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# Optical code division multiple access secure communications systems with rapid reconfigurable polarization shift key user code

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**Abstract.** An optical code division multiple access (OCDMA) secure communications system scheme with rapid reconfigurable polarization shift key (Pol-SK) bipolar user code is proposed and demonstrated. Compared to fix code OCDMA, by constantly changing the user code, the performance of anti-eavesdropping is greatly improved. The Pol-SK OCDMA experiment with a 10 Gchip/s user code and a 1.25 Gb/s user data of payload has been realized, which means this scheme has better tolerance and could be easily realized. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.54.9.096101](https://doi.org/10.1117/1.OE.54.9.096101)]

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## 1 Introduction

With rampant eavesdropping technology, the security of optical fiber communication has become a serious problem that must be contemplated. It has been demonstrated that secure optical communications based on data encryption algorithm are usually cracked, and the physical method for anti-eavesdropping is reliable. By now, there are three main physical approaches: quantum encryption key distribution technology,<sup>1</sup> secure chaotic communications,<sup>2</sup> and optical code division multiple access (OCDMA). Due to the physical mechanism limitations, quantum communication is only suitable for low-speed signal transmission,<sup>3,4</sup> and the single photon source and quantum receiver are quite expensive. Chaotic communication has been studied for many years, but there are more difficulties in practical applications.<sup>5</sup> OCDMA based on conventional technologies is often said to be inherent security and has received extensive attention.<sup>6</sup>

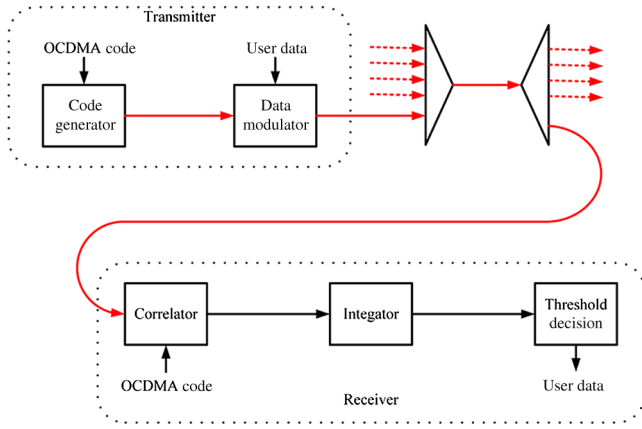
Among the approaches of OCDMA, the core technique is how to apply a physical quantity to express the user code. In 2004, McGeehan et al. demonstrated a time wavelength polarization code using the fiber delay line.<sup>7</sup> Since 2006, Kitayama et al. made a lot of advanced progress in OCDMA. In Refs. 8 and 9, a method based on a time-phase code using the hybrid planar lightwave circuit and super structured fiber bragg grating en/decoders was proposed. In 2010, a two-dimensional time-domain spectral phase encoding/wavelength hopping coherent deferential phase shift key (DPSK)-OCDMA system using fiber Bragg gratings (FBGs) and a phase modulator was proposed.<sup>10,11</sup> In 2014, they completed the 40G-OCDMA-PON system.<sup>12</sup> In 2015, Al-Khafaji et al. proposed a bipolar OCDMA solution;<sup>13</sup> binary user data bits are encoded by two alternative

spectral-amplitude encoders, which are assigned to distinct time slots representing bit 1 and bit 0, and the performance analysis shows that it has a better tolerance of multiple access interference than unipolar spectral amplitude coding-OCDMA in different transmission rates.

All of the systems above are based on a passive optical path with a fixed structure, such as FBGs or fiber delay lines that causes the limited sets of the user coder. For achieving sufficient orthogonality among the user codes, researchers utilize algorithms to construct optical orthogonal codes (OOCs), which always include a large number of chips in code. To extend the chip accommodation, the works of Refs. 7–12 and 14 utilize time, wavelength, and polarization multiplexing approaches. However, these schemes lead to complicated and redundant system structures. Besides that, OOCs are usually unipolar codes. In case of the same code length, the result of correlation between bipolar codes is much better than that of unipolar codes for multiuser access. Bipolar codes have been used in a phase shift encoder and decoder<sup>15–17</sup> based on phase modulator or FBG, but coherent detection is not easy for a reconfigurable decoder. In Ref. 15, a DPSK demodulator is needed, and the cost and complexity of the system is much higher. Furthermore, Shake<sup>14</sup> indicated that “A source cryptography provides a much greater degree of confidentiality than does time-spreading/wavelength-hopping O-CDMA encoding” and “Rapid reconfiguration of codes can also increase the difficulty of interception.” Therefore, a bipolar OCDMA scheme with reconfigurable user code has significant meaning.

