# Mitigation of signal quality degradation induced by PMD using synchronous modulation

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In-line synchronous modulation as a way of mitigating the signal quality degradation induced by polarization mode dispersion (PMD) was experimentally studied using 10-Gb/s return to zero signal. Bit error rate of the degraded signal and the synchronously modulated signal under the differential group delay (DGD) values of 10, 20, 34, and 70 ps was measured and compared. The experimental results showed that in-line synchronous modulation is useful to mitigate the signal quality degeneration induced by PMD. 1-dB power penalty reduction was obtained even when the PMD was as high as 70% of the bit interval. The limitation of method is also discussed.

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Polarization mode dispersion (PMD) is one of the most critical issues for the high-speed optical transmission system. Because of the introduced or inherent birefringence, the two propagating polarization modes in an optical fiber experience a differential group delay (DGD). This leads to pulse broadening or splitting and, hence, intersymbol interference (ISI), manifested as an increased bit error rate (BER). The optical signal degenerated by PMD must be processed before the receiver to fulfill the requirement of high-speed and long haul transmission. In recent years, various compensation schemes have been proposed or demonstrated to overcome the limitation imposed by PMD[1,2]. The most popular and up-to-date technique among them is a feedback circuit. In this circuit, a feedback signal, e.g., degree of polarization, electrical spectrum, or $Q$ value of the optical signal, is provided to a microprocessor, where an algorithm works and signals are calculated to control the polarization controllers and the variable DGD elements. One problem of such a scheme is the accuracy and the adequacy of the feedback signal, a complex measurement system is slow and costly, but a simple measurement system is not able to provide adequate information. Another problem is the speed, that is to say, measurement, calculation, and controlled component response time must be reduced to track the fast changes of PMD.

In-line synchronous modulation can in principle reduce the pulse broadening by confining pulse energy in the correct time slot; therefore it is useful to combat signal degradation induced by PMD. Although numerical simulation results[3,4] support this idea, and some experiments also use in-line synchronous modulation as an effective method to extend the transmission distance of soliton[5], in-line synchronous modulation as a way of mitigating the signal degeneration induced by PMD has not been experimentally studied. In this paper, improvement of 10-Gb/s return-to-zero (RZ) signal quality degenerated by different DGD values by in-line synchronous modulation was experimentally and quantitatively studied. The results indicate that in-line synchronous modulation can significantly mitigate the degradation of signal quality produced by PMD. The scheme dose not require the measurement of PMD value and the complex feedback loop, it has the advantages of simple configuration, fast response, and robustness.

Figure 1 shows the experimental configuration. A 10-GHz optical pulse train with a pulse width of about 20 ps was generated by an electro-absorption modulator (EAM). The pulse train was amplified by an erbium-doped fiber amplifier (EDFA) and then injected into a LiNbO3 modulator, where it was modulated by a 10-Gb/s pseudo random bit sequence (PRBS) with a code length of $2^{31}-1$. The 10-Gb/s signal was launched into a PMD emulator made up of high birefringence crystals[6]. The DGD value provided by the PMD emulator ranged from 0 to 70 ps, which deteriorated the optical signal quality to various degrees. In order to mitigate the degradation of the signal quality, in-line synchronous modulation was implemented using a configuration named optoelectronic oscillator (OEO). The configuration of OEO is shown in Fig. 2, it consists of a modulator, a section of fiber delay-line, a photodetector (PIN), an electrical amplifier, an electrical narrow bandpass filter, and a phase shifter. The OEO has its own free running frequency, but

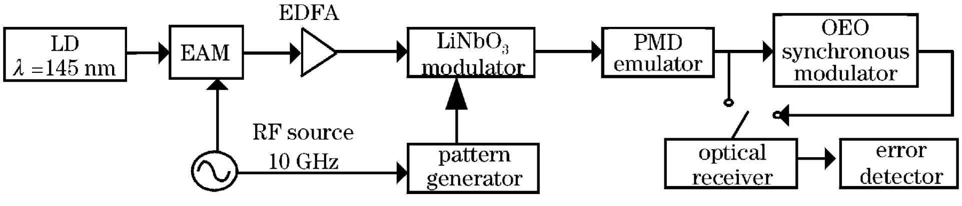

Fig. 1. Experimental setup.

