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A long-haul wavelength division multiplexed system using standard single-mode fiber in presence of self-phase modulation

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Abstract

Performance of a long-haul wavelength division multiplexed (WDM) communication system has been evaluated in presence of nonlinear effects using standard single-mode fiber. Different compensation configurations, namely, post-, pre- and bi-end compensation, have been investigated to mitigate the fiber nonlinear effects. Eye-opening degradation due to mutual interplay between self-phase modulation (SPM) and group velocity dispersion for the compensating techniques has been estimated with respect to the transmission length and the residual dispersion in case of WDM system. Maximum threshold power levels at the bit error rate of 10^{-9} limited by the SPM effect have been determined. From a comparison among the compensating techniques, bi-end compensation configuration has been found to be the most suitable technique for any fiber length in case of a WDM communication system.

Keywords: Dispersion compensation; Group velocity dispersion; Self-phase modulation; Single-mode fiber

1. Introduction

Periodical insertion of in-line erbium-doped fiber amplifiers (EDFAs) provides the opportunity to transmit optical pulses in a long fiber link irrespective of the loss. But for a transmission link using standard single-mode fiber (SMF), group velocity dispersion (GVD) causes the transmitted pulse to broaden and distort so much that it eventually limits the transmission distance. Nevertheless, a variety of dispersion-compensating techniques have been proposed and investigated for constructing long-distance transmission systems [1–5]. In the dispersion-compensating technique using dispersion-compensating fiber (DCF), the nonzero anomalous GVD of SMF is periodically compensated by the proper length of DCF placed at the input, output or both ends of the compensation interval and are termed as pre-end compensation configuration (PRCC), post-end CC (POCC) and bi-end CC (BECC), respectively. Then, in a DCF system, the bandwidth-length product of the transmission link is no longer limited by the GVD rather by the mutual interplay between the dispersion and the nonlinear effects of fiber. Among several fiber nonlinear effects, the most dominant effect in a standard SMF is the self-phase modulation (SPM), which is caused by the nonlinear dependence of the refractive index on pulse intensity [6]. Since high-speed data transmission systems require significantly large amount of received power for error-free detection, the performance of dispersion-compensated link is eventually limited by the interaction

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of SPM and the fiber dispersion. The interaction of SPM with fiber dispersion depends on the DCF position in a dispersion-compensated scheme as well.

Again, in a wavelength division multiplexed (WDM) system, it is difficult to compensate all the transmission channels completely for dispersion [7,8]. If perfect dispersion compensation is accomplished for a particular channel of the WDM system, other wavelength channels will encounter with different amount of cumulative dispersion proportional to their wavelength separations from the zero-average-dispersion wavelength channel. On the other hand, to suppress the four-wave mixing (FWM) effect, it is recommended that the GVD effect must not be completely compensated [9,10]. Mutual interplay between SPM and GVD is different in case of partial compensation than that of complete compensation. The degree of SPM effect even varies with the sign and amount of residual dispersion.

The effect of SPM in a dispersion-compensated fiber link has drawn research interest recently [11–13]. A single channel system has been studied with lumped dispersion compensation but without any EDFA in the line of transmission, which shows that the PRCC scheme is preferable to the POCC scheme in case of complete compensation [11]. Investigation of a terrestrial 5×100 km WDM system has been carried out in Ref. [12] where the dispersion and fiber loss are compensated periodically and the POCC scheme is turned out to be the suitable dispersion-compensating technique for practical implementation as compared to the PRCC scheme. However, the amplified spontaneous emission (ASE) noise due to EDFA is not considered in the study. Also to the best of the authors' knowledge, the BECC scheme has not yet been investigated and compared with the POCC and PRCC schemes in case of long-haul WDM system. Therefore, the objective of the paper is to develop a numerical study on the transmission performance of all the compensation schemes, namely, POCC, PRCC and BECC. The receiver performance is evaluated considering the eye-opening degradation due to the mutual interplay of GVD and SPM, where all the noise sources including ASE noise of in-line EDFAs are taken into account. Finally, a performance comparison is made among the three compensation schemes in order to find the most efficient scheme for practical WDM system.

