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Comparison of pre-, post- and symmetrical-dispersion compensation schemes for 10 Gb/s NRZ links using standard and dispersion compensated fibers

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Abstract

In this paper, we investigate pre-, post- and symmetrical-dispersion compensation methods for 10 Gb/s non-return to zero (NRZ) links using standard and dispersion compensated fibers through computer simulations to optimize high data rate optical transmission. The influence of EDFA power and increase in length of each type of fiber has been studied to evaluate the performance of optical communication systems. The performance characteristics like bit error rate, eye diagrams and eye closure penalty at the output are studied by simulating different systems. The results of three compensation methods have been compared and it is found that the symmetrical compensation method is superior to pre- and post-compensation methods. On comparing pre- and post-compensation methods, it is found that the later is superior to the former. Further, it has also been observed that system needs proper matching between the EDFA power and length of the fiber for optimum performance. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Compensating device; Dispersion; Electrical drivers; Group velocity dispersion; Bit error rate; Optical propagation in dispersive media; Simulation results

1. Introduction

Recently, there has been great interest in using single mode fibers [1] for high-bit-rate transmission in low loss transmission windows but dispersion is an important impairment that degrades overall system performance of an optical communication system. At high-bit-rate, the dispersion-induced broadening of short pulses propagating in the fiber causes crosstalk between the adjacent time slots, leading to errors when the communication distance increases beyond the dispersion length of the fiber [2]. The advent of erbium-doped amplifiers (EDFAs) operating in the 1.55 μm region has increased the link distance as limited by fiber loss in optical communication systems. However, these amplifiers induce nonlinear effects, which not only

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limit the bit rate but also the propagation distance in an optical fiber link. Nonlinear effects along with dispersion are the destructive forces for pulse propagation in ultra high-bit-rate optical transmission system [3] and cause power penalty and other impairments in the system. Therefore, in order to realize the high data rates over long distances down the SM fiber, techniques must be found to overcome signal degradation due to dispersion and nonlinearities. Several methods have been proposed to overcome the impairments caused by chromatic dispersion including initial pre-chirp [4], microchip compensation [5], mid-span spectral inversion [6], optical phase conjugation [7–9], dispersion-supported transmission [10], dispersion compensating devices [11–13] and differential delay method [14–18].

The use of dispersion compensated fiber is an important method for dispersion compensation and to upgrade the already installed links of single mode fiber [19]. Dispersion compensated fibers are specially designed fibers with negative dispersion. The high value of negative dispersion is used to compensate for positive dispersion over large lengths of ordinary fiber. The total negative dispersion compensates for the total positive dispersion. Spans made of single mode fibers and dispersion compensated fibers are good candidates for long distance transmission as their high local dispersion is known to reduce the phase matching giving rise to four wave mixing in wavelength division multiplexed (WDM) systems. Signal degradation in such systems is due to combined effects of group velocity dispersion, kerr nonlinearity and accumulation of amplified spontaneous emission due to periodic amplification. Compensation is done by three methods, pre-, post- and symmetrical compensation. In the first method, the optical communication system is pre compensated by the dispersion compensated fiber of negative dispersion against the standard fiber. In the second method, the optical communication system is post

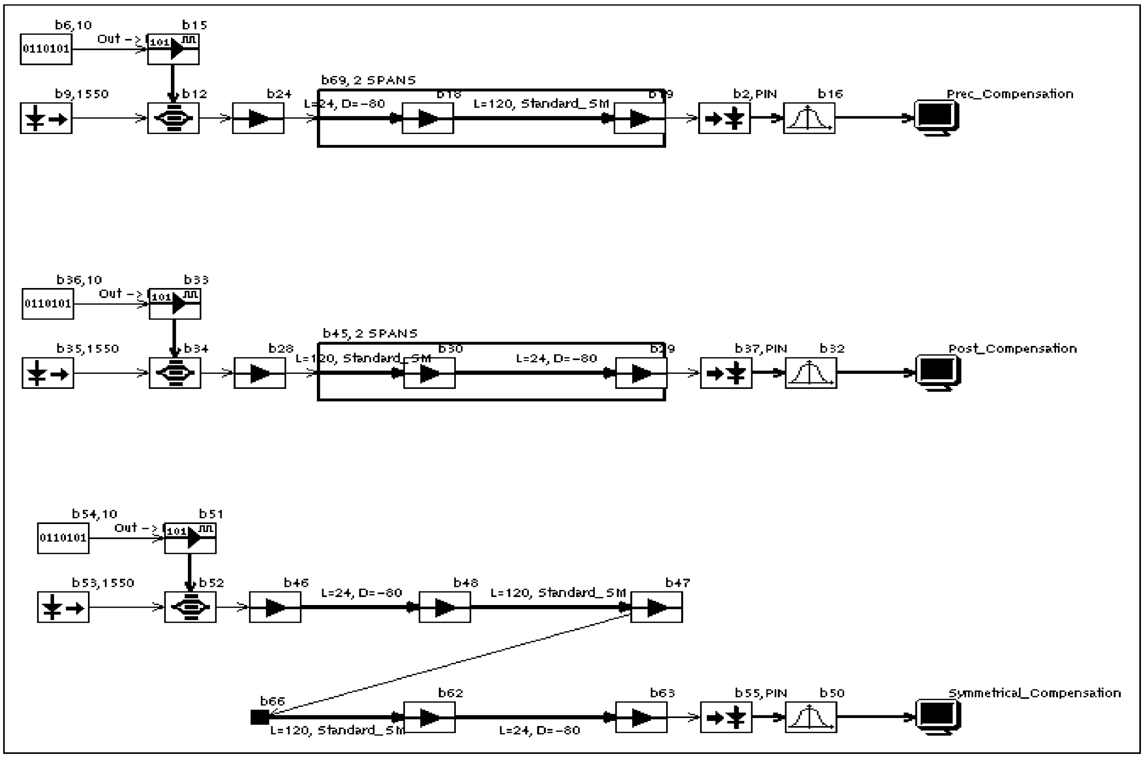

Fig. 1. Simulation setup for pre-, post- and symmetrical compensation using standard and dispersion compensated fibers.

compensated by the dispersion compensated fiber of negative dispersion against the standard fiber. In the third method, the optical communication system is symmetrically compensated by two dispersion compensated fibers of negative dispersion against the standard fiber in between. Due to the nonlinear nature of propagation, system performance depends upon power levels [20] and the position of dispersion compensated fibers [21]. In this paper, we compare these three dispersion compensation methods and evaluate the performance characteristics for dispersive optical communication systems. Earlier in the literature [19–21], pre- and post-compensation methods were discussed and compared for Q factor only. Here, the results of symmetrical compensation method are compared with pre- and post-compensation methods on the basis of important additional features like bit error rate, eye diagram and eye closure penalty. These effects have been studied as the function of important parameters like EDFA output power and lengths of each type of fiber. In Section 2, the optical simulated project and parameters are defined. In Section 3 comparison results have been reported for these compensation methods and finally in Section 4, conclusions are drawn.

2. Simulation

The block diagrams for simulation of pre-, post- and symmetrical-compensation methods using standard and dispersion compensated fibers are shown in Fig. 1.

