Polarization mode dispersion compensation in a novel dual polarization differential quadrature phase shift keying system*

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A novel dual polarization differential quadrature phase shift keying (DP-DQPSK) system is proposed, whose receiver is the same as the single polarization DQPSK system, while it does not need polarization de-multiplexing like the conventional polarization division multiplexing QPSK (PDM-QPSK). Polarization mode dispersion (PMD) is mainly considered and PMD compensation for the DP-DQPSK system is studied. As the feedback signal for PMD compensation, the degree of polarization of the signals is discussed in detail. The results show that PMD tolerance can be improved by 89 ps within 1 dB optical signal noise ratio penalty after PMD compensation for the DP-DQPSK system.

Keywords: dual polarization DQPSK system, one receiver, degree of polarization, polarization mode dispersion compensation

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1. Introduction

The ever-increasing demand for communication capacity has been pushing the development of high spectral efficient optical-fiber systems. In recent years, polarization division multiplexing and multi-level modulation formats, which have high spectral efficiency, have attracted much attention.[1] Some typical modulation formats such as polarization division multiplexed quadrature phase shift keying (PDM-QPSK), differential 8 phase shift keying (D8PSK), and quadrature amplitude modulation (QAM) are widely used.[2−6] However, there are still some drawbacks brought by the complex receiver structure. For example, D8PSK has a very complicated demodulator that consists of four Mach–Zehnder interferometers, four balanced detectors and one exclusive OR (XOR) gate;[3] PDM-QPSK is usually de-multiplexed with the method of coherent detection and electric processing,[6,7] which is limited by the speed in the electrical domain.

In this paper, a novel dual polarization DQPSK (DP-DQPSK) system with no need for polarization de-multiplexing but based on just one receiver is proposed. The DP-DQPSK signals can take advantage of both polarization and phase to carry information, providing 4bit/s/Hz spectral efficiency, two times that of DQPSK. At the same time, the DP-DQPSK signals are demodulated just by a pair of Mach–Zehnder interferometers and two balanced detectors, without using any polarization control or polarization selection at the receiver.

In our work, a 100-Gb/s DP-DQPSK transmission system is set up in Optisystem software with deduced pre-coding formula. As a major factor that affects the system performance, polarization mode dispersion (PMD) is mainly considered and PMD compensation is studied. Moreover, degree of polarization (DOP) is deeply analysed and further optimized, which is adopted as the feedback signal for PMD compensation. The result shows that PMD in the system can be fully compensated and the tolerance to PMD can be improved by 89 ps within 1 dB optical signal noise ratio (OSNR) penalty through PMD compensation.

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2. Configuration of the DP-DQPSK system and principle

2.1. Configuration of the DP-DQPSK system

Figure 1 illustrates the schematic of the 100-Gb/s novel DP-DQPSK system. At the transmitter end, linearly-polarized continuous wave (CW) light generated by a laser at centre frequency of 193.1 THZ with the line-width of 100 kHz is split by a polarization beam splitter (PBS) into two orthogonal components. They are fed separately into two in phase quadrature (IQ) modulators. A polarization controller is used to adjust the orientation angle of the CW light to make the power of the two orthogonal components different. In this work, with the purpose of distinguishing the two orthogonal components and making the errors the least, the power ratio between the two orthogonal components is set to be 2:1. The two IQ modulators are driven by four 25 Gb/s binary streams I_{1k}, Q_{1k}, I_{2k}, Q_{2k}, which are the output data streams of a pre-coder. And the input data streams of the pre-coder are obtained from pseudo-random bit sequence (PRBS) of length $2^{20}-1$ through serial to parallel conversion. After return to zero (RZ) pulse carving, one orthogonal component is delayed with respect to the other. The two de-correlated branches are then orthogonally recombined using a polarization beam combiner (PBC).The expression of the output DP-DQPSK signals is deduced, which can be expressed as follows:

