# Performance of bi-end compensation in a wavelength-division multiplexed system considering the effect of self phase modulation

**Muhammad Anisuzzaman Talukder,** MEMBER SPIE
**Mohammed Nazrul Islam**
Bangladesh University of Engineering and Technology
Department of Electrical and Electronic Engineering
Dhaka-1000, Bangladesh
E-mail: anistal@eee.buet.ac.bd

**Abstract.** An extensive investigation has been carried out, by computer simulation, to evaluate the impact of self phase modulation (SPM) on residual dispersion for a wavelength-division multiplexed (WDM) system at a bit rate of 10 Gbit/s. Degradation of the eye opening of the transmitted pulses at the output of the transmission fiber due to interplay of the SPM and the group-velocity dispersion effects is investigated for post- and bi-end compensation configurations, including residual dispersion. Hence the eye-opening penalty and the threshold power limit at 3-dB eye-opening penalty are determined for both the configurations. It is found that the bi-end compensation configuration offers the best performance in respect of the SPM effect and that for a WDM system positive residual dispersion should be used.  [DOI: 10.1117/1.2128631]

Subject terms: dispersion compensation; group-velocity dispersion; self phase modulation; single-mode fiber.

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## 1 Introduction

Because fiber losses can be efficiently managed by inline erbium-doped fiber amplifiers (EDFAs), the dispersion-compensation technique is well adopted for constructing long-distance transmission systems.[1–3] In the conventional dispersion-compensated system, the nonzero anomalous group-velocity dispersion (GVD) of standard single-mode fibers (SMFs) is periodically compensated by the proper length of dispersion-compensating fibers (DCFs) placed at the input or output end of the compensation interval.[4–6] However, for a wavelength-division multiplexing (WDM) system, it is difficult to compensate all the channels completely for dispersion.[7,8] If perfect dispersion compensation is accomplished for a particular channel of the WDM system, other wavelength channels may encounter different amounts 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 should not be completely compensated.[9,10]

Apart from fiber GVD, nonlinear effects place severe limitations on optical transmission systems, especially at high input power. The dominant nonlinear effect in an SMF is self phase modulation (SPM), which is caused by the nonlinear dependence of the refractive index on the pulse intensity. Since high-speed data transmission systems require greater received power for error-free detection, the performance of a dispersion-compensated link is eventually limited by the interaction of SPM and the fiber GVD.[11,12] Moreover, the mutual interplay between SPM and GVD depends on the sign and amount of residual dispersion. The SPM-induced power margin depends on the DCF's position with respect to the SMF as well and has been studied for a single-channel system with complete compensation[13–16] and for a WDM system with residual dispersion.[16,17] It has been found that for complete dispersion compensation, the precompensation configuration (PRCC) should be used, and for a WDM system the postcompensation configuration (POCC) must be used with positive residual dispersion. Recently, the bi-end compensation configuration (BECC) has been investigated for dispersion compensation[18] in single-channel systems where DCFs are placed at both ends of the SMF. However, to the best of the authors' knowledge, SPM effects on residual dispersion in a WDM system with bi-end compensation configuration are yet to be reported.

The objective of this paper is to investigate the performance of the BECC scheme in a WDM system in the presence of the SPM effect. The eye-opening penalty and threshold power limit are evaluated for the BECC and then are compared with those of the POCC scheme. The PRCC scheme is not considered here, because it has been found to yield poor performance in WDM system in the presence of SPM. Numerical results show that the BECC scheme with positive residual dispersion offers the best solution to the problem of SPM.