2. Theoretical model

At the modest input power level, the SMF behaves as a dispersive and linear medium, where the transmitted spectrum does not change during propagation. Only the pulse gets weaker due to attenuation and broadened in the time domain by the second- and third-order dispersion. In a dispersion-compensated link consisting of a standard SMF and a DCF, the input pulses first broaden due to propagation through the SMF and then subsequently recompress to their original shape due to propagation through the DCF, which has the dispersion coefficient parameter of opposite sign to that of SMF. As the input power is increased, the fiber nonlinear effects, especially SPM, affect significantly the pulse dynamics in the transmission link. During the propagation of a pulse through the fiber, the GVD changes the frequency across the pulse referred to as frequency chirp. The chirp $\delta\omega$ depends on the sign of the dispersion parameter. If the dispersion coefficient parameter of the fiber is negative, the frequency increases across the pulse from the leading to the trailing edge that is referred to as the positive frequency chirp. On the other hand, the frequency chirp is negative, i.e., the frequency decreases across the pulse from the leading to the trailing edge if the dispersion coefficient parameter is positive. The frequency chirp is also induced by the SPM effect and increases in magnitude with the propagated distance. Frequency chirping is positive due to the SPM effect irrespective of the sign of the dispersion coefficient parameter. Therefore, the SPM effect leads to an enhanced rate of pulse broadening in the fiber with negative dispersion coefficient parameter compared to that expected from the GVD alone. However, the broadening rate decreases during propagation in the fiber with positive dispersion coefficient parameter, as the two chirp contributions cancel each other.

The nonlinear Schrodinger equation (NLSE) can be modified to include higher-order dispersion, which has been found successful in accurately modeling the pulse propagation in SMF for many diverse applications [14,15]. The modified NLSE incorporating the effects of fiber loss, SPM and GVD is given by [6]

$$\mathrm{i}\frac{\partial A}{\partial z} = -\frac{\mathrm{i}}{2}\alpha A + \frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{\mathrm{i}}{6}\beta_3\frac{\partial^3 A}{\partial T^3} - \gamma|A|^2 A, \quad (1)$$

where A is the slowly varying amplitude of the pulse envelope, z is the longitudinal coordinate and T is the time measured in a frame of reference moving with the pulse at the group velocity v_g, $T = t - z/v_g$. The fiber nonlinearity affects the wave equation through the nonlinear parameter γ. In Eq. (1) the dispersion and dispersion slope parameters are represented by β_2 and β_3, respectively, and α is the loss coefficient. γ is related to the nonlinear-index coefficient n_2 by

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \quad (2)$$

where A_{eff} is the effective core area of the fiber.

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A normalized super-Gaussian pulse is assumed for the input signal which can expressed as

$$U(0,T) = \exp\left[-\frac{1}{2}\left(\frac{T}{T_0}\right)^{2m}\right] \tag{3}$$

with

$$T_b = 2[2\ \ln\ 2]^{1/2m} T_0, \tag{4}$$

where T_0 is the half-width at $1/e$-intensity point, T_b is the bit period and m represents the degree of the super-Gaussian pulse. In this simulation, m is assumed to have a value of 1.5. So the pulse envelope amplitude $A(z, T)$ in Eq. (1) is given by

$$A(z,T) = \sqrt{P_0}\ \exp(-\alpha z/2)U(z,T), \tag{5}$$

where P_0 is the peak power.

In this paper, only SPM is considered as the source of nonlinear effects. Actually, in practical SMF transmission, multi-wavelength nonlinear effects have a little impact on the overall system performance [16]. In particular, the FWM effect is substantially suppressed by large chromatic dispersion, and cross phase modulation (XPM) introduces only a little penalty in densely spaced systems [17]. The XPM effect does not have a great impact on the SMF-based systems because of the high walk-off; it simply reduces the power margins by some decibels. Other higher-order nonlinear effects such as Raman contribution to the nonlinear refractive index and the shock term have also been neglected, as these effects are significant only for very short pulses ($\leqslant$100 fs).

3. Results

A 10 Gb/s non-return-to-zero IM/DD system has been analyzed using the split-step Fourier transform method. Isolated chirp-free input pulses are simulated for the WDM communication systems shown in Fig. 1. The transmission links are composed of a number of spans each consisting of 100 km SMF and L km DCF. Each span is followed by an EDFA so that the fiber loss is compensated. The number of spans is varied to simulate the pulse propagation in long-haul transmission link. The DCF length L in each span is kept variable to vary the residual dispersion. Fiber dispersion, dispersion slope, attenuation, nonlinear coefficient and effective area are assumed to be 17 ps/nm/km, 0.07 ps/nm^2/km, 0.2 dB/km, 1.36 W^{-1} km^{-1}, 80 μm^2, respectively, for the SMF, and −100 ps/nm/km, 0.09 ps/nm^2/km, 0.6 dB/km, 5.4 W^{-1} km^{-1}, and 20 μm^2, respectively, for the DCF. Therefore, a 17 km long DCF is required to completely compensate for the dispersion of a 100 km long SMF. Any deviation of the DCF length from 17 km results in residual dispersion at the end of each span. Such residual dispersion is accumulated from one span to the other down the transmission link. Positive residual dispersion accumulates down the transmission fiber if the DCF length is less than 17 km and negative residual dispersion accumulates if the DCF length is greater than 17 km.

