Two-stage adaptive PMD compensation in 40-Gb/s OTDM optical communication system

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An experiment of two-stage adaptive compensation for polarization mode dispersion (PMD) in a 40-Gb/s optical time-division multiplexed communication system is reported. The PMD monitoring technique based on degree of polarization was adopted. The particle swarm optimization (PSO) algorithm was introduced in adaptive PMD compensation. The comparison was made to estimate the effectiveness between PSO algorithms with global neighborhood structure (GPSO) and with local neighborhood structure (LPSO). The LPSO algorithm is shown to be more effective to search global optimum for PMD compensation than GPSO algorithm. The two-stage PMD compensator is shown to be effective for both first- and second-order PMD, and the compensator is shown to be bit rate independent. The optimum searching time is within one hundred milliseconds.

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In high speed optical communication system, when bit rate is beyond 10 Gb/s, the adaptive compensation for polarization mode dispersion (PMD) must be taken into consideration. In our previous works[1−4], we have successfully realized one- and two-stage adaptive PMD compensation for 10-Gb/s optical communication system, and one-stage adaptive PMD compensation for 40-Gb/s optical communication system. In this paper, we report the experiment of two-stage adaptive PMD compensation for 4×10-Gb/s optical time-division multiplexed (OTDM) communication system. In the experiment, the PMD motoring technique based on degree of polarization (DOP) was used to generate feedback signals. The particle swarm optimization (PSO) algorithm was introduced as an integral part of the adaptive feedback control system. In comparison with the one-stage compensator[4], the two-stage PMD compensator is shown to be able to compensate PMD for up to second-order.

There are mainly two proposed PMD monitoring techniques for adaptive PMD compensation. One is to observe the power level of specific tones in the received radio frequency (RF) spectrum of base-band signal[1,5−7]. The other is to evaluate the DOP of optical signal in the fiber link[2−4,8−10]. For a PMD monitor based on DOP, an in-line polarimeter is used to judge the states of polarization of optical signal in fiber link through measuring the Stokes parameters s_0, s_1, s_2, s_3. The DOP is calculated by

$$\mathrm{DOP} = \frac{\sqrt{s_1^2 + s_2^2 + s_3^2}}{s_0}. \qquad (1)$$

The relationship between DOP and differential group delay (DGD) for 10-, 20- and 40-Gb/s return-to-zero (RZ) optical signals with power splitting ratio $\gamma = 0.5$ between two principal states of polarization (PSP) is shown in Fig. 1. It shows that DOP can be a good indicator of PMD with monotonically deceasing of DOP as DGD increasing. It also shows that the PMD monitor based on DOP is bit rate independent.

Figure 2 shows the experimental setup we used for our two-stage adaptive PMD compensator in a 4×10-Gb/s OTDM optical communication system. An actively mode-locked fiber ring laser with 1560.5-nm operation wavelength and 7-ps pulse width was used as light source[11]. A 10-Gb/s pseudo-random binary sequence (PRBS) of RZ pulse is produced by a 10-GHz Mach-Zehnder $LiNbO_3$ modulator. A 40-Gb/s optical signal was produced through a fiber based optical time-division multiplexer as shown in Fig. 3(a). In order to use DOP as PMD monitoring feedback signal, it is required to ensure all of the multiplexed optical pulses in each channel have the same polarization states. We used a polarization controller (PC) in every channel of fiber multiplexer to adjust the polarization state of optical signal, and at the output of fiber multiplexer a polarizer is used. The demultiplexer is configured with a self-cascade electronic-

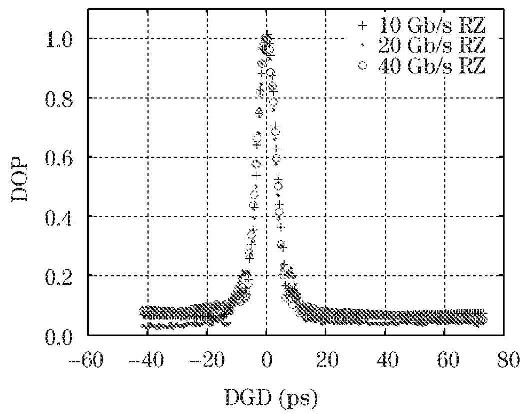

Fig. 1. The relationship between DOP and DGD for 10-, 20-, and 40-Gb/s RZ optical signals.

