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Enhancement of Spectral Efficiency FSO Links Using Linear Polarizer-Based MLPolSK Detection

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ABSTRACT This paper proposes the enhancement of spectral efficiency (SE) by linear polarizer based multilevel linear polarization shift keying (MLPolSK) detection in free-space optical (FSO) communication. At the transmitter end, in order to improve SE of FSO links, the various linear state of polarizations (SOPs) with an equal magnitude-spacing of x- or y-polarization are modulated for MLPolSK signal. At the receiver end, the cascaded polarization-independent semiconductor optical amplifier (SOA) and linear polarizer are introduced to detect MLPolSK signal. Polarization-independent SOA is applied to effectively mitigate the turbulence induced scintillation effect by the gain saturation without the distortion of polarization. Linear polarizer with high extinction ratio (ER) is used to transform various SOPs into the signal with an equal intensity-spacing of x- or y-polarization. Besides, the amplified spontaneous emission (ASE) noises are reduced by the polarization of ASE noises by linear polarizer. Finally, MLPolSK is detected by a single photodiode (PD) and decided by multilevel-thresholdings. In experiments, the performance of the proposed technique is evaluated under turbulence channels, which are emulated using Mach–Zehnder modulator (MZM)-based fading simulator. Experimental results show that the SE is improved up to 3 bit/s/Hz under the effective scintillation mitigation using the proposed technique.

INDEX TERMS Multilevel linear polarization shift keying, spectral efficiency, polarization-independent semiconductor optical amplifier, linear polarizer, free space optical communication.

I. INTRODUCTION

Recent decades, free-space optical (FSO) communication has been researched intensively due to the characteristics of higher data rate, wider bandwidth, higher power efficiency, compact size, unlicensed spectrum, and higher security when comparing with the radio-frequency (RF) communication [1]. The FSO technique has a large number of potential application fields, which includes ground-to-satellite, satellite-to-ground, inter-satellite, aircraft-to-satellite, satellite-to-aircraft, inter-aircraft, building-to-building, and mobile backhaul wireless communication [2]. With regard to the fifth-generation (5G) mobile networks, and beyond, the exponentially increasing demand for ultra-high capacity requires the study of high spectral efficient FSO techniques [1]–[3].

Various higher-order modulation techniques, i.e. multilevel pulse amplitude modulation (MPAM), multilevel differential phase-shift keying (MDPSK), and multilevel polarization-shift keying (MPolSK) have been researched to improve the spectral efficiency (SE) in FSO [4]–[6]. However, there are difficulties for the application of these higher-order modulation techniques in practice. As to MPAM, it is difficult to obtain the precise knowledge of atmospheric turbulence channel state information in practical application [4]. Regarding MDPSK, it is evident that the precise control of a one-bit delay interferometer is difficult in case of the transmission of variable data rates [5]. As to MPolSK, the different state of polarizations (SOPs) are estimated through the symbol-by-symbol calculation of Stokes parameters, which are detected by multiple-photodiodes (PDs) [6], [7]. It causes the issues of a large amount of calculations, the difficulties of real-time processing, and the complexity of system. Therefore, a high polarization-dependent gain optical amplifier (PDG-OA) based multilevel linear polarization shift keying (MLPolSK) modulation and detection was researched in our previous work to simplify the detection process of multiple SOPs transmission [8]. The cascaded polarization-independent semiconductor optical amplifier (SOA) and polarization-dependent reflective semiconductor

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optical amplifier (RSOA) were used to mitigate the scintillation effect and convert various SOPs into different intensity information. However, the SE was limited to 2 bit/s/Hz due to the limitation of PDG (20 dB) of RSOA and the amplified spontaneous emission (ASE) noises from SOA and RSOA. Therefore, it is desired to enhance the SE of MLPolSK by improved PDG and reduced ASE noises.

