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On duty cycle selection of RZ optical pulse to optimize the performance of dispersion compensated 10 Gbps single channel optical communication system using dispersion compensating fibers

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Abstract

We present results for duty cycle selection of optical RZ pulse to optimize the performance in 10 Gbps single channel dispersion compensated optical communication system. The system has link length of 240 km with two spans. Each of the spans consists of 120 km standard single mode fiber (SSMF) of 16 ps/nm/km, whose chromatic dispersion is compensated using pre-, post- and symmetrical-dispersion compensation schemes by 24 km dispersion compensating fiber (DCF) of −80 ps/nm/km. The performance of the three compensation schemes is compared by taking 8, 10, 12 and 14 dBm Er-doped fiber amplifier (EDFA) power levels in the link with a duty cycle range (0.1–0.9) of RZ optical pulse. The graphical results obtained show a relationship among the duty cycle, EDFA power and dispersion compensation scheme which predicts the best performing duty cycle case. To optimize performance of the system, we recommend in general, duty cycle less than 0.3 and EDFA power below 8 dB irrespective of compensation scheme. However, with post compensation duty cycle less than 0.7 and EDFA power below 12 dBm give optimum performance. The results conclude that for the high value of duty cycle, post dispersion compensation scheme should be used.

Keyword: Duty cycle; Dispersion compensation; Timing jitter; Bit error rate; *Q* value

1. Introduction

The impact of optical communication because of its numerous advantages has been observed in the field of long-haul signal transmission systems and networks. Upgrading of them make use of Er-doped fiber amplifiers (EDFAs) to compensate fiber loss and extend the non-regenerated signal transmission distance. Since the use of EDFAs requires an operation in the wavelength region around 1550 nm, chromatic dispersion will be the primary limitation for future up gradation of embedded networks comprised of conventional single-mode fiber with zero dispersion wavelengths near 1300 nm. This development demands

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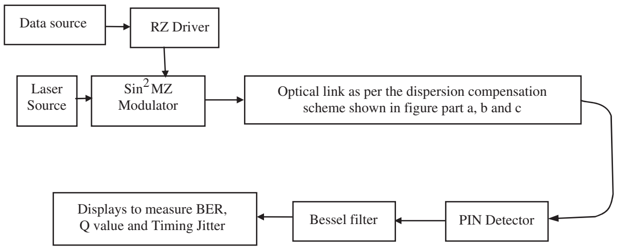
dispersion management as an essential technique for upgrading the bit rate of existing optical links to meet the increasing traffic demand [1]. In fact, for systems operating above 10 Gbps over standard single mode fiber (SSMF), dispersion compensation is mandatory, even for metro distances. A number of methods have been proposed to overcome the impairments caused by chromatic dispersion including initial pre-chirp [2,3], microchip compensation [4], mid-span spectral inversion [5], optical phase conjugation [6–8], dispersion-supported transmission [9], dispersion compensating devices [10–12] and differential delay method [13–17]. The use of dispersion compensated fiber (DCF) is an important method for dispersion compensation and to upgrade the already installed links of single mode fiber [18,19]. The DCFs 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. The spans having SSMFs and DCFs 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. The compensation is done by three methods, pre-, post- and symmetrical-compensation. In the first method, the optical communication system is pre compensated by DCF of negative dispersion against the dispersion of SSMF. In the second method, the optical communication system is post-compensated by DCF of negative dispersion against SSMF's dispersion. In the third method, the optical communication system is symmetrically compensated by two DCFs of negative dispersion against SSMFs in between. Due to the nonlinear nature of propagation, the system performance depends upon power levels [20] and the position of DCFs [21].