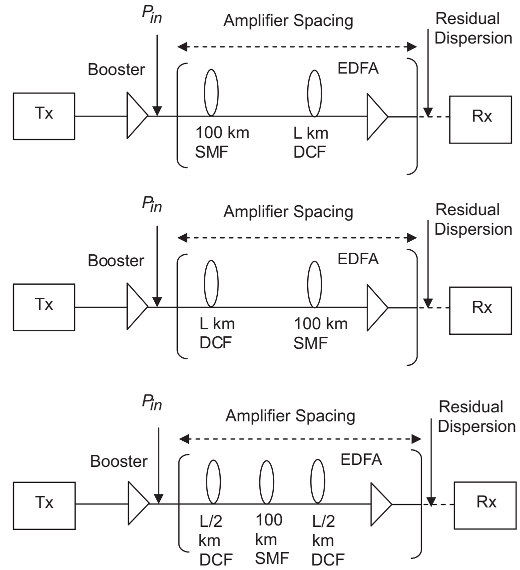

Fig. 1. Schematic diagram of (a) post- (b) pre- and (c) bi-end compensation configuration.

The in-line EDFAs are assumed to be placed at regular interval in the system. Besides amplifying the signal, each amplifier generates ASE noise and adds to the amplified signal. The amplifiers are assumed to have a noise figure of 5.5 dB and a gain characteristic that is flat with respect to wavelength in this study. The receiver consists of an optical pre-amplifier, a 0.4 nm optical filter and an electrical receiver. The transmission performance is evaluated considering the worst case of received geometrical eye diagram, receiver noise and the ASE noise of the EDFAs. It may be mentioned that the accumulated ASE noise of the in-line EDFAs has not been considered in our simulations to highlight the effect of SPM.

3.1. Complete compensation

The SPM effects on the POCC, PRCC and BECC configurations have been investigated with dispersion completely compensated. Input power levels have been varied to determine the degree of SPM intensity in each of the compensation techniques. By input power levels it is meant in this paper the peak power levels of the input pulses. The transmission lengths have also been varied to show the suitability of the compensation techniques in case of long distance transmission. Transmission performances are manifested using the eye diagrams in

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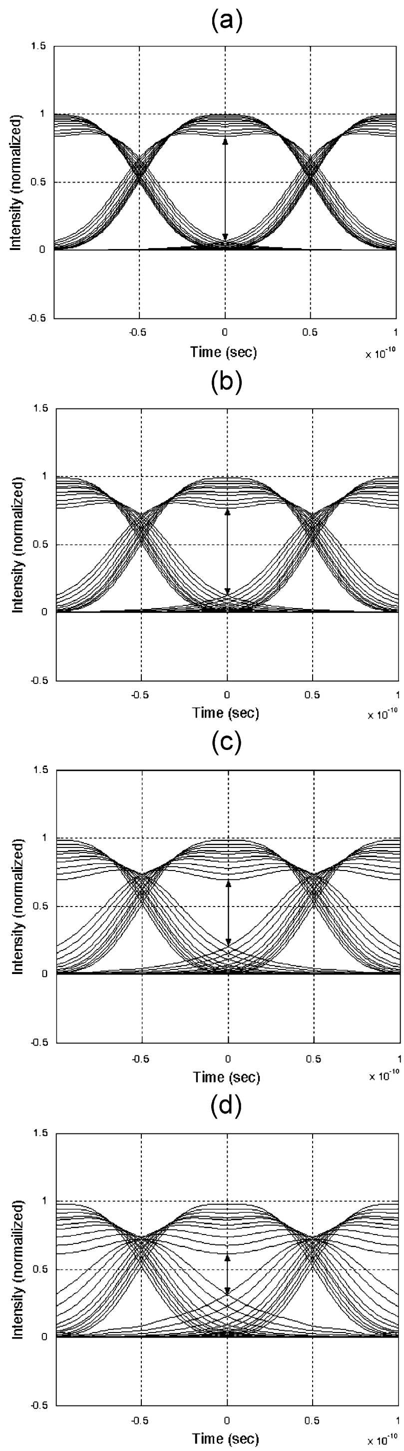

Fig. 2. Eye diagrams for a post-compensated (POCC) transmission link at (a) 1000 km, (b) 2000 km, (c) 3000 km and (d) 4000 km. Peak input power varied from −10 to 7 dBm.