In this paper, we propose the enhancement of SE by linear polarizer based MLPolSK detection in FSO. As to the modulation part, multiple linear SOPs are mapped into MLPolSK signal, which have an equal magnitude-spacing of x- or y-polarization of SOPs. As to the receiver end, firstly, the scintillation effect is effectively mitigated by the gain saturated and polarization-independent SOA without the distortion of SOPs. Then, linear polarizer is rotated to transform various SOPs into the signal with an equal intensity-spacing. Linear polarizer is able to distinguish multiple SOPs due to high extinction ratio (ER) approximate to 40 dB, and the ASE noises are reduced by the polarization of the ASE noises using linear polarizer. Finally, MLPolSK signal is simply detected by a single PD and decided by multilevel-thresholds instead of the estimation of symbol-by-symbol SOPs. The proposed technique was experimentally verified using Mach-Zehnder modulator (MZM)-based fading simulator. Experimental results demonstrate that the SE was improved up to 3 bit/s/Hz using the proposed technique with 8LPolSK transmission.

II. OPERATION PRINCIPLE

Fig. 1 illustrates the block diagram of the principles of the proposed technique. MLPolSK signal is modulated with multilevel SOPs and transmitted into the atmospheric turbulence channel. Then, a polarization-independent SOA is used as a pre-amplifier to mitigate the scintillation effect. Then, the SOPs of MLPolSK signal are converted into the information of signal intensity levels by the adjustment of the coordinate axis of linear polarizer. Finally, the transformed MLPolSK signal is simply detected by the signal intensity instead of symbol-by-symbol SOPs estimation. The detailed principle is described below.

A. TURBULENCE CHANNEL

In FSO, the received optical signal suffers the distortion of power loss and atmospheric turbulence effect from the atmospheric channel [1]. The power loss mainly caused by the absorption and scattering losses and the beam divergence loss, which have a large power attenuation to the received optical signal. This issue can be mitigated by the power boosting at transmitter end and pre-amplification at receiver end using high gain optical amplifiers [2]. As to the atmospheric turbulence, it causes beam wander, beam spreading, and beam scintillation effects. Among these three effects, the turbulence induced beam scintillation is from the variation of pressure and temperature of atmosphere, which causes the significant intensity fluctuations of the received optical signal. Thus, turbulence induced scintillation effect is the major issues in the turbulence channel [3]. Therefore, turbulence channel was simplified into the turbulence induced scintillation effect in this study. The degree of scintillation effect is represented in terms of scintillation index σ_I^2, which means the variance of the intensity fluctuations for the received optical signal. σ_I^2 is represented by [3]

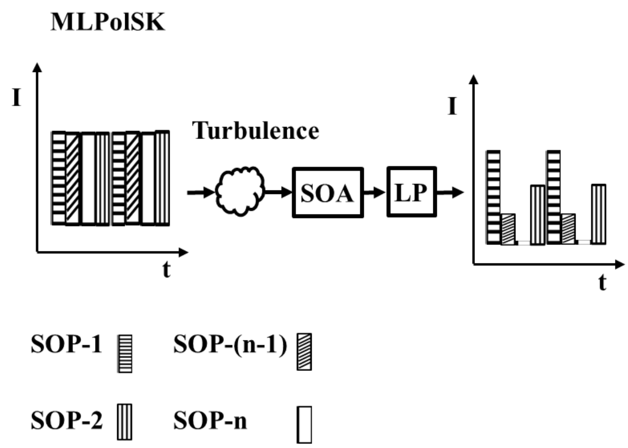

FIGURE 1. Principles of the proposed technique. SOA: semiconductor optical amplifier, LP: linear polarizer, SOP: state of polarization.

$$\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1, \tag{1}$$

where I is the signal intensity, and $\langle . \rangle$ is the ensemble average.

B. THE PROPOSED MLPolSK MODULATION AND DETECTION TECHNIQUE

When a laser beam propagates through the turbulence channel with the characteristics of spatially coherent plane wave, the polarization of signal keeps a stable state [9]. Thus, various SOPs can be transmitted and received to improve the SE in FSO. There are two types polarization, i.e. circular and linear polarizations [6]. The estimation of circular polarization requires the knowledge of both intensity and phase of polarization, thus, linear polarization is applied in the modulation of MLPolSK signal. Besides, it is sufficient to improve the SE in the circumstance of densely spaced linear SOPs.

