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Radio-Over-Free Space Optical Space Division Multiplexing System using 3-core Photonic Crystal Fiber Mode Group Multiplexers

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Abstract: Ro-FSO systems have previously relied on the intensity, wavelength and polarization for multiplexing data streams in order to increase the signal quality and to increase the achievable link range. This work leverages on optical space division multiplexing by using novel three-core PCF mode group multiplexer and hexagonal mid-gapped tiered PCF mode group equalizers for improving the signal quality and increasing the achievable link range in a rural environment. At the transmitter, a three-core PCF mode group demultiplexer converts the fundamental mode into three distinct mode groups used as carriers for independent transmission of three radio frequency signals. At the receiver, the three PCF successfully equalizes the power from the received signal, with the channel impulse responses showing an improvement in the signal quality. An increment between 13.6% and 31.1% in the achievable link range for all channels is evident under medium and heavy fog conditions at the same bit error rate level, using the designed PCF mode group multiplexers and equalizers.

Keywords: radio over free space optics, space division multiplexing, multiple-input-multiple-output, photonic crystal fiber, mode multiplexer, digital divide

1. Introduction

The upcoming fifth generation (5G) and sixth generation (6G) communications systems are expected to be game changers for automotive, healthcare, manufacturing, data analytics, disaster management, utilities monitoring, augmented/virtual reality services [1-3]. Next generation smart communication systems are expected to connect people, smartphones, sensors devices for transporting an enormous amount of data more rapidly and reliably. It is projected that by the year 2025, there will be 75 billion Internet of Things (IoT) devices and sensors which require real-time data streaming [4]. The annual mobile data traffic is expected to grow three-fold from 2017 to the end of 2022 from these smart services [5].

Inevitably, microwave spectrum bands below 6 GHz utilized by legacy wireless systems are growing increasingly congested and licensing is expensive. To extend the coverage to larger areas, wired connections based on optical fibers have been used for higher bandwidth gains but at a high deployment cost and without the capacity for reconfiguration. On the other hand, the introduction of wireless connectivity at optical frequencies offers high data capacities, while allowing rapid and dynamic deployment. Free space optics (FSO) technology may be used as an alternative to optical fiber for backhaul connectivity [6-8]. The key advantages of FSO are reconfigurability, unlicensed spectrum, high transmission rates, inherent security and insusceptibility to electromagnetic interference [9, 10].

Radio over free space technology (Ro-FSO) may be deployed to extend high-speed network connectivity to underserved areas and geographical terrains where optical fiber installations may not be viable [11, 12]. Ro-FSO provides a high-bandwidth, cost-effective and flexible solution for resolving the spectrum crisis for evolution towards 5G [13, 14]. There is currently a large disparity between urban and rural communities in Internet access, especially in developing countries. The need to bridge this digital gap is necessary for the development of the digital economy of developing countries [15, 16]. Studies have shown that the rural communities in developing countries, such as Malaysia lack the infrastructure for affordable high-speed Internet access [16-18]. Rural communities also lack knowledge and skills in information communications technology (ICT), which contributes to digital divide [19, 20]. Digitization through the provision of high-speed low cost Internet services based on Ro-FSO is a powerful agent of change. FSO networks would potentially enable rural communities to access the wealth of online material and spur the creation of new digital start-ups, which contributes towards the development and sustainability of the digital economy of developing countries.

Nevertheless, the main challenge for Ro-FSO systems is the performance degradation due to low visibility and turbulence, as optical are not capable of penetrating structures and other obstacles [9, 10, 21, 22]. Space division multiplexing (SDM) is a recent spatial diversity strategy transpired by utilizing different eigenmodes in optical fiber as independent channels to create multiple-input-multiple-output systems [22-27]. SDM enables the provision of multiple links during harsh weather conditions in case of failure of any of the links and increases the achievable link distance [28-34].

The paper is organized as follows. Section 2 provides a literature review on previous work on SDM for improving the signal quality and increasing the transmission link, and the design of PCFs for SDM. Section 3 highlights the novelty of our work and its impact. Section 4 discusses the novel design of the three-core PCF mode group multiplexer and hexagonal mid-gapped tiered PCF mode group equalizers for increasing the achievable link range of a Ro-FSO system. Section 5 compares the signal quality and achievable distance of the Ro-FSO transmission, prior to and after the incorporation of the novel PCF mode group multiplexers and equalizers, in terms of the intensity distribution, channel impulse response versus normalized effective index, eye diagrams and achievable distance for all channels.

2. Related Work

The role of SDM has recently been extended from optical fiber networks to FSO networks. In [35], researchers have modulated information over FSO transmission link of 143km by multiplexing of $\ell = \pm 1, \pm 2$ and ± 3 orbital angular momentum (OAM) modes at various relative phases to connect two islands. In [36], SDM in conjunction with polarization division multiplexing (PDM) was adopted for experimental transmission of 1.44 Tbps data over FSO link of 1.8m using 24 OAM modes. In another experiment [37], two OAM modes ($\ell = \pm 3$) were used in transmitting 40Gbps 16 QAM data over FSO link of 260m. In [38], 400 Gbps data is experimentally transmitted over a 120-meter FSO link using four OAM beams $l = \pm 1$ and $l = \pm 3$, each carrying 100Gbps data, with the aid of two reflective spatial light modulators (SLMs). Another experiment [39] reported the transmission of 200 Gbps data over a 1-meter FSO link using two SLM-generated Laguerre–Gaussian (LG) beams with different radial indexes $\rho = 0$ and $\rho = 1$ at a fixed azimuthal index $\zeta = 0$. SDM was realized in a 50km-long FSO system in [40] through spiral-phased LG and Hermite–Gaussian (HG) modes to realize an aggregate data rate of 80 Gbps at 160 GHz for