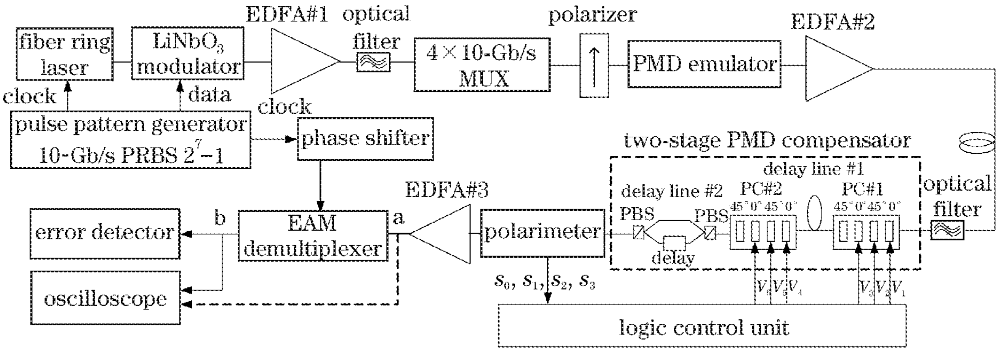

Fig. 2. Experimental setup. EDFA: erbium-doped fiber amplifier; MUX: multiplexer; PBS: polarization beam splitter.

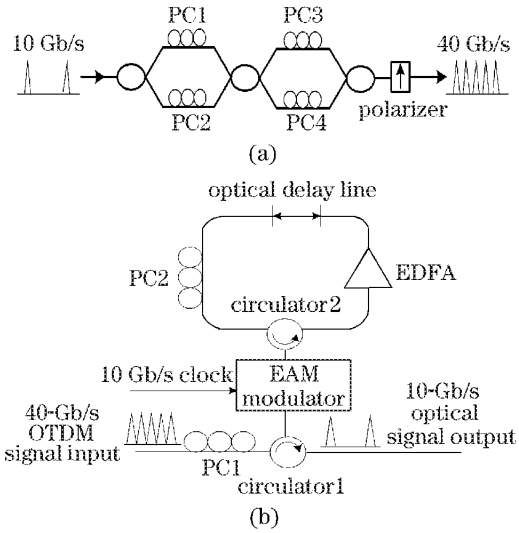

Fig. 3. The configuration of 40-Gb/s multiplexer (a) and demultiplexer (b).

absorption modulator (EAM) as shown in Fig. 3(b). We can obtain each of four demultiplexed 10-Gb/s channel by adjusting the phase shifter as shown in Fig. 2.

The PMD emulator consists of two-section units of two manually adjusted polarization controllers and two polarization maintaining fiber (PMF) pieces with DGDs of 16 and 14 ps, respectively. Through adjusting the PCs the PMD emulator can generate DGD ranging from 2 to 30 ps and PSP rotation rate (PSPrr) ranging from −14 to 14 ps. The optical filters were used to suppress amplified spontaneous emission (ASE) noise from the erbium-doped fiber amplifiers (EDFAs). For two-stage PMD compensator, each stage has an electrically controlled PC and a delay line. For the electrically controlled PC#1 and PC#2 (PolaRITE^{TM}II, General Photonics Co.), each of them has four fiber-squeezer cells to be adjusted with 0−10V voltage, out of which only three cells are used in the experiment. Therefore there are six voltages (V_1, V_2, V_3, V_4, V_5, V_6) to be controlled, which is a 6 degrees of freedom (DOF) problem. The delay line #1 is a PMF with 15-ps DGD, and delay line #2 is an air gap delay line which produces a DGD of 15 ps by adjusting the length of air gap. As the PMD monitor, an in-line polarimeter with analog bandwidth of 700 kHz (PolaDetect^{TM}, General Photonic Co.) is

