power coupling variation over time for LG_{11} beam under the interface effects. Such dynamic modal power loss would induce a time-varying SNR at the receiver, and thereby affect the BER performance. If multiple modal channels are multiplexed, the dynamic power coupling could further degrade the link by inducing channel crosstalk. Fig. 5 (b) shows the BER performance of a single LG_{11} channel under various scenarios. The results show that the combination of 4 Hz curvature and aerosol with 1-2 dB attenuation could result in a 3-dB power penalty for a BER at the FEC limit, which might be due to the dynamic modal power loss shown in Fig. 5 (a).

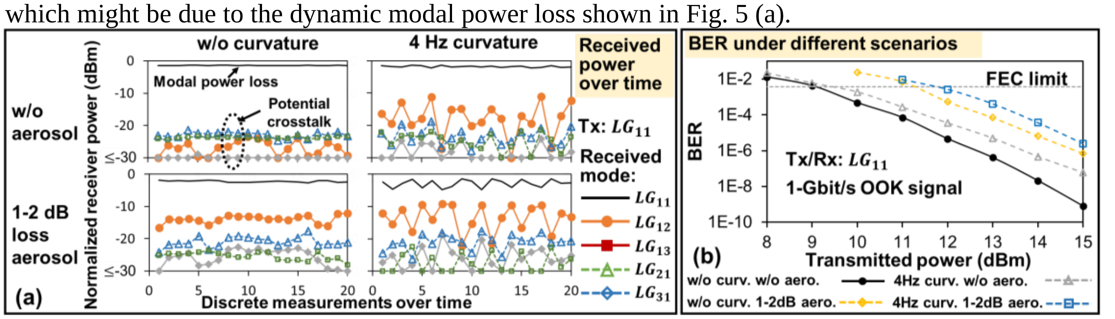

Fig. 5 (a) The power of each mode when LG_{11} is transmitted. Each measurement takes ~0.1 ms and the time difference between adjacent measurements is ~ 0.07 s. The measurement with the same measurement number under different scenarios have different aerosol and curvature conditions, and therefore they can't be compared directly. (b) The BER under various interface effects. The measurement of each data point takes >30 s.

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Reference: [1] V. Chan VW. J. Light. Technol **24**, 4750 (2006). [2] H. Kaushal et al., IEEE Access **4**, 1518 (2016). [3] J. Baghdady et al, Opt. Express **24**, 9794 (2016). [4] Z. Zeng et al., IEEE Commun. Surv. Tutor. **19**, 204 (2016). [5] X. Sun et al., IEEE Access **8**, 160480 (2020). [6] O. Alharbi et al., Laser Comm. and Prop. through the Atmosphere and Oceans, 1077002 (2018). [7] R. F. Lutomirski, Ocean Optics, 110 (1978). [8] P. Land et al., Ocean Sensing and Monitoring, 982703 (2016). [9] J. Wang et al., Nat. Photonics **6**, 488 (2012). [10] H. Song et al., OFC, W6A.25 (2021). [11] H. Song et al., CLEO, W6A.25 (2021). [12] L. Allen et al., Phys. Rev. A **45**, 8185 (1992). [13] Y. Zhou et al., Photonic Networks and Devices, NeW2B-5 (2020).