OFDM signals. In [41], three 40 GHz signals are optically modulated at 20 Gbps and transported over a 50km-long FSO link in a OFDM-SDM system using three HG modes, HG 00, HG 01 and HG 02. [28] reported on the design of two spiral-phased HG modes for transmission of 2.5Gbps 10GHz radio signals each in a Ro-FSO system under the impact of beam divergence and atmospheric turbulence. In [42], a mode filtering technique using a single mode fiber was experimentally and theoretically shown to mitigate modal effects of a radio-over-fiber-FSO system and improved the system bandwidth by 2 GHz.

Various PCF designs have been explored for mode excitation in SDM systems, largely used in optical fiber systems. In [43], authors demonstrated 100 Gbps data transmission over 1.15 km of low loss photonic band gap fiber (PBGF) and 1 km of solid core fiber. In [44], a six-mode nineteen-core fiber was designed for an ultra-dense quadrature phase shift keying system based on space, wavelength and phase multiplexing at 2.05 Pbit/s with a spectral efficiency of 456 bit/s/Hz for a distance of 9.8 km. In another work [45], a PCF was designed to minimize dispersion in an optical fiber communication systems with potential sensor applications. In [46], the authors designed a mode selective coupler based on dual core PCF for mode conversion between LP₀₁ and LP₁₁ modes. In [29, 47], solid core PCFs are designed as mode converters for excitation of LG modes. Recently [48], authors fabricated polarization beam splitters based on dual core PCF with magnetic fluids in air holes, which allows the proportion of polarization modes to be adjusted by controlling the magnetic field strength. In another work, a long-period fiber grating mode converter based on a two-mode polarization-maintaining PCF was fabricated [49] to convert between LP₀₁ modes and LP₁₁ modes and separate the linearly polarized LP₁₁ output modes at different wavelengths. In [50], an analysis on a 4-moded PCF is performed to investigate the effect of hole diameters and the separation between them. In [51], a circular PCF with a defect in the first layer was designed numerically and shown to support 14 OAM modes with low confinement loss at around 1.55 μ m. In [52, 53], fiber amplifiers with erbium-doped rings within a PCF structure were been designed to equalize the gain of different modes in an OAM SDM system. In [54], a multiplexing coupler is designed using a five-core microstructure optical fiber to demultiplex LP₁₁, LP₂₁, LP₀₂ and LP₀₁ modes simultaneously at 1550nm. In [55], a dual-core PCF mode demultiplexer was designed for mode generation and equalization.

3. Novelty

To augment the capacity of Ro-FSO systems, various modulation and multiplexing schemes have been investigated, largely based on intensity, wavelength and polarization. Despite recent SDM initiatives in Ro-FSO systems, the application of PCF mode multiplexers and equalizers in Ro-FSO systems remains largely untapped. The contribution of this work is to increase the signal quality and achievable distance of a Ro-FSO system with the intricate design of novel three-core PCF mode and hexagonal mid-gapped tiered PCF mode group equalizers for generating three independent mode groups as data carriers. For equalizing the modal power between mode groups, tiering gaps were used instead of doping rings to minimize the differences in mode power. In addition, while most previous mode converters enabled the conversion of a single mode into another single mode, in this work, we considered the conversion of the fundamental mode to three mode groups of relatively wider effective indices so that they are less susceptible to power coupling from weather fluctuations than individual modes. Ro-FSO provides a high-bandwidth, cost-effective and flexible solution for the evolution towards next generation communication systems, particularly for rural connectivity in developing countries