In this paper, a novel bipolar OCDMA network is proposed by analyzing the Jones matrix of a polarization shift keying (Pol-SK) modulation. We take advantage of the fact that light can be transmitted on two orthogonal polarization states to encode  $\{p\text{-state}, s\text{-state}\}$  as chips that indicate a bipolar code  $\{+1, -1\}$  in a CDMA system. We demonstrate a back-to-back Pol-SK OCDMA system, which

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**Fig. 1** Architecture of optical code division multiple access (OCDMA) system.

generates polarized chips at 10 Gbps and recovers 1.25 Gbps original datum from this Pol-SK optical signal. This bipolar code could be rapidly reconfigured and has the advantages of enlarging the capacity of a code set and being easily judged.

This paper is structured as follows. Section 2 describes how to map a bipolar value to orthogonal linear polarization states. Section 3 is devoted to the experimental setup and result analysis. Finally, Sec. 4 briefly presents the main conclusion of this work.

## 2 Principle of Polarization Shift Key Optical Code Division Multiple Access

Figure 1 shows the basic architecture of the proposed OCDMA system, which consists of a transmitter and receiver. In the transmitter, there is a software-defined user code generator and a payload data modulator. The receiver consists of an optical correlator, in which the correlation operation between the received optical signal and the local code is achieved, a balanced detector with a differential circuit, an integrator to accumulate the chips, and a device for threshold decision to recover the payload data.

In our proposed system, a pair of linear orthogonal states of polarization (SOP),  $[1, 1]^T$  and  $[-1, 1]^T$ , are used in describing the OCDMA chips. The polarization modulator rotates input SOP to a perpendicular state or maintains it unchanged according to the polarity of the electronic signal. The operations of rotation are expressed as Jones matrices

**Table 1** Result of states of polarization (SOP) rotation.

	Input SOP	
	$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 1 \end{bmatrix}$
$J_{\text{PolM}}$	$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 1 \end{bmatrix}$
$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 1 \end{bmatrix}$
$\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$

**Table 2** True-table of bipolar multiplier.

		Input SOP	
		$\theta = 0$	$\theta = \pi/2$
	Value	+1	-1
SOP operation	Pass	+1	-1
	Switch	-1	+1

$$J_{\text{PolM}} = \text{diag}[e^{i2\theta}, 1].$$

When the degree of rotation  $\theta$  is equal to 0 or  $\pi/2$ , the result of the polarization modulation is shown in Table 1.

Transmitting through the polarization device, the linear SOP is passed remaining unchanged or switched to an orthogonal SOP. The electronic signal applied to polarization device is between  $+V_{\text{PolM}}$  and  $-V_{\text{PolM}}$ . In detection of the SOPs, the output voltage of a balanced detector is  $+V_D$  or  $-V_D$ . Consequently, the normalization form of the electronic signal  $\pm V_{\text{PolM}}$  and detection signal  $\pm V_D$  are digit  $\pm 1$ . Considering that the input and output SOPs correspond to bipolar value  $\pm 1$ , the rotation of SOPs have the properties of bipolar multiplication with  $\pm 1$ . A true-table of bipolar multipliers is shown in Table 2.

As a continuous wave (CW) linear light is encoded by a polarization modulator, a special SOP sequence can be obtained. This is the principle of generating the Pol-SK OCDMA code.