$$E_{\text{out}} = \sqrt{P_{\text{total}}} \left(\begin{array}{l} \sqrt{\frac{2}{3}} \left[\frac{\sqrt{2}}{2} \exp\left(\mathrm{i} \left(\pi I_{1k} + \frac{\pi}{2} \right) \right) + \frac{\sqrt{2}}{2} \exp(\mathrm{i}\,\pi Q_{1k}) \right] \\ \sqrt{\frac{1}{3}} \left[\frac{\sqrt{2}}{2} \exp\left(\mathrm{i} \left(\pi I_{2k} + \frac{\pi}{2} \right) \right) + \frac{\sqrt{2}}{2} \exp(\mathrm{i}\,\pi Q_{2k}) \right] \end{array} \right) \times \cos\left[\frac{\pi}{2V_\pi} (V_{\text{clock}}(t) - V_{\text{bias}}) \right] \exp\left(\mathrm{i}\, \frac{V_{\text{bias}}\pi}{2V_\pi} \right), \quad (1)$$

where P_{total} is the power of CW light, $V_{\text{clock}}(t)$ is clock signals applied to the RZ carver, V_π is the driving voltage to obtain a phase shift of π and V_{bias} is the bias voltage on Mach-Zehnder modulator (MZM).

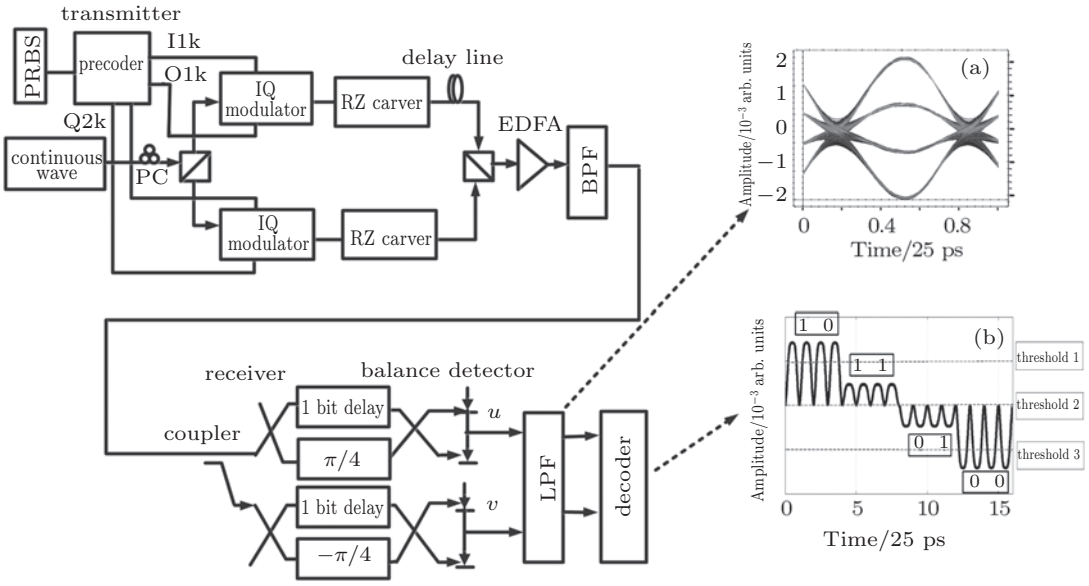


Fig. 1. Schematic diagram of the novel DP-DQPSK system. EDFA: erbium doped fibre amplifier, LPF: low-pass filter, BPF: band-pass filter.

The receiver for the novel DP-DQPSK system is the same as the single polarization DQPSK receiver, including two Mach–Zehnder interferometers and two balanced detectors, without any polarization control or polarization selection. Because the two branches of polarization signals are orthogonal to each other and

de-correlated to each other, they are incoherent and the signals at each branch are self-coherent. Therefore, one DQPSK demodulator can demodulate the two branches of orthogonal polarization signals independently. Unlike the conventional PDM-DQPSK system, the DP-DQPSK system does not need demultiplexing before demodulation. Therefore, it only requires one demodulator instead of two used in the conventional PDM-DQPSK system.

The eye diagram and multilevel detection are shown as insets (a) and (b) in Fig. 1 respectively. Applying the three thresholds in Fig. 1(b), four signal levels can be detected simply as 2-bit digital signals of 10, 11, 01, 00, in grey-code order.

