Dynamic PMD compensation in 40-Gb/s optical communication system

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A 40-Gb/s optical time division multiplexing (OTDM) return-to-zero (RZ) transmission experiments including a dynamic polarization mode dispersion (PMD) compensation was reported. The dynamic PMD compensator is made up of two-stage four degrees of freedom (DOF). The first stage adopts polarization controller and fixed time-delayed line. The second stage is variable differential group delay (DGD) element. The PMD monitoring technique is based on degree of polarization (DOP) as error signal. A novel practical adaptive optimization algorithm was introduced in dynamic adaptive PMD compensation. The experimental results show that the performance of the PMD compensator is excellent for 40-Gb/s RZ transmission systems with the large DGD. With this compensator, a significant improvement of system performance can be achieved in the eye pattern of a received signal. The first-order compensating ability of the compensator is greater than 30 ps. The second-order compensating ability is greater than 200 ps^2. The first-order optimum compensating time is within 10 ms. The second-order optimum compensating time is within 24 ms.

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Polarization mode dispersion (PMD) is one of the most serious obstacles facing high bit rate fiber optic communication systems, and ways to mitigate PMD have been in focus of optical transmission research for more than ten years[1−3]. Since PMD mitigation has proven a difficult task, it would then be of great interest to verify the PMD mitigation potential of compensators[4−6].

The first-order PMD is defined as differential group delay (DGD) between two principal states of polarization, and second-order PMD is related to rotating, depolarization and polarization depending on dispersion. First-order and second-order PMD effects are the main reasons that lead to the impairment of system transmission.

The PMD compensation methods can be subdivided into electrical[7] and optical[8] compensation methods, and it is generally acknowledged that the optical methods have better performances.

Typically, an optical PMD dynamic compensator consists of three major segments: 1) Compensating part, which includes polarization controllers, fixed or variable delay line and etc.; 2) control electronic circuit; 3) controlling algorithm. Corresponding with PMD compensating competence and response rate, we developed a two-stage four degrees of freedom (DOF) optical PMD compensator, and the first stage composed of lithium niobate polarization controllers and fixed delay line formed by a section of polarization maintaining fiber (PMF), is used to compensate second-order PMD; the second stage composed of a variable DGD element that consists of the magneto-optical-crystals. It is used to compensate first-order PMD. The structure of a two-stage four DOF optical PMD compensator is shown in Fig. 1.

In the figure, PC1 and PC2 are lithium niobate polarization controllers with 100-ns response time. PMF is polarization maintaining fiber of 20 m that has 30 ps DGD. The variable DGD module is capable of changing the relative delay between two orthogonal linear polarization states. The value of DGD can be digitally switched from 0 to 45 ps with a resolution of 1 ps. The average DGD switching speed is 500 μs. A control circuit provides digital signals for feedback control, and computer interface within 500 ns process time. The polarimeter is for obtaining error signal from DOP, and takes on 5 μs sampling speed.

On the PMD dynamic compensation system, an adaptive optimized controlling algorithm is adopted based on Stokes and feedback signal of signal DOP combining with a traditional dynamic closed-loop controlling system. The following relations can be calculated by the polarimeter.

$$\begin{gathered}S_0 = V_1 + V_2,\\ S_1 = (V_1 - V_2)/(V_1 + V_2),\\ S_2 = (2V_3 - (V_1 + V_2))/(V_1 + V_2),\\ S_3 = (2V_4 - (V_1 + V_2))/(V_1 + V_2),\\ \mathrm{DOP} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}.\end{gathered}$$

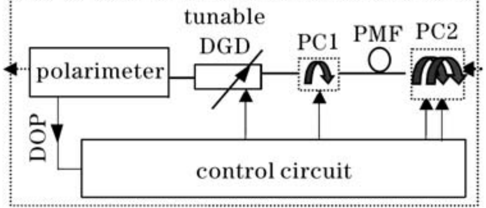


Fig. 1. The structure of a two-stage four DOF optical PMD compensator.