In order to describe the behaviors of the Pol-SK OCDMA system, we use the vector as a user code for the payload data. A special user code could be expressed as follows:

$$\mathbf{C}_{\text{user}} = \{c_1, c_2, \dots, c_n\}, \quad (1)$$

where  $n$  is the code length;  $c_i = \pm 1, (i = 1, 2, \dots, n)$ . Thus, the payload data of the user could be expressed as

$$\mathbf{D}_{\text{payload}} = [d_1, d_2, \dots, d_m], \quad (2)$$

where  $m$  is the sequence length;  $d_i = \pm 1, (i = 1, 2, \dots, m)$ . Modulating the repeated OCDMA code sequence by the user data, the spreading spectrum matrix can be written as

$$\mathbf{S}_{m \times m}^{\text{in}} = \text{diag}[d_1 \mathbf{C}_{\text{user}}, d_2 \mathbf{C}_{\text{user}}, \dots, d_m \mathbf{C}_{\text{user}}]. \quad (3)$$

In the correlator of the receiver, its property can be described by the matrix as follows:

$$\mathbf{M}_{m \times m} = \text{diag}[\underbrace{\mathbf{C}_r, \mathbf{C}_r, \dots, \mathbf{C}_r}_m]. \quad (4)$$

The result of correlation is

$$\begin{aligned} \mathbf{S}_{m \times m}^{\text{out}} &= \mathbf{M}_{m \times m} \mathbf{S}_{m \times m}^{\text{in}} \\ &= \text{diag}[d_1 \mathbf{C}_r \cdot \mathbf{C}_{\text{user}}, d_2 \mathbf{C}_r \cdot \mathbf{C}_{\text{user}}, \dots, d_m \mathbf{C}_r \cdot \mathbf{C}_{\text{user}}]. \end{aligned} \quad (5)$$

After the integrator, the recovery data are

$$D_{\text{recovery}} = (\mathbf{C}_r \cdot \mathbf{C}_{\text{user}})[d_1, d_2, \dots, d_m]. \quad (6)$$

We define the correlation coefficient as follows:

$$R = (\mathbf{C}_r \cdot \mathbf{C}_{\text{user}}). \quad (7)$$

Because  $c_i = \pm 1$ , ( $i = 1, 2, \dots, n$ ), the weight  $K$  is equal to  $n$  in any case of the user code.

$$K = (\mathbf{C}_{\text{user}} \cdot \mathbf{C}_{\text{user}}) = \sum_{i=1}^n c_i^2 = n. \quad (8)$$

The cross-correlation coefficient is

$$X_r = (\mathbf{C}_r \cdot \mathbf{C}_{\text{user}}) = \sum_{i=1}^n c_{ri}c_i. \quad (9)$$

From Eq. (9), the maximum cross-correlation coefficient is no more than  $(n - 2)$ , and the difference between the weight and the cross-correlation coefficient depends on the number of distinct chips in  $\mathbf{C}_r$  and  $\mathbf{C}_{\text{user}}$ . By updating the user code, the number of changed chips is  $q$ , and the cross-correlation coefficient  $X_r$  becomes  $(n - 2q)$ , which means it is easier to make the threshold decision invalid, this could result in enhanced security in a reconfigurable OCDMA system.

### 3 Experiments of Polarization Shift Key Optical Code Division Multiple Access System

#### 3.1 Experimental Setup

For demonstrating the theory above, the experimental setup of the Pol-SK OCDMA system is shown in Fig. 2. We demonstrate data transmission for only a single user. In the transmitter, the CW light source is IDPhotonics Tunable Laser at 1567.1 nm with a 100-kHz band width and 10-dBm output power providing continuous and stabilized SOPs. Polarization controllers are deployed to adjust the incident light to be a linearly polarized beam, whose direction is 45 deg azimuth with the polarization axis of the lithium niobate (LN) phase modulator (PM). PC1 regulates the input SOP to the  $p$ -state. The first LN phase modulator (LN-PM1) is the Pol-SK OCDMA code generator. The input electric signal is bipolar square signal at 10 Gchip/s with  $\sim 7V_{pp}$ , and the input light is continuous with a linearly stabilized SOP called the  $p$ -state. The output of LN-PM1 is a sequence of SOPs consisting of  $p$ -states and  $s$ -states. When splitting the orthogonal SOPs' sequence into two independent beams by using a polarization beam splitter (PBS), the pattern of the  $s$ -states' beam is approximate to the encoding signal and the other one is inverted. The second LN phase modulator (LN-PM2) is the payload modulator with 1.25 Gbit/s ( $2^9 - 1$  pseudo-random bit sequence). When the bipolar payload bit is  $-1$ , SOPs are changed again. Otherwise, for a bit equal to  $+1$ , the SOPs remain unchanged. These modulators are GETC44 1550 nm LiNbO<sub>3</sub> phase modulators with a

