Study on the 4×10 Gb/s, 400 km dispersion compensation by chirped optical fiber grating

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In this paper, the dispersion compensation for 4×10 Gb/s, 400 km G.652 fiber by chirped optical fiber Bragg grating (FBG) is introduced. For the first time, we have measured and compensated the polarization mode dispersion (PMD) of FBG, which in each channel is less than 1.1 ps. When the bit error rate (BER) is 10^{-10} and the bit error is zero, the transmission power penalty of each channel is less than 2 dB, and the best result is negative which means that the receiver sensitivity is increased after transmission.

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With the development of optical device, system technology, and the unending pursuing for broadband technology, people began to recognize the importance of dispersion compensation[1].

Now, a lot of G.655A fibers have been paved, but it does not solve the dispersion problem radically. Dispersion compensation is still needed in high speed, long distance transmission system, and it is difficult to build the WDM system with 50 GHz of channel spacing. G.652 fiber has high dispersion at wavelength 1.55 μm, so the nonlinear effect can be decreased effectively, and the WDM system is easy to be achieved with 50 GHz of channel spacing through dispersion compensation. There are more than 200 million kilometers G.652 fiber have been paved in the world, so dispersion compensation has become the most key problem for the high speed system with such fiber.

At present, two dispersion compensation schemes are very popular. One is to use the dispersion compensation fiber (DCF). But DCF is very expensive, and its dispersion slope does not match those of G.652 and G.655 fiber. We have done a lot of measurements and the results are listed in Table 1.

It shows that when the dispersion at certain wavelength is completely compensated by DCF, the residual dispersion will exist at the other wavelengths. If the transmission length is very long, the whole residual dispersion will be very large, and very expensive EDFA is needed to compensate the insertion loss of DCF.

Another method is to use the FBG. The FBG is very well compatible with the present optical fiber communication system, it has low transmission and insertion loss, and its refractive modulation can be controlled by exposure course easily. So the dispersion compensation of FBG has been considered as the very good scheme with great application foreground.

In the chirped FBG, the light with different wavelengths is reflected at different location and has different time delay, so it can be used for the dispersion compensation. The theory model of chirped FBG could be made by coupled mode equation[2]. From the Maxwell equation, we get

$$\frac{\mathrm{d}A^+}{\mathrm{d}z} = K(z)\exp\left[-j\int_0^z B(z')\mathrm{d}z'\right]A^-,$$

$$\frac{\mathrm{d}A^-}{\mathrm{d}z} = K(z)\exp\left[j\int_0^z B(z')\mathrm{d}z'\right]A^+, \qquad (1)$$

where A^+ and A^- are the amplitude of forward and backward wave, respectively. $K(z)$ is the coupled coefficient change along the propagated direction of the FBG. For the lineally chirped FBG,

$$\int_0^z B(z') = 2\Delta\beta z - \Phi(z), \qquad (2)$$

where $\Delta\beta$ is the mismatch of propagation constant, $\Phi(z)$ is the phase function.

The local reflectivity coefficient of the FBG is defined as

$$\gamma(z) = \frac{R(z)}{T(z)}\exp(j\phi). \qquad (3)$$

From Eq. (3), we get

$$\gamma' = K(z)(1 - r^2) + i[2\Delta\beta - \Phi'(z)]\gamma, \qquad (4)$$

where γ' is the derivative of γ. The length of FBG is L, the coupled region of FBG is $-L/2 \le z \le L/2$, then

$$\gamma(L/2) = 0. \qquad (5)$$

The response of FBG is

$$R' = \gamma(-L/2) \times \gamma^*(-L/2). \qquad (6)$$

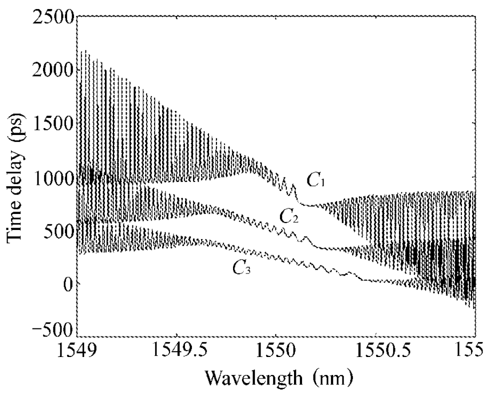

Fig. 1. The time delay of the FBGs.