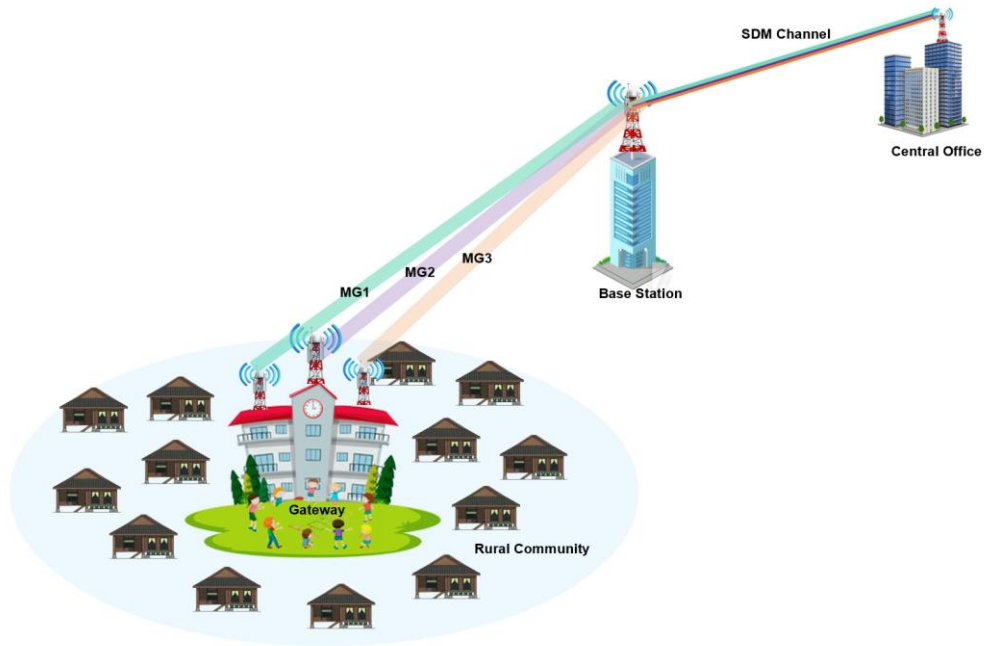


Fig. 1. SDM Ro-FSO system architecture for rural connectivity

4. System Design

The architecture for the proposed Ro-FSO system is illustrated in Fig. 1. The central office is connected to the base station through a 2km FSO link. The base station is connected to several gateways, which are mounted on a tall structure in a rural area. The Ro-FSO system comprises three segments: (i) radio links from houses to gateways in a rural area (ii) Ro-FSO links from the gateways to base station using individual mode groups for each channel (iii) SDM Ro-FSO links from base station to central office combining three mode groups. The Ro-FSO system is developed to aggregate/demultiplex data signals on radio frequencies from houses in a rural area onto/from an optical mode group and to allow spatial diversity through three mode group links using SDM in case of link failure. The application of a PCF multiplexer/demultiplexer for SDM presents a potential alternative to WDM for point-to-multipoint access, thus provides a means for mitigating spectrum shortage in the low gigahertz range in rural areas. The small size and weight of these PCFs are attractive features for SDM-based compact transceivers at the base station for wireless Ro-FSO systems.

Fig.2 shows a schematic diagram of the PCF mode group multiplexer and equalizers used in the Ro-FSO system. Mode group multiplexer/demultiplexer PCF A and mode group equalizers PCFs B, C and D are designed using the finite element method at a wavelength of 1550 nm with the condition of perfect matched layer. The parameters for the PCFs are given in Table 1. The channel is modelled in MATLAB.

The refractive index profile of PCF A is given in Fig. 3. The three larger cores at the center have a higher refractive index than the surrounding smaller cores in order to reduce inter-mode group crosstalk. PCF A is designed such that all three channels have approximately equal power distribution at the output. Mode coupling is described by [56]:

$$\frac{dA_m}{dz} = -j \sum_{n \neq m} K_{mn} A_n(z) \exp(j\Delta\beta_{mn}z) \quad (1)$$

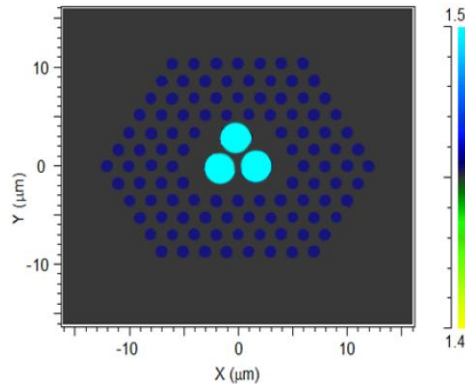


Fig. 3. Refractive index profile of dual-core PCF A at transmitter

where A_n is the modal amplitude in core n , z is the propagation direction, K_{mn} is the mode group coupling coefficient from core n to core m , $\Delta\beta_{mn} = \beta_m - \beta_n$ is the propagation constant difference, where β_m and β_n are the propagation constants of mode groups in core m and core n respectively.

Different mode groups are excited by controlling the PCF length, which is given by:

$$l = \frac{\pi}{\beta_{even} - \beta_{odd}} = \frac{\lambda}{2(n_{even} - n_{odd})} \quad (2)$$

where β_{even} and β_{odd} are the propagating constants of even and odd modes respectively; n_{even} and n_{odd} are the corresponding effective refractive indices respectively. By adjusting the refractive index profile and length of the PCF, the power may be coupled into distinct mode groups. From Fig. 4, in PCF A, the power in each mode group increases oscillatorily with length until 32.1%, 33% and 30.6% of the input power are coupled into the first, second and third mode groups respectively at a length of 200 μm . The insertion loss is 1% and the remainder of the power is lost to evanescent modes.

Fig. 5 depicts the channel impulse response versus normalized effective index of mode groups at output of three-core PCF A, computed using the overlap integral between the transverse electric field from the relevant channel, E_{ch} with the effective transverse electric field of each mode group, E_{mg} .

