Group velocity dispersion and polarization mode dispersion compensation by high-birefringence linearly chirped fiber Bragg grating

Muguang Wang (王目光), Tangjun Li (李唐军), and Shuisheng Jian (简水生)

Lightwave Technology Institute, Beijing Jiaotong University, Beijing 100044

Received October 12, 2003

A high-birefringence linearly chirped fiber Bragg grating (FBG) is written into a polarization-maintaining photosensitive fiber by ultraviolet (UV) beam through a linearly chirped phase mask. Its performance as group velocity dispersion (GVD) and polarization mode dispersion (PMD) compensator is demonstrated in short pulse fiber optical transmission systems.

OCIS codes: 060.2330, 060.2420, 060.2340, 060.5530.

Group velocity dispersion (GVD) and polarization mode dispersion (PMD) have been acknowledged as two main limitation factors for high speed and long-haul wavelength division multiplexing (WDM) optical communication systems. Since PMD is characterized as a random stochastic change with many environmental fluctuations, such as temperature, strain, and wavelength etc., it is necessary to compensate PMD dynamically which is more challenging than static GVD compensation with dispersion compensating fiber or chirped fiber Bragg grating (FBG). Numerous optical and electronic PMD compensation techniques have been proposed in recent years[1]. Typically, a PMD compensator comprises of three main parts: 1) feedback/feedforward signal, 2) control electronic circuit, 3) compensating part composed of polarization controller (PC) and time delay line. The usually used time delay elements are free-space optics[2], high-birefringence polarization maintaining fiber, $\mathrm{LiNbO_3}$ waveguides[3], and FBG[4]. The free-space optics tends to be bulky and its performance may be easily affected by operational environment. The high-birefringence polarization maintaining fiber was limited due to the tunability and flexibility, while FBG is very promising for the advantages that it is all-fiber based, compact and has large amount of differential group delay (DGD) compensation.

Recently, high-birefringence nonlinearly chirped FBG (HN-FBG) was proposed for PMD compensation, where a differential time delay can be tunable for different states of polarization (SOPs)[4]. However, the fabrication and design of the HN-FBG will increase the scheme's cost and complexity, otherwise adjustment of DGD induces a chirp into the PMD compensated signal. This chirp may limit the transmission distance after the device due to its impact on fiber GVD. Though a chirp-free scheme in a dual-pass configuration is proposed to reduce the chirp[5], the interferometrical effect between two arms is introduced for the imperfect reflection of grating instead. Otherwise, the coherent noise due to the transmitted power through the grating also will limit the compensation performance.

Recent studies[6] have shown that the performance of a fix-DGD compensator is very close to that of the compensator with a variable-DGD element. Therefore in this paper, a high-birefringence linearly chirped FBG (HL-FBG) is proposed as a fix-DGD compensator for its simple structure and better cost-effective performance. Compared with HN-FBG, it can be easily fabricated by writing into a polarization-maintaining photosensitive fiber through a linearly chirped phase mask. Simultaneously, the fiber GVD also can be compensated using this grating. Its performance for short pulse transmission systems is assessed experimentally.

To simplify our analysis, we consider the fiber used for HL-FBG fabrication is just affected by a uniform linear birefringence, i.e., there is a large refractive index difference δn between fiber fast and slow principle axes of polarization. That results in a shift of the central Bragg wavelength $\delta\lambda$. The relation between δn and $\delta\lambda$ can be expressed as

$$\delta\lambda = 2\delta n\Lambda, \tag{1}$$

where Λ is the period of grating. Consequently, the Bragg reflection locations from the grating for a signal wavelength are polarization dependent, and essentially the position difference would introduce a shift of group delay (GD) curve for fast and slow SOPs

$$\mathrm{GD_f}(\lambda) = \mathrm{GD_s}(\lambda + \delta\lambda). \tag{2}$$

For a linearly chirped FBG, the GD for the wavelength $\lambda + \delta\lambda$ can be written by

$$\begin{aligned}&\mathrm{GD}(\lambda + \delta\lambda)\\ &= \mathrm{GD}(\lambda) + D\delta\lambda + \mathrm{GDR}(\lambda) - \mathrm{GDR}(\lambda + \delta\lambda),\end{aligned} \tag{3}$$

where D is the dispersion of grating, and $\mathrm{GDR}(\lambda)$ represents the group delay ripple (GDR) at a wavelength λ. Thus, the DGD between the two polarization axes can be expressed as[7]

$$\mathrm{DGD}(\lambda) = \left| D\delta\lambda + \mathrm{GDR}(\lambda) - \mathrm{GDR}(\lambda + \delta\lambda) \right|. \tag{4}$$

It is straightforward to observe that the DGD of grating was determined by these three parameters, namely, the initial linear birefringence of the fiber, GVD, and GDR oscillations of the grating. In particular for a HL-FBG, GDR is small enough to be omitted comparing with the impact of fiber birefringence, and Eq. (4) can be simplified as

$$\mathrm{DGD} = D\delta\lambda = 2D\delta n\Lambda. \tag{5}$$

It is noted that the DGD of HL-FBG is constant in the grating transmission bandwidth and equals to the product of GVD and Bragg wavelength shift $\delta\lambda$ of grating.