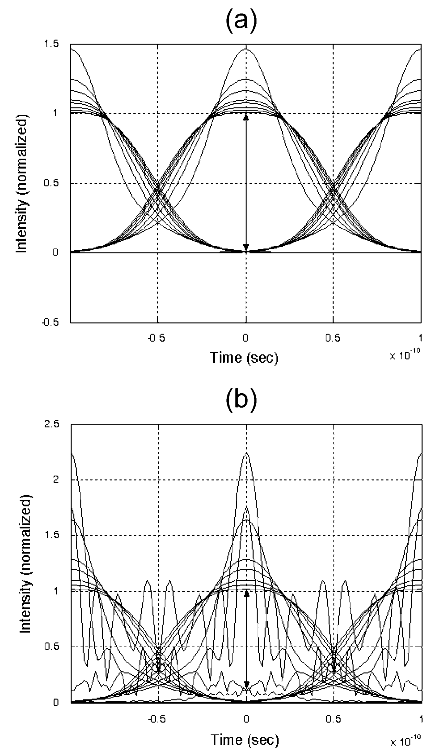

Fig. 3. Eye diagrams for a pre-compensated (PRCC) transmission link at (a) 1000 and (b) 2000 km. Peak input power varied from −10 to 4.77 dBm.

Figs. 2–4 for POCC, PRCC and BECC configuration, respectively. Fig. 2 shows that the eye opening decreases with the increase of input power for a fixed fiber length because of the SPM dependence on input power level. The maximum eye opening is found for −10 dBm and the minimum eye opening is found for 7 dBm input power. Again the eye opening at a fixed input power decreases with the fiber length due to the accumulation of the SPM and dispersion effects as can be observed from Figs. 2(a)–(d).

It is found that the impacts of GVD and SPM are different in a PRCC and a BECC configuration. The positive chirping of DCF and that of SPM support one another and so when a positively chirped pulse enters the SMF then it gets compressed. So the eye opening increases with the increase of peak input power for a given fiber length, and also increases with the fiber length for a given input power as illustrated in Figs. 3 and 4. However, the pulse compression reaches its maximum at a certain input power or a certain fiber length. Beyond this input threshold power, the pulse shape gets distorted and oscillating. In the PRCC scheme the rate of compression is too high that the increase of input peak power distorts the output pulse at a much lower input power as shown in Fig. 3. At the input power of 4.77 dBm, the output pulse of a 2000 km pre-compensated fiber link gets oscillating and distorted such that further increase of input power or fiber length will greatly deteriorate the eye diagram. On the other hand, though the compression effect is exhibited in Fig. 4 for BECC, the propagating pulse does not break even at 7 dBm input power at 4000 km transmission link. Thus the rate of compression is less in the BECC scheme with respect to that in the PRCC scheme. For BECC,

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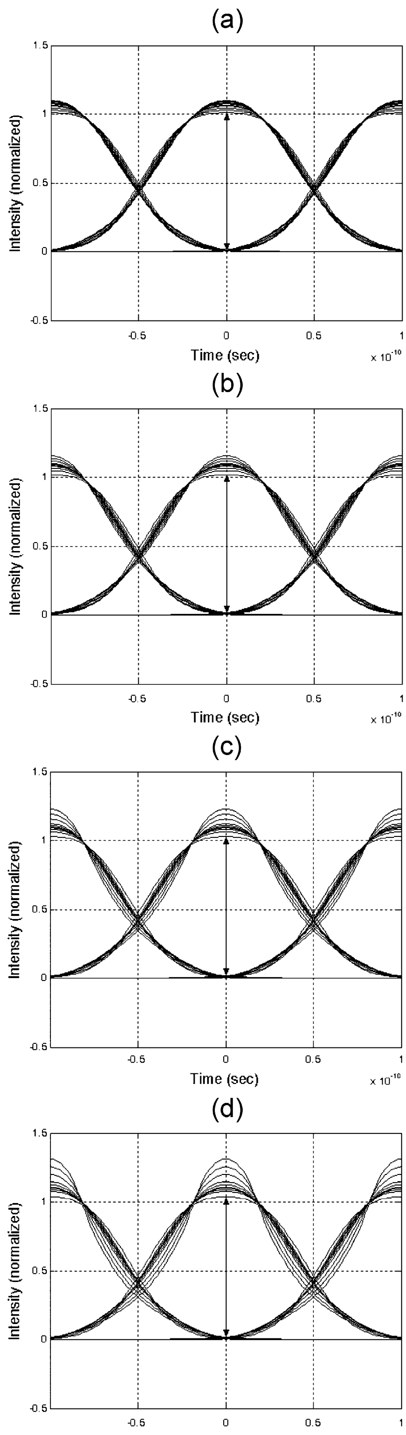

