Simultaneously compensating tunable CD and adaptive PMD using two different nonlinearly chirped fiber Bragg gratings

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Experimental research of simultaneous tunable chromatic dispersion (CD) and adaptive polarization mode dispersion (PMD) compensations in optical fiber communication system was reported. Two different nonlinearly chirped fiber Bragg gratings fabricated through the equivalent chirp technology were adopted in the experiment. One of the gratings was used as CD compensator, with a tunable dispersion range from 300 to 600 ps/nm. The other made of photosensitive polarization maintaining fiber was used as a tunable delay line of PMD compensator, which provided a varying amount of differential group delay (DGD) from 40 to 110 ps. Our experiment was operated at 10-Gb/s non-return-to-zero (NRZ) system and the results showed that the eye pattern recovery is excellent after both PMD and CD are compensated. Especially, the power penalty at a bit error rate (BER) of 10^{-9} is about 1 dB.

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There are mainly two kinds of dispersion inducing pulse distortion in high speed optical fiber communication systems. The first one is the chromatic dispersion (CD), which causes time domain pulse broadening due to different traveling velocity of the pulse's spectral components. CD is usually optically compensated by the methods such as using dispersion compensating fibers or linearly chirped fiber Bragg gratings, but only a fixed amount of dispersion can be compensated. Actually, many factors can cause CD varying with time, such as temperature changing, reconfigurable networking for which the path changes. Generally, the higher speed the optical communication system is with, the lower dispersion the system can be tolerable for a specific bit error rate (BER). So it is necessary to compensate for CD in tunable manner with increasing the data rate of system.

The second kind of dispersion is polarization mode dispersion (PMD) in high bit rate ($\geq$ 10 Gb/s) lightwave systems, known to induce waveform distortion just like CD. Because of temperature changing, cable vibration, and so on, PMD is a stochastic, random process that changes with time. Tunable and adaptive PMD compensation is required. Typically, PMD compensator consists of polarization controllers (PCs) and delay lines, in which differential group delays (DGDs) are either fixed or variable. In order to lower the penalty due to PMD, some of delay lines should be adjustable.

Nonlinearly chirped fiber Bragg grating (NC-FBG) with a linear stretcher can provide adjustable dispersion, which can be used as tunable CD compensator. High-birefringence nonlinearly chirped fiber Bragg grating (HBNC-FBG) with a linear stretcher can provide the selectability of varying amounts of DGD, which can be used as component of PMD compensator. Unfortunately, the NC-FBG used as CD compensator usually introduces a few undesired DGD[1], which is deleterious in CD compensation system. And the CD induced by the HBNC-FBG is also deleterious in PMD compensation system. Combination use of the two kinds of gratings is at least with two purposes: one for compensating both CD and PMD that co-exist in optical fiber communication system at the same time, the other for offsetting negative effects mentioned above. Furthermore, NC-FBGs are in-line, adjustable, low insertion loss, and regarded as promising compact optical components.

Up to now, though the schemes have been proposed for PMD compensation using HBNC-FBG[2,3] or for tunable CD compensation using NC-FBG[4], few are proposed to compensate for both of them together. In this letter, we report the experiment of CD and PMD compensations in 10-Gb/s non-return-to-zero (NRZ) transmission system by using the NC-FBG and HBNC-FBG as tunable elements, which are fabricated by the equivalent chirp technology[5,6].

For a linearly chirped FBG (LC-FBG), as group delay is linear with wavelength, the slope of curve (group delay versus wavelength), corresponding to the dispersion, is constant over the grating bandwidth. When the grating is stretched, the dispersion keeps unchanged because of the group delay line shift remaining its shape. Thus, it can only compensate for a fixed amount of CD whether stretched or not. In contrast, for a NC-FBG, group delay is nonlinear with wavelength, which results in that the slope of the group delay curve, corresponding to the dispersion, is different at each wavelength. With the grating stretched, although the whole group delay line shifts remained unchanged, the dispersion varied for a specific wavelength within the bandwidth. So the NC-FBG can be used as tunable CD compensator.