In the figure, each transmitter section consists of data source, electrical driver, laser source and amplitude modulator. The data source is non-

Table 1
Steps for variation in fixed output EDFA power

Step	1	2	3	4	5	6	7
Power	0 dBm	2 dBm	4 dBm	6 dBm	8 dBm	10 dBm	12 dBm

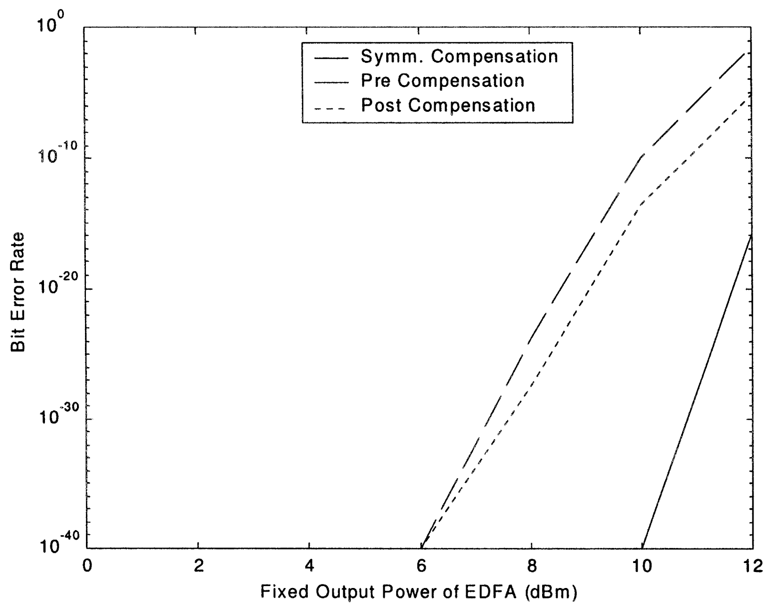

Fig. 2. Bit error rate vs. fixed output power of EDFA for pre-, post- and symmetrical compensation methods.

return to zero format at 10 Gb/s bit rate and is indicated by b6, b36 and b54 blocks for pre-, post- and symmetrical compensation respectively as shown in figure. The electrical driver is important component that generates the desired data transmission format. It converts the logical input signal, a binary sequence of zeros and ones into an electrical signal. It is indicated by b15, b33 and b51 blocks for pre-, post- and symmetrical configurations, respectively. The laser source (b9, b35 and b53 for three configurations) generates laser beam at 1550 nm. The output of modulator (b12, b34 and b52) is fed to optical link through EDFA amplifier (b24, b28 and b46). The pre- and post-

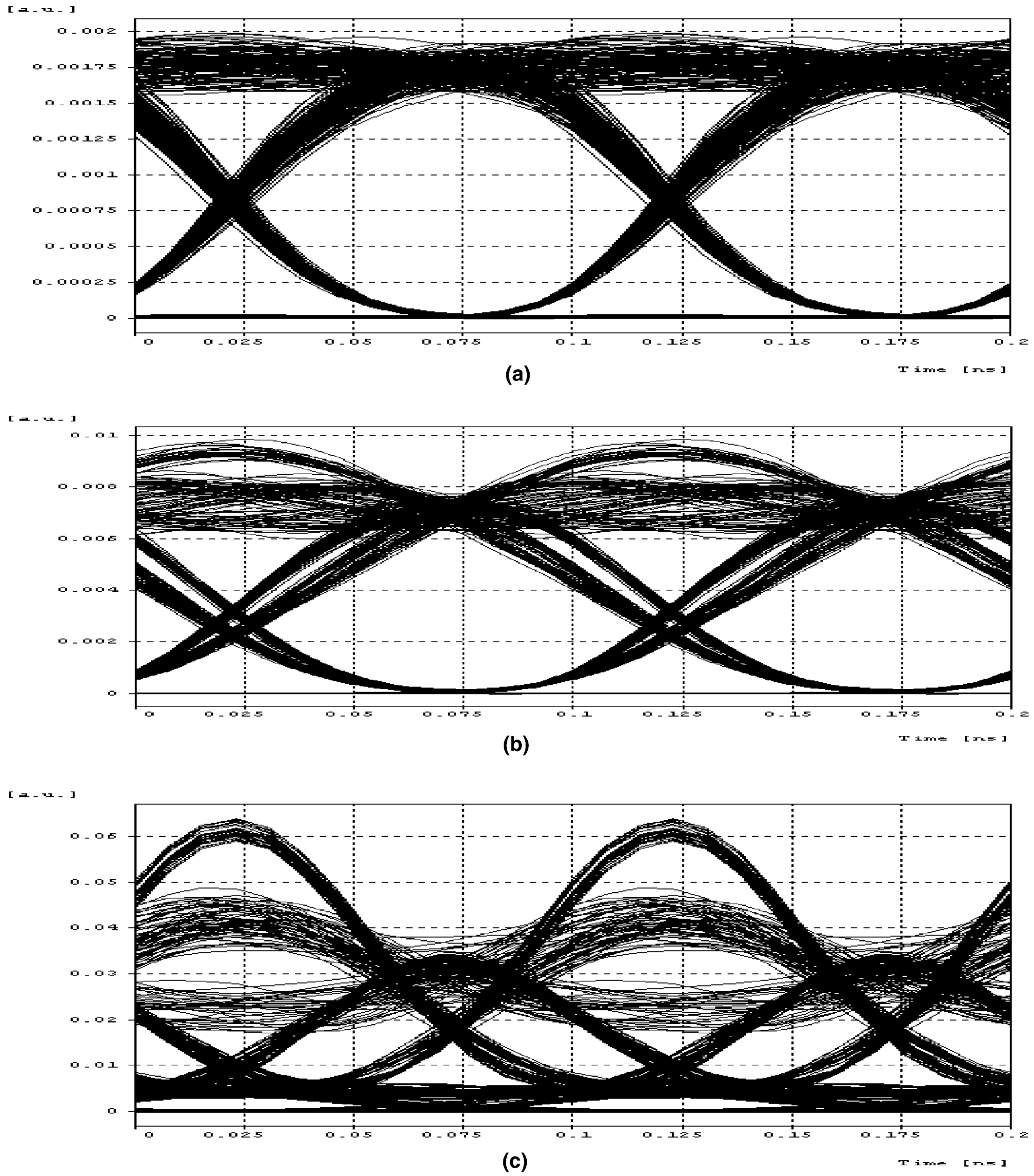

Fig. 3. Eye diagrams for pre-compensation for various values of EDFA output power: (a) 0 dBm (b) 6 dBm (c) 12 dBm.

compensations are defined over the span. Two spans are considered so that there are two dispersion compensated fibers each of length 24 km with −80 ps/nm/km dispersion and two single mode fibers each of length 120 km with 16 ps/nm/km dispersion. The optical signal is amplified after both types of fibers with EDFA amplifiers (b18 and b19 for pre-compensation and b30 and b29 for post-compensation over one span) so there are total of five EDFA amplifiers in the link. In the first case, the optical communication system is pre-compensated by the dispersion compensated fiber

