# 4×100-Gb/s PAM-4 FSO Transmission Based on Polarization Modulation and Direct Detection

Rui Zhang, Peng-Chun Peng, Xinying Li, Siming Liu, Qi Zhou, Jiale He, You-Wei Chen, Shuyi Shen, Shuang Yao and Gee-Kung Chang, *Fellow, IEEE, Fellow, OSA*

***Abstract*—For the first time, we experimentally demonstrate a 400-Gb/s (4×100-Gb/s wavelength division multiplexing (WDM)) pulse-amplitude-modulation-4 (PAM-4) transmission based on free space optics (FSO) utilizing the polarization modulation (PolM) and direct detection (DD) scheme. Each WDM channel comprises a polarization modulator, a polarizing beam splitter (PBS), and two photodetectors (PD). Four wavelengths, each carrying a 100-Gb/s PAM-4 signal (aggregate 400 Gb/s) are transmitted over the free space. At the receiver side, the PBS separates the two orthogonal polarizations, and then the two polarized signals are detected by two PDs, respectively. Then the two detected signals are combined by a subtractor, followed by digital signal processing (DSP). The PolM-DD system can achieve higher data rate while maintaining the required forward-error-correction (FEC) threshold compared with intensity modulation and direct detection (IM-DD) scheme. Moreover, owing to the stable polarization state in the free space and the mitigation of the common mode noise by the subtraction, the PolM-DD system provides enhanced tolerance to the amplitude fluctuations attributable to weather turbulence, which makes it more reliable than the conventional IM-DD FSO system. To the best of our knowledge, this is the first experimental demonstration of 400-Gbps FSO system using PolM-DD scheme with the transmission distance of 1.2 m.**

***Index Terms*—Free space optical communication, polarization modulation, direct detection**

## I. Introduction

With the exponential growth of the bandwidth-hungry interconnects applications, the desired optical network capacity has to be increased up to 100/400 Gbps [1-3]. Optical fibers can be a good solution for high-capacity connection with massive bandwidth. For the areas where fiber installation is problematic, free space optical (FSO) communication stands out with flexibility of setup and tear down, and no purchasing and installing of fiber, similar system components to fiber, high capacity and unlicensed operating wavelength, which is a complementary technology to the radio frequency (RF) technology [4, 5]. Commercially, FSO employs intensity modulation and direct detection (IM-DD) scheme. However, this scheme does not offer immunity to atmospheric or weather turbulence and shading, resulting in scintillation and performance degradation [6-8]. Error control coding was proposed to eliminate the degradation, but it is inefficient and exhibits significant processing delays [9].

Considering the turbulence only introduces intensity distortion, and the polarization state is stable in FSO channel [10], the implementation of polarization modulation (PolM) is feasible and attractive to enhance the system performance and mitigate the atmospheric turbulence-induced fading in FSO communication systems [11-13]. Moreover, the subtraction of the two signals lessens the common mode noise. The PolM-DD FSO communication systems for OOK signal have been intensively investigated and demonstrated with a ~3-dB sensitivity gain compared with intensity modulation [14-16]. However, PolM-DD FSO communication systems for 100-Gbps transmission utilizing PAM modulation have not been experimentally studied.

In our work, we firstly propose a 4×100-Gbps, PolM-DD FSO system utilizing a cost-effective electro-optic polarization modulator, the PAM-4 modulation and wavelength division multiplexing (WDM). It provides a first-ever analysis of operation principle and experimental demonstration of implementing PAM modulation to achieve high-speed transmission in a PolM-DD system. The system achieves a better system tolerance against atmospheric turbulence and supports high-data-rate transmission with enhanced power margins. For the FSO systems installed under effects of vibrations, circle polarization modulation [14] and dynamic polarization control [15, 17] can be utilized to reduce signal degradation. Our proposed scheme can be applied to communication between objects with fixed positions, such as an outdoor-to-indoor relay, building-to-building communication, or table-to-ceiling communication where vibration is small and predictable.

