PMD compensation based on a new type dynamic first-order PMD compensator

Jiajun Wang (汪佳俊), Shilong Pan (潘时龙), Jia Jia (贾 佳),
Yanfu Yang (杨彦甫), and Caiyun Lou (娄采云)

Department of Electronic Engineering, Tsinghua University, Beijing 100084

Received October 27, 2005

A dynamic first-order polarization mode dispersion (PMD) compensator based on garnet and yttrium vanadate crystal has been proposed and implemented. Consisting of a differential group delay (DGD) generator and a Faraday rotator (FR), this PMD compensator has only two degrees of freedom. Feedback control and compensation algorithm are both very simple. Experimental results reveal the compensator behaviors to be excellent for PMD compensation in 40-Gb/s optical time domain multiplexing (OTDM) system.

OCIS codes: 060.2330, 230.5440.

As the increasing bit rate per channel in optical fiber communication presently, polarization mode dispersion (PMD) has attracted much attention and is regarded as a major limitation in $\geq$ 40-Gb/s per channel optic transmission system. Extensive research efforts have been made on PMD compensation. As PMD is a stochastic phenomenon and different signal formats have different bandwidths, PMD compensator properly designed with a large number of control parameters is more flexible and capable of compensation for first and higher order PMD. Though researches on PMD compensation have been launched since 1997[1-3], practical use of PMD compensation is not available so far due to complexity of compensation as well as high cost. No eligible PMD compensator (PMDC) that devised is one of the chief reasons. It is known that the variable-delay compensator provides superior performance as compared to a fixed-delay compensator. As the first-order PMD is the dominant factor in optic fiber communication systems[4,5], the emulation, measurement and compensation of first-order PMD is always the major problem in researches.

In this paper, we analyze current PMDCs and introduce a dynamic first-order PMDC based on crystal. Consisting of a differential group delay (DGD) generator[6,7] and a Faraday rotator (FR)[6], this PMDC has only two degrees of freedom. Thus, feedback control and compensation algorithm are very simple.

A typical PMD compensation system configuration is usually composed of two groups of polarization controller (PC) and polarization maintaining fiber (PMF). The two PMFs with DGD values of $\Delta\tau_1$ and $\Delta\tau_2$ respectively are coupled within a certain angle θ, as shown in Fig. 1. The overall DGD ($\Delta\tau$) counts up to

$$|\Delta\tau| = \sqrt{\Delta\tau_1^2+\Delta\tau_2^2+2\Delta\tau_1\Delta\tau_2\cos(\theta)}. \qquad (1)$$

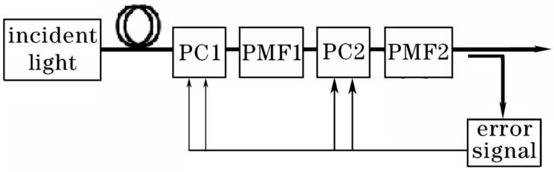


Fig. 1. Typical configuration of PMD compensation system.

While changing the value of θ, any DGD between $|\Delta\tau_1 - \Delta\tau_2|$ and $\Delta\tau_1 + \Delta\tau_2$ is available, especially when $\Delta\tau_1$ equals $\Delta\tau_2$, the overall DGD varies from 0 to $2\Delta\tau_1$. However, as first-order and high-order PMD effects often coexist in the above device, it is difficult to acquire the anticipated DGD exactly. Also, as this device requires four controlling parameters in compensation, the compensation algorithm can be extremely complex. Although tunable DGD generator has been devised, when connected with PC as PMDC, controlling parameter is still a problem because a PC has two degrees of freedom. Excessive degree of freedom intrinsically requires complicated compensation algorithm.

PMD compensator consisting of a FR made of garnet crystal and a DGD generator[6] with only two degrees of freedom is proposed, as shown in Fig. 2. The DGD generator consists of six birefringent crystals. Length of each crystal is twice than the one before. Polarization switches (PSs) are placed between two consecutive crystals to rotate the polarization of light, the rotating angle can be either 0° or 90°. If DGDs of the two crystals are $\Delta\tau_1$ and $\Delta\tau_2$ respectively, the overall DGD can be either $(\Delta\tau_1 + \Delta\tau_2)$ or $(\Delta\tau_1 - \Delta\tau_2)$. DGD ranging from -35 to 35 ps with a resolution of 1 ps is available by diverse combination of the rotating angle of PSs in experiment.