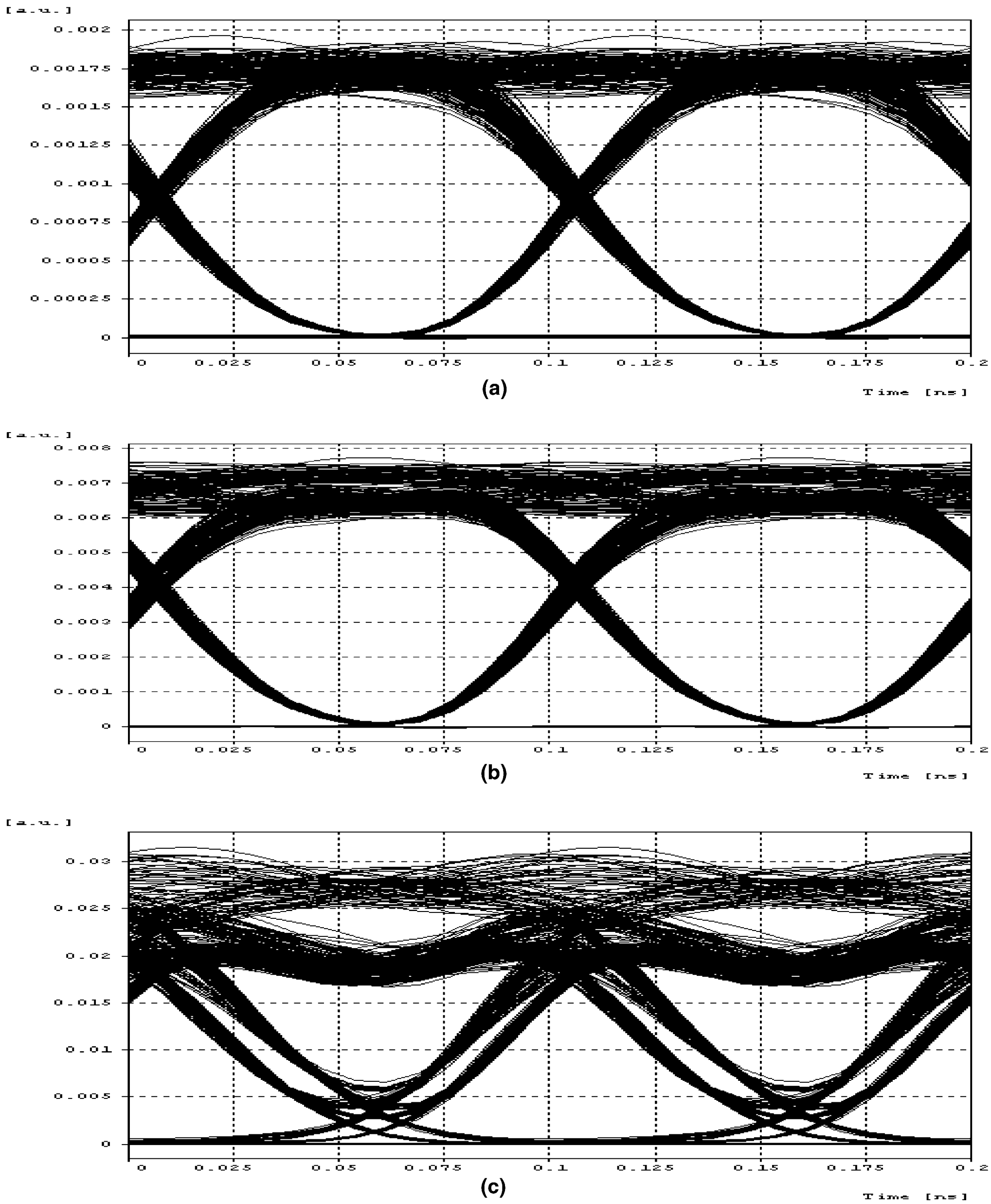

Fig. 4. Eye diagrams for post-compensation for various values of EDFA output power: (a) 0 dBm (b) 6 dBm (c) 12 dBm.

of negative dispersion (−80 ps/nm/km of length 24 km) against the standard fiber (16 ps/nm/km of length 120 km) over the span. In the second case, the optical communication system is post-compensated by the dispersion compensated fiber of negative dispersion (−80 ps/nm/km of length 24 km) against the standard fiber (16 ps/nm/km of length 120 km) over the span. In order to compare the three compensation configurations, we define equivalent symmetrical compensation configuration in the third case whereby the system is symmetrically compensated by two dispersion compensated fibers of negative dispersion (−80 ps/nm/km each of length 24 km) against two standard fibers (16 ps/nm/km of length 120 km) in between with EDFA amplifiers (b48, b47, b62 and b63) after each type of fiber. So there are also five EDFA amplifiers for this configuration also. The

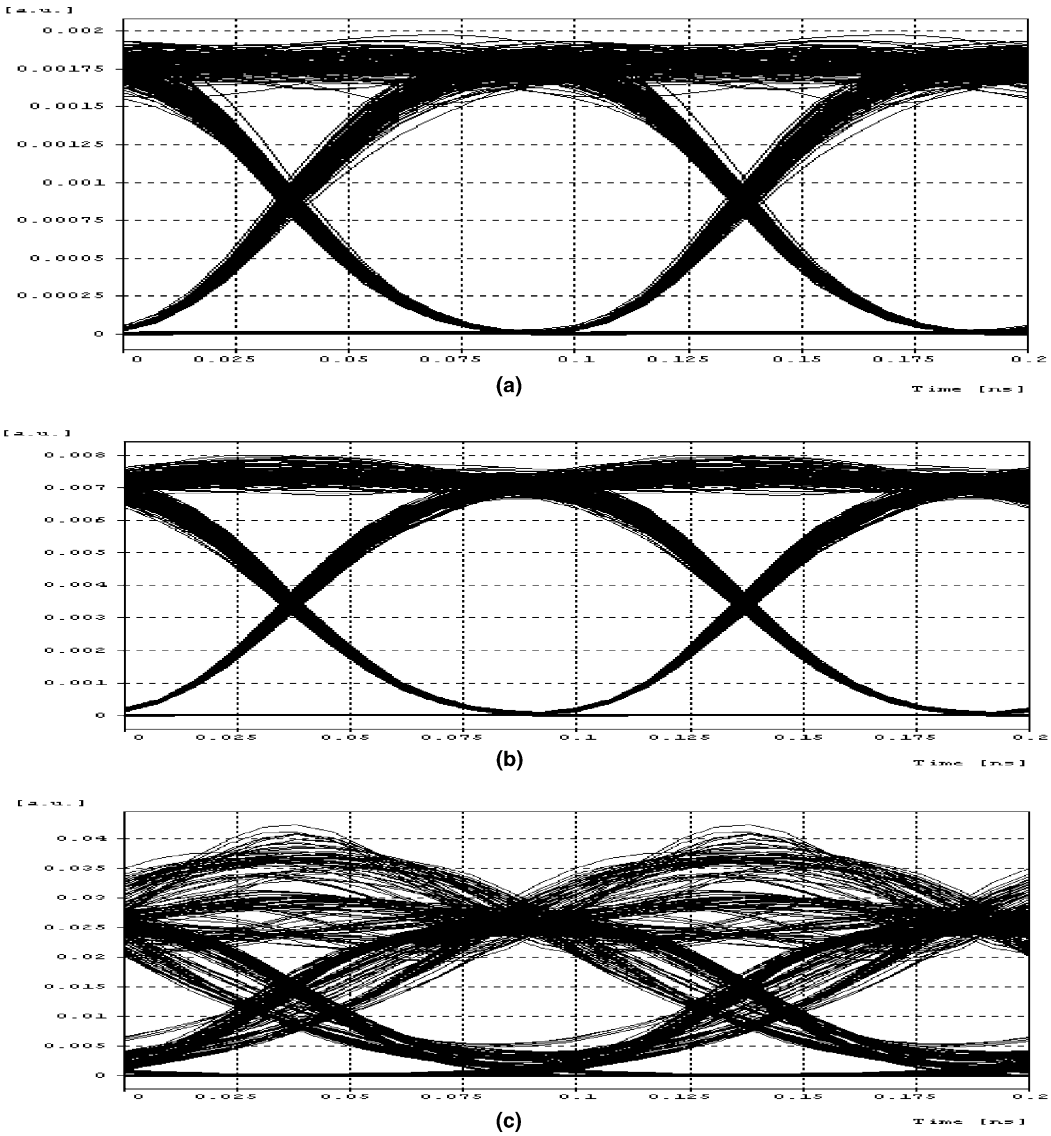

Fig. 5. Eye diagrams for symmetrical compensation for various values of EDFA output power: (a) 0 dBm (b) 6 dBm (c) 12 dBm.

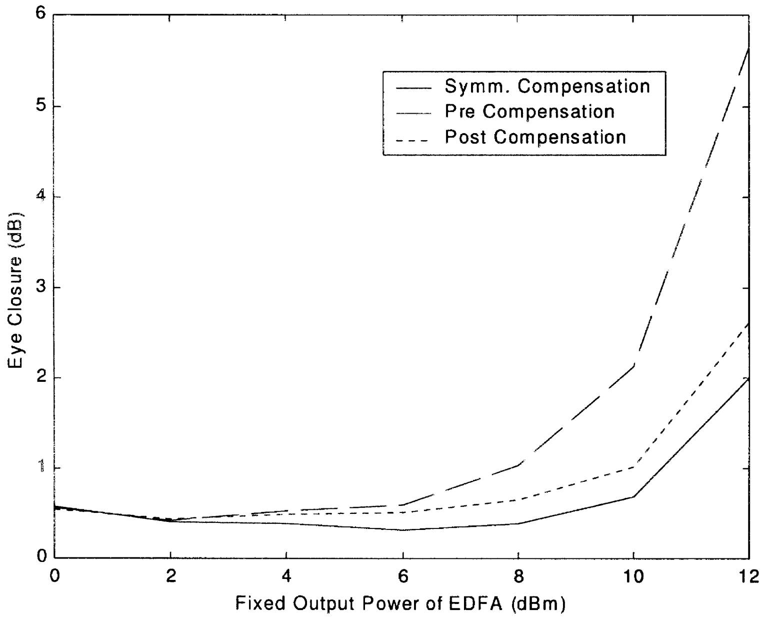

Fig. 6. Eye closure penalty for pre-, post- and symmetrical compensation for different values of EDFA power.

arrow joining EDFA amplifier (b47) and start of second single mode fiber (b66) indicates the optical link. The output is detected at the receiver by PIN detector (b2, b37 and b55 for three configurations) and is passed through electrical filter (b16, b32 and b50) and output is observed on electroscope. The electroscope gives eye diagram, Q value, bit error rate and eye closure penalty.

