Simple all-fiber-optic component for first-order polarization mode dispersion compensation

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Abstract. A simple and reliable all-fiber-optic component for a first-order polarization mode dispersion compensator is presented and tested in a 10-Gbit/s transmission system. The proposed component incorporates tunable differential group delay (DGD) provided by several pieces of polarization maintaining (PM) fibers of different DGD that were spliced together with short lengths of single-mode fibers between them. The total DGD of the compensator is determined by the alignment of fast and slow axes of the PM fiber sections. Applying this component as a first-order polarization mode dispersion (PMD) compensator, we demonstrate that a component with seven pieces of PM fiber segments could possibly compensate the first-order PMD up to 63.5 ps with 1-ps steps and a switching time of 300 ms. We also optimize the number of PM fiber sections in this component for a first-order PMD compensation in a 10-Gbit/s system based on experimental results. [DOI: 10.1117/1.1473796]

Subject terms: polarization; polarization mode dispersion; polarization mode dispersion compensation; optical fiber communication; optical fiber.

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1 Introduction

Polarization mode dispersion (PMD) is one of the major obstacles in long-haul transmission systems of over 10 Gbit/s speed.[1] The physical characteristics of PMD and the resulting signal distortion have been studied extensively,[2,3] and different techniques for the first-order PMD compensation have been reported.[4–10] The difficulties in PMD compensation lie in the fact that PMD fluctuates due to the change of environmental conditions, meaning a PMD compensator should be tunable in both differential group delay (DGD) and principal state of polarization (PSP). Recently, fiber optic first-order PMD compensators composed of polarization maintaining (PM) fiber sections for variable DGD have been suggested,[7,8,10] and they employ a large number of PM fiber sections separated by polarization transformers to achieve different DGD values. In this paper, we propose and demonstrate a much simpler and practical approach to the tuning of DGD applicable to PMD compensation with a minimum number of PM fiber sections and environmentally stable means to control the net DGD. The reduction of the number of PM fiber sections is achieved by using a geometric series of DGDs, and the net DGD is controlled by twisting short sections of non-PM fiber by a fixed angle.

2 Principle and Structure

Figure 1 shows the schematic structure of the constructed component for first-order PMD compensation. The device is composed of different lengths of seven segments of elliptic-core PM fibers that were spliced together with short lengths of SMFs between them. The lengths of the SMFs that connected the PM fibers were less than 15 cm and had negligible PMD. One end of each PM fiber section was fixed and the other end was attached to the axis of a dc stepping motor so that the birefringence axis of each PM fiber can be mechanically rotated by a predetermined angle with respect to that of the next PM fiber section. The maximum net DGD of the device is obtained when the fast (and therefore the slow) axes of all the PM fiber segments are aligned, and the net DGD can be changed by aligning the fast axes of some segments with the slow axes of the adjacent segments. The rotation angle applied to the PM fiber segments should be 97 deg to compensate for the effect of induced circular birefringence due to the twist of SMF spliced between the PM fiber segments.

The length of each PM fiber section was determined so that their DGD values become the increasing value of $2^{N-1}\tau_{\min}$, where $\tau_{\min}$ is the DGD of the shortest PM fiber segment and an integer N ($1 \leqslant N \leqslant$ number of PM fiber sections). Since the rotation of selected PM fiber segments corresponds to the addition or subtraction of the DGD of the rotated sections, it is possible to generate an arbitrary value of DGD between the DGD of the shortest PM fiber and the total sum of DGD of all PM fiber sections with a step of $2\tau_{\min}$. The relationship between the maximum available DGD $\tau_{\max}$ and the number of PM fiber sections can be obtained by

$$\tau_{\max} = \tau_{\min}(2^N - 1). \tag{1}$$

For the component built in this work, $\tau_{\min} = 0.5$ ps and $\tau_{\max} = 63.5$ ps, and this range can be easily designed to fit different operating requirements.