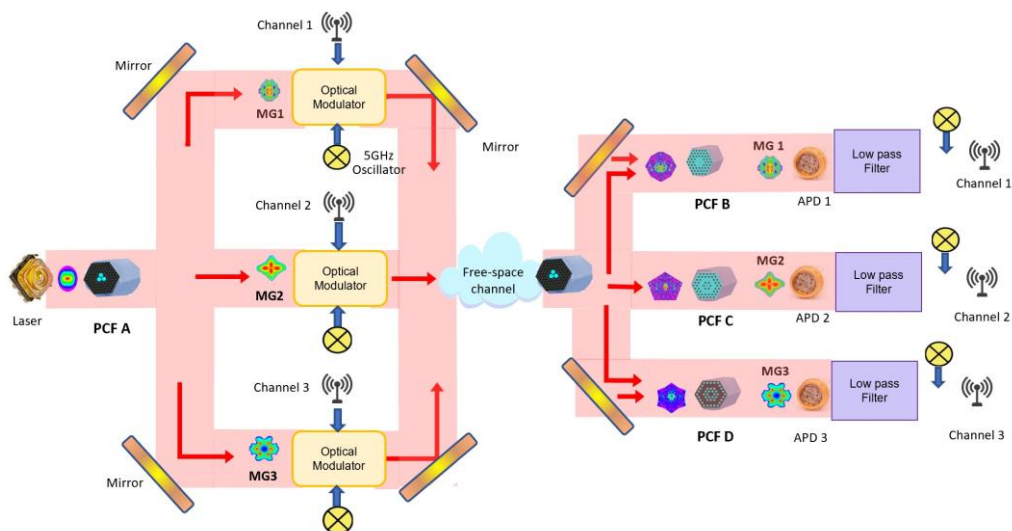


Fig. 2. SDM in Ro-FSO system based on selective mode group excitation using PCFs

$$\eta = \frac{\left| \iint \mathbf{E}_{ch}(x, y) \mathbf{e}_{mg}^*(x, y) dx dy \right|^2}{\iint |\mathbf{E}_{ch}(x, y)|^2 dx dy \cdot \iint |\mathbf{e}_{mg}(x, y)|^2 dx dy} \quad (3)$$

The effective indices in Fig. 5 have been subtracted with respect to the average effective index of the mode groups in consideration, n_{bar} so that the graph is centered at $n_{eff} - n_{bar}$. The effective indices for each channel are 1.5, 1.4 and 1.3. The channel impulse response illustrates that the power between the three output modes are divided to an approximately equal distribution at the transmitter across the three channels.

For uplink transmission, at the base station, a continuous wave light wave is generated by a distributed feedback laser at 1550 nm at the fundamental mode and split into three mode groups by PCF A as a mode group demultiplexer. Three independent pseudorandom non-return-to-zero baseband signals are generated at 30 MHz to emulate radio signals from rural houses, which are converted into passband signals at 2.6 GHz at the gateways. The passband signals are used to modulate the optical beams from the PCF A-generated mode groups at 1550nm using a Mach-Zehnder modulator at 10Gbps. At the base station, the output of the modulator is amplified by an erbium-doped fiber amplifier and the signals are transmitted based on SDM over a free space channel of 2km in length to the central office.

The FSO link is described as [57]:

$$P_R = P_T \frac{d_R^2}{(d_T + \theta R)^2} 10^{-\mu R/10} \quad (4)$$

where P_T is the transmitted power, P_R is the received power, d_R is the receiver aperture diameter, d_T is the transmitter aperture diameter, θ is the beam divergence and R is the FSO range, μ is the atmospheric attenuation.

The FSO channel and radio channel are modeled by the generalized Malaga (M) and $\eta - \mu$ distributions respectively. The atmospheric attenuation, μ is assumed to be 0.11dB/km for clear weather, 9dB/km for light fog, 15dB/km for thin fog and 21dB/km for heavy fog, based on Malaysian weather conditions [58-60]. The probability of a given intensity is given by [61]:

TABLE I PCF PARAMETERS

Parameters	PCF A	PCF B	PCF C	PCF D
Diameter of large rods, b (μm)	3.2	-	-	-
Diameter of small rods, d (μm)	0.95	1.22	1.22	1.22
Distance between small rods, Λ (μm)	0.72	0.72	0.72	0.72
Ratio of distance between rods to rod diameter, Λ/d	0.758	0.590	0.590	0.590
Background index	1.46	1.5	1.4	1.4
Length (μm)	200	40	40	40

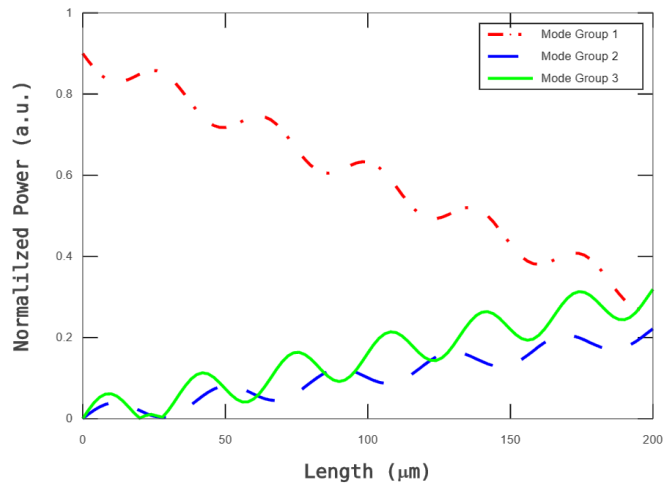


Fig. 4. Power coupling for three mode groups versus length in PCF A

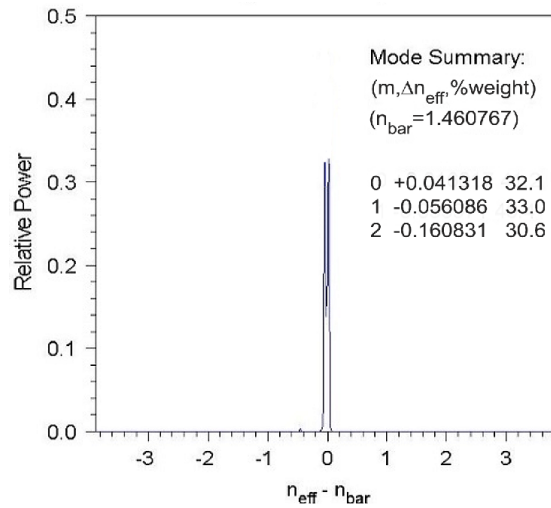


Fig. 5. Channel impulse response versus normalized effective index of three-core PCF A at output