At the same time, exploration on data formats of optical signal found in literature for dispersion compensated optical communication systems, which play a vital role in its performance. The need of proper data format of optical pulse is the basic requirement, have equal importance. For WDM systems, single-channel data transmission rates of 10 Gbps have been studied by comparing three different modulation formats: NRZ; RZ without initial chirp; and chirped return to zero (CRZ) [22]. It is suggested that in order to obtain a transmission distance greater than 5000 km with reasonable power margins, CRZ modulation format and symmetric dispersion compensation is preferred. RZ optical signal pulse duty cycle has been investigated in 10-Gbps/ch long-distance transmission and observed that the optimum duty factor depends on GVD compensation interval for single-channel transmission. Also, the reduced duty factor value suppresses XPM induced waveform distortion in WDM transmission. Analysis of both single-channel and WDM transmission showed that duty factors 0.5 were suitable for a dispersion managed system with GVD compensation interval of 500 km and a fiber dispersion parameter of 1 ps/nm/km [23]. Numerically, the performance of dispersion-managed 40 Gbit/s TDM-transmission systems over the already installed standard fiber has been analyzed in simulations assuming conventional NRZ and RZ-modulation format with different duty ratios. It is shown that for 40 Gbps TDM-systems, RZ-modulation format with a duty cycle of 0.5 is inherently superior to the conventional NRZ-transmission scheme [24].

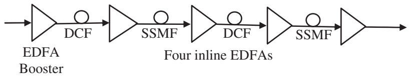
The authors have already presented an investigation on NRZ data format giving comparison of different dispersion compensation schemes [27]. Here, the study is further extended through this paper by taking range of duty cycle 0.1–0.9 of RZ optical pulse to have more comprehensive look at the optimized performance with RZ data format. In addition to duty cycle variation and the importance of proper EDFA power is shown in three dispersion compensation schemes with the use of DCFs [25]. Earlier in the literature [26–27], pre- and post-compensation methods were discussed and compared for Q factor and eye penalty. Here, the results of pre-, post- and symmetric-compensation methods on the basis of important additional features like bit error rate (BER), timing jitter are compared. In Section 2 of this paper, the optical simulated project and parameters are defined. In Section 3 comparative results have been reported for these compensation methods and finally in Section 4, conclusions are drawn.

2. Simulations

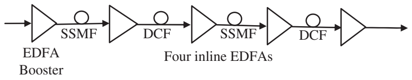
The block diagram of the communication system used is shown in Fig. 1, whose optical link details are separately shown in the Fig. 1a–c for pre-, post- and symmetrical-compensation methods, respectively, using SSMFs and DCFs. The figure shows transmitter section consists of data source, electrical driver, laser source and amplitude modulator. The data source gives random logical pulses at 10 Gbps bit rate to electrical driver. The driver is an important component that generates desired duty cycle 'return to zero' data modulation format. It also converts a logical input signal of a binary sequence (consisting zeros and ones) into an electrical signal. The CW laser source generates laser beam at 1550 nm whose output along with the output of the electrical driver is given to a modulator. The output of modulator is fed to optical link through an EDFA acting as a booster



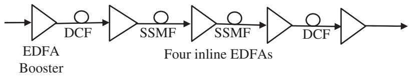
10 Gb/s single channel optical communication system model considered in each compensation scheme



(a) Optical link with pre compensation scheme



(b) Optical link with post compensation scheme



(c) Optical link with symmetric compensation scheme

Fig. 1. 10 Gbps single channel optical communication system model of optical link length 240 km using DCF of 24 km ($D = -80$ ps/nm/km) and SSMF 120 km ($D = 16$ ps/nm/km) with three dispersion compensation schemes: (a) pre, (b) post and (c) symmetric.

