Nonlinear polarization effects and mitigation in polarization-division-multiplexed coherent transmission systems

(Invited Paper)

Chongjin Xie (谢崇进)

Bell Laboratories, Alcatel-Lucent, 791 Holmdel-Keyport Road, Holmdel, NJ 07733, USA

E-mail: chongjin.xie@alcatel-lucent.com

Received July 5, 2010

Using numerical simulations, the nonlinear transmission performance of polarization-division-multiplexed quadrature-phase-shift-keying (PDM-QPSK) coherent systems is studied. It is found that inter-channel cross-polarization modulation (XPolM) induced nonlinear polarization scattering can significantly degrade the transmission performance of PDM-QPSK coherent systems and change the perspective of dispersion management in optical coherent transmission systems. Some techniques to mitigate nonlinear polarization scattering in dispersion-managed PDM coherent transmission systems are discussed, including the use of time-interleaved return-to-zero (RZ) PDM formats, the use of periodic-group-delay PGD dispersion compensators, and the judicious addition of some polarization-mode-dispersion (PMD) in the transmission link. It is shown that if nonlinear polarization scattering can be well mitigated, a polarization multiplexed optical coherent transmission system with dispersion management could perform better than that without it.

OCIS codes: 060.2330, 060.4370, 260.5430.
doi: 10.3788/COL20100809.0844.

Polarization-division-multiplexing (PDM)[1,2], which transmits two channels with orthogonal states of polarization (SOPs) at an identical wavelength, is an effective technique to increase the capacity of fiber-optic communication systems. This technique was proposed a long time ago, but it was only until recently that it attracted much attention due to the demand for highly spectral efficient optical communication systems and advances in digital signal processing and high speed electronics[3−5]. With coherent detection and digital signal processing, polarization demultiplexing, which was considered cumbersome in the optical domain, can be easily performed in the electrical domain, although there is still some interest to do polarization demultiplexing using optical methods[6,7]. Therefore, PDM is almost considered a standard option for today's optical coherent systems.

Compared with single-polarization (SP) signals, PDM signals are more susceptible to fiber nonlinearities, especially inter-channel nonlinearities in wavelength-division-multiplexed (WDM) systems[8]. Inter-channel nonlinearities mainly originate from cross-phase-modulation (XPM) between channels in a WDM system. It is well known that inter-channel XPM induces timing jitter and nonlinear phase noise. In addition, it also causes cross polarization modulation (XPolM)[9,10]. Except in systems with optical polarization-mode-dispersion (PMD) compensators, XPolM in general can be neglected in systems using SP signals, but can have a significant impact on PDM signals[9,11−15]. We have found that XPolM induced nonlinear polarization scattering could significantly degrade the performance of PDM transmission systems and make the technique of dispersion management, which has been successful in reducing nonlinear impairments in a fiber-optic transmission system using SP signals, less effective in polarization multiplexed transmission[12,13]. To improve the performance of PDM signals in dispersion-managed transmission systems, many techniques to mitigate nonlinear polarization scattering have been proposed and demonstrated, such as using time-interleaved return-to-zero ILRZ PDM formats (also called iRZ)[11−13], using periodic-group-delay (PGD) for inline dispersion compensators[14], and adding some PMD along the transmission links[15].

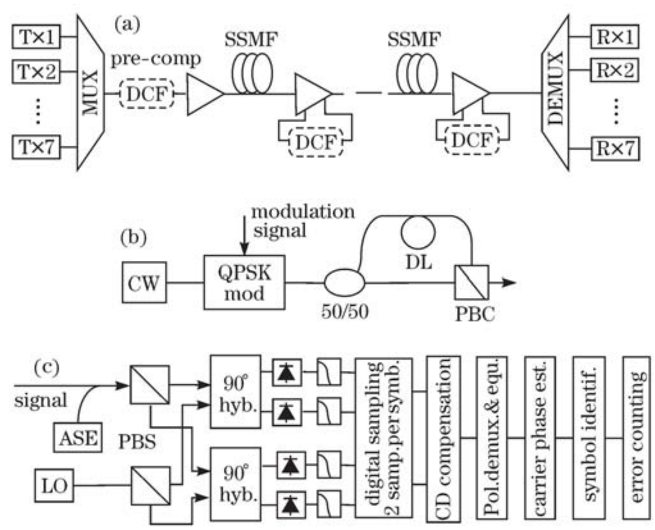

Fig. 1. System model. (a) Diagram of the transmission link; (b) block diagram of the NRZ-PDM-QPSK transmitter; (c) block diagram of the coherent receiver. DCF is removed for systems without dispersion management. Tx: transmitter, Rx: receiver, MUX: multiplexer, DEMUX: demultiplexer, Mod: modulator, DL: delay line.

This letter discusses nonlinear polarization effects and the mitigation techniques in PDM coherent transmission systems. Starting with the Manakov equation, we first show how the nonlinear interaction between WDM channels changes the polarization state of each of the channels. Then we analyze the impact of nonlinear polarization scattering on the performance of PDM quadrature-phase-shift-keying (QPSK) coherent transmission systems. The difference of the nonlinear polarization scattering between PDM-QPSK coherent systems with and without inline optical dispersion compensators is discussed. After that, we focus on nonlinear polarization scattering mitigation techniques. Three techniques to mitigate nonlinear polarization scattering in dispersion-managed PDM coherent transmission systems are presented.