This paper is organized as follows. Section II describes the principle of the PolM-DD system. Section III and IV present the experimental setup and discuss the experimental results, respectively. Section V provides concluding remarks.

## II. Principle of operation

Fig.1 depicts the configuration of the PolM-DD based FSO

R. Zhang, X. Li, S. Liu, Q. Zhou, J. Le, Y.-W Chen, S. Shen, S. Yao, G.-K. Chang are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30308 USA (e-mail: ruizhangece@gatech.edu;xli615@mail.gatech.edu; siming.liu@ece.gatech.edu; qi.zhou@gatech.edu; jiale.he@ece.gatech.edu; yu-wei.chen@ece.gatech.edu; ssyzoe@gatech.edu; syao65@gatech.edu; gkchang@ece.gatech.edu).

P.-C. Peng is with the Department of Electro-Optical Engineering, National Taipei University of Technology, Taipei 10608, Taiwan. (e-mail: pcpeng@mail.ntut.edu.tw )

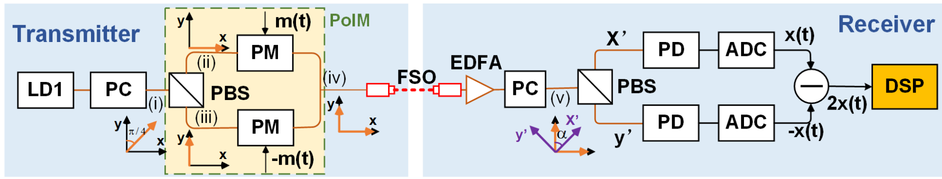


Fig. 1. Configuration of the PolM-DD based FSO system. (i) to (v) are the polarization sates of the signal with respect to principal axis. PM: phase modulator, PC: polarization controller, EDFA: Erbium-doped fiber amplifier, PD: photodetector, ADC: analog-to-digital converter, PolM: polarization modulator, PBS: polarization beam splitter. LD: Laser diode.

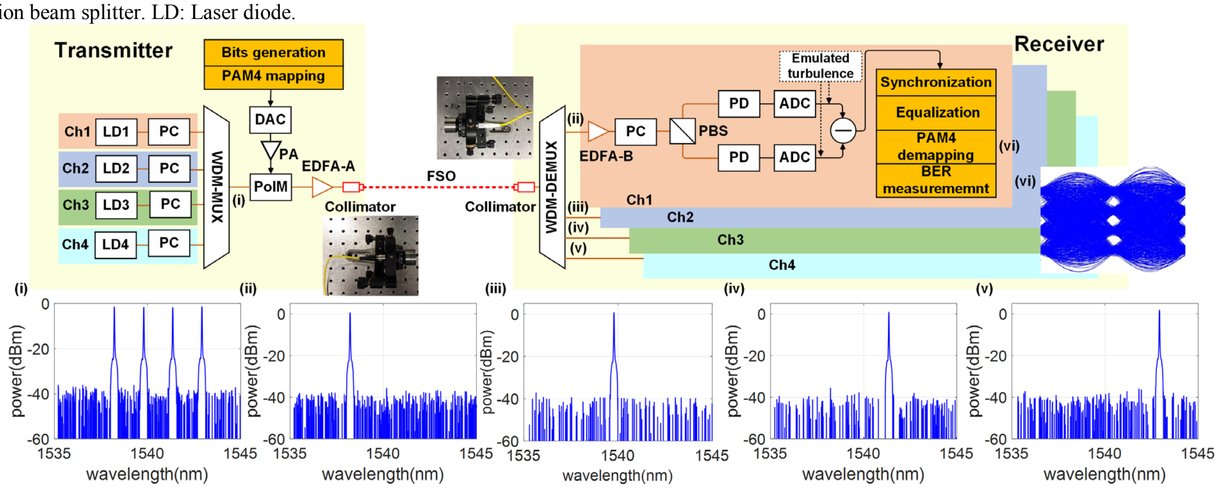


Fig. 2. Experimental setup of 4×100-Gb/s FSO transmission based on PolM-DD scheme. (i) Optical spectrum after WDM-multiplexer. (ii-v) are the optical spectra after WDM-demultiplexer of the four channels (resolution bandwidth equals 0.01 nm), respectively. (vi) The eye diagram of the received signal.

