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Bit-pattern-dependent polarization rotation in first-order PMD-compensated WDM systems

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Abstract

We demonstrate both numerically and experimentally that the phase-change due to fiber nonlinearities induces a bit-pattern-dependent rotation of the state-of-polarization which translates to uncertainty in the principal states of polarization. This effect severely limits the performance of the first-order PMD post-compensation and suggests the use of in-line compensators. Our simulation shows that fiber nonlinearities cause significant distortion (more than 4-dBm *Q*-penalty after 600-km transmission at 10 Gbit/s) after first-order PMD compensation. For optical powers as low as 3 dBm/channel in systems where PMD is not uniformly distributed along the transmission link, first-order PMD compensation may be ineffective.

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1. Introduction

Polarization-mode-dispersion (PMD) is one of the key limitations in optical fiber communication systems, especially in the presence of high-PMD legacy fiber or high-PMD in-line components. Deleterious PMD effects are stochastic, time-varying,

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temperature-dependent, and worsen as the bit rate increases, leading to a growing need for PMD mitigation. To the first-order, PMD can be represented by a differential group delay (DGD) between the two principal states of polarization (PSP) [1]. DGD is a function of fiber birefringence which varies randomly along a link. As a result, DGD is a random variable that has a Maxwellian probability density function. Therefore, the effects of PMD are random and time varying [2].

First-order PMD compensation is the simplest technique to counteract PMD. It is accomplished by simply delaying one state-of-polarization (SOP) with respect to the other by the DGD amount. There have been several experiments to demonstrate first-order PMD compensation [3,4]. However, nearly all of these experiments were performed on single-channel optical links, and the potentially significant effects of fiber nonlinearities in WDM systems on first-order PMD compensation were overlooked.

In this letter, we demonstrate that the phase-change due to the fiber nonlinearities introduces bit-pattern-dependent variations of the PSP, making it impossible to fully compensate for first-order PMD. We analyze the effect of cross-phase-modulation (XPM)-induced polarization change quantitatively using simulation and experiments utilizing a fiber recirculating loop. We show that in a WDM system, where different channels experience phase changes due to fiber nonlinearities, first-order PMD compensation is not as effective as in the case of a single channel system. In fact, for optical power as low as 3 dBm/channel in systems where PMD is not uniformly distributed along the transmission link, first-order PMD compensation might be ineffective.

2. Nonlinear transformation of the SOP

The index of refraction is changed by the optical power, resulting in a nonlinear birefringence [5–7]. In WDM systems, XPM induces a nonlinear birefringence along the fiber link whenever there is optical power present at other wavelengths, causing bit-pattern-dependent variations in the SOP. Fig. 1 illustrates this concept for a simple two-channel system. The bits at wavelength λ_1 that propagate alongside a long series of “1”s in the channel at λ_2 experience a small change in the birefringence of the fiber that changes their original SOP. This effect becomes significant when the relative SOPs of the channels are preserved over a distance that is long enough for nonlinear interactions to accumulate. Consequently, the nonlinear change in SOPs is more prevalent in fibers with very low PMD, in which the relative polarization states of channels remain correlated over long distances.

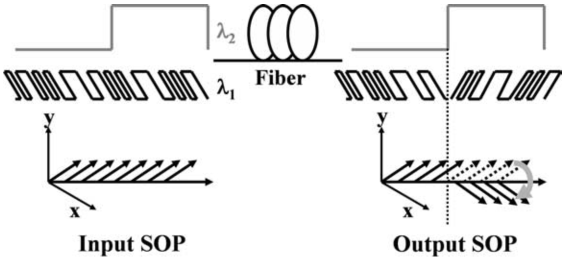

Fig. 1. Optical power induces a small nonlinear birefringence that randomizes the SOP, limiting the effectiveness of first-order PMD compensation.

If PMD is not uniformly distributed along the transmission fiber (e.g., high PMD sections of fiber are followed by low PMD sections), the overall link will still require compensation. However, the nonlinear change of the SOPs in the low PMD fiber sections can seriously reduce the effectiveness of PMD compensators. This is due to the fact that the overall PSP is dependent on the power of other optical channels and their SOPs. First-order PMD compensation depends on applying the appropriate amount of DGD aligned with the PSPs of the transmission link. Therefore, if the PSP is bit-pattern-dependent, PMD compensation cannot be effectively realized.