## 2 Theoretical Model

The nonlinear Schrödinger equation (NLSE), modified to include higher-order dispersion, has been successful in accurately modeling pulse propagation in single-mode fibers in many diverse applications[19,20] and can therefore be employed with confidence for system design. The modified NLSE incorporating the combined effects of SPM, GVD, and loss on pulse propagation in an SMF is given by[21]

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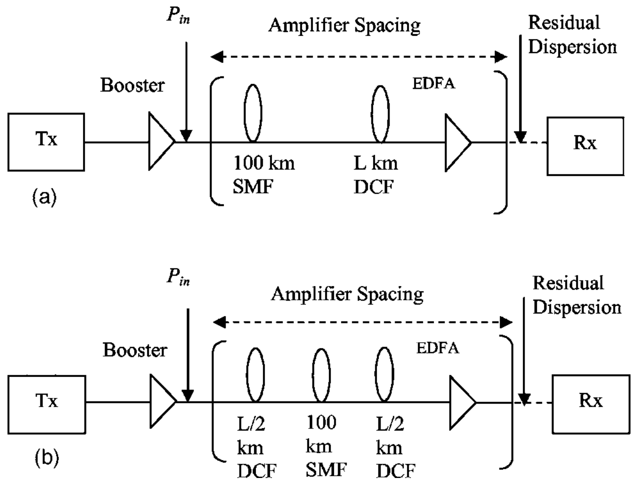


**Fig. 1** Schematic diagram of (a) post- and (b) bi-end compensation configuration.

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

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 $v_g$, i.e., $T=t-z/v_g$. Also, $\beta_2$ and $\beta_3$ are the dispersion and dispersion slope parameters, respectively, of the fiber; $\alpha$ is the loss coefficient; and $\gamma$ is the nonlinearity coefficient.

In our simulation, only SPM is considered as the nonlinear effect, since multiwavelength nonlinear effects have little effect on the performance of SMF transmission systems.[22] In practice, FWM is substantially suppressed by the high chromatic dispersion of SMFs. Cross-phase modulation introduces only a little penalty in densely spaced systems and hence does not have a large effect on standard SMF-based systems, because of its high walk-off.

Pulse propagation has been simulated using the split-step Fourier transform method[21] for the systems shown in Fig. 1. A single channel, modulated with a 10-Gbit/s non-return-to-zero (NRZ) bit sequence, is generated through a chirp-free transmitter and is launched into a link composed of spans of 100 km of SMF and $L$ km of DCF. The DCF length $L$ is kept variable to adjust the residual dispersion of the transmission system. A normalized super-Gaussian pulse is used as the input for the numerical analysis as given by[23]

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

with

$$T_b = 2(2\ln 2)^{1/2m}T_0, \tag{3}$$

where $T_0$ is the half width at the $1/e$-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

$$A(z,T) = \sqrt{P_0}\exp(-\alpha z/2)U(z,T), \tag{4}$$

where $P_0$ is the peak power.

## 3 Results

In the performance evaluation, the 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$^{-1}$, and 80 $\mu$m$^2$, respectively, for SMF, and −100 ps/(nm km), 0.09 ps/(nm$^2$ km), 0.6 dB/km, 5.4 W$^{-1}$ km$^{-1}$, and 20 $\mu$m$^2$, respectively, for DCF. Thus the dispersion is compensated completely in each amplifier spacing of 100-km SMF when the DCF length is 17 km. On the other hand, if the DCF length is different from 17 km, then the dispersion is partially compensated in each span, and a residual dispersion accumulates down the transmission fiber. The residual dispersion is positive if the DCF length is less than 17 km, and negative if the DCF length is greater than 17 km. The total length of the WDM system is taken as 1000 km. The inline amplifiers are assumed to be flat and noiseless, with gain equal to the span loss. The accumulated amplified spontaneous emission (ASE) noise of the inline amplifiers has not been considered in our simulations, so as to highlight the effects of SPM and to compare our results with those reported in Ref. 17. However, because of the high fiber dispersion, the effect of nonlinear propagation on the ASE spectrum (i.e., modulation instability) is negligible. Thus the effect of the accumulated ASE noise is simply to add an extra penalty, which decreases with increasing input power, and can easily be calculated as in a linear link.[24]

During propagation of a pulse through the fiber, GVD changes the frequency across the pulse; this is referred to as frequency chirp. The chirp $\delta\omega$ depends on the sign of the dispersion parameter. In the case of DCF with negative (positive) dispersion, the frequency increases (decreases) across the pulse from the leading to the trailing edge, which is referred to as positive (negative) frequency chirp.

