Phase-locked all-optical differential polarization demodulation*

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A novel scheme of differential polarization demodulation is presented and demonstrated based on a polarized asymmetrical Mach–Zehnder interferometer configuration with polarization control. To enhance the stability of the demodulator, a phase-lock device is designed, and it is composed of a symmetric 3×3 coupler and a feedback circuit. For further establishing a differential polarization-shift keying (DPolSK) transmission system, we successfully carry out the demodulation experiments on 10-Gb/s DPolSK optical signals for the first time. Due to the all-optical structure with phase-lock, our scheme is available to realize the DPolSK optical communication in practical optical fiber systems.

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1. Introduction

Polarization-shift keying (PolSK) modulation is widely used in free-space optical communication especially in quantum key distribution.[1–7] Recently, the PolSK also attracted much attention in optical fiber communications.[8–10] To develop a practical PolSK transmission system, the demodulator is relatively important since it can accurately retrieve the original information and ultimately determine the communication quality. In 1992, Benedetto and Poggiolini[11] built the theoretical foundation of PolSK communication, where they presented for the first time the block diagram of a PolSK demodulator (PolSKD) to extract the Stokes parameters of the received optical signals. Several years later, they further optimized the proposed demodulating scheme, and developed three kinds of PolSK detectors to retrieve the polarization modulated signals.[12] Subsequently, a few other PolSKDs have appeared in the last decade, such as multilevel PolSKD,[13] modified duobinary PolSKD,[14] and differential polarization-phase-shift keying demodulator.[15] However, most of them focus on theoretical analysis or simulation, and their schemes are complicated for experimental implementation. In this paper, we present a relatively simple differential polarization demodulator (DPolD) based on a polarized asymmetrical Mach–Zehnder interferometer (MZI), and develop a phase-lock device to enhance the stability of the demodulator, while for the first time experimentally demonstrate the all-optical demodulation for 10-Gb/s differential PolSK (DPolSK) optical signals.

2. Principle of differential polarization demodulation

Figure 1 shows schematically the configuration of the all-optical DPolD.

At the input end of the DPolD, the DPolSK optical signals are firstly 135° linearly polarized by a polarization controller (PC) and a fiber polarizer, which introduces an extra π phase shift between original P and S signals. Then, the polarized signals enter into the MZI basically composed of a 2×2 coupler and a 3×3 coupler. The optical fields at input ends of the 2×2 coupler can be described by

$$\begin{pmatrix} E_1 \\ E_2 \end{pmatrix} = \begin{pmatrix} E \exp(-\mathrm{i}(\omega t + a_i \pi + \varphi_0)) \\ 0 \end{pmatrix}, \qquad (1)$$

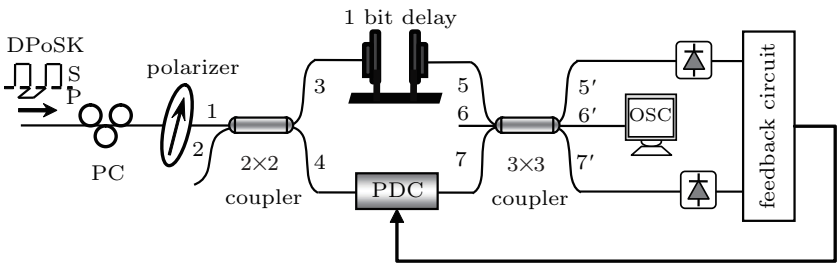


Fig. 1. Configuration of an all-optical DPolD, PC: polarization controller, PDC: phase drift compensator.