3. Numerical system model and experimental set-up

Our simulations concentrated on terrestrial systems operating at 10 Gbit/s. Each dispersion map consists of 85 km of single-mode fiber (SMF), 15 km of dispersion compensating fiber (DCF), and two gain stages. The average input powers are set to 5 and −2 dBm for the SMF and DCF fibers, respectively. We considered six stages of dispersion-mapped links, totaling 600 km. The WDM channel spacing is assumed to be 0.8 nm. A low-pass filter with a 6 GHz cut-off frequency is used at the receiver. The sampling time and decision threshold are optimized to account for PMD-induced bit-pattern shifts. Amplified spontaneous emission (ASE) noise is assumed as the dominant noise source.

For our experiment, we used an optical recirculating loop, which consists of ∼82 km SMF and ∼12 km DCF. The signal was passed through a single-section PMD compensator with ∼76 ps DGD after six passes through the loop.

4. Results

To evaluate the effects of XPM on PMD compensation, we first consider the simple case of a two-channel system as shown in Fig. 2(a). The first channel contains a random 64-bit signal with 50 ps DGD applied to its two orthogonal polarization states, and is transmitted over 600 km of low PMD fiber (0.1 ps/km$^{1/2}$). First-order PMD compensation is applied at the end of the transmission. The second channel is used to induce XPM, and consists of a long series of “1”s followed by a long series of “0”s to represent the worst case patterns.

Fig. 2(b) shows the power penalty distributions for a two-channel system at different optical power levels of the XPM-inducing channel. Fig. 2(c) shows the 10% worst-case penalty for different initial DGD values and different XPM-inducing optical powers. Although in a single channel system without XPM the initial DGD can be fully compensated at the end of transmission, first-order PMD compensator cannot fully compensate the initial DGD in a WDM system. Higher initial DGD values are more susceptible to the uncertainty in PSPs, as a small deviation in their orientation results in a higher penalty after compensation. It is seen that average optical powers as low as 3 dBm can cause severe penalties after first-order PMD compensation.

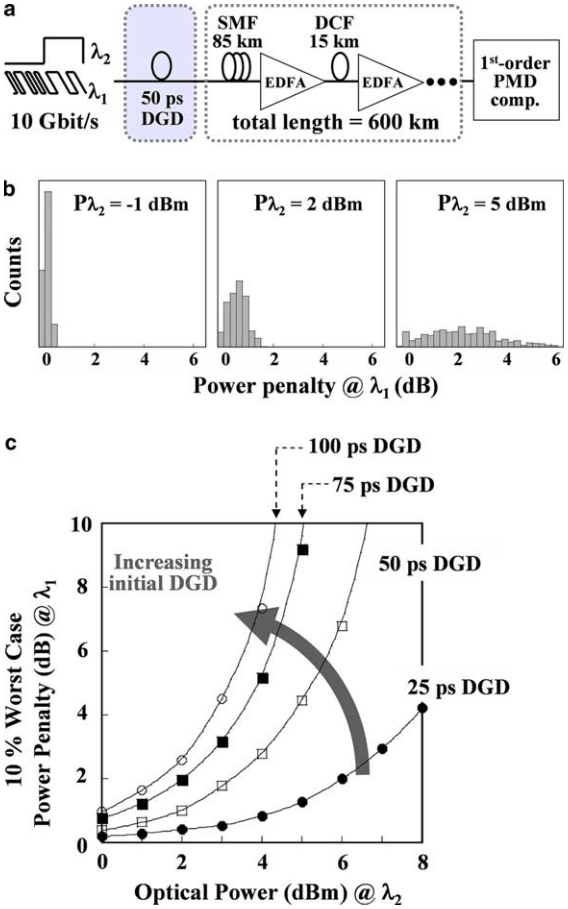

Fig. 2. Simulation – (a) The set up of a 600 km transmission link, two-channel 10 Gbit/s system, 0.8 nm channel spacing. (b) Power penalty distributions for different XPM-inducing optical powers (average power = −1, 2, 5 dBm) after first-order PMD compensation, 50 ps initial DGD. (c) 10% worst-case penalty after first-order PMD compensation for different initial DGD values and different XPM-inducing optical powers.