When polarization effects can be neglected and the signal is launched in a single polarization, the scalar nonlinear Schrödinger equation (NLSE) is a good model to study transmission impairments in fibers including nonlinear effects. However, to consider polarization effects such as PMD and nonlinear polarization effects and to study the propagation of PDM signals in optical fibers, the coupled nonlinear Schrödinger equation (CNLSE) has to be used as[16,17]

$$\frac{\partial \mathbf{E}}{\partial z} - \mathrm{i}\Delta\beta_0 \Sigma \mathbf{E} + \Delta\beta_1 \Sigma \frac{\partial \mathbf{E}}{\partial t} + \frac{\mathrm{i}}{2}\beta_2 \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mathrm{i}\gamma \left[|\mathbf{E}|^2 \mathbf{E} - \frac{1}{3}\left(\mathbf{E}^{+}\sigma_3 \mathbf{E}\right)\sigma_3 \mathbf{E} \right], \quad (1)$$

where $\mathbf{E} = [E_x, E_y]^{\mathrm{T}}$ is the electrical field column vector, $\Delta\beta_0$ is the birefringence parameter, $\Delta\beta_1$ is the differential group delay (DGD) parameter related to PMD coefficient, Σ is the local Jones matrix describing polarization changes, β_2 is the chromatic dispersion (CD) coefficient, γ is the fiber nonlinear coefficient, $\mathbf{E}^{+} = [E_x^*, E_y^*]$ is the transpose conjugate of $\mathbf{E}$, σ_3 is one of the Pauli spin matrices, which will be given later, z is the distance along the fiber axis, t is the retarded time moving at group velocity of the carrier frequency of the signal, and $\mathrm{i} = \sqrt{-1}$ is the imaginary unit. By averaging the nonlinear effects over the Poincaré sphere under the assumption of complete mixing (averaging over the random polarization changes that uniformly cover the Poincaré sphere) and neglecting PMD, the CNLSE can be transformed to the Manakov equation[16,17]:

$$\frac{\partial \mathbf{E}}{\partial z} + \frac{\mathrm{i}}{2}\beta_2 \frac{\partial^2 \mathbf{E}}{\partial t^2} - \mathrm{i}\frac{8}{9}\gamma |\mathbf{E}|^2 \mathbf{E} = 0. \quad (2)$$

Suppose that we have a WDM system with two channels, a and b, and the two channels have non-overlapping spectra. By neglecting four-wave mixing (FWM) between the two channels, we can obtain the equations for channel a[9,10]:

$$\frac{\partial \mathbf{E}_a}{\partial z} + \frac{\mathrm{i}}{2}\beta_2 \frac{\partial^2 \mathbf{E}_a}{\partial t^2} - \mathrm{i}\frac{8}{9}\gamma \left(|\mathbf{E}_a|^2 \mathbf{E}_a + |\mathbf{E}_b|^2 \mathbf{E}_a + \mathbf{E}_b^{+}\mathbf{E}_a \mathbf{E}_b \right) = 0. \quad (3)$$

In the parenthesis, the first term is the self-phase modulation (SPM), the second term is the polarization independent cross-phase modulation (XPM), and the third term is the polarization dependent XPM. SPM does not depend on the polarization, but XPM is polarization dependent. The third nonlinear term is the same as the second one when the two channels have the same polarization and it is zero when they are orthogonally polarized, which means that the XPM between two channels with parallel polarizations is two times that with orthogonal polarizations. The last two terms show that XPM between channels also causes XPolM. An intuitive way to describe XPolM is to use the three-dimensional (3D) Stokes vector $\mathbf{S}$ in the Stokes space. Its three real components, corresponding to the electrical field vector, can be expressed as $S_i = \mathbf{E}^{+}\sigma_i \mathbf{E}$, where the symbols σ_i are the Pauli spin matrices, which are defined as[18]

$$\sigma_1 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -\mathrm{i} \\ \mathrm{i} & 0 \end{pmatrix}. \quad (4)$$

Neglecting CD, we can determine the evolution of the Stokes vector of channel a due to XPolM from channel b in transmission according to Eq. (3):

$$\frac{\mathrm{d}\mathbf{S}_a}{\mathrm{d}z} = \frac{8}{9}\gamma(\mathbf{S}_a \times \mathbf{S}_b) = \frac{8}{9}\gamma(\mathbf{S}_a \times \mathbf{S}_{\mathrm{sum}}), \quad (5)$$

where $\mathbf{S}_a = (S_{a1}, S_{a2}, S_{a3})$ and $\mathbf{S}_b = (S_{b1}, S_{b2}, S_{b3})$ are the Stokes vectors for channels a and b, respectively, and $\mathbf{S}_{\mathrm{sum}} = \mathbf{S}_a + \mathbf{S}_b$. The evolution of $\mathbf{S}_b$ can be obtained by exchanging the subscripts in Eq. (5). The relation was originally derived by Mollenauer *et al*[9]. It shows that the nonlinear interaction between channels modifies the SOP of each channel and causes the Stokes vector of each channel to precess around the other. It can also be considered that the SOP of each channel precesses around the sum of the Stokes vectors of all the channels, which is convenient for analysis when there are more than two channels.

When channels are loaded with signals of amplitude, phase or polarization modulation, and fiber CD is present, the amplitude and SOP of each channel generally change with time, and the XPolM acts in the same way as Eq. (4) describes at all temporal instances, generating time dependent nonlinear polarization scattering. Nonlinear polarization scattering causes the SOP to change at the speed of symbol rates, which is hard to follow with either optical methods in direct detection receivers or digital signal processing in coherent receivers, and may induce severe impairments in optical communication systems.