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where E, ω, and φ_0 are the amplitude, frequency, and initial phase of the optical signal, and a_i (i is the bit serial number) equals 1 or 0 for P or S signal respectively. After the symmetric 2×2 coupler, the optical fields become

$$\begin{pmatrix} E_3 \\ E_4 \end{pmatrix} = \frac{\sqrt{2}E}{2}\begin{pmatrix} \exp(-\mathrm{i}(\omega t + a_i\pi + \varphi_0)) \\ \exp\left(-\mathrm{i}\left(\omega t + a_i\pi + \varphi_0 - \dfrac{\pi}{2}\right)\right) \end{pmatrix}. \quad (2)$$

In the upper arm of the MZI, the tunable fiber delay line produces a 1-bit delay, which means that the bit serial number will be reduced from i to $i-1$. Further, consider the fiber length L, random phase shift φ_r caused by environmental disturbance, and the compensated phase φ_c generated by the phase drift compensator (PDC), then the input optical fields of the 3×3 coupler can be expressed as

$$\begin{pmatrix} E_5 \\ E_6 \\ E_7 \end{pmatrix} = \frac{\sqrt{2}E}{2}\begin{pmatrix} \exp(-\mathrm{i}(a_{i-1}\pi + \varphi_\mathrm{r} + \varphi)) \\ 0 \\ \exp\left(-\mathrm{i}\left(a_i\pi + \varphi_\mathrm{c} - \dfrac{\pi}{2} + \varphi\right)\right) \end{pmatrix}, \quad (3)$$

where $\varphi = \omega t - \beta L + \varphi_0$ (β is the carrier wave number). After the symmetric 3×3 coupler, according to Ref. [16], the output optical fields can be written as

$$\begin{pmatrix} E_{5'} \\ E_{6'} \\ E_{7'} \end{pmatrix} = \frac{\sqrt{6}E}{6}\begin{pmatrix} \exp(-\mathrm{i}(a_{i-1}\pi + \varphi_\mathrm{r} + \varphi)) + \exp\left(-\mathrm{i}\left(a_i\pi + \varphi_\mathrm{c} - \dfrac{7\pi}{6} + \varphi\right)\right) \\ \exp\left(-\mathrm{i}\left(a_{i-1}\pi + \varphi_\mathrm{r} - \dfrac{2\pi}{3} + \varphi\right)\right) + \exp\left(-\mathrm{i}\left(a_i\pi + \varphi_\mathrm{c} - \dfrac{7\pi}{6} + \varphi\right)\right) \\ \exp\left(-\mathrm{i}\left(a_{i-1}\pi + \varphi_\mathrm{r} - \dfrac{2\pi}{3} + \varphi\right)\right) + \exp\left(-\mathrm{i}\left(a_i\pi + \varphi_\mathrm{c} - \dfrac{\pi}{2} + \varphi\right)\right) \end{pmatrix}. \quad (4)$$

Equation (4) shows that each output is actually the superposition of two optical waves, thus the output intensity inevitably depends on their phase differences, which are

$$\begin{aligned} \delta_{5'} &= (a_i - a_{i-1})\pi + \varphi_\mathrm{c} - \varphi_\mathrm{r} - \frac{7\pi}{6}, \\ \delta_{6'} &= (a_i - a_{i-1})\pi + \varphi_\mathrm{c} - \varphi_\mathrm{r} - \frac{\pi}{2}, \\ \delta_{7'} &= (a_i - a_{i-1})\pi + \varphi_\mathrm{c} - \varphi_\mathrm{r} + \frac{\pi}{6}. \end{aligned} \quad (5)$$

To lock the phase drift φ_r between two arms of the asymmetrical MZI, the optical intensities of output ports $5'$ and $7'$ are monitored and balanced by two identical PINs, a feedback circuit, and a PDC. The locking condition is $I_{5'} = I_{7'}$, which is equal to $\cos\delta_{5'} = \cos\delta_{7'}$ or $\delta_{5'} = -\delta_{7'} + 2k\pi$. According to Eq. (5), we further obtain

$$\varphi_\mathrm{c} - \varphi_\mathrm{r} = \frac{\pi}{2} + 2k'\pi, \quad (6)$$

where k' is also an arbitrary integer like k. In experiment, the feedback circuit is usually designed to ensure $k' = 0$, thus the output intensity of port $6'$ becomes

$$I_{6'} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta_{6'} = \frac{2}{3}E^2\cos^2\frac{(a_i - a_{i-1})\pi}{2}. \quad (7)$$

Since $a_i = 0$, or 1, $a_i - a_{i-1} = 0$, 1 or -1. When $a_i - a_{i-1} = 0$, we obtain

$$I_{6'} = \frac{2}{3}E^2, \quad (8)$$

which corresponds to logic "1" in digital communication. When $a_i - a_{i-1} = 1$ or -1, we have

$$I_{6'} = 0, \quad (9)$$

which represents logic "0".