AU

$$P(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)^2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta} \left[2(\alpha\beta I)^{1/2} \right] \quad (5)$$

where α^{-1} and β^{-1} are variances of small and large scale eddies respectively, Γ is the gamma function and $K_{\alpha-\beta}$ is the modified Bessel function of the second kind. The Rytov variance is assumed for atmospheric scintillations [61], where the refraction structure parameter, C_n^2 values of $10^{-17} \text{ m}^{-2/3}$, $10^{-15} \text{ m}^{-2/3}$, $10^{-13} \text{ m}^{-2/3}$ represent weak, moderate and strong turbulence respectively. The fluctuation in the refractive index structure causes the power from the transmitted mode groups to scatter into various other mode groups.

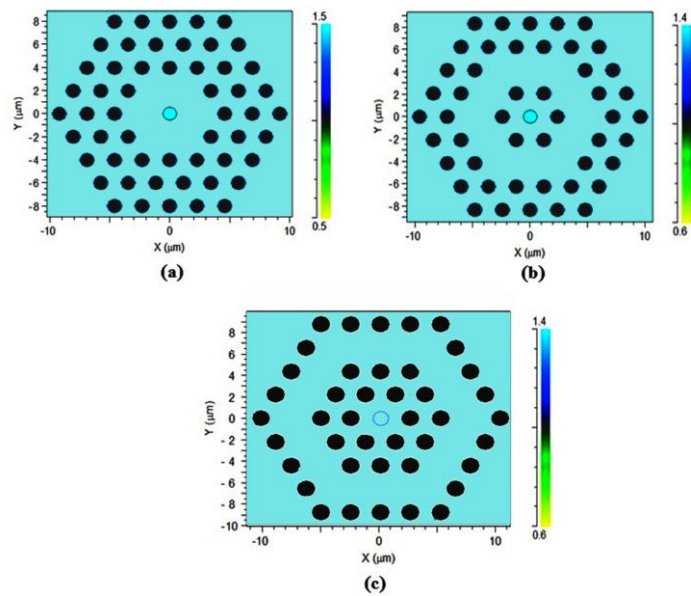


Fig. 6. Cross section of refractive index profile for PCFs at the receiver for compensation of mode coupling: (a) PCF B for Channel 1 (b) PCF C for Channel 2 (c) PCF D for Channel 3

For downlink transmission, the signals from the central office to the base station are transmitted using optical SDM. At the base station, the optical SDM-ed signals are then demultiplexed into optical mode groups. Each optical mode group is directed to a specific gateway in a rural area. To avoid power loss in mode converters, retrieval of mode groups is performed in two stages. In the first stage, the number of output modes should be larger than the number of input modes to alleviate transition into unavailable modes [62]. Thus, following the free space channel, PCF A as a mode group demultiplexer is designed such that the number of output mode groups exceeds the number of input mode groups. Then in the second stage, in order to select only the relevant mode groups in that channel, PCFs B, C and D perform to inverse the channel matrix, in order to offset mode coupling in the channel, so that the original mode groups for each channel may be recovered. Fig. 6 depicts the refractive index profiles of PCFs B, C and D.

At the gateway, photodiodes convert the optical signals to electrical signals and low pass filtered. The signal is then down converted to 30 MHz using a local oscillator running at the same frequency of 2.6 GHz as in the transmitter and delivered to respective houses in the rural area.

5. Results

After propagation through the free-space channel, the intensity distributions at the receiver are shown in Fig. 7. The speckles indicate optical intensity fluctuations and fading caused by the random variation of the air refractive index. For a quantitative analysis of Fig. 7, the channel impulse response versus normalized effective index are shown in Fig. 8 for Channels 1 to 3, taken immediately after the free-space channel. The effective indices in Fig. 8 have been subtracted from the average effective index, n_{bar} so that the graph is centered at $n_{eff} - n_{bar}$. The channel impulse response plots for all channels reveal that the power from the transmitted mode group is found to couple into other mode groups with different effective indices. The power is distributed across several mode groups with the dominant group receiving approximately only 62% of the input power for all channels. Thus, the power is unequal across mode groups prior to power modal equalization.