The HL-FBG was fabricated by phase mask technique based on near-contact exposure through a phase mask. A hydrogen-loaded high birefringence fiber was written into the grating by scanning the ultraviolet (UV) beam from a KrF excimer laser operating at 248 nm over a linearly chirped phase mask. An appropriate apodization function was designed to suppress spectral side lobes. The selected phase mask has a central period of 1060 nm with a chirp 9.29×10^{-9}, and the zero-order suppression is achieved with 2.6%. Real-time monitoring of grating growth is carried out during the writing process by illuminating the grating with an erbium-doped fiber amplifier (EDFA) and an optical spectrum analyzer (Ando AQ-6317) to display the reflected signal. Simultaneously a PC is introduced to adjust the SOPs into the grating. Figure 1 shows the measured reflection spectra of a HL-FBG length of 14 cm with two input SOPs. While to measure the GD of grating, a chromatic dispersion analyzer (EG&G CD400) and a Fabry-Perot laser (HP 8164A) with a tuned step of 0.01 nm were used based on phase technique. The measured GD of the grating as a function of wavelength for these two orthogonally input polarization signals was illustrated in Fig. 2.

It is straightforward to observe that there is a wavelength shift of 0.19 nm for the reflection spectra with different input SOPs. The effective reflection bandwidth for both orthogonally SOPs is from 1546.66 to 1547.92 nm. The group delay dispersion of HL-FBG is 702 ps/nm. Therefore, the DGD of grating is obtained as 133.38 ps.

An experiment as depicted in Fig. 3 was carried out to demonstrate the HL-FBG capability to compensate GVD and PMD in waveform distortion for short pulse transmission systems. 25.52-ps pulses with a repetition rate of 2.5 GHz at 1547.25 nm, generated from an external cavity laser with direct intensity modulation, were launched over 50-km length of G.652 single-mode fiber (SMF) and 2.16-km SMF with large PMD. This section of fiber has large average DGD of 127.49 ps measured by Jones matrix method. The result is shown in Fig. 4. PC was used to control the input SOP into HL-FBG. For the cases with and without GVD and PMD compensation, the transmitted signals were monitored using a digital communications analyzer (Agilent 86100B). GVD of 52.16-km SMF was almost completely compensated by the linear chirp of HL-FBG. While the waveform distortion originated from PMD of the 2.16-km SMF was mitigated by tuning PC to right input SOP of HL-FBG.

Figure 5 shows the measured results. The input pulse waveform has a pulse width of 25.52 ps (Fig. 5(a)). After transmitted through 50-km SMF and 2.16-km SMF with average DGD of 127.49 ps, the pulse was seriously distorted as shown in Fig. 5(b). Without adjusting the PC to optimum condition, it is observed that the pulse is still unacceptable due to large PMD in the link adding the DGD of grating, though GVD is compensated by linear chirp of grating. Figure 5(c) shows one output pulse waveform at certain time. By adjusting PC to optimize input SOP of HL-FBG, the distorted pulse was

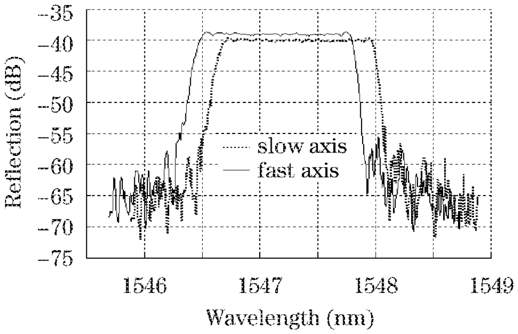

Fig. 1. Reflection of the grating.

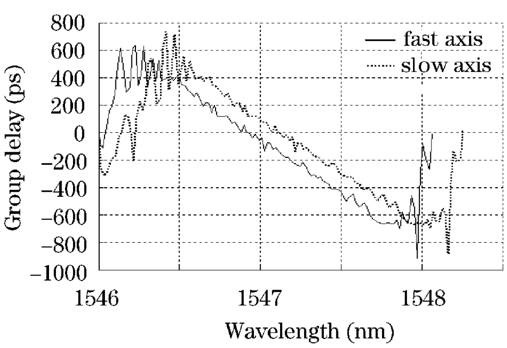

Fig. 2. Group delay of the grating.