Fig. 2 illustrates the modulation of MLPolSK signal with an equal magnitude-spacing of x-polarization and y-polarization of SOPs. The different linear SOPs of MLPolSK signal are composed by the variation of orthogonal x- and y-polarizations. It is calculated by [7]

$$\begin{aligned} A &= \sqrt{(A_x)^2 + (A_y)^2} \\ &= \sqrt{(A\cos(\theta))^2 + (A\sin(\theta))^2}, \end{aligned} \tag{2}$$

where A, A_x, and A_y are amplitude of MLPolSK signal, x-polarization of MLPolSK, and y-polarization of MLPolSK respectively. θ is the angle of SOP. Both an equal magnitude-spacing of x- or y-polarization of SOPs can be mapped by

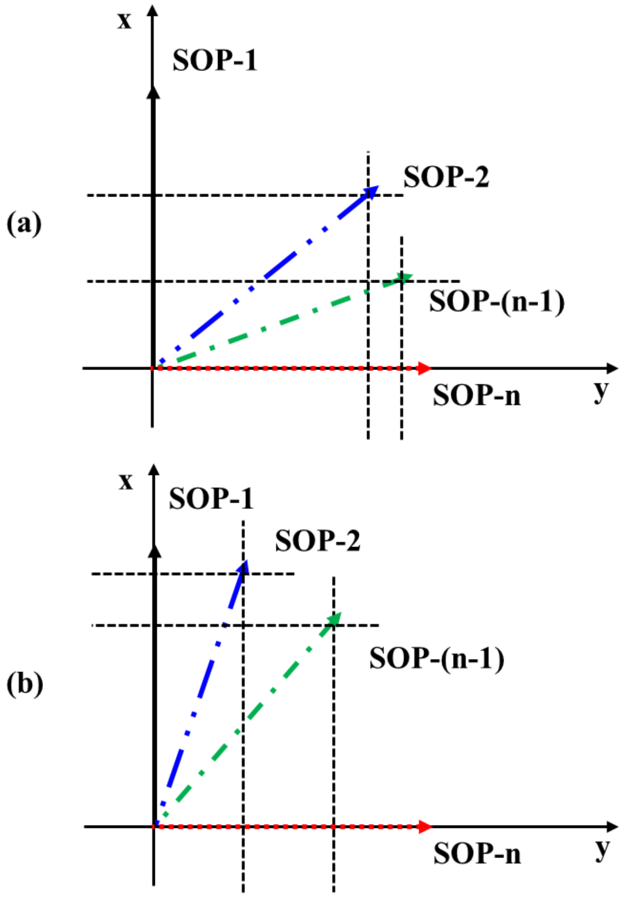

FIGURE 2. MLPolSK modulation with an equal magnitude-spacing of (a) x-polarization, (b) y- polarization of SOPs.

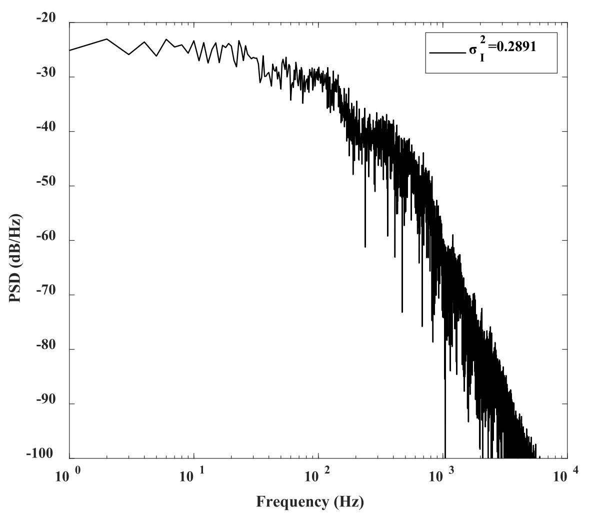

FIGURE 3. The power spectrum density of the turbulence channel with σ_I^2 of 0.2891. PSD: power spectrum density.

varying the degree of θ. As to the receiver end, polarization-independent SOA and linear polarizer are applied to detect MLPolSK signal. Firstly, a polarization-independent SOA is used as a pre-amplifier to mitigate the scintillation effect

