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Turbulence-resistant free-space communication using few-mode pre-amplifiers

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ABSTRACT

Turbulence can distort the signal wavefront in free space optical (FSO) communications, leading to errors. The state-of-the-art method for correcting distortions is adaptive optics (AO). We show that improvements in turbulent FSO communication link performance can be obtained using a few-mode optical pre-amplified receiver, without AO. We compare pre-amplified few-mode and single-mode receivers for both OOK and DPSK modulation formats.

Keywords: Turbulence, Adaptive optics, Free-space optical communications, Few-mode, Optical pre-amplifier, Erbium-doped fiber amplifier, OOK, DPSK

1. INTRODUCTION

Free-space optical (FSO) communications offers five orders of magnitude greater bandwidth than widely deployed radio-frequency (RF) communications.[1] Optical communication also has the advantage over RF that its spectrum does not need to be licensed.[1] However, FSO communications is susceptible to atmospheric turbulence causing wavefront distortions which lead to detection errors and reduced system reliability.[2]

The state-of-the-art method for distortion correction is adaptive optics (AO).[3] Adaptive optics senses and corrects for wavefront distortions by applying the reciprocal distortion using reconfigurable devices, such as deformable mirrors or spatial light modulators. For maximum theoretical receiver sensitivity, AO can be used with a single-mode (SM) pre-amplified receiver to achieve a sensitivity of 10s of photons per bit at Gb/s rates.[4] However, AO's ability to compensate for wavefront distortions is often less than ideal, limited by the system resolution, dynamic range, and response time. Due to these limitations, AO often performs worse than the theoretical sensitivity limit and can have variable efficacy. Currently, the main impediment to widespread FSO communication adoption is robustness.[2] Therefore, finding FSO systems that are resilient to wavefront distortions is critical.

Wavefront distortions lead to the generation of higher order modes and the formation of a multimode (MM) beam. If all photons in all modes are collected and the photocurrent is added constructively, wavefront corrections, like those performed by adaptive optics AO, become unnecessary. While MM photodetectors collect all photons, they are thermal noise limited with a corresponding sensitivity of 1000s of photons per bit at Gb/s rates at room temperature.[4] Few-mode (FM) pre-amplified receivers also collect roughly all modes of the distorted wavefront, but with higher sensitivity than MM photodetectors.

Previous experiments have demonstrated, using on-off keying (OOK) modulation, a turbulence-resistant communication link using a few-mode pre-amplified receiver, which had a 6 dB greater power budget compared to a single-mode pre-amplified receiver.[2,5] In these experiments, a cladding-pumped 10-mode Erbium-doped fiber amplifier (EDFA) was used and there was a wavefront distortion of 4π across the receiving aperture.[2,5]

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In this paper, we demonstrate numerically that FM optically pre-amplified receivers should have better performance than SM pre-amplified receivers in turbulent links. We compare pre-amplified FM and SM receivers for both OOK and differential phase-shift keying (DPSK) modulation formats. We also describe an experiment that can be used to experimentally verify our numerical results. Few-mode optical pre-amplified receivers offer a robust and comparatively inexpensive alternative to AO.

2. THEORY

In turbulent media, wavefront distortions of an optical signal produce a MM beam. Coupling efficiency of the distorted signal into a FM fiber is higher than into a SM fiber, due to the presence of higher order modes. Increased coupling efficiency will lead to better system performance. However, there exists a balancing force.

In MM pre-amplified receivers, as the number of modes supported by the pre-amplified receiver increases, so does the ASE noise, thereby reducing the sensitivity of the detector. To achieve better performance with a FM pre-amplified receiver, compared to a SM pre-amplified receiver, the coupling efficiency improvement must be greater than the sensitivity degradation. We explore the interplay between these two factors in the following sections.

2.1 Coupling Efficiency

As turbulence increases, the beam on average should be comprised of more modes and the coupling efficiency for low mode number fibers should decrease. To evaluate coupling efficiency performance of SM and FM receivers, coupling efficiency was calculated for a SMF and 10-mode fiber as a function of $(D/r_0)^{5/6}$, for a fixed beam diameter of 1 cm and a coherence length, r_0. For each coherence length, 20 wavefront distortions were generated which followed the Kolmogorov turbulence model $\Phi(\kappa) = 0.023 r_0^{-5/3} \kappa^{-11/3}$, where κ is a two-dimensional spatial-frequency vector.[6]