The optical band pass filter we used is a second-order Gaussian filter and the electrical filter is a fifth-order Bessel filter.[8] Considering the impact of filter bandwidths on the performance of receiver, we find the optimum bandwidth value through simulation in Optisystem software and Matlab program. As shown in Fig. 2, the optimized 3-dB optical bandwidth $B_{\rm opt}$ and the electrical filter bandwidth $B_{\rm bel}$ are 1.8 Rs (45 GHz) and 0.75 Rs (18.75 GHz) respectively, where Rs is the symbol rate.

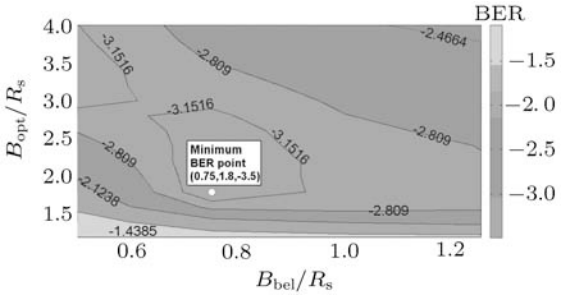


Fig. 2. Bit error rate (BER) at different optical filter bandwidth and electrical filter bandwidth.

2.2. Pre-coding principle

The digital differential pre-coder is a key component in the DP-DQPSK system transmission.[9] The input data streams of the pre-coder are defined as u_{1k}, u_{2k}, v_{1k}, v_{2k} and the output streams of the pre-coder as I_{1k}, Q_{1k}, I_{2k}, Q_{2k}; and I_{1k-1}, Q_{1k-1}, I_{2k-1}, Q_{2k-1} are the predecessor bits of I_{1k}, I_{2k}, Q_{1k}, Q_{2k}, respectively. At the transmitter, I_{1k} and Q_{1k}, I_{2k} and Q_{2k} are input into the two IQ modulators respectively to generate modulated optical signals with a certain phase. Table 1 shows the relationship between differential signals and the phases of the modulated optical signals.

Table 1. relationship between differential signals and the phases of the modulated optical signals.

I_{1k}, Q_{1k} (I_{2k}, Q_{2k})	$\phi_1(\phi_2)$
0 0	$\pi/4$
0 1	$3\pi/4$
1 1	$5\pi/4$
1 0	$7\pi/4$

After transmission, the optical signals are demodulated at the receiver. The output optical signals of the two Mach–Zehnder interferometers are as follows:

$$
\begin{aligned}
E_{\mathrm{cons},\frac{\pi}{4}} &= \sqrt{P_{\rm total}/3}\begin{pmatrix} \left[\exp\left(\mathrm{i}\left(\phi n, 1+\frac{\pi}{4}\right)\right)+\exp(\mathrm{i}\,\phi n-1,1)\right] \\ \sqrt{\frac{1}{2}}\left[\exp\left(\mathrm{i}\left(\phi n, 2+\frac{\pi}{4}\right)\right)+\exp(\mathrm{i}\,\phi n-1,2)\right]\end{pmatrix}, \\
E_{\mathrm{des},\frac{\pi}{4}} &= \sqrt{P_{\rm total}/3}\begin{pmatrix} \left[\exp\left(\mathrm{i}\left(\phi n, 1+\frac{\pi}{4}\right)\right)-\exp(\mathrm{i}\,\phi n-1,1)\right] \\ \sqrt{\frac{1}{2}}\left[\exp\left(\mathrm{i}\left(\phi n, 2+\frac{\pi}{4}\right)\right)-\exp(\mathrm{i}\,\phi n-1,2)\right]\end{pmatrix}, \\
E_{\mathrm{cons},-\frac{\pi}{4}} &= \sqrt{P_{\rm total}/3}\begin{pmatrix} \left[\exp\left(\mathrm{i}\left(\phi n, 1-\frac{\pi}{4}\right)\right)+\exp(\mathrm{i}\,\phi n-1,1)\right] \\ \sqrt{\frac{1}{2}}\left[\exp\left(\mathrm{i}\left(\phi n, 2-\frac{\pi}{4}\right)\right)+\exp(\mathrm{i}\,\phi n-1,2)\right]\end{pmatrix}, \\
E_{\mathrm{des},-\frac{\pi}{4}} &= \sqrt{P_{\rm total}/3}\begin{pmatrix} \left[\exp\left(\mathrm{i}\left(\phi n, 1-\frac{\pi}{4}\right)\right)-\exp(\mathrm{i}\,\phi n-1,1)\right] \\ \sqrt{\frac{1}{2}}\left[\exp\left(\mathrm{i}\left(\phi n+1, 2-\frac{\pi}{4}\right)\right)-\exp(\mathrm{i}\,\phi n-1,2)\right]\end{pmatrix}. \qquad (2)
\end{aligned}
$$

