Impact of polarization dependent loss on degree of polarization as feedback signal of polarization mode dispersion

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Polarization dependent loss (PDL) has been recognized as a critical issue because various inline optical components may have nonnegligible PDL effect that interacts with polarization mode dispersion (PMD). We investigated the impact of PMD-PDL interaction on degree of polarization (DOP), which is the most commonly used feedback signal in PMD compensation. The simulation results of a 40-Gb/s NRZ code optical transmission system show that the maximum PMD increases from approximately 40 ps to more than 45 ps, while minimum DOP declines from approximately 0.6 to approximately 0.2. The interaction of PMD and PDL also induces residual PMD underestimation of 5—8 ps, which causes degradation of PMD compensation performance.

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With continuous development of high bit rate and capacity in optical fiber transmission systems, polarization mode dispersion (PMD) is becoming a major hindrance, especially in dense wavelength division multiplexing (DWDM) systems[1]. PMD-induced pulse broadening is difficult to be compensated since it varies frequency dependent statistically and randomly over time. Various PMD compensation techniques have been proposed, including feedback and feed-forward schemes[2,3]. In feedback scheme, feedback signal is used to estimate the residual PMD at the output, while in feed-forward scheme PMD is monitored at the input of the compensation device. Degree of polarization (DOP) is the most commonly used feedback signal in feedback PMD compensation, because DOP is fast and independent of bit rate and chromatic dispersion[4]. It has been pointed out that different modulation formats and nonlinear effects influence system signal DOP[5]. Moreover, inapplicability of DOP as feedback signal has been proved when higher order PMD is taking into consideration[6].

Polarization dependent loss (PDL) has been recognized as a critical issue because various inline optical components, such as amplifiers, switches, isolators, couplers, filters, and circulators, may have nonnegligible PDL, which attenuates two orthogonal polarization modes differently. Recent researches have showed theoretically and experimentally that the mutual interaction between PMD and PDL leads to a significant performance degradation in optical transmission systems, including increase of penalty power, Q factor, bit error rate and system outage probability[7]. The interaction also degrades the performance of PMD compensation devices using DOP as feedback signal[8]. However, the reason of the compensation performance degradation is not yet discussed with the presence of PDL, to the best of our knowledge. In this letter, we focus on the impact of PDL and PMD interaction on DOP as feedback signal and discuss the cause of performance degradation of PMD compensation.

The optical transmission system is simulated as a transmitter, a receiver, and the fiber link in between, as shown in Fig. 1. The transmitter is composed of a code generator, a Gaussian filter, and a modulator. The receiver includes a PMD monitoring device and a polarimeter, to measure PMD and DOP at the output of the fiber link. Transmission fiber is modeled as a concatenation via polarization scramblers (PSs) of 1000 PDL plates (PDL units) and 1000 independent birefringent fiber sections (DGD units) with around 100 beat lengths each. The length of the fiber sections changes randomly over a range of ±1 beat length.

We use $\beta_i = \sqrt{\frac{3\pi l_i}{8}} b\omega$ and $\alpha_i = \ln(\frac{I_{\max}}{I_{\min}})/2$ to represent the propagation constant and the loss coefficient of the ith section ($i = 1$—1000) respectively, where ω is the optical carrier frequency, b is the PMD coefficient of the fiber, l_i is the length of the section, and $I_{\max}$ and $I_{\min}$ are the maximum and minimum optical intensities. β_i and α_i indicate the magnitude of the birefringence and the PDL effect, respectively.