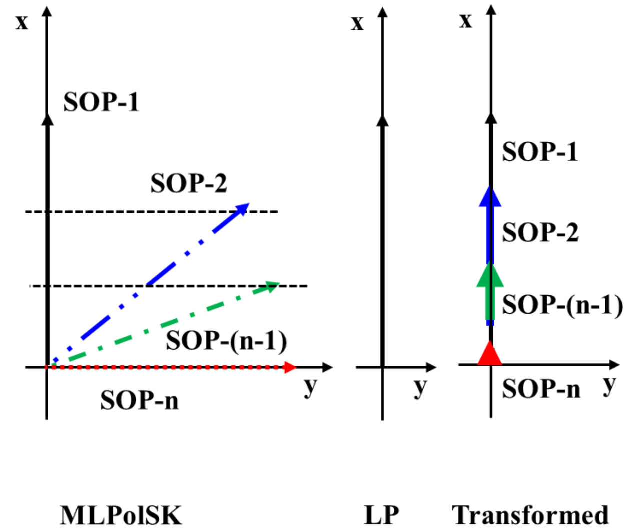

FIGURE 4. The detection of MLPolSK signal with an equal magnitude-spacing of x-polarization of SOPs.

using the gain saturation characteristics. The feature of polarization independence avoids the distortion of SOPs for MLPolSK during the process of scintillation mitigation. Fig. 3 shows the power spectrum density of the turbulence channel with σ_I^2 of 0.2891, and the temporal spectrum is smaller than few KHz. It is obvious that the dynamic gain frequency (approximate to 10 GHz) of SOA is much higher than the turbulence frequency [10]. Therefore, the scintillation effect can be effectively mitigated by the gain saturation SOA. Then, linear polarizer of high ER is used to transform MLPolSK signal into the signal with an equal intensity-spacing levels, and the coordinate axis of linear polarizer is optimized by the rotation of polarization controller (PC). Finally, the transformed signal is detected by a single PD and decided by multilevel-thresholdings without the estimation of symbol-by-symbol SOPs. Fig. 4 shows the detection of MLPolSK signal with an equal magnitude-spacing of x-polarization of SOPs. MLPolSK signal is converted into multiple intensity levels with x-polarization using linear polarizer. Linear polarizer has the characteristics of high ER, which is able to convert more different SOPs into multiple intensity levels. Besides, linear polarizer can improve the SE of MLPolSK by the reduction of ASE noises. The total ASE noises $\sigma^2_{ASE-total}$ are accumulated from the ASE of erbium-doped fiber amplifier (EDFA) $\sigma^2_{ASE-EDFA}$ and the ASE of SOA $\sigma^2_{ASE-SOA}$, and it is calculated by

$$\sigma^2_{ASE-total} = \sigma^2_{ASE-EDFA} + \sigma^2_{ASE-SOA}. \tag{3}$$

The ASE noises are unpolarized light, since they are generated by spontaneous emission from optical amplifiers. Linear polarizer can decrease $\sigma^2_{ASE-total}$ to $\sigma^2_{ASE-total}/\sqrt{2}$ by the polarization process of the ASE noises. Therefore, it is evident that the SE of MLPolSK can be enhanced by the proposed technique due to the high ER of linear polarizer and reduced ASE noises.

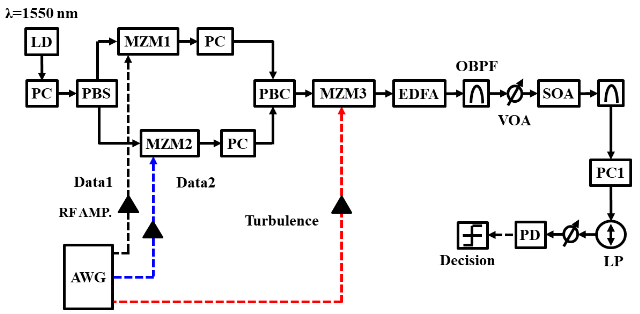

FIGURE 5. Experimental setup. AWG: arbitrary waveform generator, RF AMP.: RF amplifier, PC: polarization controller, PBS: polarization beam splitter, PBC: polarization beam combiner, MZM: Mach–Zehnder modulator, EDFA: erbium-doped fiber amplifier, SOA: semiconductor optical amplifier, LP: linear polarizer, VOA: variable optical attenuator, PD: photodiode.