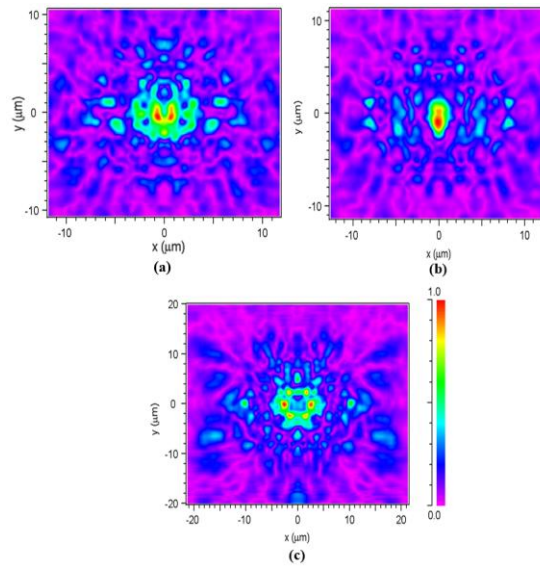


Fig. 7. Intensity distribution at the receiver prior to PCF equalizers: (a) Channel 1 (b) Channel 2 (c) Channel 3

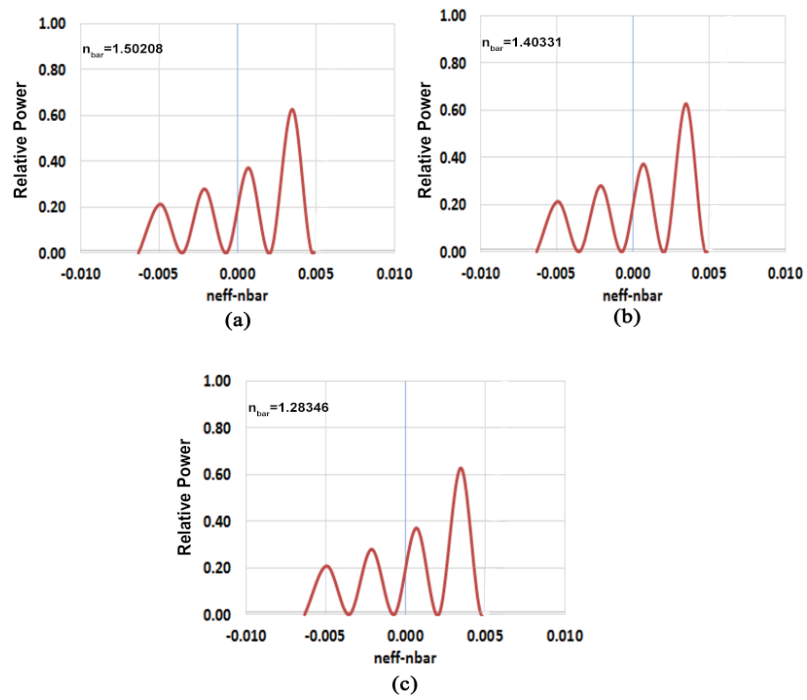


Fig. 8. Channel impulse response versus normalized effective index after FSO link before PCF modal equalization for: (a) Channel 1 (b) Channel 2 (c) Channel 3

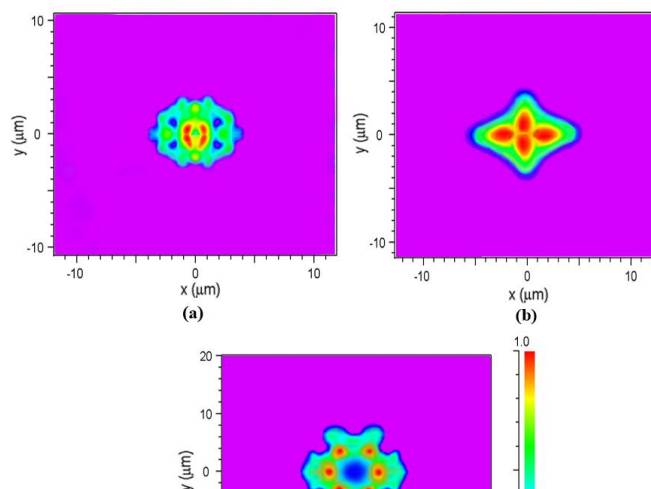


Fig. 9 shows the intensity distributions at the receiver after the PCF equalizers, which

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shows a reduction of speckles compared to in Fig. 7 and that three distinct mode groups are

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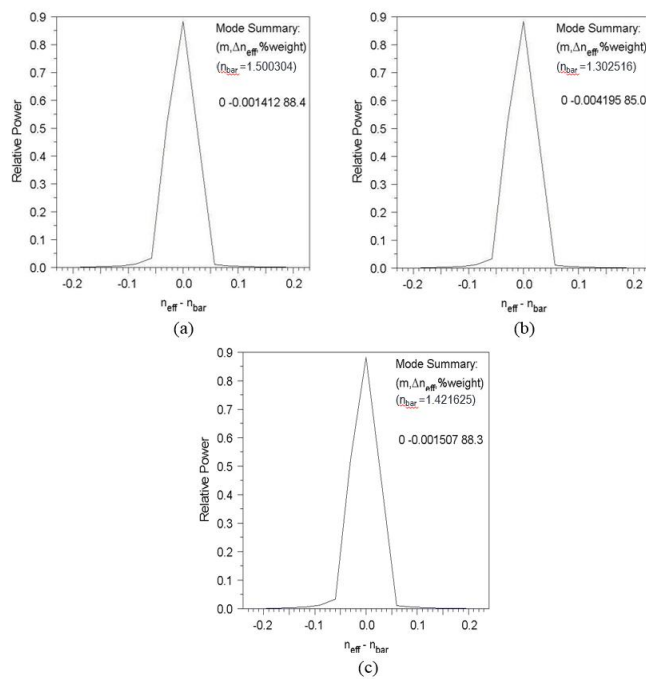


