Performance comparison between sampling methods using DOP as feedback signal for higher-order PMD compensator

Min Yao (姚 敏)[1,2], Huanyou Wang (王焕友)[1,3], and Lin Chen (陈 林)[2]

[1] *Department of Physics, Xiangnan University, Chenzhou 423000*
[2] *College of Computer and Communication, Hunan University, Changsha 410082*
[3] *School of Material Sciences and Engineering, Central South University, Changsha 410082*

Received November 7, 2006

We numerically analyzed the performance of the two polarization-mode dispersion (PMD) compensation methods of the single degree of polarization (DOP) sampling and DOP ellipsoid sampling methods. The numerical results show that the single DOP sampling method can generate the maximum DOP, and may result in a small overall differential group delay (DGD) or the principal state of polarization (PSP) launching. By the PSP launching, just the first-order PMD is compensated while second-order PMD not. When the DOP ellipsoid sampling method is used the performance is evidently better, because the effect of high-order PMD on PMD compensation is reduced.

OCIS codes: 060.0060, 060.2330, 060.4510.

In high-speed optical transmission system beyond 10 Gb/s, signal distortion caused by polarization mode dispersion (PMD) is a major limitation on transmission distance. PMD compensation is indispensable and many PMD mitigation techniques have been proposed and demonstrated in the past decade[1−3]. The performance and complexity of PMD compensator are deeply affected by the choice of feedback. Various feedback signals, including degree of polarization (DOP)[4], the powers in a narrow band or tone of the radio-frequency (RF) spectrum of the detected signal[5], and the eye monitor commonly measuring the electrical eye opening[6], are used in most adaptive PMD compensation schemes proposed so far. For optical PMD compensation, the DOP is a very attractive feedback signal, especially at very high data rates, the DOP of signal is independent of bite rate, requires no high-speed electronics, and shows little sensitivity to chromatic dispersion. Unfortunately, multistage PMD compensator (PMDC) must be adopted to compensate higher PMD. Some authors theoretically verify that two-stage compensator can only compensate one item of second-order PMD, i.e., the principal state of polarization (PSP) rotate rate, while three-stage compensator can compensate completely the first- and second-order PMDs[6,7]. The degree of freedom (DOF), which embodies actual capability of compensation in the experiments, denotes the tuning parameters of the compensators. Actually, the three-stage compensator may bring about much higher-order PMD in the compensation system because of larger amount of DOF.

There are mainly two DOP sampling methods[8,9]. One is the single state of polarization (SOP) sampling method. The DOP of a single SOP signal checked in receiver is used as a feedback signal. When the maximum DOP is obtained by searching algorithm, PMD is compensated. The other is the DOP ellipsoid sampling method. By scrambling the SOP at the transmitter, a DOP ellipsoid is obtained, whose short axis is used as a feedback signal. The performance of several PMD compensators with different feedback signals was studied and compared[10,11], but the performance of these two DOP sampling methods for higher-order PMD compensator had not carefully been studied.

In this paper, we present a comparison between the two sampling methods using DOP as feedback signal in three-stage PMD compensators. A numerical model is founded to analyze the performance of the two sampling methods for three-stage PMD compensator in 40 Gb/s optical fiber communication system. The performance of higher-order PMD compensation is discussed and the operation strategy by two DOP sampling methods for three-stage PMD compensators is analyzed. It is shown that the DOP ellipsoid sampling is very efficient to reduce the effect of high order PMD on DOP monitors for multistage PMD compensator with more number of DOF.

