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Theoretical and numerical characterization of a 40 Gbps long-haul multi-channel transmission system with dispersion compensation

Kaikai Xu[a,*], Yang Ou[b]

[a]*State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 610054, China*
[b]*Southwest China Research Institute of Electronic Equipment (SWIEE), Chengdu, China*

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Abstract
When updating the 10 Gbps optical transmission system to 40 Gbps, the main limits are chromatic dispersion, nonlinear effect, especially the interactions of dispersion and intra-channel nonlinearity. To optimize the performance of standard WDM in a 40 Gbps four-channel transmission system, numerical simulations are carried out to compare three different dispersion compensation techniques (without compensation; periodic dispersion compensation at the front end; and dispensation compensation all at the end of the system by means of highly dispersed pulses) for chromatic dispersion on a terrestrial 40 Gbps system. Both the loss and dispersion of the transmission fiber are periodically compensated, since two dispersive elements are placed at the input and the output ends of a compensation period. Due to the interplay between dispersion, nonlinearity and signal power, and the effect of dispersion on the pulse evolution, the pulse compress can be optimized and the system performance can be improved to compare with the system with either pre- or post-dispersion compensation. On comparing pre- and post-compensation methods, it is found that the latter is superior to the former. Further performance optimization includes how to properly match the EDFA power and length of the fiber.

1. Introduction

A linear dispersion analysis on system performance can be used to predict the future needs of ultra-long haul and 40 Gbps systems as it relates to dispersion compensation. The equations developed in Ref. [1] clearly show that the

*Corresponding author.
E-mail address: kaikaix@uestc.edu.cn (K. Xu).
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amount of residual dispersion at the end of a system that one can accommodate is of the order of 1500 ps/nm for 10 Gbps systems and only of the order 100 ps/nm for 40 Gbps system. By considering an ultra-long haul transmission at 10 Gbps system, it is seen that as we go to distance longer than 600 km we need to start using dispersion compensating devices in some of the in-line amplifiers. As soon as transmission bit rates increase from 10 to 40 Gbps and beyond, chromatic dispersion compensation becomes a critical issue on all kind of fibers, and the periodic dispersion compensation for 40 Gbps terrestrial systems has been investigated, with a new method being proposed on highly dispersed pulses to provide the evidence that the position of dispersion compensating devices can be placed all at the end of the system [2]. Pizzinat et al. further analyzed these techniques using computer simulations [3].

Although the 40 Gbps transmission systems have been intensively studied and commercial almost nine years ago, there is still a lot of progress towards increasing capacity and transmission distance for future optical communication networks. It is evident that accurate compensation at 40 Gb/s would benefit from tunable compensation modules, and several papers have demonstrated the comparison between three dispersion compensation techniques: pre-, post- and symmetrical- for different fibers [4,5]. 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 [6]. On comparing pre- and post-compensation methods, it is found that the later is superior to the former [7].

In the paper, we further observe that system needs proper matching between the Erbium-doped Optical Fiber Amplifier (EDFA) power and length of the fiber for optimum performance, with the optimization of different types of dispersion compensation of interest in transmission systems at operating wavelength of 1550 nm using the multi-channel 40-Gb/s dispersion compensating using dispersion-compensation fiber (DCF).

The theoretical model and the impact of fiber nonlinearities on fiber dispersion are given in Section 2. The characteristics of pulse propagation without fiber dispersion compensation and the impact of the compensation of the pre- and post-fiber dispersion will be considered via implementing the same parameters of the experimental system in Section 3, where system performance is characterized by the feature like power map and eye diagram. Finally, conclusions are drawn in Section 4.

2. System configuration, parameters, and basic equations

Both the loss and dispersion of the transmission fiber are periodically compensated with a period of L_C where the fiber loss is compensated by the EDFA. Fig. 1 shows a schematic, where only the first period and the location of EDFA are shown, of the transmission system considered in this paper. We consider a 40 Gbps system using initial pulses having a full-width at half-maximum (FWHM) of a few pico-seconds. The simulation setup for dispersion compensation consists of transmitter, fiber link and receiver. Fig. 1 shows the schematic configuration of an implementation of the system, here, post-compensation is demonstrated. If DCF is prior to single-mode fiber (SMF), it is pre-compensation.