We use 42.8-Gb/s and 112-Gb/s PDM-QPSK signals to study nonlinear polarization scattering in PDM transmission systems. The system model is shown in Fig. 1. The system has seven channels with channel spacing of 50 GHz. The transmission line consists of 10 spans of standard single mode fiber (SSMF) with a CD coefficient of 17.0 ps/(nm·km), a nonlinear coefficient of 1.17 $(\mathrm{km}\cdot\mathrm{W})^{-1}$, and a loss coefficient of 0.21 dB/km. The span length is 100 km and lumped amplification is provided by erbium-doped fiber amplifiers (EDFAs) after each span to compensate for the transmission loss. Two different transmission systems are studied and compared, one with dispersion management and the other with no optical dispersion compensators provided at the transmitter and in the transmission line. In the system with dispersion management, there is −400-ps/nm dispersion pre-compensation and the CD in each span is compensated by dispersion compensation fiber (DCF), resulting in residual dispersion per span (RDPS) of 30 ps/nm. The net residual dispersion after transmission is compensated in the electrical domain by digital signal processing in the coherent receiver. The dispersion map used here is a typical map for a direct-detection fiber-optic transmission system, and no effort is made to optimize the dispersion map. In the system without any optical dispersion compensators, the CD is entirely compensated in the electrical domain in the coherent receivers.

For the non-return-to-zero (NRZ) PDM-QPSK transmitters, continuous-wave (CW) light is modulated with a nested Mach-Zehnder QPSK modulator by a 2^{11} De Bruijn bit sequence at 21.4-Gb/s or 56-Gb/s Gray mapped to QPSK symbols to generate 21.4-Gb/s or 56-Gb/s NRZ-QPSK signal. Then the SP-QPSK signal is split into two parts and the two parts are shifted relative to each other by about 511 symbols and combined with a polarization beam combiner (PBC) to form a 42.8-Gb/s or 112-Gb/s NRZ-PDM-QPSK signal, as shown in Fig. 1(b). The QPSK signal is differentially encoded to avoid cycle slips[19].

The block diagram of the PDM-QPSK coherent receiver is depicted in Fig. 1(c). In the system, the WDM channels are demultiplexed with a 4th-order super-Gaussian optical filter of 45-GHz bandwidth. After passing through a polarization beam splitter (PBS), each polarization of the demultiplexed signal is combined with a local oscillator (LO) in a 90° hybrid to provide both polarization and phase diversity. An ideal LO with 0-Hz linewidth is assumed (0-Hz linewidth is also assumed for the transmitter laser). After the hybrids, the four tributaries of the signal are detected by four balanced photo-detectors, filtered by anti-aliasing electrical filters, and sampled at two samples per symbol. The digital signal processing is comprised of four steps: 1) CD compensation with two finite impulse response (FIR) filters; 2) polarization demultiplexing with four FIR filters employing the constant modulus algorithm (CMA)[20,21]; 3) carrier phase estimation using the Viterbi-Viterbi algorithm[19], where the block length of 10 is used in the carrier phase estimation; and 4) symbol identification and bit error rate (BER) calculation. The BER is evaluated by the direct error counting method.

In the simulations, the signal of 1024 symbols first propagates in the transmission line. The bit sequence length is sufficient to capture the nonlinear interaction for the system studied here[22]. Then amplified spontaneous emission (ASE) noise is loaded at the receiver side. 204800 symbols with 200 different ASE noise realizations are used to calculate BER.

To investigate the difference of the inter-channel nonlinear effects between SP signals and PDM signals, the performances of a 42.8-Gb/s NRZ-PDM-QPSK channel surrounded by six 21.4-Gb/s NRZ-SP-QPSK channels (three channels at each side) and that by six 42.8-Gb/s NRZ-PDM-QPSK channels is first analyzed and compared. The bit rate of the SP-QPSK is half that of the PDM-QPSK so that they have the same symbol rate. Figure 2 shows the required optical signal-to-noise ratio (OSNR) at a BER of 10^{-3} after 1000-km transmission for the system with and without DCF versus the per channel launch power. The same power (including both polarizations) is used for all the WDM channels. For the system with inline DCF, at 1-dB OSNR penalty, the allowed launch power is reduced by about 3 dB when the channel is surrounded by the NRZ-PDM-QPSK channels compared with that when it is surrounded by the NRZ-SP-QPSK channels. This indicates that the inter-channel nonlinearities from the PDM channels are different from those from the SP channels in the dispersion-managed system. When there is no DCF in the system, the performance difference between the system with the surrounding SP channels and PDM channels becomes much smaller. Figure 2 also shows that when the surrounding channels are the SP signals, at 1-dB OSNR penalty, the dispersion-managed system can tolerate about 2 dB more launch power than that without dispersion management, whereas when the surrounding channels are the PDM signals, the tolerable power for the dispersion-managed system is about 1.5 dB less than that without dispersion management.