Fig. 4. Eye diagrams for a bi-end compensated (BECC) transmission link at (a) 1000 km, (b) 2000 km, (c) 3000 km and (d) 4000 km. Peak input power varied from −10 to 7 dBm.

the minimum eye opening is found for −10 dBm and the maximum eye opening is found for 7 dBm input power. Maximum power threshold levels at 3 dB eye opening in relation to the transmission fiber length have been determined for the POCC, PRCC and BECC schemes

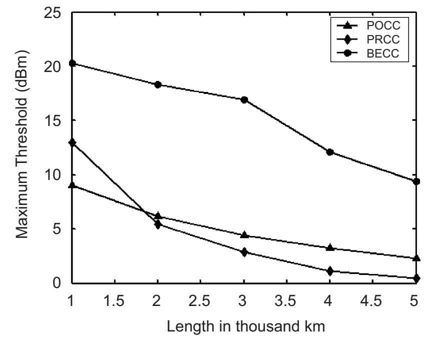

Fig. 5. Maximum threshold input peak power at 3 dB eye-opening penalty with fiber length for POCC, PRCC and BECC schemes.

and plotted in Fig. 5. It is found that for a longer fiber both the POCC and PRCC schemes show considerable degradation of the threshold power due to SPM accumulation. But even at 5000 km transmission fiber, the BECC scheme allows up to 9.4 dBm input power. So it is evident from the figure that the BECC scheme is the most suitable technique for a long-haul transmission system.

3.2. Partial compensation

Performance of the compensating techniques has also been investigated for a WDM system with fiber link of 1000 km using SMF where the dispersion and loss are compensated periodically as described earlier. Eye diagrams for the transmitted pulses with residual dispersion have been estimated and shown in Figs. 6–8 for the POCC, PRCC and BECC schemes, respectively. Fig. 6 shows that the eye opening decreases with the increase of input power, and the minimum eye opening is obtained for 7 dBm input power and the maximum eye opening is obtained for −10 dBm input power. In Fig. 6(a) small compression effect is exhibited with 500 ps/nm residual dispersion and the eye opening is found to increase at low input power levels. But with the increase of input power, increased SPM effects broaden the output pulse and decrease the eye opening. Negative residual dispersion is considered in Figs. 6(c) and (d) where it is found that the eye opening is less with negative residual dispersion which justifies results in Ref. [12]. At −1000 ps/nm residual dispersion the eye opening decreases so much that acceptable performance from the system cannot be achieved. In Fig. 7(a) pulse compression seizes at 5.44 dBm and as a result the eye opening decreases at 5.44 dBm. The minimum eye opening in Fig. 7(b) is found to be at an input power of 4 dBm. Compression goes on up to 7 dBm in Fig. 7(c). Fig. 7(d) shows the minimum eye opening for 7 dBm input power. For eye diagrams in Figs. 8(a), (c) and (d),

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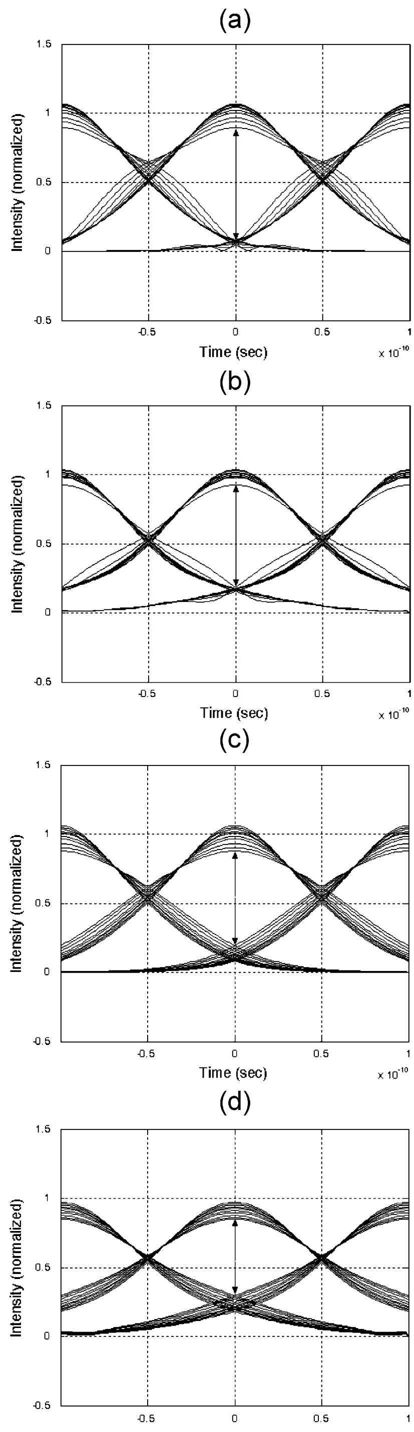