It notes that S_0, S_1, S_2, and S_3 are four stocks of polarization state, and V_1, V_2, V_3, and V_4 are four voltages outputted from the parallel interface of error signal monitoring.

The mathematic model of controlling algorithm for the PMD can be expressed as follows. It is clear that, the first-order PMD function of the whole system is

$$\vec{\Omega}(\omega,\vec{x}) = \vec{\Omega}_{\mathrm{L}}(\omega,\vec{x}) + \vec{\Omega}_{\mathrm{C}}(\omega,\vec{x}), \tag{1}$$

where $\vec{\Omega}_{\mathrm{L}}(\vec{x})$ is the first-order PMD in the fiber link, $\vec{\Omega}_{\mathrm{C}}(\vec{x})$ is the first-order PMD of PMD compensator. Equation (2) is the derivative of Eq. (1) with respect to ω, and it represents the value of second-order PMD.

$$\begin{aligned}\left|\vec{\Omega}'_{\mathrm{total}}\right| &= \left|\vec{\Omega}'_{\mathrm{L}} + \vec{\Omega}_{\mathrm{C}} \times \vec{\Omega}_{\mathrm{L}}\right| \\ &= \left|\Delta\tau_\omega\right| + \Delta\tau \cdot \left|\vec{\Omega}_{\mathrm{C}} \times \vec{q} + \vec{q}_\omega\right|,\end{aligned} \tag{2}$$

where $\Delta\tau = \left|\vec{\Omega}_{\mathrm{L}}\right|$ is DGD of the fiber link, $\Delta\tau_\omega = \Delta\tau/\Delta\omega$, $\vec{q} = \vec{\Omega}_{\mathrm{L}}/\Delta\tau$ is normalized PMD vector, and $\vec{q}_\omega$ is polarization-rotating speed. From Eqs. (1) and (2) we can find, when $\vec{\Omega}_{\mathrm{C}} = -\vec{\Omega}_{\mathrm{L}}$, first-order PMD is completely compensated, but second-order PMD is not compensated. When we change $\vec{\Omega}_{\mathrm{C}}$ until $\vec{\Omega}_{\mathrm{C}} \times \vec{q} + \vec{q}_\omega = 0$, the item lost of second-order PMD is completely compensated but part of first-order PMD remains uncompensated. So we add an extra compensation unit behind the first-order PMD compensator. This compensation unit consists of the polarization rotator and the variable delay line. Then, a two-stage PMD compensator is formed. The first stage PMD compensator is used to compensate the item lost of second-order PMD in the fiber, and the second stage is used to compensate the remained first-order PMD. As a result, both first-order and second-order PMDs are well compensated.

The mathematic model of optimized algorithm is founded as follows. $\vec{F}(F_1,\cdots,F_m)$ represents the objective value of PMD, $\vec{f}(f_1,\cdots,f_m)$ represents PMD function, and $\vec{x}(x_1,\cdots,x_n)$ represents control variable of compensator. Here, F_i is the objective value of the ith-order PMD, f_i is the ith-order PMD function, and x_j is the jth control variable of PMD compensator. Now, problems about PMD compensation can be treated as the problem that how to get the solution of nonlinear equations.

The system of nonlinear equations is

$$\begin{array}{c} F_1 = f_1(x_1,\cdots,x_n) \\ \vdots \\ F_m = f_m(x_1,\cdots,x_n) \end{array}. \tag{3}$$