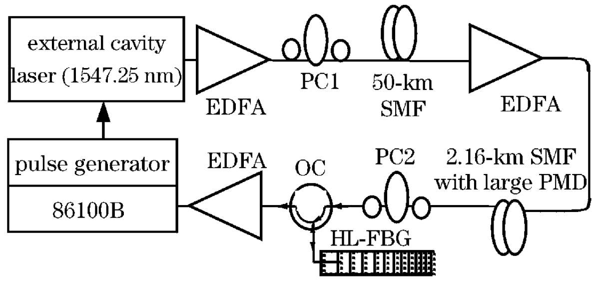

Fig. 3. Setup for short pulse transmission system.

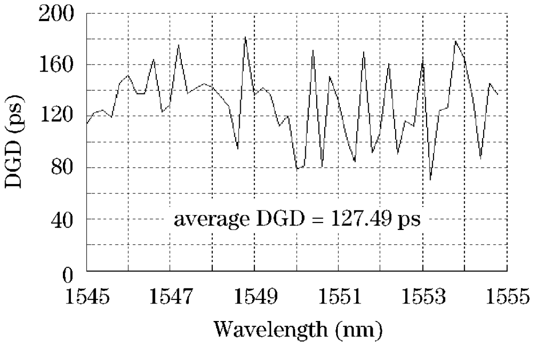

Fig. 4. PMD of 2.16-km SMF.

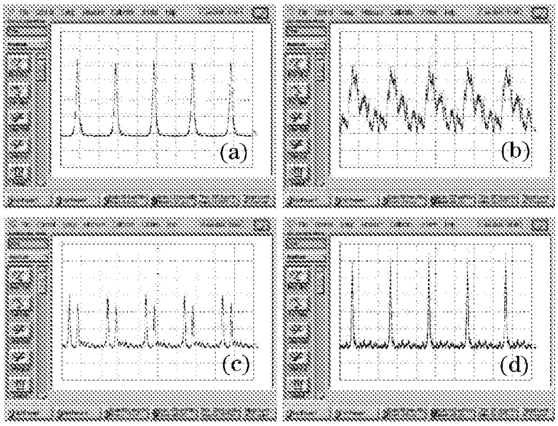

Fig. 5. (a) Original pulse, (b) output pulse transmitted through 52.16-km SMF only, (c) output pulse with GVD compensation only, (d) output pulse with PMD and GVD compensation.

successfully restored back to initial shape with pulse width of 25.60 ps (Fig. 5(d)). These results confirm the capability and robustness of HL-FBG as a GVD and PMD compensator in high bit rate, short pulse transmission systems. However, it is worthy to point out that this combination device for simultaneous GVD and PMD compensation has limitations in application. GVD and DGD of the HL-FBG have certain correlation as expressed in Eq. (5). This complicates the parameter design of HL-FBG. In this case, we typically consider the right DGD of grating to compensate the PMD in the links first of all, and then the residual GVD can be compensated using another standard chirped FBG.

In this paper, we have written a HL-FBG into a hydrogen-loaded high-birefringence fiber by the phase mask techniques. The device plus a PC used as a fix-DGD PMD compensator is assessed experimentally in a short pulse transmission system with large PMD. Simultaneously, fiber GVD was also compensated using this grating.

M. Wang's e-mail address is wangmuguang@263.net.

References

1. D. Penninckx and S. Lanne, in *Proceedings of OFC'2001* TUP1, 1 (2001).
2. F. Heismann, D. A. Fishman, and D. L. Wilson, in *Proceedings of ECOC'1998* 529 (1998).
3. R. Noe, D. Sandel, M. Yoshida-Dierolf, S. Hinz, V. Mirvoda, A. Schopflin, C. Gungener, E. Gottwald, C. Scheerer, G. Fischer, T. Weyrauch, and W. Haase, J. Lightwave Technol. **17,** 1602 (1999).
4. S. Lee, R. Khosravani, J. Peng, V. Grubsky, D. S. Starodubov, A. E. Willner, and J. Feinberg, IEEE Photon. Technol. Lett. **11,** 1277 (1999).
5. Z. Pan, Y. Xie, S. Lee, A. E. Willner, V. Grubsky, D. S. Starodubov, and J. Feinberg, in *Proceedings of OFC'2000* THH2, 113 (2000).
6. A. Lima, I. Lima, B. Marks, C. Menyuk, and W. Kath, in *Proceedings of OFC'2003* THA3, 419 (2003).
7. D. Wang, M. Maatthews, and J. Brennan, in *Proceedings of OFC'2003* WC3, 313 (2003).