2.1. Transmitter

Electrical generator generates 4×10 Gb/s NRZ signals that will be modulated by 4 continuous-wave lasers. For such a high bit rate, external modulation is used. The characteristics of M–Z modulator can be described as below:

- Modulator frequency response:

$$\frac{V_{signal}(f)}{V_{signal}(0)} = \frac{Coef1}{\sqrt{1+(Coef2 \cdot f)}},\ f(\text{GHz}) \text{ is frequency of optical carrier} \tag{1}$$

- Transmitting power intensity response:

$$\frac{I_0}{I_i} = \begin{cases} \sin^2\left[\frac{\pi}{2}\left(\frac{V_{signal}+V_{bias}-V_{offset}}{V_{PI}}\right)\right], & \frac{I_0}{I_i} \geq \frac{1}{R_{on/off}} \\ \frac{1}{R_{on/off}}, & \frac{I_0}{I_i} < \frac{1}{R_{on/off}} \end{cases}, \tag{2}$$

where I_0 is the modulated optical power intensity, I_i is electric power intensity and $R_{on/off}$ is the maximum ratio of optical power (dBm).

2.2. Dispersion compensation fiber

Chromatic dispersion compensation in optical fiber communication systems is still an open issue. This dispersion refers to the combined effects of material dispersion and waveguide dispersion. Although generally smaller than material dispersion, waveguide dispersion does shift the wavelength at which the total chromatic dispersion is minimal [8].

Since chromatic dispersion limits the performance of single-mode fibers (SMF), more advanced fiber designs aim at reducing this effect by using graded-index cores with refractive-index profiles selected such that the wavelength at which waveguide dispersion compensates material dispersion is shifted to the wavelength at which the fiber is to be used. Dispersion-shifted fibers have been successfully fabricated by using a linearly tapered core refractive index and a reduced core radius. This technique can be used to shift the zero-chromatic-dispersion wavelength from 1300 nm to 1550 nm, where the fiber has its lowest attenuation. Other grading profiles have been developed for which the chromatic dispersion vanishes at two wavelengths and is reduced for intermediate wavelengths. This is dispersion-flattened fiber.

Fiber with other refractive index profiles may be engineered such that the combined material and waveguide dispersion coefficient is proportional to that of a conventional SI fiber but has the opposite sign. This can be achieved over an extended wavelength band. The pulse spread introduced by a conventional fiber can then be reversed by concatenating the two types of fiber. A fiber with a reversed dispersion coefficient is known as a dispersion compensating fiber (DCF), as shown in Fig. 2. A short segment of the DCF may be used to compensate the dispersion introduced by a long segment of conventional fiber [9].

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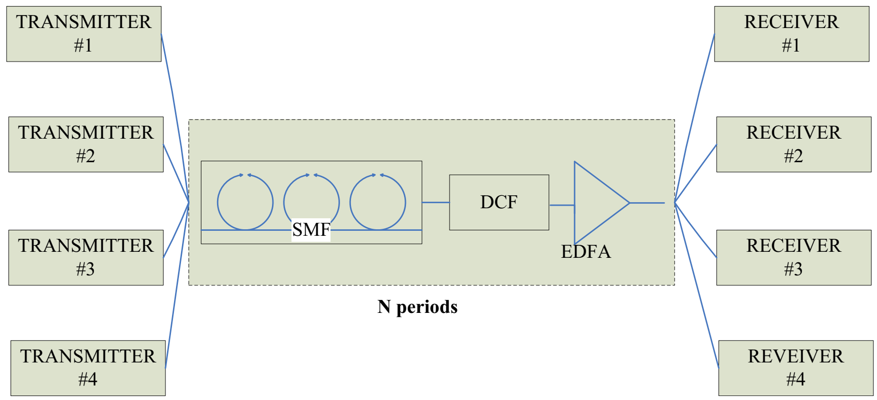

Fig. 1 40 Gbps experimental setup for evaluation of the tunable dispersion compensator: the entire transmission setup with tunable post-dispersion compensation.

