Demonstration of Field Trial Experiments to Investigate the Cascadability of a 10 Gb/s Optical 3R Regenerator with All-optical Clock Recovery

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Abstract: We demonstrate field trial experiments to evaluate a 10-Gb/s optical 3R regenerator using fiber recirculation loops built with 264-km and 462-km SSMF fiber in field. Error-free transmission over 264,000-km with 1,000 optical 3R regeneration stages has been achieved. Experimental results indicate only 1.5-dB power penalty at BER 10^{-9} after 264,000-km.

Keywords: Optical regeneration, Field trial, All-optical clock recovery, Semiconductor optical amplifier based Mach-Zehnder interferometer, Fabry-Perot filter

1. Introduction

The remarkable growth of the Internet traffic has spurred research and development of efficient and scalable optical network systems that can deliver high-speed data over long transmission distance across many switching nodes. Optical 3R regeneration (Re-amplifying, Re-shaping and Re-timing) is a promising enabling technology to overcome signal impairments from the physical layer limitations due to signal-to-noise ratio (OSNR) degradation, chromatic dispersion (CD), polarization mode dispersion (PMD), and fiber nonlinearities [1]. While previous experimental investigations have demonstrated optical 3R regeneration techniques that achieved 1,250,000 km transmission at 10 Gb/s [2], and 1,000,000 km transmission at 40 Gb/s [3, 4] in well-controlled lab environments, only a few of them reported field trial experiments [5] that assessed the 3R techniques under relatively realistic conditions. In this paper, we demonstrate, for the first time to our knowledge, experimental evaluations of a 10 Gb/s optical 3R regenerator in fiber recirculation loops built with field fiber links. The optical 3R regenerator consists of a 2R regeneration stage with semiconductor optical amplifier based Mach-Zehnder interferometers (SOA-MZIs) and a retiming stage using all-optical clock recovery based on a Fabry-Perot filter (FPF). The field trial experiments investigate the optical 3R spacing's impact on the cascadability of the regenerator by setting up recirculation loops with 264 km and 462 km loop lengths, and achieve error-free transmission without error correction over 264,000 km (1,000 × 264 km) field fiber by cascading 1,000 optical 3R regeneration stages.

2. Experimental Setup

Fig. 1(a) shows the map of the field fiber, which runs from Burlingame to Palo Alto and loops back. As indicated in Fig. 1(b), each field fiber span consists of 66 km (2 x 33 km) standard single-mode-fiber (SSMF). After each span, there are one two-stage Erbium-doped fiber amplifier (EDFA) and dispersion compensating fiber (DCF) located at Burlingame to compensate for the loss and the chromatic dispersion (CD) of the fiber transmission. Fig. 1(c) plots the OSNR evolution through the fiber spans. In the experiments, we set up fiber recirculation loops with 3R spacings of four field fiber spans (264 km) and seven field fiber spans (462 km). The corresponding signal OSNRs after 264 km and 462 km field fiber transmission are 23.5 dB and 20.6 dB (0.1 nm resolution bandwidth), respectively. The residual CD is 26 ps/nm after 264 km, and is 80 ps/nm after 462 km, at the operating wavelength 1551.5 nm.

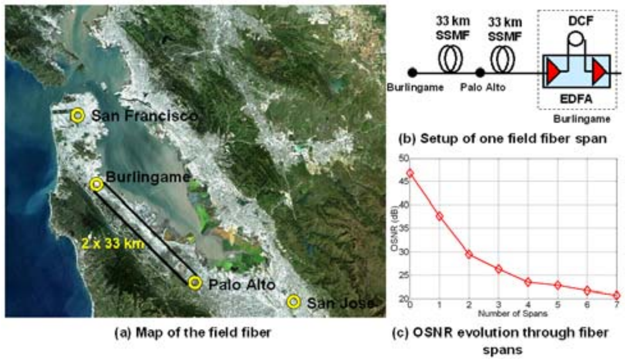

Fig. 1: (a) Map of the field fiber; (b) Setup of one field fiber span, SSMF: Standard Single-Mode Fiber, DCF: Dispersion Compensating Fiber, EDFA: Erbium-doped Fiber Amplifier; (c) OSNR evolution through field fiber spans