The schematic of the multistage PMD compensator shown in Fig. 1 is designed as a cascade of polarization controllers (PCs), which transform any input polarization state into any desired output polarization state, and the polarization dependent delay lines (PDDLs), one of which is a variable differential delay line, with the feedback signals used to adjust the PC and the delay line. PCs are made up of 1/4, 1/2, and 1/4 wave plates, which are adjusted by direct current voltage. The total Jones matrix of PC is the continued multiplication of Jones matrixes for the three plates. Supposing the azimuth of 1/2 wave plate is θ_h, Jones matrix of 1/2 plate is

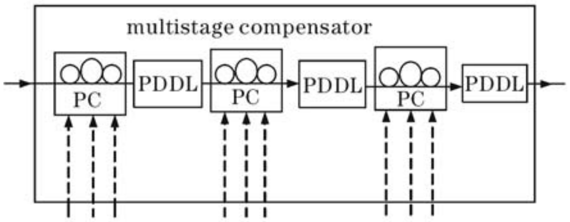

Fig. 1. Multistage PMD compensator.

1671-7694/2007/080445-04 © 2007 Chinese Optics Letters

$$\mathbf{T}_h = \begin{bmatrix} \cos\theta_h & \sin\theta_h \\ -\sin\theta_h & \cos\theta_h \end{bmatrix} \begin{bmatrix} e^{j\frac{\pi}{2}} & 0 \\ 0 & e^{-j\frac{\pi}{2}} \end{bmatrix} \begin{bmatrix} \cos\theta_h & -\sin\theta_h \\ \sin\theta_h & \cos\theta_h \end{bmatrix}. \tag{1}$$

Jones matrix of 1/4 wave plate is

$$\mathbf{T}_q = \begin{bmatrix} \cos\theta_q & \sin\theta_q \\ -\sin\theta_q & \cos\theta_q \end{bmatrix} \begin{bmatrix} e^{j\frac{\pi}{4}} & 0 \\ 0 & e^{-j\frac{\pi}{4}} \end{bmatrix} \begin{bmatrix} \cos\theta_q & -\sin\theta_q \\ \sin\theta_q & \cos\theta_q \end{bmatrix}. \tag{2}$$

If θ_{q1}, θ_{q2} are the azimuths of the two 1/4 wave plates, the total Jones matrix of PC is

$$\mathbf{T}_{\mathrm{PC}}(\theta_{q1}, \theta_h, \theta_{q2}) = \begin{bmatrix} -\cos\alpha\cos\beta - i\sin\beta\sin\gamma & -\sin\alpha\cos\beta - i\sin\beta\cos\gamma \\ -\sin\alpha\cos\beta - i\sin\beta\cos\gamma & -\cos\alpha\cos\beta + i\sin\beta\sin\gamma \end{bmatrix}, \tag{3}$$

where $\alpha = \theta_{q1} - \theta_{q2}$, $\beta = 2\theta_h - (\theta_{q1} + \theta_{q2})$, $\gamma = (\theta_{q1} + \theta_{q2})$.

Supposing the differential group delay (DGD) produced by birefringence element is τ_i, then Jones matrix is

$$\mathbf{T}_{\mathrm{PMF}} = \begin{bmatrix} e^{j(\omega-\omega_0)\tau_i/2} & 0 \\ 0 & e^{-j(\omega-\omega_0)\tau_i/2} \end{bmatrix} \tag{4}$$

and the total Jones matrix of multistage PMD compensator is[12]

$$\mathbf{U}_n = \prod_{i=n}^{1} \mathbf{T}_{\mathrm{PMF}i}\mathbf{T}_{\mathrm{PC}i}, \qquad n = 2, 3. \tag{5}$$

It is well known that DOP in the frequency domain is described as[12]

$$\mathrm{DOP}\,(\omega) = \frac{\sqrt{s_1^2\,(\omega) + s_2^2\,(\omega) + s_3^2\,(\omega)}}{s_0\,(\omega)}, \tag{6}$$

where $s_0\,(\omega)\,, s_1\,(\omega)\,, s_2\,(\omega)\,, s_3\,(\omega)$ are the Stokes vectors in frequency domain. For an input signal in a fiber, a specific shape of the spectrum $f\,(\omega)$ occupies a bandwidth in the frequency domain, which is normalized to satisfy the normalized condition, $\int_{-\infty}^{+\infty} |f\,(\omega)|^2 \frac{\mathrm{d}\omega}{2\pi} = 1$. A PMD fiber, without considering group velocity dispersion (GVD) and attenuation, is described as the Jones Matrix[12]