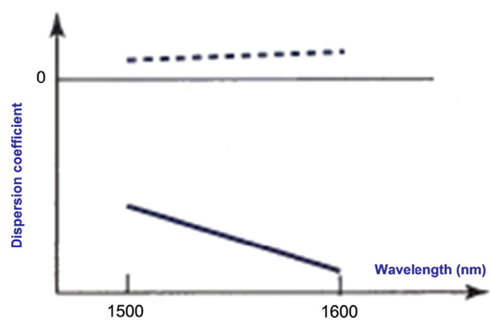

Fig. 2 Dispersion value versus the transmitting wavelength for Dispersion Compensation Fiber (DCF).

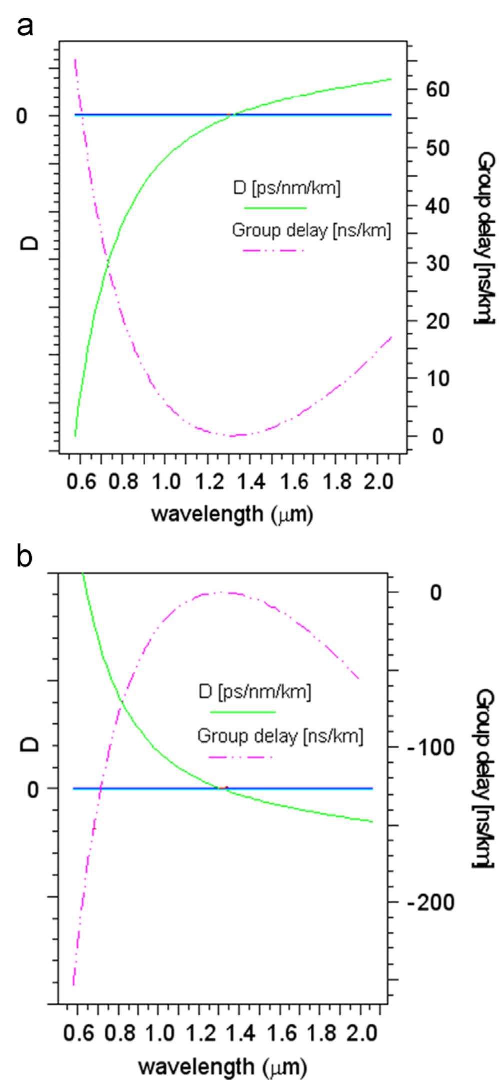

Fig. 3 Correlation between the dispersion (*D*) and the group delay versus wavelength (a) in the (a) SMF and (b) in the DCF.

Use of DCF is now a well-proven and commercially available technique for compensation of the dispersion of standard-shifted single mode fiber [10]. The condition for obtaining zero dispersion slope at the operating wavelength of a link composed of SMF and DCF is that the relative dispersion slope (RDS) of the DCF should be equal to the RDS of the SMF at the operating wavelength. It is assumed that the length of the DCF is chosen so the total dispersion is zero at the operating wavelength. The relative dispersion slope is defined as the dispersion slope divided by the dispersion

$$RDS = \frac{S}{D} \tag{3}$$

The investigated SMF is a SSMF with a loss of 0.25 dB/km, a dispersion of 16 ps/nm km, a dispersion slope of 0.05 ps/nm^2 km and a nonlinear coefficient of 1.317 W km^{-1}. Fig. 3 shows SMF and DCF fiber used in the experiment.