transmission. The continuous-wavelength (CW) light beam is linearly polarized and has a π/4 polarization with respect to the principal axes of the phase modulator (PM). The PBS decomposes the π/4 polarization of the input carrier into two equal orthogonal components: x and y polarizations. Assume the input normalized data is $m(t)$, then the two modes are separately phase modulated by phase modulators with opposite phase modulation index [18]. The output signal from the PolM, $\vec{E}_{Tx}(t)$, is given below:

$$\vec{E}_{Tx}(t)=\frac{\sqrt{2P_0}}{2}\begin{bmatrix}\exp\left(j\left(\omega_c t+\frac{\pi}{2}m(t)\right)\right)\hat{x}\\ \exp\left(j\left(\omega_c t-\frac{\pi}{2}m(t)\right)\right)\hat{y}\end{bmatrix} \quad (1)$$

where $P_0$ is output power of the LD, the normalized data is $m(t)\in[0,1]$, and $\omega_c$ is the angular frequency of optical carrier.

As shown in Fig.1, after propagation through the free space, the two modes are separated by a PBS with principal axis of x′ and y′. Assume the angle between the principal axis of PolM and PBS (y and x′) is $\alpha$, and the gain of the EDFA is $G$. Then the two signals along the x′ axis and y′ axis of the PBS is:

$$\vec{E}_{BPS}(t)=\frac{\sqrt{2GP_0}}{2}\begin{bmatrix}\begin{bmatrix}\sin(\alpha)\exp\left(j\left(\omega_c t+\frac{\pi}{2}m(t)\right)\right)+\\ \cos(\alpha)\exp\left(j\left(\omega_c t-\frac{\pi}{2}m(t)\right)\right)\end{bmatrix}\hat{x}'\\ \begin{bmatrix}\sin(\alpha)\exp\left(j\left(\omega_c t-\frac{\pi}{2}m(t)\right)\right)-\\ \cos(\alpha)\exp\left(j\left(\omega_c t+\frac{\pi}{2}m(t)\right)\right)\end{bmatrix}\hat{y}'\end{bmatrix} \quad (2)$$

The two signals detected by the two PDs with the same responsivity are expressed as:

$$\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}=\frac{1}{2}GRP_0\begin{bmatrix}\left(1+\sin(2\alpha)\cos(\pi m(t))\right)+n_c+N_1\\ \left(1-\sin(2\alpha)\cos(\pi m(t))\right)+n_c+N_2\end{bmatrix} \quad (3)$$

Where $R$ is the responsivity of the PD, and $n_c$ is the common mode noise from the circuits, $N_1\sim\left(0,\sigma^2/2\right)$ and $N_2\sim\left(0,\sigma^2/2\right)$ are the noise terms which are statistically independent and stationary Gaussian processes with zero mean and variances $\sigma^2/2$. The following subtractor mitigates the common mode noise, and the obtained signal after the subtractor can be expressed as:

$$S(t)=GRP_0\sin(2\alpha)\cos(\pi m(t))+N \quad (4)$$

Where $N=(N_1-N_2)\sim\left(0,\sigma^2\right)$. It can be observed when $\alpha=\pi/4$ we can get the optimized amplitude. Then we apply DSP to recover the signal $m(t)$.