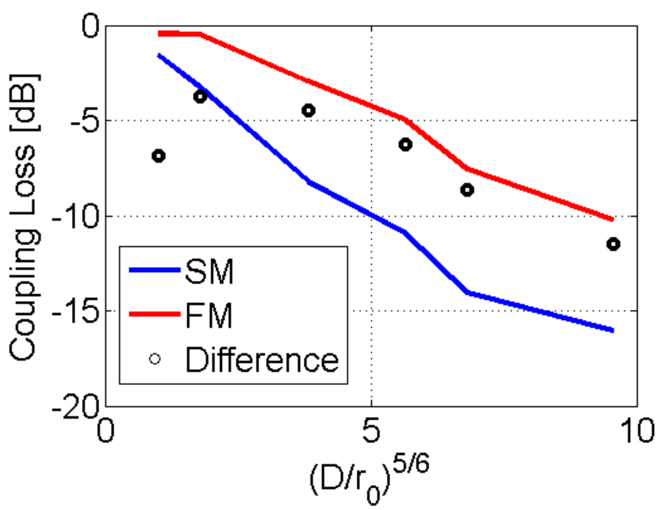

Figure 1. Coupling loss increased with stronger turbulence for both the SMF and 10-mode FMF. The SMF was more affected by turbulence and as turbulence increased, the difference in coupling efficiency between the SMF and FMF increased.

Coupling loss increased for both fibers as turbulence became stronger, as shown in Fig. 1. The coupling loss was larger for the SMF than the FMF though and as turbulence became stronger, the difference in the coupling loss between the two fibers became greater. The difference in coupling efficiency was as large as -10 dB for $(D/r_0)^{-5/6}$ of approximately 10. In addition, the standard deviation of the coupling loss was smaller for the FMF than SMF. Three conclusions can be made from the coupling efficiency calculations: 1) the FMF has a higher average coupling efficiency than SMF in a turbulent link, 2) the FMF has less variation in its performance than the SMF leading to a more robust system, and 3) the difference in coupling efficiency increases with stronger turbulence.

2.2 Sensitivity

In this section, we find the theoretical sensitivity of SM and FM pre-amplified receivers with OOK and DPSK modulation formats. A schematic of the pre-amplified receivers used for the two modulation formats are pictured in Fig. 2. For DPSK, both balanced detection and single-port detection are shown. These calculations do not include the effect of pulse distortion due to the optical bandpass filter.

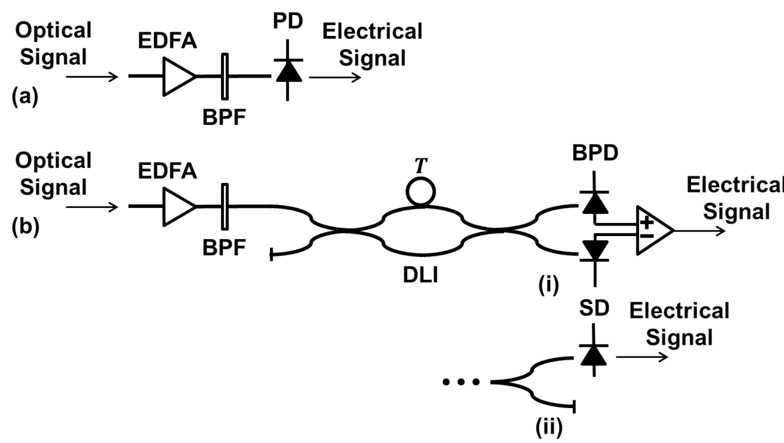

Figure 2. Pre-amplified receiver for (a) OOK modulation and (b) DPSK modulation with (i) balanced photodetection or (ii) single-port detection. EDFA: Erbium-doped fiber amplifier, BPF: bandpass filter, PD: photodetector, T: bit period, DLI: delay line interferometer, BPD: balanced photodetector, SD: single detector.

2.2.1 On-off keying

In OOK, bits are encoded by modulating the signal amplitude and a zero bit corresponds to zero signal intensity. The BER of a system using OOK modulation can be found using,

$$BER = \frac{1}{2}\left[\int_0^x P_1(y)dy + \int_x^\infty P_0(y)dy\right], \quad (1)$$

where $P_1(y)$ and $P_0(y)$ are the probability density functions (pdf) of the current for a bit 1 or 0, respectively, and x is the threshold current. Currents above the threshold are measured as a bit 1 and those below are measured as a bit 0. An error occurs when the measured current is improperly below or above the threshold due to noise.