Figure 2 clearly shows that the PDM-QPSK channels cause more inter-channel nonlinearities than the SP-QPSK channels in the dispersion-managed system. In the simulations, the SOP of the SP-QPSK is set at S_1 in the Stokes space, and SOP of the PDM-QPSK signal changes among S_2, $-S_2$, S_3, and $-S_3$ depending on the data carried by the two polarizations[12,13]. With the same power, on average the PDM-QPSK and the SP-QPSK generate similar XPM on the reference

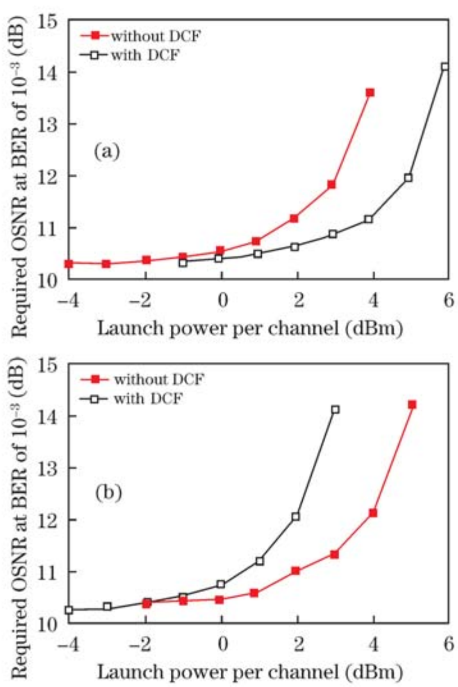

Fig. 2. Required OSNR at BER of 10^{-3} after 1000-km transmission versus launch power per channel for the 42.8-Gb/s NRZ-PDM-QPSK coherent system with and without inline DCF. (a) Surrounding six channels are 21.8-Gb/s NRZ-SP-QPSK signals; (b) surrounding six channels are 42.8-Gb/s NRZ-PDM-QPSK signals.

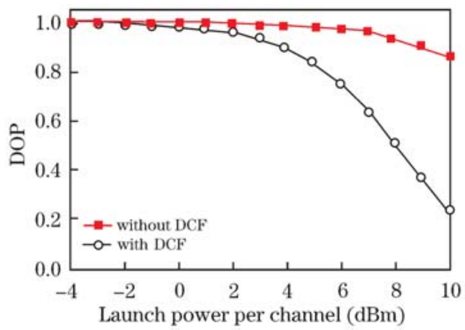

Fig. 3. DOP of 21.4-Gb/s NRZ-SP-QPSK reference channel after 1000-km transmission versus launch power per channel in the system with and without inline DCF. Surrounding channels are 42.8-Gb/s NRZ-PDM-QPSK signals.

PDM-QPSK channel. This indicates that the performance difference of the reference 42.8-Gb/s PDM-QPSK channel between the systems with the SP surrounding channels and that with PDM surrounding channels and the difference between the system with and without dispersion management are not caused by XPM, but by the XPolM induced nonlinear polarization scattering[12,13]. To estimate the level of the nonlinear polarization scattering in the system, the degree of polarization (DOP), which is usually used to measure the depolarization of a signal, of a 21.4-Gb/s SP-QPSK reference channel surrounded by six 42.8-Gb/s PDM-QPSK channels with 50-GHz channel spacing is calculated, as shown in Fig. 3. For the NRZ-PDM-QPSK system with inline DCF, DOP decreases rapidly with the launch power, indicating that the nonlinear polarization scattering significantly depolarizes the signal at each polarization of the PDM signal and induces large crosstalk between the two polarizations. For the system without inline DCF, the nonlinear polarization scattering is small and the system penalties mainly come from inter-channel XPM and intra-channel nonlinearities.

It is well known that lumped dispersion compensation at the transmitter or receiver is suboptimal for nonlinear transmission in a SP WDM system compared with dispersion management, which distributes dispersion compensating modules (DCMs) along a transmission link, with dispersion pre-compensation and post-compensation at the transmitter and the receiver. Dispersion management is developed based on SP signals with direct detection. It can effectively reduce intra-channel and inter-channel nonlinear impairments in such systems. Figures 2 and 3 clearly show that dispersion management can still reduce the intra-channel nonlinear effects and inter-channel XPM in coherent systems, but it generates larger nonlinear polarization scattering in polarization multiplexed WDM transmission. This is the main reason that makes dispersion management less effective in polarization multiplexed WDM transmission systems[12,13].

The transmission performances of a 112-Gb/s NRZ-PDM-QPSK reference channel surrounded by six 56-Gb/s NRZ-SP-QPSK channels and six 112-Gb/s NRZ-PDM-QPSK channels are given in Fig. 4. Because of a higher symbol rate, compared with the 42.8-Gb/s PDM-QPSK system, the inter-channel nonlinearities of the 112-Gb/s PDM-QPSK system are smaller as 112-Gb/s PDM-QPSK signals are dispersed faster than 42.8-Gb/s PDM-QPSK signals due to CD. Therefore, for 112-Gb/s NRZ-PDM-QPSK signals, the difference between the transmission system with inline DCF and that without inline DCF is smaller. Similar to the 42.8-Gb/s system, when the surrounding channels are 56-Gb/s NRZ-SP-QPSK channels, dispersion management increases the nonlinearity tolerance. The system with inline DCF can tolerate about 1-dB more launch power than that without inline DCF. But XPolM induced nonlinear polarization scattering from the neighboring 112-Gb/s NRZ-PDM-QPSK channels eliminates the benefits of dispersion management and reduces the nonlinearity tolerance for the dispersion-managed system. As shown in Fig. 4, at 1-dB OSNR penalty, if the neighboring channels are 112-Gb/s NRZ-PDM-QPSK signals, the allowed launch power for the system with inline DCF is about 1 dB less than that for the system without inline DCF.

Figure 5 depicts the nonlinear polarization scattering induced depolarization in the 112-Gb/s PDM-QPSK system with and without inline DCF, which is quantified by the DOP of a 56-Gb/s NRZ-SP-QPSK reference channel surrounded by six 112-Gb/s NRZ-PDM-QPSK channels with 50-GHz channel spacing in the transmission system. As expected, the nonlinear polarization scattering in the system without inline DCF is smaller than that with inline DCF. Comparison with Fig. 3 shows that the depolarization caused by the nonlinear polarization scattering in the 112-Gb/s PDM-QPSK system is smaller than that in the 42.8-Gb/s system, especially for the system with inline DCF. As explained above, the increased symbol rate reduces the inter-channel nonlinearities, including nonlinear polarization scattering.