amplifier. The optical link is defined as pre-, post- and symmetric-compensated according to the order of fiber spans placed. Two spans are considered so that there are two DCFs each of length 24 km with −80 ps/nm/km dispersion and two SSMFs each of length 120 km with 16 ps/nm/km dispersion. The optical signal is amplified after each span of fiber, with EDFAs so that there are total of five EDFAs in the each link. In the first case, the optical communication system is pre-compensated by DCF of negative dispersion against SSMF over the span. In the second case, the system is post-compensated by the same DCF against SSMF 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 DCFs of negative dispersion against two SSMFs and amplification with in-between EDFAs after each type of fiber. So, there are five EDFAs for this configuration also. Length of the optical link comes out 240 km [= 2 × (120 km of SSMF)] in each case and kept equal to obtain comparative results for them. The output is detected at the receiver by PIN detector and is passed through electrical filter and its output is observed on BER meter, *Q* meter and timing jitter to read corresponding values which are subsequently plotted. Moreover, the laser is of type CW Lorentzian with laser center emission frequency 1550 nm (193.4145 THz). The amplitude modulator is of sine square type with excess loss of 3 dB. The simulated bit rate is 10 GHz. The in-line EDFAs are of fixed output power type with noise figure of 4.5 dB. The 3 dB bandwidth of electrical Bessel filter is 8 GHz. The detector consists of PIN diode with response 0.875. For comparison, 1 mW signal power is fed into modulator then power of the each optical amplifier in optical communication link is simultaneously changed from 8 to 14 dBm in 2 dBm steps to find a power level to achieve optimum performance. Fiber nonlinear, birefringence and polarization mode dispersion effects are assumed to be present in the simulations. The PMD coefficient of both SSMFs and DCFs is 0.1 ps/km$^{0.5}$. The attenuation and nonlinear coefficient for DCFs is 0.6 dB/km and 1.8 W^{-1}/km and that of SSMFs is 0.2 dB/km and 1.2 W^{-1}/km, respectively.

3. Results and discussion

The second order chromatic dispersion of SSMF is compensated in each of three models considered with DCFs as per the compensation scheme used. The relation $D_1L_1 + D_2L_2 = 0$ may be used to verify compensation, where D_i and L_i are the first dispersion parameter and the length of respective SSMFs and DCFs. The third order dispersion can cause dispersion to small extend and thus neglected in compensation. For single-channel light wave systems, the dominant nonlinear phenomenon that limits the system performance is self-phase modulation (SPM). If the launch power over the amplified link is satisfying the relation (1) of peak power then SPM due to phase accumulation over multiple amplifiers is of little concern [23].

$$P_{\text{in}} < 0.1\alpha/(\gamma N_{\text{A}}) \tag{1}$$

where P_{in} (W) is input peak power, α (dB/km) is attenuation, γ (W^{-1}/km) is nonlinear coefficient, N_{A} is number of amplifiers in link. A generalized equation called nonlinear Schrodinger equation (NLSE) with neglecting third order dispersion term has the form shown by Eq. (2) [23].

$$\frac{\partial A}{\partial z} + \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = -\frac{\alpha}{2}A + \mathrm{i}\gamma|A|^2 A \tag{2}$$

Where $A(z,t)$ is slowly varying amplitude of pulse envelope, β_2 is group velocity dispersion, α is attenuation and γ is nonlinear coefficient related to SPM. Because of nonlinear nature of the Eq. (2), it is usually solved numerically. A repeated sequence of 1024 bits length is used to decrease error less than ±1 dB in the calculation of *Q* value and also to keep the corresponding error in BER and timing jitter under control. The calculation of propagation in the optical fibers is performed by standard split-step algorithm with adaptive step-size [23]. In order to observe the dependence of duty cycle of RZ optical pulse on the output of the

