PMD mitigation using 3R regeneration based on EAM with wavelength conversion

Li Huo (霍 力), Shilong Pan (潘时龙), Yanfu Yang (杨彦甫),
Caiyun Lou (娄采云), and Yizhi Gao (高以智)

Department of Electronic Engineering, Tsinghua University, Beijing 100084

Received October 27, 2005

Polarization mode dispersion (PMD) mitigation is performed using an optical 3R (re-amplification, re-shaping, re-timing) regenerator based on electro-absorption modulator (EAM) with wavelength conversion. System performance without and with 3R regeneration was separately studied by eye analysis and bit-error rate (BER) measurements. The signal quality was significantly improved by 3R regeneration under serious first order PMD (up to 40% of the bit interval) combined with second order PMD (up to about 520 ps^2). The PMD mitigation margin of the proposed method is also investigated by measuring the sensitivity at BER 10^{-10}. Further studies indicate that 3R regenerators have the potential to combat with the effects of PMD combined with polarization dependent loss (PDL) and polarization hole-burning (PHB).

OCIS codes: 060.2330, 260.5430, 070.6020.

Polarization mode dispersion (PMD) is one of the most critical issues for the high-capacity and long-haul optical communication systems. There are several techniques available to mitigate PMD, using a feedback loop is the most popular way. Although this method has been in research focus for more than ten years, there are a number of problems[1] which are obstacles of the scheme to be deployed in commercial systems. Meanwhile, 3R (re-amplification, re-shaping, re-timing) will play an important role in high speed communication networks based on optical time domain multiplexing (OTDM) techniques. It preserves data quality and allows for improved transmission distances. 3R based on electro-absorption modulator (EAM) with wavelength conversion is polarization insensitive and expected to operate at 40 Gb/s or higher bit rate. Moreover, wavelength conversion is important to avoid wavelength blocking at nodes of the optical networks. As a result, 3R regenerator is considered to be an attractive approach for the mitigation of the PMD. Different from the feedback way, 3R needs no feedback signal, no control loop and no algorithm, thus can overcome the problems discussed in Ref. [1]. But up-to-date, there is not adequate work on the 3R regenerator to mitigate PMD[2,3]. In this paper, 3R scheme based on EAM with wavelength conversion is studied experimentally to mitigate PMD effects. The results show that the scheme has excellent performance in mitigating the signal quality degeneration induced by first order PMD combined with second order PMD.

The experimental setup is schematically shown in Fig. 1. A 40-Gb/s pseudo random binary sequence (PRBS) return-to-zero (RZ) data signal, which was comprised of 2-ps full-width at half-maximum (FWHM) pulses, was generated by an OTDM 4 × 10-Gb/s source. A PMD emulator followed by a polarization scrambler was used to degrade the signal. The PMD emulator was made up of six cascade high biregringence crystals separated by Faraday rotators[4]. If the six Faraday angles were set between 0° and 90°, the emulator could generate second order PMD combined with first order PMD. In experiment, we generated second order PMD combined with first order PMD to simulate the actual transmission link. After degradation, 40-Gb/s data were injected into the 3R regenerator. The regenerator consists of a clock recovery module based on dual-ring mode-locked laser[5] and an EAM optical decision gate. The clock recovery module can extract 10 GHz clock in both optical and electrical forms from the 40-Gb/s degraded data signal. The 10-GHz optical clock pulse at 1555-nm wavelength was further compressed into 2-ps FWHM and also multiplexed to 40 GHz. A commercial bulk EAM biased at −3 V was used as the optical decision gate. The 40-Gb/s

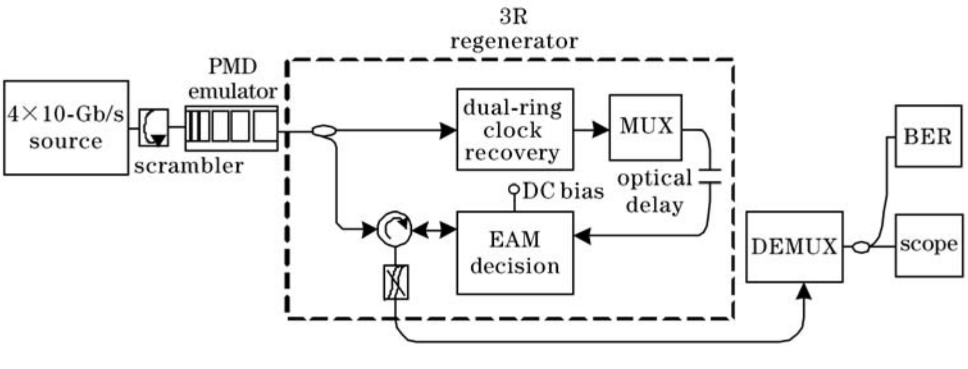

Fig. 1. Experimental setup for PMD mitigation using 3R based on optical decision gate.

degraded data signal was injected from one side of the EAM via an optical circulator and the 40-GHz clock signal was injected from the other side. The EAM was switched on and off by the mark and space in the data signal respectively, so the information at 1545 nm was copied to 1555 nm without any distortion. An optical delay line was used to adjust the relative phase between the clock and the pump data signal. Another EAM driven by the recovered 10-GHz electrical clock was used to demultiplex the 40-Gb/s 3R wavelength-converted signal at 1555 nm to 10 Gb/s in order to perform bit error rate (BER) test.