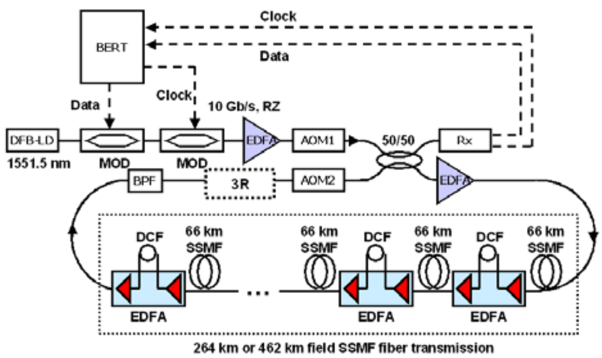

Fig. 2: Experimental setup, BERT: Bit-error-rate-tester, DFB-LD: DFB laser diode; MOD: $LiNbO_3$ modulator; AOM: Acoustic optical modulator; BPF: Optical band-pass filter; EDFA: Erbium-doped fiber amplifer; SSMF: Standard single-mode fiber; DCF: Dispersion compensating fiber; RX: Optical receiver

Fig. 2 shows the experimental setup. The pattern generator on the bit-error-rate-tester (BERT) produces 10 Gb/s data using Pseudo-Random-Bit-Sequence (PRBS) 2^{23}-1. The two $LiNbO_3$ modulators in tandem impose data and clock modulations onto the CW emission from the DFB laser, and produce a 10 Gb/s return-to-zero (RZ) optical signal at 1551.5 nm. The fiber recirculation loop consists of four or seven field fiber spans with a total length of 264 km or 462 km and one optical 3R regenerator. The two acoustic optical modulators (AOMs) control the timing of the recirculation loop to facilitate the bit-error-rate (BER) measurement of any specific lap.

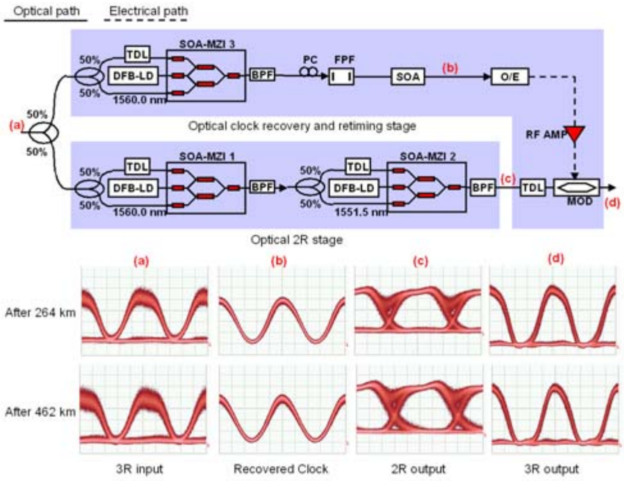

Fig. 3: All-optical 3R regenerator setup, TDL: Tunable delay line; DFB-LD: DFB laser diode; SOA-MZI: Semiconductor optical amplifier based Mach-Zehnder interferometer; BPF: Optical band-pass filter; PC: Polarization controller; FPF: Fabry-Perot filter; SOA: Semiconductor optical amplifier; O/E: Optical-to-electrical converter; RF AMP: RF amplifier; MOD: $LiNbO_3$ modulator

Fig. 3 illustrates the setup of the optical 3R regenerator. The degraded optical signal after field transmission is split into two paths: signal path and clock path. The signal path processing consists of two SOA-MZIs for signal reshaping (optical 2R) to suppress amplitude noise. Each SOA-MZI operates in the differential mode with a 35 ps relative delay between the two interferometric arms. The SOA-MZIs translate the signal wavelength from 1551.5 nm to 1560.0 nm and vice versa, to maintain the same wavelength (1551.5 nm) in the fiber recirculation loop. Fig. 3(a) shows the eye-diagrams of the 10 Gb/s degraded RZ signals after 264 km and 462 km field fiber transmissions. Fig. 3(c) shows the output eye-diagrams of the optical 2R stage. The optical 2R regeneration effectively suppresses the amplitude noise on the mark- and space-levels of the incoming distorted signals. In the clock path, all-optical clock recovery is achieved through extracting the clock spectral components from the RZ signal with the FPF that has a free spectral range matched to the data rate (10 GHz) and a relatively large finesse (100) [2, 6]. Before this processing, the SOA-MZI 3 converts the input RZ signal wavelength to match to one pass-band of the FPF and fixes the signal polarization state to adapt the polarization sensitivity of the FPF [2]. Due to the passive nature of the FPF based all-optical clock recovery, the recovered clock amplitude decays when long sequences of repeated zeros occur, resulting in significant pattern-dependent amplitude variations [6]. The limiting amplification property of the gain-saturated semiconductor optical amplifier (SOA) helps to reduce these pattern-dependent amplitude variations [2, 7]. The inset (b) of Fig. 3 shows the recovered 10 GHz optical clock signals, which exhibit almost no amplitude variation. The optical clock signals have a Full-Width at Half-Maximum (FWHM) of 45 ps. The recovered clock signal drives an O/E converter and an RF amplifier that supplies the synchronous modulation clock to the $LiNbO_3$ modulator for retiming. This configuration decouples the re-shaping and the re-timing processes in the optical 3R regenerator, and simplifies the system optimization. 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-MZIs [2]. Note that, the O/E conversion can be avoided if the O/E converter and the $LiNbO_3$ modulator are replaced by another SOA-MZI. The tunable delay line (TDL) aligns the timing of the reshaped data signal to the recovered clock. Fig. 3(d) shows the eye-diagrams of the final 3R outputs taken at the output of the $LiNbO_3$ modulator. The amplitude and time noise on the input signals are effectively suppressed, and signals with clean eye-diagrams are produced for retransmision.