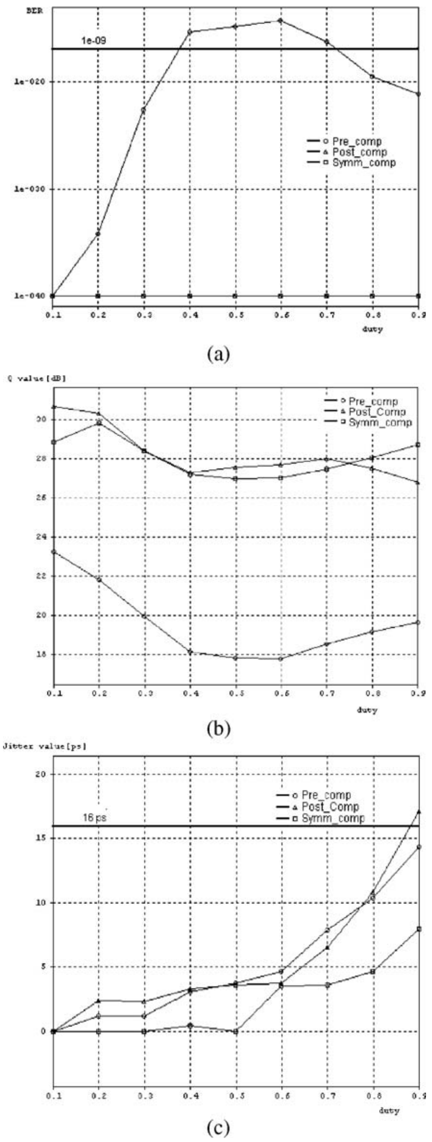


Fig. 2. Duty cycle comparison among pre, post and symmetrical dispersion compensation schemes at EDFA power = 8 dBm in terms of: (a) BER, (b) Q value and (c) timing jitter.

communication link, duty cycle is varied from 0.1 to 0.9 in 0.1 steps. Five fixed-output EDFAs are used in link whose gains are changed simultaneously in the link to provide output power 8–14 dBm in 2 dBm steps to observe the role of EDFAs. The graph between BER and duty cycle value at 8 dBm fixed-output power of EDFA is shown in Fig. 2a. It gives indication that pre dispersion compensation is sharply affected by duty cycle. The system is only useful (i.e. BER $< 10^{-9}$) for pre compensation if duty cycle is kept <0.3 or 30%, the corresponding Q value seen from Fig. 2b show decline in Q value below 20 dB i.e. changes from 23 dB at duty cycle value 0.1 to 18 dB at duty cycle value 0.4. The other schemes post and symmetric dispersion compensation perform well on the same basis throughout the range of duty cycle providing BER $< 10^{-9}$ and Q value > 27 dB for each trial. Similarly Fig. 2c illustrates timing jitter increase for every dispersion compensation scheme as the duty cycle is increased beyond 0.6 because of ASE noise accumulation and nonlinearities which are giving pronounced effect on the performance after 0.6 duty cycle value. The figure also shows that the symmetric scheme offers lower timing jitter. Thus, at 8 dBm power of EDFAs, post and symmetric schemes give better performance over the range of duty cycle.

By increasing EDFA power to 10 dBm, the variation of BER is plotted against the duty cycle range 0.1–0.9, in reference to Fig. 3a. It shows that pre-dispersion compensation performs better within duty cycle strictly less that 0.3 whereby other two dispersion compensation

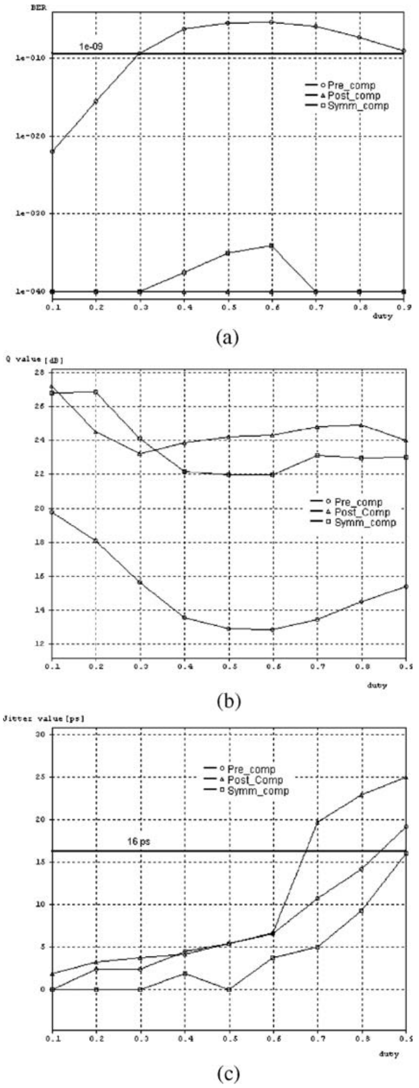


Fig. 3. Duty cycle comparison among pre, post and symmetrical dispersion compensation schemes at EDFA power = 10 dBm in terms of: (a) BER (b) Q value and (c) timing jitter.

techniques perform well in complete range of duty cycle. In same figure, increase in BER has been reported in mid-values (0.3–0.7) of duty cycle but not significant. The Q value of pre compensation, in comparison to other dispersion compensation schemes in Fig. 3b, is almost 10 dB low. The Q value of post scheme is even better by 2 dB from symmetric scheme at some value of duty cycle. The timing jitter performance in Fig. 3c, each scheme produces jitter higher than permissible value (16 ps) for duty cycle more than 0.6 which is a specified standard for 10 Gbps single-channel optical communication systems [19,27].

