Postnonlinearity compensation with data-driven phase modulators in phase-shift keying transmission

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A novel scheme for postnonlinearity compensation is proposed to reduce the phase jitter in phase-shift keying transmission. A phase modulator is used to modulate the phase of the data pulses in front of the receiver. The magnitude of the phase modulation is proportional to the detected pulse intensity, and the sign is opposite to that of the nonlinear phase shift caused by self-phase modulation. Thus, the nonlinear phase noise induced by amplitude fluctuation and self-phase modulation is partially compensated for. We show by numerical simulations that a differential phase-shift keying dispersion-managed soliton system at 10 Gbits/s with such postnonlinearity compensation can provide greater than 3 dB of improvement in ultralong-haul dense wavelength-division multiplexing transmissions.

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Interchannel cross-phase modulation (XPM), i.e., soliton collision, is the leading nonlinear transmission penalty in a dense wavelength-division multiplexing (DWDM) on-and-off keying dispersion-managed soliton (DMS) system. It is well known that soliton collisions result in timing jitters of data pulses and therefore degrade system performance.[1] It has been shown that differential phase-shift keying (DPSK) is particularly suited for high-spectral-efficiency systems and (or) for systems employing polarization-division multiplexing and multilevel coding.[2] The ability of DPSK to mostly eliminate XPM penalties and its significant optical signal-to-noise ratio advantage when balanced receivers are employed[3] recently generated impressive transmission results.[4] Furthermore, the implementation of DPSK is straightforward at 10 and 40 Gbits/s.[4–6] However, nonlinear phase noise caused by amplitude fluctuations and self-phase modulation (SPM) poses new limitations on any phase-shift-keying (PSK) systems. Since SPM and XPM depend on the intensity, amplitude fluctuations caused by amplified spontaneous emission (ASE) or nonlinear interactions will translate into phase noise through both SPM and XPM. It is known that a single-channel PSK system is fundamentally limited by ASE- and SPM-induced nonlinear phase noise.[7]

Nonlinear phase noise can be mostly eliminated through a nonlinearity management scheme. Methods of nonlinearity management, either distributed or lumped, have been proposed.[8–10] However, transmission fibers with negative nonlinear refractive indices (n_2) simply do not exist. There are materials with intrinsic negative n_2 but typically with associated two-photon absorption loss in the same wavelength region. Furthermore, the practicalities of using these materials in optical fiber transmissions are yet to be explored. The use of nonlinear crystals is hampered by bandwidth limitations, peak power requirements, and polarization sensitivities, which cannot be solved by polarization-diversity schemes because of the intensity dependence of nonlinear effects. In this Letter we propose to use a phase modulator to generate the effects that are typically achievable only with negative n_2 materials. A phase modulator is used to modulate the phase of the data pulses in front of the receiver. The magnitude of the phase modulation is directly proportional to the detected pulse intensity, and the sign is opposite the nonlinear phase shift caused by SPM. This scheme is parallel to dispersion management (compensation) in most DWDM systems today. In practice, such a nonlinearity management scheme will be costly if used on a per-scan basis. Thus, we propose to use it only in front of the receiver; i.e., we propose postnonlinearity compensation (PNC), again parallel to postdispersion compensation. As an example, we show by numerical simulations that DPSK DMS at 10 Gbits/s with such a PNC scheme can significantly enhance the system's reach.

We now describe the model of our numerical simulations. The system has as many as ninety 100-km spans, with each span consisting of 50 km of D_+ fiber [$D_+ = 12.6$ (ps/nm)/km] and 50 km of D_- fiber [$D_- = -12.4$ (ps/nm)/km]. The designed path-averaged dispersion ($\overline{D}$) of 0.1 (ps/km)/nm is achieved. The precompensation and postcompensation are simply half-spans (i.e., 25 km) of D_- fibers. A uniform distributed amplification system is assumed. ASE noise is added after each 100-km span, with a realistic noise figure such that at 100 km an optical signal-to-noise ratio (at 0.1-nm bandwidth) of ~34 dB is achieved with a path-averaged power of −8.7 dBm. The soliton pulse trains have an ~33% duty cycle at 10 Gbits/s. We use 2^8 pseudorandom bit sequences in the simulation. We use an energy-enhancement factor of ~2.5 [i.e., 13.5 fJ/pulse with $\gamma = (1.8/\text{km})/\text{W}$] for such a DMS system.[11] Seven WDM channels are simulated at channel separations of 50 GHz. It is known that a handful of WDM channels are more than adequate for simulating interchannel interactions in a dispersion-managed system. A 30-GHz FWHM fourth-order Gaussian filter is used to demultiplex the channels. A 7.5-GHz second-order Gaussian electrical filter is used postdetection. Details of the PNC scheme are shown in Fig. 1. A p-i-n diode with a FWHM electrical bandwidth of 10 GHz is used to detect the incoming data stream. The output of the p-i-n diode is used to drive a phase modulator with