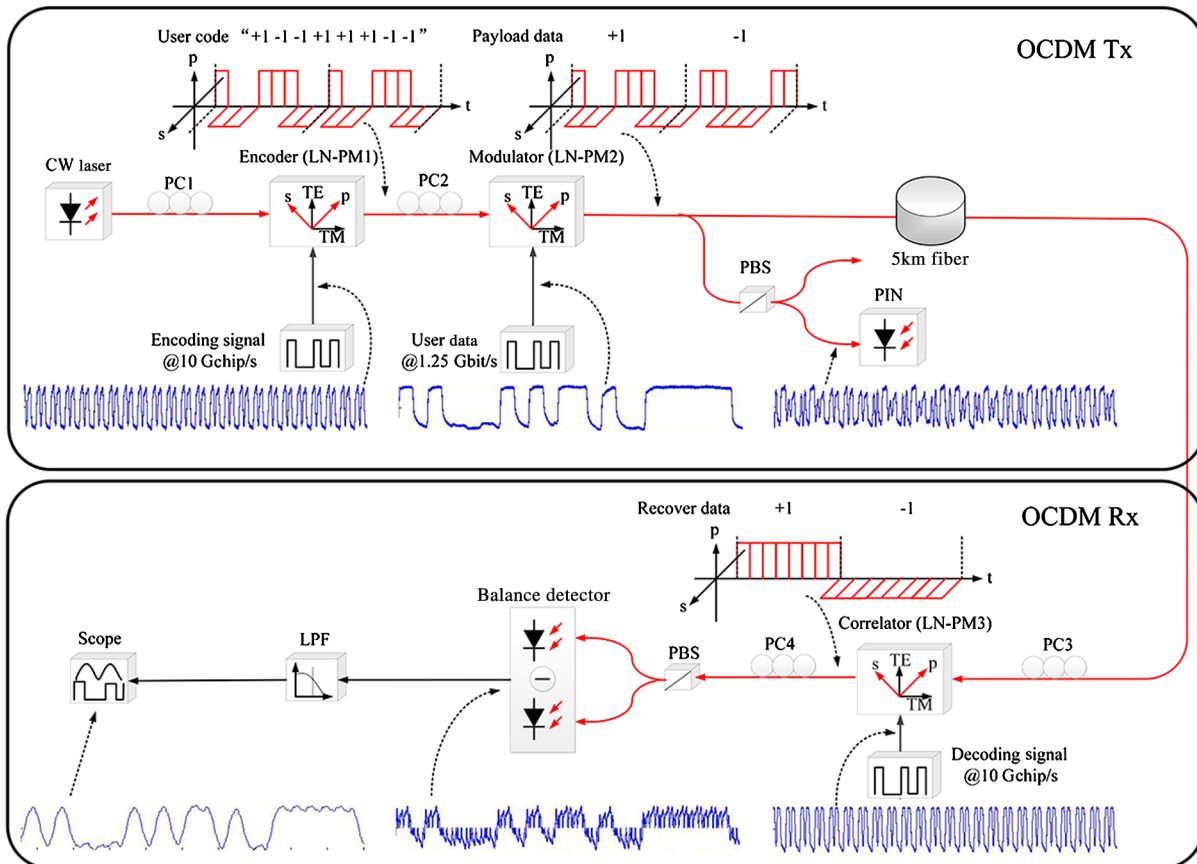


Fig. 2 Experimental system of polarization shift key OCDMA.

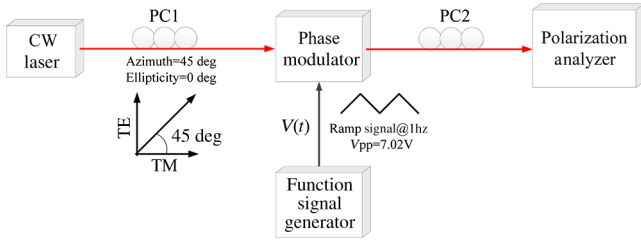


Fig. 3 Schematic of polarization modulation.