$$M\,(\omega) = \begin{pmatrix} u_1 & u_2 \\ -u_2^* & u_1^* \end{pmatrix}, \tag{7}$$

where u_1 and u_2 satisfy the relationship $|u_1|^2 + |u_2|^2 = 1$. Assuming $[s_x, s_y]^{\mathrm{T}}$ is the input SOP, which is independent of frequency and satisfies the normalization relationship $|s_x|^2 + |s_y|^2 = 1$, the output SOP of the fiber can be expressed as $[\; s_{ox} \quad s_{oy} \;]^{\mathrm{T}} = M\,(\omega)\,[\; s_x \quad s_y \;]^{\mathrm{T}}$. If the Jones vector of the output SOP is transformed into the corresponding Stokes vector $\widehat{t}$[13], the output average SOP of signal is averaged in the whole signal frequency domain weighted by the spectrum intensity[14]

$$\vec{r} = \int \frac{\mathrm{d}\omega}{2\pi} |f(\omega)|^2 \hat{t}. \tag{8}$$

The module of vector $\overrightarrow{r} = [r_1, r_2, r_3]$ is DOP of optical signal. Obviously, the DOP of signal is related to SOP, PMD, and frequency spectrum of the signal. Therefore, knowing total Jones matrix of integrating PMD emulator with PMD compensators, one can calculate DOP of signal by Eq. (8).

Figure 2 is a kind of PMD compensation configuration using DOP as a feedback controlling signal. Light-beam port produces signal format such as NRZ and RZ. In Fig. 2(a), after passing through the PMD emulator and PMD compensator, DOP is detected by a polarimeter and then transmitted into the PMD feedback controlling unit. The PMD emulator is modeled as a cascade of 100-wave plates, and the simulated receiver is an optical pre-amplified receiver with a $2R$ bandwidth Gaussian optical filter and a $0.75R$ bandwidth 5th-order Bessel electrical filter. The searching algorithm adjusts PC and variable differential delay line in the PMD compensator to compensate PMD until the DOP arrives at an optimum value. We adopt particle swarm optimization (PSO)[13] as the searching algorithm. The response time and complexity of the feedback signals are not considered.

If a scrambler is added before PMD emulator in Fig. 2(b) to disperse the input SOPs on the whole Poincare sphere, the points (r_1, r_2, r_3) form an ellipsoid surface. A DOP ellipsoid, which has three axes, is obtained in Stokes space. DOP ellipsoid sampling method uses short axis of DOP ellipsoid as a feedback signal.

The purpose of using PMD compensator is to reduce

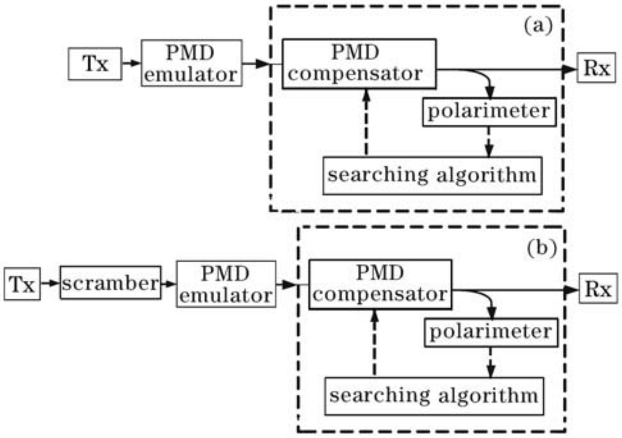

Fig. 2. Feedback controlling scheme in PMD compensation using DOP as feed-back signal. (a) Single DOP sampling method; (b) DOP ellipsoid sampling method.