Fig. 10. Channel impulse response versus normalized effective index after PCF modal equalization for: (a) Channel 1 (b) Channel 2 (c) Channel 3

achieved after power modal equalization. For a quantitative analysis of Fig. 9, the channel

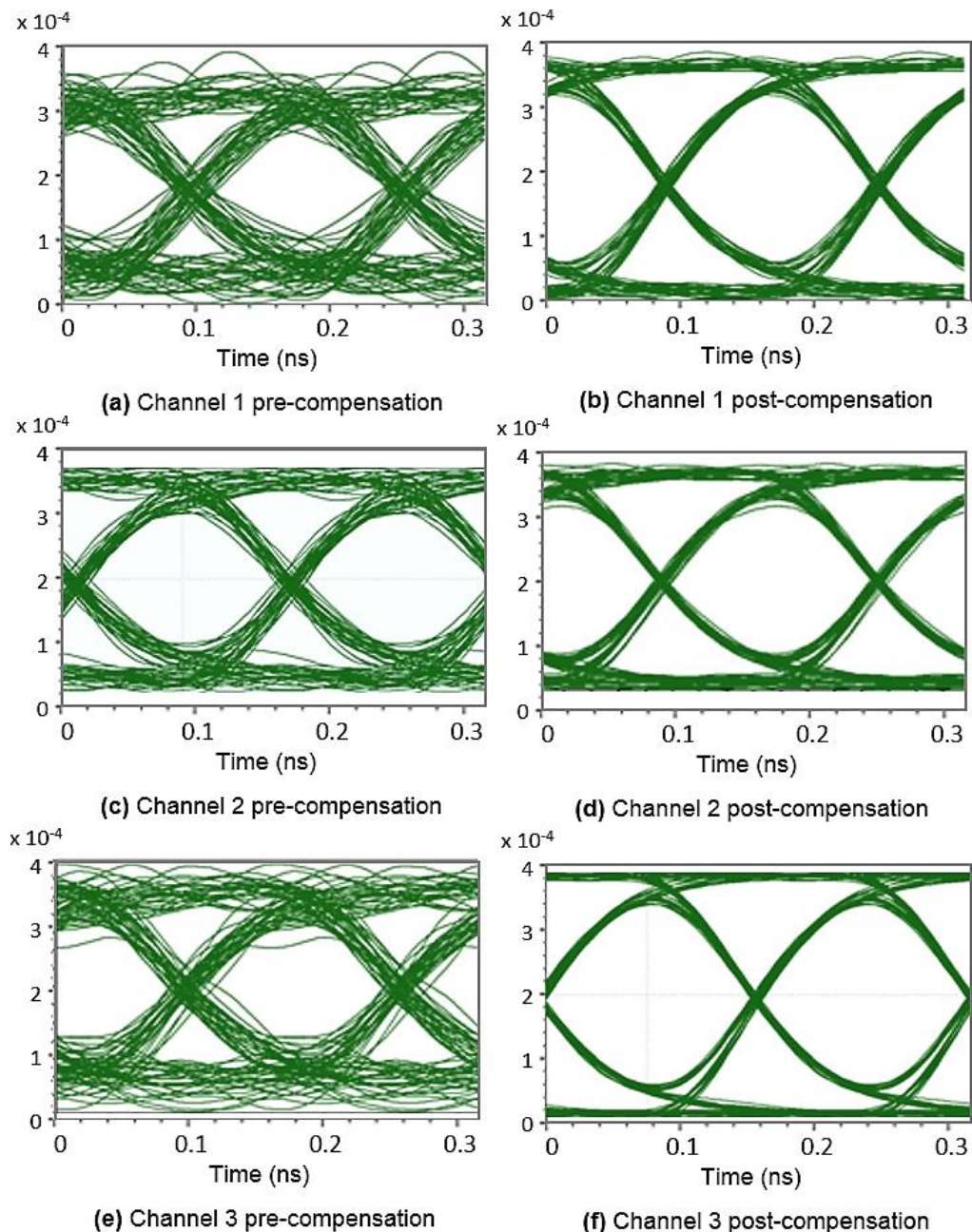


Fig. 11 Eye diagrams under medium fog conditions pre-compensation and post-compensation by PCF at the receiver at 2000 m for: (a) Channel 1 (b) Channel 2 (c) Channel 3

impulse response versus effective index is shown in Fig. 10, computed after PCF mode equalization at the receiver for all channels. It is observed that for each channel, a significant portion of the received power falls into a mode group of a unique effective index, thus indicating that channel crosstalk is reduced. A high portion of the received optical power is coupled into the same dominant mode at the transmitter, at 88.4%, 85.0% and 88.3% at output of PCF B for Channel 1, PCF C for Channel 2 and PCF D for Channel 3. This is in contrast to only 62% of the received optical power being coupled into same dominant mode prior to PCF modal equalization, thus showing 23% to 26.4% improvement in power coupling into the dominant mode after modal power compensation by the PCF.