Fig. 6. Eye diagrams with residual dispersion (a) 500 ps/nm, (b) 1000 ps/nm, (c) −500 ps/nm and (d) −1000 ps/nm for a post-compensation (POCC) configuration. Input power levels have been varied from −10 to 7 dBm.

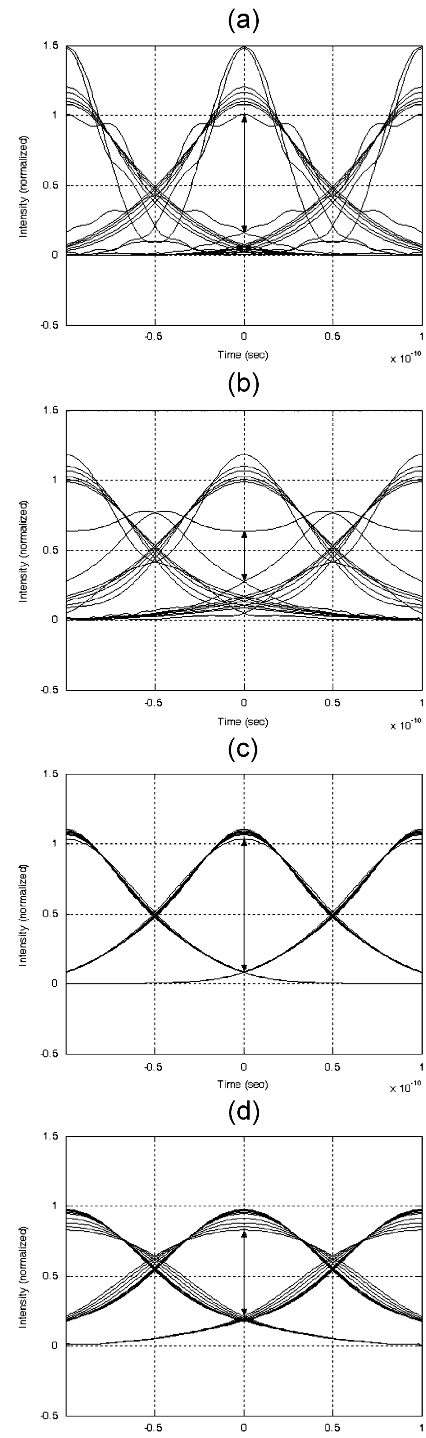

Fig. 7. Eye diagrams with residual dispersion (a) 500 ps/nm, (b) 1000 ps/nm, (c) −500 ps/nm, and (d) −1000 ps/nm for pre-compensation (PRCC) configuration.

the input power levels have been varied from −10 to 7 dBm and for Fig. 8(b) a maximum of 5 dBm input power has been used. Pulse compression occurs for both cases of Figs. 8(a) and (b). But compression is still present at 7 dBm input power in Fig. 8(a), whereas the eye opening distorts at 5 dBm input power in Fig. 8(b). Figs. 8(c) and (d) show eye opening decreasing with the increase of input power. It is found that, like PRCC, compression also occurs in BECC but at a slower rate.

