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SOP Change Robust Optical Modulation Based on Dual Polarization Modulation for Multi-Dimensional Optical Transmission

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ABSTRACT In optical transmission technique using optical polarization, the change of state of polarization (SOP) and the rotation of SOP (RSOP) during optical transmission has a significant impact o the transmission performance. We propose polarized intensity rotational frequency shift keying (PIR-FSK) as a novel modulation technique in change of SOP and RSOP-tolerant optical transmissions. The proposed PIR-FSK signal does not affect the entire intensity of the optical carrier by modulating the sinusoidal signals on each X and Y-polarized optical carrier. Therefore, the proposed PIR-FSK modulation and optical carrier intensity modulation can operate at the same time. Moreover, since the proposed technique does not modulate the signal using the SOP unlike the PolSK, PIR-FSK is not affected by SOP changes that occur during transmission, and the signal does not be degraded even with RSOP. We demonstrated that the signals modulated using the proposed PIR-FSK modulation have higher signal capacity and efficiency compared to the signal modulated using PolSK modulation.

INDEX TERMS Frequency shift keying, Multi-dimensional optical transmission,Polarization shift keying, Rotation of State of Polarization(RSOP).

I. INTRODUCTION

The demand for high data capacity in optical access networks using optical intensity modulated signals has increased exponentially in recent years. Therefore, various signal modulation techniques based on intensity modulation, such as digital signal modulation and multi-subcarrier modulation, have been studied by researchers in this field. However, the limited physical modulation bandwidth of the optical modulator also limits the bandwidth of the modulated signal. Therefore, in conventional optical access networks, numerous studies have been conducted on efficient data transmission. In particular, research pursuing high data rates and high spectral efficiency is expected to continue over the next decade. Multicarrier transmissions have been researched to efficiently use resources, and coherent transmissions have been studied for increasing the receiver sensitivity to the high signal-to-noise ratios (SNRs) of received signals [1-4]. However, the modulation technique using only optical intensity resources cannot support high data traffic. Therefore, the need exists for a multidimensional transmission technique that utilizes not only optical intensity modulation but also other resources of an optical carrier, such as optical phase, polarization, and wavelength [5-7], is required for high-capacity efficient signal transmission.

The data capacity of the technique using optical wavelength for modulation can be easily increased because it can modulate different signals at various wavelengths. However, the system becomes complex because it requires a transmitter and receiver for each wavelength. Therefore, multi-dimensional transmission within a single wavelength is needed. Polarization shift keying (PolSK) is an optical polarization technique widely used as a multi-dimensional modulation resource within a single wavelength [8,9]. In PolSK modulation, a signal is modulated by changing the state of polarization (SOP). Because it can be modulated independently from the optical intensity, PolSK has the advantage of increasing the transmission capacity. However, PolSK have critical drawbacks such that it is vulnerable to SOP change, especially rotation of SOP (RSOP). When transmitting an optical signal, the polarization changes according to the characteristics of the optical fiber and optical active devices; specifically, external environmental factors can cause SOP changes from a few kilorads per second to a few megarads per second [10–13]. Thus, when the signal is modulated and transmitted through optical fiber, it is received in a different polarization state. In addition, the rotated signals affect each other as interference. In the PolSK technique, the signal power decreases after RSOP whereas the interference signal power increases leading to low SNR. Therefore, the RSOP must be compensated to use the PolSK. This was achieved by tracking the polarization state of the signal through a reference pilot tone or a training symbol and by controlling the SOP of the signal before receiving the signal [14]. The additional time or frequency resource for tracking the reference signals made the system complex. Furthermore, tracking and controlling the rapid polarization rotation is extremely difficult. Therefore, the PolSK technique is not suitable as a modulation resource that uses polarization for high transmission capacity. Therefore, it is necessary to develop a new modulation technique using optical polarization, which is tolerant toward the RSOP.

In this paper, we propose polarized intensity rotational frequency shift keying (PIR-FSK) modulation as a polarization modulation technique for multi-dimensional optical modulation. We validate the proposed technique by demonstrating that the PIR-FSK modulation can be applied independent of the optical intensity modulation. The feasibility of the scheme is theoretically and experimentally verified to demonstrate that PIR-FSK offers improved RSOP immunity compared to the PolSK.

II. SCHEMATICS

We used the Mach–Zehnder modulator (MZM) for external modulation of the optical carrier at the quadrature bias point (QP), maximum intensity transmission point (MATP), and minimum intensity transmission point (MITP). The QP is employed mainly in intensity modulation and direct detection (IM/DD) systems because it modulates the input signal to the intensity of the optical carrier without nonlinear distortion. In contrast, MITP is employed for optical field modulation, because it can change the phase of the signal by 2π. However, the squared component of the signal is modulated by the intensity of the optical source. When the signal is modulated at the MITP of the MZM, as shown in Fig. 1, the signal of the square component of the frequency of the input signal is modulated to the carrier. Therefore, the sine squared component is modulated on the optical carrier if the sine signal is modulated. The signal modulations at the MATP and MITP of the MZM follows the same process. The signal modulations at the MATP and MITP of the MZM follow the same process [15–18].