## III. Experimental Setup

Fig.2 illustrates the experimental setup of the 4×100-Gbps PolM-DD based WDM FSO system. The system transmitter comprises several sub-transmitters. Each sub-transmitter incorporates a polarization modulator and a laser diode (LD). For the PAM-4 data generation, a pseudo-random binary sequence is mapped into PAM 4 with Gray coding. The data is uploaded to a 50-GSa/s digital-to-analog converter (DAC), and the bandwidth of the generated signal is 25 GHz. After DAC, the signal is boosted through a power amplifier (PA). Meanwhile, four distributed feedback lasers working at 1538.22 nm, 1539.8 nm, 1541.36 nm, and 1542.92 nm are coupled by a WDM multiplexer. The CW lightwaves from the four laser diodes (LD) are linearly polarized. The input laser light is adjusted to two orthogonal linear polarization modes and modulated by the 25-GHz signal with the opposite modulation index in the polarization modulator. The polarization modulator is from Versawave Technologies Inc, with an insertion loss of 4 dB. Subsequently, the output signals from the modulator are passed through an Erbium-doped fiber amplifier (EDFA). The output power of the EDFA-A is 14 dBm and its gain is 12 dB. After the EDFA-A, a collimator is placed for signal transmission in the free space. Fig. 2(i) shows the optical spectrum after WDM multiplexer.

After propagation through the 1.2-m free space with a total loss of 5.8 dB, at the receiver, the transmitted signals with four different wavelengths are collected by a symmetric collimator. The loss of the free space link mainly comes from the coupling loss of optical free-space alignment. A WDM de-multiplexer with a total loss of 6 dB separates the signals with different wavelengths into different channels, followed by several sub-receivers. Every channel consists of an EDFA-B for signal boosting and a PBS to split signal into two orthogonal polarizations. The insertion loss of the PBS is 4 dB. The output power of the EDFA-B is 10 dBm, and its gain is 8 dB. It is worth noting that the additional EDFA-B is utilized to compensate for the insertion loss of PBS and PC due to low responsivity of the PD. In practice, PDs with high responsivity or avalanche photodiodes can be used for signal detection without pre-amplifier. Then the two orthogonal signals are converted to two electrical signals with opposite sign by two PDs. Finally, the signals are sampled by an oscilloscope (OSC) with 80-GSa/s sampling rate and 26.3-GHz 3-dB bandwidth and recovered by the off-line digital signal processing (DSP). After synchronization of the signal, channel estimation, and PAM-4 decoding, bit-error-ratio (BER) is counted to analyze the system performance. The DSP part is simpler than the coherent receiver. Fig. 2(ii-v) show the spectra after de-multiplexer.

Atmospheric turbulence induces fluctuation of signal irradiance at receiver side. It can be characterized as the variance of optical intensity. The variance is modeled as [19]:

$$\sigma_I^{\,2} = \frac{< I^2 > - < I >^2}{< I >^2} \qquad (5)$$

To evaluate the performance of the system with different atmospheric variance, after DC removal and normalization of the raw data, turbulence is imitated and added to the data with an intensity variance of $n \sim N(0, \sigma_I^2)$. Within the region of $\sigma_I^2$ from 0.001 to 0.005, the offline variation embedding system performs close match to the experimental measurement of the weak turbulence regimes [20].

The interchannel crosstalk, which arises from the imperfect nature of the demux and the collection of different atmospheric links via the same path of the mux, is an important topic for the FSO based WDM-PON [21]. The desired signal is contaminated by the unwanted interference from other channels and the interchannel crosstalk is more destructive for the FSO based WDM-PON upstream. However, in our demonstration, the interchannel crosstalk of turbulence by different paths is negligible since the four different wavelengths are combined with mux, and then transmitted through the same FSO link. Also, for the imperfect demux, since we operate four wavelength channels with channel spacing of 1.6 nm (i.e., 200 GHz), the interchannel crosstalk is not significant. Only less than 1-dB power penalty is measured between single channel and four-channel WDM scheme in the experiment.

