GVD compensation schemes with considering PMD

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Three group velocity dispersion (GVD) compensation schemes, i.e., the post-compensation, pre-compensation and hybrid-compensation schemes, are discussed with considering polarization mode dispersion (PMD). In the 10- and 40-Gbit/s non-return-zero (NRZ) on-off-key (OOK) systems, three physical factors, Kerr effect, GVD and PMD are considered. The numerical results show that, when the impact of PMD is taken into account, the GVD pre-compensation scheme performs best with more than 1 dB better of average eye-opening penalty (EOP) when input power is up to 10 dBm in the 10-Gbit/s system. However the GVD post-compensation scheme performs best for the case of 40 Gbit/s with input power less than 13 dBm, and GVD pre-compensation will be better if the input power increased beyond this range. The results are different from those already reported under the assumption that the impact of PMD is neglected. Therefore, the research in this paper provide a different insight into the system optimization when PMD, Kerr effect and GVD are considered.

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Researches on GVD and Kerr effect have been extensively carried before the impact of PMD draws extensive attention. In particular, many results have revealed that the GVD hybrid-compensation scheme has the best performance compared with the GVD post-compensation and pre-compensation schemes[1,2]. Recent studies indicate that, as the bit rate in a single channel increases to 10 Gbit/s or beyond, the impairment of PMD will form an ultimate limitation to the design of an ultra high-speed long haul light-wave transmission systems. Many theoretical and experimental researches on the PMD have been reported in the past a few years[3]. However, it is firstly noted by the authors that, when the limitation induced by PMD is considered, the GVD compensation schemes have the different character from that reported in Refs. [1,2]. By numerical simulation, we find that in the system of 10 Gbit/s, the GVD pre-compensation scheme performs best. However in the 40-Gbit/s system, the GVD post-compensation scheme performs best. It is indispensable to consider the interactions of the PMD, GVD and Kerr effect in the optimization of the systems with bit rate of 10 Gbit/s or beyond. Therefore this paper provides a valuable instruction of choosing a suitable GVD management scheme for different bit rate systems when the impact of PMD cannot be neglected.

Starting from the nonlinear coupling Eqs. (1), (2) and (3)[4], we use a cascade of unequal sections of birefringence fiber with randomly changed birefringence axes between the adjacent sections[3] as fiber model.

$$\frac{\partial u}{\partial z} + \beta_{1u}\frac{\partial u}{\partial t} + \frac{i}{2}\beta_2\frac{\partial^2 u}{\partial t^2} - \frac{1}{6}\beta_3\frac{\partial^3 u}{\partial t^3} + \frac{\alpha}{2}u = i\gamma(|u|^2 + \frac{2}{3}|v|^2)u, \quad (1)$$

$$\frac{\partial v}{\partial z} + \beta_{1v}\frac{\partial v}{\partial t} + \frac{i}{2}\beta_2\frac{\partial^2 v}{\partial t^2} - \frac{1}{6}\beta_3\frac{\partial^3 v}{\partial t^3} + \frac{\alpha}{2}v = i\gamma(|v|^2 + \frac{2}{3}|u|^2)v, \quad (2)$$

$$\gamma = n_2\omega_0/cA_{\text{eff}}. \quad (3)$$

To characterize the performance of different GVD compensation schemes, we define a parameter of eye-opening penalty (EOP) as