The optical carrier from the laser is passed through the polarizing beam splitter (PBS) and is divided into X and Y polarizations. As shown in Fig. 2 (a) and (b), the FSK signal in the sine and cosine form is modulated to each polarization through MZM. Hence, the squared component of the signal is modulated at the MATP or MITP on each polarized optical carrier, as shown in Fig. 2 (c) and (d). When an unpolarized optical signal is received by a Hence, the squared component of the signal is modulated at the MATP or MITP on each polarized optical carrier. When an unpolarized optical signal is received by a photodetector (PD), no beating or mixing occurs between X and Y polarizations. The signal received is the summation of the signals modulated on the optical X and

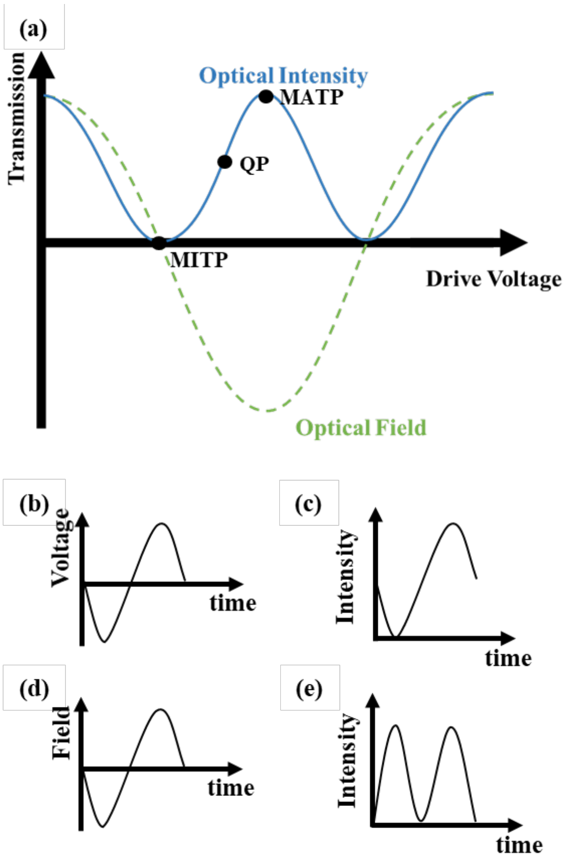


Figure 1 **Modulation characteristics of the MZM: (a) transfer curve of the MZM; (b) input electrical signal; (c) output optical signal modulated at the QP; (d) field of the output optical signal modulated at the MITP; (e) intensity of output optical signal modulated at the MITP.**

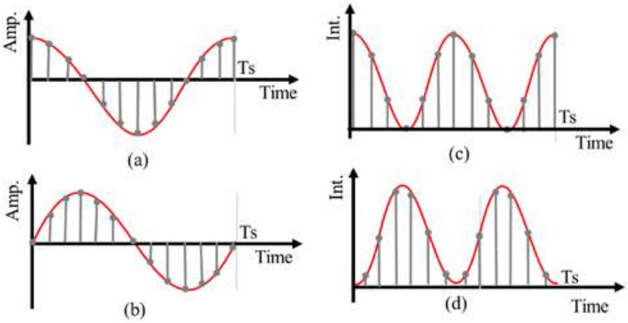


Figure 2 **Schematics of optical carrier modulated by PIR-FSK: (a), (b) input signal on x- and y-polarized optical carrier; (c), (d) output optical signal on each polarized optical carrier.**

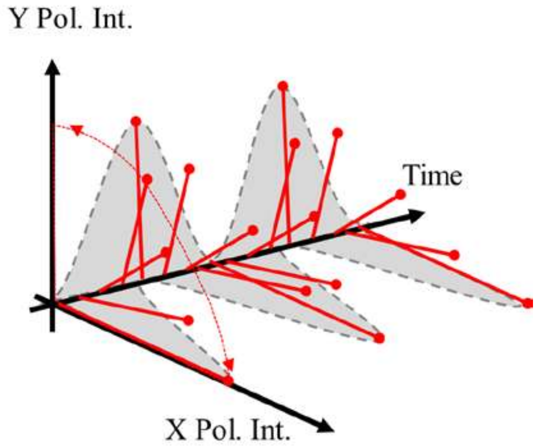


Figure 3 PIR-FSK signal on the unpolarized optical carrier

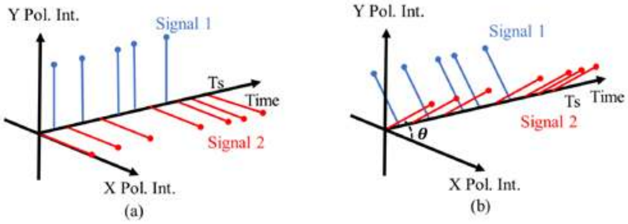


Figure 4 PolSK signal without RSOP; (b) PolSK signal with RSOP.