The eye diagrams presented in Fig. 11 indicate that the insertion of the solid-core PCFs widens the eye openings for all channels, indicating that the PCFs at the receiver have compensated for the atmospheric turbulence by redistributing the power into desired modes while

suppressing the power into higher order modes. This addresses the loss of information coupled into undesirable modes.

The designed system offers better achievable link distance following the compensation of mode coupling effects from the PCFs at the receiver, more strongly for medium and heavy fog conditions, as shown in Fig. 12. For Channel 1, for a BER of 1×10^{-12} , under medium fog condition, the link range is increased from 1250 m to 1420 m; and under heavy fog, the link range is increased from 495 m to 650 m, after insertion of PCF B. For Channel 2, for a BER of 1×10^{-15} , under medium fog condition, the link range is increased from 1310 m to 1600 m; and under heavy fog, the link range is increased from 720 m to 890 m, after insertion of PCF C. For Channel 3, for a BER of 1×10^{-15} , under medium fog condition, the link range is increased from 1520 m to 1900 m; and under heavy fog, the link range is increased from 740 m to 930 m, after insertion of PCF D.

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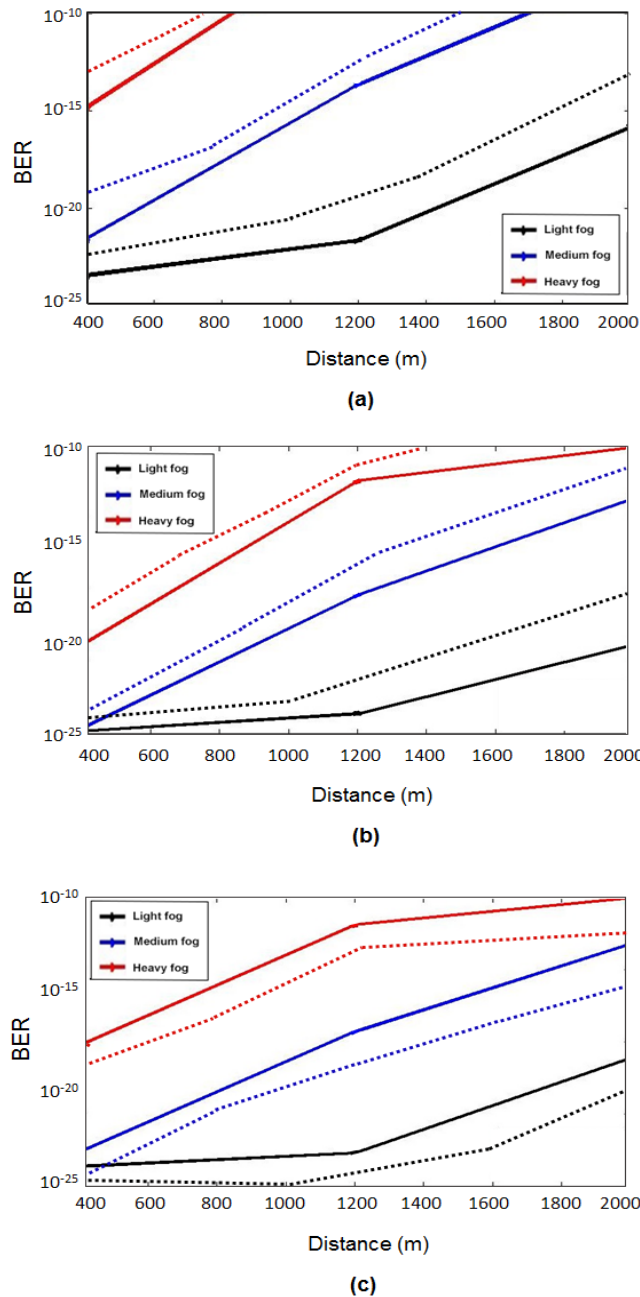


Fig. 12. BER under light, medium and heavy fog conditions for: (a) Channel 1 (b) Channel 2 (c) Channel 3. Solid line are for pre-compensation, dotted line plots are for post-compensation by PCF respectively

Thus, for Channel 1, there is an increment of 13.6% and 31.1% in the achievable link range under medium and heavy fog conditions respectively. For Channel 2, there is an improvement of 22.1% and 23.6% in the achievable link range under medium and heavy fog conditions respectively. Meanwhile, for Channel 3, there is an improvement of 25% and 25.7% in the achievable link range under medium and heavy fog conditions respectively. The results show that the effects of the PCFs are more pronounced under heavy fog.

6. Conclusion

The wireless Ro-FSO system using novel three-core PCF mode multiplexer at the transmitter successfully decomposes the fundamental mode into three distinct mode groups with effective indices of 1.5, 1.4 and 1.3 respectively, for the transmission of three independent 2.5Gbps

channels in a 2km-long Ro-FSO system, and demultiplexes the signal into three independent channels after the free space link. Channel impulse responses, eye diagrams and BER plots have demonstrated that the novel PCF mode group equalizers system improve the signal quality and the transmission distance of a Ro-FSO system. The PCF mode group equalizers successfully increase the received power in the dominant mode by 40%, with an increment between 13.6% and 31.1% in the achievable link range for all channels under medium and heavy fog conditions at the same bit error rate.

The proposed SDM-based wireless Ro-FSO system based on the PCF mode group multiplexer and equalizer is an initiative for potentially bridging the digital divide in rural areas.

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