In what follows, polarization-mode dispersion, intra-pulse Raman scattering, and fourth- or higher order dispersions are all neglected. Spatial evolution of the pulse envelope $u(z,t)$ in a moving frame at a transmission distance z and a time t is then described by the following generalized nonlinear Schrödinger equation:

$$i\frac{\partial u}{\partial z} = -i\frac{\Gamma}{2}u + \frac{\beta_2}{2}\frac{\partial^2 u}{\partial t^2} + i\frac{\beta_3}{6}\frac{\partial^3 u}{\partial t^3} - \gamma u^2 u \tag{4}$$

where Γ is the fiber loss, β_2 and β_3 are the GVD and the TOD, respectively, and γ is the nonlinear parameter that denotes the Kerr non-linearity which is responsible for SPM and signal-noise FWM. The parameters β_2, β_3, and γ are related by commonly used parameters as follows:

$$\beta_2 = -\frac{\lambda^2}{2\pi c}D \tag{5}$$

$$\beta_3 = \left(\frac{\lambda^2}{2\pi c}\right)^2 D' + \frac{\lambda^3}{2\pi^2 c^2} D \tag{6}$$

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{7}$$

where λ is the center wavelength of pulse, c is the speed of light in a vacuum, and A_{eff} and n_2 are the effective beam cross section and the nonlinear refractive index of the DCFs, respectively [11]. The dispersion parameter is $D = -((2\pi c/\lambda^2)/\beta_2)$ [12]. Eq. (4) could be numerically solved using the split-step Fourier method [13].

Although the fiber non-linear effect plays an important role on the system performance, such transmission regime is named pseudo-linear regime. Accordingly, in the case of non-linear transmission along the SMFs, the optimum amount of dispersion D_{pre} introduced by the electrical dispersion compensator is given by:

$$D_{pre} = \frac{-D}{\alpha} \ln\left[\frac{2}{1+\exp(-\alpha \cdot L)}\right] \tag{8}$$

where L is the length of the SMFs considered in the section of the transmission link [14].

In summary, chromatic dispersion and non-linearity of the fiber are still the main destructive forces for pulse propagation in ultra-high rate optical transmission system and cause power penalty and other impairments in an optical DWDM communication system [15]; hence dispersion management must be managed properly to achieve transmission over an appreciable capacity [16].

2.3. Dispersion methods and WDM

The dispersion compensation can be accomplished by arranging the dispersion of the transmission fiber or by the use of a dispersive element in which its sign of dispersion is opposite to the transmission fiber. For every span, the dispersive element can be placed at either the input or output end of the transmission fiber to compensate for the fiber dispersion. The former is called pre-compensation configuration (PRCC) and the later is called post-compensation configuration (POCC).

However, fiber nonlinearities complicate the system design. Because the average dispersions of such a system are low, four-wave (FW) between signal and amplifier noise is serious. This leads to the distortion of signal, the broadening of signal spectrum, and the increase of noise power which is converted from signal through FWM. On the other hand, signal suffers from pulse distortion owing to the residual frequency chirping induced by self-phase modulation (SPM). Fortunately, by properly utilizing SPM to compress the signal pulse, the system performance can be improved.

Indeed, WDM technique has been studies actively for higher bit-rate transmission such as 10 Gbps system etc. for this technique, slope compensation and suppressed nonlinearity are desired. In order to discuss the flat compensation at a wide wavelength range, a dispersion slope compensation rate is given as follows:

$$\text{Compensating rate } (\%) = \left(\frac{\text{Slope}_{DCF}}{\text{Slope}_{SMF}}\right) \Big/ \left(\frac{\text{Dispersion}_{DCF}}{\text{Dispersion}_{SMF}}\right) \tag{9}$$

where slope was defined as the difference of dispersion values from 1.53 μm to 1.56 μm divided by a wavelength interval. The nearer to 100% this rate, the higher the compensating efficiency. On the WDM transmission, optical power density becomes very large because plural optical signals are inputted into a fiber at the same time [17].

3. Tunable multi-channel dispersion compensation

We make simulations by means of the split step Fourier method, implementing the same parameters of the experimental system. The wavelengths of 4 carriers are 1525 nm, 1550 nm, 1575 nm, and 1600 nm. We consider the transmission over G. 652 step-index fibers and G. 655 non-zero dispersion ones. With regards to the arrangement of dispersion compensation, we analyze three compensation schemes: (1) without compensation; (2) pre-compensation; (3) post-compensation. The realized total link is 600 km and the amplifier spacing is 100 km. For each period, the distance is 100 km in which it consists of 80 km SMF and 20 km DCF, and the total number of period is 6. EDFA is applied periodically in the long-haul optical communication system to overcome fiber loss at 1550 nm region. In all the three compensation schemes, the number of amplifiers the same, since they are after every 100 km of fiber and also after each DCF module.