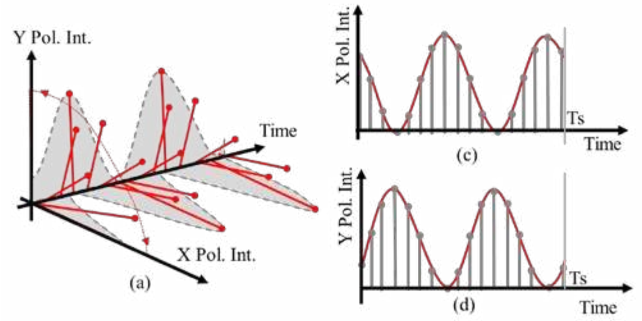


Figure 5 PIR-FSK signal with RSOP: (a) signal on the unpolarized optical carrier; (b), (c) signal on each polarized optical carrier.

Y polarization intensity and not the summation of the signals modulated on optical phase. Therefore, no signal is modulated on the total intensity of the optical carrier when the X- and Y-polarized optical carriers are modulated by sine and cosine waves. However, each polarized carrier has a frequency, as shown in Fig. 3.

The frequency modulated to the carrier is polarized intensity rotational frequency (PIR-F). The proposed PIR-FSK technique can be used independent of the optical intensity modulation because the total optical carrier intensity is maintained constant. Therefore, dimensional expansion is possible using the proposed PIR-F. Each PIR-F is represented by a symbol with a different bit. That is, the PIR-FSK technique is a modulation technique based on FSK using PIR-F. This is significantly different from polarization division multiplexing FSK (PDM-FSK) and PolSK because it modulates the same FSK signal in the form of sine and cosine for each X and Y polarization. Since the proposed technique generates a signal based on the FSK technique, the modulation and demodulation method of the proposed technique are the same as those of the existing FSK techniques.

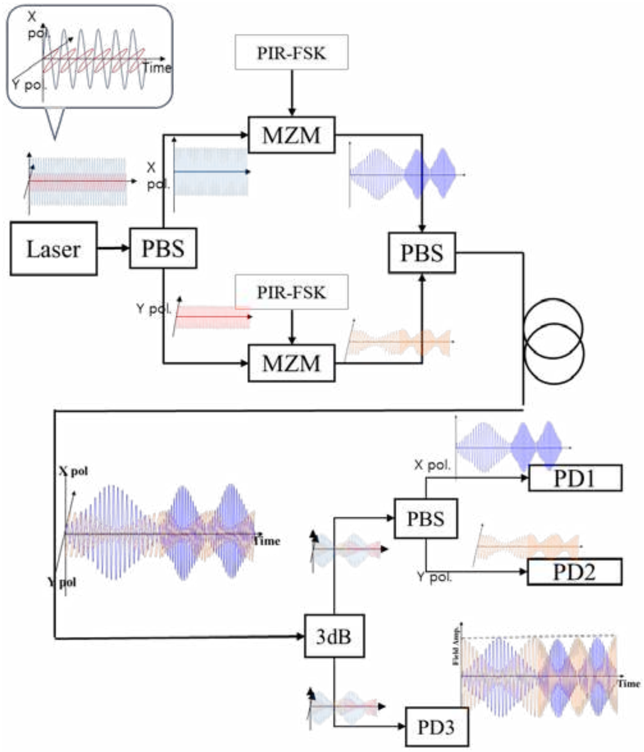


Figure 6 Block diagram of proposed technique

When a PolSK signal experiences RSOP changes during transmission, the signal modulated on X- and Y-polarization rotates, shown in Fig. 4. The interference between the two modulated signals results in the rotated signals of both polarization. Equation (1) reveals that the rotated signals 1 and 2 are projected to the X-polarization. The projection of signal 2 on the X-polarization decreases corresponding to the decrease in the RSOP angle (ϕ). However, the projection of rotated signal 1 increases corresponding to the decrease in the RSOP angle (ϕ) because interference degrades the signal-to-interference-noise ratio (SINR) at the receiver of the X-polarization.