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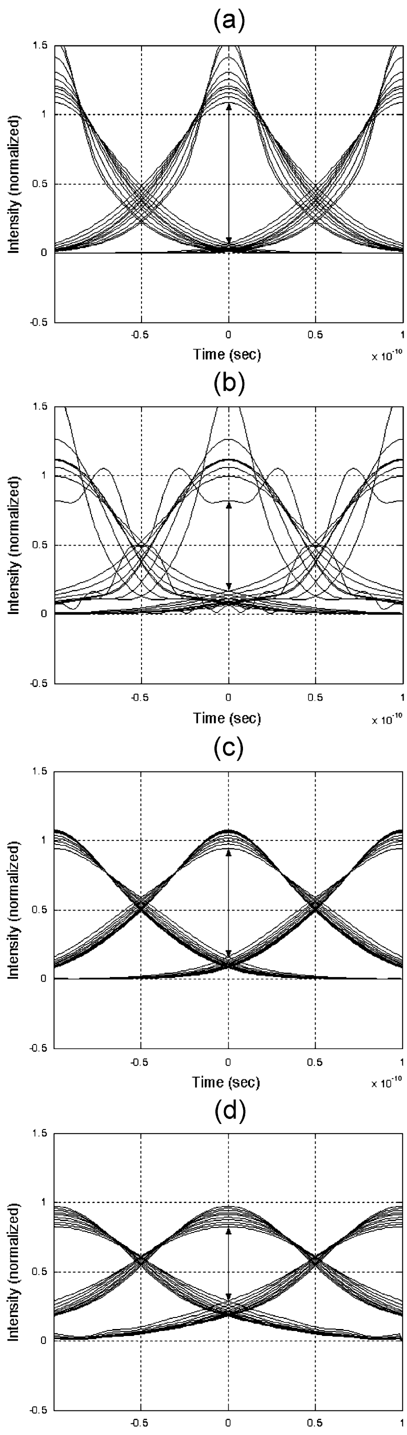

Fig. 8. Eye diagrams with residual dispersion (a) 500 ps/nm, (b)1000 ps/nm, (c) −500 ps/nm and (d) −1000 ps/nm for a bi-end compensation (BECC) configuration.

Again the comparison between positive and negative residual dispersion regimes shows that positive residual dispersion supports better eye opening in the BECC scheme.

Maximum threshold power levels at a bit error rate (BER) of 10^{-9} limited by the SPM effect have been determined for all the POCC, PRCC and BECC schemes and plotted in Fig. 9. It can be observed that the maximum threshold power is much higher in the BECC scheme at zero and at most of the positive and negative residual dispersion region compared to the POCC and PRCC schemes. It is worth noticing that all of the compensation configurations show steady threshold power in positive than negative residual dispersion region. Therefore, for a WDM system with larger number of channels, positive residual dispersion region should be used.

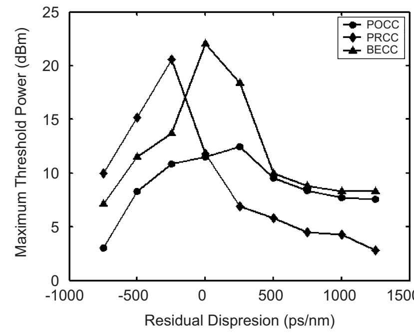

Fig. 9. Maximum threshold input power at 10^{-9} BER at 1000 km transmission fiber for post-, pre- and bi-end compensation configuration.

4. A WDM design rule

Because of the fiber dispersion slope, the residual dispersion of the most distant channels of a WDM system can differ by several hundreds of ps/nm. For an 8-channel system with 0.8 nm channel spacing, the channels will have a total of approximately 550 ps/nm residual dispersion in the 1000 km transmission link. In order to achieve the best performance for all the channels, the dispersion map must be designed so that the residual dispersion of every channel fall in the best performance region. From Fig. 9 it is found that the residual dispersion regimes of −250 to 300, −550 to 0 and −200 to 350 ps/nm may be selected for the POCC, PRCC and BECC schemes, respectively. For a 16-channel system with 1000 km transmission link, 1100 ps/nm residual dispersion regime is required. Therefore, the residual dispersion window of −500 to 600, −850 to 250 and −600 to 500 ps/nm can be selected for the POCC, PRCC and BECC schemes, respectively. The lowest maximum threshold power at 10^{-9} BER for these residual dispersion windows are listed in Table 1. It is found that in a WDM system, the BECC configuration yields the acceptable residual dispersion regime with higher threshold input power.

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Table 1. Lowest threshold power at 10^{-9} BER for WDM system for POCC, PRCC and BECC

No. of channels	POCC (dBm)	PRCC (dBm)	BECC (dBm)
8	11	12	15
16	8.5	8	10

5. Conclusion

The effects of SPM on a long-haul WDM system have been extensively investigated for the post-, pre- and bi-end compensation configurations. It is evident from the analysis that the SPM effects limit the transmission distance and maximum threshold power significantly. Nevertheless, the SPM effects are less serious in a bi-end compensated system compared to other schemes. Besides, zero, positive and negative residual dispersion regimes behave differently and the positive residual dispersion regime offers better transmission performance than the negative dispersion regime in case of a WDM system. So the channel wavelengths of a WDM system should be selected in a way so that most of the channels lie in the positive residual dispersion region.