It is important to note that if PMD of the link is significant, the relative SOPs of WDM channels change quickly over a very short distance and become uncorrelated. As a result, the effects of nonlinearities on PSPs are averaged out, and the impact of XPM-induced PSP variations on PMD compensation is minimized. This is illustrated in Fig. 3(a). In a fiber link with low PMD, the relative SOP of the channels remains unchanged over a longer distance. Fig. 3(b) shows the power penalty caused by XPM-induced PSP variations for a signal with 50 ps initial DGD. It can be seen that the penalty is initially reduced as PMD increases.

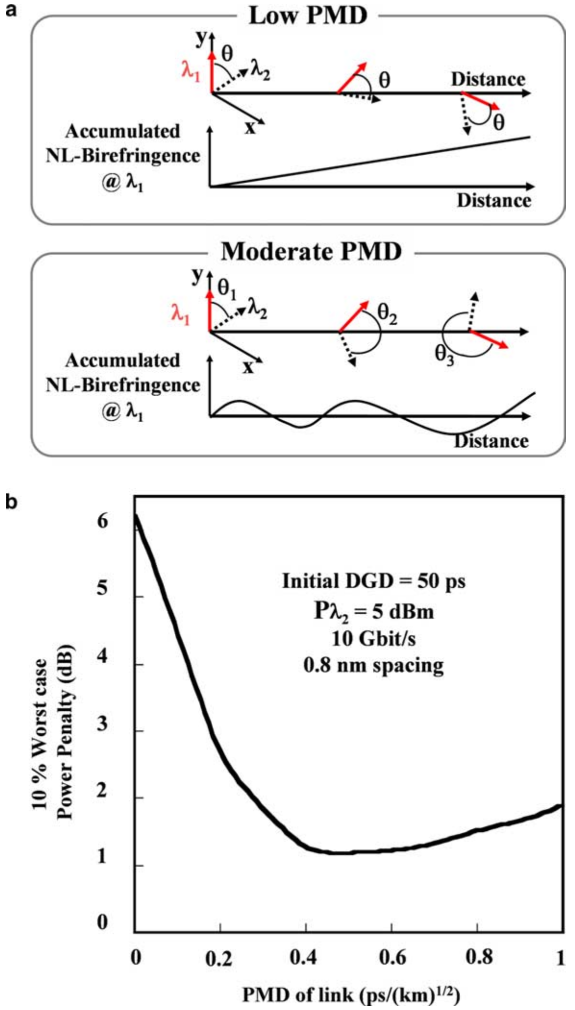

Fig. 3. (a) The illustration of PMD effect on the accumulated nonlinear-birefringence in the link. (b) 10% worst-case penalty after first-order PMD compensation vs. PMD of the link, 50 ps initial DGD, 5 dBm/channel.

However, as PMD continues to increase, additional penalties are generated due to higher-orders of PMD which are not compensated with a first-order compensator.

In order to confirm our simulation results, we set up an experiment as shown in Fig. 4(a). We transmitted two optical signals (one with modulated data and the other as a continuous wave). By adjusting the polarization controller (PC1) before the PM fiber, we first optimized the performance of the system and measured the bit-error-rate (BER). Then, we changed the relative polarization of the two optical signals by changing PC2 to get the worst performance. The BER curves for different optical powers of the XPM-inducing channel are shown in Fig. 4(b). A significant change in the system performance (BER) was observed.

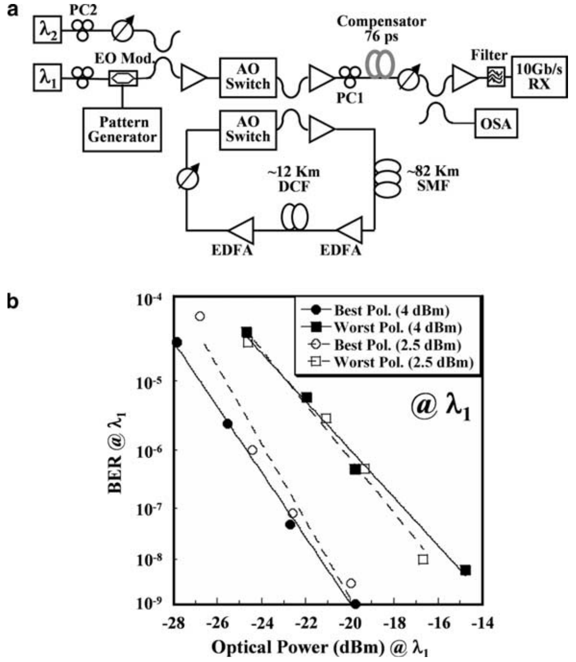

Fig. 4. Experiment – six times re-circulation in the loop, 0.8 nm channel spacing: (a) experimental set-up; (b) BER curves for the best and worst relative polarizations of the two signals. The input power of the XPM-inducing channel was set to 2.5 dBm (dashed line) and 4 dBm (solid line).

