Experimental Demonstration of a 100-Gbit/s 16-QAM Free-Space Optical Link Using a Structured Optical “Bottle Beam” to Circumvent Obstructions

Huibin Zhou [(1)], Nanzhe Hu[(1)], Xinzhou Su[(1)], Runzhou Zhang[(1)], Haoqian Song[(1)], Hao Song[(1)], Kai Pang[(1)], Kaiheng Zou[(1)], Amir Minoofar[(1)], Brittany Lynn[(2)], Moshe Tur[(3)], and Alan E. Willner[(1)]

[(1)] Department of Electrical Engineering, Univ. of Southern California, Los Angeles, CA 90089, USA
[(2)] Naval Information Warfare Center Pacific, San Diego, CA, 92152, USA
[(3)] School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, Israel
huibnzh@usc.edu

Abstract *We experimentally demonstrate a 100-Gbit/s 16-QAM free-space optical link using/tailoring an optical bottle beam to circumvent obstructions with different sizes and locations. Experimental results show ~10-dB less obstruction-induced power penalty compared to using a Gaussian beam for the obstruction with a diameter of ~4.5 mm.*

Introduction

Free-space optical (FSO) communication links can provide higher capacity and lower probability of intercept when compared to RF links [1,2]. These advantages are partially due to the smaller carrier wavelength and beam divergence [1,2]. One key limitation of FSO links is the susceptibility to beam obstructions, which can cause power loss and link outage.

Often, these obstructions could be of the same order of magnitude as the beam diameter itself [3]. Moreover, some techniques have been shown to locate the size and distance of obstructions, even if they are dynamically moving [4,5]. In such a scenario, a possible desirable feature could be to tailor a beam at the transmitter such that the beam curves around the obstruction to circumvent its deleterious effects, and subsequently reforms into its original shape and straight propagation direction. One such structured beam is a “bottle beam”, in which the beam forms an empty space at a specially designed location and a particular size [6].

In this paper, we experimentally demonstrate a 100-Gbit/s 16 quadrature amplitude modulation (16-QAM) FSO link using an optical bottle beam to circumvent obstructions. During the propagation, the energy of an optical bottle beam flows through a three-dimensional curved shell which creates a bottle-like region with low or null intensity. The bottle beam could circumvent an obstruction that is located inside the bottle region. The bottle beam is generated by structuring a Gaussian beam with a waist diameter of 7 mm. Experimental results show that, for the obstruction with a diameter of ~4.5 mm, the bottle beam suffers ~10-dB less obstruction-induced power penalty as compared to a Gaussian beam. We also experimentally demonstrate tailoring the bottle beam to circumvent obstructions with different sizes and locations.

Concept and experimental setup

Figure 1(a) shows the concept of utilizing a bottle beam to circumvent the obstruction for an FSO communication link. As shown in Fig. 1 (a1), the obstruction could degrade the performance of an FSO link using a Gaussian beam. Since the transmitted beam is partially blocked by the