We can obtain the output electrical signals of the balanced detectors and u data branch and v data branch respectively as follows:

$$\begin{aligned} V_{\rm u} &\propto |E_{{\rm des},\frac{\pi}{4}}|^2 - |E_{{\rm cons},\frac{\pi}{4}}|^2 \\ &= P_{\rm total}/3\{2[\cos(\Delta\phi_{\rm u1}) - \sin(\Delta\phi_{\rm u1})] \\ &\quad + [\cos(\Delta\phi_{\rm u2}) - \sin(\Delta\phi_{\rm u2})]\}, \\ V_{\rm v} &\propto |E_{{\rm des},-\frac{\pi}{4}}|^2 - |E_{{\rm cons},-\frac{\pi}{4}}|^2 \\ &= P_{\rm total}/3\{2[\cos(\Delta\phi_{\rm v1}) + \sin(\Delta\phi_{\rm v1})] \\ &\quad + [\cos(\Delta\phi_{\rm v2}) + \sin(\Delta\phi_{\rm v2})]\} \end{aligned} \tag{3}$$

where $\Delta\phi_{\rm u1}$, $\Delta\phi_{\rm u2}$, $\Delta\phi_{\rm v1}$, $\Delta\phi_{\rm v2}$ are phase differences between the current signal and the former signal at u and v branches. According to Eq. (3), four signal levels can be obtained for both u and v branches and they can be detected as 2-bit digital signals of 10, 11, 01, 00, in grey-code order, as shown in Fig. 3.

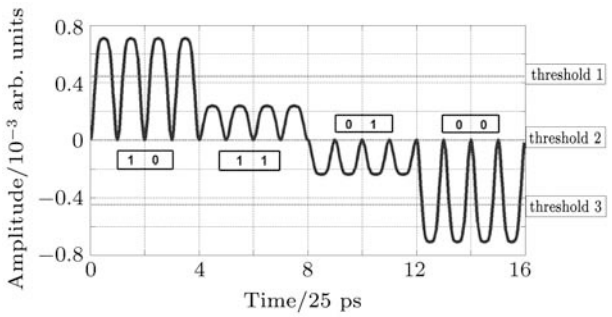


Fig. 3. Timing-domain signals at the receiver of the DP-DQPSK system.

The detection relationship is shown in Table 2.

Table 2. The relationship between the four signal levels and the 2-bit signal.

Electrical signal level	0	1	2	3
$(u1, u2)$ or $(v1, v2)$	00	01	11	10

Through the above analysis, Karnaugh map concerning the input and output data streams of the pre-coder can be obtained. Then we can deduce the logic expressions of the DQPSK pre-coder from the Karnaugh map as follows:

$$\begin{aligned} I_{1,k} &= \overline{u_{1,k}v_{1,k}}\,\overline{I_{1,k-1}} + \overline{u_{1,k}}v_{1,k}Q_{1,k-1} \\ &\quad + u_{1,k}\overline{v_{1,k}}\,\overline{Q_{1,k-1}} + u_{1,k}v_{1,k}I_{1,k-1}, \\ Q_{1,k} &= \overline{u_{1,k}v_{1,k}}\,\overline{Q_{1,k-1}} + \overline{u_{1,k}}v_{1,k}\overline{I_{1,k-1}} \\ &\quad + u_{1,k}\overline{v_{1,k}}I_{1,k-1} + u_{1,k}v_{1,k}Q_{1,k-1}, \\ I_{2,k} &= \overline{v_{1,k}v_{2,k}}\,\overline{I_{2,k-1}Q_{2,k-1}} + \overline{u_{1,k}u_{2,k}}\overline{I_{2,k-1}}Q_{2,k-1} \\ &\quad + \overline{v_{1,k}}v_{2,k}I_{2,k-1}Q_{2,k-1} + v_{1,k}\overline{v_{2,k}}I_{2,k-1}Q_{2,k-1} \\ &\quad + v_{1,k}v_{2,k}\overline{I_{2,k-1}Q_{2,k-1}} + \overline{u_{1,k}}u_{2,k}I_{2,k-1}\overline{Q_{2,k-1}} \\ &\quad + u_{1,k}\overline{u_{2,k}}I_{2,k-1}\overline{Q_{2,k-1}} + u_{1,k}u_{2,k}\overline{I_{2,k-1}}Q_{2,k-1}, \\ Q_{2,k} &= \overline{u_{1,k}u_{2,k}}\,\overline{I_{2,k-1}Q_{2,k-1}} + \overline{v_{1,k}v_{2,k}}I_{2,k-1}\overline{Q_{2,k-1}} \\ &\quad + \overline{v_{1,k}}v_{2,k}\overline{I_{2,k-1}}Q_{2,k-1} + v_{1,k}\overline{v_{2,k}}\,\overline{I_{2,k-1}}Q_{2,k-1} \\ &\quad + v_{1,k}v_{2,k}I_{2,k-1}\overline{Q_{2,k-1}} + \overline{u_{1,k}}u_{2,k}I_{2,k-1}Q_{2,k-1} \\ &\quad + u_{1,k}\overline{u_{2,k}}I_{2,k-1}Q_{2,k-1} + u_{1,k}u_{2,k}\overline{I_{2,k-1}Q_{2,k-1}}, \end{aligned} \tag{4}$$

where $\bar{x}$ means NOT x in logic operations.

3. Adaptive PMD compensation

As both the orthogonal polarizations are used to carry the signals, polarization multiplexed (PolMux) formats will highly suffer from the polarization effect in fibres such as PMD.[10] Therefore, it is necessary to apply a PMD compensator in the novel DP-DQPSK system. By using DOP as the feedback signal, particle swarm optimization (PSO) algorithm as the searching algorithm, optical PMD compensation is carried out.

3.1. DOP analysis

The DOP is defined as[11]

$$\text{DOP} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}, \tag{5}$$

where S_0, S_1, S_2, S_3 are four Stokes intensity parameters. The optical beam i with arbitrary SOP $\boldsymbol{S}_1$ can be characterized by Stokes vector as[11]

$$\boldsymbol{S}_i = \begin{bmatrix} S_{i0} \\ S_{i1} \\ S_{i2} \\ S_{i3} \end{bmatrix} = \begin{bmatrix} P_i \\ P_i\cos 2\varepsilon_i\cos 2\theta_i \\ P_i\cos 2\varepsilon_i\sin 2\theta_i \\ P_i\sin 2\varepsilon_i \end{bmatrix}, \tag{6}$$

where P_i is the optical power, ε_i is the ellipticity angle and θ_i is the orientation angle. Choosing the transmission axes of the PBS as reference coordinates x and y for convenience, the corresponding Mueller matrix of the PBS can be expressed as[11]

$$\boldsymbol{M}_x = \frac{1}{2}\begin{bmatrix} 1&1&0&0 \\ 1&1&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \end{bmatrix}, \quad \boldsymbol{M}_y = \frac{1}{2}\begin{bmatrix} 1&-1&0&0 \\ -1&1&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \end{bmatrix}. \tag{7}$$

After passing through the PBS, the Stokes vectors along the x and y direction are $M_x\boldsymbol{S}_{\rm cw}$ and $M_y\boldsymbol{S}_{\rm cw}$. Due to non-coherence of the two orthogonal components, the Stokes parameters of two completely independent optical beams can be added (in coherent

superposition of intensities).[11] Then the Stokes parameters can be obtained as follows:

$$\boldsymbol{S}_{\rm PM} = \boldsymbol{M}_x\boldsymbol{S}_{\rm cw} + \boldsymbol{M}_y\boldsymbol{S}_{\rm cw} = \begin{bmatrix} S_{x0} \\ S_{x1} \\ S_{x2} \\ S_{x3} \end{bmatrix} + \begin{bmatrix} S_{y0} \\ S_{y1} \\ S_{y2} \\ S_{y3} \end{bmatrix}. \quad (8)$$