Frequency chirp is also induced by SPM. That contribution increases in magnitude with the propagated distance, and is positive irrespective of the sign of the dispersion coefficient.

In a postcompensated transmission link, GVD-induced negative frequency chirp is reduced by SPM induced positive frequency chirp on the pulse within the SMF, and as a result the pulse is actually less broadened than if there were no SPM. So the DCF length used for zero residual dispersion actually overcompensates the incoming pulse from the SMF in the presence of SPM. Thus, to obtain less distorted pulses, the DCF length should be such as to undercompensate the dispersion effects of SMF. That means the DCF length should be less than the length required for zero residual dispersion. Therefore, positive residual dispersion should give better eye-opening performance than does zero residual dispersion. But, if the positive residual dispersion becomes so large as to undercompensate the dispersion, then the eye opening may deteriorate. So there must be some optimum residual dispersion at which the best performance is obtained. On the other hand, if the DCF length is set for negative residual dispersion, the pulse dispersion will be more overcompensated than at zero residual dispersion. As the negative residual dispersion increases, the

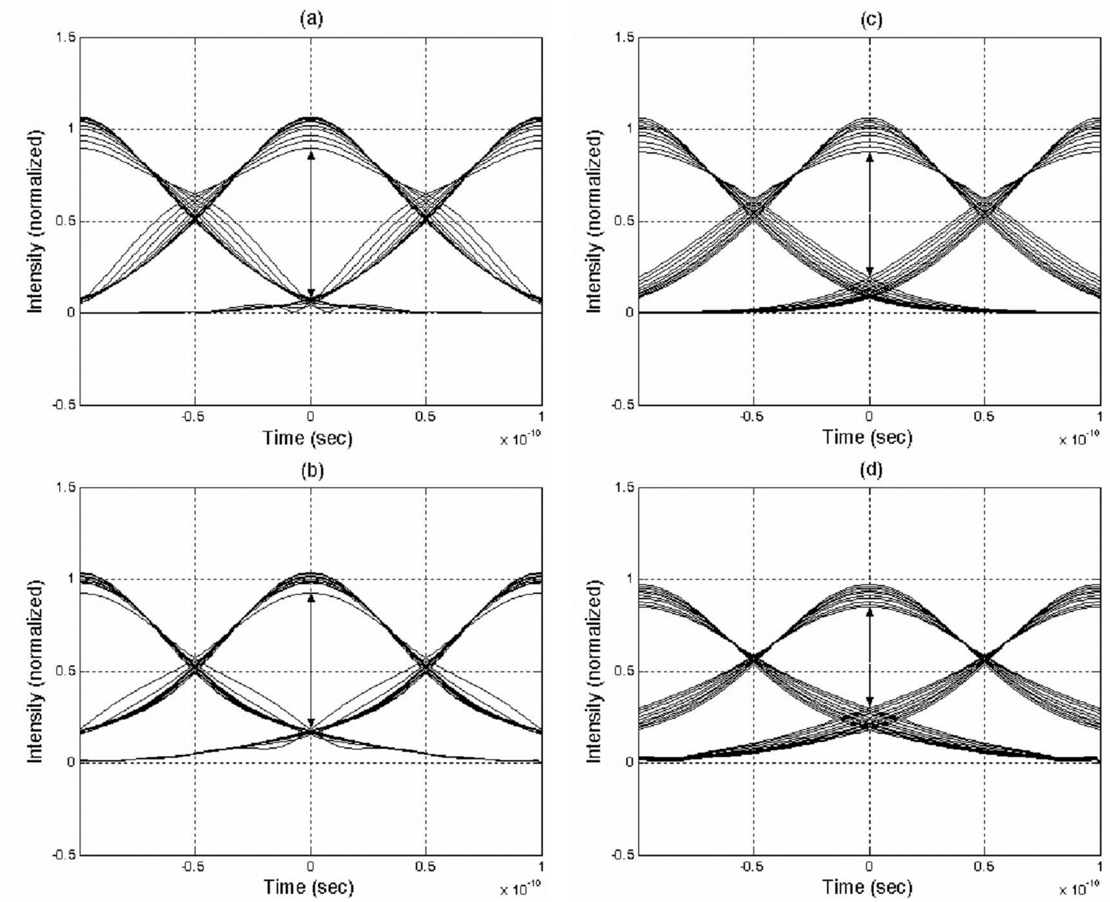


**Fig. 2** Eye diagrams with (a) 500-ps/nm, (b) 1000-ps/nm, (c) −500-ps/nm, and (d) −1000-ps/nm residual dispersion for a postcompensation configuration. Peak input power levels are varied from −10 to 7 dBm.

amount of overcompensation increases, the pulse shape distorts, and the pulse broadens outside its dedicated bit period.