The laser is of type CW Lorentzian with laser center emission frequency 1550 nm (193.4145 THz). The amplitude modulator is of type sine square with excess loss of 3 dB. The simulated bit rate is 10 GHz. The EDFAs are of fixed output power type each with noise figure of 4.5 dB. The electrical filter is of the type Bessel with −3 dB bandwidth equal to 8 GHz. The detector is PIN diode with response 0.875. For comparison, 1 mW signal power is fed into the optical communication link. All fiber nonlinear, birefringence and polarization mode dispersion effects are considered in the simulations. The PMD coefficient of both single mode fiber and dispersion compensated fiber is 0.1 ps/$\sqrt{\text{km}}$. The attenuation and nonlinear coefficient for dispersion compensated fiber is 0.6 dB/km and 1.8 W^{-1} km^{-1} and that of standard fiber is 0.2 dB/km and 1.2 W^{-1} km^{-1}.

3. Results and discussions

Sequence lengths of 1024 bits are used to obtain realistic output values at the receiver. The calculation of the propagation in the optical fibers is performed by standard split-step algorithm with adaptive step-size [22]. In order to observe the dependence of the output power(s) of EDFA(s) on the output of the communication link, the gain of EDFA is varied. The variation is done in seven steps from 0 to 12 dBm with step size of 2 dBm as shown in Table 1.

The total length of communication link is 288 km and five-fixed output gain EDFAs are used. The graph between bit error rate and the fixed

Table 2
Different cases for variation of lengths for dispersion compensated fiber and standard single mode fiber

Case	Length of dispersion compensated fiber (km)	Length of standard single mode fiber (km)
1	6	30
2	12	60
3	18	90
4	24	120
5	30	150

output power of EDFA is shown in Fig. 2. It is observed that the bit error rate increases with increase in the output power of EDFA. For symmetrical compensation, the bit error rate is minimum indicating the best performance. For EDFA power up to 10 dBm, the bit error rate is 10^{-40} but if the power is increased from 10 to 12 dBm, it increases to 10^{-16} which is acceptable for high data rate optical transmission. Increasing the optical amplifier power further will bring the BER higher than the defined acceptable level. Both for post- and pre-compensation methods, the bit error rate is again 10^{-40} up to 6 dBm EDFA power but on increasing the power further to 12 dBm, it increases more rapidly for pre-compensation as compared to post-compensation method thereby indicating that the performance of post-compensation is better than the pre-compensation method. These results agree with results reported in [19] where the comparison was made with Q factor with pre- and post-compensation methods only. It is also observed that for acceptable bit error rate of 10^{-12}, the EDFA power can range from 0 to 10.2 dBm for post-compensation whereas it can only be varied from 0 to 8.8 dBm for pre-compensation method. The comparison for 0, 6 and 12 dBm EDFA power in terms of eye diagrams for the three configurations is shown in Figs. 3–5. Eye opening is defined as the difference between the minimum values of the samples decided as logical one and maximum value of the sample decided as logical zero. Average eye opening corresponds to difference between the average values for the samples. It is observed that as the EDFA power is increased, the eye opening decreases in all the three configurations. This can be explained on the basis of the fact that increase in EDFA power will bring more dominance to nonlinear effects. This decrease is minimum for symmetrical compensation and maximum for pre-compensation method thereby indicating best and worst performance, respectively. The eye opening for symmetrical compensation is better than pre- or post-compensation. The ratio of average eye opening and eye opening expressed in dB is a measure of eye closure penalty. The plot of this penalty and EDFA power is shown in Fig. 6. As is clear from the figure, the penalty for symmetrical compensation is minimum followed by post- and pre-compensation.

In order to see the influence of transmission distance on the three compensation methods, we

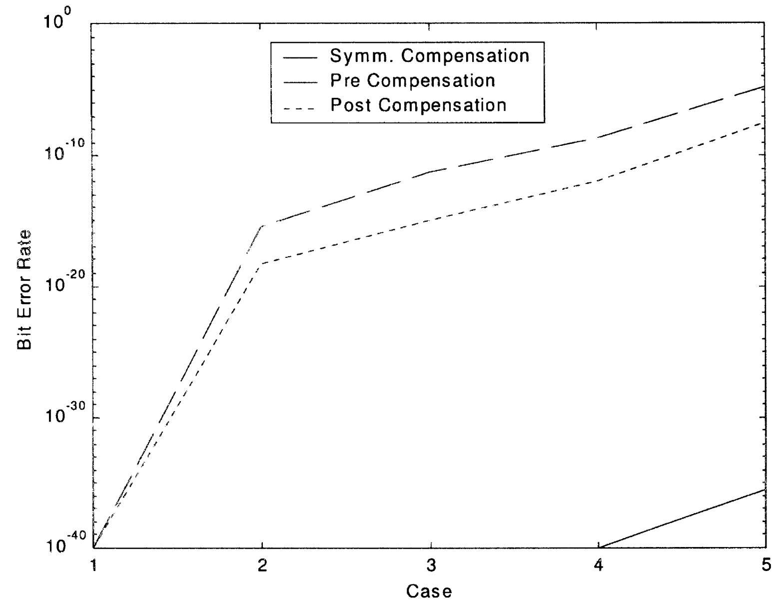

Fig. 7. Bit error rate for different cases indicated in Table 2 for pre-, post- and symmetrical compensation methods.

now change the lengths of fibers in Fig. 1. We increase simultaneously the lengths of dispersion compensated fibers and standard single mode fibers in the original setups for pre-, post- and symmetrical compensation methods for five different cases as shown in Table 2. The cases are so chosen that the dispersion compensation is ensured for all the configurations. The spans for pre- and post-compensation configurations remain the same as indicated in the figure. The value of EDFA power is now chosen to be 5 dBm for all the cases.

