Alignment Monitor for Free-Space Optical Links in the Presence of Turbulence using the Beating of Opposite-Order Orbital-Angular-Momentum Beams on Two Different Wavelengths

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Abstract: We experimentally demonstrate an approach for monitoring misalignment between transmitter and receiver for free space optical links under turbulence effects using the beating of two opposite-order orbital-angular-momentum beams on two different wavelengths.

OCIS codes: (060.2605) Free-space optical communications; (010.1330) Atmospheric turbulence; (050.4865) Optical vortices.

1. Introduction

There is growing interest in free-space optical (FSO) communication links in a terrestrial that can transmit large quantities of data [1]. Such links can be composed of a single data-carrying laser beam, such as a fundamental Gaussian beam [2]. There have also been advances in using multiple data-carrying beams simultaneously to potentially increase data capacity. One approach is the use of mode-division-multiplexing (MDM), which is a subset of space-division-multiplexing. In an MDM link, multiple orthogonal beams can be multiplexed at the transmitter (Tx) aperture, spatially co-propagate through air, and demultiplexed at the receiver (Rx) aperture [3]. One example of MDM is to transmit each beam on a different orthogonal orbital-angular-momentum (OAM) mode [4].

In all FSO links, and especially in links involving moving platforms such as airplanes, ships, and drones, a key challenge is to accurately align the Tx and Rx apertures. One typical approach for alignment is to transmit a fundamental Gaussian beacon beam, and use its intensity gradient as an error signal to monitor alignment and correct any offset [5]. This approach can also be extended to using OAM beams [6].

However, atmospheric turbulence can significantly corrupt the intensity profile of Gaussian and OAM beams, making it difficult to use the intensity gradient for misalignment monitoring purposes [7,8]. A laudable goal would be to monitor the Tx-Rx aperture misalignment in both conventional and OAM-based FSO links using an approach that is tolerant to a turbulent environment.

In this paper, we show by experimental demonstration and simulation an alignment monitor for FSO links in the presence of turbulence using the beating of opposite-order OAM beams on two different wavelengths. Two OAM $l = +1$ and $l = -1$ beams carried by two different wavelengths are transmitted co-axially through various emulated turbulence (1-mm Fried parameter) and Tx-Rx misalignment conditions. A free space photodetector is used to collect the distorted and truncated OAM beams, and the received beating strength (i.e., tone at their frequency difference) is utilized to estimate the horizontal and vertical offsets between Tx and Rx. The measured dependence of tone strength on the misalignment matches with simulation results. Experimental results show that (i) Different turbulence realizations do not significantly affect the monitoring performance of this approach: this is verified by the measured similar dependence of tone strength on the misalignment under 5 different turbulence realizations; and (ii) With such tolerance to turbulence effects, alignment monitoring ranges of ~3.7 mm and ~4.1 mm, and monitoring dynamic ranges of 30.4 dB and 34.8 dB are measured for vertical and horizontal offsets, respectively.

