

# New optical compensator for higher-order polarization mode dispersion in optical fiber channels

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**Abstract.** We propose a new optical compensator for both first-order and higher-order polarization mode dispersion (PMD) effects in an optical fiber channel. The compensation scheme needs just one more polarization controller and one more variable differential group delay (DGD) element than first-order optical compensators with adjustable DGD elements. And the control algorithm for this compensator is easier and more stable than that for the typical higher-order optical polarization mode dispersion compensators. By an advised control method, the proposed compensator can always have better performance than first-order optical compensators. Numerical results are given to prove the efficiency of the proposed compensation scheme. © 2006 Society of Photo-Optical Instrumentation Engineers.  
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Subject terms: optical first-order compensator; optical higher-order compensator; feedback control; polarization mode dispersion.

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## 1 Introduction

Today, as the bit rate and the transmission distance of optical fiber communication systems continue to increase, the signal distortion caused by polarization mode dispersion (PMD) in optical fiber channels is becoming a major limitation of system performance improvement. The use of optical PMD compensators (OPMDCs) is effective to reduce the system degrading effects caused by PMD.<sup>1-3</sup> The design of OPMDCs is mainly based on launching the signal into the principal state of polarization (PSP) or a cascade of polarization controllers (PCs) and differential group delay (DGD) elements.<sup>1-3</sup> PSP launch and the OPMDCs with one PC and one fixed or variable DGD element are typical first-order OPMDCs which can only compensate the PMD to first order.<sup>2,3</sup> A cascade of more than one PC and one fixed or variable DGD element compose typical higher-order OPMDCs which can compensate PMD to second order or even higher order.<sup>2-4</sup> All the compensators mentioned above require feedback signals to control the PCs and the variable DGD segments. Especially for the typical higher-order OPMDCs, a very complex software algorithm for the feedback control must be used to correlate the several composed sections to achieve the optimum compensation

effects.<sup>2-4</sup> In fact the compensators always tend to get trapped in suboptima and cannot always ensure a better performance than the first-order OPMDCs.<sup>3</sup>

We demonstrate a new higher-order optical compensator to compensate first-order and higher-order PMD effectively. It just requires one more DGD element and one more PC compared with the first-order OPMDCs using adjustable DGD element.<sup>3</sup> And the optimum working condition can be easier to track than the typical higher-order OPMDCs mentioned above. By an advised control method, the compensation scheme can always have better efficiency than the first-order optical compensators.

## 2 Principle of the Proposed Higher-order Optical Compensator

### 2.1 Proposed Higher-order OPMDC Model

The frequency-dependent PMD vector can be defined in terms of a Taylor expansion in angular frequency  $\omega$ .<sup>2</sup> Second-order PMD is decided by the change of DGD with wavelength and the rotation of PSPs with frequency (PSP depolarization).<sup>2</sup> The frequency-dependent eigenvector of the transmission matrix of the PMD dominated fiber channel tends to process at a nearly constant PSP depolarization rate within a certain limited bandwidth.<sup>2,5</sup> Based on this theory, we propose the new higher-order OPMDC. The transmission matrix of the proposed compensator can be described by Jones matrix as:

$$U_{com}(\omega) = \begin{pmatrix} \exp\left(-\frac{j\omega\tau_2}{2}\right) & 0 \\ 0 & \exp\left(\frac{j\omega\tau_2}{2}\right) \end{pmatrix} R_2^{-1}(\theta_2) \times \begin{pmatrix} \exp\left(-\frac{j\omega\tau_1}{2}\right) & 0 \\ 0 & \exp\left(\frac{j\omega\tau_1}{2}\right) \end{pmatrix} R_2(\theta_2)R_1(\theta_1),$$

where  $\omega$  is the deviation from the central carrier angular frequency  $\omega_0$ . The compensator is depicted in Fig. 1. This compensator has two adjustable DGD elements  $\tau_1, \tau_2$ , which are both decided by PSP depolarization rate  $p_\omega$  and DGD  $\Delta\tau$  in the optical fiber channel. The relations are:  $\tau_1 = (p_\omega^2 + \Delta\tau^2)^{1/2}, \tau_2 = p_\omega$ .  $R_1(\theta_1)$  is the transmission matrix of PC1, which is used to transform the optical fiber channel output PSPs to linear polarization states.  $R_2(\theta_2)$  and  $R_2^{-1}(\theta_2)$  are transmission matrices of PC2 and  $\overline{PC2}$ , which make opposite transformation. The control information of  $\overline{PC2}$  can be completely obtained from the setting of PC2. And  $\theta_2 = (1/2)\arctg(p_\omega/\Delta\tau)$ . The two delay sections both have a polarization splitter and a polarization combiner before and