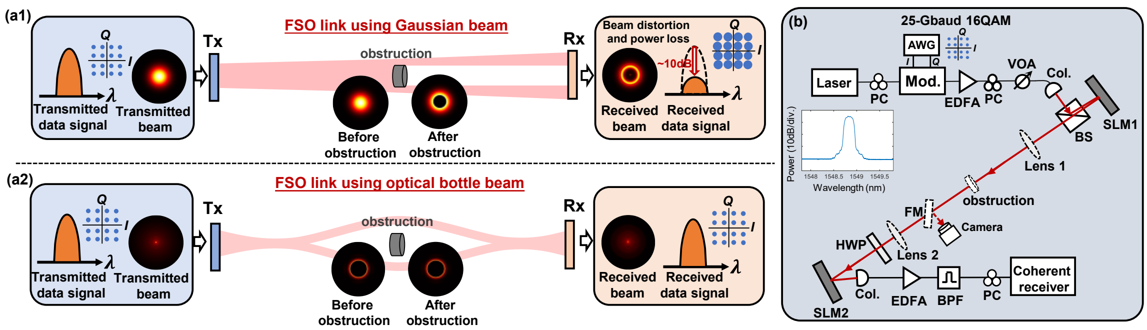

Fig. 1: (a1) FSO link using a Gaussian beam could suffer from obstruction-induced power loss and beam distortion, and (a2) the optical bottle beam could circumvent the obstruction to mitigate the degredation effects. Tx; transmitter; Rx: receiver. (b) Experimental setup for a 25-Gbaud 16QAM FSO link using an bottle beam to circumvent an obstruction. Inset shows the optical spectrum of the generated signal. PC: polarization controller; VOA: variable optical attenuator; Col.: collimator; BS: beam splitter; SLM: spatial light modulator; FM: flip mirror; HWP: half-wave plate; BPF: band pass filter.

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obstruction, less power could be received at the receiver (Rx). Moreover, the obstruction also distorts the beam's spatial mode structure and induces modal power coupling to higher-order mode [7]. If the beam is coupled back to a single-mode fiber (SMF) at Rx, such modal coupling could further degrade the performance because of the power in the higher-order modes not being efficiently coupled into the fiber [8]. As shown in Fig. 1 (a2), the optical bottle beam has a bottle-like propagation property with a low or null intensity region in the middle surrounded by 3-dimensional regions of higher intensity [6]. The energy of the optical bottle beam flows through a 3D curved shell and could circumvent the obstruction. A bottle beam could be generated by spatially structuring a Gaussian beam using a designed structuring pattern [9]. Moreover, some techniques have been shown to detect the size and location of obstructions [3,4]. Once these obstructions' information is obtained, the size and location of the beam's bottle could be tailored by changing the structuring pattern to circumvent different obstructions in an FSO link [10,11].

Figure 1 (b) shows the experimental setup for a 25-Gbaud 16-QAM FSO link using an optical bottle beam to circumvent an obstruction. At the transmitter (Tx), an I/Q modulator is used to modulate a Nyquist-shaped (roll-off factor 0.35) 25-Gbaud 16-QAM signal. After being amplified by an EDFA, the signal is coupled into free space through a collimator. A VOA is used to control the transmitted power. The Gaussian beam with a waist diameter of 7 mm is incident on the spatial light modulator (SLM1). The optical bottle beam is generated by Fourier-transforming (FT) an appropriately apodized beam whose radial oscillations are chirped by a cubic phase term

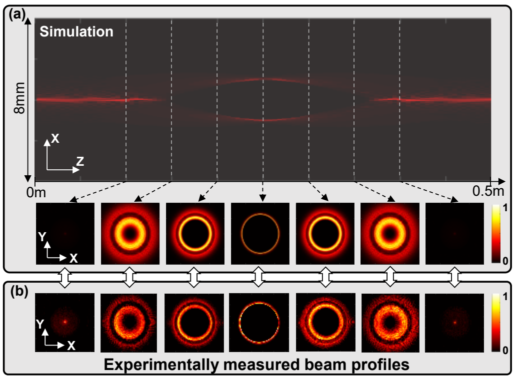

Fig. 2: (a) Simulated beam propagation and profiles of the bottle beam. (b) Experimentally measured beam intensity profiles of the generated bottle beam.

[6,9]. The designed pattern is loaded on the SLM1 for the optical bottle beam generation [9]. The bottle of the beam is generated at the back focal plane of the FT-lens (Lens1 with a focal length of 250 mm). A circle-like obstruction with a diameter (D) of ~3 mm (smaller obstruction) or ~4.5 mm (larger obstruction) is placed on the axis of the propagation path. The link propagation distance is 0.5 m (between Lens1 and Lens2). At Rx, the SLM2 with the conjugated phase pattern is used to convert the bottle beam back to a Gaussian beam, and subsequently, the beam is coupled to SMF and detected by a coherent receiver. We note that for the demonstration of an FSO link using a Gaussian beam, the Lens1 and Lens2, which are used for generation and detection of the bottle beam, are removed. Moreover, SLM1 and SLM2 only reflet the beam without modulating its spatial profile.