The Fig. 4a shows large variation in BER output, if EDFA power rises to 12 dBm. It results that pre compensation is no longer useful candidate of dispersion compensation over the range of duty cycle. Theoretically, if we substitute parameters of our model considered ($N_A = 5$, $\alpha_{SMF} = 0.6$ dB/km, $\gamma_{SMF} = 1.8\,W^{-1}$/km, $\alpha_{DCF} = 0.2$ dB/km, $\gamma_{DCF} = 1.2\,W^{-1}$/km) in relation (1). The values of threshold power to cause SPM are $P_{th} = 11.7$ dBm for SMF while 8.8 dBm for DCF. It shows that shifting EDFA power from 10 to 12 dBm distortion in link is due to SPM nonlinearity of SSMF as launched power exceeds the limit 11.7 dBm. Moreover, the power is effectively depends on the average value of signal power thus duty cycle and compensation scheme show certain safe regions of operation. The symmetric dispersion compensation is useful only for the duty cycle value less than 0.4. But the post compensation scheme can give good performance over all the range of duty cycle. The concerned Q value and timing jitter justify system performance on the same lines and can be observed in Fig. 4b and c indicating system becoming poorer with the increase in duty cycle. Lastly, in Fig. 5a gives indication that symmetric dispersion

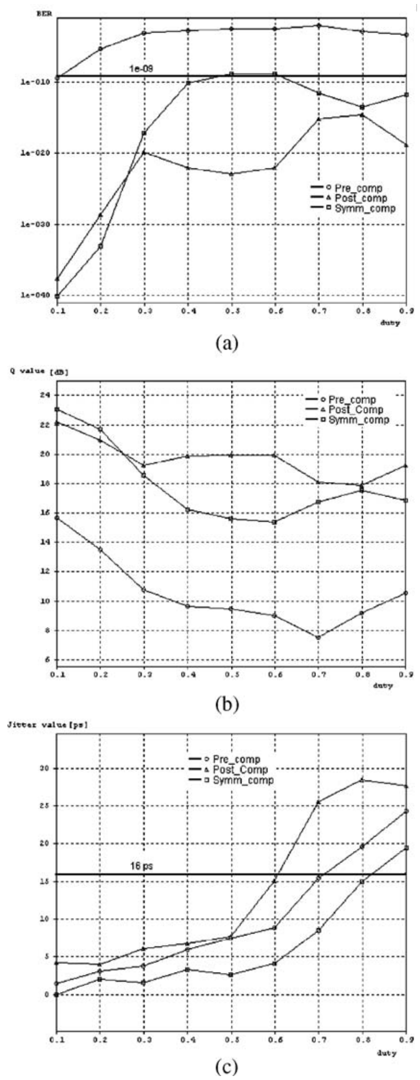


Fig. 4. Duty cycle comparison among pre, post and symmetrical dispersion compensation schemes at EDFA power = 12 dBm in terms of: (a) BER, (b) Q value and (c) timing jitter.