DGD unit and PDL unit are represented by Jones matrices, $J_\beta(\beta_i)$ and $J_\alpha(\alpha_i)$,

$$J_\beta(\beta_i) = \begin{bmatrix} e^{i\beta_i/2} & 0 \\ 0 & e^{-i\beta_i/2} \end{bmatrix}, \tag{1}$$

$$J_\alpha(\alpha_i) = \begin{bmatrix} e^{\alpha_i/2} & 0 \\ 0 & e^{-\alpha_i/2} \end{bmatrix}. \tag{2}$$

Each PS is represented by two Jones matrices

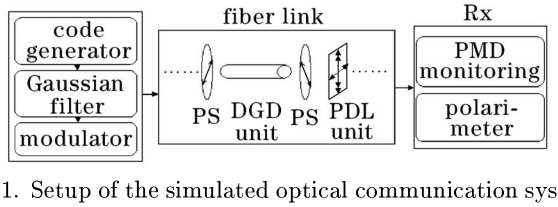

Fig. 1. Setup of the simulated optical communication system.

$$J_\theta(\theta_{ij}) = \begin{bmatrix} \cos\theta_{ij} & -\sin\theta_{ij} \\ \sin\theta_{ij} & \cos\theta_{ij} \end{bmatrix}, \tag{3}$$

$$J_\phi(\phi_{ij}) = \begin{bmatrix} \cos\frac{\phi_{ij}}{2} & i\sin\frac{\phi_{ij}}{2} \\ i\sin\frac{\phi_{ij}}{2} & \cos\frac{\phi_{ij}}{2} \end{bmatrix}, \tag{4}$$

where $i = 1$—1000, $j = 1 \sim 2$, $J_\theta(\theta_{ij})$ indicates a polarization rotator that rotates the azimuth angle by θ_{ij}, and $J_\phi(\phi_{ij})$ indicates a ϕ_{ij} phase shifter with 45° linearly polarized birefringence axis in physical space. θ_{ij} and ϕ_{ij} are randomized between ±180° to simulate the statistic nature of the fiber.

Therefore, the transmission matrix of the fiber link is

$$U = \prod_{i=1}^{1000} \{[J_\theta(\theta_{i1})J_\phi(\phi_{i1})J_\beta(\beta_i)J_\phi(-\phi_{i1})J_\theta(-\theta_{i1})] \cdot$$

$$[J_\theta(\theta_{i2})J_\phi(\phi_{i2})J_\alpha(\alpha_i)J_\phi(-\phi_{i2})J_\theta(-\theta_{i2})]\}, \tag{5}$$

then the PMD of the fiber link can be obtained using eigenvalue analysis of the transmission matrix. Also we have the relationship between input and output fields,

$$\widetilde{\vec{E}}_{\text{out}}(\omega) = U(\omega)\,\widetilde{\vec{E}}_{\text{in}}(\omega), \tag{6}$$

where $\widetilde{\vec{E}}_{\text{in}}(\omega)$ and $\widetilde{\vec{E}}_{\text{out}}(\omega)$ are the Fourier transformation of the input and output electric field vectors of the fiber link, respectively.

The DOP of the optical signal is defined as

$$P = \left\{1 - \frac{4|J_{\text{c}}|}{[\text{Tr}(J_{\text{c}})]^2}\right\}^{1/2}, \tag{7}$$

where J_{c} is the coherency matrix of the pulse, $J_{\text{c}} = \int_{-\infty}^{\infty} \text{d}t\vec{E}(t)\vec{E}^\dagger(t)$. By substituting the Fourier transformation $\vec{E}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \text{d}\omega\widetilde{\vec{E}}(\omega)\text{e}^{-j\omega t}$ and performing the integration with respect to t, J can be written in the frequency domain as

$$J_{\text{c}} = \frac{1}{2\pi}\int_{-\infty}^{\infty} \text{d}\omega\widetilde{\vec{E}}(\omega)\widetilde{\vec{E}}^\dagger(\omega). \tag{8}$$

With the above formulas, we simulate the interaction between PMD and PDL effects and its impact on DOP as the feedback signal of PMD compensation. In calculations, we use 40 Gb/s ($T = 25$ ps) Fourier transformation limited non-return to zero (NRZ) signal of 2^7-1 pseudorandom bit sequence (PRBS) length generated by Mach-Zehnder optical modulators.