$$SINR_X = \frac{S_2\cos\phi}{Noise + S_1\sin\phi},\quad SINR_Y = \frac{S_1\cos\phi}{Noise + S_2\sin\phi} \tag{1}$$

$$Rx_X = \left[\cos(f_{fsk}t)\cos\phi - \sin(f_{fsk}t)\sin\phi\right]^2 + N = \cos^2(f_{fsk}t+\phi) + N \tag{2}$$

$$Rx_Y = \left[\sin(f_{fsk}t)\cos\phi + \cos(f_{fsk}t)\sin\phi\right]^2 + N = \sin^2(f_{fsk}t+\phi) + N \tag{3}$$

Fig. 5 shows the transmitted PIR-FSK signal after RSOP. Fig. 5 (a) demonstrates that the entire optical carrier is rotated to a particular angle due to RSOP. Due to RSOP, the signal is distorted when viewed from each polarization axis in Fig. 5 (b) and (c). Equations (2) and (3) reveal that the signal is received as the square of the sum of the original

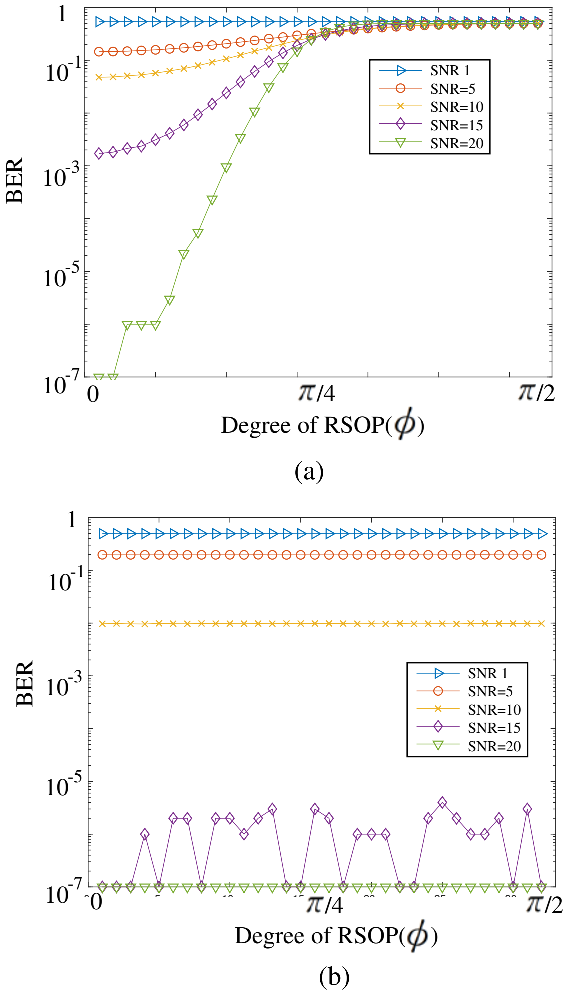


Figure 7 BER performance according to RSOP with different SNR: (a) BPolSK; (b) PIR-BFSK