Some characteristics of NC-FBG used as CD compensator are shown in Fig. 1. The measured reflection spectrum and group delay line are shown in Fig. 1(a), where the original central wavelength is 1542.6 nm and the bandwidth is about 1 nm (for the limited bandwidth, the grating cannot be used to realize multi-channel dispersion compensation). The peak-to-peak group delay

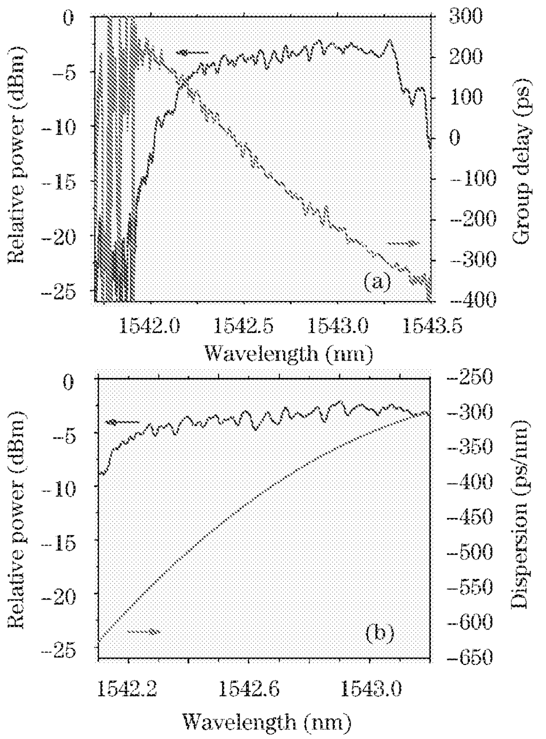

Fig. 1. Some characteristics of NC-FBG used as CD compensator. (a): Reflection spectrum and group delay line; (b): tunable range of CD.

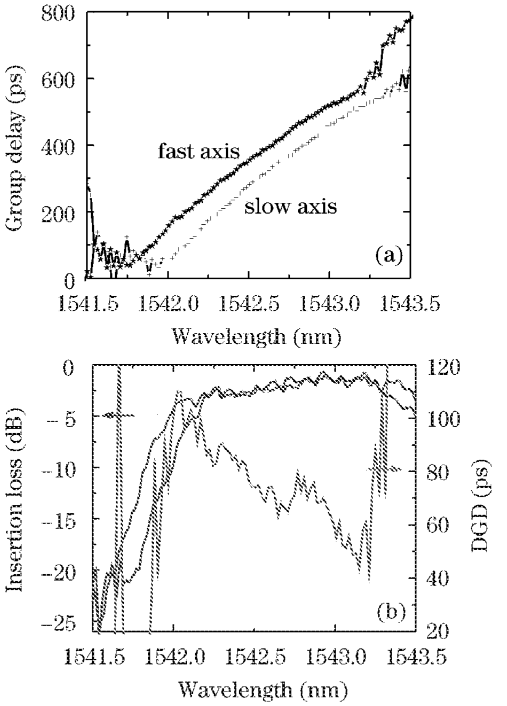

Fig. 2. Some characteristics of HBNC-FBG used as adjustable time delay line. (a): Group delay lines; (b): DGD tuning range and spectra.

ripple is ±12 ps. Figure 1(b) shows the dispersion tuning range before the grating is stretched. Pre-stretching technology adopted in our experiment makes it possible for the original central wavelength to have the tuning range of the dispersion being just the same as the dispersion range of grating, which is about 300 ps/nm, as shown in Fig. 1(b), where the maximum and minimum dispersions are −600 and −300 ps/nm, respectively.

The high birefringence of the grating results that the optical signals polarize in fast and slow axes, reflecting at different locations when they transmitted along the grating. Hence, two group delay lines will be generated, corresponding to fast and slow axes, respectively. The nonlinear chirp of the grating results that the difference of group delays between two orthogonal polarizations will vary with wavelength, which provides the selectability of varying amounts of differentiable polarization time delay when the grating is stretched. We can use it as tunable time delay line in PMD compensation system.