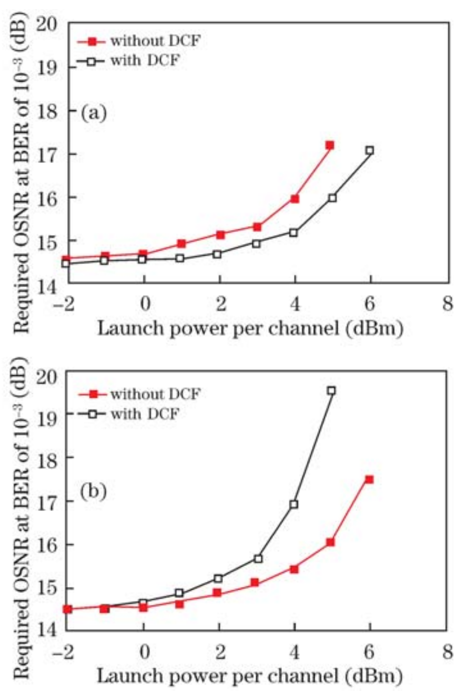

Fig. 4. Required OSNR at BER of 10^{-3} after 1000-km transmission versus launch power per channel for the 112-Gb/s NRZ-PDM-QPSK coherent system with and without inline DCF. (a) Surrounding six channels are 56-Gb/s NRZ-SP-QPSK signals; (b) surrounding six channels are 112-Gb/s NRZ-PDM-QPSK signals.

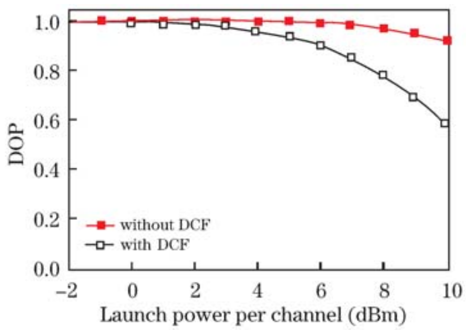

Fig. 5. DOP of the 56-Gb/s SP-QPSK reference channel after 1000-km transmission versus launch power per channel in the system with and without inline DCF. Surrounding channels are 112-Gb/s NRZ-PDM-QPSK signals.

As shown above, nonlinear polarization scattering is the dominant nonlinear effect in dispersion-managed PDM coherent optical transmission systems. Therefore, reducing nonlinear polarization scattering could significantly increase the system performance and transmission distance. The above results also indicate that nonlinear polarization scattering is affected by the data dependent SOP of a PDM signal and the walk-off between channels. Therefore techniques that can reduce the data dependent SOP of a signal and increase the walk-off between channels can be used to mitigate nonlinear polarization scattering in PDM transmission systems. Here we will discuss three nonlinear polarization scattering mitigation techniques for dispersion-managed PDM coherent transmission systems, including ILRZ-PDM modulation formats, PGD inline dispersion compensators, and adding some PMD in the transmission links.

For a NRZ-PDM-QPSK signal, the SOPs at different symbols change among four points on the Poincaré sphere, S_2, $-S_2$, S_3, and $-S_3$, depending on the data carried by the two polarizations[12,13]. In a dispersion-managed system with inline DCF, the pulses suffer minimally from CD accumulation, and the SOPs of a PDM-QPSK signal remain closely fixed to these four points after each span. In addition, there is small walk-off between channels due to low RDPS. The few data dependent SOPs and small walk-off between channels increase nonlinear polarization scattering in a dispersion-managed system. One technique to suppress nonlinear polarization scattering is to use the ILRZ-PDM modulation format, which can reduce or eliminate the dependence of SOP on the data carried by the two polarizations. This modulation format uses RZ pulses and time interleaves the two polarizations by half a symbol period. The waveform and SOP diagram of ILRZ-PDM-QPSK are depicted in Fig. 6. We can see that at the center of each symbol, the SOP is either at S_1 or $-S_1$ on the Poincaré sphere, and it does not depend on data carried by the two polarizations. In addition, an ILRZ-PDM signal has other two features that help reduce nonlinear polarization scattering in a dispersion-managed system: 1) the SOP at each symbol alternates between S_1 and $-S_1$ on the Poincaré sphere, and the SOPs at S_1 and $-S_1$ cause opposite nonlinear polarization rotation according to Eq. (5); 2) the time interleaving reduces the signal peak power, leading to reduced XPolM between channels. An ILRZ-PDM signal can be generated by adding a pulse carver before the data modulators and setting proper time delay between the two polarizations before the PBC in the transmitter.

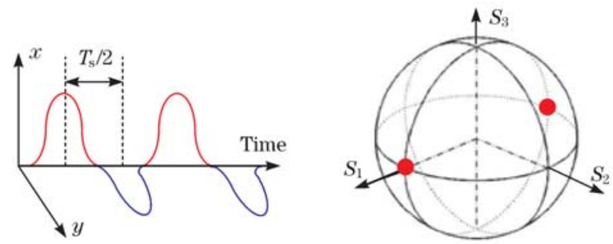

Fig. 6. Waveform and SOP diagram of ILRZ-PDM-QPSK. T_s: symbol period.