## IV. Experimental Results

Fig. 3 shows the benchmarks of the BER performance versus data rate for IM-DD and PolM-DD based FSO system. To compare the two systems fairly, we employ a polarization modulator and use a PBS after the modulator to build up an IM-DD system. We evaluate the performance of the systems operated at bit rates from 50 Gbps to 100 Gbps. Different intensity variances are also investigated. Reference lines with FEC thresholds of 3.8e-3 and 2e-2 are provided. When the system is operated in good channel condition, that is, the intensity variation is zero, the PolM-DD system can support the data rate that is higher than 100 Gbps with maintaining the 3.8e-3 BER threshold while the IM-DD zexceeds the threshold when the data rate is higher than 95 Gbps. Compared with the IM-DD, PolM achieves 20-Gbps gain in data rate tolerance under intensity turbulence with the variance of 0.001. As for higher intensity variance that equals to 0.005, PolM-DD system still falls below the FEC threshold of 2e-2 for data rate that is below 90 Gbps while the IM-DD system far exceeds the FEC threshold of 2e-2. Therefore, the PolM-DD system can support higher data rate transmission and provide enhanced tolerance to the intensity turbulence from the atmosphere.

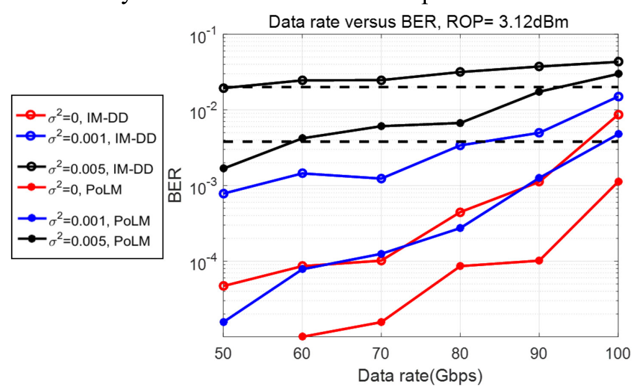


Fig. 3. BER versus data rate under different intensity variances at Received optical power (ROP) = 3.12dBm.

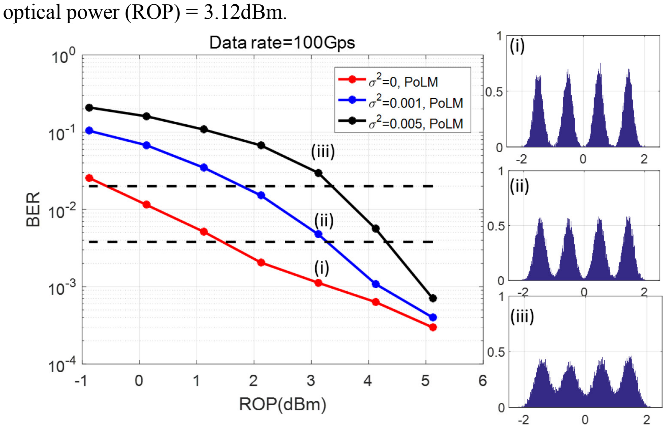


Fig. 4. Power sensitivity of the PolM-DD FSO system under different intensity turbulences. (i), (ii), (iii) are the probability density of the received symbols in 100-Gbps PolM-DD based FSO system with ROP = 3.2 dBm, and variance = 0,0.001,0.005, respectively.

Fig. 4 presents the power sensitivity of PolM-DD system with 100-Gbps data rate under different intensity variances. The received optical power is measured after EDFA-B at the input of the receiver side. The PolM-DD system shows ~1.8-dB penalty with variance = 0.001, and ~3-dB penalty with variance = 0.005 compared with no variance at the FEC threshold of 3.8e-3. The variance tolerance of the PolM-DD FSO system with 100-Gbps data rate is over 0.005.