Results

Figure 2 shows the simulation and experimental results of the generation and propagation of the

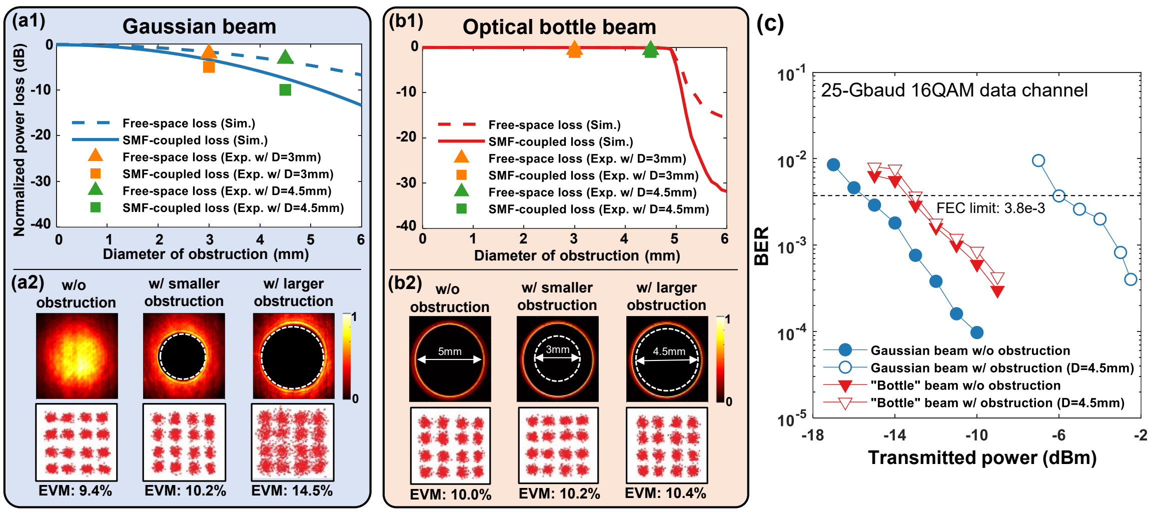

Fig. 3: Simulated and experimentlly measure free-space and SMF-coupled power loss for the Gaussian (a1) and bottle beam (b1). Sim.: simulation; Exp.: experimental. Experimentally measured beam profiles and the EVM performance of the data signal w/ and w/o obstructions for the Gaussian (a2) and bottle beam (b2). (c) BER performance for the Gaussian and bottle beams w/o and w/ the larger obstruction under different transmission optical power.