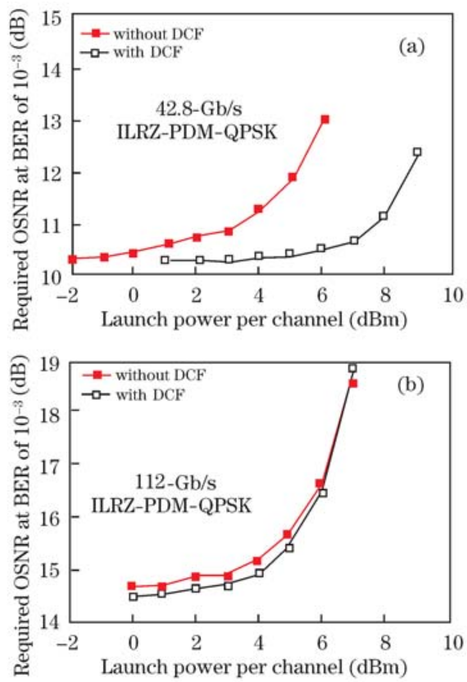

Fig. 7. Required OSNR at BER of 10^{-3} after 1000-km transmission versus launch power per channel for the 42.8-Gb/s and 112-Gb/s ILRZ-PDM-QPSK WDM coherent systems with and without inline DCF.

The transmission performances of 42.8-Gb/s and 112-Gb/s ILRZ-PDM-QPSK WDM systems are given in Fig. 7, which shows the required OSNR at a BER of 10^{-3} after 1000-km transmission for the systems with and without inline DCF. The RZ pulses used here have 50% duty cycle. For the 42.8-Gb/s system with inline DCF, using ILRZ-PDM-QPSK can increase the allowed launch power by 7 dB at 1-dB OSNR penalty compared with NRZ-PDM-QPSK (Fig. 2), from about 1-dBm per channel launch power to about 8 dBm. For the system without inline DCF, the performances of ILRZ-PDM-QPSK and NRZ-PDM-QPSK are similar. With ILRZ-PDM-QPSK, the 42.8-Gb/s system with inline DCF performs better than that without DCF, with the tolerable launch power about 4 dB higher. For the 112-Gb/s system, the improvement obtained by using ILRZ-PDM-QPSK is smaller than that for the 42.8-Gb/s system due to the symbol rate increase, but it can still increase the launch power tolerance by about 3 dB compared with NRZ-PDM-QPSK (Fig. 4). Figure 7 (b) shows that with ILRZ-PDM-QPSK, the 112-Gb/s system with inline DCF can achieve similar performance to the system without DCF. The less improvement from using ILRZ-PDM-QPSK in the 112-Gb/s system compared with the 42.8-Gb/s system is due to the fact that the inter-channel nonlinearity including XPolM in the 112-Gb/s system is smaller than that in the 42.8-Gb/s system. Figure 7 also shows that for both 42.8-Gb/s and 112-Gb/s systems without inline DCF, there is a slight improvement on nonlinearity tolerance if ILRZ-PDM-QPSK is used.

The level of the nonlinear polarization scattering of the systems using ILRZ-PDM-QPSK is given in Fig. 8. It clearly shows that using ILRZ-PDM-QPSK significantly reduces nonlinear polarization scattering in both the 42.8-Gb/s and 112-Gb/s systems with inline DCF. Compared with NRZ-PDM-QPSK, at 6-dBm launch power, the ILRZ-PDM-QPSK modulation format increases the nonlinear polarization scattering induced DOP reduction of the reference channel from about 0.75 to 0.96 and from 0.90 to 0.95 for the dispersion-managed 42.8-Gb/s and 112-Gb/s systems, respectively. Compared with Figs. 3 and 5, we can see that there is a slight reduction of nonlinear polarization scattering even for the system without inline DCF when ILRZ-PDM-QPSK is used.

A technique to increase the walk-off between channels without affecting the signal variations within channels is to use PGD devices as inline dispersion compensators[14,23]. Figure 9 plots the relation of group delay with the frequency of a PGD dispersion compensator with −1700-ps/nm CD and 50-GHz period. As shown in the figure, the group delay of a PGD dispersion compensator is periodic. If the period of the group delay is the same as the channel spacing in a WDM system, the mean group delay for each channel is the same, but within each channel, the group delay of a PGD dispersion compensator is the same as that of a

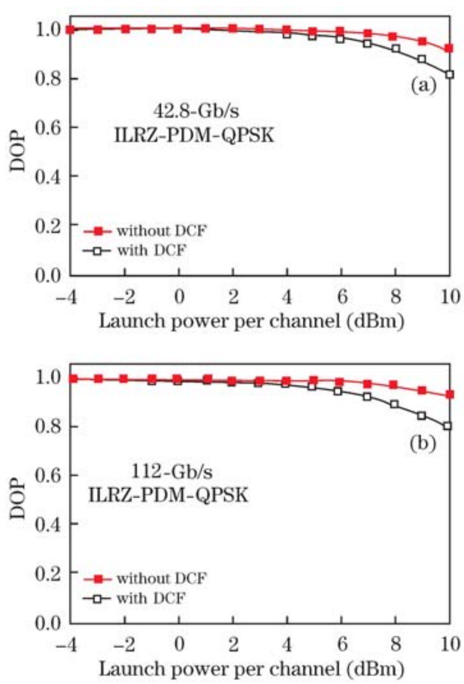

Fig. 8. DOP of 21.4-Gb/s and 56-Gb/s SP-QPSK reference channels after 1000-km transmission versus launch power per channel in the 42.8-Gb/s and 112-Gb/s ILRZ-PDM-QPSK WDM systems with and without inline DCF.