Fig. 5 depicts the power sensitivity performances of the four channels with different wavelengths in WDM-PolM-DD FSO system. The performance of the four channels shows no apparent difference. As shown in Fig.5 (i to iv), the received signals in four channels exhibit four sharp peaks in probability density distribution and show similar performance.

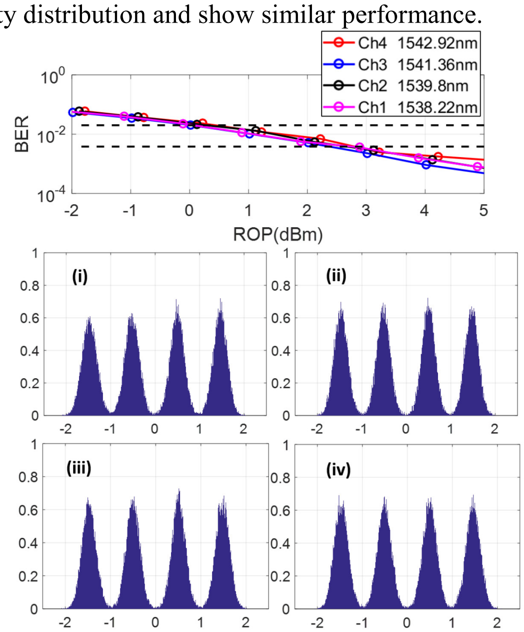


Fig. 5. Power sensitivity of the four channels in 4×100-Gbps PolM-DD based FSO system. (i-iv) are the probability density of the received signal of channel 1,2,3, and 4, respectively, with ROP = 3.12dBm.

## V. Conclusion

We have successfully transmitted the 400-Gbps signal by incorporating PolM-DD-based FSO and WDM scheme. It is the first experimental demonstration of the high-speed PolM-DD FSO system. The system can reduce the effect of fading caused by atmospheric turbulence. The PolM-DD system provides enhanced power margins, and more tolerance to the intensity fluctuations, and can support higher data rate compared to the IM-DD scheme. It offers a promising and flexible option to solve the ever-increasing requirement to large capacity with simple system implementation at a reasonable cost.

## References

[1] J. Zhang, J. Yu, and H.-C. Chien, "Linear and nonlinear compensation for 8-QAM SC-400G long-haul transmission systems," *Journal of Lightwave Technology,* vol. 36, pp. 495-500, 2018.

[2] J. Shi, J. Zhang, Y. Zhou, Y. Wang, N. Chi, and J. Yu, "Transmission performance comparison for 100-Gb/s PAM-4, CAP-16, and DFT-S OFDM with direct detection," *Journal of Lightwave Technology,* vol. 35, pp. 5127-5133, 2017.

[3] K. Fang, J. Yu, H. Wang, and X. Li, "56Gbps signal generation from one 10-G class laser diode for 400G intra-data center interconnection," *Optical Fiber Technology,* vol. 36, pp. 210-214, 2017/07/01/ 2017.

[4] N. Chi, Y. Zhou, S. Liang, F. Wang, J. Li, and Y. Wang, "Enabling Technologies for High-Speed Visible Light Communication Employing CAP Modulation," *Journal of Lightwave Technology,* vol. 36, pp. 510-518, 2018.

[5] E. Ciaramella, Y. Arimoto, G. Contestabile, M. Presi, A. D'Errico, V. Guarino*, et al.*, "1.28 Terabit/s (32× 40 Gbit/s) WDM transmission over a double-pass free space optical link," in *Optical Fiber Communication-incudes post deadline papers, 2009. OFC 2009. Conference on*, 2009, pp. 1-3.

[6] A. Prokeš, "Modeling of atmospheric turbulence effect on terrestrial FSO link," *Radioengineering,* vol. 18, pp. 42-47, 2009.

[7] W. Ni, Y. Miyamoto, K. Wakamori, K. Kazaura, M. Matsumoto, T. Higashino*, et al.*, "Experimental study of atmospheric turbulence effects on RoFSO communication systems," *PIERS Online,* vol. 5, pp. 65-70, 2009.