Recalling the DPolSK signals, logic "1" and "0" denote that the states of the polarization (SOPs) of adjacent optical pulses are parallel and orthogonal to each other respectively. In the DPolD, the phase coefficient difference $a_i - a_{i-1} = 0$ equals zero for adjacent parallel optical pulses, thus logic "1" is outputted from port $6'$, according to Eq. (8). While for orthogonal pulses, the output will be logic "0" correspondingly. As a result, the DPolD shown in Fig. 1 can definitely demodulate the DPolSK optical signals.

3. 10-Gb/s DPolD experiment

According to the above principle with the DPolD configuration of Fig. 1, we set up a DPolSK optical communication system as described in Fig. 2, and experimentally demonstrate 10-Gb/s all-optical DPolSK demodulation.

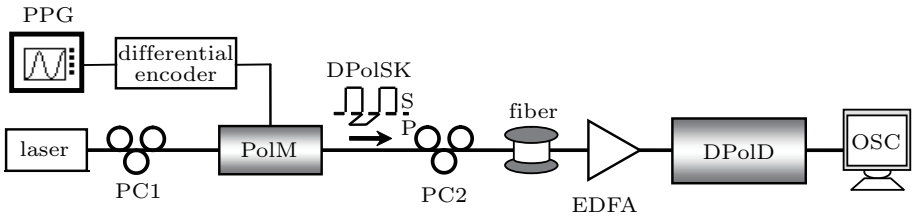


Fig. 2. DPolD experimental scheme, PPG: pulse pattern generator, PolM: polarization modulator.

The pulse pattern generator (PPG) is set to produce a repeated data sequence with fixed data or pseudorandom-bit-sequence (PRBS), and then is encoded to the differential data by a differential encoder before going to the polarization modulator (PolM), which finally generates the orthogonal DPolSK optical signals. After transmitting from a PC and a disk of optical fiber, it is amplified and goes into the DPolD, while the demodulated signals are observed and analyzed by a high-speed oscilloscope (OSC).

In order to qualify the performance of the proposed DPolD, we measure and compare the signals before and after the demodulator. Firstly, the PPG (MP1800A, Anritsu) is set to generate repeated fixed data "1000 0110 0011 1100 0001", and after the PolM it becomes the DPolSK optical signals with fixed data "0111 1101 1110 1011 1111". To verify the input DPolSK signal, a PC and a polarization beam splitter (PBS) are used to divide the signal under test into two orthogonal parts (P-state and S-state signals), and then observed by an OSC (WaveExpert 100H, LeCroy). Figure 3 shows the waveforms of the signals before the DPolD.

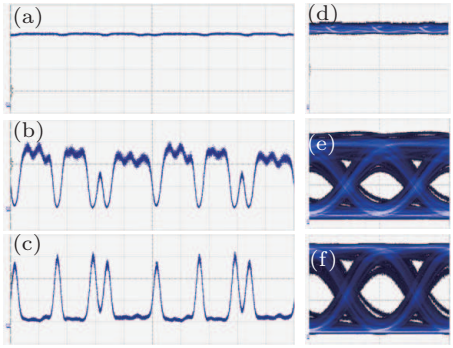


Fig. 3. (color online) Waveforms (400 ps/div) and eye diagrams (20 ps/div) of input signal for the DPolD, (a) total DPolSK signal, (b) P-state signal, and (c) S-state signal, (d)–(f) eye diagrams of signals in (a)–(c).

From Fig. 3, we can find that the input signal keeps excellent power equalized, and the P-state and S-state signals have fully complementary waveforms, which demonstrate that the input is definitely the DPolSK signal.