The vector form of the nonlinear equations is

$$\vec{F} = \vec{f}(\vec{x}). \tag{4}$$

Dynamical controlling procedure is established according to the following steps: Firstly, initialize the independent variable $\vec{x_0}$ of the system control. Measure the value of PMD in the fiber link with polarimeter. And calculate the value of $\vec{F_0}$. Secondly, add a little increment ∂x_i to each control independent variable. Remeasure the value of PMD in the fiber link and recalculate $\vec{F}$. Then we use the difference quotient to form the coefficient matrix of linear equations. The matrix of coefficient is

$$A = \left|\begin{array}{ccc} \frac{\delta f_1}{\delta x_1} & \cdots & \frac{\delta f_1}{\delta x_n} \\ \vdots & \vdots & \vdots \\ \frac{\delta f_m}{\delta x_1} & \cdots & \frac{\delta f_m}{\delta x_n} \end{array}\right|. \tag{5}$$

Replace nonlinear Eq. (3) by the linear equations

$$\begin{array}{c} F_1 = F_{01} + \frac{\delta f_1}{\delta x_1}(x_1 - x_{01}) + \cdots + \frac{\delta f_1}{\delta x_n}(x_n - x_{0n}) \\ \vdots \\ F_m = F_{0m} + \frac{\delta f_m}{\delta x_1}(x_1 - x_{01}) + \cdots + \frac{\delta f_m}{\delta x_n}(x_n - x_{0n}) \end{array}. \tag{6}$$

If $\Delta\vec{F} = \vec{F} - \vec{F_0}$ and $\Delta\vec{x} = \vec{x} - \vec{x_0}$, Eq. (6) is changed to

$$A\Delta\vec{x} = \Delta\vec{F}, \tag{7}$$

or it can be rewritten in this form: $\varphi(\vec{x}) = A\Delta\vec{x} - \Delta\vec{F}$.

Now, problems about PMD compensation can be treated as an optimization problem that how to get the minimum value of $\varphi(\vec{x})$. And step size of control variable is the constraint condition, that is, $|\Delta \mathrm{x}_i| = r_i$. In traditional optimized algorithm, step size r of control variable is a constant, or it changes in the same amplitude Δr. The optimized algorithm proposed in this letter is different from the traditional one, and the step size r_i of different control variable x_i change in different amplitudes Δr_i. Δr_i follows the feedback signal to change adaptively. By this method, the rapidity of convergence is improved. The direction of control variable should be adjusted according to the feedback signal. Or in other words, step size r_i of control variable x_i should be adjusted according to the feedback signal. All these adjustments should make sure that DOP of the feedback signal reaches its maximum value.

When $m < n$, Eq. (7) is sub-positive definite equation which has infinitely many solutions. We have to think about how to choose the solution that we need. Step size r_i of control variable is the key factor to solve this problem. If step length is oversize, it may induce the signal fluctuates around the optimal position. If step length is undersize, the change of DOP may be annihilated due to the fiber link's non-linearity, amplifier's noise and instability of optical source. So accurate orientation of optimum result may be lost during the next adjustment. As a result, in order to compensate PMD efficiently, we have to choose different step sizes and determine how many times we should make the adjustment according to the different DOP thresholds in the algorithm. We also have to pay attention to the different response time of polarization controller (PC) and variable delay line in practical situations. The response time of PC is less than 100 ns. The response time of variable delay line is longer than that of PC, and it is 500 μs. Because of the difference of response time between PC and variable delay line, the algorithm still needs to be optimized. We focus on the adjustment of PC firstly. Then we adjust DGD of variable delay line. Note: Optimal values of the parameters in the algorithm are different due to different practical situations. It is necessary to attain the optimal values in experiments.

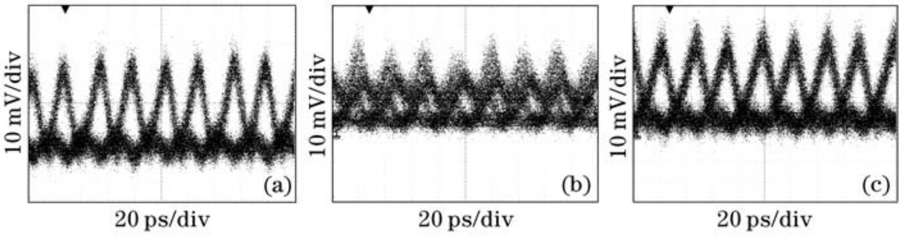


Fig. 2. The eye diagram in 40-Gb/s OTDM system. (a) Back-to-back, (b) without compensation, (c) with compensation.