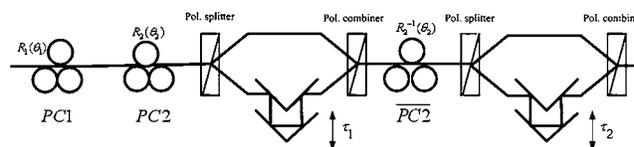


Fig. 1 Sketch map of the proposed higher-order optical compensator.

after the variable delay. The PMD vector of the proposed compensator realizes procession at the constant PSP depolarization rate. So the PSP depolarization caused by higher-order PMD can be compensated effectively within a certain bandwidth.<sup>2,5</sup>

### 2.2 Control Algorithm of the Proposed Compensator

The two delays  $\tau_1, \tau_2$  and  $PC2, \overline{PC2}$  all have a direct and certain relationship with  $p_\omega$  and  $\Delta\tau$ . So the optimization of them is easy and stable if  $p_\omega$  and  $\Delta\tau$  are measured exactly. And the widely proposed feedback control using RF spectrum, RF power, eye monitor signal, or degree of polarization<sup>2-4</sup> as feedback control signal still has better efficiency on our proposed compensation scheme than the typical higher-order OPMDCs mentioned in the introduction because of the certain relation between the four variable parameters. The control to  $PC2$  and can be decoupled from the setting of variable delays directly.

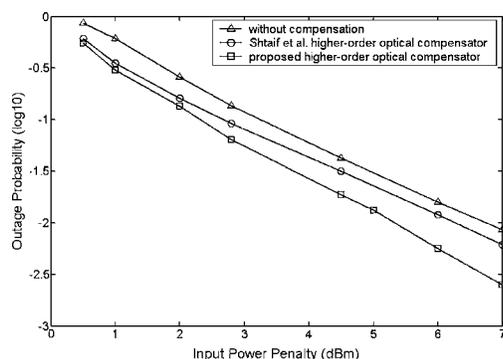
For our proposed compensator, a control method is advised following Ref. 6. First, set  $\tau_2$  to be 0. Use  $PC1$  and  $\tau_1$  as a first-order PMD compensator and optimize its compensation effect. Then based on the first-order compensation, optimize  $\tau_2, R_2(\theta_2)$  and change the setting of  $\tau_1$ . In the process, the setting of  $PC1$  is not changed. The control algorithm can always promise our proposed compensator a better performance than first-order optical compensators while the typical higher-order optical compensators cannot ensure a better performance than first-order optical compensation all the time.<sup>3</sup>

### 3 Efficiency Analysis of the Proposed Higher-order Compensator

The efficiency of our proposed higher-order optical compensator is proved by the comparison with the higher-order compensation scheme of Shtauf et al.<sup>6</sup> which has the same degree of freedom (DOF) with the proposed compensation scheme but different design theory. Like our compensation scheme, the adjustable PCs and DGD elements of the referenced compensator are also related with each other to ensure a better performance than the first-order OPMDCs all the time.<sup>6</sup> The Jones transmission matrix of the higher-order optical compensator of Shtauf et al. is<sup>6</sup>:

$$\begin{aligned}
 U_{comp}(\omega) &= R^{-1}(\omega\vec{K}) \begin{bmatrix} \exp\left(\frac{j\omega\tau}{2}\right) & 0 \\ 0 & \exp\left(\frac{j\omega\tau}{2}\right) \end{bmatrix} R(\omega\vec{K})R(\vec{\theta}) \\
 &= R_2^{-1}(\theta_2) \begin{bmatrix} \exp\left(\frac{j\omega\tau_1}{2}\right) & 0 \\ 0 & \exp\left(-\frac{j\omega\tau_1}{2}\right) \end{bmatrix} \\
 &\quad \times R_2(\theta_2) \begin{bmatrix} \exp\left(\frac{j\omega\tau_2}{2}\right) & 0 \\ 0 & \exp\left(-\frac{j\omega\tau_2}{2}\right) \end{bmatrix} \\
 &\quad \times R_2^{-1}(\theta_2) \begin{bmatrix} \exp\left(-\frac{j\omega\tau_1}{2}\right) & 0 \\ 0 & \exp\left(\frac{j\omega\tau_1}{2}\right) \end{bmatrix} R_2(\theta_2)R_1(\theta_1)
 \end{aligned}$$