Some characteristics of HBNC-FBG which was fabricated through nonlinear equivalent chirp written into a photosensitive polarization maintaining fiber are shown in Fig. 2. The group delay lines, corresponding to fast and slow axes, are shown in Fig. 2(a), in which each one varies nonlinearly with wavelength and the peak-to-peak of each group delay ripple is about ±12 ps. The DGD tuning range and reflection spectra of two orthogonal polarization directions are shown in Fig. 2(b). When the stretcher is operated in different working manner, the spectra will experience a shift either to the longer or shorter wavelength direction. So DGD at the central Bragg wavelength (operation wavelength in this paper) is changed accordingly and the tuning range is just the same as the DGD tuning range shown in Fig. 2(b), which is from 40 to 110 ps, the central wavelength and bandwidth are about 1542.6 nm and 1 nm, respectively.

Figure 3 shows the experimental setup of our 10-Gb/s NRZ transmission system using two kinds of NC-FBGs as the tunable CD compensator and the component of PMD compensator repectively to realize both tunable CD and adaptive PMD compensations. It mainly consists of four parts: transmitter, PMD emulator, tunable CD compensator and a unit of adaptive PMD compensation, and receiver. A tunable continuous wave (CW) laser, whose 1542.6-nm wavelength is adopted to be in accord with the central wavelength of NC-FBGs, is modulated by a 10-Gb/s $2^{23}-1$ NRZ pseudorandom bit sequence (PRBS). The PMD emulator used to generate waveform distortion caused by PMD, which consists of two manual PCs and polarization-maintaining fiber (PMF) pieces of 20- and 60-ps DGDs, can provide not only first-order, but also second-order PMD. The unit for adaptive PMD compensation includes three parts: PMD compensator, in-line polarimeter, and feedback control unit. PMD compensator consists of electrically controlled PCs and two time delay lines, one is a section of PMF providing a fixed DGD of 29 ps and the other is HBNC-FBG with a linear stretcher providing a variable DGD from 40 to 110 ps. In-line polarimeter is used to measure instantaneously the four Stokes parameters s_0, s_1, s_2, s_3, and then the degrees of polarization (DOPs). The obtained DOPs were used as feedback signals for feedback control unit, which consists of A/D converter, control algorithm, and D/A converter. The A/D converter is used to convert the analog DOP-sampling signals detected by the polarimeter to digital signals, which are processed by control algorithm later. Then, as the

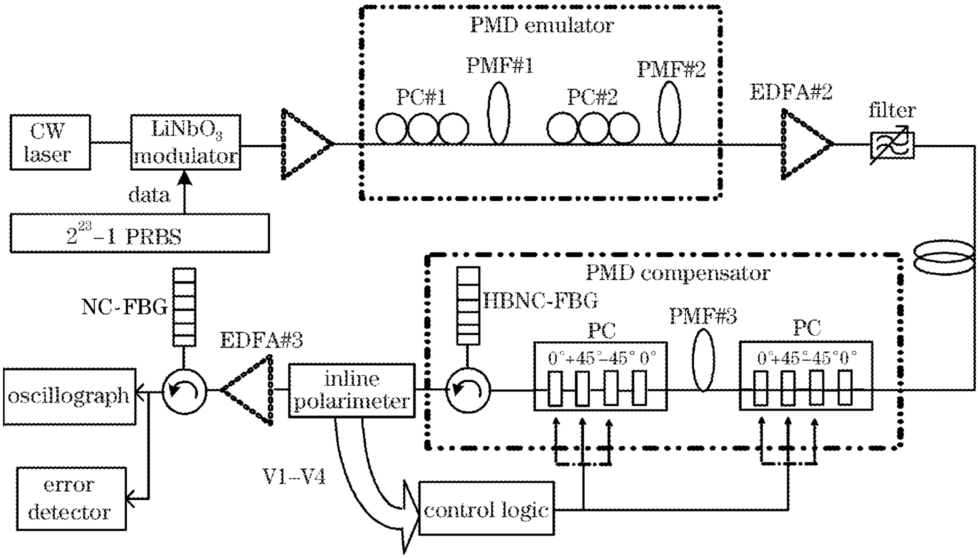

Fig. 3. The experimental setup to compensate for CD and PMD.