III. EXPERIMENTS AND RESULTS

Fig. 5 illustrates the setup of experiments in order to verify the improvement of the SE using the proposed technique. Since the SOPs of MLPolSK signal maintain a stable state in the turbulence channel, turbulence induced scintillation effect was discussed in this study. In experiments, the scintillation effect was accommodated by MZM-based fading simulator, which can effectively emulate the atmospheric turbulence channel. MZM-based fading simulator was established by MZM and the time-varying intensity fluctuation signal. The time-varying intensity fluctuation signal was derived from the temporal spectrum of log-amplitude fluctuations. During the transformation process, the inverse Fourier transform and first-order Rytov approximations were adopted. Then, this time-varying intensity fluctuation signal was imported into the RF port of MZM3 to alter the intensity of the travelling optical signal. Fig. 6 shows the distribution of turbulence channel generated by MZM-based fading simulator. It fitted well with the lognormal distribution with a high correlation coefficient larger than 0.9. Therefore, the turbulence channel was effectively accommodated into the experiment. Various SOPs of MLPolSK signal were mapped using two MZMs. MLPolSK signal with an equal magnitude-spacing of x- or y-polarization was obtained by the configuration of electrical signals injected into MZM1 and MZM2. A polarization-independent SOA was deployed to effectively mitigate the scintillation effect. PC1 was applied to have a polarization tracking at the initial stage of transmission. PC1 was adjusted to match the coordinate axis between linear polarizer (GENERAL PHOTONICS POL-001) and MLPolSK signal. The polarization of linear polarizer was altered by PC1 to match the polarization of MLPolSK signal with an equal magnitude-spacing. Finally, the received signal with an equal intensity-spacing were detected by a single PD and distinguished by multilevel-thresholds.

Table 1 shows the experimental parameters which were applied in experiments. The symbol rate was set to 1.25 Gsymbol/s. EDFA (PDG of 0.3 dB) and polarization-independent SOA (PDG of 1 dB) were used to amplify the received optical power and mitigate the scintillation effect, respectively. The average input optical power of SOA was amplified with EDFA in order to have a gain saturation

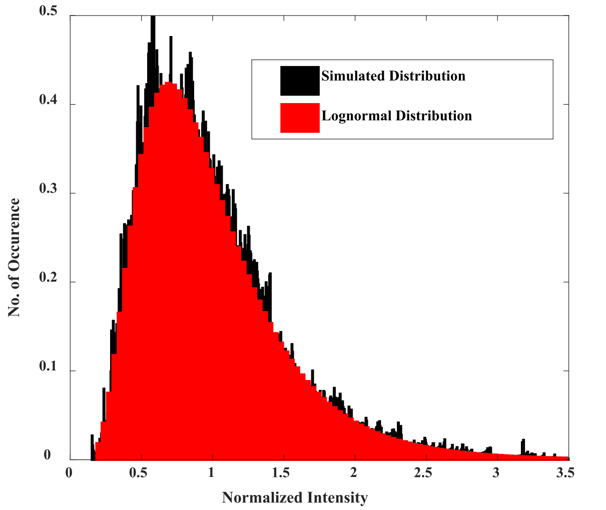

FIGURE 6. MZM-based fading simulator generated turbulence channel under σ_I^2 of 0.2891.

TABLE 1. Experimental parameters.

PARAMETER	VALUE
Symbol rate	1.25 Gsymbol/s
PDG of SOA	1 dB
ER of LP	40 dB
PDG of EDFA	< 0.3 dB
PDG of RSOA	20 dB
σ_I^2	0.2891

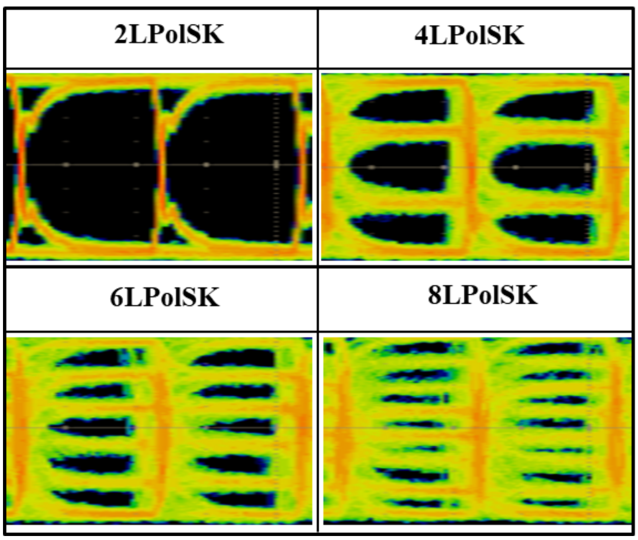

FIGURE 7. Eye patterns for the proposed technique with 2LPolSK, 4LPolSK, 6LPolSK, and, 8LPolSK transmissions.