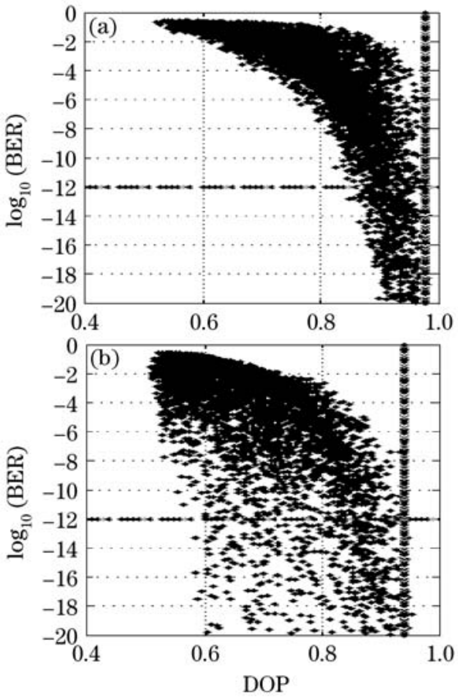

Fig. 3. BER versus DOP for (a) single SOP sampling and (b) DOP ellipsoid sampling.

the bit error rate (BER) caused by PMD. Therefore, in order to achieve a good performance, the feedback signals of PMD compensators need to have a strong correlation. The scatter plots of BER versus the DOP value of different DOP sampling in Fig. 3 obtained from simulation clearly show the correlation between different DOP sampling with BER. The purpose of PMD compensation is to reduce the biggest BER of all sampling dots. By comparing the upper envelope of Fig. 3(a) with Fig. 3(b), We can know that the BER upper envelope obtained from the DOP ellipsoid sampling method is more correlated with DOP than the single SOP sampling method. From Figs. 3(a) and (b), we can see that if the BER is less than 10^{-12}, the DOP value for single SOP single sampling must be larger than 0.98, whereas the DOP value for the DOP ellipsoid sampling must be larger than 0.94. So, the DOP threshold value is higher for single SOP sampling than DOP sampling. It is very difficult for single SOP sampling to get so large DOP. In addition, the BER is more sensitive to DOP ellipsoid than to single SOP sampling.

We create 1000 random fibers where 40-Gb/s NRZ pseudo random sequence ($2^6 - 1$) is used for each fiber, resulting in 1000 BER-samples at a power margin of 2 dB. Here average DGD of PMD emulator is chosen to be 20 ps.

Figure 4 compares the uncompensated and compensated DOPs by each of the two sampling methods using three-stage compensator with 6 DOF for NRZ formats. The uncompensated and compensated DOPs by single SOP sampling method is shown in Fig. 5(a), and the results by DOP ellipsoid sampling method are shown in Fig. 4(b). Note that in no instance the DOP is ever decreased by the two sampling methods, the compensated DOP by single SOP sampling is larger than that by DOP ellipsoid sampling method.

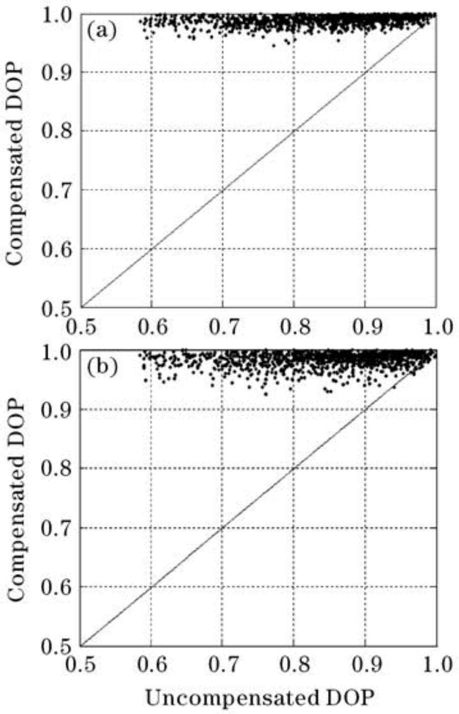

Fig. 4. Uncompensated DOP versus compensated DOP for (a) the single SOP sampling method and (b) the DOP ellipsoid sampling method.

