All-optical 3R regeneration in monolithic SOA-MZI to achieve 0.4 million km fiber transmission

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Abstract: An all-optical 3R regenerator that combines reshaping in SOA-MZIs and retiming in synchronously modulated $LiNbO_3$ modulator is demonstrated in a fiber-recirculation loop to achieve up to 0.4 million km linear transmission maintaining Q-values above 20-dB.

Introduction: Optical 3R regeneration (Re-amplification, Re-shaping and Re-timing) is a key function in controlling the quality of transmission data in future all-optical networks. While 3R is far more complex compared to 1R (re-amplification), it provides far more effective signal regeneration especially in the time domain. Previous studies have demonstrated various optical 3R regeneration technologies, including cross-phase modulation in interferometric devices [1], inline synchronous modulation of soliton pulses [2], and cross-absorption modulation in electro-absorption modulators [3]. On the other hand, due to the complexity optical 3R added to transmission systems, performance comparison is highly desired to identify the value of optical 3R and to justify the implementation of inline 3R regenerators. In this paper, we demonstrate a fiber recirculation loop experiment with and without an optical 3R regenerator in the loop and characterize the effective operation region of the inline 3R by comparing the Q factors of the signals.

Experimental setup and results: Fig. 1(a) shows the experimental setup. The bit-error-rate-tester (BERT) produces 10 Gb/s data stream using PRBS pattern 2^{23}-1. The two $LiNbO_3$ modulators (MOD) in cascaded operation generate a 10 Gb/s optical RZ signal at 1552.5 nm. The fiber re-circulation loop consists of two fiber spans with a total length of 125 km (65 km + 60 km) LEAF fibers. The chromatic dispersion of the LEAF fibers is compensated by 4 km DCF fibers. An optical band-pass filter (BPF) is inserted after the fiber spans to emulate the channel dropping filter in a real transmission system. In the experiment, two regeneration schemes are compared: 1R (re-amplifying) using EDFA only and 3R (re-amplifying + re-shaping + re-timing) using an optical 3R regenerator. The major components of the optical 3R regenerator are two semiconductor optical amplifier based Mach-Zehnder interferometers (SOA-MZI), one 10 Gb/s electrical clock recovery module (CR) and one $LiNbO_3$ modulator. Instead of using the conventional 3R scheme that provides an optical clock signal into SOA-MZIs as a probe light [1], we used CW probe sources for both SOA-MZIs and placed the optical clock modulator at the output of the second SOA-MZI for synchronous modulation. This configuration helps overcome the speed limitation of the SOA-MZIs and generate fast optical pulses even without complicated differential MZI operation [1]. In addition, the adjustable negative chirp operation of the $LiNbO_3$ modulator partially compensates for the positive chirping (linewidth enhancement factor) effect of the SOA-MZI. Most importantly, this configuration delineates the re-shaping and the re-timing functions and simplifies system optimization. Both SOA-MZIs operate in inverting mode (positive chirping) to provide faster response while mutually canceling the logic inversion at each stage. The SOA-MZIs convert wavelengths from 1552.5 nm to 1560 nm, and vice versa. The tunable delay line (TDL) aligns the timing of the reshaped data to the recovered clock.

Fig. 1(b) shows the BER measurement results. The BER curves indicate that there is no penalty between lap 1, 20 and 60 when inline optical 3R is included in the loop. On the other hand, the 1R scheme has 0.8 dB penalty between lap 1 and 10 at BER 10^{-9}, and the BER curve for lap 20 has an error floor at around 10^{-6}. Fig. 2 shows the Q measurement results and eye-diagrams. The Q measurements for 1R scheme show that the Q factor drops below 15.5 dB (BER = 10^{-9}) after 16 loops (2000 km). The Q factor of the 3R scheme is lower than that of the 1R scheme for lap 1 to 9. This is because the 3R regeneration has a penalty for a high-Q input signal. Beyond 10 loops, the Q factor of the 1R scheme keeps dropping while the Q factor of the 3R scheme stabilizes at around 20.3 dB, indicating effective optical regeneration of the inline 3R regenerator alleviating further accumulations of signal degradations. The eye-diagrams of 1R scheme also indicate strong jitter and amplitude noise accumulation beyond 10 laps. However, the eye shape for the 3R scheme stays nearly unchanged with clear eye openings even after 1000 and 3200 loops (0.125 and 0.4 million km transmission, respectively). This indicates that the 3R regenerator has excellent stability and cascadability for ultra-long haul transmissions. On the other hand, the experimental results also indicate that with the current setup, 1R regeneration is sufficient for a transmission distance below 1250 km

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without introducing inline 3R regenerators. The advantage of inline 3R regenerator becomes obvious when transmission distance is above 2000 km. The single channel experiment presented here can be extended to multi-channel cases where increased signal-to-noise ratio degradations through multi-channel optical amplification can be properly considered.