12 GHz band width. A programmable pattern generator (PPG) produces the electronic signal of the user code sequence. In the transmission link, an erbium-doped fiber amplifier is deployed to compensate the optical power attenuation of the modulators and a 5 km fiber. In the receiver, there is another LN phase modulator as the correlator and an electric channel of PPG to produce the local OCDMA code. The PPG is an Anritsu MP1800A Signal Quality Analyzer. In order to synchronize the arriving optical signal and the local code, an adjustable fiber adapter is mounted to tune the optical path. The chip cycle of 10 Gchip/s is 100 ps during which the light wave travels  $\sim 2$  cm in the fiber. A fiber cutter with a measurable scale could the control error within 1 mm, which means the fiber delay control has a  $<5$  ps scale. Each user data is detected respectively by using a  $u^2t$  photonics balanced photodetector for differential detection, as only the local code matches user code. The detected electrical signal is passed through a low pass filter (LPF) instead of the integrator and is received by a LeCroy Wave Expert 100H Sampling Oscilloscope for waveform observation.

### 3.2 Experiment of Polarization Rotation

In the experimental system shown in Fig. 2, the code generator, the modulator of the user data, and the correlator are all LN-PM. Figure 3 shows an experiment of polarization rotation in the LN-PM, which demonstrates how to rotate the SOP to a perpendicular state. Because of the limitation of the sampling rate in the polarization analyzer (PA), a bipolar ramp signal with a low repetition rate (1 Hz) is applied. When the LN-PM is used as the code generator, we use a CW laser as the incident light source and deploy a polarization controller to make the arriving light a linear polarized light whose direction is  $\pi/4$  azimuth to the polarization axis of LN-PM with a single-mode fiber pigtail. In the LN-PM, light is separated into  $E_x$  and  $E_y$ , two polarized components with the same amplitude and phase. Then a ramp signal  $V(t)$  at a 1-Hz output from the EE1641B1 function generator is applied on the LN-PM to change the refractive index in the direction of the  $E_x$  component in order to achieve the polarization rotation.

The PA is a General Photonics POD-101D DSP Inline Polari meter. Data acquired from the PA and the ramp signal that periodically correspond to Stokes vector are shown in Fig. 4. When the  $V_{pp}$  of the modulating signal is 7.02 V, the track's endpoints of the output SOPs, which are labeled as the  $p$ -state and  $s$ -state, are orthogonal.

The relationship between the modulation signals and degrees of polarization rotation on the equator of the Poincare sphere is shown in Fig. 5. The rotation angle is equal to  $2\theta$  in the Jones matrix  $J_{\text{PolM}}$ . The range of  $2\theta$  covers from 0 to  $\pi$ , which indicates that the LN-PM achieves the orthogonal polarization rotation brilliantly.