[8] S. Rajbhandari, Z. Ghassemlooy, J. Perez, H. Le Minh, M. Ijaz, E. Leitgeb*, et al.*, "On the study of the FSO link performance under controlled turbulence and fog atmospheric conditions," in *Telecommunications (ConTEL), Proceedings of the 2011 11th International Conference on*, 2011, pp. 223-226.

[9] W. O. Popoola, Z. Ghassemlooy, J. Allen, E. Leitgeb, and S. Gao, "Free-space optical communication employing subcarrier modulation and spatial diversity in atmospheric turbulence channel," *IET optoelectronics,* vol. 2, pp. 16-23, 2008.

[10] S. Trisno and C. C. Davis, "Performance of free space optical communication systems using polarization shift keying modulation," in *Free-Space Laser Communications VI*, 2006, p. 63040V.

[11] Z. Ghassemlooy, X. Tang, and S. Rajbhandari, "Experimental investigation of polarisation modulated free space optical communication with direct detection in a turbulence channel," *IET communications,* vol. 6, pp. 1489-1494, 2012.

[12] T. Özbilgin and M. Koca, "Polarization diversity in MIMO communication over atmospheric turbulence channels," *Journal of Lightwave Technology,* vol. 34, pp. 3981-3992, 2016.

[13] X. Tang, Z. Ghassemlooy, S. Rajbhandari, W. O. Popoola, C. G. Lee, E. Leitgeb*, et al.*, "Free-space optical communication employing polarization shift keying coherent modulation in atmospheric turbulence channel," in *Communication Systems Networks and Digital Signal Processing (CSNDSP), 2010 7th International Symposium on*, 2010, pp. 615-620.

[14] X. Zhao, Y. Yao, Y. Sun, and C. Liu, "Circle polarization shift keying with direct detection for free-space optical communication," *Journal of Optical Communications and Networking,* vol. 1, pp. 307-312, 2009.

[15] Y. Su and T. Sato, "Analysis of CPolSK-based FSO system working in space-to-ground channel," *Optics Communications,* vol. 410, pp. 660-667, 2018/03/01/ 2018.

[16] F. Bai, Y. Su, and T. Sato, "Performance Analysis of Polarization Modulated DirectDetection Optical CDMA Systems over Turbulent FSO LinksModeled by the Gamma-Gamma Distribution," in *Photonics*, 2015, pp. 139-155.

[17] X. Lin, N. Chi, L. K. Oxenlowe, J. Mork, Y. Siyuan, and P. Jeppesen, "A new orthogonal labeling scheme based on a 40-Gb/s DPSK payload and a 2.5-Gb/s PolSK label," *IEEE Photonics Technology Letters,* vol. 17, pp. 2772-2774, 2005.

[18] X. Liu, W. Pan, X. Zou, L. Yan, B. Luo, and B. Lu, "Investigation on Tunable Modulation Index in the Polarization-Modulator-Based Optoelectronic Oscillator," *IEEE Journal of Quantum Electronics,* vol. 50, pp. 68-73, 2014.

[19] L. C. Andrews and R. L. Phillips, *Laser beam propagation through random media* vol. 152: SPIE press Bellingham, WA, 2005.

[20] X. Tang, Z. Ghassemlooy, S. Rajbhandari, W. O. Popoola, M. Uysal, and D. Wu, "Experimental demonstration of polarisation shift keying in the free space optical turbulence channel," in *Communications in China Workshops (ICCC), 2012 1st IEEE International Conference on*, 2012, pp. 31-36.

[21] A. O. Aladeloba, M. S. Woolfson, and A. J. Phillips, "WDM FSO Network With Turbulence-Accentuated Interchannel Crosstalk," *Journal of Optical Communications and Networking,* vol. 5, pp. 641-651, 2013/06/01 2013.