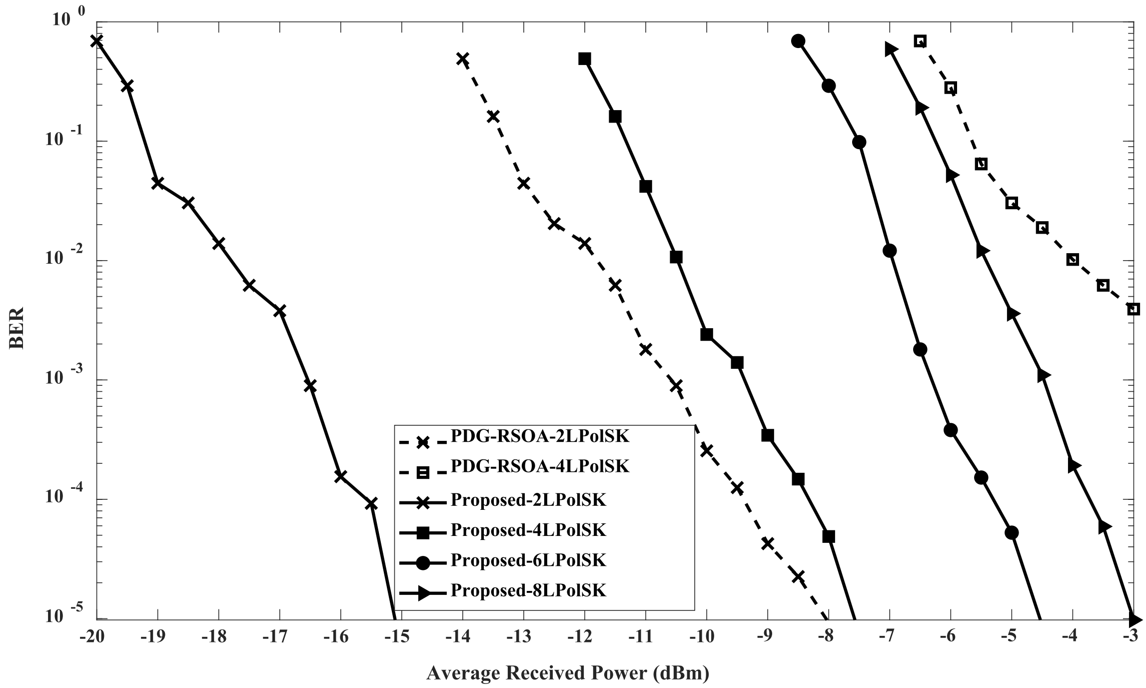

FIGURE 8. BERs performance for the proposed technique.

at SOA. Linear polarizer with ER of 40 dB was applied for the proposed technique. Turbulence channel with σ_I^2 of 0.2891 was adopted in experiments.

Fig. 7 shows the observation of eye patterns for the proposed technique with 2LPolSK, 4LPolSK, 6LPolSK, and 8LPolSK transmissions. MLPolSK signal with an equal magnitude-spacing of x-polarization was modulated, and linear polarizer with x-polarization was applied to extract the x-polarization components of MLPolSK. Since it is impossible to measure the eye diagram under the scintillation effect due to the significant fluctuations of the received optical power, therefore, the eye patterns were measured under a high average received power of −4 dBm at SOA to effectively mitigate scintillation effect, which was referred to the previous works [8]. Besides, the average received power at PD was set to −4 dBm to reduce the PD noises. The eye patterns were optimized in case of 2LPolSK with SOPs of 0 and $\pi/2$; 4LPolSK with SOPs of 0, asin(1/3), asin(2/3), and $\pi/2$; 6LPolSK with SOPs of 0, asin(11/25), asin(13/25), asin(15/25), asin(19/25), and $\pi/2$; 8LPolSK with SOPs of 0, asin(11/56), asin(19/56), asin(25/56), asin(31/56), asin(37/56), asin(45/56), and $\pi/2$. It is obvious that the scintillation effect was thoroughly mitigated using the gain saturated SOA due to a good eye opening of eye diagrams were observed. Besides, 8 level of SOPs were effectively distinguished via the decision of different signal intensity levels using multilevel-thresholds.