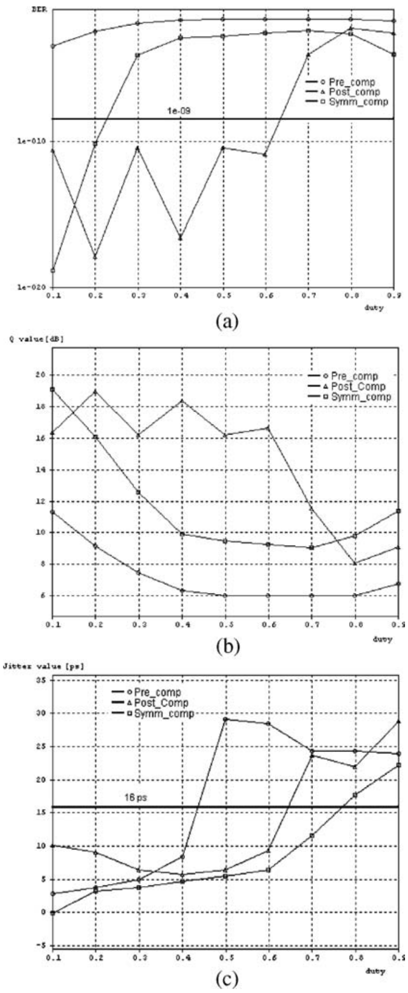


Fig. 5. Duty cycle comparison among pre, post and symmetrical dispersion compensation schemes at EDFA power = 14 dBm in terms of: (a) BER, (b) Q value and (c) timing jitter.

Table 1. Depicting the highest useful duty cycle (i.e. at BER = 10^{-9}) for each dispersion compensation scheme for the single channel optical communication system considered.

Dispersion schemes	RZ optical pulse duty cycle at various EDFA powers			
	8 dBm	10 dBm	12 dBm	14 dBm
Pre	<0.35	<0.3	Not feasible	Not feasible
Post	Any	Any	Any	<0.5
Symmetrical	Any	Any	<0.4	<0.2

compensation is useful if duty cycle is less than 0.2, post dispersion compensation if duty less than 0.6. The respective Q value, timing jitter variation can be observed through diagram Fig. 5b and c and limiting values duty cycle with each compensation technique are provided in tabular form in Table 1.

In the above trials, while going from 0.1 to 0.9 duty cycle, actually we move from RZ pulse shape to very near NRZ pulse shape. In the RZ format, each optical pulse represents bit 1, shorter than bit slot and its amplitude RZ before the bit duration is over. In NRZ format the optical pulse remains on throughout the bit slot and its amplitude does not drop to zero between two or more successive 1 bits. As a result, pulse width varies depending on bit pattern, whereas it remains same in the case of RZ format. An advantage of the NRZ format is that the bandwidth associated with bit stream is smaller than that of RZ format by a factor of two simply because on–off transitions occur fewer times. However, its use requires tighter control of pulse width and may lead to bit pattern dependent effects if optical pulse spreads during transmission which is cause of deterioration of BER at high duty cycle value visible in each BER versus duty cycle plot in the investigations. But NRZ format is often preferred in practice because of a smaller signal bandwidth associated with it. Comparatively the use of RZ format in the optical domain helps in the design of high capacity light wave systems [19,23]. Here, it is found that there is always a limit for higher value of duty cycle of the optical pulse on the basis of BER, Q value and timing jitter to be kept under control but there is also a limit on the smaller value of duty cycle on the basis of its spectral bandwidth. Thus considering the spectral aspect of duty cycle of optical pulse only higher side limit of duty cycle should be used which is recommended and listed in Table 1.

4. Conclusions

The performance of pre-, post and symmetric-dispersion compensation schemes is compared in the range 8–14 dBm with 2 dBm steps of fixed-output EDFA power in single channel optical communication link with duty cycle of RZ optical pulse in the range 0.1–0.9. A significant relationship among the duty cycle, power of in-line amplifiers and dispersion compensation scheme implemented for the system is established. It is found that in order to optimize the performance of system; we should use duty cycle less than 0.3 and EDFA power below 8 dB irrespective of the dispersion compensation schemes. However, if post compensation is used, the duty cycle less than 0.7 and EDFA power less than 12 dBm give optimum performance because of smaller SPM nonlinearity. The results recommend low duty cycle of RZ optical pulse and post dispersion compensation scheme being more resilient to impairments. The conclusion drawn are concerned with single channel but may be extended to WDM systems for future works. Then the nonlinearities like XPM, FWM and spectrum widening in frequency domain would be important to consider in discussion.

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