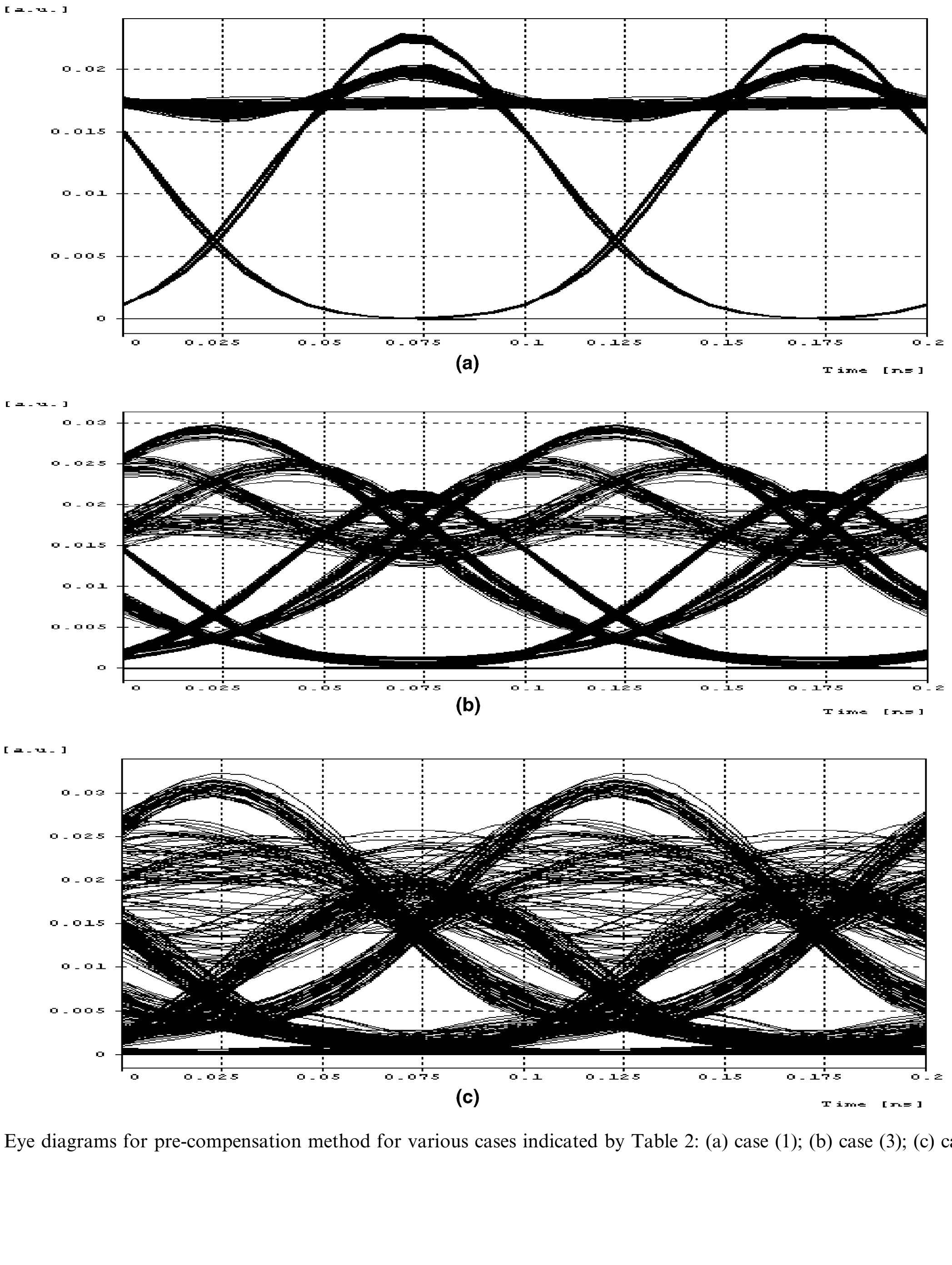

Fig. 8. Eye diagrams for pre-compensation method for various cases indicated by Table 2: (a) case (1); (b) case (3); (c) case (5).

The graph between bit error rate and cases indicated in Table 2 (lengths of fibers) is shown in Fig. 7. It is seen that as the length of the fibers is increased, the bit error rate increases. Again for symmetrical compensation method, the bit error rate is minimum. For increase in lengths of fibers up to case (4) (24 km DCF and 120 km SMF with two spans), the bit error rate for symmetrical compensation method is 10^{-40} and this increases to 10^{-36} for the fifth case. There is further scope for increase in length for this configuration. But for pre- and post-compensation methods, the situation is drastic. It is seen that for acceptable bit error rate of 10^{-12}, the maximum transmission

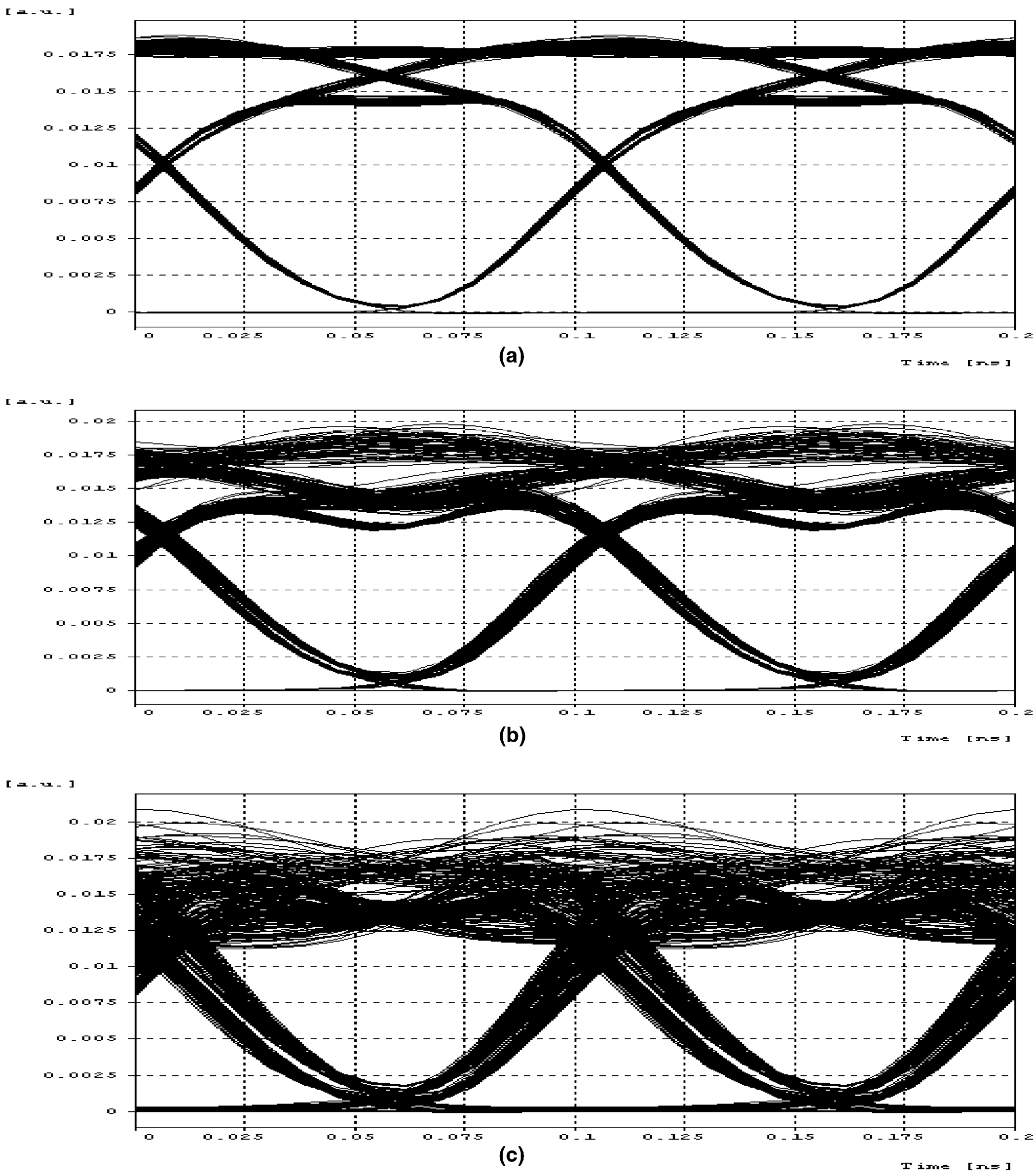

Fig. 9. Eye diagrams for post-compensation method for various cases indicated by Table 2: (a) case (1); (b) case (3); (c) case (5).

distance for post-compensation is up to case (4) (total = 288 km) whereas it is approximately equal to case (3) (total = 216 km) for pre-compensation method. This clearly indicates that symmetrical compensation method is far superior to pre- and post-compensation methods. On comparing the two pre- and post-compensation methods again it is found that the later is superior to the former.

