Compensating large PMD by a fiber grating

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In this paper, the first- and second-order polarization mode dispersion (PMD) with the amount of 132.994-ps differential group-delay (DGD) and maximum 476.129-ps/nm second-order PMD can be compensated by a two-stages PMD compensator at a 40-Gb/s optical fiber communication system. The first stage has one free degree that is used for first order and high orders PMD compensations by rotating the state of polarization. The second-stage is used for remainder PMD compensations. After compensation, the average DGD and the maximum second-order PMD are reduced to 345.310 fs and 3.102 ps/nm, respectively.

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Polarization mode dispersion (PMD) is not usually a problem for optical communication systems operating at lower-speed transmission. With the growth of the transmission channel rates up to 10 Gb/s or above, PMD becomes a major performance limit factor[1]. Today's optical networks are straining to support data and voice needs, and the increase in bandwidth is an inevitable requirement. They are also bringing with new inherent challenges that have not been seen before in lower rate systems. One of those challenges is how to dynamically compensate PMD on the system of those higher data rates. After chromatic dispersion compensated, PMD is the most likely effect limiting the transmission bandwidth of single-mode fiber in future high-speed systems. PMD can be characterized to first order in term of differential group-delay (DGD). Second-order effects such as polarization-state rotation or depolarization and polarization chromatic dispersion are of concern[3]. PMD is a significant factor limiting the distance data traveling without regeneration in optical fiber at 10 and 40 Gb/s. Reducing the effects of PMD directly through PMD compensation is a new and powerful technology, especially in existing networks which have a large PMD.

PMD is caused by birefringence of the fiber and the fiber core eccentricity. The stress is induced by environmental factors. PMD induces RMS pulse width broadening, intersymbol interference and power penalty of optical communication system. PMD has been extensively studied[2], and can be characterized to first order in terms of differential group-delay (DGD-1) in the fiber principle states of polarization (PSP-1). Second-order effects such as polarization-state rotation or depolarization (DEP-2), and polarization chromatic dispersion (PCD-2) are of concern, as 40-Gb/s channel data rates become commercial reality. It is therefore to be expected that some degree of PMD mitigation will be required, and at progressively higher orders[3].

The stochastic characteristics of PMD make its compensation difficult. Key components for PMD compensation are polarization controller, variable DGD element, and penalty signal extraction scheme.

Poincare sphere and Stokes vector for TEM waves, E field is represented by[4]

$$\hat{E}_x(t) = a_x \cos(\omega t + \phi_x)\hat{i}, \quad (1)$$

$$\hat{E}_y(t) = a_y \cos(\omega t + \phi_y)\hat{j}, \quad (2)$$

$$\hat{E}_r(t) = \hat{E}_x(t) + \hat{E}_y(t) = \mathrm{Re}(a_x \mathrm{e}^{j\omega t}\hat{x} + a_y \mathrm{e}^{j\omega t}\hat{y}). \quad (3)$$

Stokes vector on Poincare sphere is defined by

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I \\ I_0 - I_{90} \\ I_{45} - I_{-45} \\ I_{\mathrm{rcp}} - I_{\mathrm{lcp}} \end{bmatrix} = \begin{bmatrix} a_x^2 + a_y^2 \\ a_x^2 - a_y^2 \\ 2a_x a_y \cos\Delta\phi \\ 2a_x a_y \sin\Delta\phi \end{bmatrix}$$

$$= \begin{bmatrix} 1 \\ \cos 2\omega \cos 2\alpha \\ \cos 2\omega \sin 2\alpha \\ \sin 2\omega \end{bmatrix}, \quad (4)$$

where 2ω is longitude, 2α is latitude (azimuth of ellipse), and $\Delta\phi = \phi_x - \phi_y$.

PMD vector is given by

$$\hat{S}(z,\omega) = \hat{R}(z,\omega)\hat{S}(0,\omega), \quad (5)$$

where $\hat{R}$ is 3×3 rotation matrix and $\hat{R} = \mathrm{e}^{2a\hat{b}x}$,

$$\frac{\partial \hat{S}(z,\omega)}{\partial \omega} = (\frac{\mathrm{d}\hat{R}(z,\omega)}{\mathrm{d}\omega})\hat{S}(0,\omega). \quad (6)$$

From Eqs. (5) and (6), we can obtain

$$\frac{\partial \hat{S}(z,\omega)}{\partial \omega} = (\frac{\mathrm{d}\hat{R}(z,\omega)}{\mathrm{d}\omega})\hat{R}^{-1}(z,\omega)\hat{S}(z,\omega)$$

$$= \hat{\Omega}(z,\omega) \times \hat{S}(z,\omega). \quad (7)$$

By the same principle, we obtain

$$\frac{\partial \hat{S}}{\partial z} = \hat{W}(z,\omega) \times \hat{S}, \quad (8)$$

where $\hat{W}(z,\omega)$ is randomly varying birefringence vector. Equation (7) is given by the dimensional evolution of the polarization state at a fixed frequency. Equation (8) shows polarization state changing with frequency at a fixed position.