2. Concept and experimental setup

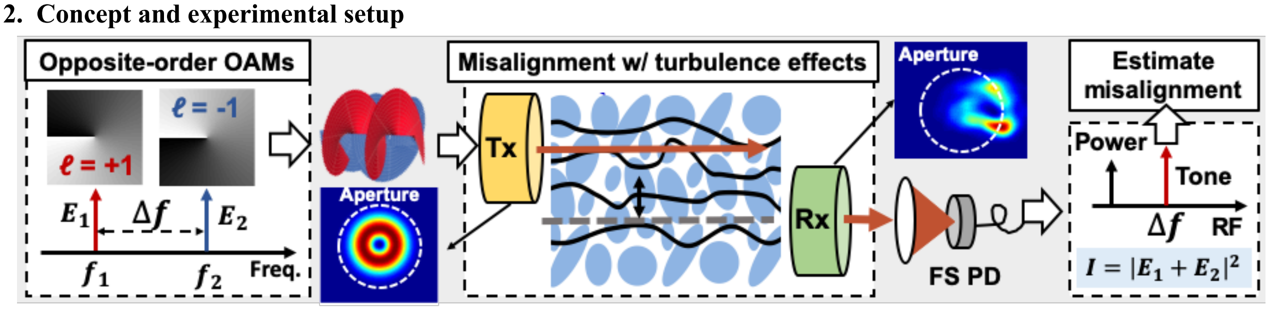

Figure 1. Concept for using the beating tone of two opposite-order OAM beams on different wavelength to monitor the misalignment of an FSO link in the presence of atmospheric turbulence. Two OAM beams with opposite order $l = +1$ and $l = -1$, respectively, are transmitted co-axially through emulated turbulence and then received by a misaligned Rx and focused to a free-space photodetector (PD). These two distorted OAM beams would beat at the surface of the PD and contribute to a tone located at their frequency difference. The strength of such a tone is measured to estimate the misalignment of such an FSO link.

Figure 1 shows the concept of monitoring the misalignment in a turbulence-affected FSO link by measuring strength of the beating tone between two OAM beams with opposite orders at different wavelengths. At the Tx, OAM $l = +1$ and $l = -1$ beams on two different wavelengths (spaced by frequency difference Δf) are transmitted co-axially through turbulence effects. The turbulence is emulated by a single-phase screen, whose random transfer function $\boldsymbol{U}(x, y) = \exp(j\psi(x, y))$ multiplies the two incident OAM beams $\boldsymbol{E}_1(x, y)$ and $\boldsymbol{E}_2(x, y)$. Since the $l = +1$ and $l = -1$ beams share the same spatial intensity profile, they would experience similar turbulence distortions and the emerging light fields are $\boldsymbol{U} \cdot \boldsymbol{E}_1$ and $\boldsymbol{U} \cdot \boldsymbol{E}_1$, respectively. At the Rx, the collected distorted beams are focused into and beating at the surface of a free space photodetector (PD) which converts the light power to an AC current component at frequency Δf(i.e. beating tone) by [9,10]: $I \propto \iint A(x, y) \cdot (\boldsymbol{U} \cdot \boldsymbol{E}_1) \cdot (\boldsymbol{U} \cdot \boldsymbol{E}_1)^* dxdy$, where $A(x, y)$ is the aperture function. If the Rx is perfectly aligned (i.e., $A(x, y) = 1$), such an integral would vanish because of orthogonality between these two beams $\iint \boldsymbol{E}_1 \cdot \boldsymbol{U} \cdot \boldsymbol{U}^* \cdot \boldsymbol{E}_2^* dxdy = \iint \boldsymbol{E}_1 \cdot \boldsymbol{E}_2^* dxdy = 0$ and there is little power on the tone. However, more importantly, if the Rx is misaligned, these two beams' orthogonality would degrade such that the integral would contribute to the tone at frequency Δf and the tone strength can be utilized to infer the misalignment of this FSO link.

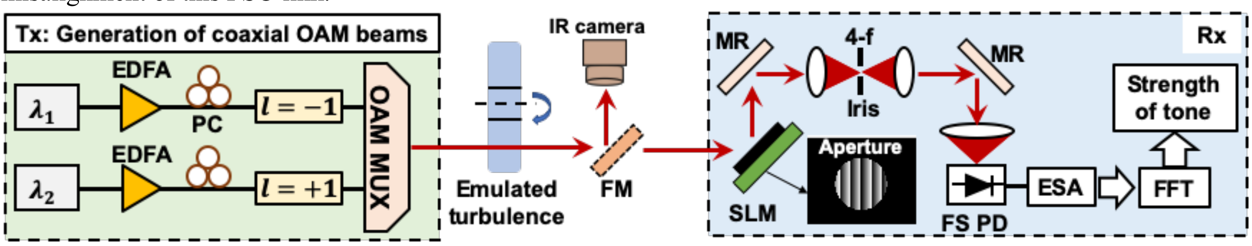

Figure 2. Experimental setup of monitoring the misalignment of an FSO link under turbulence effects: the OAM beams are transmitted separately through the emulated turbulence effects. The beating strength of OAM $l = \pm 1$ beams is used to estimate the Rx misalignment. EDFA: erbium-doped fiber amplifier; PC: polarization controller; SLM: spatial light modulator; FM: flip mirror; IR: infrared; FS PD: free space photodetector.