Eye diagrams for the transmitted pulses in a postcompensated WDM transmission system are given in Fig. 2. Generally, the eye opening decreases when the input power levels are high due to increase of SPM effects. In Fig. 2(a) with 500-ps/nm residual dispersion, a small compression effect is exhibited 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. With 1000-ps/nm residual dispersion in Fig. 2(b), residual dispersion is almost counterbalanced by SPM-induced positive chirping at low input power levels. In both Fig. 2(c) and 2(d), negative residual dispersion is considered. It is found from a comparison between Fig. 2(a) and 2(c) or between Fig. 2(b) and 2(d) that the eye opening is less with negative residual dispersion, which confirms the results reported in Ref. 17. At −1000-ps/nm residual dispersion, the eye opening decreases so much that acceptable performance of the system cannot be achieved.

An eye-opening penalty is calculated using the relation

$$\text{penalty} = 20 \log_{10}\left(\frac{a}{b}\right), \tag{5}$$

where $a$ and $b$ are the eye openings at the bit center at the input and the output ends, respectively, of the transmission fiber. The eye-opening penalty is shown in Fig. 3. For positive residual dispersion, SPM compensates broadening due to residual dispersion. The compensation is optimum at a particular input power level. The penalty curve for 1000-ps/nm residual dispersion in Fig. 3, therefore, shows a change in sign of the slope at the input power where the optimum compensation occurs. With negative residual dispersion, SPM rather aids the residual dispersion. Therefore the eye-opening penalty increases with the increase of input power as SPM increases.

Eye diagrams for a bi-end compensation configuration are evaluated and given in Fig. 4. For Figs. 4(a), 4(c), and 4(d), the peak input power levels are varied from −10 to 7 dBm. For Fig. 4(b), a maximum of 5-dBm peak input power is used. At 500-ps/nm residual dispersion, the eye opening increases with increase of input power, due to the compression effect in the presence of SPM. Maximum

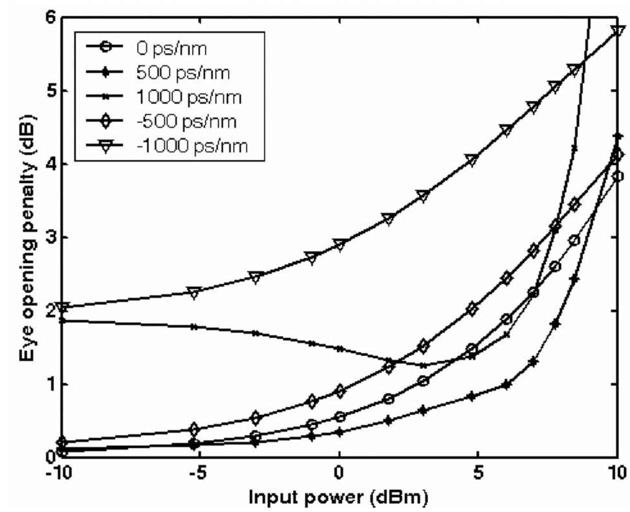


**Fig. 3** Eye-opening penalty with peak input power for different residual dispersions of a postcompensated transmission fiber.