The meaning of PMD vector is

$$|\Omega| = \Delta\tau(\mathrm{DGD}). \quad (9)$$

The direction of PMD is same as output PSP+ (PSP: principal states of polarization). The magnitude of PMD relates to rotation rate

$$\gamma = |\Omega|\, \Delta\omega = \Delta\tau \cdot \Delta\omega. \tag{10}$$

In order to get high-order PMD, $\Omega(z,\omega)$ can be expanded to a progression around the center frequency ω_0

$$\Omega(\Delta\omega) = \Omega^{(0)} + \Omega^{(1)}\Delta\omega + \Omega^{(2)}\frac{\Delta\omega^2}{2} + \cdots , \tag{11}$$

where $\Omega^{(n)}$ denotes $(n+1)$th-order PMD. Figure 1 is sketch map about the first-order and high-order PMD.

From Eqs. (7) and (8), the dynamic equations for PMD vector at the optical fiber Bragg grating (FBG) are given by

$$\begin{cases} \frac{\partial S}{\partial z} = W(z,\omega) \times S, \\ \frac{\partial S}{\partial \omega} = \Omega(z,\omega) \times S, \\ \frac{\partial \Omega}{\partial z} = \frac{\partial W}{\partial \omega} + W + \Omega. \end{cases} \tag{12}$$

On the other hand, the PMD can also be expressed as a function of birefringence W, dispersion D, and Bragg wavelength λ_0

$$\Delta\tau(\mathrm{DGD}) = \lambda_0 \cdot W \cdot D. \tag{13}$$

The first-order PMD is proportional to the dispersion and birefringence, and the PMD of fiber grating is bigger than that of multi kilometers polarization maintenance fiber (PMF). So, the FBG is excellent for the PMD compensation at a large PMD link.

In order to assess the impact on the PMD of birefringence in a fiber grating, under conditions of constant temperature, it is known that when a linearly chirped FBG is stretched by axial strain $\varepsilon(z)$ at grating position z, the wavelength of the grating due to pull or press is changed to[5]

$$\Lambda[z,\varepsilon(z)] = (\Lambda_0 + c_0 \cdot z)[1 + \varepsilon(z)], \tag{14}$$

where Λ_0 is the grating period at position $z = 0$ without strain, constant c_0 denotes the initial linear chirp of the grating and is represented as

$$c_0 = \left.\frac{d\Lambda}{dz}\right\|_{\varepsilon=0} . \tag{15}$$

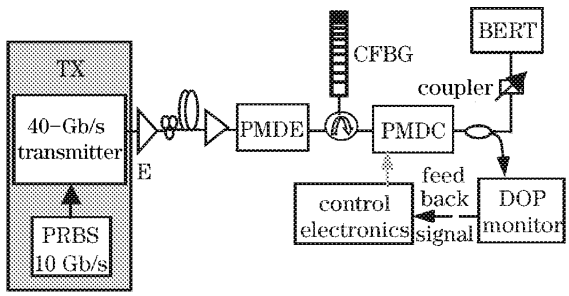

Fig. 1. The two-stage PMD compensator.

The induced change in fiber index by photoelastic effects is expressed as

$$\frac{\mathrm{d}n_{\mathrm{eff}}(z)}{n_{\mathrm{eff}}} = -\rho_e \cdot \varepsilon(z), \tag{16}$$

where we have subsumed the photoelastic contributions into ρ_e, and factor ρ_e has a typical value of ~ 0.22. Thus Bragg wavelength $\lambda(z)$ at grating position z becomes

$$\lambda(z) = 2n_{\mathrm{eff}}[(\Lambda_0 + c_0 z) + (\Lambda_0 + c_0 z)(1 - \rho_\varepsilon)\varepsilon(z)]. \tag{17}$$

It is straight forward to observe that the reflection wavelength shift of the grating is proportional to the applied strain. If a strain gradient is added to a FBG, Bragg wavelength will vary nonlinearly with the fiber length. The nonlinear relationship between the reflection wavelength and its reflection position determines the group delay characteristics of the grating. Therefore, the expected group delay characteristics of the grating can be obtained by an appropriate design of the strain distribution.

On the basis of above analyzed, PMD can be compensated by a two-stage PMD compensator after a optical fiber link which has the amount of 132.994-ps DGD and maximum 476.129-ps/nm second-order PMD, as shown in Fig. 2.

The first-stage is made up of a polarization controller and 20-m PMF, that has 30-ps DGD approximately. The stage has one free degree that is used for first-order and high-order PMD compensations by rotating the state of polarization. The second-stage is made up of a polarization controller and a tunable linearLY chirped grating at a 1553.68-nm central wavelength. This stage has three free degrees. The stage is used for remainder PMD compensations.