$$\text{EOP} = -20\log(B_L/B_0), \quad (4)$$

where B_0 is the eye opening of the input signal and B_L is the eye opening after the transmission distance L. We make use of the split-step transforming method and assume that the launching signal is a 2^6-1 pseudo random bit sequence (PRBS). The polarization state of the input signal is random but fixed all through the simulations, and in this paper the input polarization state is a 50 : 50 combination of the two input principal states of polarization. The transmission span is made up of 100 km single mode fiber (SMF) and 20 km dispersion compensation fiber (DCF), and the parameters of the fibers are listed in Table 1. In this paper, we use the erbium-doped fiber amplifier (EDFA) as the pure power amplification and neglect the impact of all the noise. The cutoff frequency of the electrical filter at the receiver end is 0.75 bit rate. Considering the statistics character of the PMD, we obtain the results averaged on 1000 times simulation. Figures 1 and 2 show the relation of average EOP and input power in the three GVD compensation systems of 10 and 40 Gbit/s, respectively. Then we define the cumulative probability P_X as $P_X = P(\text{EOP} \geq X)$. By linearly fitting the curve of P_X versus EOP, we obtain the value of EOP corresponding to the cumulative probability of

Table 1. Parameters of the Fibers

Parameters @ $\lambda = 1550$ nm	SMF	DCF
Fiber Loss (dB/km)	0.2	0.5
Dispersion (ps/(km·nm))	16.0	−80.0
Dispersion Slope (ps/(nm^2·km))	0.057	−0.216
Nonlinear Index (m^2/W)	2.9×10^{-20}	4.3×10^{-20}
Effective Core Area (μm^2)	80.0	14.3

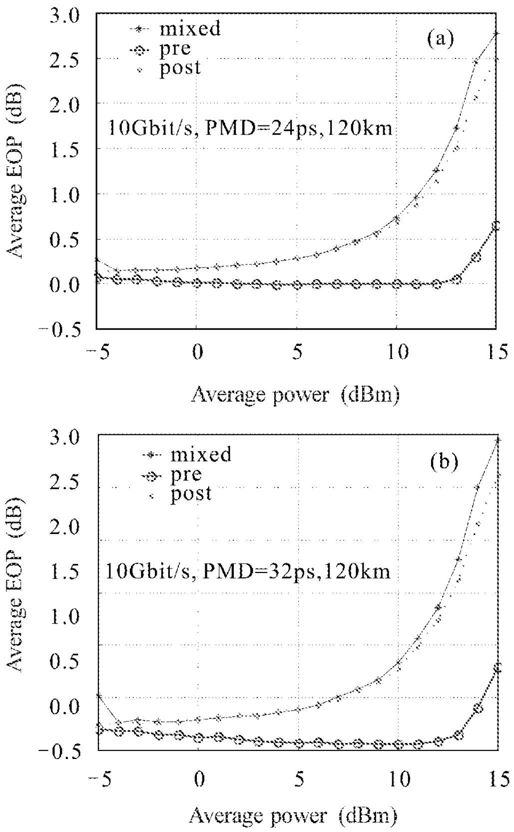

Fig. 1. Average EOP in three GVD compensation schemes after 120 km fiber for the bit rate of 10 Gbit/s.

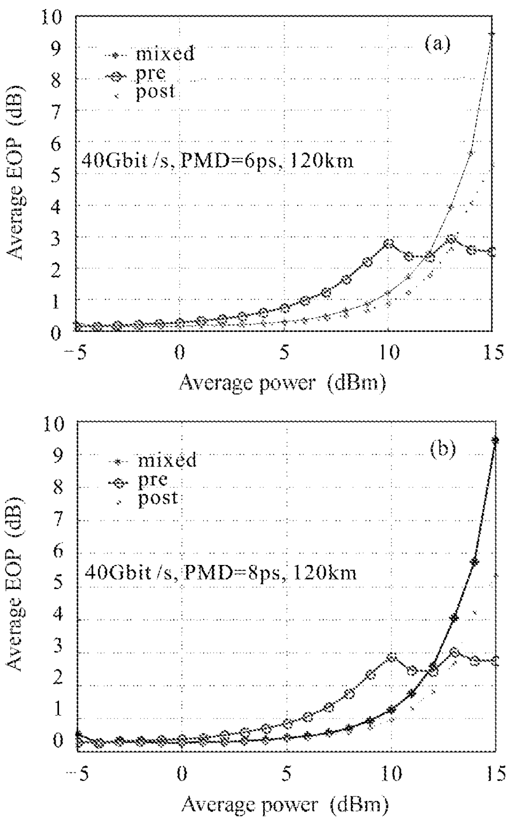

Fig. 2. Average EOP in three GVD compensation schemes after 120 km fiber for the rate of 40 Gbit/s.