According to the principle described in Section 2, there are two important steps in the demodulation experiment. The first one is fine adjustment of the one bit delay. For a 10-Gbit/s optical signal, the time duration of one bit is 100 ps, which equals the space length of 20 mm in an optical fiber. By using a fiber delay line, we obtain one bit delay with high accuracy about 5 fs. Figure 4(a) shows the waveforms of the signals in the two arms of the DPolD, while in one arm, the signal is delayed by one bit.

The second is the phase-lock of the two arms in the DPolD. Environmental disturbance causes a random phase shift in the interference arm, which will degrade the stability of the DPolD and lead to incorrect demodulation. According to the theoretical analysis in Section 2, when the compensated phase satisfies Eq. (6), the phase drift will be locked. So we carefully balance the optical intensities of the two out ports $5'$ and $7'$ to ensure $I_{5'} = I_{7'}$, which is realized by fine adjustment of the optical loss in the two arms while it is further compensated by electrical feedback. After these operations, we measure the demodulated signals, and compare them with the input optical signal and original electrical signal through eye diagram measurement. Figure 4 partly presents the experimental results.

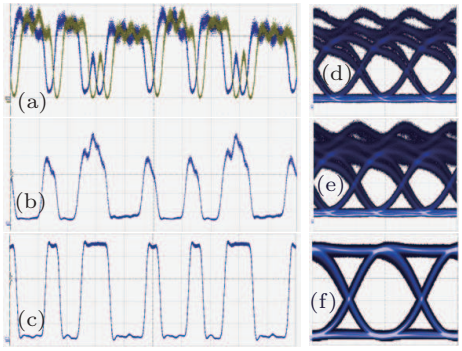


Fig. 4. (color online) Waveforms (400 ps/div) and eye diagrams of signals in and after the DPolD, (a) signals in the two arms of the DPolD where 1-bit is finely delayed between them, (b) demodulated signal, and (c) original electrical signal, (d)–(f) eye diagrams of signals in panels (a)–(c).

Comparing Fig. 4(b) with Fig. 4(c), we can find that the DPolD works well and retrieves the original signal with a better signal-to-noise ratio. Although the eye diagram in Fig. 4(e) is not as good as in Fig. 4(f) from the PPG, it is very close to the DPolD's input signal as shown in Fig. 4(d). That is to say, the degradation of the signal is mainly caused in the transmission route such as the fiber, EDFA, PCs, etc., while the DPolD itself does not introduce any noise, which verify that our proposed DPolD can fulfill the function of demodulating the DPolSK optical signals without any error addition.

To further confirm this, we measure the BER of the signals inputting to and outputting from the DPolD. The results are partly shown in Fig. 5, which are obtained under the

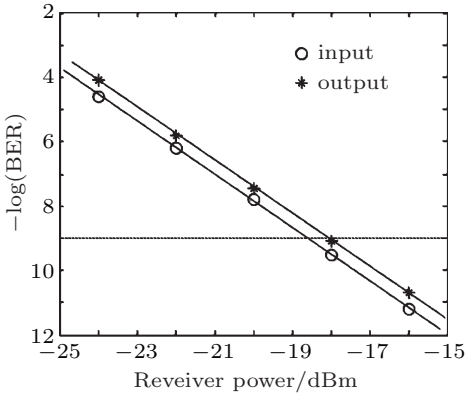


Fig. 5. Measured BER results for input and output signals of the DPolD.

condition of perfect one bit delay. From Fig. 5, we can find that at the same BER, the two receiving powers are very close, while at the BER of 10^{-9}, the power penalty of the DPolD is less than 0.5 dB, which demonstrates that our phase-locked DPolD has excellent performance.

4. Conclusions

In this paper, we present and demonstrate a novel scheme of differential polarization demodulation based on a polarized asymmetrical MZI configuration with polarization control. To enhance the stability of the demodulator, we develop a phase-lock device based on a symmetric 3×3 coupler with feedback circuit. Furthermore, we set up the DPolSK transmission system, and successfully carry out experiments on the demodulation of 10-Gb/s DPolSK optical signals for the first time, to the best of our knowledge. Owing to the all-optical and compact structure with phase-lock, our scheme is feasible to realize the DPolSK optical communication in practical optical fiber systems, which will greatly promote the development of ultrahigh speed optical communication.

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