The work principle of the proposed PMDC can be explained in the following way. There are two methods for complete compensation of first-order PMD[8], as shown in Fig. 3. (The compensation principle of our compensator is the same as that of the compensator discussed in Ref. [8]. There exists slight difference that adjustable parameters in the two compensators are not identically the same. Our compensator adjusts FR and DGD in compensation while compensator in Ref. [8] adjusts PC.)

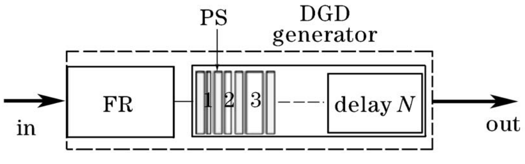
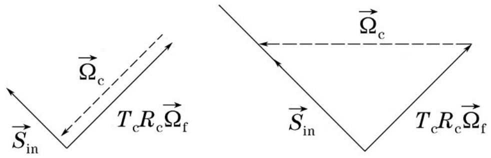


Fig. 2. Configuration of the compensator.



method A
(a)

method B
(b)

Fig. 3. Two compensation methods. $\overrightarrow{S_{in}}$ is the state of polarization in Stokes space, $\overrightarrow{\Omega_f}$ and $\overrightarrow{\Omega_c}$ are PMD vectors of transimission fiber and PMD compensator respectively, T_c and R_c are muller delay matrix induced by DGD generator and muller rotation matrix induced by FR respectively.

According to the concatenation rule, the total PMD vector $\overrightarrow{\Omega_T}$ after compensation is[9]

$$\overrightarrow{\Omega_T} = \overrightarrow{\Omega_c} + T_cR_c\overrightarrow{\Omega_f}, \tag{2}$$

$\overrightarrow{\Omega_c}$, T_c, R_c, and $\overrightarrow{\Omega_f}$ are defined in Fig. 3.

The first method is to fully eliminate PMD as represented in Fig. 3(a). During compensation, we can adjust the compensator to make total PMD vector $\overrightarrow{\Omega_T}$ to be zero. Apparently, without PMD in transmission system, the signal waveform will never distort. The other way is to align one of the PSPs of the whole system to the state of polarization (SOP) of the incident signal. As shown in Fig. 3(b), we adjust PMD vector of compensator to make direction of total PMD vector $\overrightarrow{\Omega_T}$ the same as or reverse to the direction of SOP $\overrightarrow{S_{in}}$. In this method, we can also compensate PMD since light propagating along PSP does not distort. PMD compensation with three degrees of freedom (PC+DGD) can definitely work in both methods. Generally, our two degrees of freedom compensator works in method B, however it can also work in method A on condition that $\overrightarrow{\Omega_f}$ is parallel to the equatorial plane of Poincare sphere. By continuously adjusting FR and DGD in this compensator, we can align the PSP of whole transmission system together with compensator to SOP of incident light. In this way, PMD compensation is achieved. To fully eliminate PMD induced by transmission link with various DGD, PMD compensator with two degrees of freedom requires large $\left|\overrightarrow{\Omega_c}\right|$. The same as the three degrees of freedom PMD compensator, maximal DGD of the compensator determines the compensation range arbitrarily. If DGD of fiber link exceeds the compensation range, outage might happen when compensator is not handled properly. In these cases, we can adjust FR and DGD in the compensator to make total PMD length $\left|\overrightarrow{\Omega_T}\right|$ as small as possible. As we know, transmission system has a certain tolerance of PMD. By adjusting compensator, we can alleviate $\left|\overrightarrow{\Omega_T}\right|$ to keep it within the PMD tolerance of transmission system, no outage would occur after compensation even if $\left|\overrightarrow{\Omega_f}\right|$ of fiber link is very large.

The experimental setup is shown in Fig. 4. A 10-GHz optical pulse train[10] with 2-ps full-width at half-maximum (FWHM) at the wavelength of 1545 nm is generated by a pulse generator, which is made of a pulse carving (electro-absorption modulator, EAM) and a two-stage nonlinear compressor. The 10-GHz pulse train is modulated by a $\mathrm{LiNbO_3}$ modulator with a pseudo random bit sequence (PRBS) of 2^7-1 at 10 Gb/s and then multiplexed to 40 Gb/s with a passive fiber multiplexer. Working speed of PMD emulator (PMDE) is up to 1 ms and distribution of DGD can be either Maxwellian or any other kind favored in researches. Deteriorated signal enters the PMDC where it is split into two beams and then coupled into degree of polarization (DOP) measuring device and optic light monitoring system. DOP compensation is accomplished by field programmable gate array (FPGA) chip with Stokes vector from DOP measuring device as error signal.

