Performance of DOP Technique Used to Control PMD Compensation*

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Abstract Based on principal state of polarization (PSP) theory, an analytical expression of the degree of polarization (DOP) of optical signal is obtained. The effects of various factors on signal DOP degradation are presented by numerical simulation for 40 Gb/s optical transmission system. The results show that DOP technique is able to effectively monitor and control polarization mode dispersion (PMD) compensation of 40 Gb/s optical transmission system with the different group delay (DGD) less than 37.5 ps. Furthermore, an optimal pulse width is found with regard to maximizing the tolerable DGD range, which is 1/e-intensity half width equal to 0.45 bit period (11.25 ps).

Keywords Optical fiber communication; PMD compensation; Differential group delay; Degree of polarization

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0 Introduction

In fiber optical communication systems operating over 40Gb/s per channel, polarization mode dispersion (PMD) is a very serious hurdle[1~4]. The PMD can be characterized by the differential group delay (DGD), which is the difference of time delay between the two principal states of polarization (PSP)[5]. Because of the variation of surrounding temperature, external stress and operating wavelength, both the DGD and PSP vary randomly, which is called higher order PMD[6]. This requires PMD compensation scheme to dynamically adapt to these random variation.

The PMD on the optical fiber can be treated as a vector quantity, with DGD as the magnitude and PSP as the direction. When a PMD compensation component with equal magnitude and opposite direction is applied to the signal at the output end, the PMD vector for the whole optical link becomes zero. To accomplish this, an accurate and feasible technique used to monitor and control the DGD of the link is required. Recently, a compensation method called DOP technique has been proposed, which uses the DOP of output optical signal as the monitoring and controlling signal to adjust the polarization controller and optical delay in the PMD compensator[7,8]. However, the performance of DOP technique has not been investigated completely by a handy and effective way, in particular, the tolerable DGD range and monitoring sensitivity.

In this paper, we derive an analytical expression to calculate the signal DOP degradation induced by various factors, based on the PSP theory and first-order assumption. For 40 Gb/s optical transmission system, the performance of DOP technique is shown by simulation results. We also find the optimal value of pulse width that maximizes the tolerable DGD range.

1 Theory

Due to the existence of PMD, the DOP of optical signal will degrade after transmitting through the optical links even if the launched optical signal is completely polarized. In a frequency interval in which the first-order approximation for the PSP's is valid, any fiber whose losses are polarization independent can be characterized by Jones matrix[9]

$$M(\omega)=e^{j\beta(\omega)}R_{out}^{-1}M_d(\tau)R_{in} \tag{1}$$

where β is a quantity not essential for calculation of the DOP of optical signal, ω denotes frequency deviation from the central frequency, τ is the DGD of the fiber. R_{out}^{-1} and R_{in} are matrices depending on the PSP's

$$R_{out}^{-1}=\begin{pmatrix} e^{j\Psi} & 0 \\ 0 & e^{-j\Psi}\end{pmatrix}\begin{pmatrix}\cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta\end{pmatrix}$$

$$R_{in}=\begin{pmatrix}\cos\xi & -\sin\xi \\ \sin\xi & \cos\xi\end{pmatrix}\begin{pmatrix} e^{-j\chi} & 0 \\ 0 & e^{j\chi}\end{pmatrix}$$

$$M_d(\tau)=\begin{pmatrix} e^{j\omega\tau/2} & 0 \\ 0 & e^{-j\omega\tau/2}\end{pmatrix} \tag{2}$$

where the angles ξ, χ [ζ, Ψ] describe the input [output] PSP's. Since both R_{out}^{-1} and R_{in} just result in a uniform coordinate rotation of the output state of polarization for all frequency components and do

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not cause depolarization, the DOP of output signal only depends on $M_d(\tau)$. Assume input Jones vector is $\boldsymbol{V}_{in}=(c_s, c_f)^T$ and $|c_s|^2+|c_f|^2=1$. The output Jones vector is given by

$$\boldsymbol{V}_{out}=\boldsymbol{M}_d(\tau)\boldsymbol{V}_{in}=\begin{pmatrix} c_s e^{j\omega\tau/2} & 0 \\ 0 & c_f e^{-j\omega\tau/2} \end{pmatrix} \qquad (3)$$

Using the relation between Stokes vectors and Jones vectors[10], the output signal can be written as

$$\langle \boldsymbol{S} \rangle=\begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix}=\begin{bmatrix} R(0) \\ (|c_s|^2-|c_f|^2)R(0) \\ (c_s c_f^*+c_s^* c_f)R(\tau) \\ j(c_s c_f^*-c_s^* c_f)R(\tau) \end{bmatrix} \qquad (4)$$

where $R(\tau)=\int_{-\infty}^{+\infty} X(\omega)\exp(-i\omega\tau)d\omega$, which is the autocorrelation function of the input signal. $R(0)$ is the total power of optical signal. The DOP of output optical signal is given by

$$D=\sqrt{s_1^2+s_2^2+s_3^2}/s_0=\sqrt{1+4(\gamma^2-\gamma)[1-(R(\tau)/R(0))^2]} \qquad (5)$$

where, $\gamma=|c_s|^2$ (or $|c_f|^2$) is the power splitting ratio along the PSP's. Formula (5) means that, due to presence of PMD, the polarization state of every frequency components of optical signal evolve differently. This results in autocorrelation decrease and signal DOP degradation.