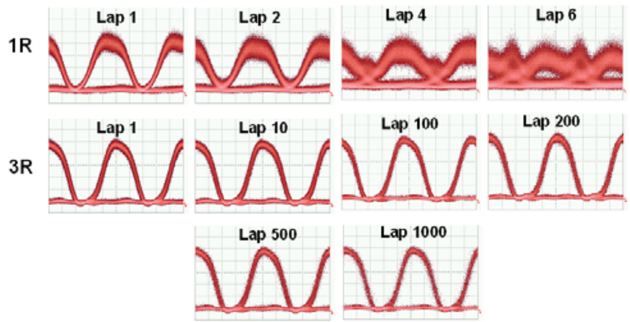

Fig. 4: Eye-diagrams of 264 km fiber recirculation loop experiments

3. Experimental results and discussion

The fiber recirculation loop is first setup with 264 km field fiber and the signal OSNR is degraded from 46.8 dB to 23.5 dB after one lap. To benchmark the effectiveness of the optical 3R regeneration, the experiments also include the scheme that the optical 3R regenerator is removed from the fiber recirculation loop. Since the optical signal is only re-amplified by the EDFAs in this scheme, we refer it as optical 1R. Fig. 4 shows the eye-diagram results. The eye-diagrams of the 1R scheme become closed and noisy at Lap 6 (total transmission distance of 1,584 km) due to the addition of amplitude and time domain noise in each lap. In comparison, the eye-diagrams of the 3R scheme remain almost unchanged through Lap 1 to Lap 1,000 (264 ~ 264,000 km field transmission), and clean and open eye-diagram can be obtained at Lap 1,000. This is because the 3R scheme effectively suppresses the amplitude and time noise accumulation after each lap and retransmits the refreshed signals. The BER measurement results in Fig. 5 indicate that the optical 3R scheme achieves error-free operation (BER < 10^{-9}) at Lap 1,000. The BER curves of 3R Lap 1 to Lap 200 are overlapping with that of the back-to-back signal before transmission. At Lap 1,000 (after 264,000 km), there is only 1.5 dB power penalty at 10^{-9} BER relative to the back-to-back case. On the other hand, the BER curves of the 1R scheme show error-floor around 10^{-5} at Lap 6. For Lap 1, the 3R scheme achieves 2 dB negative power penalty at 10^{-9} BER compared to the 1R scheme. The experiment results indicate that the optical 3R regenerator has very stable operation and can effectively extend the transmission reach.