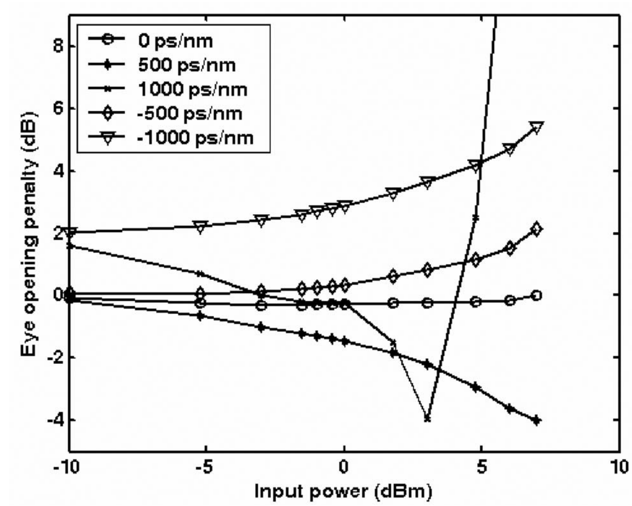


**Fig. 5** Eye-opening penalty versus peak input power for different residual dispersions in a bi-end dispersion compensation configuration.

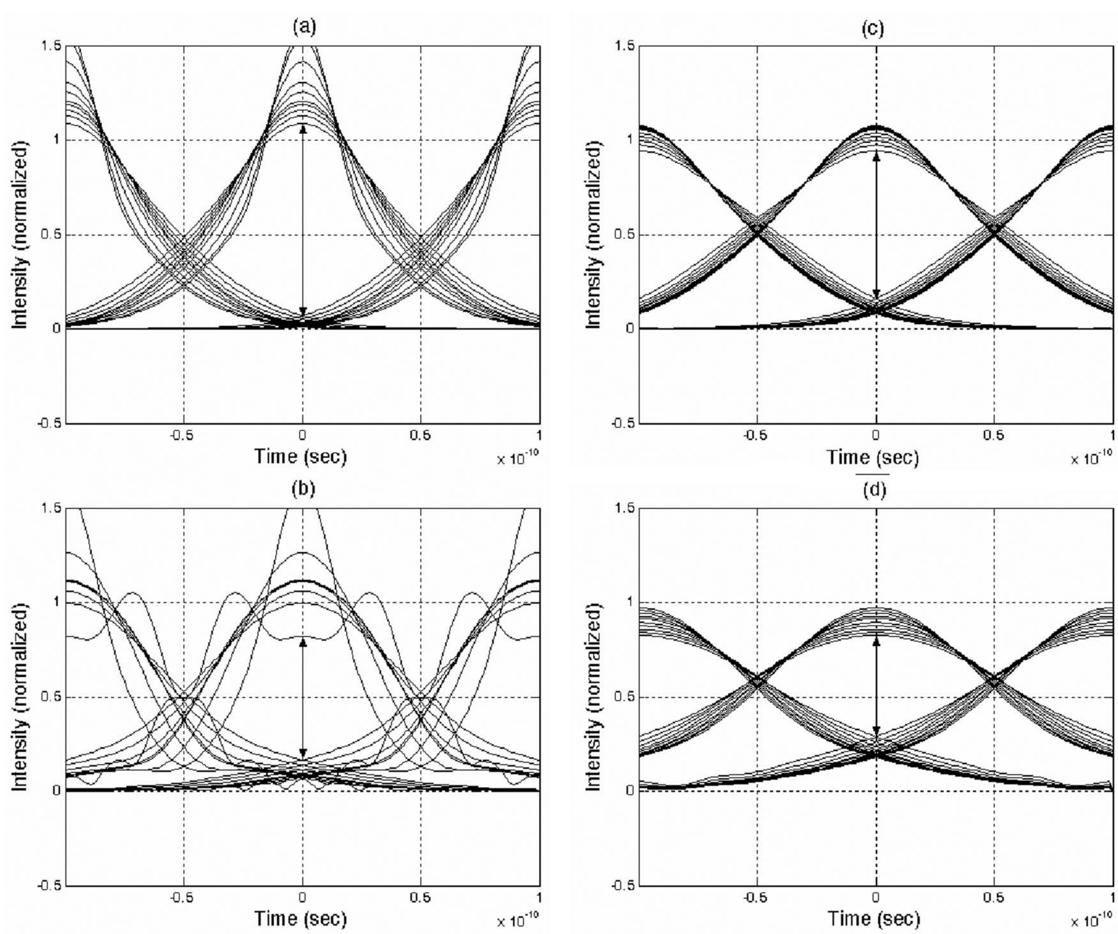


**Fig. 4** Eye diagrams with residual dispersion (a) 500 ps/nm, (b) 1000 ps/nm, (c) −500 ps/nm, and (d) −1000 ps/nm for a bi-end compensation configuration.

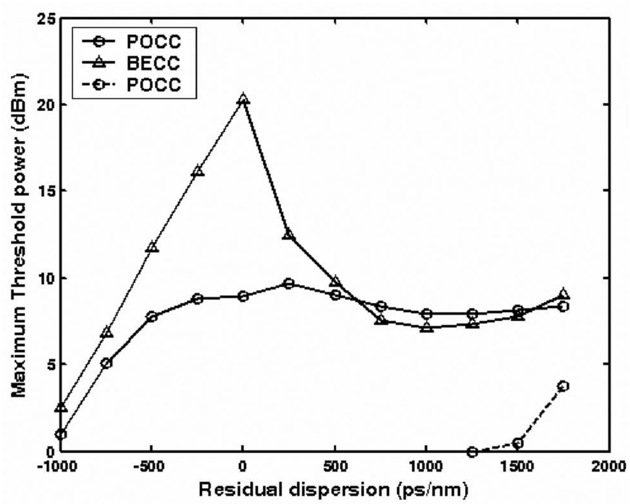


**Fig. 6** Threshold power at 3-dB eye-opening penalty against residual dispersion for post- and bi-end compensation configuration. Solid curves represent maximum threshold power levels, and dashed curve represents minimum threshold power levels.

eye opening is obtained for 7 dBm of input power. This effect is better illustrated in Fig. 5, where the eye-opening penalty is plotted against the input power for various residual dispersions in the BECC as in Fig. 3. It is observed that the eye-opening penalty gradually decreases with increase of input power up to 7 dBm for 500 ps/nm. At 1000-ps/nm residual dispersion, pulse compression occurs at even lower input powers. But after applying 5-dBm input power, the pulse can no longer be compressed. As a result, the pulse is distorted due to the interplay between GVD and SPM. This effect is also illustrated in Fig. 5 where it is found that the eye-opening penalty increases very sharply beyond 3 dBm of input power for 1000 ps/nm. In Fig. 4(c), the eye diagram for −500-ps/nm residual dispersion shows that the minimum eye opening is for the maximum input power of 7 dBm and the maximum eye opening is for the minimum input power of −10 dBm. It indicates that the pulse compresses only at low input power. At higher input power, such as 3 dBm, the pulse broadens. As a result, the peak power of the pulse decreases, and it interferes with the neighboring pulses. Due to high residual dispersion at −1000 ps/nm, the interplay between GVD and SPM broadens the pulse so much that the eye opening decreases greatly for 7-dBm input power. The eye diagram degrades even at −10-dBm input power, where the SPM effect is very low. This is mainly because GVD is overcompensated at such a high level of residual dispersion. Again, comparison between the positive- and negative-residual-dispersion regimes shows that positive residual dispersion supports better eye opening in a BECC.