The eye diagrams for pre-, post- and symmetrical configuration for three cases (case (1), (3) and (5)) are shown in Figs. 8–10. It is clear that as the lengths of fibers are increased (case number increases), the eye opening reduces. Again it is found that there is more eye opening for symmetrical compensation method. The eye opening for the post-compensation method is better than the pre-compensation method. For case (5) with pre-

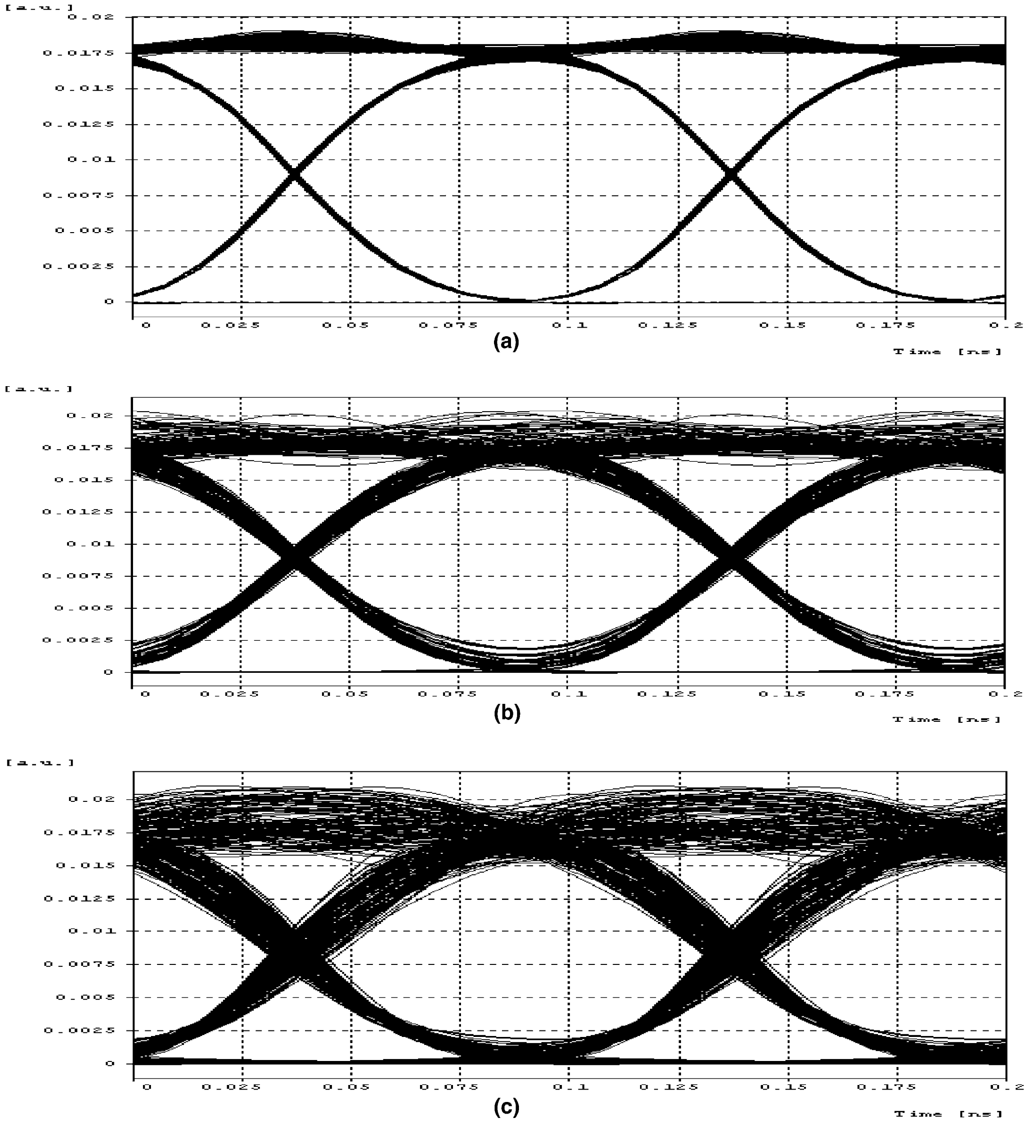

Fig. 10. Eye diagrams for symmetrical-compensation method for various cases indicated by Table 2: (a) case (1); (b) case (3); (c) case (5).

compensation method, the deterioration is so large that further increase in length is not feasible. This is also indicated by eye closure penalty as shown in Fig. 11. It is seen that the eye closure penalty is minimum for symmetrical compensation method. This penalty is again less for post-compensation as compared to pre-compensation method. The eye closure penalty above 2.8 dB indicates bit error rate more than 10^{-9} and unacceptable which is for case (5) of pre-compensation.

The influence of combined effects of EDFA power and transmission distance on the three compensation methods is now studied by varying both the parameters. We increase simultaneously the EDFA power and lengths of the fibers in the original setups for pre-, post- and symmetrical compensation methods for five different cases as shown in Table 3. The lengths of fibers are again so chosen that the dispersion compensation is ensured for each case. The spans for pre- and post-compensation configurations remain the same as indicated in Fig. 1.

The graph between bit error rate and cases indicated in Table 3 is shown in Fig. 12. The same comparison results are observed, i.e., performance is better for symmetrical configuration followed by post- and pre-configuration. However, an improvement in performance up to case (4) is clearly observed in the figure. It is seen that bit error rate is zero up to the fourth case whereas it is not equal to zero for the simulations in which only lengths were increased (Fig. 7). This signifies the need of optimization between the EDFA power and the length of the fiber over which the signal is propagated. For smaller EDFA power, the length of the fiber should be small and if we have larger EDFA power for small length, the situation instead of improving will deteriorate on account of more nonlinear effects. On the contrary, if we have less EDFA power for larger length of the fiber, the situation will be worse as indicated by the case (5). The corresponding bit error rate is found to be unacceptable for this case. This can also be judged from the performance analyses of the eye diagrams of the three configurations that are indicated for three cases (case (1), (3) and (5)) as shown in Figs. 13–15. Further, the eye closure penalty diagram shown in Fig. 16 indicates that the system has been optimized for the first four cases for EDFA power and lengths of fibers and for the fifth case, there is

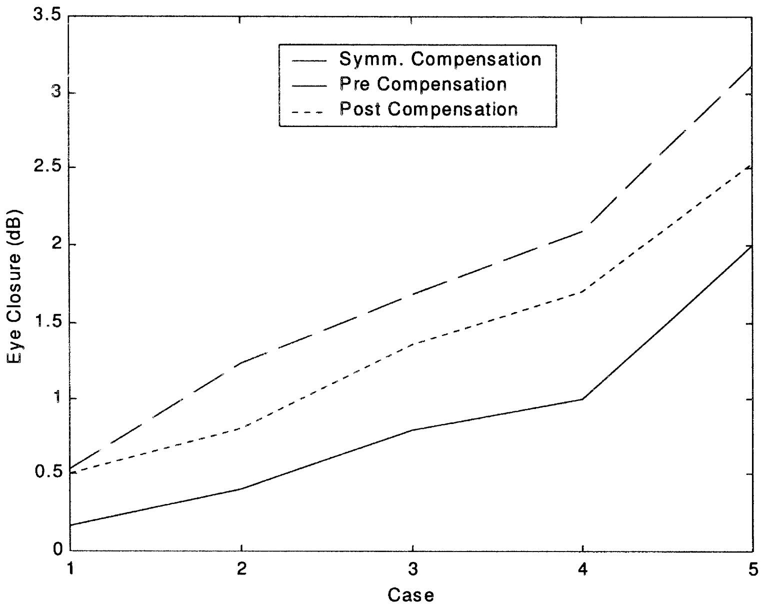

Fig. 11. Eye closure penalty for pre-, post- and symmetrical compensation for different cases indicated in Table 2.

Table 3
Different cases for variation of EDFA powers and lengths for dispersion compensated fiber and standard single mode fiber

Case	EDFA power (dBm)	Length of dispersion compensated fiber (km)	Length of standard single mode fiber (km)
1	0	6	30
2	3	12	60
3	6	18	90
4	9	24	120
5	12	30	150

mismatch between the EDFA power and length of the fiber.