Figure 2 shows the experimental setup. At the Tx, two different lasers with wavelength 1548.94 nm and 1548.967 nm (shown in Fig. 3a) are amplified by erbium-doped fiber amplifiers (EDFAs) and fed into an OAM multiplexer (CAILabs) to generate co-axial OAM $l = +1$ and $l = -1$ beams, respectively. Their polarizations are controlled to be at the same linear polarization and propagate co-axially through the emulate turbulence. Such turbulence effect is emulated by a thin phase plate which obeys Kolmogorov spectrum statistics with an effective Fried coherence length $r_0 = 1$ mm. Different realizations of turbulence effects are implemented by rotating the phase plate to random orientations. At the Rx, a spatial light modulator (SLM) is used to emulate different aperture sizes, horizontal and vertical offsets (misalignment). A 4-f system is placed after the SLM to filter the 1st-order diffracted light and then the beams are focused into a free-space photodetector (FS PD, Thorlabs DET08C). An electrical spectrum analyzer (ESA) is connected to a free space PD to measure the strength of the beating tone.

3. Experimental results and discussion

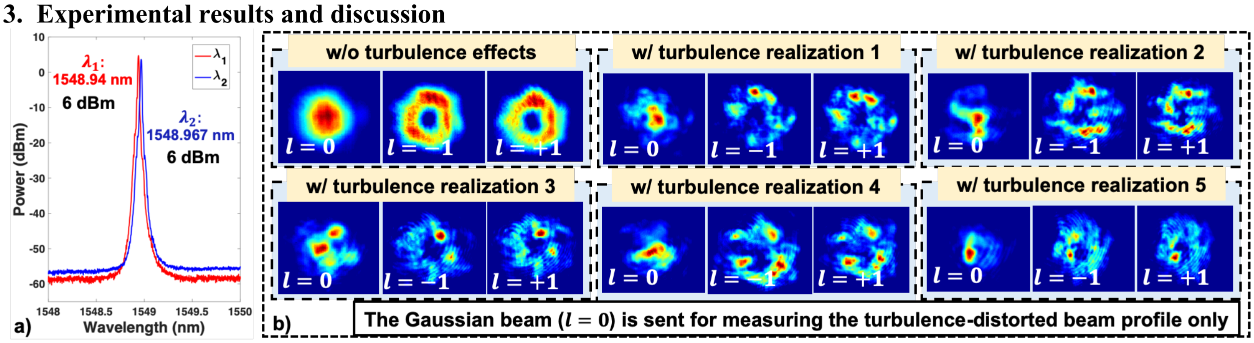

Figure 3. a) Measured optical spectrum of two laser sources around 1550 nm; b) Measured intensity profiles for Gaussian ($l = 0$) and OAM $l = \pm 1$ beams under effects of 5 different turbulence realizations: each beam is sent one at a time. The Gaussian beam is transmitted for beam profile measurement only (to indicate the turbulence distortions) and the two OAM modes would be sent simultaneously for alignment monitoring.

The launched power for each OAM mode coupling to the free space is measured to be ~6 dBm. Fig. 3b shows the measured intensity profiles of the Gaussian and OAM beams under different turbulence realizations. Their beam profiles may vary greatly as the turbulence realization changes. The measured and simulated tone strength versus different misalignment without turbulence effects are shown in Fig. 4a: The simulated tone strength is symmetric about the zero offset and have the same dependence on the horizontal and vertical offsets. It is shown in Fig. 4a that the measured data points fit with the simulation. The measured electrical spectrum with effects of turbulence realization 2 are shown in Fig. 4b and Fig. 4c: if there is no misalignment, there is little power at the beating frequency; if a horizontal offset of -1.84 mm is induced, a tone strength of ~24.4 dB is observed.