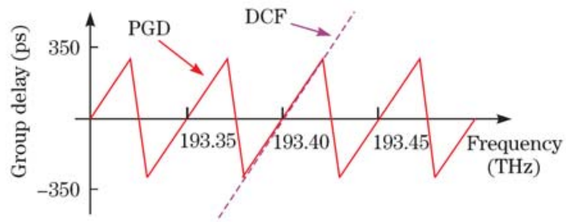

Fig. 9. Group delay of an ideal PGD dispersion compensator designed for a channel spacing of 50 GHz (0.4 nm) and with about −1700-ps/nm CD within a channel. The dashed line is the group delay for a DCF.

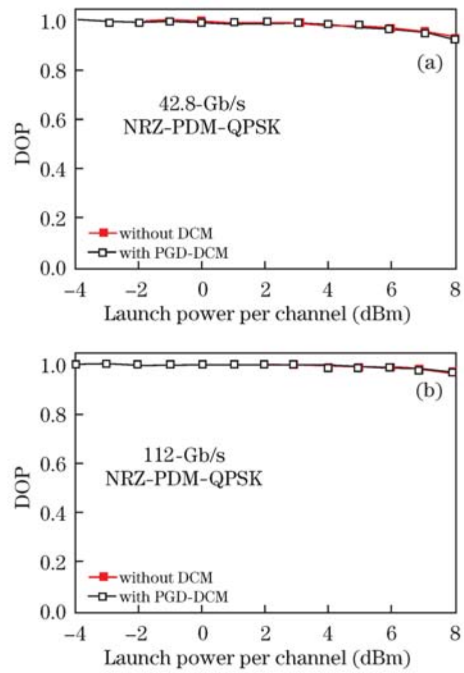

Fig. 10. DOP of 21.4-Gb/s and 56-Gb/s SP-QPSK reference channels after 1000-km transmission versus launch power per channel in the 42.8-Gb/s and 112-Gb/s NRZ-PDM-QPSK WDM systems with PGD-DCM and without DCM.

DCF and can compensate the CD in each channel. This means that within a channel, a PGD CD compensator performs CD compensation in a transmission link as DCF, but induces little walk-off between channels. Unlike in a dispersion-managed system using DCF, data patterns carried by different WDM channels in a dispersion-managed system using PGD-DCM pass through each other in the transmission fiber and are not brought back to overlap again at the PGD-DCM. Therefore, the pattern walk-off in a dispersion-managed system with PGD-DCM is the same as that in the system without any inline DCM.

The performances of the 42.8-Gb/s and 112-Gb/s PDM-QPSK WDM dispersion-managed systems using PGD-DCM are shown in Figs. 10 and 11[14]. The same system parameters as those in Fig. 1 are used except that the inline DCF in the system is replaced with PGD-DCM. In Figs. 10 and 11, we use NRZ-PDM-QPSK, and better performance can be achieved if ILRZ-PDM-QPSK is used in the system with PGD-DCM. Figure 10 plots the nonlinear polarization scattering induced depolarization in the 42.8-Gb/s and 112-Gb/s NRZ-PDM-

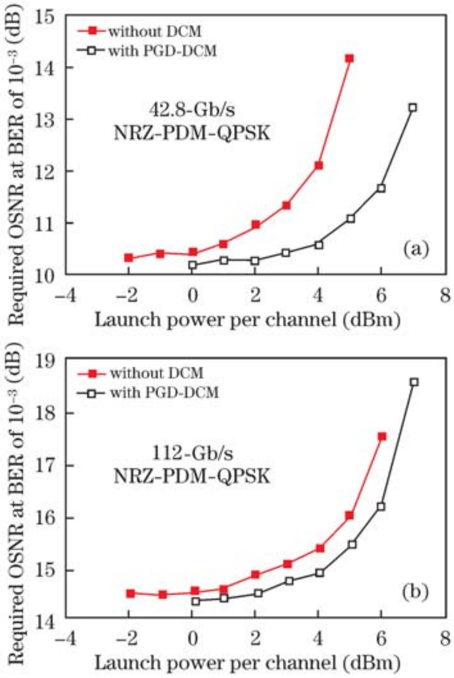

Fig. 11. Required OSNR at BER of 10^{-3} after 1000-km transmission versus launch power per channel for the 42.8-Gb/s and 112-Gb/s NRZ-PDM-QPSK WDM coherent systems with PGD-DCM and without DCM.

QPSK dispersion-managed system with PGD-DCM and in the system without dispersion management. It shows that the depolarization caused by nonlinear polarization scattering in the dispersion-managed transmission using PGD-DCM is similar to that in the system without any dispersion management for both 42.8-Gb/s and 112-Gb/s systems. Figure 11 compares the required OSNRs at BER of 10^{-3} after 1000-km transmission versus launch power per channel between the dispersion-managed system with PGD-DCM and that without dispersion management. It shows that for both the 42.8-Gb/s and 112-Gb/s NRZ-PDM-QPSK WDM transmission, the dispersion-managed system using PGD-DCM has higher nonlinearity tolerance than the system without any DCM.

PMD effects in general are detrimental to fiber-optic transmission systems and have long been considered as one of the obstacles that limit the reach and bit rates of optical communication systems using direct detection[24]. PMD causes the depolarization of signals carried by each polarization and it also introduces decorrelation between two polarizations for PDM signals during transmission. These effects are helpful to reduce inter-channel nonlinearities including XPolM in PDM transmission systems. As the linear PMD effects can be easily compensated by digital signal processing in coherent receivers, adding some PMD in transmission links should be able to mitigate inter-channel nonlinear effects in PDM coherent transmission systems.