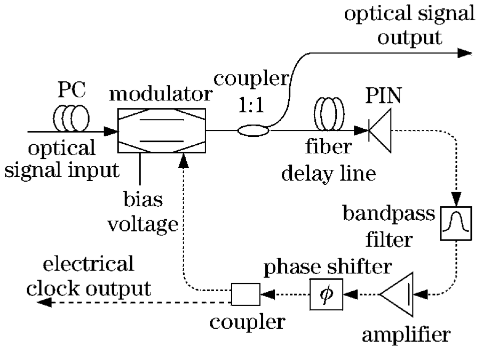

Fig. 2. Configuration of OEO.

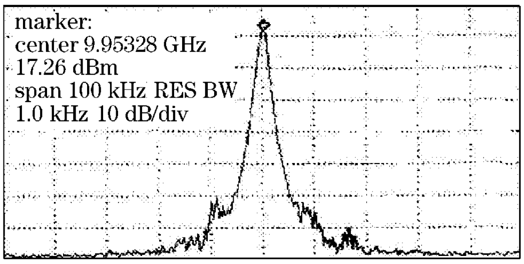

Fig. 3. Electrical spectrum of extracted clock by OEO.

this frequency can be injection-locked to an external optical signal. This injection-locking property was used to extract clock from the optical signal[7]. When the extracted clock signal was fed to the modulator in the OEO, a temporal window was formed to synchronously modulate the degraded optical signal. The temporal window suppressed the wings of the split pulses and confined optical energy in the correct time slot, therefore, reduction of ISI and improvement of signal quality was realized by this in-line synchronous modulation process. In the experiment, phase alignment of temporal window and the optical signal was achieved with the phase shifter in the OEO. Compared with the commonplace configuration of clock extraction using only an electrical narrow bandpass filter, the OEO excelled by drastically reducing the phase noise, because the $Q$ value of the OEO loop was much higher than that of the bandpass filter[8].

Figure 3 shows the spectrum of the extracted clock signal, the timing jitter of the clock calculated with spectral integration in a 5-MHz bandwidth was only 0.24 ps, the quality of the extracted clock in terms of timing jitter was not affected by the DGD value of the PMD emulator. The high quality of the extracted clock provided a good condition for the accomplishment of the in-line synchronous modulation.

BER of the optical signals degenerated by PMD and synchronously modulated by OEO was measured when the DGD value of the PMD emulator was set as 10, 20, 34, and 70 ps, respectively. An optical receiver which consisting of a 10-GHz, 3-dB bandwidth PIN photodetector and a clock and data recovery module (NEL-MOS43CM) was deployed to convert optical signals into electrical domain and to provide the clock and data signals needed by the error detector set. Figure 4 shows the BER curves of the signal degraded by different DGD values, these lines are almost in parallel with each other, and the introduced power penalty increases with increasing DGD. The comparison of BERs of the degraded signal and the synchronously modulated signal under the DGD values of 34 and 70 ps is illustrated in Fig. 5. As can be seen, in-line synchronous modulation reduced the power penalty and improved the BER performance. The slope of the BER line of the synchronously modulated signal is different from that of the degenerated signal, which implies that the waveform of the degenerated signal was reshaped by the synchronous modulation process. Figure 6 compares the power penalties before and after the in-line synchronous modulation as the DGD value was changed. The result proved that the method was useful in various conditions and the mitigation effect was more appreciable for larger DGD: when the DGD was large (34 and 70 ps), 1-dB power penalty reduction was achieved using synchronous modulation; only about 0.3-dB power penalty reduction was observed if the DGD was small. Figure 6 also reveals the limitation of in-line synchronous modulation that the power penalty increases with increasing DGD value. In fact, when the DGD value is larger, e.g., 50% of the bit interval, optical pulses in adjacent bit slot but in different principle states of polarization (PSP) would have a large overlap with each other, even when synchronous modulation was applied, the ISI could not be avoided. Another drawback of the method is the relatively large insertion loss. In this experiment, the total insertion loss was about 10 dB, mainly introduced by the modulator in the OEO loop, but this problem could be partially alleviated by using modulator with low insertion loss.