At the first step, we changed the 4 × 10-Gb/s OTDM multiplexer to a 2×10-Gb/s OTDM multiplexer to ensure clear eye diagrams, which does not affect the experimental results. Figure 2 gives the eye diagrams of the PMD degraded signals and the 3R regenerated counterparts at different degraded degrees while the state of polarization (SOP) of signal fast scrambled by the polarization scrambler. The split ratio between the two polarization branches was changed very fast due to the fast rotating SOP, which caused the eye opening deterioration. Combining with timing jitter, the effect of PMD degradation was more and more serious as the differential group delay (DGD) increasing, which is shown in Figs. 2(a), (b), (c), (g), (h) and (i). However, the regenerated signals (in Figs. 2(d), (e), (f), (j), (k), and (l)) kept the same shape and low timing jitter. As the polarization state rotating, the energy between the fast axis and slow axis was changed, which varied the shape of optical decision gate, and further affected the transmissivity of the clock signal. Thus, an amplitude jitter was observed when the DGD in the link increased to 34 ps. But when the DGD value was smaller than 20 ps, the amplitude jitter was slight. In addition, we measured the second order PMD of the emulator when the DGD value was 20 ps by Jones Matrix eigenvalue method. The typical second order PMD was 542.5 ps^2, which could cause significant impact on output pulse distortion. The clear eye opening and low timing jitter of the regenerated signal (in Fig. 2(k)) under DGD value of 20 ps show that 3R based on EAM has excellent performance in mitigating first and second order PMDs altogether. This is mainly due to the regenerated distorted signals independent of polarization and frequency.

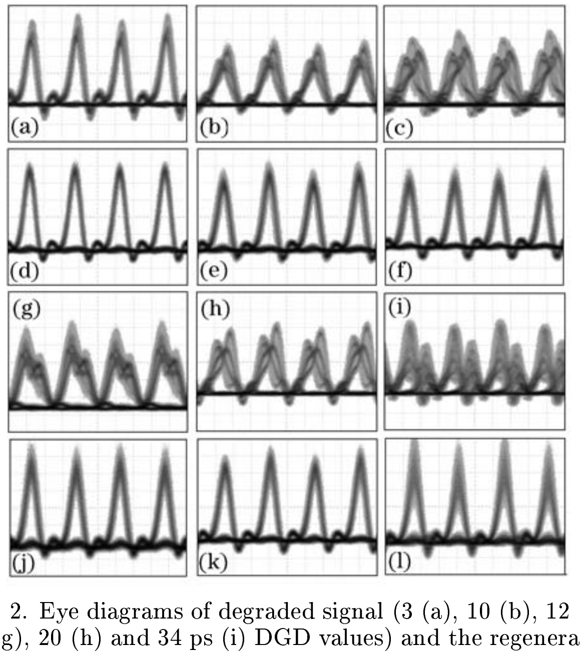

Fig. 2. Eye diagrams of degraded signal (3 (a), 10 (b), 12 (c), 15 (g), 20 (h) and 34 ps (i) DGD values) and the regenerated signal (3 (d), 10 (e), 12 (f), 15 (j), 20 (k) and 34 ps (l) DGD values) at 20 Gb/s.

The comparison of BER at 40 Gb/s of the degraded signal and the 3R regenerated signal under DGD values (first order PMD) of 7 and 10 ps, combined with second order PMD 317.9 and 519.6 ps^2 respectively, is shown in Fig. 3. As can be seen, when the DGD values is 7ps, which is 28% of the bit interval, the degraded signal has a BER floor of 10^{-10}, while the 3R regenerated signal can reach error free, and a 2.7-dB power penalty reduction is achieved at the BER of 10^{-9}. When the DGD value is 10 ps, which is 40% of the bit interval, combined with the effects of first and second order PMDs, the inter-symbol interference (ISI) is very serious, while the regenerated signal has a significantly improved quality. The degraded signal and the regenerated signal have BER floor at 2.5×10^{-6} and 2.5×10^{-9}, respectively. Although the regenerated signal can not reach error free, the BER distinction can also demonstrate the improvement of the signal quality.