The magnitude of the DGD and direction are changed by the polarization controller and the grating in the second-stage. The first- and second-stage are combined which enables compensation of first- and second-orders PMD on both static and dynamic basis. The feed back signal is monitored. We applied algorithm for the compensator to control its action.

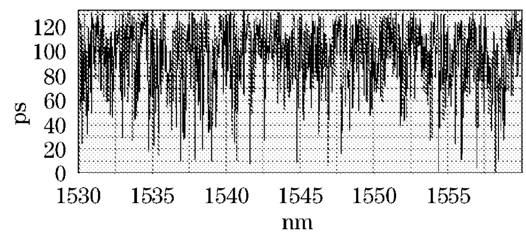

Fig. 2. DGD versus wavelength without compensation.

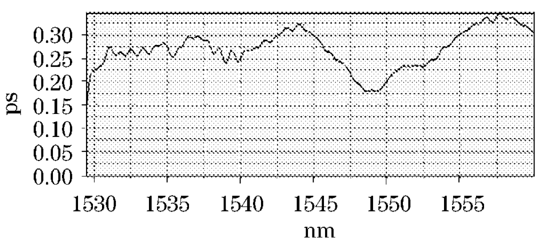

Fig. 3. DGD versus wavelength after compensation.

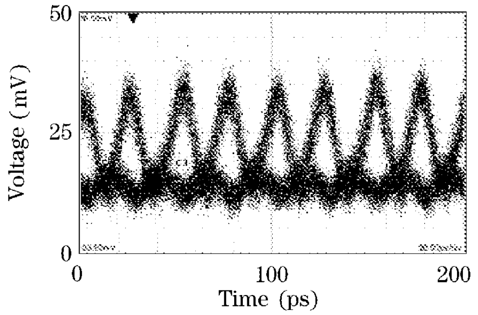

Fig. 4. Initial 40-Gb/s modulated signal eye digram.

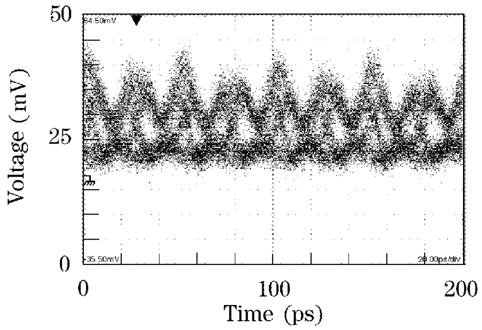

Fig. 5. Signal eye digram after put in a large PMD fiber.

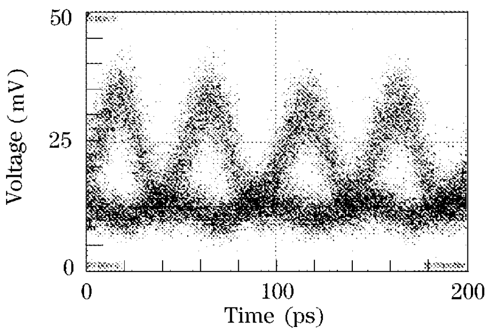

Fig. 6. Signal eye digram after compensation.

We have demonstrated a two-stage PMD compensator. By dynamic adaptive technique, we adjust the polarization controller's direction, change magnitude of the FBG's PMD, and achieve PMD dynamic compensation. The first- and second-order PMD can be compensated for the amount of 132.994-ps DGD and maximum 476.129-ps/nm second-order PMD by a two-stage PMD compensator at a 40-Gb/s optical fiber communication system. After compensation, the average DGD and the maximum second-order PMD are reduced to 345.310 fs and 3.102 ps/nm, respectively. The dispersion in 120-km SMF was successfully compensated too. The curve of DGD versus wavelength after compensation is shown in Fig. 3. Figure 4 is initial 40Gb/s modulated signal eye digram. Figure 5 is the signal eye digram after put in a large PMD fiber. Figure 6 is the signal eye digram after the compensation. The results show that this technique could improve the signal quality. The proposed PMD compensator can be potentially useful, because it is inexpensive, its structure is simple, and it has a fast compensation speed. However, the device still needs refinement to improve on stability, if it is used for DWDM dispersion compensation and PMD compensation.

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References

1. N. Y. Kim, J. Park, H. Kim, and N. Park, in *Proceedings of OFC2002* W16, 239 (2002).
2. M. C. Parker, in *Proceedings of OFC2002* THGG56, 691 (2002).
3. E. Corbel, in *Proceedings of OFC2002* TuN1 (Invited), 35 (2002).
4. Y. D. Gong, Ph. D. Dissertation of Beijing Jiaotong University (Mar. 16, 1998).
5. M. G. Wang, T. J. Li, and S. S. Jian, Opt. Express **11,** 2354 (2003).