where  $\tau_1=p_\omega/2, \tau_2=\Delta\tau$ .  $R_1(\theta_1)$  and  $R_2(\theta_2)$  stand for the Jones transmission matrices of PCs.  $R_1(\theta_1)$  here operates the same function as the  $R_1(\theta_1)$  in our proposed compensator. We applied the two higher-order optical compensators in the same optical fiber communication system model. In the simulations, we launch 40-Gb/s 2<sup>7</sup>-1PRBS sequences with raised cosine NRZ pulses in to the optical fiber channel which is built up by a concatenation of 50 birefringent fibers using the scheme suggested by Forno et al.<sup>7</sup> The total fiber length  $L$  in the model is 100 km. The accuracy of the all-order PMD fiber channel has been verified in several published papers.<sup>2,7</sup> The optical compensators under test are placed at the output of the optical fiber channel. After the compensator and before detection, the optical signal is amplified by an erbium-doped fiber amplifier (EDFA) with 20-dB gain and passes an optical band-pass filter with 125-GHz bandwidth. After directly detection,<sup>3</sup> the output electrical signal is filtered by a low-pass 5th-order Bessel filter (bandwidth is 24 GHz, which is optimized in the back-to-back system). Since the gain  $G$  of EDFA preamplifier is  $\gg 1$ , shot noise and thermal noise can be ignored in the receiver. Signal-spontaneous beat noise and spontaneous-spontaneous beat noise are dominating.<sup>8</sup> The noise is expressed as:  $N_i=4\mu_i h\nu n_{sp}(G-1)B_e + [h\nu n_{sp}(G-1)]^2(2B_o-B_e)B_e, i=0,1$ .<sup>9</sup> The subscript 'i' means signal '0' or '1' is launched at the optical transmitter,  $\mu_i$  refers to the detected signal power,  $h=6.626 \times 10^{-34}$  J/s,  $n_{sp}=3$  dB, and  $B_o$  and  $B_e$  are the optical band-pass filter bandwidth and the electrical low-pass filter bandwidth. We use Q values and BERs to qualify the system performance.  $BER=(1/2)\text{erfc}((Q/\sqrt{2}))$  and  $Q=(\mu_{1d}-\mu_{0d})/(\sqrt{N_{1d}}+\sqrt{N_{0d}})$ .<sup>8,9</sup> Here, the subscript 'd' means the values are obtained at the sampling time when the electrical eye opening is the largest at the end of the receiver. We use outage probabilities to measure the efficiency of the two compensation schemes. Outage is defined as the probability of  $BER > 10^{-12}$ . The input power of the back-to-back system is -26.6 dBm for  $BER=10^{-12}$ . When the efficiency of PMD compensators are discussed, the fiber nonlinearity, chromatic dispersion, and polarization-dependent loss in the optical fiber channel are always neglected and only PMD and noise are taken into account.<sup>3</sup> We use the same premises in our simulations, which is effective to estimate the quality of optical PMD compensators.<sup>3</sup> We calculate 10,000 independent optical fiber channel realization also with the average DGD = 10.2 ps to get enough BER samples to calculate outage probability for every input power for the two higher-order optical compensators under test which are applied separately in the same system model. For the two under-tested higher-order compensators, the variable parameters are all decided by DGD  $\Delta\tau$  and PSP depolarization rate  $p_\omega$  in the optical fiber channel. In the comparison simulations,  $\Delta\tau$  is gained by measuring DGD at the carrier frequency  $\omega_0$  and  $p_\omega$  is obtained by measuring the change rate of the direction of PMD vector in the vicinity of the carrier frequency  $\omega_0$ . The PCs in the two compensation schemes are all set to try to maintain the PMD vector of the whole system to be zero at the carrier frequency  $\omega_0$ . It must be emphasized that the values of  $\Delta\tau, p_\omega, PCs$ , and variable delays can be optimized by active feedback mechanism mentioned in Sec. 2, which ensure the higher-order optical compensators will have better performance. The aim of our parameter setting here is to