For a quantitative evaluation of the PMD mitigation potential using 3R based on EAM, we experimentally measured the sensitivity at BER 10^{-10} under different DGDs for both degraded signal and regenerated signal, as shown in Fig. 4. Different from the dynamical cases above, all the data are achieved when the power of the two polarization branches was equal. The result shows that 3R based on EAM is useful to mitigate effects of PMD only when the DGD value in the transmission link is less than 12 ps, which is approximately 50% of the bit interval, while the best performance occurs at 7 ps. The

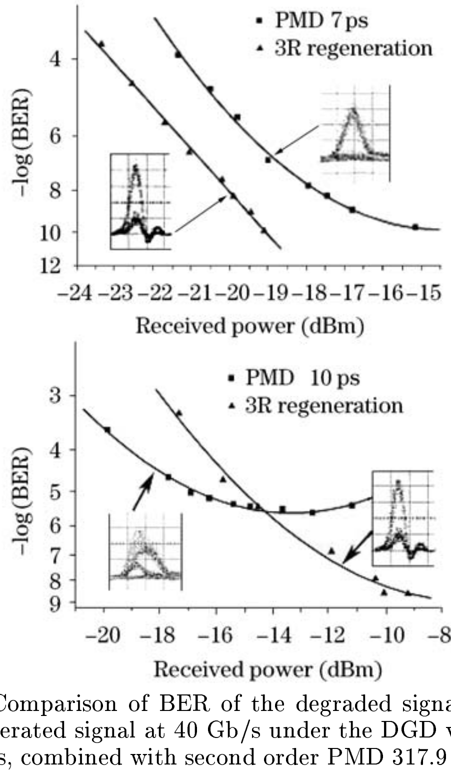

Fig. 3. Comparison of BER of the degraded signal and the 3R regenerated signal at 40 Gb/s under the DGD values of 7 and 10 ps, combined with second order PMD 317.9 and 519.6 ps^2 respectively.

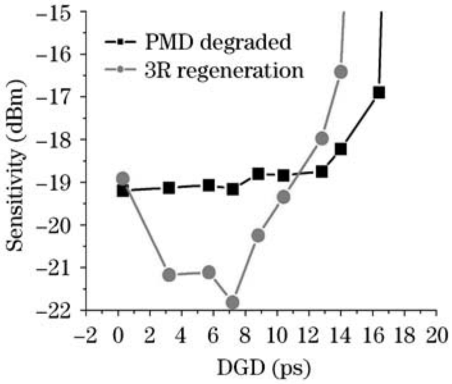

Fig. 4. Comparison of the sensitivity at BER 10^{-10} of degraded signal and regenerated signal under different DGDs.

most important reason for the limitation may be the amplitude jitter and the robustness of clock recovery.

Compared with other 3R schemes, such as synchronous modulation[6], 3R regenerator based on EAM with wavelength conversion does not directly operate on the original pulses, it copies signal from one wavelength to another, so the signal degradation caused by PMD and other effects can be alleviated more efficiently, that is to say, in principle, this 3R scheme has superior performance in mitigating all polarization effects altogether, include PMD, polarization dependent loss (PDL), and polarization hole-burning (PHB).

Another advantage of this method is that its clock signal is comprised of narrow pulses, so it can track large DGD if the clock recovery module is robust enough. But how to alleviate the amplitude jitter and improve the robustness of clock recovery is still subject to research. The only drawback of 3R regeneration in PMD mitigation is that if a bit error has occurred, it can never improve the BER, which means, the schemes must be deployed where little outage occurs. However, by distributed deploying this 3R scheme in the transmission systems, the first order and second order PMDs will be mitigated more efficiently.

In conclusion, we experimentally studied the performance of a 3R regenerator based on EAM with wavelength conversion which used to mitigate PMD. Eye analysis and BER measurements show that the scheme has excellent performance in mitigating the signal quality degeneration induced by first-order PMD combined with second-order PMD. Although the method has some limitation, it is attractive for its simple control, fast response and robustness.

This work was supported by the National Natural Science Foundation of China under Grant No. 60444008904010247 and 60577033. S. Pan is the author to whom the correspondence should be addressed, his e-mail address is psl2000@mails.tsinghua.edu.cn.

References

1. H. Rosenfeldt, in *Proceeding of OFC'2005* OWO1 (2005).
2. M. Karlsson, H. Sunnerud, and B. E. Olsson, in *Proceedings of ECOC'2004* We1.4.2 (2004).
3. C. Bornholdt, J. Slovak, Ch. Schmidt, and B. Sartorius, in *Proceedings of OFC'2005* OTuO6(2005).
4. L.-S. Yan, C. Yeh, G. Yang, L. Lin, Z. Chen, Y. Q. Shi, and X. S. Yao, in *Proceedings of OFC'2002* FA5-1 (2002).
5. Z. Wang, T. Wang, C. Lou, L. Huo, and Y. Gao, Opt. Commun. **219,** 301 (2003).
6. L. Huo, Y. Yang, C. Lou, H. Yao, X. Song, and Y. Gao, Chin. Opt. Lett. **2,** 505 (2004).