The dc stepping motors in the constructed device were controlled by a personal computer via RS232C. Figure 2 shows the measured values of all possible DGDs that the

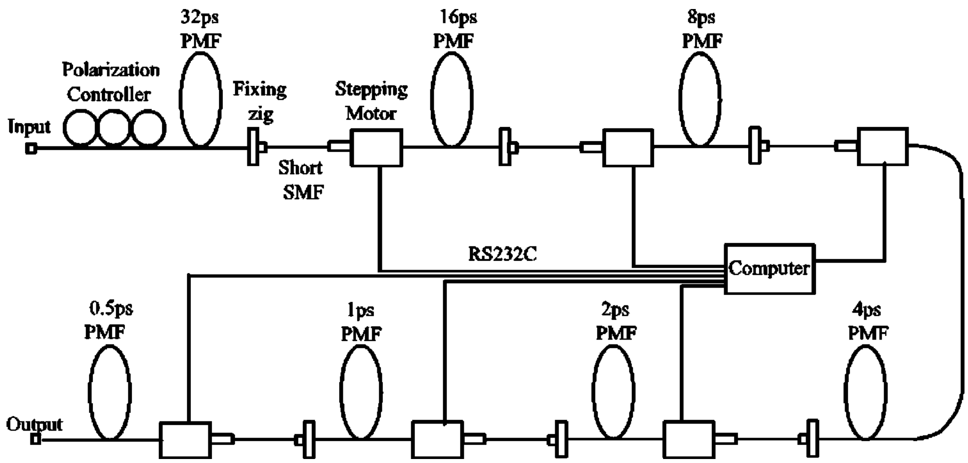

Fig. 1 Schematic structure of an all-fiber-optic component for a first-order PMD compensator (PMF, polarization maintaining fiber; SMF, single-mode fiber).

constructed component with seven PM fiber segments can generate. The vertical axis represents DGD measured by fixed analyzer method[11] and the horizontal axis represents all possible rotational combinations by dc stepping motors. The insertion loss of the constructed device was about 16 dB due to the exceptionally large splicing loss (1.1 dB/ splice for 14 splices) between the elliptical core PM fiber and the SMF. This loss can be reduced to a negligible value of less than 1 dB if properly matched PM and SMF are used. The switching time of the constructed component to achieve the required value of DGD was about 300 ms, limited by the dc motor speed used.

3 Optimizing Number of PM Fiber Section

Figure 3 shows the experimental setup to estimate the optimal number of PM fiber sections in the proposed component used as a compensator of first-order PMD in a 10-Gbit/s transmission system. The output from a 1550-nm distributed feedback (DFB) laser was externally modulated by a high-speed electro-optic modulator with 2^{23-1} pseudo-random binary sequence (PRBS) data pattern at 10 Gbit/s and sent through an optical amplifier, a first-order PMD emulator, another optical amplifier, a polarization controller, and the PMD compensator. The output signal from the

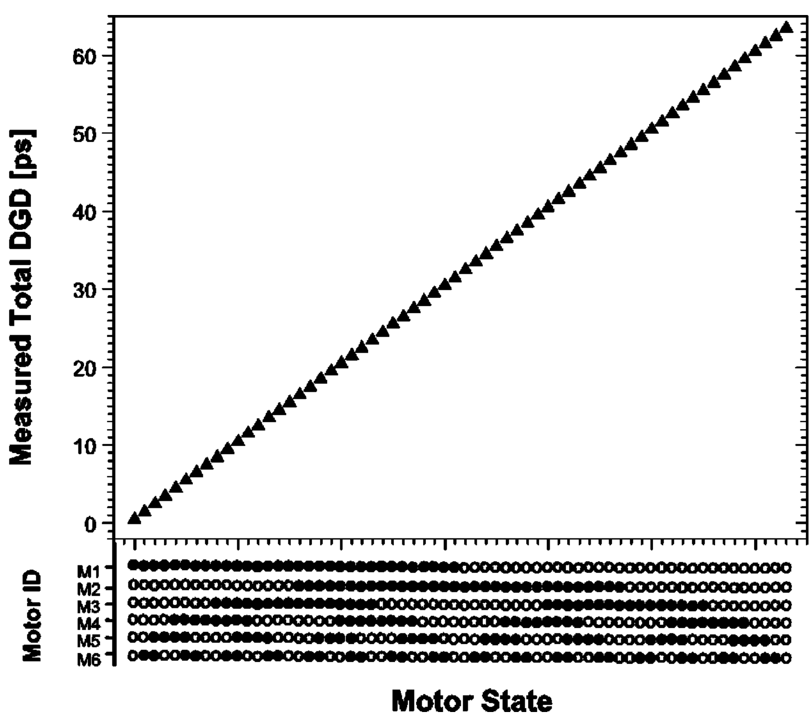

Fig. 2 Measured net DGD of compensator versus rotational combination of dc stepping motor with seven PM fiber segments: M1, connecting 32 ps, 16 ps; M2, connecting 16 ps, 8 ps; M3, connecting 8 ps, 4 ps; M4, connecting 4 ps, 2 ps; M5, connecting 2 ps, 1 ps; M6 connecting 1 ps, 0.5 ps; ●, 97-deg rotation; ○, 0-deg stationary.