Figures 2 and 3 show the relationship between DOP and PMD with or without PDL effect in the fiber link, based on 2000 statistically independent samples. α_i equals 0.05 in both cases. In the case of Fig. 2, the incident directions are set to be parallel with the S_1 axis of the Stocks space. In the case of Fig. 3, the incident directions are adjusted to be parallel with the bisector of the two principle states of polarization (PSPs). This aggravates the interaction.

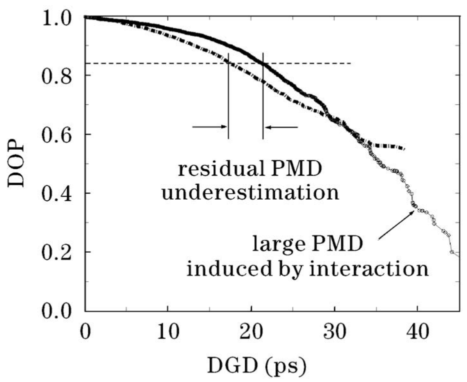

Fig. 2. DOP versus PMD with (solid) or without (dashed) PDL for incident directions parallel to S_1 axis.

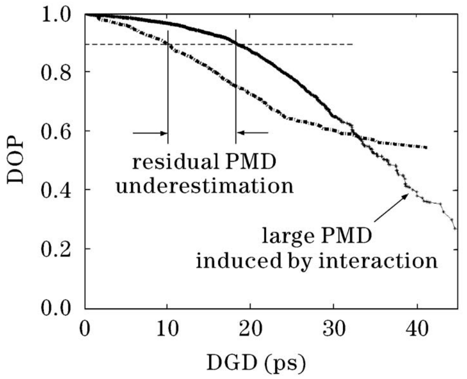

Fig. 3. DOP versus PMD with (solid) or without (dashed) PDL for incident directions parallel to bisector of PSPs.

From the figures one can see: 1) The probability of large PMD increases when PDL interacts with PMD, which causes significant decline of DOP and system performance. The maximum PMD increases from approximately 40 ps to more than 45 ps, while minimum DOP declines from approximately 0.6 to approximately 0.2. 2) When PMD is relatively small, the interaction of PMD with PDL induces underestimation of residual PMD, which causes degradation of PMD compensation performance. For example, if the threshold of the DOP in the PMD compensation optimizing algorithm is set to be 0.9, there will be a residual PMD underestimation of 5 ps in the case of Fig. 1, and 8 ps in the case of Fig. 2.

Above results can be explained by analyzing the PMD-PDL interaction. When PMD effect is large enough to be dominant, it causes further pulse broadening and distortion, and thus decline of DOP. On the other hand, when PMD effect is small and PDL is dominant, DOP is increased as extreme PDL effect equals to a linear polarizer.

Based on the simulation results, we suggest that PMD and PDL effects should be compensated at the same time, in either lumped or distributed way. Feed-forward scheme or combination of feed-forward and feedback scheme is recommended in the PMD compensation techniques, to overcome the inapplicability of DOP as feedback signal. Also, if a feedback PMD compensation scheme is used, the feedback control algorithm should be modified considering the PMD-PDL interaction. For example, threshold DOP value (i.e. the DOP value when