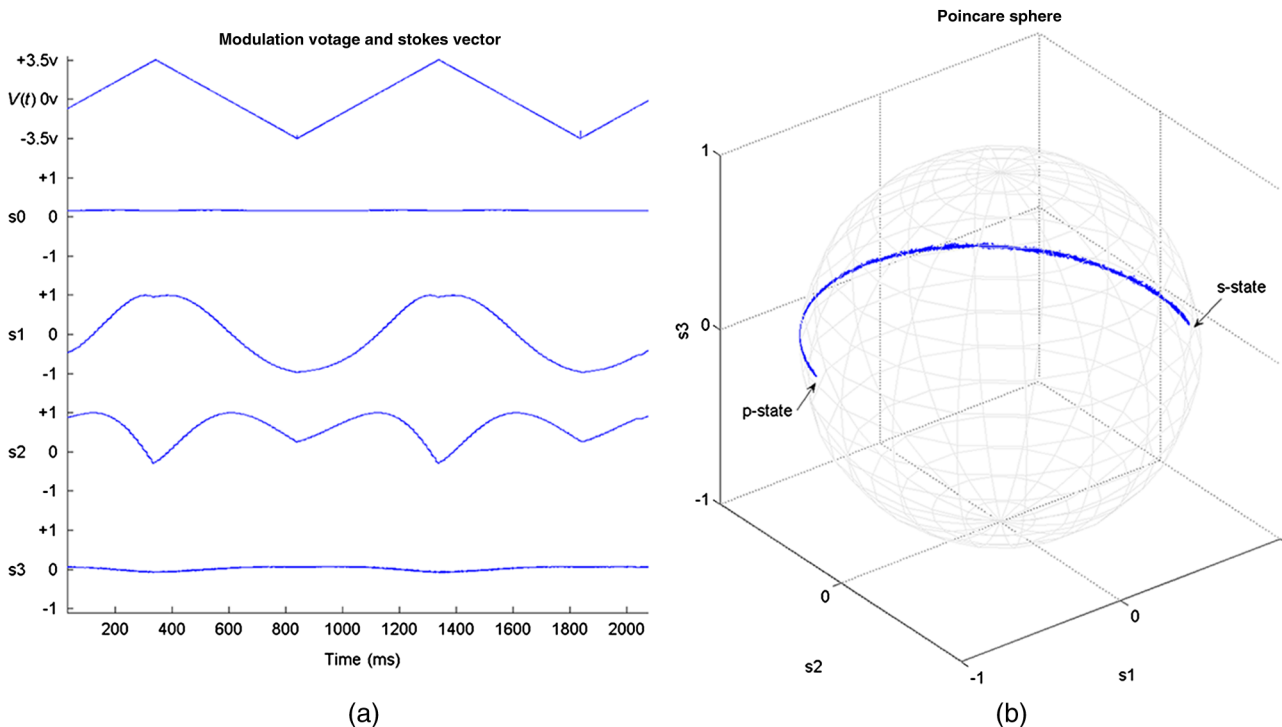


Fig. 4 Modulation voltage and Stokes vector: (a) waveform in time domain and (b) track of states of polarization on Poincare sphere.

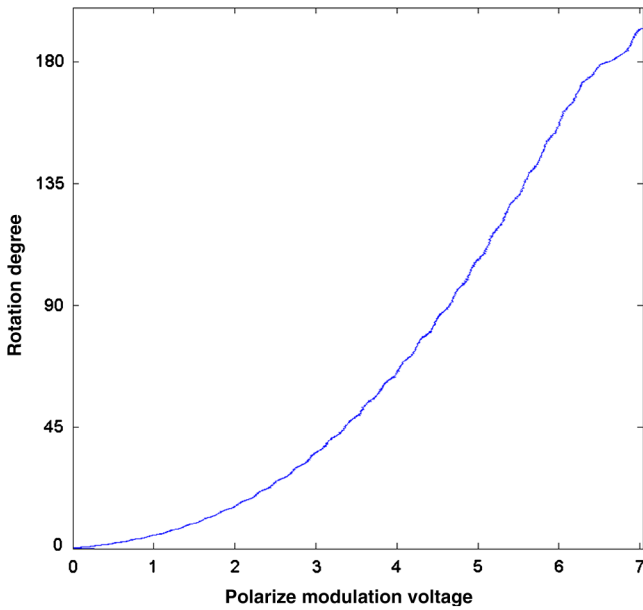


Fig. 5 Modulation voltage versus degree of polarization rotation.

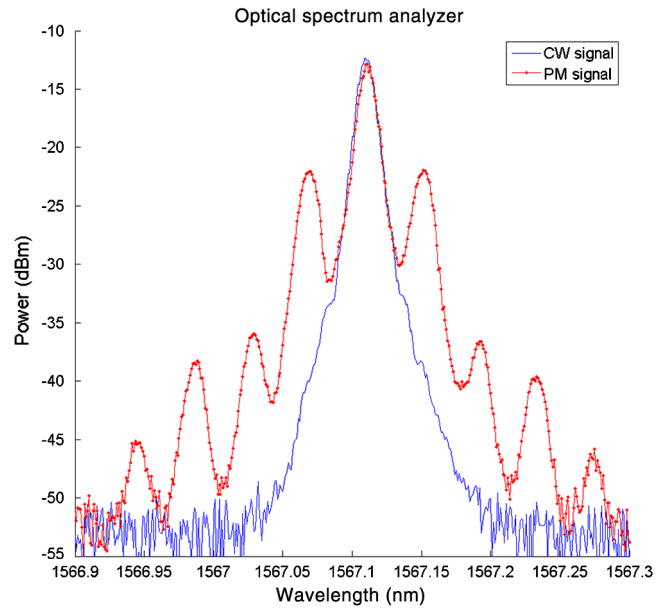


Fig. 7 Optical spectrum of optical signal.