Because a 3-dB eye-opening penalty is considered to be the standard for acceptable performance of an optical communication system, the maximum power levels that can be applied to the system for this penalty criterion with different residual dispersion in both post- and bi-end compensation configurations have been estimated and plotted in Fig. 6. Performance results for other penalty criteria can easily be evaluated using the present simulation. It is observed that the maximum threshold power is much higher in bi-end compensation—at zero residual dispersion, and also in most parts of the positive and negative residual dispersion regions—than in postcompensation. It is worth noticing that both POCC and BECC show higher threshold power at positive than at negative residual dispersion. Though at high positive residual dispersion, postcompensation shows more threshold power, it is also to be noted that the minimum power required for obtaining a 3-dB eye opening penalty increases. With high positive residual dispersion at low input power, the SPM effect is low, and as a result, the pulse broadens greatly due to dispersion. As the input power is increased, SPM counterbalances the broadening due to positive residual dispersion, and an eye-opening penalty of 3 dB or less can be obtained. But if the input power level continues to increase, SPM effects dominate and the pulse shape starts to distort. It can be concluded from Fig. 6 that positive residual dispersions greater than 1250 ps/nm should not be used in a postcompensated link. Though the BECC shows an extended positive-residual-dispersion region, gradual increase of the minimum threshold power is also observed, but it is not shown in the figure, because the minimum threshold power is less than 0 dBm up to the residual dispersion levels considered. From Fig. 6 it is also evident that for both single-channel and multichannel systems bi-end compensation is the preferable solution. Also, for a WDM system with a larger number of channels, positive residual dispersion should be used.

## 4 Conclusion

The effect of SPM on residual dispersion in a dispersion-compensated fiber scheme for an optical WDM system has been extensively investigated for both post- and bi-end compensation configurations. Because only one channel in the WDM system can be fully dispersion-compensated, other channels will have residual dispersion. Thus the results presented in this paper can be applied to any WDM channel having a varying amount of residual dispersion. It is evident from the performance results that the zero-, positive-, and negative-residual-dispersion regimes behave differently and that positive residual dispersion offers better transmission performance in a WDM system than does negative residual dispersion. So the channel wavelengths of a WDM system should be selected so that most of the channels lie in the positive-residual-dispersion region.

It is observed that residual dispersion is not the only figure of merit, but the performance of a WDM system also depends on the position of DCFs with respect to SMFs as well. In this respect, the bi-end compensation configuration is found to perform better than the postcompensation configuration.

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**Muhammad Anisuzzaman Talukder** received his BSc and MSc in electrical and electronic engineering in the years 2000 and 2004, respectively, both from Bangladesh University of Engineering and Technology (BUET). In 2001, he joined the department of Electrical and Electronic Engineering, BUET, where he is currently working as an assistant professor. His research interests are in the area of fiber and nonlinear optics. He is a member of the Optical Society of America.

**Mohammed Nazrul Islam** received his BS in engineering in 1991 and his MS in engineering in 1994, both in electrical and electronic engineering, from Bangladesh University of Engineering and Technology. He joined the same university in 1992, where he is now an associate professor. He received his DrEng degree in optical communication and optoelectronics from Muroran Institute of Technology, Japan, in 1999. Dr. Islam worked as a co-investigator in a research project on optical pattern recognition funded by the National Science Foundation of the USA. He is currently working as a visiting researcher at the University of South Alabama in the USA. He has published his research work in more than 75 refereed journals and conference proceedings. He was the Chairman of IEEE Bangladesh Section in 2003–2004. His research interests include optical communication, optoelectronics, optical pattern recognition, image processing, and wireless communication.