Table 1. The Dispersion Slope of G.652, G.655 and DCF Fiber

	S Band (ps/nm^2·km)	C Band (ps/nm^2·km)	L Band (ps/nm^2·km)
G.652 Fiber (Corning SMF-28)	0.09404	0.0922	0.0901
G.655 (Leaf)	0.0931	0.1055	0.1013
DCF (Lucent Type DK-60)	−0.33457	−0.3986	−0.3049

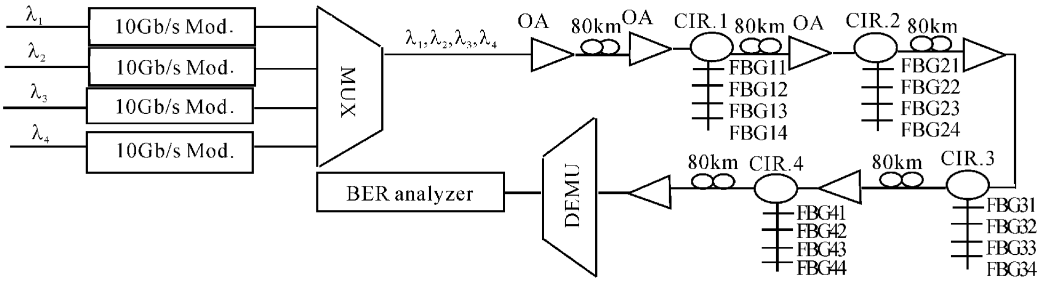

Fig. 2. Transmission system of 4 × 10 Gb/s, 400 km dispersion compensation. Mod: modulator; OA: optical amplifier; CIR: circulator.

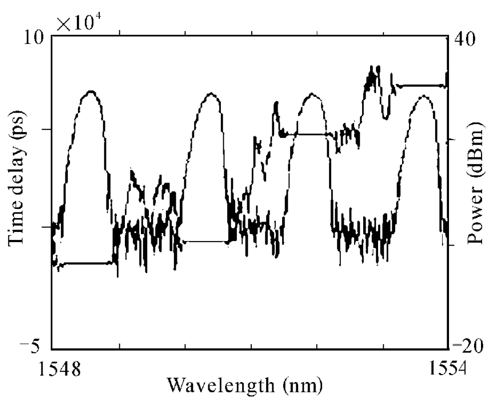

Fig. 3. The reflectivity and time delay of the whole FBG after 400 km transmission.

Taking $L = 4$ cm, $\Delta n = 1 \times 10^{-4}$, $C_1 = 1 \times 10^{-4}$, $C_2 = 7 \times 10^{-4}$, $C_3 = 1 \times 10^{-3}$, where C is the chirp of FBG. The time delay of the FBGs are shown in Fig. 1.

It can be seen that when the FBG length is fixed, the less of its chirp, the narrower of its bandwidth, and the bigger of its dispersion. In order to get the good quality FBG dispersion compensator, it must be sure that the FBG has the best combination of dispersion, bandwidth and reflectivity, and the ripple coefficient of time delay should be as small as possible.

The 4×10 Gb/s, 400 km transmission system on G.652 fiber is successfully implemented with chirped FBGs used for dispersion compensation[3]. The system is shown in Fig. 2.

The 10 Gb/s signal is amplified after multiplexing, the fiber length is 400 km with 80 km span. In each span, a FBG is used for dispersion compensation. At the same time, the ASE noise of EDFA can be filtered by the FBG. Six EDFAs have been used for the power compensation.

The FBGs used in the system are made by using the double lens exposure stage and phase mask. After 400 km transmission, the reflectivities of the whole FBGs are shown in Fig. 3. We can see that the time delay slope is zero, which means that the dispersion is fully compensated. The center wavelengths of each channel are 1549.322, 1550.842, 1552.544 and 1554.136 nm, respectively. The 3-dB bandwidths are 0.350, 0.348, 0.353 and 0.331 nm, respectively. The channel spacing is about 1.6 nm, and the wavelengths fit the ITU-T wavelength criterion.

The Jones matrix eigen analysis method is used for the PMD measurement of the FBGs. Taking channel 1 as an example (in each channel, there are 4 FBGs), before PMD compensation, its average differential group delay (DGD) is 8.39 ps. After PMD compensation, its average DGD is decreased to 0.69064 ps. The measurement result is shown in Fig. 4.

After PMD compensation, the PMDs of FBGs of channel 1 to channel 4 are 0.69064, 0.93054, 1.07646 and 0.87 ps, respectively.