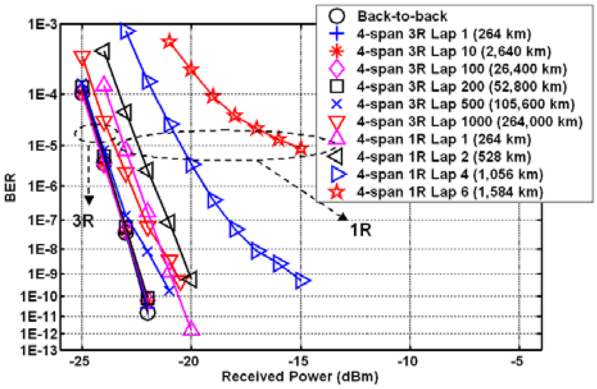

Fig. 5: BER measurement results of 264 km fiber recirculation loop experiments

To investigate the relation between the optical 3R cascadability and the optical 3R spacing, we increase the field fiber length in the recirculation loop to 462 km. As indicated in Fig. 1(c), the input OSNR to the optical 3R regenerator will be 20.6 dB in this case. Fig. 6 shows the eye-diagrams. The eye-diagrams of the 1R scheme exhibit much faster noise accumulation due to the increased loop length. The eye-diagram of the 1R scheme closes at Lap 3 (1,386 km), while the eye-diagrams of the 3R scheme remain clean and open even at Lap 20 (9,240 km). However, due to the relatively low input OSNR, the falling edges of the eye-diagrams are slightly fuzzy and amplitude noise dots can be observed around the space- and mark-levels. Fig. 7 shows the BER measurement results. Without the optical 3R regenerator, the BER curves of the 1R scheme start to bend at Lap 2 and the curve for Lap 3 has an error-floor around 10^{-5}. For the 3R scheme, the error-free operation can be maintained at Lap 4. For Lap 1, the 3R scheme achieves 2 dB negative power penalty at 10^{-9} BER relative to the 1R scheme. The BER curves of the 3R scheme shows bending at Lap 8 and the curve for Lap 14 has an error-floor around 10^{-9}. This is an indication that the relative low input OSNR makes the optical 3R regenerator operate at the margin. It is well known that the origin overlap between noise distributions associated to a degraded signal cannot be suppressed but only minimized through optical 3R regeneration [1]. Thus, low input OSNR will limit the cascadability of an optical 3R regenerator. On the other hand, the BER measurement results also indicate that for this optical 3R regenerator, the 3R spacings of 264 km and 462 km have comparable performance when the total transmission distance is less than 1,848 km. Hence, the 3R spacing can be extended in transmission system design and the number of optical 3R locations can be reduced.

4. Summary

We demonstrated a 10 Gb/s optical 3R regenerator in field trial experiments. The experiments evaluated the 3R regenerator using fiber recirculation loops built with 264 km and 462 km SSMF fiber in field, and investigated the relation between the optical 3R cascadability and the optical 3R spacing. With a loop length of 264 km and an input OSNR of 23.5 dB, the 3R regenerator achieved 2 dB negative power at 10^{-9} BER and demonstrated error-free transmission over 264,000 km field fiber without forward error correction (FEC). After 264,000 km transmission, the power penalty at 10^{-9} BER is 1.5 dB relative to the back-to-back case. With a loop length of 462 km and an input OSNR of 20.6 dB, the 3R regenerator maintained error-free transmission at Lap 4 (1,848 km) and the BER curve exhibited an error-floor around 10^{-9} at Lap 14 (6,468 km). The relatively low input OSNR in this scheme limited the cascadability of the optical 3R regenerator. In terms of the BER performance, the 3R spacings of 264 km and 462 km provided comparable performance when the total transmission distance was less than 1,848 km.

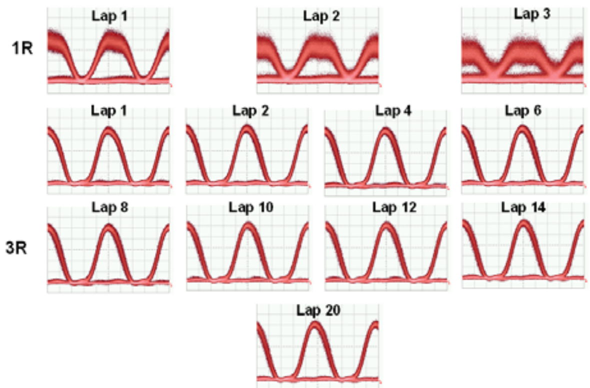

Fig. 6: Eye-diagrams of 462 km fiber recirculation loop experiments

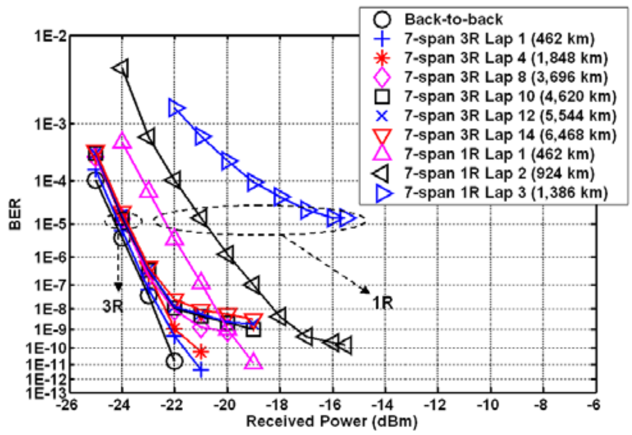

Fig. 7: BER measurement results of 462 km fiber recirculation loop experiments

5. Acknowledgement

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6. References

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