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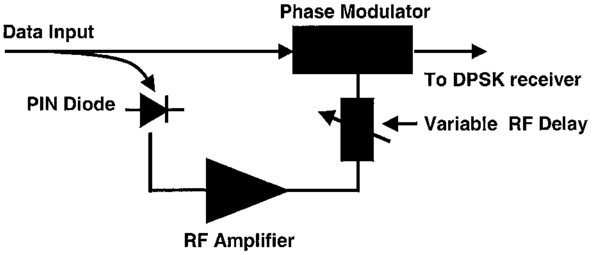

Fig. 1. Schematic drawing of a PSK system with PNC.

an electrical bandwidth of 10 GHz. A variable rf delay line is required so that the optical and electrical signals of the same data pulse arrive simultaneously at the phase modulator. In practice, polarization-diversity schemes may be needed if the phase modulators are polarization sensitive. (The p-i-n diode detects the optical power before the polarization-diversity scheme so that the drive voltage to the modulators is independent of the input polarization states.)

The bit-error rate (BER) analysis is slightly complicated in a DPSK system. An error occurs whenever the sign of a bit has flipped, which can be caused by both amplitude noise and phase noise. In the linear region (low per-channel power), amplitude noise dominates, whereas in the nonlinear region (high per-channel power), which is the case for the DMS transmission discussed here, phase noise completely determines the BER.[7] Hence, we use the differential phase Q [defined as $Q_p = \pi/(\Delta\varphi_0 + \Delta\varphi_\pi)$, where $\Delta\varphi_0$ and $\Delta\varphi_\pi$ are the standard deviations of the differential phase at the zero and the π rails] to assess the system performance in this Letter. Compared with an on-and-off keying system with ASE noise, where Q of 6 is needed for BER $< 10^{-9}$, for DPSK a differential phase Q_p of 6 (or 15.6 dB) is required for BER $< 10^{-9}$.

The performance of a DPSK system can be examined graphically in the complex plane of the electric-field [(E-field) i.e., the phasor diagram]. Each data pulse is represented by a single point (or a vector connecting the origin to that point) in the phasor diagram, in which the radial component represents the E-field amplitude and the angular component is the E-field phase. In a completely linear system, noises on the E-field amplitude and phase are of exactly the same magnitude. In a nonlinear system, however, amplitude noise can be transferred to phase noise through SPM. Thus, the distribution of the data points after the transmission can become highly distorted; i.e., phase noise and amplitude noise can have different magnitudes. Because a DMS requires that one use SPM to compensate for linear dispersion, the amount of nonlinear phase shift through SPM can be significantly higher than the optimum value of ~1 rad.[7] Thus, the nonlinear phase-noise limitation is most pronounced when the DMS transmission format is used. Figure 2(a) shows the phasor diagram of the E-field at a transmission distances of 6000 km with our model system. Note the asymmetry in the E-field distribution. The system performance is clearly dominated by nonlinear phase noise. The transmitted eye diagram is shown in Fig. 3(a). Quantitatively, we show Q_p as a function of transmission distance in Fig. 4. The requirement of $Q_p > 6$ limits the error-free transmission distance of DMS–DPSK to ~4000 km. We note that the simulation results presented above were obtained with a realistic ASE noise level for field deployment (under which current "hero" experimental on-and-off keying–DMS transmissions are usually limited to ~4000 km without forward error control). The error-free transmission distance for DPSK will be much greater (>7500 km even without our proposed compensation scheme) if an ideal noise level is assumed.

Figure 2(b) shows the phasor diagram of the E-field of the same transmission system at a transmission distance of 6000 km after PNC. The transmitted eye diagram is shown in Fig. 3(b). The fluctuations in the phase are dramatically reduced, and the eye opening is significantly improved. Note that phase modulation does not change the distribution of the amplitude noise. Figure 4 also shows Q_p as a function of transmission distance after PNC. An error-free reach of ~6000 km is now achieved. We have repeated our simulations many times (>3000 bits) with different bit sequences and ASE noise. The results were similar. An improvement of >3 dB in Q factor is obtained for all transmission distances greater than 3500 km.

An important distinction between our proposed nonlinearity management method and other methods using true optical negative n_2 is in their response times. Optical negative n_2 generally has an ultrafast response time (<1 ps), whereas our method uses much slower optoelectronic components (~100 ps). However, we show in Fig. 5 that optical negative n_2 with an ultrafast response is not necessary in PNC. The effective electrical bandwidth of our phase-modulation scheme, i.e., the electrical bandwidth of the p-i-n diode, the rf amplifier, and the phase modulator combined, needs to be greater than 4 GHz (or 40% of the line rate) for one to obtain the full benefit of the PNC. Therefore, the bandwidth of the line-rate components is more than sufficient for PNC. In addition, the optimum value of the PNC is approximately half the total accumulated nonlinear phase shift,

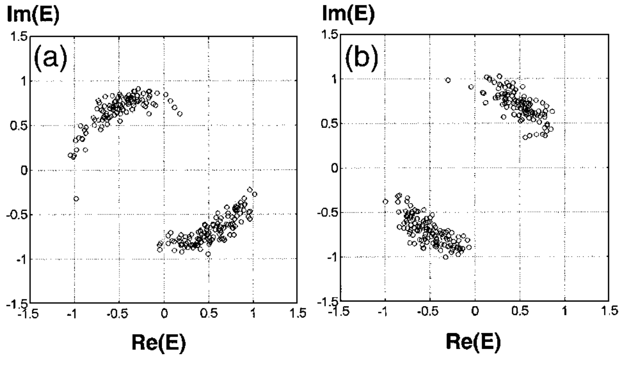

Fig. 2. Phasor diagrams of the E-field at a transmission distance of 6000 km (a) without and (b) with PNC. Re(E), real part of the E-field; Im(E), imaginary part of the E-field.