The eye diagram of 10 Gb/s signal modulation is shown in Fig. 5. The eye diagrams of 10 Gb/s signal after transmission and dispersion compensation in 400 km G.652 fiber are shown in Fig. 6. We can see that the pulse width has been retrieved, and the eyes open well which means that the signal-to-noise ratio (SNR) is good.

The BER of 10 Gb/s signal in each channel after demultiplexing is measured. When the BER is 10^{-10} and

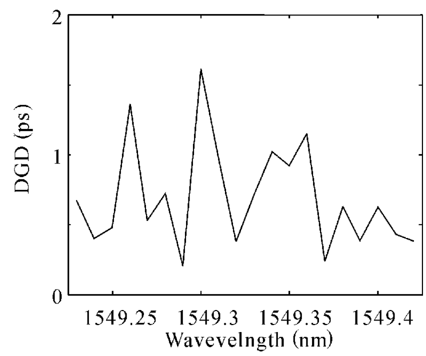

Fig. 4. The PMD of FBGs in channel 1# after PMD compensation.

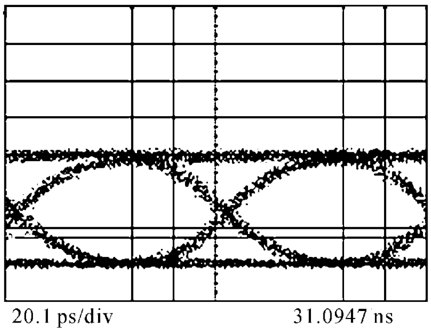

Fig. 5. The eye diagram of 10 Gb/s signal modulation.

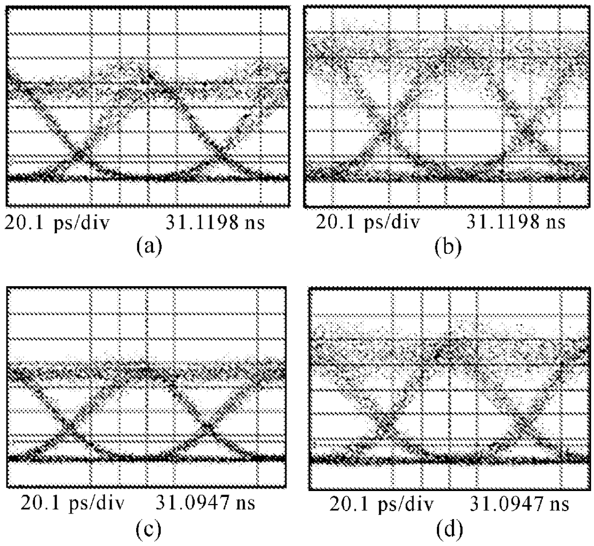

Fig. 6. The eye diagram of 10 Gb/s signal after transmission and compensation in 400 km G.652 fiber. (a) Channel 1#; (b) channel 2#; (c) channel 3# and (d) channel 4#.

the bit error is zero, the power penalties of transmission in each channel are 1.2, 1.98, −0.9 and 0.4 dB, as shown in Fig. 7. The power penalty in channel 2# is bigger, because a different package material is used. After changing it, the power penalty is improved to be 0.9 dB.

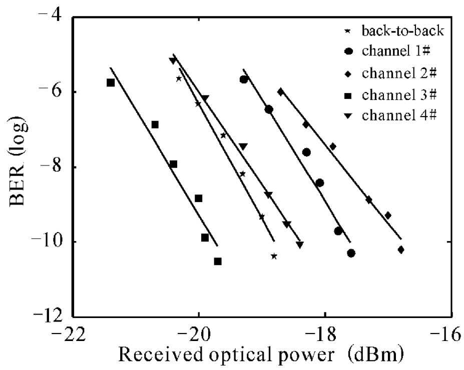

Fig. 7. The BER of 4 × 10 Gb/s, 400 km FBG dispersion compensation.

Because of its huge communication capacity and cheap building cost, the optical fiber communication provides an infinite broadband communication stage, and it is developing for the all-optical network at present. Now the world focus more attention on how to solve the dispersion of G.652 fiber. By chirped FBG dispersion compensation, we implement the 4×10 Gbs, 400 km transmission, and the experimental results are good. This means that it is feasible for the FBG dispersion compensation scheme. We can respect that the chirped FBG will play a more and more important role in optical fiber communication fields.

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