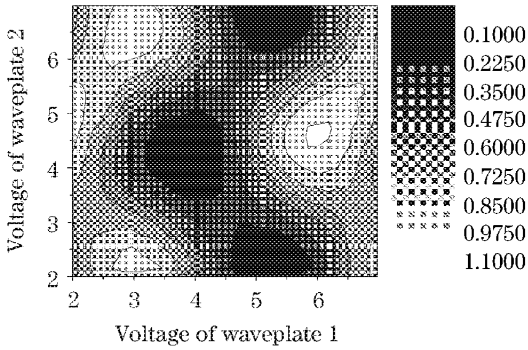

Fig. 4. DOP map.

used to measure instantaneously the Stokes parameters and the DOP in fiber link. By using PSO algorithm, the logic control unit automatically adjusts the voltages of six cells of PC#1 and PC#2 to search the optimum for DOP to reach the global maximum. The compensated 40-Gb/s signal was demuliplexed to 10-Gb/s signal by a demultiplexer. The effectiveness of PMD compensation can be observed by the eye diagram on the oscilloscope (HP83480), or by the bit-error-rate (BER) analyzer (D3186/3286, ADVANTEST Co.)

The adaptive PMD compensation is required to reach the global maximum DOP in fiber link through finding the best optimal combination of six control voltages (V_1, V_2, V_3, V_4, V_5, V_6) of PC#1 and PC#2, which is a 6-DOF problem. For multi-DOF problem the existence of many local sub-optima increases the computational task of the searching algorithm. Figure 4 is DOP map for our two-stage PMD compensation system, where the bright colors denote higher DOP values. We can see that, there are several sub-maxima beside a global maximum in the searching space. In contrast, in the first-order PMD compensation using one-stage compensator[4] only three control voltages need to be adjusted, which is a 3-DOF problem. Generally, the more the DOFs are, the more sub-maxima exist, which would increase the hard task of the searching algorithm. Therefore it is more difficult for a searching algorithm to achieve finding global optimum in the second-order PMD compensation using two-stage compensator in Fig. 2 than that in the first-order PMD compensation using one-stage compensator in Ref. [4].

Generally used searching algorithm is the gradient peak

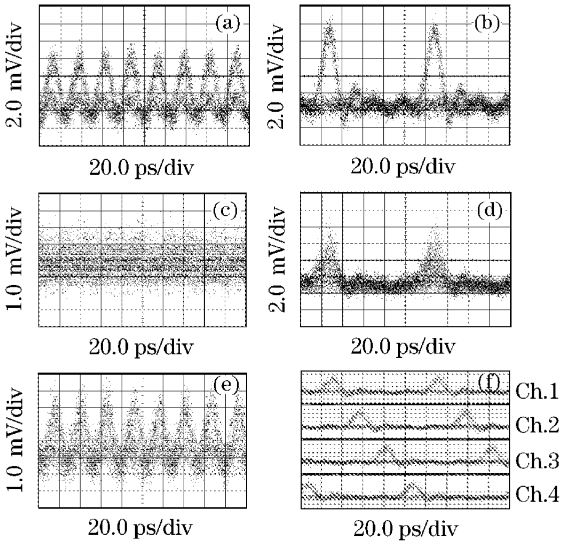

Fig. 5. Eye diagrams to show the procedure of adaptive PMD compensation for 40-Gb/s OTDM optical communication. (a): Back-to-back 40-Gb/s OTDM signal; (b): back-to-back demultiplexed 10-Gb/s signal; (c): 40-Gb/s signal without PMD compensation; (d): demultiplexed 10-Gb/s signal without PMD compensation; (e): 40-Gb/s signal with PMD compensation; (f): four demultiplexed 10-Gb/s signals with PMD compensation.

search method[7]. A great disadvantage of gradient based searching algorithm is often being trapped in a local sub-optima rather than the global optimum. Besides, the gradient based algorithm would be less effective for a system with a relatively high noise level in PMD monitor, because the gradient information between neighboring signals would be submerged in noise.