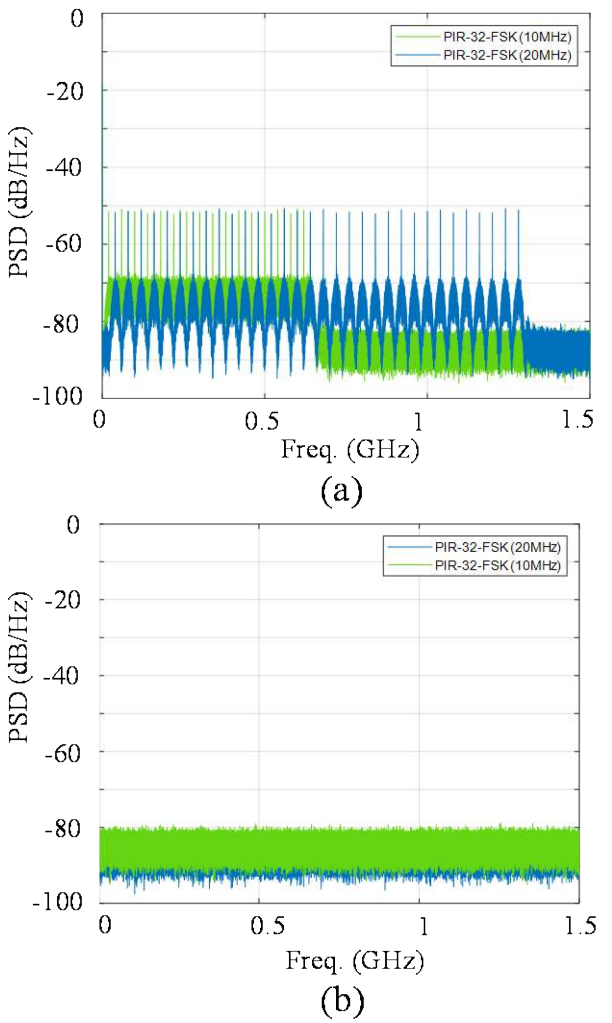


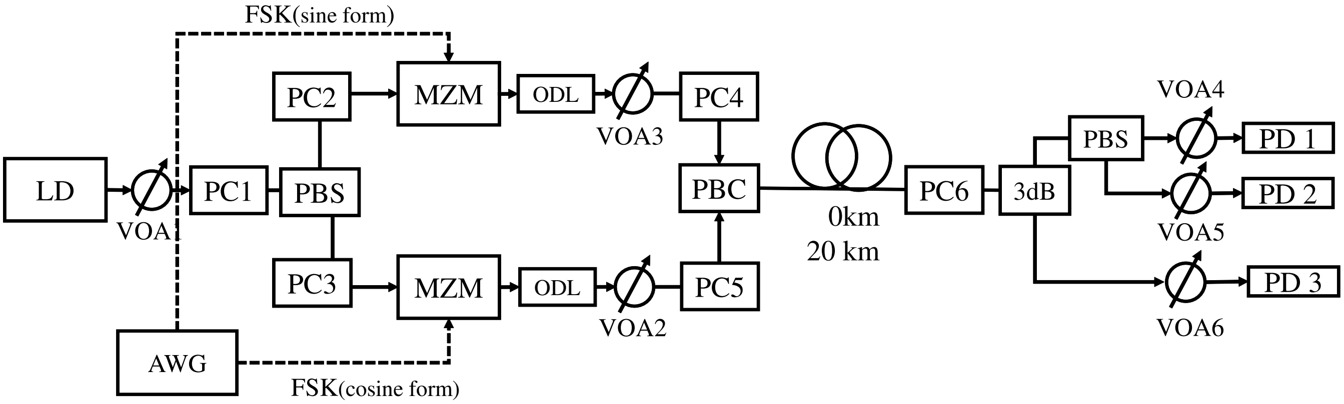
Figure 8 Received signal spectrum from the (a) polarized optical carrier and (b) unpolarized optical carrier.

signal and interference signal, with the noise. The distortion appears as a phase change (ϕ) in the FSK signal. The The distortion does not have any impact on the frequency of the signal as shown in Equations (2) and (3). Therefore, the component distorted by RSOP does not cause interference to each polarization. Moreover, the FSK signal is determined using the frequency rather than the phase component. Therefore, the PIR-FSK signal suffered by RSOP can be received without distortion. Furthermore, the proposed technique can neglect the optical phase even if the phase change of each polarization and the SOP change occurs during transmission because only the intensity of polarized carrier is received in the PIR-FSK technique..

III. SIMULATIONS AND EXPERIMENTS

The proposed technique was verified by simulation and experimentation. Fig. 6 shows a schematic diagram of the proposed transmission scheme. In the proposed modulation technique, the polarization beam splitter (PBS) splits the optical carrier generated by a laser into two polarizations, and the two MZMs modulate the PIR-FSK to each polarized carrier. Both modulated polarized signals are combined through the polarization beam combiner (PBC) and then transmitted. A 3 dB coupler splits the signal at the receiver, and a photodetector (PD 3) receives the intensity of the optical carrier through direct detection. The optical signal is divided into each polarization through PBS at the other side of the 3 dB coupler, and the polarized signals are received at PD 1 and PD 2. A binary PolSK (BPolSK) signal with a data rate of 1 Gbps is transmitted, and a PIR-binary FSK (PIR-BFSK) with symbol duration equal to that of BPolSK is modulated. The PIR-BFSK is used with 0.5 GHz and 1 GHz tones. The tones become squared values after modulation at MATP. Therefore, BPolSK and PIR-BFSK have the same symbol duration, that is, 1ns.

Simulation was performed using the proposed technique and the conventional PolSK to analyze the bit error rate (BER) performance according to RSOP. Additive white Gaussian noise (AWGN) was applied after RSOP by transmitting each PIR-BFSK and BPolSK. Fig. 7 (a) and (b)



LD : Laser Diode, PC : Polarization Controller, PBS : Polarization Beam splitter, MZM : mach-zehnder modulator, AWG : arbitrary waveform generator, ODL : optical delay line, PBC : polarized beam combiner, 3dB : 3dB coupler, PD : Photodetector, VOA : variable optical attenuator;