Given the noise sources in a pre-amplified receiver, the pdfs for pre-amplified OOK are given by a non-central chi-squared distributions. The pdfs are $P_1(x|4NM, 1, \frac{4n_p}{n_{sp}})$ and $P_0(x|4NM, 1, 0)$ for no polarization filtering. Here N is the number of spatial modes, M is related to the optical bandwidth by $\Delta\nu_{opt} = \frac{M}{T}$, where T is the bit period, n_p is the average number of photons per bit, and n_{sp} is the noise enhancement factor.

2.2.2 DPSK

In DPSK, each bit has a constant amplitude and the signal is encoded as a 0 or π phase shift between adjacent bits. DPSK with balanced detection has an ~3-dB advantage in sensitivity over OOK.[7,8] This advantage is a result of the symbol distance being $\sqrt{2}$ larger for DPSK than OOK with the same optical power, but is only present when balanced photodetection is used.[8]

The BER of a system using DPSK modulation and balanced photodetection can be found using,

$$BER = \int_0^{\infty} \left(\int_0^{x} P_1(y)dy \right) P_0(x)dx, \quad (2)$$

where $P_1(y)$ and $P_0(y)$ for a pre-amplified receiver are given by the same equations as for pre-amplified OOK. In DPSK with balanced photodetectors, an error occurs when the difference in current between the two ports is the incorrect sign due to noise.

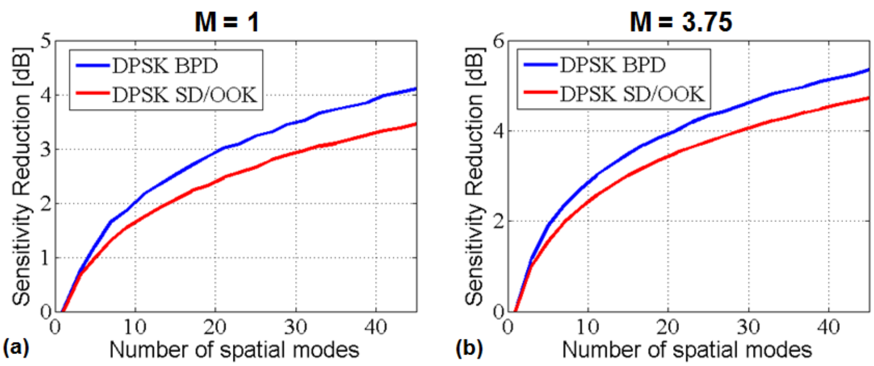

Figure 3. Reduction in sensitivity compared to a single-mode pre-amplified receiver for multi-mode pre-amplified receivers using DPSK with a balanced photodetector (BPD) and single-port detector (SD) and OOK with (a) M = 1 and (b) M = 3.75 corresponding to an optical bandwidth of 80 and 300 pm, respectively.

DPSK with single-port detection is equivalent to OOK with colored ASE and the BER can be found using Eq. 1.[7] Like in OOK, an error occurs in single-port DPSK when the measured current is improperly below or above a threshold current due to noise.

2.2.3 Sensitivity Results

The sensitivity of pre-amplified receivers was found using Eq. 1 and 2 for a 10 GHz symbol rate, 4 dB noise figure, and no polarization filtering. As the number of modes in the pre-amplifier increased, the sensitivity of the detector was reduced, as shown in Fig. 3. For a 10 Gbps system, M = 1 corresponds to an ideal bandpass filter ($\Delta\lambda = 0.08nm$), but is not easily realizable for FM applications, while M = 3.75 corresponds to a realistic thin-film filter bandwidth ($\Delta\lambda = 0.3nm$). DPSK with balanced detection suffered from larger sensitivity degradation than OOK or DPSK with single-port detection as the number of modes increased for both optical bandwidth cases. For a typical FM pre-amplifier, where the number of spatial modes is less than 10, the sensitivity was reduced by less than 2 dB for M = 1 and less than 3 dB for M = 3.75.

3. EXPERIMENTAL SET-UP

In this section, an experimental set-up to test the theoretical results of this paper is described. A schematic of the set-up is shown in Fig. 4. A continuous-wave laser ($\lambda = 1.55\mu m$) is used as the light source. For OOK, the pseudorandom binary sequence (PRBS) pattern is imposed on the light using an intensity modulator. For DPSK, the PRBS pattern passes through a DPSK modulator to encode the data in the proper form for DPSK transmission and then a phase modulator is used to encode the pattern. The light is then collimated and transverses a free-space path where a random phase plate acts as a turbulence simulator. Random phase plates can be produced by spraying transparent acrylic paint on glass slides.[9] The average phase variation of the plates can be characterized using a Mach-Zehnder interferometer.