Erbium-doped fiber amplifiers are generally used to provide gain in the optical transmission link, and they also introduce ASE noise. Considering the effect of ASE noise, the DOP of output signal can be given by

$$D_2=\frac{D_1}{1+(P_n/P_s)} \qquad (6)$$

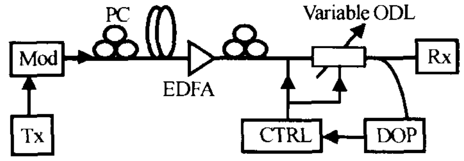
here, P_s and P_n are the power of the optical signal and ASE noise. D_1 is the signal DOP without ASE noise.

2 Numerical simulation and discussion

The model used to investigate the DOP degradation caused by the fiber DGD is shown in Fig. 1. The complete-polarized optical signal emitted from the transmitter is launched into the fiber with power splitting ratio $\gamma=0.5$ after proper transform induced by a polarization controller. The 2^7-1 PRBS launched pulses take the following form[11]

$$E(t)=E_0\sum_{n=1}^{127}\exp\left[-\frac{1+i\alpha}{2}\left(\frac{t-nT_b}{T_0}\right)^{2m}\right]e_n \qquad (7)$$

where E_0 is the peak amplitude of the pulse, α is the chirp factor, T_0 is the half-width at the 1/e-intensity point, T_b is the bit period, m is the pulse shape parameter and the pulse approach the ideal rectangular wave as m increasing. e_n is a coefficient related with extinction ratio. For convenience to show the following simulation results, a pulse width index defined as T_0/T_b is introduced.



Tx: Transmitter; Mod: Modulator; PC: Polarization controller; EDFA: Erbium-doped fiber amplifier; ODL: Optical delay line; CTRL: Control circuit; DOP: DOP measurement; Rx: Receiver

Fig. 1 Model of PMD compensation using DOP technique

To investigate the effects of pulse chirp, pulse shape and pulse width on the tolerable DGD range, we perform the numerical simulation of signal DOP for 40 Gb/s system. In Fig. 2, the tolerable DGD ranges of DOP technique are shown. It indicates that the tolerable DGD ranges will extend obviously with the decrease of chirp and the increase of the pulse width. Although at low chirp and large pulse width, the tolerable DGD range will extend rapidly, and larger pulse width is disadvantageous to the detection at the receiver, because it brings more serious inter-symbol interference (ISI). Smaller pulse width (for example, $T_0<0.4T_b$) will depress the tolerable DGD, and this is against the target of DOP technique. It should be noted that there exists some local peaks when pulse width equals to 0.45 bit period (11.25 ps). In fact, this local peak always appears when m is an integer greater than 1. (For brevity, the simulation results have not shown here

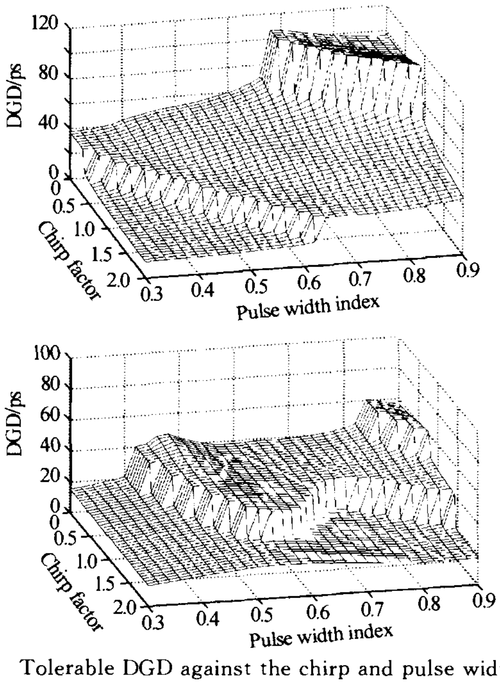


Fig. 2 Tolerable DGD against the chirp and pulse width for 40 Gb/s transmission system with $\gamma=0.5$, extinction ratio=20 dB. Top: Gaussian pulse ($m=1$), bottom: super Gaussian pulse ($m=3$)

expect for $m=1$ and 3.) So, in view of reducing the ISI and increasing the tolerable DGD range, 1/e-intensity half width of pulse should equal to 0.45 bit period(11.25 ps). On the other side, if the pulse width index is chosen to be about 0.6, the DOP technique can tolerate more intense chirp. It is clear that the tolerable DGD can be over 1.5 bit period (37.5 ps) for most pulse width and chirp.