Figure 9 **Experimental setup of the PIR-FSK.**

show the BER performance according to the RSOP angle. As shown in Fig. 7 (a), the BER performance of the BPolSK signal deteriorated as the RSOP increased; when the RSOP angle exceeded π/4, the entire signal became distorted. When the signal was subjected π/4 of the RSOP angle, PD 1 received the signal and the interference, both having the same power. Hence, SNR became less than 1, deteriorating the signal performance. That is, when using the BPolSK technique, the interference occurred because of the RSOP. However, as shown in Fig. 7 (b), the signal using PIR-BFSK showed no degradation according to the RSOP. When SNR equal to 15dB, fluctuation occurs due to insufficient transmission bits, and it is negligible. Because the polarization rotation did not affect the frequency of the signal, the BER performance of the PIR-BFSK was not degraded by the RSOP. Therefore, the BER performance of the PIR-FSK depended only on SNR.

The proposed technique was simulated with 32 frequencies (PIR-32-FSK) for high-order modulation, as shown in Fig. 8. In Fig. 8 (a), PIR-32-FSK, each frequency spacing was set to 10 MHz and 20 MHz. The symbol duration was equally set to 0.05 µs. The received signals of PD 1 and PD 2, which received the polarized optical carrier, detected the FSK signal. The received FSK signals have orthogonality between each symbol. However, in Fig. 8 (b), the PD 3, which received the unpolarized optical carrier, did not receive any signal. This indicates that the signal was not modulated with the total intensity of the optical carrier using the sum of the FSK signals modulated for each polarization. The modulation of the PIR-FSK signal does not affect the total carrier intensity. The signal modulated on polarized carrier had twice the bandwidth of the input signal because it was received by modulating the squared frequency..

Fig. 9 presents the experimental setup of the proposed technique. An experiment was conducted based on the system scheme shown in Fig. 6 using the same BPolSK and PIR-BFSK signals employed in the simulation. The BER performances of these signals according to the RSOP were

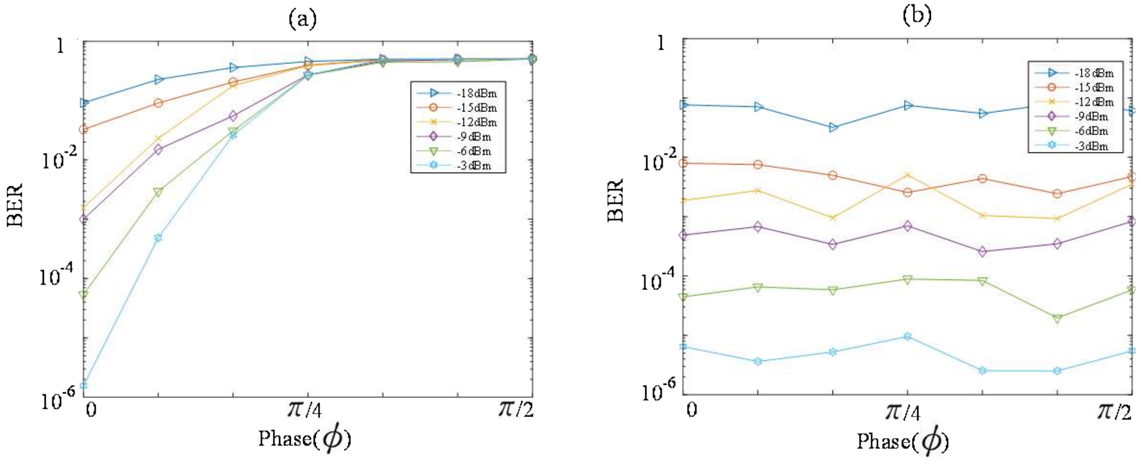


Figure 10 **BER performance for optical back to back according to RSOP with different received optical power: (a) BPolSK; (b) PIR-BFSK.**