After free-space propagation, the light is split equally into a SMF and a FMF. The light is then incident on either an OOK pre-amplified receiver (Fig. 4(b)) or a DPSK pre-amplified receiver (Fig. 4(c)). An OOK pre-amplified receiver is composed of an EDFA for optical pre-amplification, an optical bandpass filter to reduce ASE noise, and a photodetector (PD). A DPSK pre-amplified receiver is composed of an EDFA, a bandpass filter,

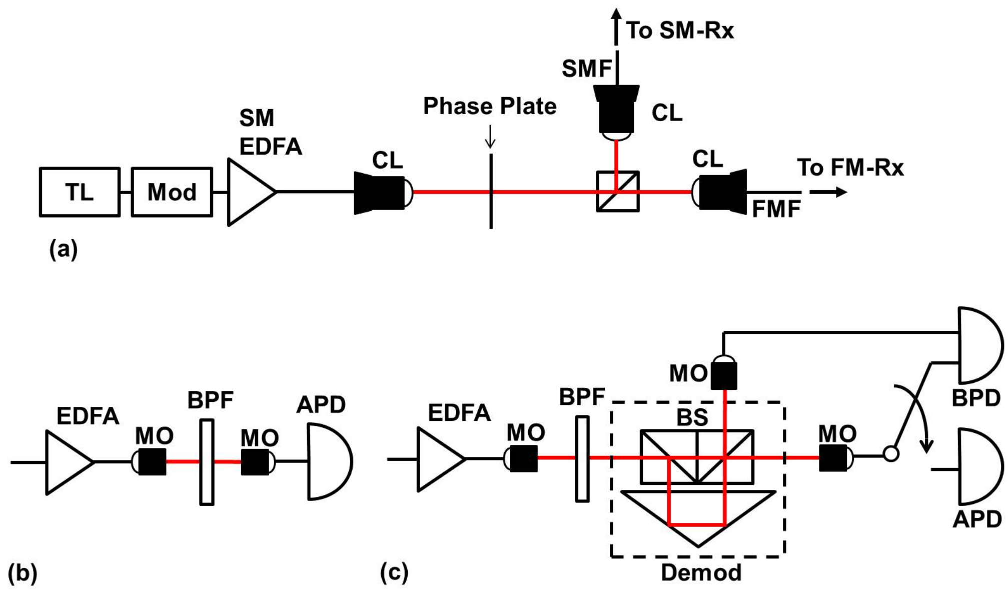

Figure 4. Experimental set-up (a) before receivers, (b) pre-amplified receiver for OOK, and (c) pre-amplified receiver for DPSK with single-port or balanced detection. TL: tunable laser, Mod: modulator, SM EDFA: single-mode Erbium-doped fiber amplifier (EDFA), Iso: isolator, CL: collimating lens, MO: microscope objective, BPF: bandpass filter, APD: avalanche photodiode, BS: beam splitter, BPD: balanced photodetector.

a DPSK demodulator, and either a single PD or a balanced photodetector (BPD). The DPSK demodulator can be comprised of a delay line interferometer using two non-polarizing beam splitters and a prism. The same optical bandpass filter should be used for both the FM and SM EDFA for a fair comparison. A description of a 10-mode FM EDFA that was built to for this experiment can be found in subsection 3.2.

3.1 Previous Experiment

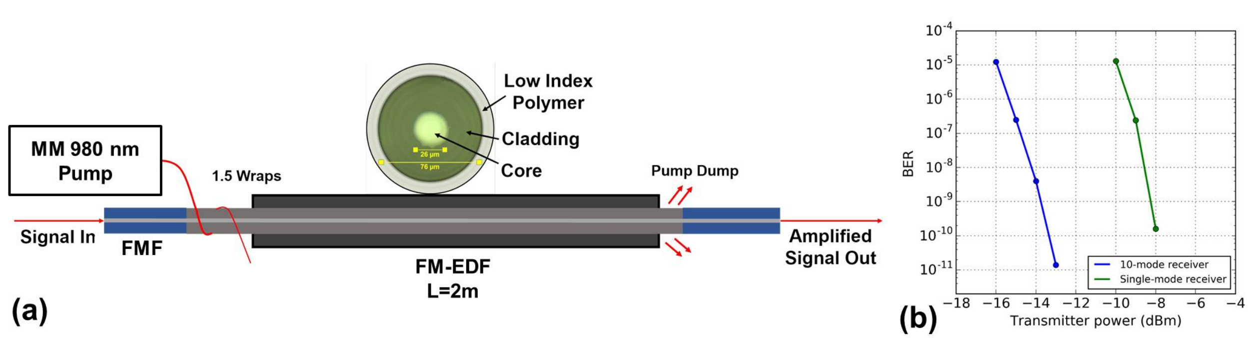

Figure 5. (a) 10-mode few-mode forward- and cladding-pumped Erbium-doped fiber amplifier schematic. (b) BER as a function of transmitted power for SM (green) and FM (blue) pre-amplified receivers. Figure adapted from Ref. 2 and 5.[2,5]

