8×10-Gb/s transmission system over 1500 km on G.652 fiber dispersion compensated by chirped fiber gratings

Zhongwei Tan (谭中伟), Yan Liu (刘 艳), Yong Chen (陈 勇),
Jihong Cao (曹继红), Xiaowei Dong (董小伟), Lina Ma (马丽娜),
Deyuan Chang (常德远), Tigang Ning (宁提纲), and Shuisheng Jian (简水生)

Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044

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A low cost 8×10-Gb/s transmission system over 1500 km on conventional fiber using chirped fiber Bragg grating (CFBG) as dispersion compensator is demonstrated. The bit error rate (BER) below 10^{-10} at 1500 km is obtained. The channel spacing is 0.8 nm and the optical amplifier spacing is 100 km. Only 16 erbium-doped fiber amplifiers (EDFAs) are used.

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The impact of dispersion on system performance increases as the operating bandwidth increases and also as the transmission distance and bit rate increase. To overcome the dispersion limit, various dispersion compensation techniques have been used. Dispersion compensation fiber (DCF) has been used popularly. However, DCF is expensive. Sometimes, erbium-doped fiber amplifier (EDFA) is needed to compensate for the insertion loss of the DCF and the costs are high. Besides that, the effective mode area of the DCF is small, and the nonlinear effects are considerably enhanced[1]. Chirped fiber Bragg gratings (CFBGs) present some interesting features as dispersion-compensation devices. They can compensate for large dispersion in a very short length. They are also compact and passive, low loss, low cost, and act as both dispersion compensators and bandwidth in-line filters which have been proved to improve the performance of the system considerably[2].

The straight line 10-Gb/s soliton transmission over 1000 km of standard fiber with in-line chirped fiber grating for partial dispersion compensation[3] has emerged for a long time. The using of CFBGs in wavelength division multiplexing (WDM) system encountered some problems. The large number of closely spaced wavelengths and long transmission distance significantly stress the wavelength uniformity, bandwidth, and cascadability of the fiber gratings[4]. Many efforts have been put into the investigation of sampled fiber Bragg gratings[5−7]. However, the saturation of the photo-induced refractive index change can be the cause of phase and amplitude distortions, which would harm the characteristics of the grating[8]. No report has been found that using CFBGs as dispersion compensators in ultra-long haul WDM transmission system longer than 1000 km.

We have succeeded in 4×10-Gb/s 800 km transmission system with dispersion compensation using CFBGs[9]. In this letter, we use CFBG to compensate the dispersion of the 1500-km conventional fiber, and the chirped gratings are written on the hydrogen-loaded fiber using a scanning mask/fiber technique in which the periodic reflective index modulation is induced under irradiation with a ultraviolet (UV) laser[4]. The dispersion of the fiber is about 17 ps/(nm·km), and one CFBG could compensate for the dispersion of 160-km fiber. The EDFAs are placed every 100 km. The chirps of the gratings in different channels are designed to compensate for the dispersion slope of the fiber.

The specifications of the gratings are 8 channels, channel spacing of 100 GHz, dispersion of $\geq$ 2600 ps/nm, dispersion tolerance of $<5\%$, insertion loss of <3.5 dB, insertion loss ripple of <0.5 dB, and inter-channel insertion loss variation of <1 dB. The length of the gratings is 14 cm. The wavelengths of the gratings range from 1549.32 to 1557.36 and the chirps range from 0.386 to 0.378, as shown in Table 1. The gratings are made using the asymmetric apodization.

The grating temperature stabilization is a very important parameter and limits the using of chirped fiber gratings. The temperature coefficient of the packed fiber grating is below 0.0005 nm/°C. The tested temperature curve is shown in Fig. 1.

To reduce the influence of the nonlinear effects, the loss and dispersion managements are used in our system. The major nonlinear phenomenon affecting the performance of a single-channel system is self phase modulation (SPM). The dispersion could suppress the SPM effects. However, the dispersion-induced pulse broadening can transfer a part of the pulse energy to spread beyond the allocated bit slot and lead to inter-symbol interference. So the periodic dispersion management is used so that the total dispersion over each period is close to zero. The effect of the inter-symbol interference could be minimized in that way. Wave propagation can be described by the nonlinear Schrödinger equation

Table 1. Optical Parameters of the Chirped Fiber Gratings

Wavelength (nm)	1549.32	1550.12	1550.92	1554.13	1554.94	1555.75	1556.55	1557.36
Group Delay Ripple (ps)	22.5	28.4	22.5	26.4	23.8	19.3	26.0	15.1
Chirp	0.386	0.386	0.386	0.380	0.379	0.378	0.378	0.378