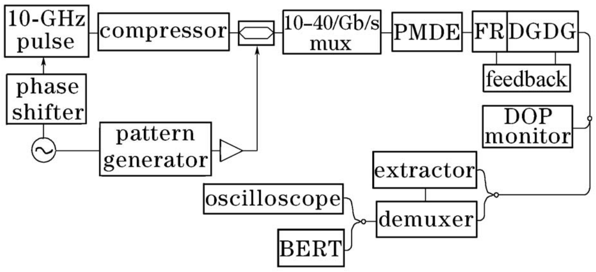


Fig. 4. Configuration of PMD compensation system.

Compensation is achieved through maximizing DOP of optic light by adjusting the delay of DGD generator (DGDG). Compensation results can be observed on oscilloscope or bit error rate tester (BERT). As the PMDC has only two degrees of freedom, compensation algorithm is so simple that improved Newton algorithm is sufficient. With such a simple algorithm, PMD compensation can be accomplished within several milliseconds.

Compensation behavior is monitored on Agilent 81600A sampling oscilloscope and Ando AQ22-11 BERT. Maximum link DGD of 40-Gb/s optical (RZ) signal is up to 35 ps. After compensation, error free is achieved (error rate is measured after demultiplexing). A series of

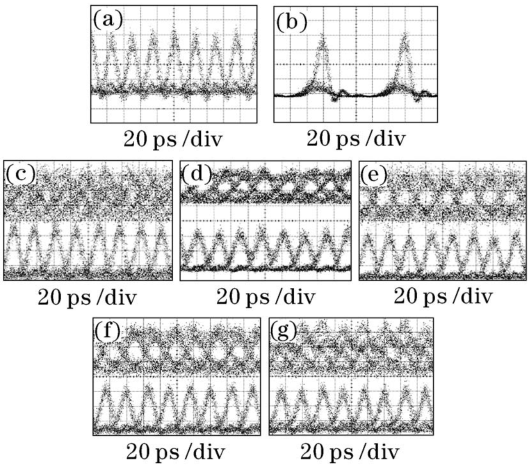


Fig. 5. Experimental results in 40-Gb/s OTDM system. Eye pattern of 40-Gb/s signal (a) and 10-Gb/s signal (b); eye patterns of signal after PMDE (upward) and signal after compensation (downward) with DGD of PMDE 35 ps (c), 21 ps (d), and 10.25 ps (e); eye patterns of signal after PMDE (upward) and signal after compensation (downward) when DGD of PMDE is changing randomly (f) and (g).

experimental results of different DGD values induced by PMDE are shown in Fig. 5. It can be concluded from these experimental results that PMD compensation in 40-Gb/s optical time domain multiplexing (OTDM) system is achieved.

In conclusion, we report a new type of PMDC based on garnet and yttrium vanadate crystal. PMD compensation with this PMDC in 40-Gb/s OTDM system is demonstrated. Experimental results have shown that dynamic PMD compensation is successfully obtained with this new type PMDC. Feedback control and compensation algorithm are both very simple.

This work was supported by the National "863" Project of China (No. 2003AA10316X) and the Specialized Resear Fund for the Doctoral Program of Higher Education (SRFDP) (No.20050003010). J. Wang's e-mail address is wangjiajun00@mails.tsinghua.edu.cn.

References

1. H. Rosenfeldt, C. Knothe, R. Ulrich, E. Brinkmeyer, U. Feiste, C. Schubert, J. Berger, R. Ludwig, H. G. Weber, and A. Ehrhardt, in *Proceedings of OFC'2001* PD27 (2001).
2. 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).
3. D. Sandel, V. Mirvoda, S. Bhandare, F. Wust, and R. Noé, J. Lightwave Technol. **21,** 1198 (2003).
4. H. Rosenfeldt, in *Proceedings of OFC'2005* OW01, pp.74—76 (2005).
5. H. Bulow, in *Proceedings of OFC'99* WE1, pp.74—76 (1999).
6. L. Zeng, H. Yao, X. Song, and E. Zhang, Tsinghua Science and Technol. (in Chinese) **45,** 174 (2005).
7. L. Yan, C. Yeh, G. Yang, L. Lin, Z. Chen, Y. Shi, and X. Yao, in *Proceedings of OFC'2002* FA5-1 (2002).
8. C. Xie and H. Haunstein, IEEE Photon. Technol. Lett. **15,** 1228 (2003).
9. J. P. Gordon and H. Kogelnik, Proc. Nat. Acad. Sci. (USA) **97,** 4541 (2000).
10. L. Huo, C. Lou, and Y. Gao, Chin. Phys. Lett. **22,** 353 (2005).