PMD emulator is used for our experiments. The variation range of DGD is from −35 to +35 ps during a bit period. The changing speed is 0.1 step/s. The DGD accord with Maxwellian distribution, and it also changes gradually as in real fiber. Azimuth angle of the scrambler in PMD emulator changes linearly between 0° and 180°. On the other hand, DGD in real fiber is 0.015 ps/min at most, and the rotating speed of principal state of polarization (PSP) is 7 deg./min[9]. So the changing speed of this emulator is lager than that of PMD in real fiber.

The shape of pulse can be used to estimate and verify the result of PMD compensation, and the pulse is measured with a 50-Gb/s optical communication signal analyzer. Figure 2(a) illustrates the back-to-back eye diagram of 40-Gb/s signal, which has passed the PMD emulator. Because DGD and SOP of the PMD emulator change randomly, quality of output eye diagram degrades randomly. Figure 2(b) illustrates the eye diagram of signal, which has passed the emulator, and the signal is uncompensated at some time. The eye is almost closed. When the signal passes the emulator and is dynamical tracking compensated, the eye diagram of output signal at system terminal has a well-improved opening degree. This situation is shown in Fig. 2(c). When the state of PMD emulator is changed, compensator gives dynamical PMD tracking compensation at the same time. Now the opening degree of the eye diagram is approximately maintained at the level, which is shown in Fig. 2(c). The result shows the compensation performance of the PMD compensator and the stability of the adaptive optimized algorithm.

When PMD compensator starts working, the compensation time is defined as the time between the moment that system is in degradation state and the moment that system optimization is achieved. The eyes diagram on oscilloscope will become completely open from the closed state during a period of time. But we should pay attention to that, because the refresh frequency of oscilloscope is limited by its sampling speed, this period of time is not the real response time of the compensator. The compensation response time of PMD compensator is dependent on number of steps that controlling optimized algorithm needs, one-step processing time of the control circuit, and voltage response time of optical device. The response time of control circuit includes the response time of A/D, D/A converters, and calculating amplifiers. And it is also influenced by A/D sampling speed and processor's working frequency. The bandwidth of A/D, D/A converters and calculating amplifiers in system is above 10 MHz. As a result, the response time is mainly limited by sampling frequency. In the experiment, the feedback signal is sampled with a frequency of 200 kHz (the maximum sampling frequency is 700 kHz in this experiment system). And it is same to say that, Stokes parameter and DOP is sampled with a period of 5 μs. Figure 3 illustrates the sampling speed of polarimeter measured with the oscilloscope. The DOP measurement error will influence the compensation result. In order to overcome this influence, we calculate the average value of 20 values of feedback signal. And the average value is used as an available feedback signal. So we get an available feedback signal every 100 μs. High-speed digital signal processing (DSP) processor is used, and its working frequency is 150 MHz. The clock period is 6.67 ns. In a clock period 7—8 instructions are executed. Then about more than 15000 instructions are executed in a sampling interval 100 μs.