The PSO algorithm, proposed by Kennedy and Eberhart[12], has proved to be very effective in solving global optimization for multi-dimensional problem in static, noisy, and continuously changing environment. We have introduced the PSO technique into automatic PMD compensation in our previous works[1−4], where it was shown to be effective.

Figure 5 shows the effectiveness of our two-stage adaptive PMD compensator. Figure 5(a) shows the back-to-back 40-Gb/s signal detected at position "a" in Fig. 2. And Fig. 5(b) shows the back-to-back demultiplexed 10-Gb/s signal detected at position "b" in Fig. 2. When we adjusted the PCs of PMD emulator, the worst eye diagrams of 40-Gb/s signal and demultiplexed 10-Gb/s signal with DOP = 0.23 would be shown on the oscilloscope as shown in Figs. 5(c) and (d). After switching on the adaptive PMD compensator, the eye diagrams opened (Fig. 5(e) for 40-Gb/s signal, Fig. 5(f) for four-channel demultiplexed 10-Gb/s signals) and DOP reached 1 within one hundred milliseconds through optimum searching by the logic control unit.

We measured the BERs before and after PMD compensation, as shown in Fig. 6. After PMD compensation the power penalty at a BER of 10^{-9} was about 0.5 dB.

We also measured the first- and second-order PMD in the whole fiber link before and after PMD compensation using a PMD analyzer (FPMD5600, EXFO Co.), as shown in Figs. 7(a) and (b). It is apparent that, with

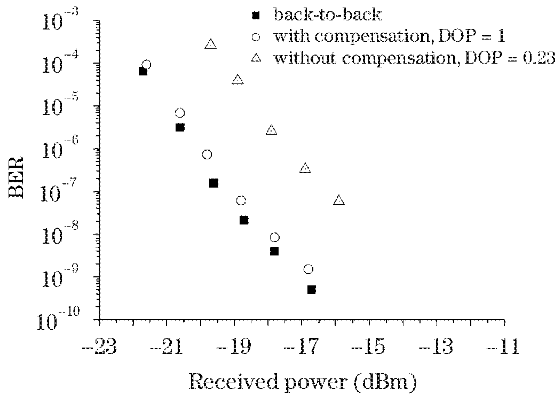

Fig. 6. Measured BER curves.

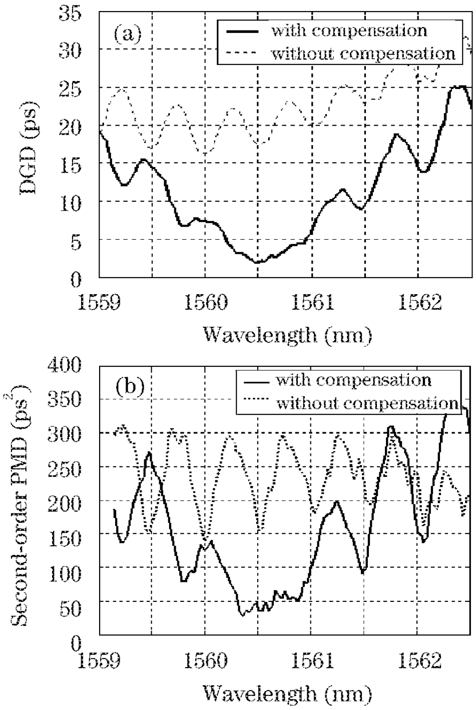

Fig. 7. First- (a) and second-order (b) PMD measurement results before (dashed line) and after (solid line) compensation.

our two-stage adaptive PMD compensator, the first- and second-order PMD can reach their minima simultaneously around the laser operation wavelength (1560.5 nm).