4. Conclusions

The paper illustrates optimization of high data rate optical transmission using dispersion compensated fibers. The output parameters like bit error rate, eye diagrams and eye closure penalty for pre-, post- and symmetrical compensation are compared for variation in fixed gain EDFA power and lengths of each type of fibers. From the simulation results, it is found that as the EDFA power increases, the bit error rate increases. The symmetrical compensation has the best performance followed by post- and pre-compensation. This is also illustrated through eye diagrams and eye closure penalty. Also, the influence of transmission distance on the three compensation methods has been discussed by simultaneously increasing the lengths of fibers and keeping the EDFA power constant. As the lengths of the fibers are increased, the bit error rate increases. The bit error rate for symmetrical compensation method is again minimum but for pre- and post-compensation methods, the situation is not so good. For acceptable bit error rate of 10^{-12}, the maximum transmission distance for post-compensation is up to 288 km whereas it is approximately up to 216 km for pre-compensation method for this simulation. The eye diagrams and eye closure penalty also illustrate the same comparison results. Further, on varying the EDFA power and lengths of the fibers simultaneously, it is found that there is need of optimization between these two parameters. If the EDFA power is small, the length of the fiber should be small and if it is not so, the situation will deteriorate on account of more nonlinear effects. For

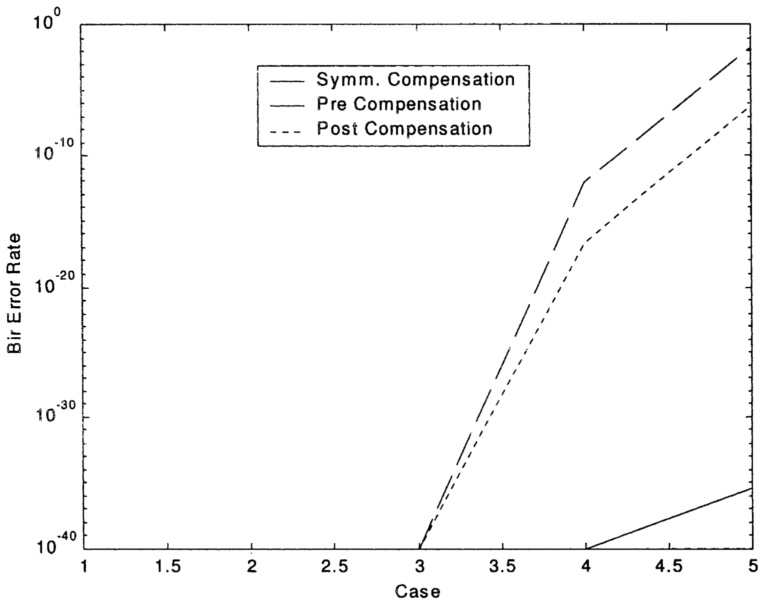

Fig. 12. Bit error rate for different cases indicated in Table 3 for pre-, post- and symmetrical compensation methods.

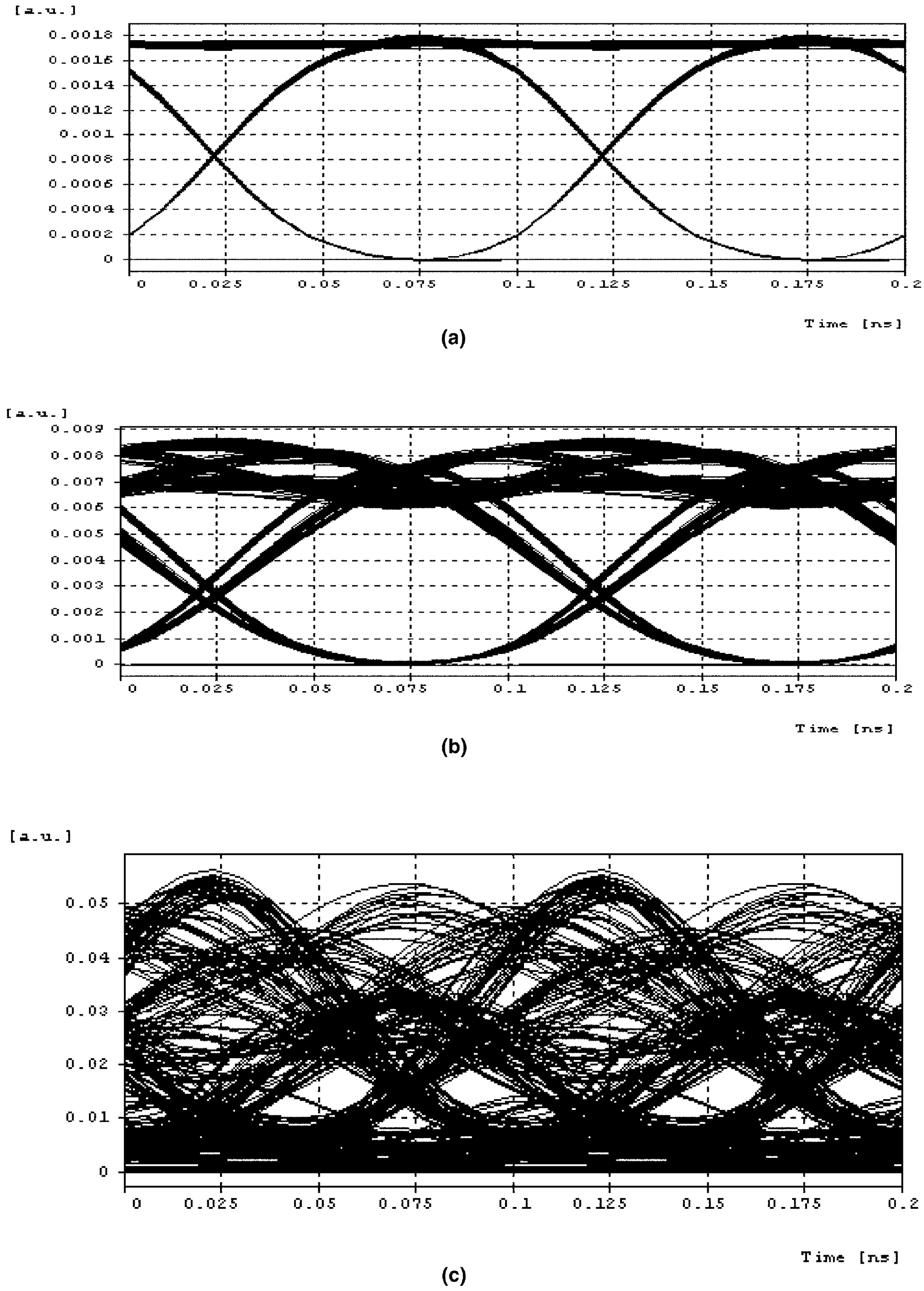

Fig. 13. Eye diagrams for pre-compensation method for various cases indicated by Table 3: (a) case (1); (b) case (3); (c) case (5).