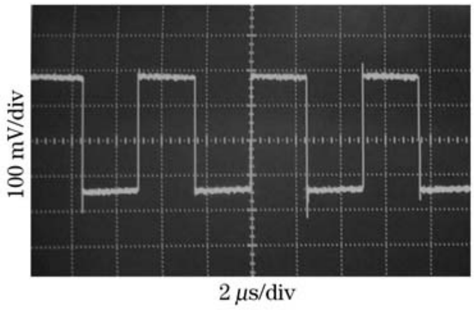
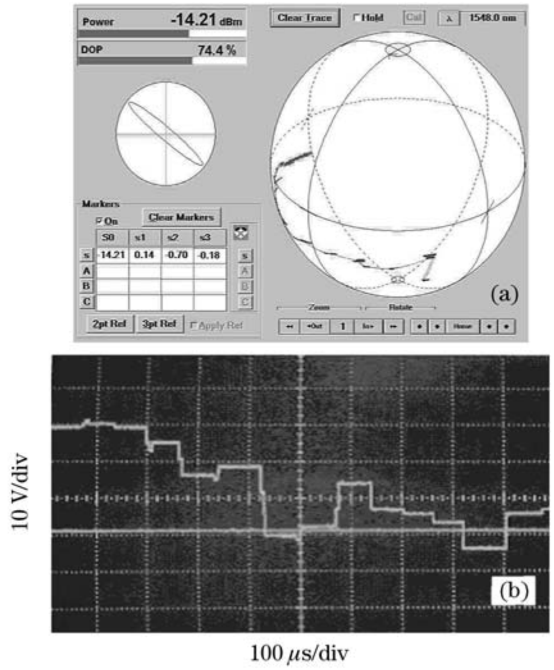


Fig. 3. The sampling speed for polarimeter.

In above sections, we have analyzed the response time of devices, the processing speed of DSP processor, and the complexity of the algorithm. The results show that, when the PC is adjusted in one step, the adjusting time is mainly dependent on the sampling speed of DOP (the response time of PC is less than 100 ns). The adjusting time is 100 μs, which is a sampling period of an available feedback signal; when DGD is adjusted in one step, the adjusting time is mainly dependent on the response time of variable delay line. The adjusting time is 500 μs. Many experimental results show that, from the moment that the procedure is initialized to the moment that system optimization is achieved, the PC and DGD need to be adjusted within 60 and 30 steps respectively at most. So the maximum response time of PMD compensation is about 60×100 μs $+30 \times (100 + 500)$ μs $= 24$ ms. After this response time of PMD compensation, the algorithm is at the state of real-time tracking compensation. Adjustment will be given in time according to the alteration of fiber link's PMD. It is noted that the PMD compensation speed is mainly dependent on the response time of DGD. Figure 4(a) illustrates changes of output state of polarization (SOP) on Poincare Sphere when the PMD emulator is at some still state and the controlling procedure is executed within one step. One step means the PC or DGD is adjusted one time, and one step is represented by one point on the Poincare Sphere. The result is measured with Agilent HP8509B. Figure 4(b) illustrates the adjustment of one of the output voltages applied on PC. It is measured with digital oscilloscope HP54600B. The maximum value of signal's DOP is 0.893. It is less than the optimal value 1 as a result of the amplifier's noise and the non-linearity of optical source and fiber link. After polarization compensating, 1-dB power loss is added to the system, as shown in Fig. 5.


Power -14.21 dBm

DOP 74.4 %

λ 1548.0 nm

Markers

	S0	s1	s2	s3
s	-14.21	0.14	-0.70	-0.18
A				
B				
C				

Fig. 4. The changing course of output polarization state (a) and the sampling of feedback control time (b).

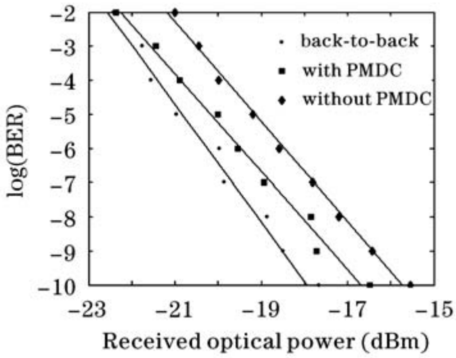


Fig. 5. The curve of BER when DGD = 30.129 ps worst case without PMDC, i.e., half of the total power into each PSP at the input of PMD emulator.

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