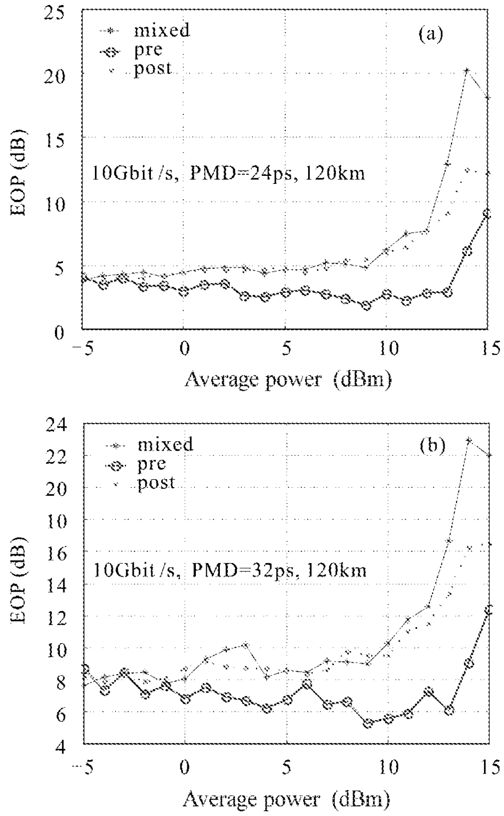

Fig. 3. EOP at 1×10^{-5} cumulative Prob. Total PMDs of the fiber length are 24 and 32 ps, respectively, in 10-Gbit/s system.

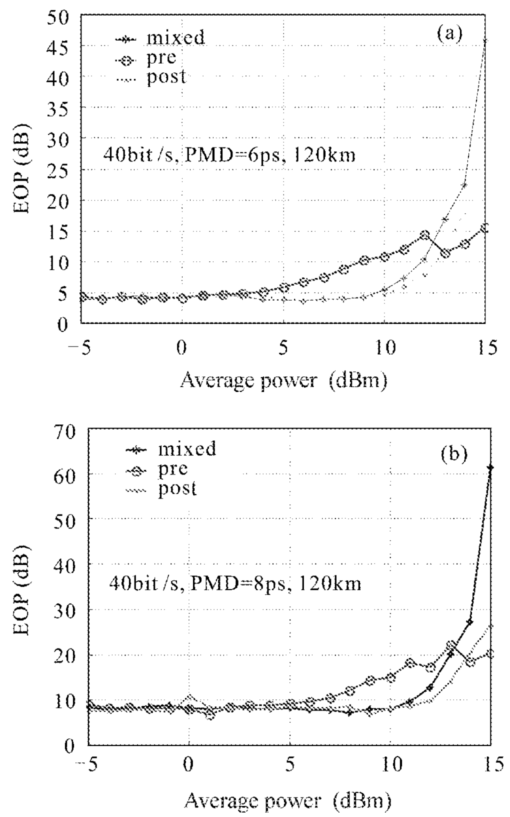

Fig. 4. EOP at 1×10^{-5} cumulative Prob. Total PMDs of the fiber length are 6 and 8 ps, respectively, in 40-Gbit/s system.

1×10^{-5}, which reflects the trailing of the differential group delay's (DGD's) Maxwell distribution. Figures 3 and 4 show the EOP at the cumulative probability of 1×10^{-5} in the three GVD compensation schemes.