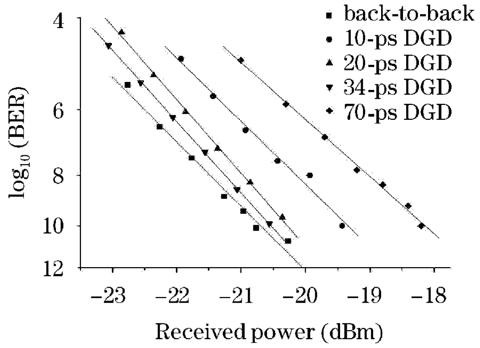

Fig. 4. BER of the degenerated signal by different DGD values.

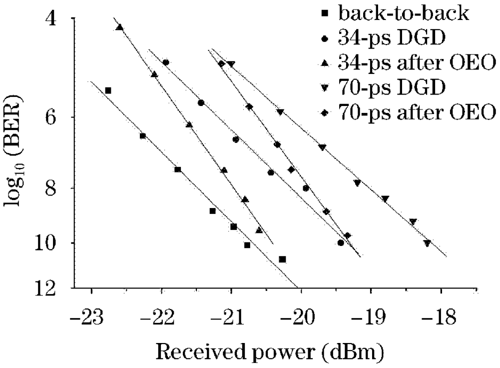

Fig. 5. Comparison of BERs of the degraded signal and the synchronously modulated signal under the DGD values of 34 and 70 ps.

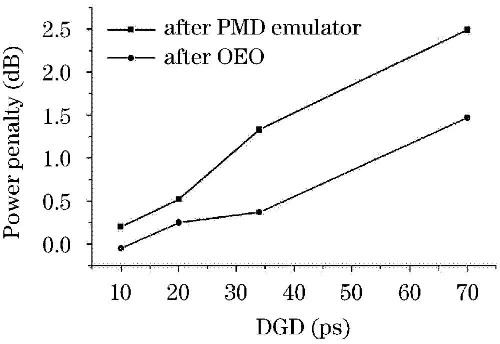

Fig. 6. Power penalties of the degraded signal and the synchronously modulated signal under different DGD values.

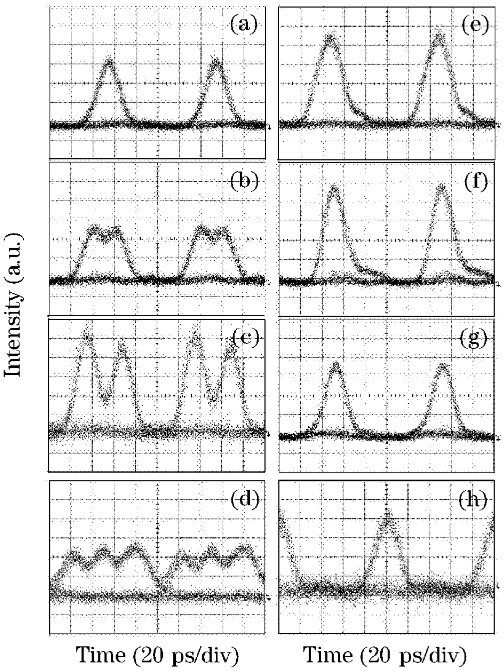

Fig. 7. Eye diagrams of the degraded signal and the synchronously modulated signal under different DGD values. (a)−(d): 10, 20, 34, and 70 ps DGD, degraded; (e)−(h): 10, 20, 34, and 70 ps DGD, synchronously modulated.

As the direct evidence that the signal quality was improved by in-line synchronous modulation, Fig. 7 gives the eye diagrams of the PMD degraded signals and the synchronously modulated counterparts. The pulse split by PMD was obviously suppressed by synchronous modulation, it explained why the power penalty was reduced.

In-line synchronous modulation as a method of improving the signal quality degraded by PMD was experimentally studied using an OEO. BER of the degraded signal and the synchronously modulated signal under the DGD values of 10, 20, 34, and 70 ps was measured and compared. The experimental results showed that in-line synchronous modulation is useful to mitigate the signal quality degeneration induced by PMD. 1-dB power penalty reduction was obtained even when the PMD was as high as 70% of the bit interval. Although the method has the limitation that it cannot completely compensate the PMD, it is attractive for its simple configuration, fast response, and robustness.

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