We have previously demonstrated an FSO link using a cladding-pumped 10-mode EDFA as the pre-amplifer, as shown in Fig. 5(a).[2,5] The EDF contained two claddings, a low refractive index outer cladding and a high refractive index inner cladding.[2,5] The EDFA was pumped via side-pumping by coupling light from a 980 nm MM laser to the inner cladding of the EDF.[2,5] FM and SM pre-amplified receivers were compared for OOK modulation with a 10 Gb/s bit rate. For a phase variation of 4π over the receiving aperture, the FM pre-amplified receiver provided a 6 dB gain in power budget over its SM counterpart, as shown in Fig. 5(b).[2,5]

3.2 Few-mode Erbium-doped Fiber Amplifier

To improve the performance of the FM EDFA, we built a forward-core-pumped FM EDFA with a 980 nm pump. Core-pumped EDFAs benefit from higher pump efficiency. The EDF supported 10 spatial modes (6-LP modes) and had a doping concentration of $4 \times 10^{25}/m^3$ and a length of ∼2.5 m. The doping concentration, length, and pump wavelength were chosen to produce a low noise figure at low input powers. The core diameter of the EDF was 13 μm. More information on the gain fiber can be found in Ref. 10.[10] The gain fiber was angle cleaved to prevent lasing. A schematic of the FM EDFA is shown in Fig. 6.

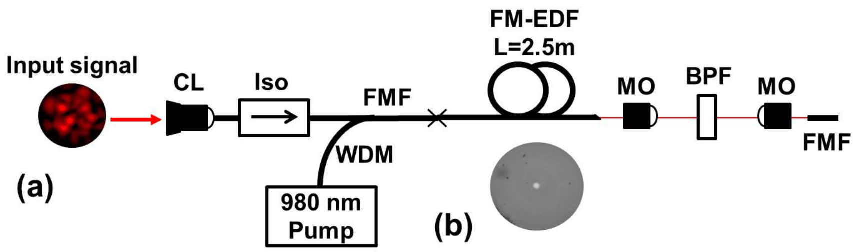

Figure 6. (a) 10-mode few-mode forward- and core-pumped Erbium-doped fiber amplifier schematic. (b) Erbium-doped fiber cross-section. CL: collimating lens, Iso: isolator, WDM: wavelength division multiplexer, FMF: few-mode fiber, EDF: Erbium-doped, MO: microscope objective, BPF: bandpass filter.

4. DISCUSSION

FM pre-amplified receivers have greater coupling efficiency than SM pre-amplified receivers for turbulent links, but they also have lower sensitivity. To achieve enhanced performance with a FM pre-amplified receiver compared to a SM pre-amplified receiver, the improvement in coupling efficiency must be greater than the degradation in sensitivity. For a 10-mode FM pre-amplified receiver and a symbol rate of 10 GHz, the sensitivity was reduced by approximately 3 dB for a realistic bandpass filter width. For turbulence, $(D/r_o)^{5/6}$, greater than 2, the improvement in coupling loss should be greater than the sensitivity loss for a 10-mode pre-amplified receiver. This leads to improved system performance with a FM compared to SM pre-amplified receiver. As turbulence increased, the difference in coupling efficiency between the FMF and the SMF increased. Sensitivity, however, is independent of turbulence. Therefore the performance difference between SM and FM pre-amplified receivers will increase with stronger turbulence.

5. CONCLUSIONS

FM pre-amplified receivers can be used to reduce the effect of turbulence in FSO communications. Previous experiments have shown FM pre-amplified receivers had enhanced performance compared to SM pre-amplified receivers for OOK modulation. We extend the theory to show that FM pre-amplified receivers should also have an advantage when DPSK modulation is used. FM pre-amplified receivers have an advantage over SM pre-amplified receivers in turbulent systems due to an increase in coupling efficiency between the distorted free-space signal and the receiver fiber. We briefly describe an experimental set-up to test the theory presented. FM pre-amplified receivers offer an attractive alternative to adaptive optics as they are robust, compact, and comparatively inexpensive.

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