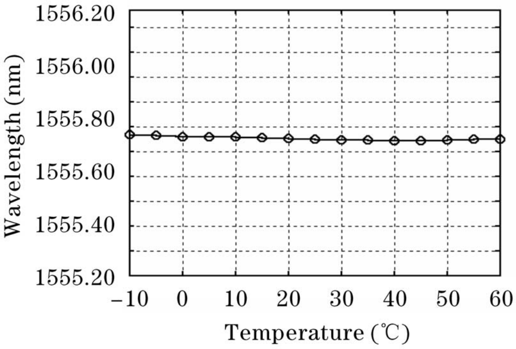

Fig. 1. The tested temperature curve.

$$\frac{\partial A(z,t)}{\partial z} = -\frac{i}{2}\beta''\frac{\partial^2 A(z,t)}{\partial t^2} + i\gamma\left|A(z,t)\right|^2 A(z,t) -\frac{\alpha}{2}A(z,t), \qquad (1)$$

where $A(z,t)$ is the electrical field, $\gamma = \varpi_0 n_2/cA_{\text{eff}}$ is the nonlinear coefficient of the fiber, ϖ_0 is the angular frequency, n_2 is the refractive index of the fiber, c is the speed of light, A_{eff} is the effective fiber core area, β'' is the fiber dispersion parameter, and α is the fiber attenuation. High-order dispersions have been ignored here. The steady-state solution of Eq. (1) is z-dependent:

$$A_0(z) = \sqrt{P_0}\exp(i\gamma\left|A_0(z)\right|^2 z)\exp(-\frac{\alpha}{2}z), \qquad (2)$$

$$\Phi_{\text{NL}}(z,t) = \left|A_0(0,t)\right|^2 (z_{\text{eff}}/L_{\text{NL}}), \qquad (3)$$

with $z_{\text{eff}} = [1-\exp(-\alpha z)]/\alpha$. Equation (3) shows that SPM gives raise to an intensity-dependent phase shift while the pulse shape governed by $|A(z,t)|^2$. SPM-induced spectral broadening is a consequence of the time dependence of Φ_{NL}. The difference is given by

$$\delta\varpi = -\frac{\partial\Phi_{\text{NL}}}{\partial T} = -\frac{\partial}{\partial T}(\left|A(0,t)\right|^2)z_{\text{eff}}/L_{\text{NL}}. \qquad (4)$$

We calculated the super Gaussian pulse that will be used in the system and found that $\delta\varpi$ is negative near the leading edge (red shift) and becomes positive near the trailing edge (blue shift), which is on the contrary to the effect of dispersion. SPM could compensate for an amount of dispersion. So it must be considered in devising the grating's chirp coefficient. In our system, each grating can compensate the dispersion of 160-km G.652 fiber, and 9 gratings can compensate the dispersion of the fiber about 1440 km completely. The system performs best when the residual of the dispersion is about 60 km.

Another nonlinear effect in the system is the modulation instability (MI), which could be seen as the four-wave mixing (FWM) between the signal and amplified spontaneous emission (ASE)[10]. With the assumption that noise power present at the input of the fiber is much smaller than the signal power, the solution of Eq. (1) can be written as

$$A(z,t) = [A_0 + a(z,t)]\exp(i\gamma\left|A_0\right|^2 z), \qquad (5)$$

where A_0 is the steady-state solution, $a(z,t)$ is a small perturbation and $a(z,t) \ll A_0$ is assumed. With linear approximation of the noise term[9],

$$\frac{\partial a(z,t)}{\partial z} = -\frac{i}{2}\beta''\frac{\partial^2 a(z,t)}{\partial t^2} + i\gamma[\left|A_0\right|^2 a(z,t) + A_0^2 a^*(z,t)]. \qquad (6)$$

It means that the perturbation is amplified by the signal through nonlinear effects. The gratings are put behind the EDFAs to filter out most of the ASE outside the transmission band, which can reduce the effect of the MI in the system considerably.

Figure 2 shows the schematic configuration of the system. LiNbO$_3$ Mach-Zehnder modulators are used to modulate the 10-Gb/s non-retrun-to-zero (NRZ) (PN-23) optical signal. The length of the conventional fiber is 100 km and the gratings are inserted every 100 km or 200 km, for the compensating length of the CFBGs is about 160 km. The insert loss of dispersion compensator including the gratings and the circulator is about 5 dB, so it is no