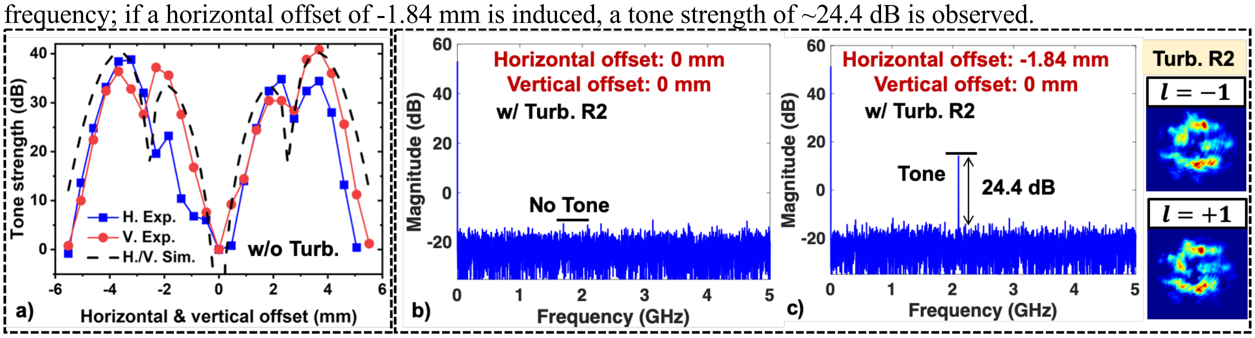

Figure 4. a) Measured and simulated tone strength versus horizontal or vertical offsets without turbulence effects; b) Measured electrical spectrum with turbulence realization 2 and without misalignment; c) Measured electrical spectrum with turbulence realization 2 and with horizontal offset -1.84 mm; The distorted profiles of OAM $l = +1$ and $l = -1$ beams are also shown. The aperture radius is 3 mm for both the experiment and simulation. H.: horizontal; V.: vertical; Exp.: experiment; Sim.: simulation; Turb. R2: turbulence realization 2.

Figure 5a and 5b shows the measured tone strength versus different vertical and horizontal offsets under different realizations (R1-R5) of turbulence effects. It is observed that turbulence-induced tone strength shows similar dependence on the Rx misalignment as the case of without turbulence effects. This further indicates that turbulence does not significantly affect the monitoring performance. With such tolerance to turbulence, we measure a monitoring range (i.e., the strength 'dip' near zero offset) of ~3.7 mm and ~4.1 mm for vertical and horizontal misalignments, respectively. The dynamic range for normalized tone strength within the monitoring range are 30.4 dB and 34.8 dB, respectively.

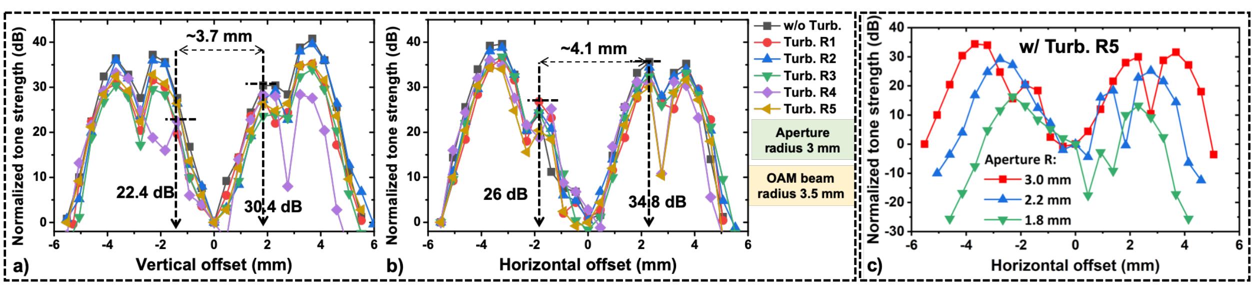

Figure 5. a) and b): Measured tone strength (normalized) versus vertical and horizontal offset under different turbulence realizations (R1-R5); The aperture radius is 3 mm for all measurements in a) and b). Results show that the alignment monitoring is tolerant to the emulated turbulence effects due to similar tone strength's dependence on the misalignment under different realizations; c) Measured tone strength versus horizontal offset with different aperture radius 1.8, 2.2, and 3.0 mm (turbulence realization 5). OAM beams' radiuses are measured to be ~3.5 mm.

The effects of aperture size on the monitoring performance under turbulence realization 5 is shown in Fig. 5c: the monitoring tends to degrade as the Rx aperture decreases from 3.0 mm to 1.8 mm because the aperture size is reaching the size of OAM beams. Therefore, the Rx aperture size may need to be optimized to obtain better misalignment monitoring performance.

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