As the CW light at the laser source is linearly polarized light, its ε_i is equal to zero. Hence, we can obtain

$$\boldsymbol{S}_{\rm cw} = \begin{bmatrix} S_{\rm cw0} \\ S_{\rm cw1} \\ S_{\rm cw2} \\ S_{\rm cw3} \end{bmatrix} = \begin{bmatrix} P_{\rm tol} \\ P_{\rm tol}\cos 2\theta \\ P_{\rm tol}\sin 2\theta \\ 0 \end{bmatrix},$$

$$\boldsymbol{S}_{\rm PM} = \begin{bmatrix} S_{\rm PM0} \\ S_{\rm PM1} \\ S_{\rm PM2} \\ S_{\rm PM3} \end{bmatrix} = \begin{bmatrix} P_{\rm tol} \\ P_{\rm tol}\cos 2\theta \\ 0 \\ 0 \end{bmatrix}. \quad (9)$$

According to Eq. (5), the DOP of the DP-DQPSK signals at the transmitter end can be rewritten as

$$\mathrm{DOP} = |\cos(2\theta)|, \quad (10)$$

where θ is the orientation angle. Equation (10) is consistent with the test results in Optisystem as shown in Fig. 4. Obviously, DOP of the DP-DQPSK signals is dependent on the orientation angle θ.

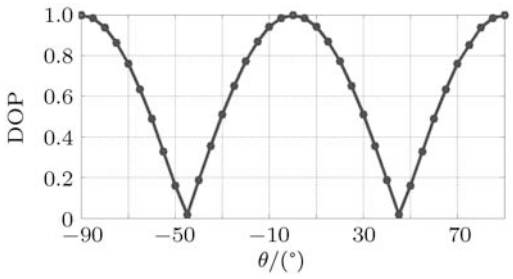


Fig. 4. DOP versus the orientation angle θ tested in Optisystem.

In this article, the orientation angle is adjusted to 35.2° to make the power ratio between the two branches of the DP-DQPSK signal be 2:1. According to Eq. (10), DOP is about 0.335.

By using the polarization meter in Optisystem software, which works at the frequency of 193.1 THz and has a bandwidth of 100 GHz, the relationship between DOP and differential group delay (DGD) for the DP-DQPSK signals has been measured, as shown by the dashed line in Fig. 5. We can see clearly that when the feedback DOP reaches the maximum value 0.335, DGD is equal to zero, that is to say, PMD in the system is compensated completely.

For the purpose of searching the maximum DOP value precisely, DOP is tripled corresponding to DGD, as shown by the solid line in Fig. 5. Then the maximum DOP value becomes 1. Taking the optimized DOP as the feedback signal, the searching process and PMD compensation will be more precisely achieved.

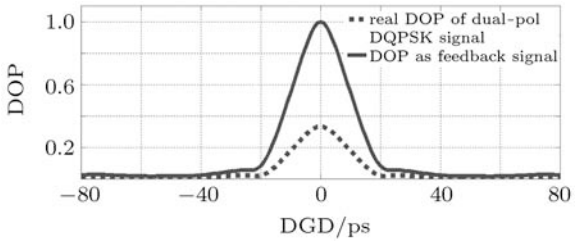


Fig. 5. DOP versus first-order DGD.

3.2. Architecture of PMD compensator (PMDC)

As shown in Fig. 6, the PMD emulator is composed of a polarization controller and a polarization maintaining fibre (PMF) with differential group delay (DGD) of 30 ps. The PMD compensator is a two-stage compensator, consisting of two PCs, one variable delay line and one fixed delay line with DGD of 15 ps. Adopting the DOP of the DP-DQPSK signals as the feedback signal and the particle swarm optimization (PSO) algorithm as searching algorithm, logic control unit realizes the control of PC1, PC2 and variable delay line.[12−15] This compensator can compensate the first-order PMD and one main part of the second-order PMD, the part of principal state of polarization rotation rate (PSPrr). While polarization-dependent chromatic dispersion (PCD), the other part of second-order PMD, cannot be compensated.[15] In fact, in real optical fibre transmission, the first-order PMD is the main part of the total PMD. For the second-order PMD in real fibre link, PCD is the minor component of the second-order PMD vector and makes less impairment to systems, while the orthogonal components related to PSPrr is the larger component and the dominant impairment factor to systems.[16] As a result, PCD can be ignored in the compensation and the PMD compensator is acceptable.