Fig. 8 illustrates the verification of the BER performance for the proposed technique. The BERs of the proposed 2LPolSK, 4LPolSK, 6LPolSK and 8LPolSK transmissions

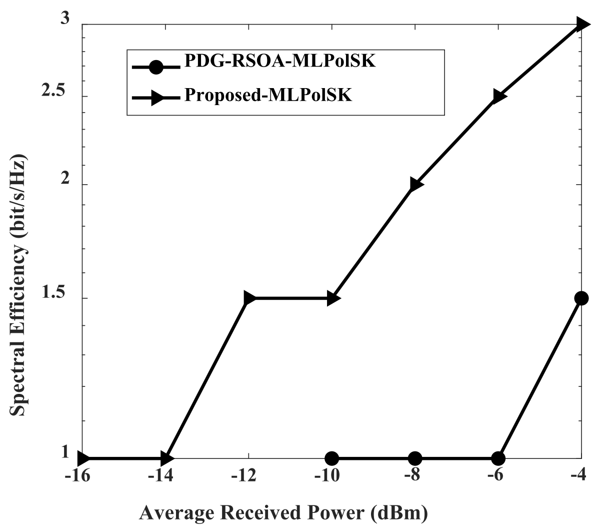

FIGURE 9. SEs comparison between the proposed technique and PDG-RSOA based MLPolSK at BER of 1×10^{-3}.

were measured under the variation of the average received powers at PD. Higher levels of SOP detection were more vulnerable to the noises due to the reduction of ER between various amplitude levels. Comparing with 2LPolSK detection, approximate 7 dB, 10 dB, and 12 dB larger average received optical powers were required for 4LPolSK, 6LPolSK and 8LPolSK detection respectively at BER of 1×10^{-3}. As to the average received power at PD of −4 dBm, the BER was below 1×10^{-3} for the proposed 8LPolSK transmission. Besides, the BERs of the proposed technique were compared to the high PDG-RSOA based 2LPolSK and 4LPolSK transmissions. As to 2LPolSK transmission, the average received optical power was reduced approximately 6 dB by the proposed technique compared to PDG-RSOA based 2LPolSK at BER of 1×10^{-3} due to the application of linear polarizer with high ER and the linearly polarized ASE noises. Fig. 9 shows SEs comparison between the proposed technique and PDG-RSOA based MLPolSK in case of BER of 1×10^{-3}. SE was improved to 3 bit/s/Hz using the proposed technique under 8LPolSK transmission compared to 1.5 bit/s/Hz using the PDG-RSOA based MLPolSK transmission in case of the average received power at PD of −4 dBm. Consequently, the SE was significantly enhanced by the proposed technique under 8LPolSK transmission, and it can be further enhanced by the application of LP with larger ER.

IV. CONCLUSION

In summary, linear polarizer based MLPolSK detection was proposed to enhance the SE in FSO. MLPolSK signal was modulated with an equal magnitude-spacing of x- or y-polarization. MLPolSK was detected through the transformation of various SOPs into different intensity levels using linear polarizer with high ER under scintillation mitigation using gain saturated and polarization-independent SOA. The proposed technique was experimentally verified under the turbulence channel emulated by MZM-based fading simulator. Experimental results demonstrated that 8LPolSK transmission was available due to the high ER of linear polarizer and reduced ASE noises. The SE was improved up to 3 bit/s/Hz using a simple single PD detection and multilevel-thresholdings under the effective scintillation mitigation. Therefore, the proposed technique is highly potential and feasible for spectral efficient real-time FSO transmissions.

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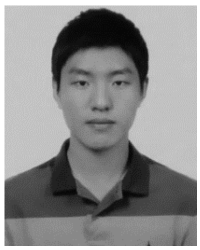

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