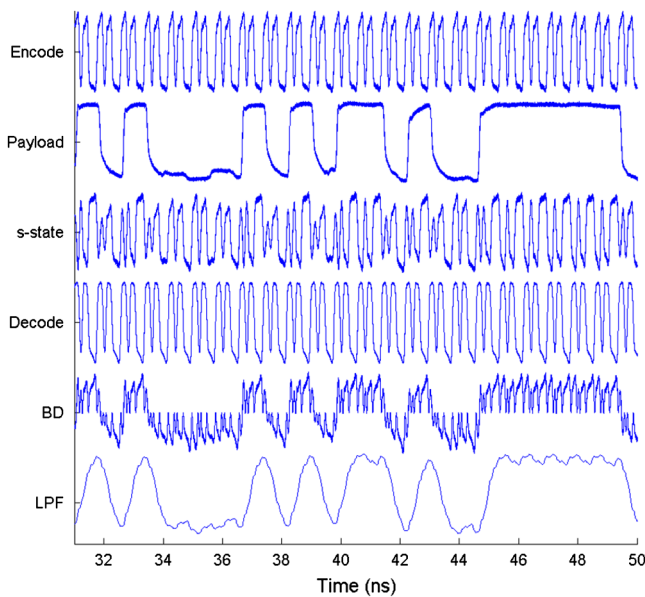


Fig. 6 Waveforms at tap points of system.

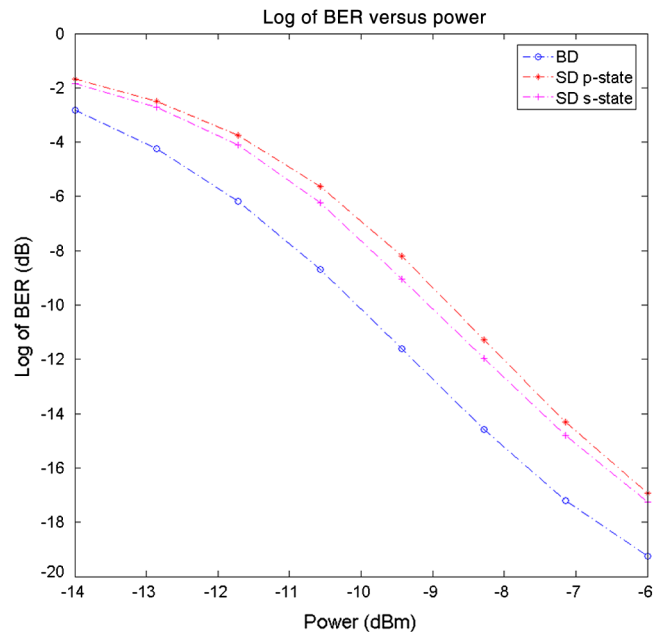


Fig. 8 Log (bit error ratio) versus power.

### 3.3 Experiment Results of Back to Back Polarization Shift Key Optical Code Division Multiple System

The waveforms from the tap points of the system are shown in Fig. 6. The *s*-state signal is detected by a PBS and positive intrinsic and negative photodiode at a tap point in the transmission part. The balance detector signal with many glitches is quite confusing. However, an LPF improves the recovery of the raw pattern of the payload signal. This demonstrates that the output data waveform from the receiver is similar to the one from the transmitter.

Because the waveform of the optical Pol-SK signal could not be observed directly, we measured its spectrum to analyze the signal. The spectrum of the CW laser source and the polarization modulated signals' output from the

code generator are shown in Fig. 7. The Pol-SK signal has more harmonics than on-off key (OOK) (nonreturn to zero or return to zero) code, containing both odd and even harmonics, increasing the frequency hopping and security.

The bit error ratio test is shown in Fig. 8, which means that the 1 to 2 dB improvement could be obtained when employing a bipolar code compared with the unipolar detection. This is because the proposed bipolar scheme takes advantage of differential detection to depress the influence of noise.

### 4 Conclusion

We have proposed and demonstrated a bipolar OCDMA scheme with a Pol-SK data format by polarization

modulation. It is proved that the polarized state and the pass-switch polarization rotation can be described by a bipolar code. A reconfigurable user code enhances system security. There are now two methods against eavesdropping attacks: data encryption and physical encryption. CDMA is a popular physical encryption method both in optical communication and wireless communication; the key technology is how to configure the user code. In traditional OCDMA, the user code is configured by OOK or by PSK. Because optical OOK code is always positive, the result of cross-correlations among user codes is unsatisfactory for threshold decision. The PSK method utilizing many FBGs is not convenient for changing codes, and bipolar phase modulation needs coherent detection, which increases the system cost. Compared to these OCDMA systems with a fixed code, by frequently changing the user code, the proposed scheme has a good performance against eavesdropping attacks, which makes it an attractive candidate for secure communication systems. In particular, the Pol-SK OCDMA experiment with a 10 Gchip/s user code and a 1.25 Gb/s user data for the payload has been realized, which means it has a better tolerance and is easy to achieve.