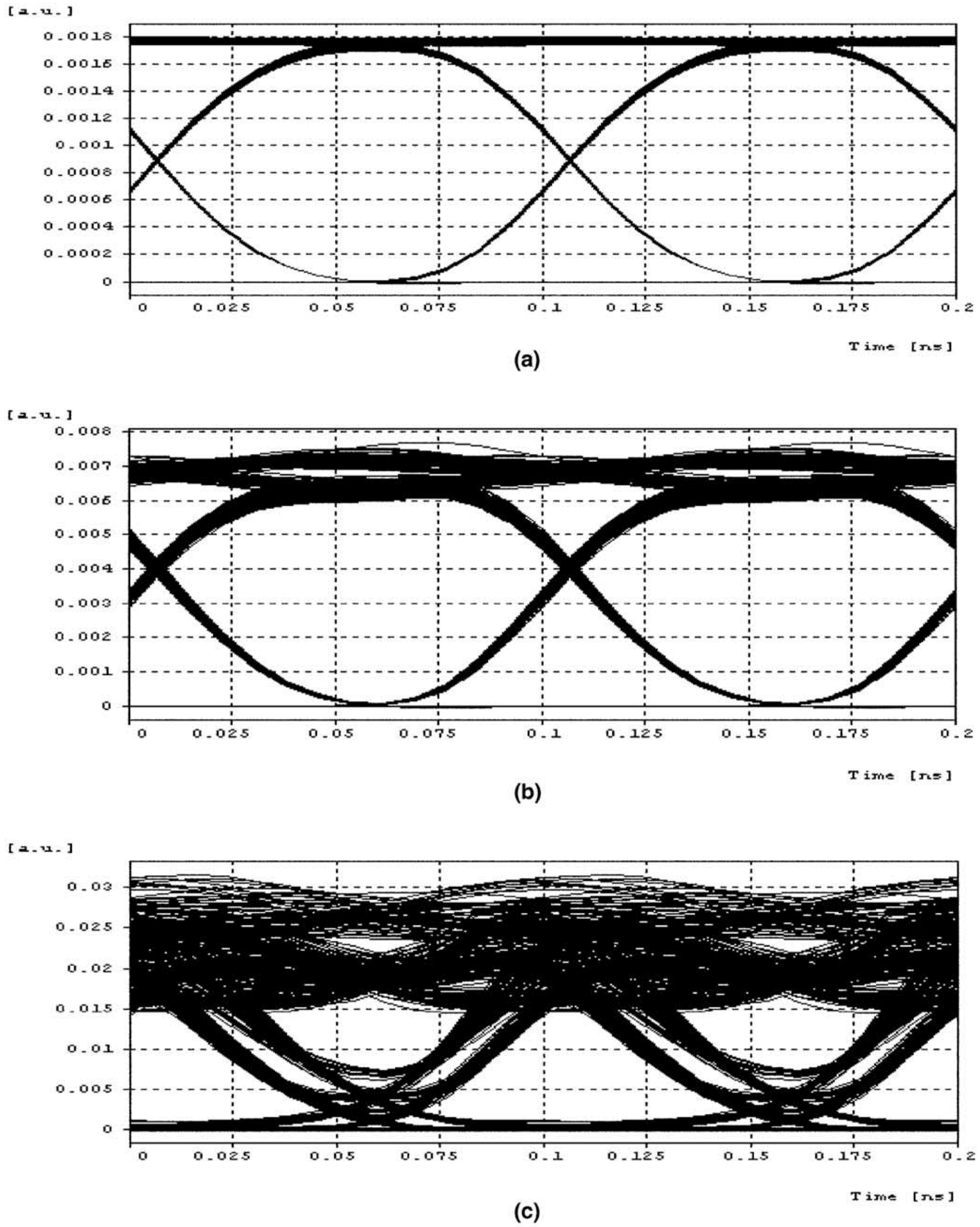

Fig. 14. Eye diagrams for post-compensation method for various cases indicated by Table 3: (a) case (1); (b) case (3); (c) case (5).

less EDFA power over larger length of the fiber, the situation will be worse as predicted. This reflects the need of optimization and there should not be any mismatch between the EDFA power and length of the fiber.

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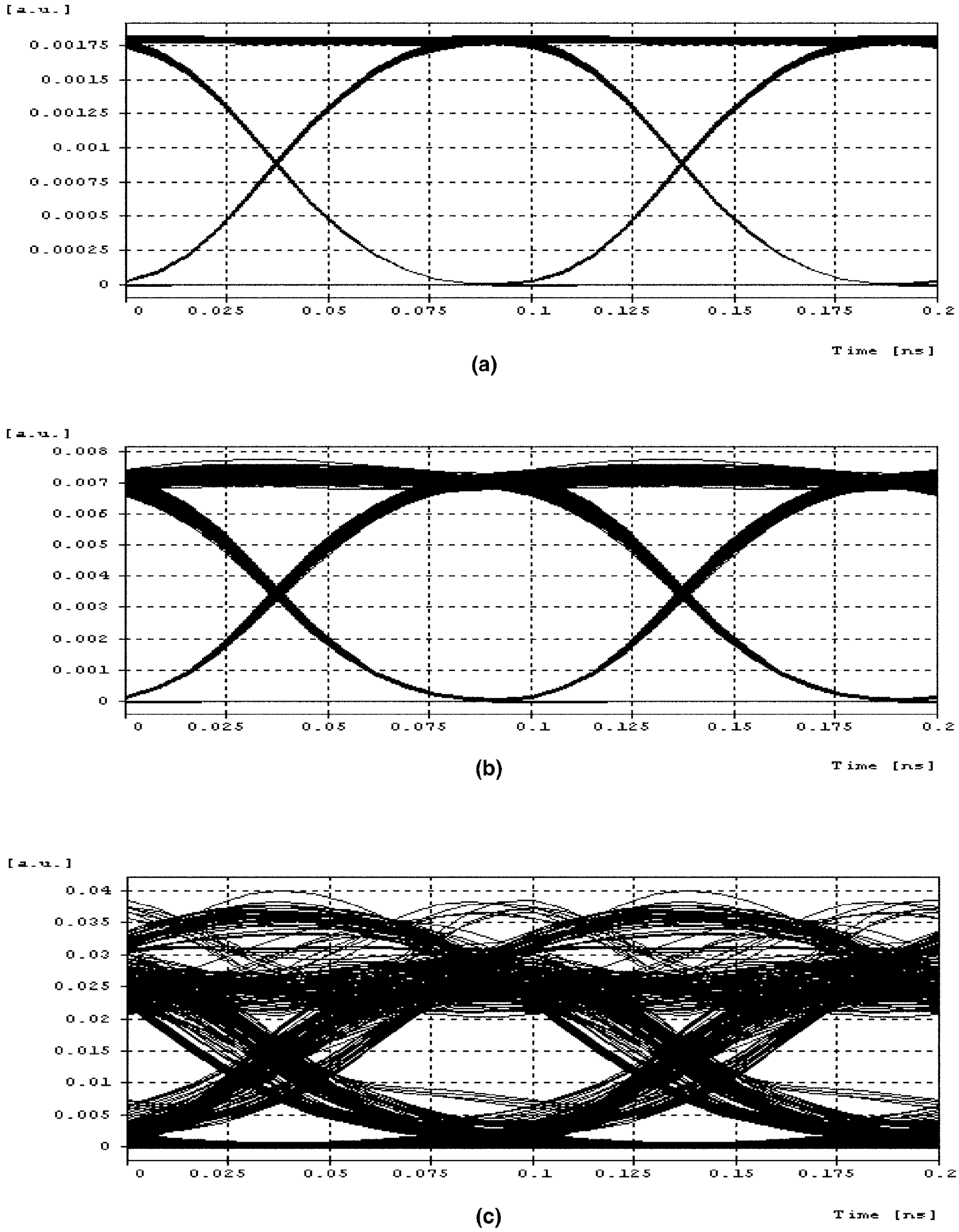

Fig. 15. Eye diagrams for symmetrical-compensation method for various cases indicated by Table 3: (a) case (1); (b) case (3); (c) case (5).

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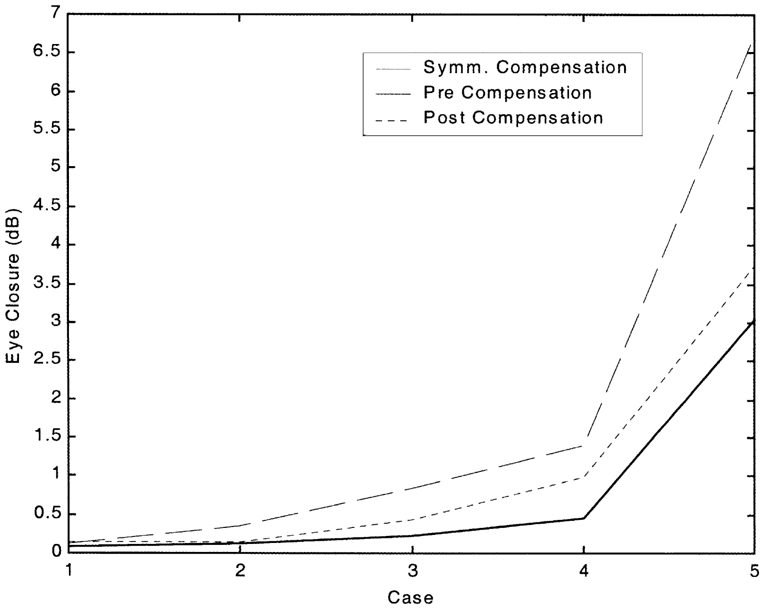

Fig. 16. Eye closure penalty for pre-, post- and symmetrical compensation for different cases indicated in Table 3.

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