This idea was demonstrated by Serena *et al*. using numerical simulations[25]. They showed that, for dispersion-managed systems, adding some PMD improves 112-Gb/s PDM-QPSK nonlinear transmission performance in both the single channel and the WDM cases. With 30-ps average DGD, the average Q factor in the single 112-Gb/s PDM-QPSK system can be improved by 0.4 dB, and in the WDM 112-Gb/s PDM-QPSK system the Q factor improvement is about 1 dB. The reason of the nonlinear tolerance improvement in the presence of PMD is that both intra-channel interactions between the X and Y components and inter-channel XPolM between channels are reduced by the walk-off and depolarization introduced by PMD. For non-dispersion-managed systems, the impact of DGD is small as the large walk-off and rapid variations of SOP mask the PMD effects.

In conclusion, using numerical simulations, we study nonlinear polarization effects in PDM-QPSK coherent transmission systems, and show that nonlinear polarization scattering is the main reason that makes dispersion management less effective in a polarization multiplexed transmission system. In a dispersion-managed NRZ-PDM-QPSK transmission system using DCF as inline CD compensators, no benefit in nonlinear tolerance can be obtained by dispersion management. Three techniques to suppress nonlinear polarization scattering in a dispersion-managed system are discussed, including the use of the ILRZ-PDM modulation format, the use of PGD dispersion compensators as inline DCMs, and the judicious addition of some PMD in the transmission links. We show that if nonlinear polarization scattering can be well mitigated, a polarization multiplexed optical coherent transmission system with dispersion management could perform better than that without DCMs.

References

1. A. R. Chraplyvy, A. H. Gnauck, R. W. Tkach, J. L. Zyskind, J. W. Sulhoff, A. J. Lucero, Y. Sun, R. M. Jopson, F. Forghieri, R. M. Derosier, C. Wolf, and A. R. McCormick, IEEE Photon. Technol. Lett. **8,** 1264 (1996).
2. A. H. Gnauck, G. Charlet, P. Tran, P. J. Winzer, C. R. Doerr, J. C. Centanni, E. C. Burrows, T. Kawanishi, T. Sakamoto, and K. Higuma, J. Lightwave Technol. **26,** 79 (2008).
3. S. J. Savory, A. D. Stewart, S. Wood, G. Gavioli, M. G. Taylor, R. I. Killey, and P. Bayvel, in *Proceedings of European Conference on Optical Communications 2006* Th2.5.5 (2006).
4. C. Laperle, B. Villeneuve, Z. Zhang, D. McGhan, H. Sun, and M. O'Sullivan, in *Proceedings of Optical Fiber Communication Conference 2007* PDP16 (2007).
5. M. Salsi, H. Mardoyan, P. Tran, C. Koebele, E. Dutisseuil, G. Charlet, and S. Bigo, in *Proceedings of European Conference on Optical Communications 2009* PD2.5 (2009).
6. Z. Wang and C. Xie, Opt. Express **17,** 3183 (2009).
7. H. Wernz, S. Herbst, S. Bayer, H. Griesser, E. Martins, C. Fürst, B. Koch, V. Mirvoda, R. Noé, A. Ehrhardt, L. Schürer, S. Vorbeck, M. Schneiders, D. Breuer, and R.-P. Braun, in *Proceedings of European Conference on Optical Communications 2009* 3.4.3 (2009).
8. C. Xie, S. Chandrasekhar, and X. Liu, in *Proceedings of European Conference on Optical Communications 2007* 10.4.3 (2007).
9. L. F. Mollenauer, J. P. Gordon, and F. Heismann, Opt. Lett. **20,** 2060 (1995).
10. B. C. Collings and L. Boivin, IEEE Photon. Technol. Lett. **12,** 1582 (2000).

11. C. Xie, Z. Wang, S. Chandrasekhar, and X. Liu, in *Proceedings of Optical Fiber Communication Conference 2009* OTuD6 (2009).
12. C. Xie, IEEE Photon. Technol. Lett. **21,** 274 (2009).
13. C. Xie, Opt. Express **17,** 4815 (2009).
14. C. Xie, in *Proceedings of European Conference on Optical Communications 2009* P4.08 (2009).
15. C. Xie, in *Proceedings of Optical Fiber Communication Conference 2009* OWE1 (2009).
16. P. K. A. Wai and C. R. Menyuk, J. Lightwave Technol. **14,** 148 (1996).
17. D. Marcuse, C. R. Menyuk, and P. K. A. Wai, J. Lightwave Technol. **15,** 1753 (1997).
18. J. P. Gordon and H. Kogelnik, PNAS **97,** 4541 (2000).
19. D.-S. Ly-Gagnon, S. Tsukamoto, K. Katoh, and K. Kikuchi, J. Lightwave Technol. **24,** 12 (2006).
20. S. J. Savory, G. Gavioli, R. I. Killey, and P. Bayvel, Opt. Express **15,** 2120 (2007).
21. D. N. Godard, IEEE Trans. Commun. **28,** 1867 (1980).
22. L. K. Wickham, R.-J. Essiambre, A. H. Gnauck, P. J. Winzer, and A. R. Chraplyvy, IEEE Photon. Technol. Lett. **16,** 1591 (2004).
23. X. Wei, X. Liu, C. Xie, and L. F. Mollenauer, Opt. Lett. **28,** 983 (2003).
24. H. Sunnerud, M. Karlsson, C. Xie, and P. A. Andrekson, J. Lightwave Technol. **20,** 2204 (2002).
25. P. Serena, H. Rossi, and A. Bononi, in *Proceedings of European Conference on Optical Communications 2009* 10.4.3 (2009).