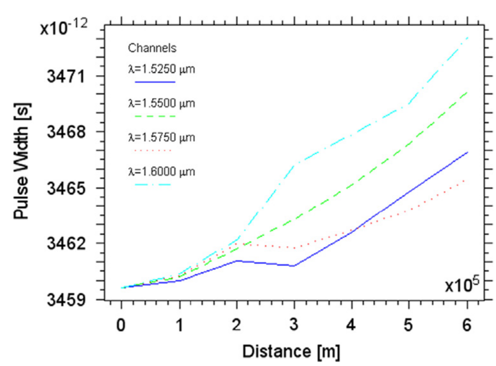

Fig. 4 Pulse Width map: without compensation.

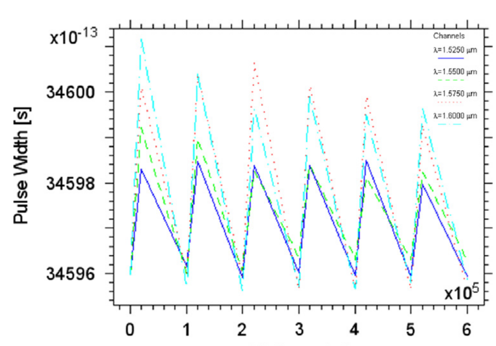

Fig. 5 Pulse Width map: pre-compensation.

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The three dispersion compensation schemes have been tested both on G. 652 and G. 655 fibers, over 6×100-km link. It is known that Pulse Width (PW) can be used to express dispersion that affect the band-width, Figs. 4-6 show the PW at the end of every compensation period along the fiber for the three different types of dispersion compensation. In Fig. 4, pulse is compressed for show distance and is broaden for long distance as expected, and the unequal accumulation pulse width for each wavelength is due to the wavelength-dependent dispersion in the fiber. As a way to characterize the system performance versus the input optical power for the fixed pulse-width of a few pico-seconds, Figs. 7-9 show the relationship between the FWHM width at different wavelengths.

Regarding the maximum transmission distance as a function of the FWHM. Fig. 10 shows the result for the SMF non-zero dispersion fiber link, whereas Figs. 11 and 12 are for

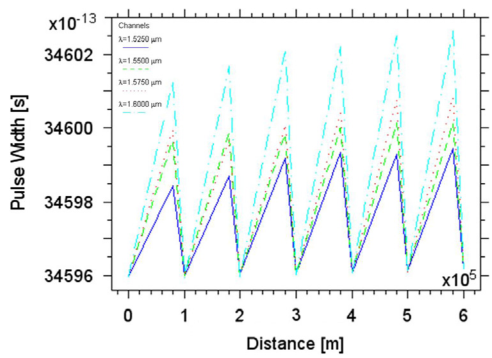

Fig. 6 Pulse Width map: post-compensation.

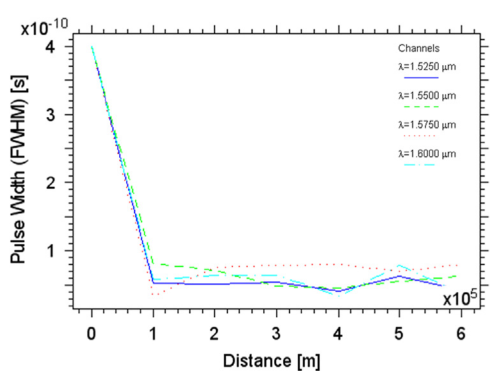

Fig. 7 FWHM map: without compensation.