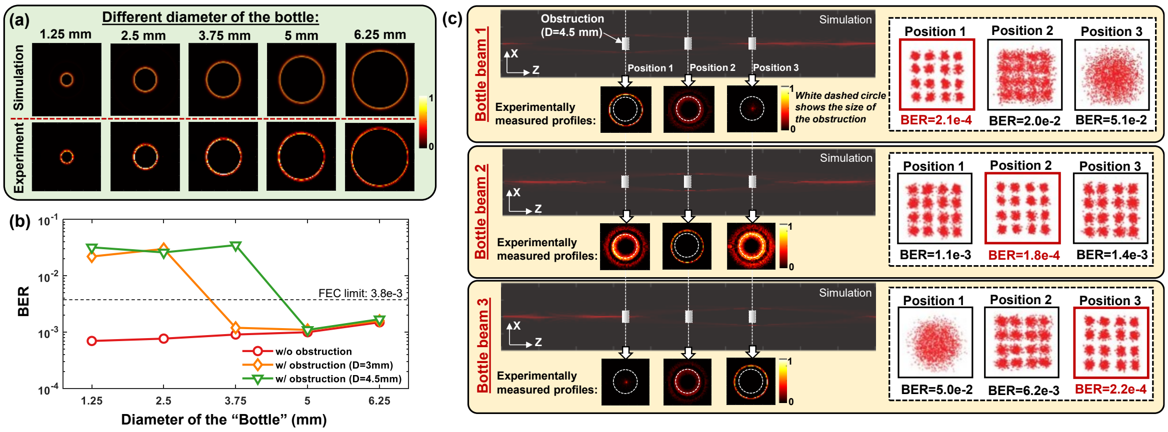

Fig. 4: (a) Simulated and experimentlly measured profiles for bottle beams with different bottle sizes. (b) BER performance for bottle beams with different bottle sizes w/o and w/ obstructions. (c) Simulated beam propagation and experimentally measure profiles of bottle beams. Constellations and BER are measured w/ the obstruction located in different positions.

bottle beam. As shown in Fig. 2 (a), during the propagation in the z-direction, the beam first starts to have a ring-like intensity profile with increasing size and low intensity at the center. Subsequently, the diameter of the ring (*i.e.* bottle size) becomes smaller and a closed "bottle" region is created. The profiles of the generated bottle beam shown in Fig. 2 (b) are closely matched with the simulation results.

We compare the performance of an FSO link using a Gaussian beam and a bottle beam (with a bottle size of 5 mm), as shown in Fig. 3. We measure the normalized power loss (dots in Fig. 3 (a1) and (b1)) induced by the obstruction in free space (loss blocked by the obstruction) and after coupling back to SMF (counting the loss caused by modal coupling). The free-space loss of the Gaussian beam is ~2 and ~5 dB for the smaller and larger obstruction, respectively. The SMF-coupled loss is ~3.2 and ~10 dB for the smaller and larger obstruction, respectively. However, since the bottle beam could circumvent the obstruction, the free-space loss and fiber-coupled loss for the bottle beam are <1 dB for both smaller and larger obstructions. We also simulate the power loss (curves in Fig. 3 (a1) and (b1)) for obstruction with different sizes. The simulation results show that the bottle beam is robust to the obstructions with a diameter of <~5 mm. Figure 3 (a2) and (b2) show the measured beam profiles and error vector magnitude (EVM) performance of the data signal w/ and w/o obstructions. The results show that the EVM degrades from 9.4 to 14.5% for the Gaussian beam, while the performance of the bottle beam is much less affected by the obstructions. Figure 3 (c) shows the bit error rate (BER) performance for the Gaussian and bottle beam w/o and w/ the larger obstruction under different transmission power. Compare to the case of w/o obstruction, the Gaussian beam suffers ~10-dB more power penalty as compared to the bottle beam at the 7% forward error correction (FEC) limit. Without obstructions, the worse performance of the bottle beam might be caused by the conversion loss when generating and detecting the bottle beam.

The bottle size and the location of the bottle could be tailored to circumvent obstructions with different sizes and locations. As shown in Fig. 4 (a), we change the diameter of the bottle (ranging from 1.25-6.25 mm) by loading different designed phase patterns on SLM1. The BER performance for different bottle sizes w/o and w/ obstructions are shown in Fig. 4 (b). The results show that, if the size of the bottle is larger than the size of the obstruction, the performance is little affected by the obstruction. However, if the bottle size is smaller than the obstruction, it is difficult to recover the data signal.

The location of the bottle in the propagation path could also be tailored by encoding an additional quadratic phase modulation onto the initial cubic phase pattern [10,11]. As shown in Fig. 4 (c), we generate three different bottle beams (bottle size is 5 mm) with their bottle located at Z=0.17 m (Position 1), Z=0.25 m (Position 2), and Z=0.33 m (Position 3). We measured the data constellations and BER performance for these three beams when the obstruction is located at one of these three positions. The results show that when the location of the bottle is closer to the location of the obstruction, the beam could be less affected and the link has a better performance.

Acknowledgments

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