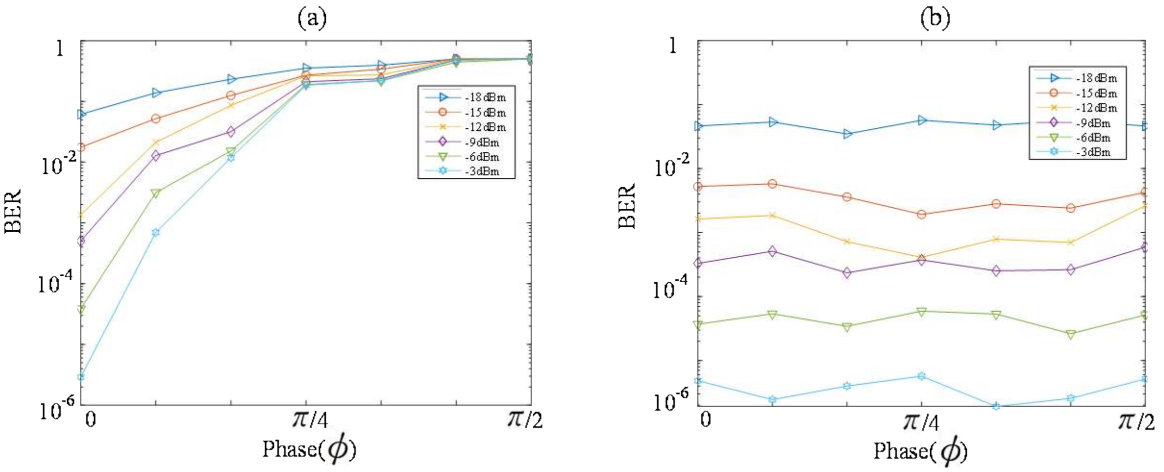


Figure 11 **BER performance for optical transmission of 20 km SMF according to RSOP with different received optical power: (a) BPolSK; (b) PIR-BFSK.**

measured by varying the received optical power. The launch power of laser diode (LD) (SFL1550S) was 10dBm. The optical carrier launched from LD was polarized at SOP 45º by a polarization controller1 (PC 1) and passed through the PBS. Subsequently, the two optical carriers possessed two orthogonal polarization states each. The two orthogonally polarized optical carriers were tuned in PC 2 and PC 3 for maximum output modulation of the MZMs (MXER-LN-10-00-P-P-FA-FA). Each sine and cosine form of FSK signal was applied into MZMs and was modulated into polarized optical carriers. To minimize the signal distortion, the BPolSK signal was modulated at the QP of the MZM. The PIR-BFSK signal was modulated at the MATP of the MZM for high received optical power. The BPolSK signal had a bandwidth of 1 GHz. The PIR-BFSK was used with 0.5 GHz and 1 GHz frequencies. The modulated optical carriers were optically synchronized through optical delay lines (ODLs), and each optical carrier power was matched using variable optical attenuators (VOA 2 and VOA 3). The two optical carriers were again set orthogonal to each other through PC 4 and PC 5 in a polarization state (X-, Y-polarization). Two orthogonal optical carriers were combined through the PBC. The combined optical carriers were conducted with for optical back-to-back and 20 km transmission. Thereafter, RSOP was controlled through a PC 6 set after the PBC. The polarization-rotated optical carrier was divided into two optical carriers by a 3dB optical coupler. PD 3 received unpolarized optical carrier and measured whether the signal is modulated over the entire intensity of the optical carrier to demonstrate that intensity modulation and the proposed PIR-FSK technique can be used independently of each other. The polarized optical carriers that passed through PBS were received at PD 1 and PD 2.

As shown in Fig. 10, the BER performance of the BPolSK signal changed corresponding to the changes in RSOP. As the RSOP increased, the BER performance of the BPolSK signal degraded. Whereas, the proposed PIR-BFSK signal showed no change in performance according to the RSOP change. Therefore, the BER performance depended only on the received optical power. To verify the orthogonality of the PIR-FSK signal and the intensity modulation, the spectrum of the polarized and unpolarized optical signals were measured.

The experiments were also conducted in optical 20km transmission. The Fig. 11 show the BER performance of the PIR-BFSK and the BPolSK according to RSOP. As shown in Fig. 11 (a) and (b), RSOP had a significantly negative impact on the 20 km standard single mode fiber (SSMF) transmission under the PolSK technique. However, RSOP had no impact on SSMF transmission under the PIR-FSK technique. The polarization mode dispersion (PMD) of fibers occurred during optical transmission. Moreover, the orthogonality between X and Y polarization was not maintained during optical fiber transmission. The PolSK signal degraded during transmission because of various issues, such as PMD, RSOP, SOP change, and unmaintained orthogonality of polarization. This is because PolSK signals modulated on X and Y polarization interfered with each other. Therefore, the SINR decreased. In addition, the proposed PIR-FSK technique is modulated only on the intensity of polarization. Therefore, the optical phase during the SOP change had no impact on the PIR-FSK modulated signal. The signal and the interference have the FSK signals having the same frequency but different phases. The PIR-FSK signal is unaffected because the RSOP and the unmaintained orthogonality of polarization affect the phase and not the frequency of the FSK signal. In addition, The PIR-FSK technique is less sensitive to the PMD than the PolSK. In the PolSK technique, the interference between polarizations was complicated by PMD and RSOP, and intersymbol interference (ISI) may also occur. The interference between polarizations did not occur in the PIR-FSK technique although PMD and RSOP occurred simultaneously. However, ISI did occur in the PIR-FSK technique. Therefore, the PIR-FSK signal can be less distorted compared to the PolSK signal during optical fiber transmission.