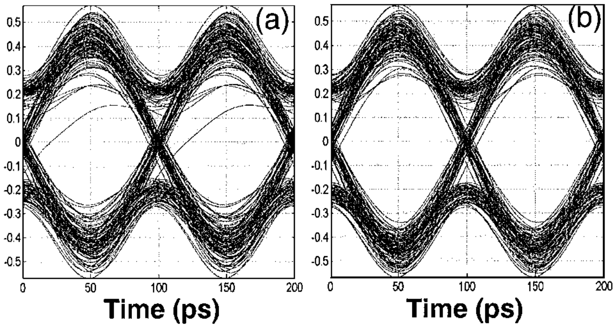

Fig. 3. Transmitted electrical eye diagrams at a distance of 6000 km (a) without and (b) with PNC.

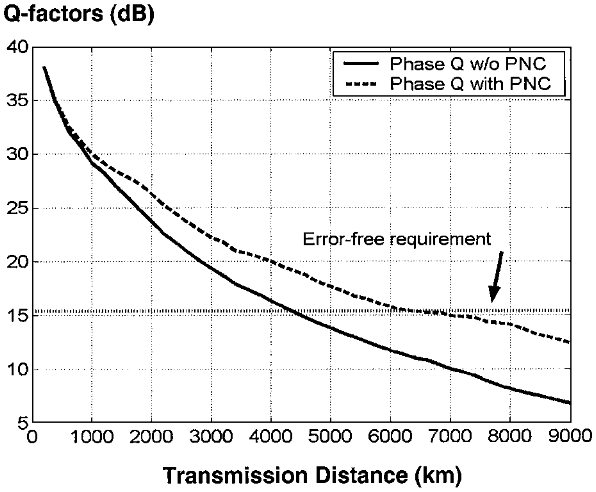

Fig. 4. Plots of Q factors versus transmission distance. The error-free Q value of 15.6 dB is also indicated.

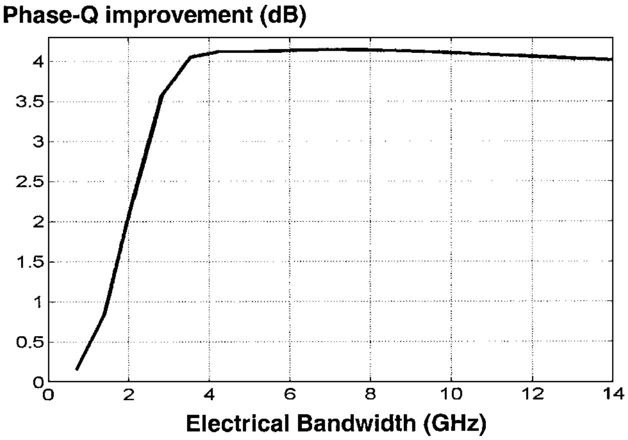

Fig. 5. Improvement of phase Q at 6000 km as a function of the effective electrical bandwidth (i.e., the electrical bandwidth of the p-i-n diode, the rf amplifier, and the phase modulator combined) for the phase modulation.

which is typically less than π in an ultralong-haul DWDM system. Thus, our method can be readily implemented in 40-Gbit/s PSK systems and beyond.

We note that PNC cannot remove all the nonlinear phase jitter in the E-field. Our PNC method does not take into account the nonlinear phase noise caused by ASE and XPM, which may become noticeable in a DWDM system with high spectral efficiencies. More intrinsically, our PNC method assumes that the total nonlinear phase shift is proportional to the intensity of the data pulse at the end of the transmission line. Although such an assumption is statistically correct, the total accumulated nonlinear phase shift is determined by the path-averaged intensity, not just the intensity at the end of the transmission. This fact is also reflected in the amount of phase modulation needed for the optimum performance. Intuitively, the optimum value for PNC is simply the average of the worst and best cases in the correlations between the pulse intensity at the end of the transmission and its phase.

In summary, a novel method of PNC has been proposed to reduce the phase jitter in PSK transmission. A phase modulator is used to modulate the phase of the data pulses in front of the receiver. The magnitude of the phase modulation is directly proportional to the detected pulse intensity, and the sign is opposite the nonlinear phase shift caused by SPM. Thus, effects of negative n_2 are generated, and the nonlinear phase noise induced by amplitude fluctuation and SPM is partially compensated for. We show by numerical simulations that DPSK DMS at 10 Gbits/s with such a PNC can provide greater than 3 dB of improvement in ultralong-haul DWDM transmissions.

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