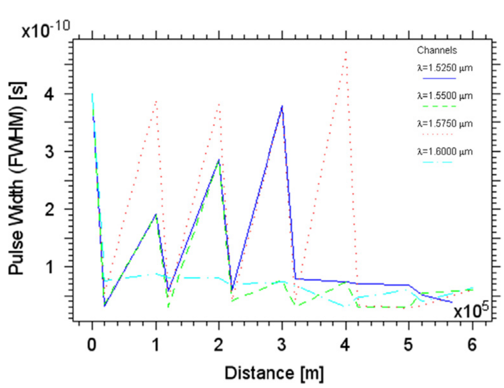

Fig. 8 FWHM map: pre-compensation.

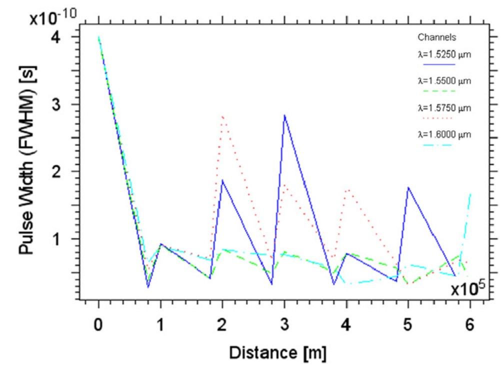

Fig. 9 FWHM map: post-compensation.

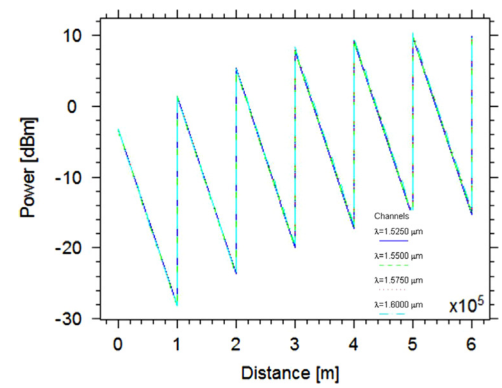

Fig. 10 Power map: without compensation.

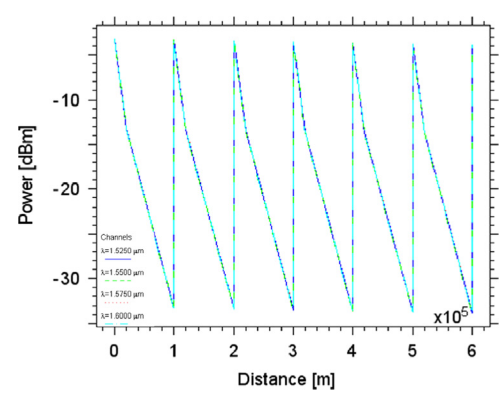

Fig. 11 Power map: pre-compensation.

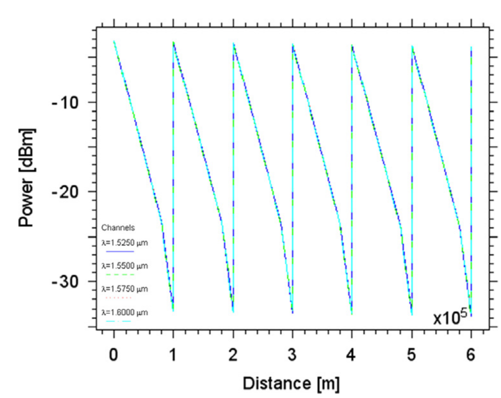

Fig. 12 Power map: post-compensation.