We first analyze the results for the 10-Gbit/s systems. Figures 1 and 3 show that the EOP is the least in the GVD pre-compensation system of 10 Gbit/s. In Fig. 1 with more than 1 dB better of average eye-opening penalty than the other two GVD compensation schemes when input power is up to 10 dBm in the 10-Gbit/s system. This means that the GVD pre-compensation scheme is best when PMD is taken into account. This result is different from the conclusion previously reported[1,2] that GVD hybrid-compensation scheme is best when PMD is not considered. This can be explained that in the 10-Gbit/s system, if the value of PMD is not too large, the signal is more vulnerable to the distortion caused by the GVD and Kerr effect than that induced by the PMD. Therefore optimum design of the GVD management system should make the net frequency chirp least, including those caused by the dispersion and nonlinear effect. As is known in Ref. [6] that, the signal spectrum is modulated by the effect of PMD, which results in the reduced frequency chirp caused by the normal chromatic dispersion and nonlinear effect. In the earlier stage of the GVD pre-compensation scheme, the frequency chirp induced by the normal GVD and Kerr effect is effectively reduced by the modulation of PMD, so is the total chirp of the whole fiber span. This leads to the signal distortion induced by GVD and Kerr effect greatly reduced. The point can be verified by the fact that the EOP difference between the pre-compensation scheme and other two compensation schemes becomes uniformly greater with the increased input power.

We also observe from Fig. 1 that in the GVD pre-compensation system of 10 Gbit/s, the EOP first decreases then increases with the increased input power. It can be explained as that PMD can be suppressed to an extent by increasing the Kerr effect; but if the input power is too large, the Kerr effect will be dominant and result in the worse performance. For example, Fig. 1 shows that when total PMD value equals 24 or 32 ps, input power can be increased up to 10 dBm to decrease the value of EOP, i.e., to suppress the impact of PMD. However when the input power is larger than 12 dBm, EOP begins to increase, which means the worse performance.

Now we analyze the results for the 40-Gbit/s system. Figures 2 and 4 indicate that GVD post-compensation has the smallest EOP. Figure 2 shows that, when the input power is greater than 8 dBm, the GVD post-compensation scheme has more than 1-dB average EOP better than the other two GVD compensation schemes, and more than 2-dB average EOP better with input power up to 10 dBm. Because of the shorter bit duration, the signal in 40-Gbit/s system is more sensitive to the pulse broadening induced by the walk-off of the two polarized components than that in 10-Gbit/s system. It is shown in Refs. [5 – 7] that nonlinear effect can effectively inhibit the broadening induced by PMD in presence of abnormal GVD, which is dominant in the earlier stage of GVD post-compensation scheme before the signal power becomes too small due to the fiber loss. Therefore, the post-compensation and hybrid-compensation perform better than the pre-compensation. However as the input power increased to a certain value that is related to the value of PMD, 13 dBm for 8-ps PMD and 14 dBm for 14-ps PMD, the nonlinear effect becomes dominant, and the pre-compensation performs better, as is similar to the case in 10-Gbit/s system. We also notice that in both 10 and 40 Gbit/s, the difference among the three compensation schemes is small when the input power is less than 0 dBm. This is because the nonlinear effect is negligible when the input power is small and makes little difference among different compensation schemes.

Based on the above discussions, it is concluded that, when PMD is taken into account, the GVD pre-compensation scheme performs best in the 10-Gbit/s system. For the case of PMD greater than 20% bit duration, the GVD pre-compensation scheme has more than 1 dB better of average EOP when input power is up to 10 dBm. However the GVD post-compensation scheme performs best for the case of 40 Gbit/s within a certain power range that is related to the value of PMD; and GVD pre-compensation will be better if the input power increased beyond the range. In both 10- and 40-Gbit/s system, the impairment of PMD can be partly suppressed by increasing the input power up to 10 dBm. The value of EOP at outage probability 10^{-5}, which reflects the impact of DGD at the trailing of the Maxwellian distribution, is also computed and verifies the above conclusion.

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