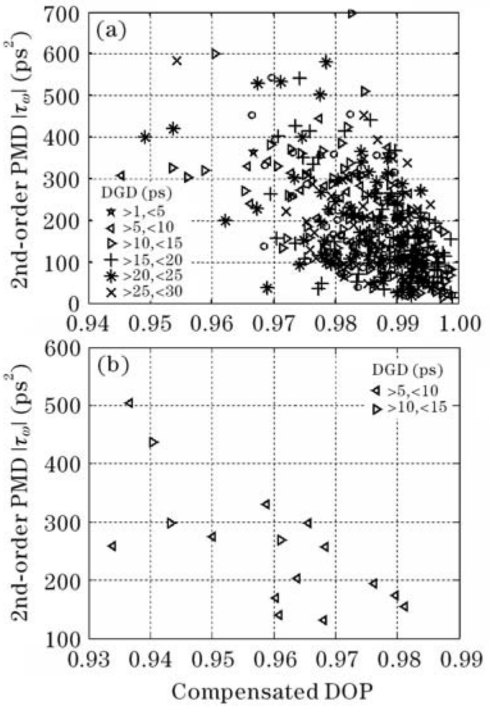

Fig. 5. Sampling points with error bits by three-stage compensator for (a) the single SOP sampling method and (b) the DOP ellipsoid sampling method.

Figure 5 compares the compensated DOP, residual DGD and higher-order PMD for two sampling methods after PMD compensation by three-stage compensator with 6 DOF. Figures 5(a) and (b) are obtained by single SOP sampling method and DOP ellipsoid sampling method, respectively. The PMD is produced by a three-section PMD emulator, which produces PMD including the first- and second-order PMD. All sample dots in Fig. 5 denote that the BER is over 10^{-12}. The abscissa of Fig. 5 is the compensated DOP, and the coordinate is the second-order PMD value

$$\vec{\tau}_\omega = \Delta\tau_\omega \hat{q} + \Delta\tau \hat{q}_\omega, \quad \tau_\omega = \sqrt{(\Delta\tau_\omega)^2 + |\Delta\tau \vec{q}_\omega|^2}, \tag{9}$$

where $\vec{\tau}_\omega$ is the second-order PMD vector, τ_ω is the value of the second-order PMD vector, $\Delta\tau$ is DGD, $\Delta\tau_\omega$ is one component of the second-order PMD called polarization-dependent chromatic dispersion (PCD). Another component, $\vec{q}_\omega$, is called the depolarization which induces change in the direction of the PSP related to frequency.

In Figs. 5(a) and (b), it is evident that the sampling points whose compensated BER is over 10^{-12} are greatly reduced for DOP ellipsoid sampling method compared with single SOP sampling method. From Fig. 5(a), we also see that the residual second-order PMD and DGD after compensation by single SOP sampling method is larger than that of compensation by DOP ellipsoid sampling method shown in Fig. 5(b). According to Fig. 5(a), higher BER appears where DOP is larger after compensation. As shown in Fig. 5, all DOPs increase after compensation. The reason why the compensated DOP is increased while BER is still larger than 10^{-12} is that at these sample dots the second PMD is not compensated because of the PSP launching for single SOP sampling method.

The average DGD of PMD emulator is chosen to be 20 ps. In Fig. 6, the compensated DGD probabilities are given for single SOP sampling and DOP ellipsoid sampling, respectively. The mean compensated DGD shown in Fig. 6(a) is 11.5108 ps for single SOP sampling while 4.6452 ps for DOP ellipsoid sampling as shown in Fig. 6(b). So for single SOP sampling the compensated mean DGD is larger than that of DOP ellipsoid sampling. In addition, the compensated DGDs in some samples are up to 20 − 50 ps for single SOP sampling, whereas the compensated DGDs are all less than 15 ps for DOP sampling. These show that the PSP launching operation strategy for single SOP sampling will cause higher BER while DOP is also larger because of second-order PMD.