The effect of ASE noise generated from the EDFA's; on the signal DOP is shown in Fig. 3. It is obvious that smaller power ratio (P_s/P_n) between signal and ASE noise results in more decrease of signal DOP, and the same power ratio causes more striking decrease of signal DOP at lower DGD than at higher DGD. However, the limit of tolerable DGD almost keeps unchanged. Therefore, DOP method is robust to the disturbance of ASE noise.

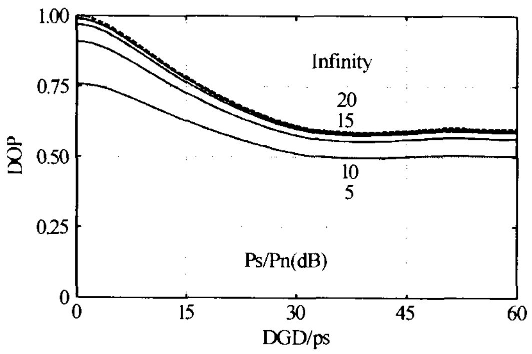


Fig. 3 Output signal DOP against DGD under different p_s/P_n for 40 Gb/s transmission system, ($m=2$, $\gamma=0.5$, extinction ratio = 20 dB)

The effect of extinction ratio on signal DOP is shown in Fig. 4. As the extinction ratio increasing, the amplitude of signal DOP decreases and this decrease becomes more distinct at higher DGD. This can be explained that higher extinction ratio induces the pulse sequence more sharp change and generates more frequency components, which is the origin of signal DOP decrease. Moreover, signal DOP becomes more sensitive to DGD at low DGD than high DGD under the same extinction ratio. It should be noted that the tolerable DGD range almost keeps over 37.5 ps even if there exist some different extinction ratios.

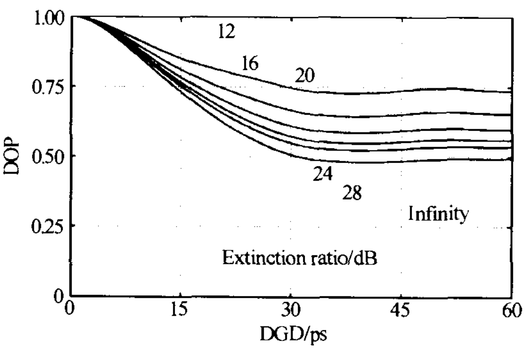


Fig. 4 Output signal DOP against DGD under different extinction ratio for 40 Gb/s transmission system ($m=2$, $\gamma=0.5$)

3 Conclusion

We have evaluated the performance of DOP technique that uses output signal DOP as the monitoring and controlling signal of PMD compensation. The tolerable DGD of the 40 Gb/s optical transmission system can be over 37.5 ps if the proper pulse width is chosen and the chirp generated from the system is limited. The existences of a local peak indicate that the tolerable DGD will extend further if the pulse width index equals to 0.45. The ASE noise and extinction ratio have no obvious effect on the tolerable DGD, but the sensitivity can be enhanced at low DGD. The tolerable DGD mainly depends on the pulse width, pulse chirp and pulse shape. It needs to balance the tolerable DGD and the tolerable chirp when the other conditions are stable.

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偏振模色散补偿控制中偏振度技术的性能

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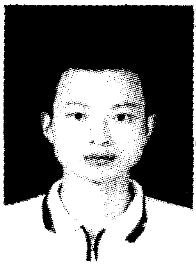
摘 要 基于主偏振态理论，导出了光信号偏振度的解析表达式。并对 40 Gb/s 光传输系统中的信号偏振度受各种因素的影响进行了数值模拟，包括啁啾、脉冲形状、脉冲宽度、自发辐射噪声以及消光比等。结果表明，偏振度技术能有效地监测和控制 40 Gb/s 系统中小于 37.5 ps 的偏振模色散。而且发现就最大化偏振度技术对差分群延时的容许范围而言，脉冲的 1/e 强度半宽取 0.45 个位宽(11.25 ps)是最优的。
关键词 光纤通信；偏振模色散补偿；差分群延时；偏振度



Liu Hankui was born in 1972, in Meishan, Sichuan, China. He is currently working toward the Ph. D. degree in physics electronics and optoelectronics in Zhejiang University. His main research interests include polarization-mode dispersion monitoring and compensation, optical subcarrier multiplex system, and polarization multiplexing transmission system.