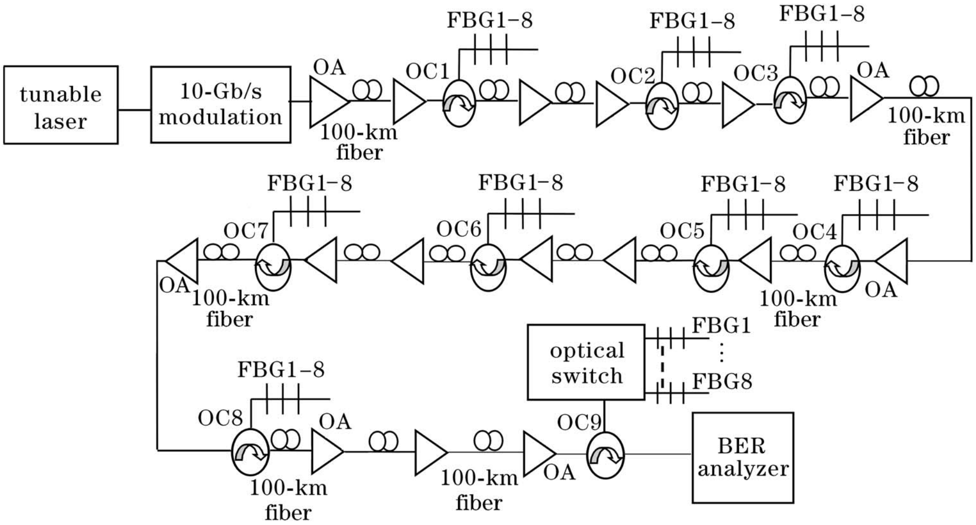

Fig. 2. 1500-km transmission system with dispersion compensated by CFBGs. OA: optical amplifier; OC: optical circular; BER: bit rate error.

need to use EDFA to amplify the dispersion compensators specially. The dispersion compensator is put after the EDFAs, so that most of the ASE is filtered out and the optical power into the fiber is almost the same. The optical input power into the conventional fiber is 3—5 dB. The nonlinear effects of the gratings could be neglected. The polarization mode dispersion (PMD) of the gratings is below 0.5 dBm each. No PMD compensation is needed in the system.

The eye diagrams of the optical signal transmission after 1500 km in different wavelengths of 1549.3 and 1557.3 nm are shown in Fig. 3. The gain of the EDFA in different wavelength is not same, the optical power in wavelength of 1549 nm is larger than that in 1557 nm, so the nonlinear effects are not the same in different channels. The optical pulses in Fig. 3(a) are compressed for the mixture of the SPM and dispersion. The shape of the eye diagrams in Fig. 3(b) is not changed much for the low nonlinear effects. However, the noise of Fig. 3(b) is larger than that of (a), because the optical power into the EDFA in (b) is small, the signal-to-noise ratio (SNR) is low.

The bit error rate (BER) performance of the system is shown in Fig. 4. An error rate below 10^{-10} is obtained at 1500 km. The cross of the curves after the transmission with that of the back-to-back is because the compression of the pulse induced by the SPM effects.

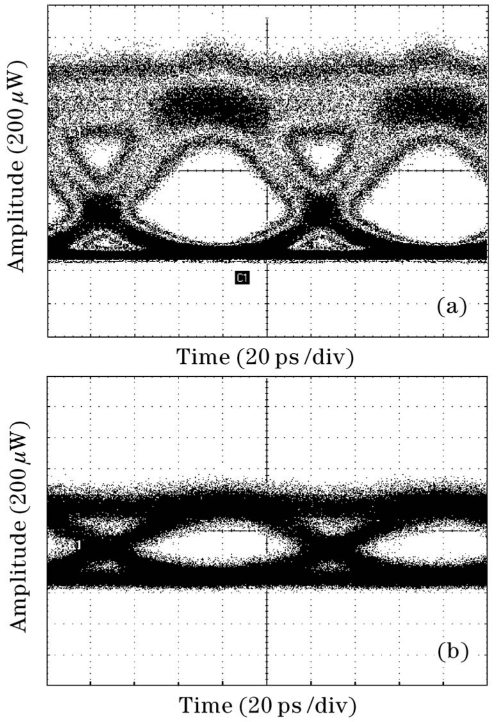

Fig. 3. Received eye patterns of 1500-km transmission system with dispersion compensated by CFBGs at wavelengths of 1549.3 (a) and 1557.3 nm (b).

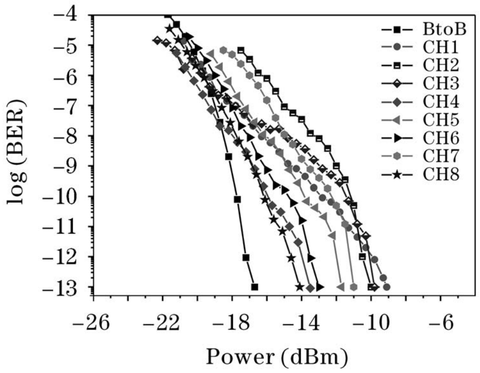

Fig. 4. Measured BER curves of the system. B to B: back-to-back.

We have shown CFBG used as dispersion compensator in ultra-long haul WDM transmission system. The signal is amplified every 100 km by the EDFAs, and 16 EDFAs are used in total. The power equalization is realized by controlling the insertion loss of the gratings in different channels. The CFBG filters the signal in every span and it could serve as a filter before the receiver associated with an optical switch. The system is very simple and the cost has been greatly reduced.

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