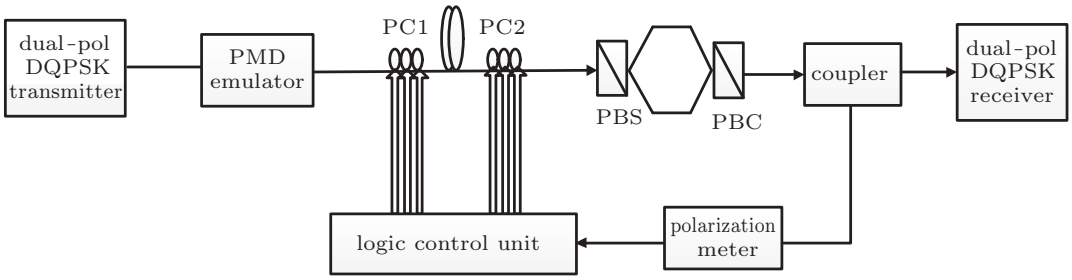


Fig. 6. Architecture of the PMD compensator.

3.3. Simulation result of PMD compensation

We set the threshold of searching function value (DOP) to 0.996 and the 256 simulation samples are recorded. It can be seen from Fig. 7 that before compensation, the DOP value is very small. While after PMD compensation, DOP values are all larger than 0.998, indicating that the compensation is accomplished successfully.

The results before and after PMD compensation are shown in Fig. 8. As shown in Figs. 8(a) and 8(b), the eye diagram becomes distorted when the DP-DQPSK signals undergo PMD. Thus, the performance degrades severely, resulting in an increased BER. After compensation, the eye opening is improved remarkably as shown in Figs. 8(c) and 8(d). In this case, the DP-DQPSK signals can be decoded correctly.

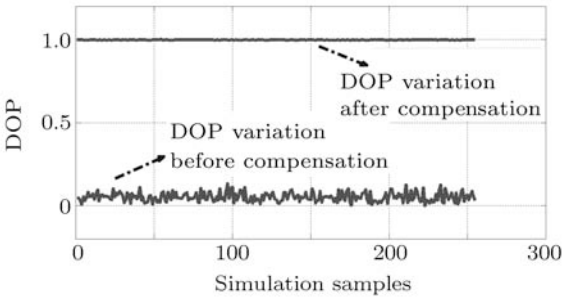


Fig. 7. DOP variation before and after PMD compensation.