As indicated above, the algorithm adopted in logic control unit is very important for adaptive PMD compensation. A compatible searching algorithm should at least satisfy the following basic characteristics: 1) rapid convergence to the global optimum rather than being trapped in local sub-optima; 2) robust to noise. The PSO algorithm we adopted just has these merits.

At the beginning, the PSO algorithm randomly initializes a population (called swarm) of individuals (called particles). Each particle represents a single intersection of multi-dimensional hyperspace. The particles evaluate their position relative to a goal at every iteration. In each iteration every particle adjusts its trajectory toward its own previous best position, and toward the previous best position attained by any member of its topological neighborhood. Generally, there are two kinds of topological neighborhood structures: global neighborhood structure, corresponding to the global version of PSO (GPSO), and local neighborhood structure, corresponding to the local version of PSO (LPSO). For the global neighborhood structure the whole swarm is considered as the neighborhood, while for the local neighborhood structure some smaller number of adjacent members in sub-swarm is taken as the neighborhood.

In the PSO algorithm, if any particle's position is close enough to the goal function, it is considered as having found the optimum and the recurrence is ended. In the global neighborhood structure, each particle's search is influenced by the best position found by any member of the entire population. In contrast, each particle in the local neighborhood structure is influenced only by parts of the adjacent members. It is widely believed that GPSO converges quickly to an optimum but has the weakness of being trapped in local optima occasionally, while LPSO is able to "flow around" local optima[13], because sub-populations explore different regions. In our experiment the GPSO and LPSO with 20 particles were used. It is proved that the LPSO algorithm is more suitable for solving multi-optima problems.

We have compared the effectiveness of GPSO and LPSO algorithm by recording the variation of best DOP values in every searching process. With 50 different initial PMD states made by adjusting the PCs of PMD emulator, we repeated the searching process 50 times, respectively using GPSO and LPSO algorithm. The results are shown in Figs. 8(a) and (b). It can be seen that, for the case of using GPSO there are some initial PMD states, which makes DOP only reach the value of 0.7 (Fig. 8(b)), corresponding to being trapped in local suboptima. In contrast, for the case of using LPSO, all final searched DOP values exceed 0.9, no matter what initial PMD state is, which means that LPSO is a better searching algorithm for multi-stage adaptive PMD compensation.

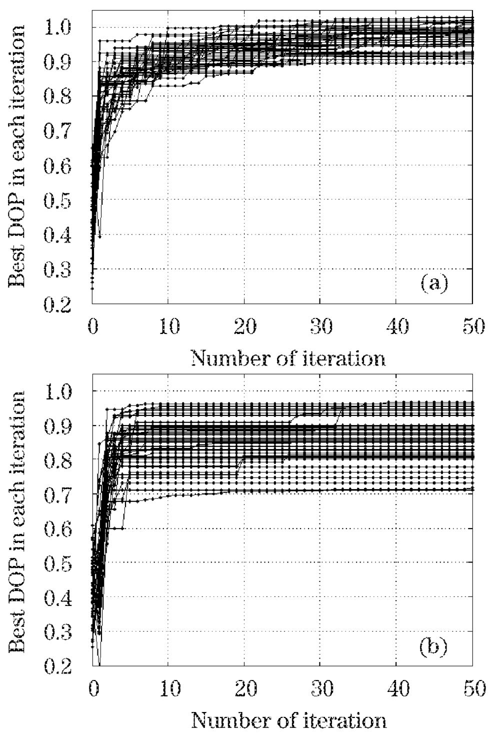

Fig. 8. The best DOP values versus iteration in searching process. (a): Result for LPSO; (b): result for GPSO.

We have made a successful experiment of adaptive PMD compensation with a two-stage compensator in 40-Gb/s OTDM optical communication system. By using PMD analyzer, eye diagrams, and BER measurement, it was proved that the two-stage compensator can automatically compensate the first- and second-order PMD. The PSO algorithm was introduced in adaptive PMD compensation. By comparison of GPSO and LPSO, it was shown that the LPSO algorithm had the powerful ability of rapid convergence to global DOP maximum without being trapped in local sub-maxima.

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