References

[1] S. Watanabe, T. Naito, T. Chikama, Compensation of chromatic dispersion in a single-mode fiber by optical phase conjugation, IEEE Photon. Technol. Lett. 5 (1993) 92–95.

[2] R. Kashyap, S.V. Chernikov, P.F. Mckee, J.R. Taylor, 30 ps chromatic dispersion compensation of 400 fs pulses at 100 Gbit/s in optical fibers using an all fiber photo-induced chirped reflection grating, Electron. Lett. 30 (1994) 1078–1080.

[3] L. Dong, M.J. Cole, A.D. Ellis, M. Durkin, M. Ibsen, V. Gusmeroli, R.I. Laming, 40 Gbit/s 1.55 nm transmission over 109 km of nondispersion shifted fiber with long continuously chirped fiber grating, in: Proceedings of OFC'97 Technical Digest, 1997, paper PD-6, pp. 391–394.

[4] J.M. Dugan, A.J. Price, M. Ramadan, D.L. Wolf, E.F. Murphy, A.J. Antos, D.K. Smith, D.W. Hall, All-optical fiber-based 1550-nm dispersion compensation in a 10 Gb/s, 150 km transmission experiment over 1310 nm optimized fiber, in: Proceedings of OFC'92 Technical Digest, 1992, paper PD-14.

[5] A.M. Vengsarkar, A.E. Miller, M. Haner, A.H. Gnauck, W.A. Reed, K.L. Walker, Fundamental-mode dispersion-compensating fibers: design consideration and experiments, in: Proceedings of OFC'94 Technical Digest, 1994, paper THK2, vol. 4, p. 225.

[6] G.P. Agrawal, Nonlinear Fiber Optics, third ed, Academic Press, San Diego, CA, 2001.

[7] S. Bigo, A. Bertaina, WDM transmission experiments at 32×10 Gb/s over nonzero dispersion-shifted fiber and standard single-mode fiber, IEEE Photon. Technol. Lett. 11 (1999) 1316–1318.

[8] A.H. Gnauck, J.M. Wiesenfeld, L.D. Garrett, M. Eiselt, F. Forghieri, L. Arcangeli, B. Agogliata, V. Gusmeroli, D. Scarano, 16×20 Gb/s, 400 km WDM transmission over NZDSF using a slope-compensating fiber-grating module, IEEE Photon. Technol. Lett. 12 (2000) 437–439.

[9] R.W. Tkach, A.R. Chraplyvy, F. Forghieri, A.H. Gnauck, R.M. Derosier, Four-photon mixing and high-speed WDM systems, J. Lightwave Technol. 13 (1995) 841–849.

[10] W. Zeiler, F.D. Pasquale, P. Bayvel, J.E. Midwinter, Modeling of four-wave mixing and gain peaking in amplified WDM optical communication systems and networks, J. Lightwave Technol. 14 (1996) 1933–1942.

[11] S. Shen, C.-C. Chang, H.P. Sardesai, V. Binjrajka, A.M. Weiner, Effects of self-phase modulation on sub-500 fs pulse transmission over dispersion compensated fiber links, J. Lightwave Technol. 17 (1999) 452–461.

[12] G. Bellotti, A. Bertaina, S. Bigo, Dependence of self-phase modulation impairments on residual dispersion in 10-Gb/s-based terrestrial transmissions using standard fiber, IEEE Photon. Technol. Lett. 11 (1999) 824–826.

[13] S. Wen, Bi-end dispersion compensation for ultralong optical communication system, J. Lightwave Technol. 17 (1999) 792–798.

[14] W.J. Tomlinson, R.H. Stolen, C.V. Shank, Compression of optical pulses chirped by self-phase modulation in fibers, J. Opt. Soc. Am. B 1 (1984) 139–149.

[15] J.P. Gordon, Dispersive perturbations of solitons of the nonlinear Schrodinger equation, J. Opt. Soc. Am. B 9 (1992) 91–97.

[16] S. Bigo, G. Bellotti, M.W. Chbat, Investigation of cross-phase modulation limitation on 10-Gbit/s transmission over various types of fiber infrastructures, Presented at the OFC'99, paper ThC3.

[17] M.A. Talukder, M.N. Islam, Performance of bi-end compensation in a wavelength-division multiplexed system considering the effect of self phase modulation, Opt. Eng. 44 (11) (2005) 115005-1–115005-6.

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