Figs. 5(a) and (b) show the *Q*-factor distribution and eye diagrams for an eight-channel system with 3 dBm/channel optical power before and after first-order PMD compensation. Again, it is assumed that all channels but one consist of a long series of “1”s followed by a long series of “0”s to simulate the worst-case pattern. The first 100 km of the link is assumed to have a high PMD of 3 ps/km$^{1/2}$, and the remaining 500 km has a low PMD of 0.1 ps/km$^{1/2}$. It is clearly seen that XPM has little effect on the *Q*-factor distribution before first-order PMD compensation, but causes

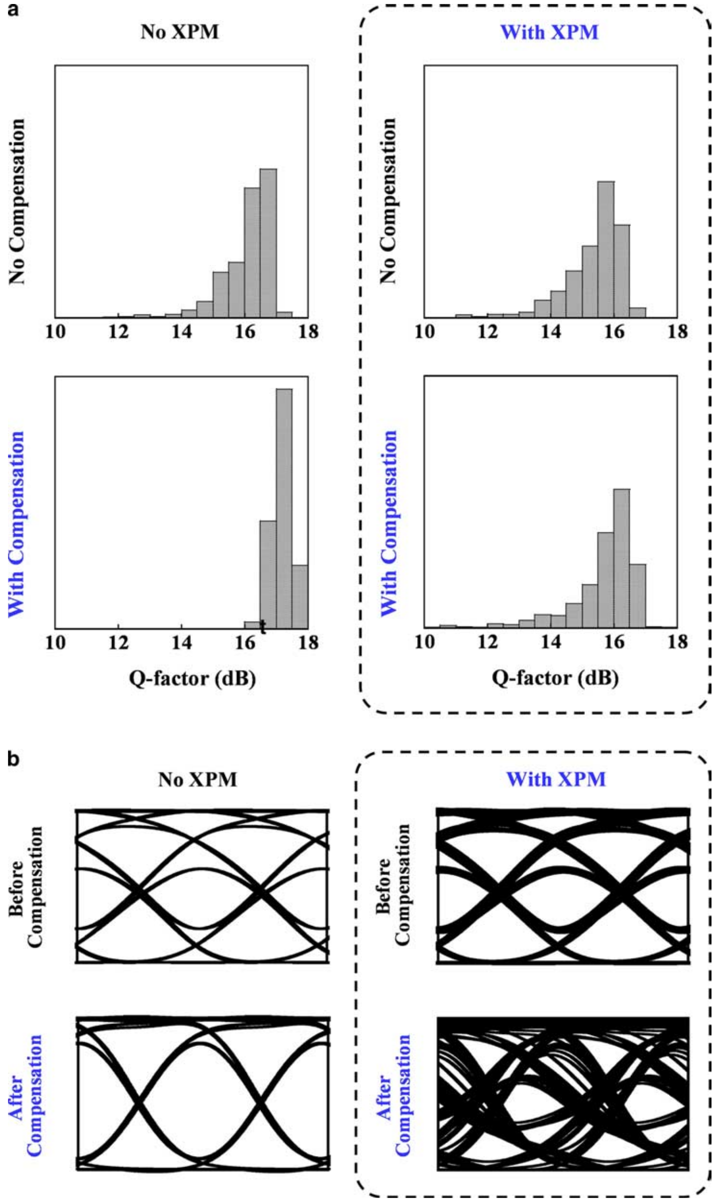

Fig. 5. (a) *Q*-factor distribution, and (b) eye diagrams of a 10 Gbit/s signal (eight-channels) after 600 km transmission. The first 100 km of the link has a high PMD of 3 ps/km$^{1/2}$, and the remaining 500 km has a low PMD of 0.1 ps/km$^{1/2}$.

significant distortion (>4 dBm penalty) after the compensation. Given that fiber nonlinearities can limit the performance of first-order PMD post-compensation, in-line compensation may be necessary to avoid accumulation of PSP uncertainties over the link.

It is important to note that, on average, system penalty will be much lower than our predicted worst-case scenario. Nevertheless, our calculations capture the occasional cases that states of polarization between the channels and their bit-patterns are relatively aligned.

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