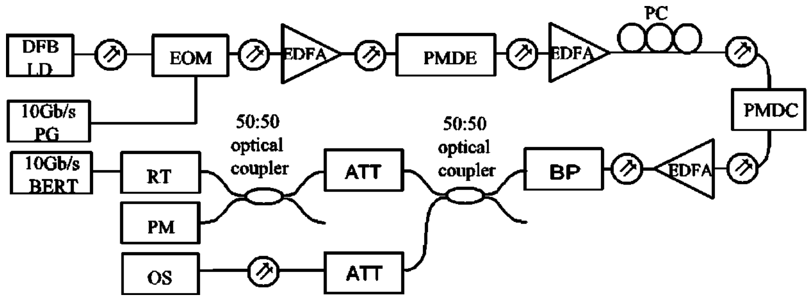

Fig. 3 Experimental setup for first-order PMD compensation in a 10-Gbit/s system: EOM, electro-optic modulator; PG, pattern generator; RT, receiver; PM, optical power meter; OS, sampling oscilloscope; ATT, variable attenuator; BP, bandpass filter; EDFA, erbium-doped fiber amplifier; PC, polarization controller; PMDE, first-order PMD emulator; PMDC, first-order PMD compensator.

compensator was amplified by an optical preamplifier and divided by a 3-dB coupler after amplified spontaneous emission (ASE) noise was removed by using a tunable bandpass filter. One of the output signals from the 3-dB coupler was divided by another 3-dB coupler and was monitored by a p-i-n receiver and a power meter. The other output signal from the first 3-dB coupler was measured by a sampling oscilloscope. Three optical amplifiers were used to compensate for optical losses from the PMD emulator and the compensator.

The first-order PMD emulator used in this experiment was a Mach-Zehnder interferometer with a variable delay constructed with two 3-dB fiber couplers, a polarization controller, and bulk optic elements.[6] The emulator was enclosed in a polyurethane box to prevent rapid changes due to temperature fluctuations. The eye diagrams and power penalties were measured at the output of the constructed compensator as the DGD of the compensator was tuned from 0.5 to 63.5 ps in the presence of 60 ps of induced DGD. The polarization controller located in front of the compensator was adjusted manually to maximize the eye opening and minimize the instantaneous BER simultaneously whenever the PMD compensator setting was changed. In the case of practical application, by partially measuring the strength of first harmonic of the modulated baseband signal using a high-speed detector and a rf bandpass filter in front of the compensator following by the measurement of the degree of polarization at the end of the compensator and using them as feedback control signals for the PM fiber sections and the polarization controller respectively, fully automatic operation of compensator can be achieved.[6,9]

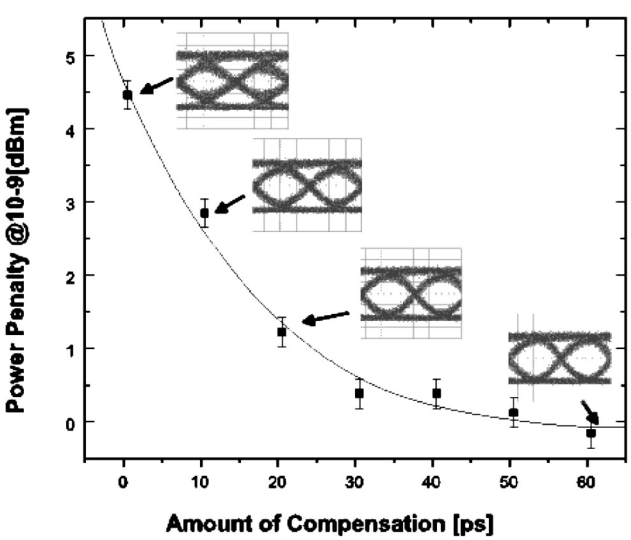

Fig. 4 Measured power penalty and eye diagrams as a function of applied DGD compensation, in the presence of 60 ps of initial DGD.