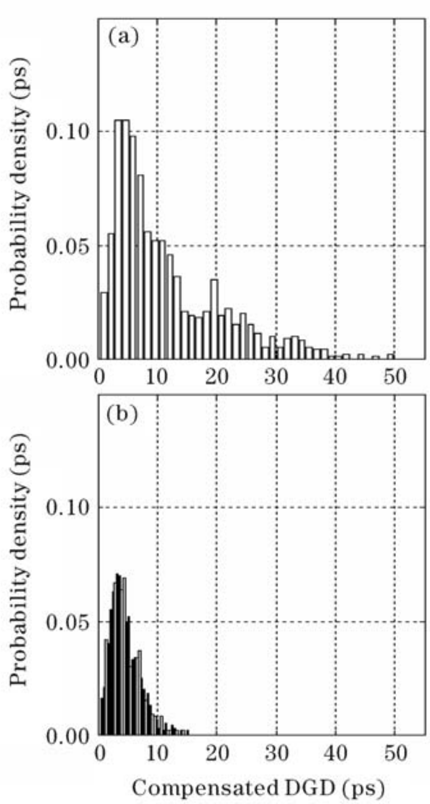

Fig. 6. Probability density of compensated DGD for (a) single SOP sampling and (b) DOP ellipsoid sampling.

We numerically compare the performance of the two DOP sampling methods. The numerical results show that although both the two methods use DOP as feedback, the operation strategy is different. The single SOP sampling can generate the maximum DOP, and may result in a small overall DGD or the PSP launching. By the PSP launching just the first-order PMD is compensated while the second-order PMD not. When the DOP ellipsoid sampling method is used in the three-stage compensator, our simulation results also show that it is feasible to reduce the effect of higher-order PMD by using short axis of DOP ellipsoid as a feedback signal and the performance of PMD compensation can be increased.

This work was supported by the Hunan Province Education Department Science and Research Project under Grant No. 06C794. M. Yao's e-mail address is yaomin8162@163.com.

References

1. F. Buchali and H. Buow, J. Lightwave Technol. **22,** 1116 (2004).
2. L. Xi, X. Zhang, L. Yu, and G. Zhou, Chin. Opt. Lett. **2,** 262 (2004).
3. X. Zhang, L. Xi, L. Yu, and G. Zhou, Chin. Opt. Lett. **2,** 316 (2004).
4. T. Takahashi, T. Imai, and M. Aiki, Electron. Lett. **30,** 348 (1994).
5. F. Buchali, S. Lanne, J.-P. Thiery, and W. Baumert, in *Proceedings of OFC'2001* Tup5-1 (2001).
6. Y. Zheng, B. Yang, and X. Zhang, IEEE Photon. Technol. Lett. **29,** 1412 (2002).
7. J. C. Rasmussen, A. Isomura, and G. Ishikawa, J. Lightwave Technol. **20,** 2101 (2002).
8. H. Rosenfeldt, C. Knothe, U. R. Brinkmeyer, and E. Feiste, in *Tech. Dig. OFC'2001* PD27-1 (2001).
9. C. Xie, L. Möller, R. M. Jopson, and A. H. Gnauck, in *Proceedings of OFC'2004* WE4 (2004).
10. C. Xie and L. Möller, IEEE Photon. Technol. Lett. **17,** 570 (2005).
11. C. D. Poole and R. E. Wagner, Electron. Lett. **22,** 1029 (1986).
12. J. P. Gordon and H. Kogelnik, Proc. Nat. Acad. Sci. **97,** 4541 (2000).
13. Y. Zheng, X. Zhang, G. Zhou, Y. Shen, and L. Chen, IEEE J. Quantum Electron. **40,** 427 (2004).
14. K. Nobuhiko, J. Lightwave Technol. **19,** 480 (2001).