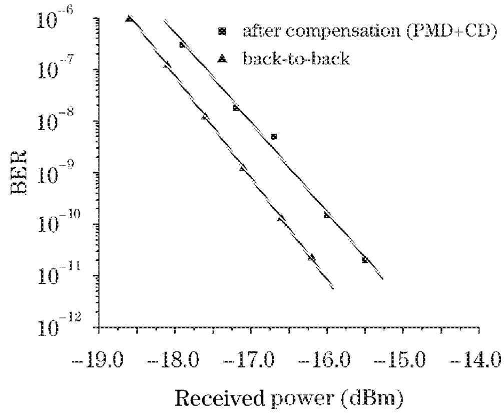

Fig. 4. Power penalty.

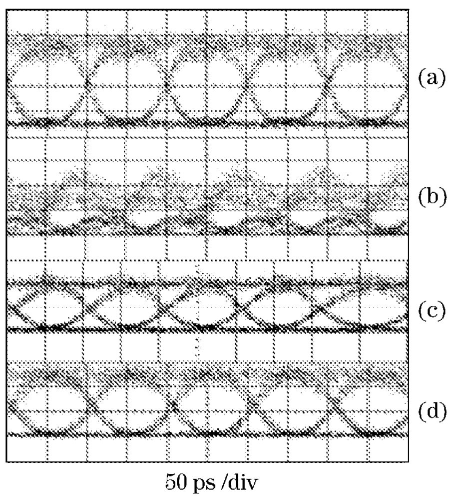

Fig. 5. Eye diagrams. (a): Back-to-back; (b): before compensation; (c) after PMD compensation; (d) after CD compensation.

outputs of D/A converter, the analog voltages are used to control the PCs. The control algorithm adopted here is named as particle swarm optimization (PSO), which has a powerful multi-dimensional searching capability. By searching the global DOP maximum value (reaches as close as 1) in the fiber link using searching algorithm, the goal of PMD compensation is achieved. After PMD compensation, the signals are also distorted due to CD generated by the grating used to compensate PMD and the single-mode fiber (SMF) added in the link. There is a changed CD produced by both the HBNC-FBG, which is tuned accordingly when the PMD emulator are being adjusted, and the change of the length of SMF. By properly regulating the NC-FBG through a linear stretcher, the other goal of CD compensation can be always achieved every time.

Figures 4 and 5 show the effectiveness of our experiment of the tunable CD and adaptive PMD compensation. Figure 4 shows the curves of bit error rate (BER) versus the received back-to-back optical power and the power after compensation of both PMD and CD, respectively. It can be seen that the power penalty at a BER of 10^{-9} was about 1 dB. The back-to-back eye diagram is shown in Fig. 5(a). When signals transmitted through PMD emulator and a section of SMF (8 km), CD and PMD (including first- and second-order) resulted in signals broadening, overshoots, and generation of satellite, so the waveform degradation was serious. The eye diagram, shown in Fig. 5(b), becomes almost closed due to PMD and CD. After PMD compensation, the signal's distortion got mitigated, as shown in Fig. 5(c). Then with CD compensation, clear eye opening is almost recovered, as shown in Fig. 5(d).

The automatic PMD compensator is required to reach the global maximum DOP in fiber link through finding the best optimal combination of six control voltages for adjusting PCs in PMD compensator. A compatible searching algorithm should at least satisfy the following basic characteristics: 1) rapid converging to the global optimum and avoiding to be trapped into local sub-optima; 2) robust to noise. The PSO algorithm, proposed by Kennedy and Eberhart[7], has proved to be very effective in solving global optimization for multi-dimensional problems in static, noisy, and continuously changing environments. Our group introduced the PSO technique into automatic PMD compensation, in which good adaptive compensation effects are obtained[8].

In conclusion, we demonstrated CD compensation and adaptive PMD compensation in 10-Gb/s NRZ transmission using two different nonlinearly equivalent chirped FBGs as dispersion compensator. The experimental results showed that we have successfully compensated for both CD and PMD by means of NC-FBGs in high speed optical fiber communication systems.

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