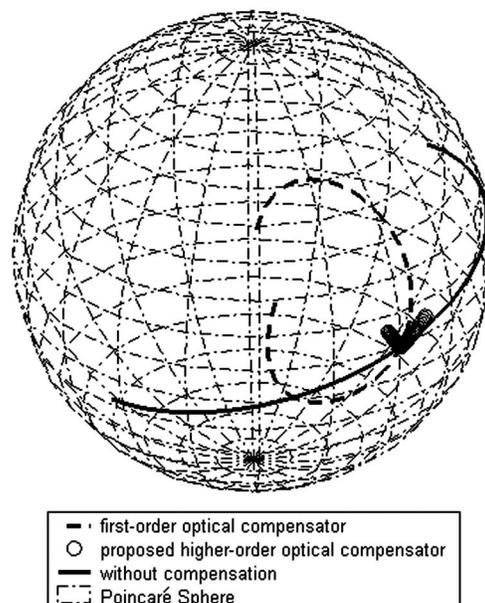
**Fig. 2** Outage probability as a function of input power penalty with the higher-order optical compensator of Shtai et al. (circles), with our proposed higher-order optical compensator (squares) and without compensation (triangles) for average DGD=10.2 ps. Outage:  $BER > 10^{-12}$ .

ensure a fair and creditable comparison.<sup>3,6</sup> Input power penalty vs. outage probability curve is given in Fig. 2. The simulation results of outage probabilities without compensation are also shown. From the curve, we can see our compensation scheme has the best performance.

We also give the states of polarization (SOPs) variation of output optical signals on a Poincaré sphere without compensation and with first-order or the proposed higher-order PMD compensation in Fig. 3. Our aim is to qualify our proposed compensator's capacity of reducing the PSP depolarization effects. The capacity is also an important quality for higher-order PMD compensators.<sup>2,6</sup> The bandwidth of simulated samples sweeps from  $-40$  to  $40$  GHz supposing that  $\omega_0=0$ . In order to keep the comparison fair and creditable, here the first-order compensator with adjustable DGD element<sup>3</sup> just matches the fiber channel PMD at the carrier frequency, and the parameters setting of the proposed higher-order compensator is unchanged. We set the power splitting of the launched input SOP  $\gamma$  to be 0.5. Then first-order and higher-order PMD effects both lead to the pulse distortion. In Fig. 3, first-order and our proposed higher-order compensator can both work to improve the system performance. And our scheme is more effective to reduce depolarization effects caused by higher-order PMD effects. The SOPs of output signals compensated by the proposed compensation scheme (circles) nearly maintain the same place on the Poincaré sphere and this good result can be obtained from arbitrary optical fiber channel realization in our simulations.

#### 4 Conclusions

In this paper, a new optical compensation scheme for higher-order PMD effects is proposed. The control algo-



**Fig. 3** SOPs of output signals without compensation, with first-order compensator using adjustable DGD element,<sup>3</sup> and with proposed higher-order compensator on Poincaré sphere.

rithm for this compensation scheme is easier and more stable than the commonly used higher-order optical compensators. And a control method is advised to ensure the proposed scheme provides better performance than the first-order compensation. The efficiency is proved by numerical calculations.

#### References

1. H. Rosenfeldt, "Deploying optical PMD compensators," *Proc. Optical Fiber Commun. Conf.*, paper OWO1 (2005).
2. I. Kaminow and T. Li, *Optical Fiber Telecommunications IVB* (Academic Press, San Diego 2002).
3. H. Sunnerud, C. Xie, M. Karlsson, R. Samuelsson, and P. A. Andrekson, "A comparison between different PMD compensation techniques," *J. Lightwave Technol.* **20**(3), 368–378 (2002).
4. U. Neukirch et al., "Time-resolved performance analysis of a second-order PMD compensator," *J. Lightwave Technol.* **22**(4), 1189–1200 (2004).
5. H. Koelnik, L. E. Neison, and J. P. Gordon, "Emulation and inversion of polarization-mode dispersion," *J. Lightwave Technol.* **21**(2), 482–495 (2003).
6. M. Shtaiif, A. Mecozzi, M. Tur, and J. A. Nagel, "A compensator for the effects of high-order polarization mode dispersion in optical fibers," *IEEE Photonics Technol. Lett.* **12**(4), 434–436 (2000).
7. A. O. Dal Forno, A. Paradisi, R. Passy, and J. P. von der Weid, "Experiment and theoretical modeling of polarization-mode dispersion in single-mode fibers," *IEEE Photonics Technol. Lett.* **12**(3), 296–298 (2000).
8. H. Büllow, "System outage probability due to first- and second-order PMD," *IEEE Photonics Technol. Lett.* **10**(5), 696–698 (1998).
9. G. Keiser, *Optical Fiber Communications Third Edition* (McGraw-Hill, New York 2000).