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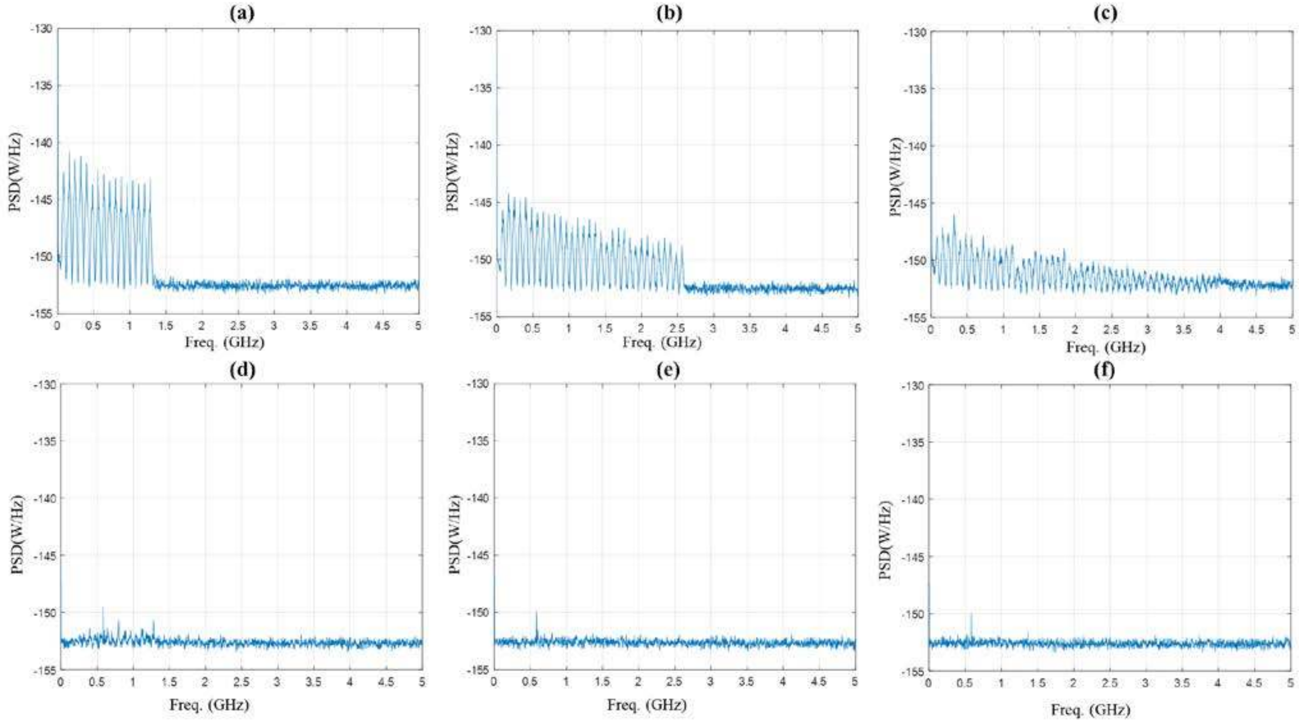

Figure 12 **Received signals from polarized optical carrier modulated by (a) PIR-16-FSK, (b) PIR-32-FSK, and (c) PIR-64-FSK; received signals from unpolarized optical carrier modulated by (d) PIR-16-FSK, (e) PIR-32-FSK, and (f) PIR-64-FSK.**

We conducted experiments for 16 to 64 frequencies (PIR-M-FSK) for the optical back-to-back configuration to test the proposed PIR-FSK technique. We set each frequency spacing to 40 MHz and the symbol duration to 25 ns. Similar to the simulation results, the polarized optical signals received from PD1 and PD2 had FSK signals as shown in Figure 12 (a), (b), (c). However, the unpolarized optical signal was not modulated with any signal, as shown in Fig. 12 (d), (e), and (f). The noises in the Fig. 12 (d), (e), and (f) represent noises for mismatches of the ODL and the bias point. Therefore, the proposed technique could modulate the signal on a polarized optical carrier without affecting the total intensity of the optical carrier.

IV. CONCLUSION

We proposed PIR-FSK as a novel modulation technique that provides optical polarization-based modulation unaffected by the changes in RSOP. The proposed technique can be used simultaneously with optical intensity modulation because it modulates and transmits the FSK signal to the intensity of each polarization and does not impact the total intensity of the optical carrier. The intensity of each polarized carrier is modulated by FSK.. The changes in RSOP have no impact on the BER performance of PIR-FSK compared to that of PolSK in which the RSOP change results in considerable degradation. Thus, the proposed PIR-FSK can relax the required polarization tracking and control functions. This technique would be useful for next-generation optical transmissions of multidimensional modulation with high spectral efficiency.

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