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#### References

1. H. F. Zhang et al., "A real-time QKD system based on FPGA," *J. Lightwave Technol.* **30**(20), 3226–3234 (2012).
2. Q. Zhao, P. Liu, and H. Yin, "Performance improvement of secure chaotic optical communications utilizing symmetrical dispersion compensation technique," *Proc. SPIE* **8309**, 83092E (2011).
3. L. Oesterling, D. Hayford, and G. Friend, "Comparison of commercial and next generation quantum key distribution: technologies for secure communication of information," in *IEEE Conf. on Technologies for Homeland Security*, pp. 156–161 (2012).
4. K. Harasawa et al., "Quantum encryption communication over a 192-km 2.5-Gbit/s line with optical transceivers employing Yuen-2000 protocol based on intensity modulation," *J. Lightwave Technol.* **29**(3), 316–323 (2011).
5. Z. Kang et al., "Multimode synchronization of chaotic semiconductor ring laser and its potential in chaos communication," *IEEE J. Quantum Electron.* **50**(3), 148–157 (2014).
6. N. Kostinski, K. Kravtsov, and P. R. Prucnal, "Demonstration of an all-optical OCDMA encryption and decryption system with variable two-code keying," *IEEE Photonics Technol. Lett.* **20**(24), 2045–2047 (2008).
7. J. E. McGeehan et al., "3D time-wavelength-polarization OCDMA coding for increasing the number of users in OCDMA LANs," in *Optical Fiber Communication Conf.*, Vol. 2, pp. FE5 (2004).
8. X. Wang and N. Wada, "Experimental demonstration of OCDMA traffic over optical packet switching network with hybrid PLC and SSFBG en/decoders," *J. Lightwave Technol.* **24**(8), 3012–3020 (2006).
9. K. Kitayama, X. Wang, and N. Wada, "Experimental demonstration of  $2 \times 10$  Gb/s OCDMA system using cascaded long-period fiber gratings formed in dispersion compensating fiber," *J. Lightwave Technol.* **24**(4), 1654–1662 (2006).
10. Z. Gao et al., "2D time domain spectral phase encoding/wavelength hopping coherent DPSK-OCDMA system using fiber Bragg gratings and phase modulator," in *Communications and Photonics Conf. and Exhibition*, pp. 439–440 (2010).
11. Z. Gao et al., "Time domain spectral phase encoding DPSK data modulation using single phase modulator for OCDMA application," in *Conference on Lasers and Electro-Optics (CLEO) and Quantum Electronics and Laser Science Conf.*, pp. 1–2 (2010).
12. R. Matsumoto et al., "40G-OCDMA-PON system with an asymmetric structure using a single multi-port and sampled SSFBG encoder/decoders," *J. Lightwave Technol.* **32**(6), 1132–1143 (2014).
13. H. M. R. Al-Khafaji et al., "A new two-code keying scheme for SAC-OCDMA systems enabling bipolar encoding," *J. Mod. Opt.* **62**(5), 327–335 (2014).
14. T. H. Shake, "Security performance of optical CDMA against eavesdropping," *J. Lightwave Technol.* **23**(2), 655–670 (2005).
15. Z. Gao et al., "Rapid reconfigurable OCDMA system using single-phase modulator for time-domain spectral phase encoding/decoding and DPSK data modulation," *J. Lightwave Technol.* **29**(3), 348–354 (2011).
16. S. Kim, K. Yu, and N. Park, "A new family of space/wavelength/time spread three-dimensional optical code for OCDMA networks," *J. Lightwave Technol.* **18**(4), 502–511 (2000).
17. I. Fsaifes et al., "Spectral phase en/decoders for OCDMA access network," in *Advanced Photonics & Renewable Energy*, 21–24 June 2010, Karlsruhe, Germany, paper BThB3, Optical Society of America, Washington, D.C.

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