Summary: We demonstrated an optical 3R regeneration scheme that combined 2R in SOA-MZIs and synchronous modulation in a $LiNbO_3$ modulator effectively performing stable signal regeneration to achieve 0.4 million km fiber transmission. We compared the performance of a transmission system with such inline 3R regenerators spaced by 125 km LEAF fibers against that with 1R regeneration alone. Inline 3R gives strong performance improvement maintaining clear eye openings and stable Q factors at 20.3 dB even after 3200 loops (0.4 million km) transmission.

References:

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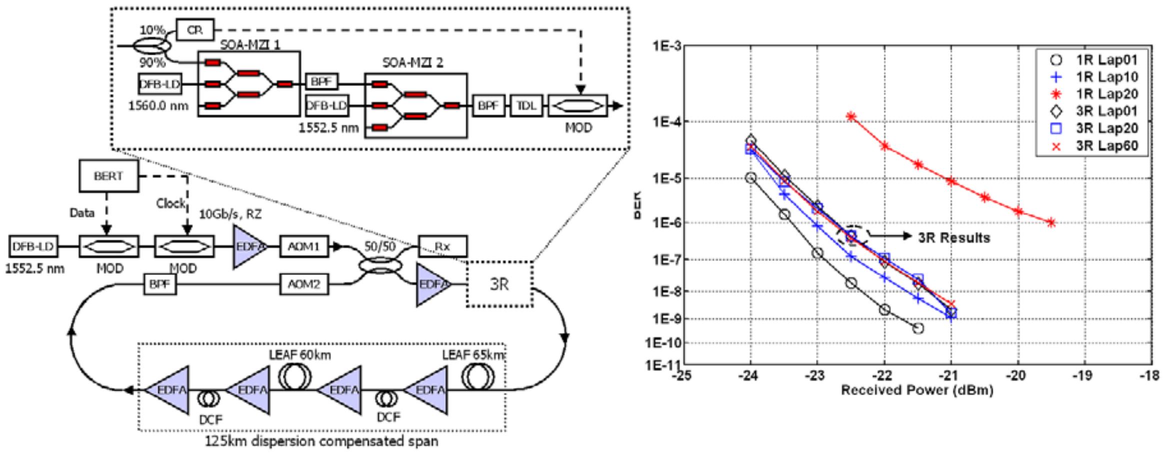

(a) (b)

Fig. 1(a) Experimental setup; DFB-LD: DFB laser diode; AOM: Acoustic optical modulator; Rx: Optical Receiver; EDFA: Erbium-doped fiber amplifier, (b) BER results.

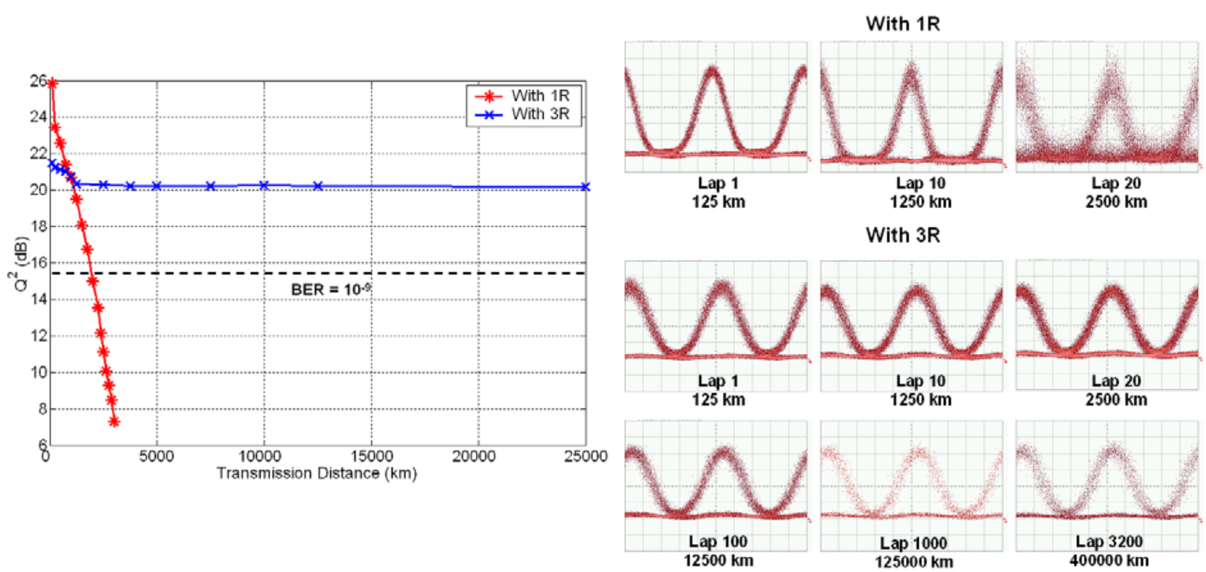

Fig. 2 Q factor vs. transmission and eye-diagrams for signals after 1R and 3R.