Figure 4 shows the system impairment with 60 ps of initial DGD and its improvement after compensation at a bit error rate (BER) of 10^{-9} with corresponding eye diagrams. The measured power penalty saturates as the net DGD is reduced, and the optimum value of the $\tau_{\min}$ can be determined by compromising between the acceptable power penalty and the number of PM fiber segments used in the compensator. For example, in our experiment, a power penalty margin of 0.26 dB enables us to use $\tau_{\min}=10$ ps with 20-ps compensation steps and therefore significantly reduce the number of PM fiber segments to three, leading to a simpler structure and control with reduced splice loss. For the case of 40-Gbit/s systems, finer DGD compensation steps should be required.

4 Conclusion

We have constructed an all-fiber-optic device for a first-order PMD compensator and tested its applicability in PMD compensation in a 10-Gbit/s system. The constructed PMD compensating device employed seven sections of PM fibers that have different DGD values of $2^{N-1}\tau_{\min}$, where $N(\leqslant 7)$ is a positive integer, and $\tau_{\min}=0.5$ ps. It could possibly compensate the arbitrary input DGD, which is smaller than the total sum of DGD, of PM fiber segments. Although the compensating device provides discrete DGD compensation values, it is tested that in a 10-Gbit/s system this device can be applied to first-order PMD compensation with good stability. From the test result, we also suggested guidelines for determining optimal number of PM fiber sections in this device.

References

1. C. D. Poole, R. W. Tkach, and A. R. Chraplyvy, "Fading in lightwave systems due to polarization-mode dispersion," *IEEE Photonics Technol. Lett.* **3**(1), 68–70 (1991).
2. C. D. Poole and R. E. Wagner, "Phenomenological approach to polarization dispersion in long single-mode fibers," *Electron. Lett.* **22**(19), 1029–1030 (1986).
3. F. Curti, B. Daino, G. De Marchis, and F. Matera, "Statistical treatment of the evolution of principal states of polarization in single-mode fibers," *J. Lightwave Technol.* **8**(8), 1162–1166 (1990).

4. F. Roy, C. Francia, F. Bruyere, and D. Penninckx, ''A simple dynamic polarization mode dispersion compensator,'' in *OFC'99 Technical Digest*, Vol. 1, pp. 275–278 (1999).
5. S. Lee, R. Khosravani, J. Peng, A. E. Wilner, V. Grubsky, D. S. Straodubov, and J. Feinberg, ''High-birefringence nonlinearly-chirped fiber Bragg grating for tunable compensation of polarization mode dispersion,'' in *OFC'99 Technical Digest*, Vol. 1, pp. 272–274 (1999).
6. H. Ooi, Y. Akiyama, and G. Ishikawa, ''Automatic polarization-mode compensation in 40-Gbit/s transmission,'' in *OFC'99 Technical Digest*, Vol. 2, pp. 86–88 (1999).
7. R. Noe, D. Sandel, M. Yoshida-Dierolf, S. Hinz, C. Glingener, C. Scheerer, A. Schopflin, and G. Fischer, ''Polarization mode dispersion compensation at 20Gbit/s with fibre-based distributed equaliser,'' *Electron. Lett.* **34**(25), 2421–2422 (1998).
8. S. Hinz, D. Sandel, M. Yoshida-Dierolf, R. Noe, R. Wessel, and H. Suche, ''Distributed fiber optic PMD compensation of a 60ps differential group delay at 40Gbit/s,'' in *Proc. ECOC'99*, pp. 136–137 (1999).
9. G. Ishikawa and H. Ooi, ''Polarization-mode dispersion sensitivity and monitoring in 40-Gbit/s OTDM and 10-Gbit/s NRZ transmission experiments,'' in *OFC'98 Technical Digest*, pp. 117–119 (1998).
10. D. Sobiski, D. Pikula, J. Smith, C. Henning, D. Chowdhury, E. Murphy, E. Koiiveit, and F. Annunziata, ''Fast first-order PMD compensation with low insertion loss for 10 Gbit/s system,'' *Electron. Lett.* **37**(1), 46–48 (2001).
11. ''Polarization-mode dispersion measurement for single mode optical fibers by the fixed analyzer method,'' TIA/EIA FOTP-113, Telecommunications Industry Association, Washington, DC (1997).

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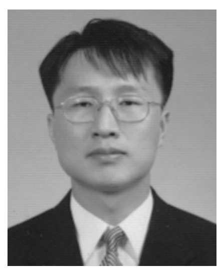

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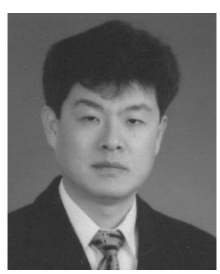

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