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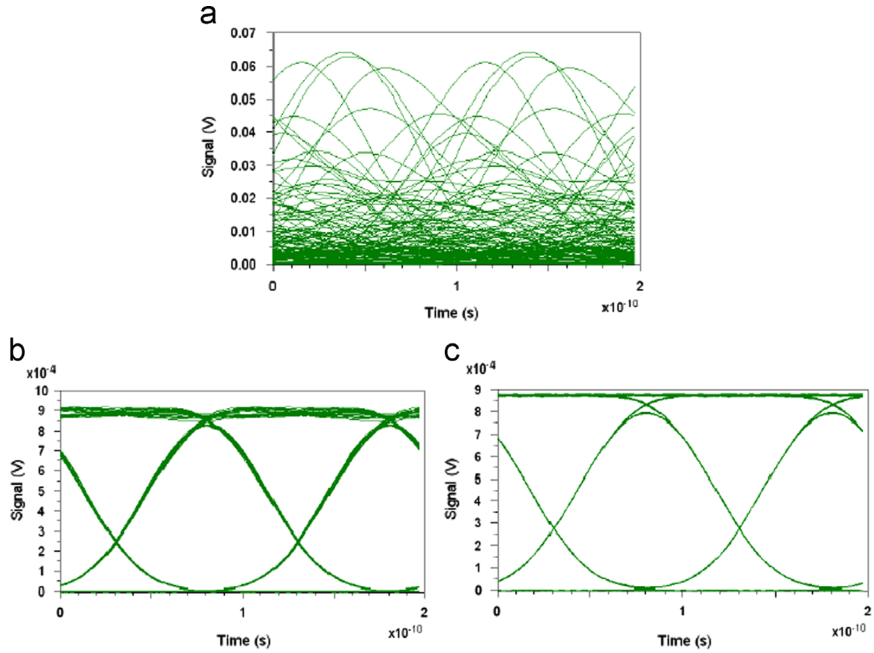

Fig. 13 Eye diagrams for 40 Gbps pseudorandom binary sequence (PRBS): (a) without compensation; (b) pre-compensation; (c) post-compensation.

the slope-compensation (i.e., dispersion compensation fiber, DCF) link in the cases of pre-compensation and post-compensation, respectively. Differences can be found in the wider band-width regime. The maximum transmission distance in the DCF link is available for higher transmission power than in the non-zero dispersion fiber link.

More detailed 4×10-Gbps dispersion compensation results are given. Figs. 10-12 show the reflected power spectrum. Without DCF, amplifier over-compensates for the attenuation at each span, and power rises with distance. As attenuation of DCF is larger than SMF, we can see that the power falls rapidly in the DCF section than in the SMF section.

Considering the 40 Gbps RZ data band-with, the actual usable bandwidth for multiple channels is $\sim$2 nm, corresponding to a tuning range from -400 ps/nm to -500 ps/nm. Figs. 7-9 also illustrate that the dispersion is not uniform within each channel's bandwidth. Therefore, the penalty induced by intra-channel dispersion is negligible. Accordingly, Fig. 13 shows eye patterns (a) without dispersion compensation; (b) in the dispersion-flattened fiber link with pre-dispersion compensation; (c) in the dispersion-flattened fiber link with post-dispersion compensation.

As can be seen in Fig. 13, the dispersion introduced by the SMF is canceled by the by the chromatic dispersion in the optical path. When DCF is employed at the front or at the back end, the dispersion tolerance is improved for the 10-Gbps NRZ data signal generated by the pattern generator with a pseudorandom binary sequence (PRBS) length of 2^{23}-1 for each channel. For the communication quality, it is compared that pre-compensation is best and without-compensation is worst, allowing the achievement of dispersion compensation at the back end is much better than that at the front end in the optical communication system.

In general, dispersion is an important impairment that degrades overall system performance of a high speed long haul optical communication system and causes crosstalk. Hence, a detailed investigation of dispersion compensated optical communication system using pre-, post- and symmetrical-dispersion compensation techniques is specifically reported.

4. Conclusion

Chromatic dispersion is a critical issue which can severely influence system performance at 40 Gb/s, and such a compensation tenability should accommodate multiple WDM channels. Since dispersion compensation is the technique used in fiber optic communication system designed to cope with the dispersion introduced by the optical fiber [18,19], the paper focuses on reporting a detailed investigation of 40 Gb/s WDM transmission experiments using periodic dispersion compensation and dispersion slope compensation. Pre-compensation decreases the signal power faster, and the signal experiences normal dispersion while signal power is higher; whereas in post-compensation, the signal power falls more slowly and the signal experiences anomalous dispersion while the signal power is higher. Pre-compensation has also been shown to result in pulse compression due to self-phase modulation (SPM), rather than the more detrimental pulse broadening effect that occurs in post-compensation. Optimally adjusting the compensation ratio of each channel will further improve the transmitted distances.

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