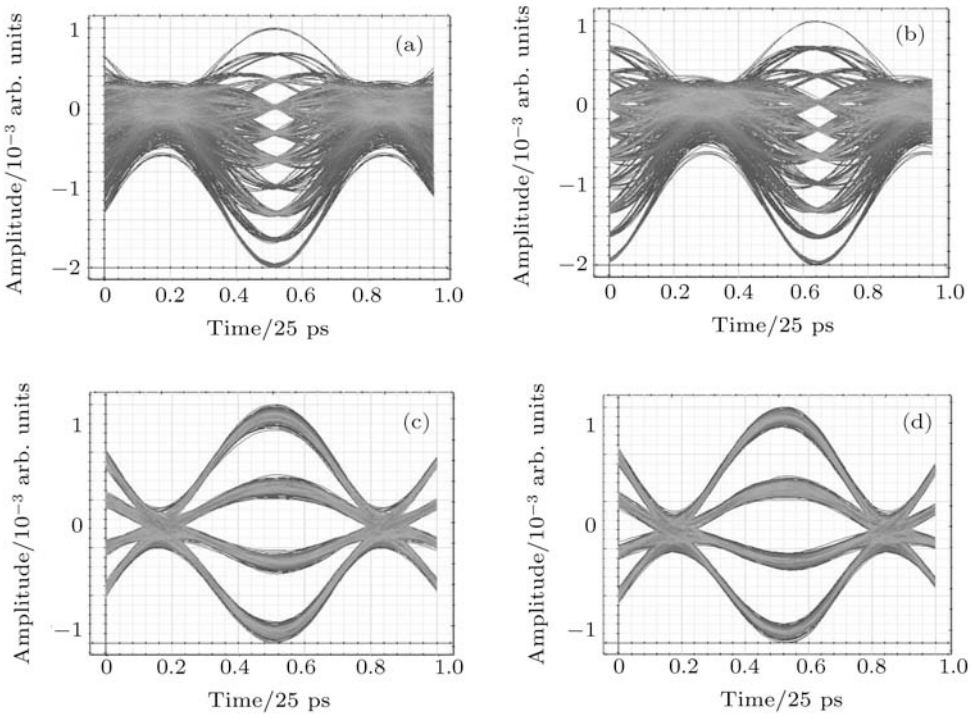


Fig. 8. Eye diagrams before PMD compensation: (a) u branch, (b) v branch. Eye diagrams after PMD compensation: (c) u branch, (d) v branch.

Figure 9 depicts the performance of the novel DP-DQPSK system with and without PMD compensation under the effect of first-order PMD (DGD of 30 ps). The results show that PMD causes large penalty to the performance of the system, which keeps BER remaining to be about 5×10^{-1} all the time. While after PMD compensation, BER can be reduced to below 10^{-3}. Only 0.7-dB OSNR penalty is required for compensation compared with 24.3-dB OSNR when without PMD at the same BER level of 10^{-3}.

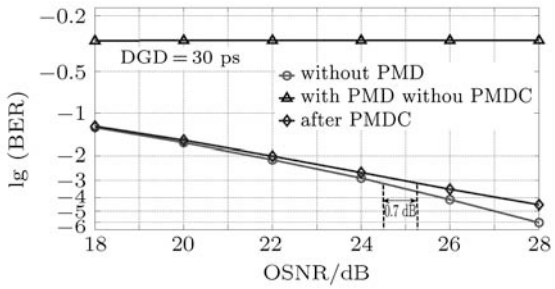


Fig. 9. BER versus OSNR with and without first-order PMD.

Figure 10 shows the OSNR penalties at the BER level of 10^{-3} versus DGD for the 100-Gbit/s DP-DQPSK system with and without PMD compensation. The results show that the tolerance to PMD can be increased from 12-ps to 101-ps within 1-dB OSNR penalty by using a PMD compensator. It is concluded that PMD compensation can greatly improve the PMD tolerance with a low OSNR penalty in the DP-DQPSK system.

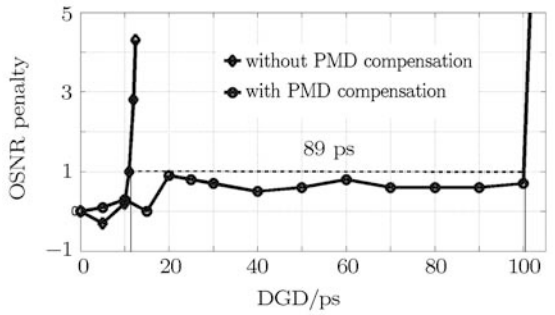


Fig. 10. OSNR penalty at BER=10^{-3} versus DGD for the 100-Gbit/s DP-DQPSK system.

4. Conclusion

In this paper, we have proposed a novel dual polarization DQPSK system. Compared with the conventional PDM-DQPSK system, it has the same spectral efficiency, while its receiver is simpler. In the system, the DP-DQPSK signals can be demodulated through balanced detection with no need for polarization de-multiplexing. PMD in the system is mainly considered. Taking the optimized DOP as the feedback and PSO algorithm as the searching algorithm, the results show that PMD compensation is implemented successfully in the system. PMD tolerance can be improved by 89 ps within 1-dB OSNR penalty after compensation.

As the 100-Gb/s PDM-QPSK coherent system has not been commercialized yet, the novel DP-DQPSK system can play an important role in the optical communication, especially in the short-distance access network.

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