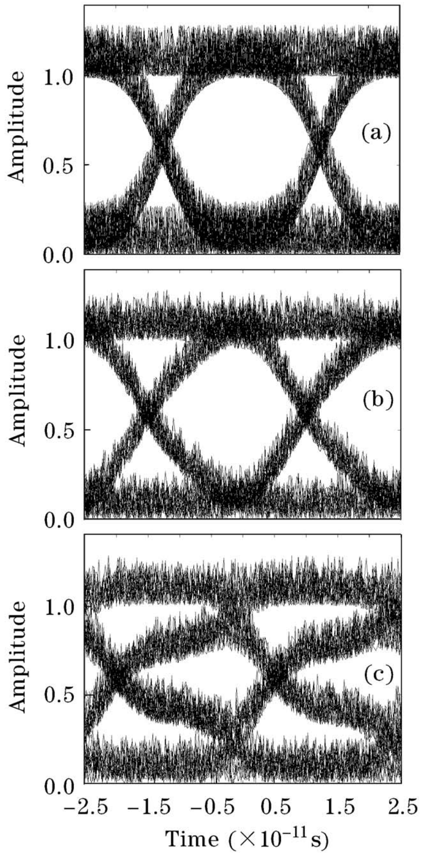

Fig. 4. Eye-diagrams when the DOP threshold is 0.9. (a) back to back; (b) without PDL; (c) with PMD-PDL interaction.

the optimization algorithm considers compensation to be achieved) should be increased to avoid the underestimation of residual PMD. Figure 4 shows the eye-diagrams of the 40-Gb/s NRZ codes when the threshold of the DOP in the PMD compensation optimizing algorithm is set to be 0.9. Eye-diagram after PMD compensation is seriously degraded when PMD interacts with PDL.

The probability density of PMD magnitude is also simulated. Figure 5 show the probability densities of PMD based on 100000 statistically independent samples when $\alpha_i = 0$, 0.035, and 0.05, respectively. In Fig. 5(a), the simulated probability density is Maxwellian distributed, as foretold by statistic theory. In Figs. 5(b) and (c), the probability density degenerates from Maxwellian shape, it decreases for PMD around the average value and increases for other PMD values. This agrees with what is reported in Ref. [8] etc..

In conclusion, we have investigated the impact of PMD-PDL interaction on DOP as feedback signal of PMD compensation. A 40 Gb/s NRZ code optical communication system is simulated as a transmitter, a receiver and the fiber link in between with PMD and PDL effects. The calculation results show that when PDL interacts with PMD, the probability of large PMD increases, causing significant decline of DOP and system performance. The maximum PMD increases from approximately 40 ps to more than 45 ps, while minimum DOP declines from approximately 0.6 to approximately 0.2. The interaction of PMD and PDL also induces residual PMD underestimation of 5—8 ps, which causes degradation of PMD compensation performance. We suggest that PMD and PDL effects should be compensated at the same time. Feed-forward scheme or combination of feed-forward and feedback scheme is recommended in the PMD compensation techniques. Control algorithm should be modified in a feedback PMD compensation scheme. For example, threshold DOP value should increase.

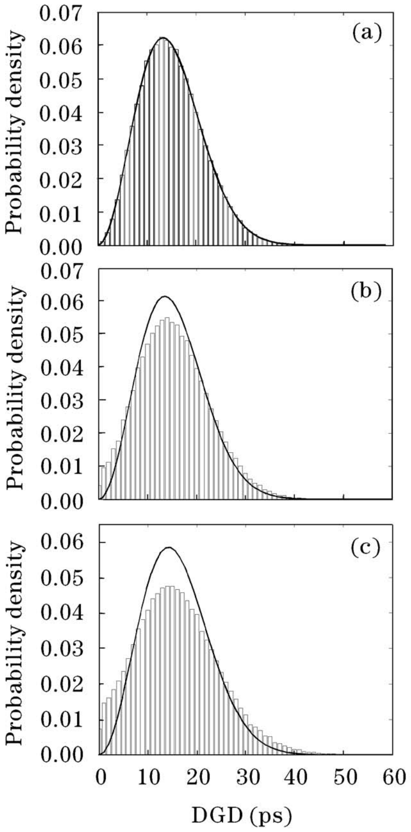

Fig. 5. Probability density of the PMD magnitude versus DGD (solid: Maxwellian distribution; histogram: simulation result) (a) $\alpha_i = 0$; (b) $\alpha_i = 0.035$; (c) $\alpha_i = 0.05$.

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