Demonstration of 264,000 km, 10 Gb/s Field Fiber Transmission using 1,000 Cascaded All-optical 3R Regeneration Stages

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Abstract *We demonstrate 10-Gb/s, error-free transmission over 264,000-km field fiber with 1,000 optical 3R regeneration stages using all-optical clock recovery. Experimental results show only 1.5-dB power penalty at BER 10^{-9} after 264,000-km transmission.*

Introduction

Optical 3R regeneration (Re-amplifying, Re-shaping and Re-timing) is a promising enabling technology for next generation optical transmission systems to overcome the signal impairments particularly from optical-signal-to-noise-ratio (OSNR) degradation and timing jitter accumulation. While previous studies have demonstrated optical 3R regeneration techniques that achieved 1,250,000 km transmission at 10 Gb/s [1], and 1,000,000 km transmission at 40 Gb/s [2, 3] in well-controlled lab environments, only a few of them reported field trial experiments [4, 5] that assessed the 3R techniques under realistic conditions. In this paper, we demonstrate, for the first time to our knowledge, experimental evaluations of a 10 Gb/s 3R regenerator in a fiber recirculation loop 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 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.

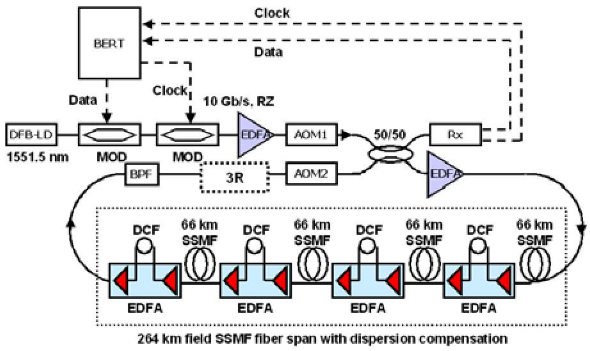

Fig. 1 Experimental setup, BERT: Bit-error-rate-tester; DFB-LD: DFB laser diode; MOD: $LiNbO_3$ modulator; EDFA: Erbium-doped fiber amplifier; AOM: Acoustic optical modulator; SSMF: Standard single-mode fiber; DCF: Dispersion compensating fiber; BPF: Optical band-pass filter; Rx: Optical receiver

Experimental Setup

Fig. 1 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 DFB laser emission, and produce a 10 Gb/s return-to-zero (RZ) optical signal at 1551.5 nm. The fiber recirculation loop consists of four field fiber spans with a total length of 264 km (4 × 66 km) and one optical 3R regenerator. As shown in Fig. 2(a), each field fiber span consists of 66 km standard single-mode-fiber (SSMF), which runs from Burlingame to Palo Alto and loops back. After each span, there are one two-stage Erbium-doped fiber amplifier (EDFA) and Dispersion compensating fiber (DCF) to compensate for the loss and chromatic dispersion (CD) of the fiber transmission. Fig. 2(b) plots the CD variations with the SSMF transmission distance at the operating wavelength 1551.5 nm. The residual CD is 26 ps/nm after 264 km. Fig. 2(c) shows the OSNR evolution through the fiber spans. The 264 km field fiber transmission degrades the signal OSNR from 46.8 dB to 23.5 dB (0.1 nm resolution bandwidth).

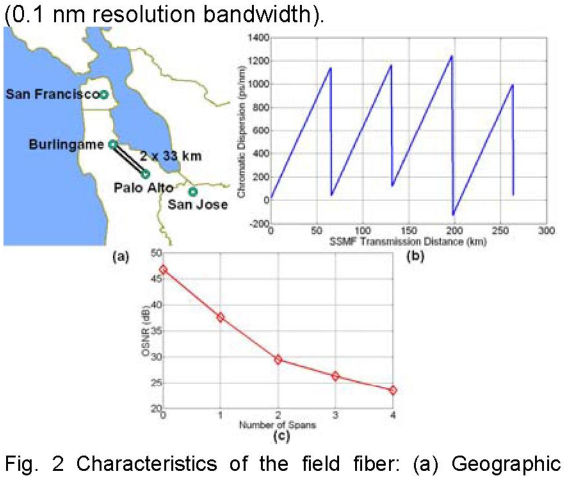

Fig. 2 Characteristics of the field fiber: (a) Geographic map, (b) Chromatic dispersion, and (c) OSNR

Fig. 3 illustrates the setup of the all-optical 3R regenerator. The optical signal is split into two paths: clock path and signal path. The clock path processing consists of a clock-enhancement stage and a clock-recovery-and-retiming stage. The SOA-

MZI in the clock enhancement stage converts the wavelength and fixes the signal polarization state [1] for the FPF with wavelength and polarization sensitivity. The clock-recovery-and-retiming stage incorporates all-optical clock recovery employing the FPF and the gain-saturated semiconductor optical amplifier (SOA), and retiming with synchronous modulation [1, 6]. The FPF has a free spectral range (FSR) of 10 GHz and a finesse of 100. Fig. 3(c) shows the recovered 10 GHz optical clock signal. The recovered clock signal drives an O/E converter and an RF amplifier that supplies the synchronous modulation clock signal to the $LiNbO_3$ modulator for retiming. The signal path processing consists of two optical 2R stages. Each 2R stage utilizes a SOA-MZI operating in the differential mode with a 35 ps relative delay between the two interferometric arms. The 2R stages 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(d) and (e) shows the output eye-diagrams of the two 2R stages. The 2R regeneration effectively suppresses the amplitude noise on the mark level of the incoming distorted signal. Fig. 3(f) shows the eye-diagram of the final 3R output taken at the output of the $LiNbO_3$ modulator.

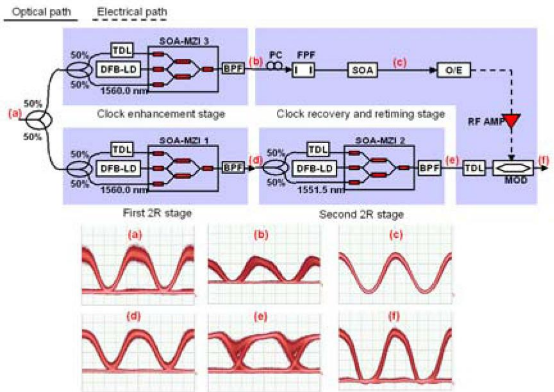

Fig. 3 All-optical 3R regenerator setup, TDL: Tunable delay line; DFB-LD: DFB laser diode; SOA-MZI: Semiconductor optical amplifier based Mach-Zehnder interferometer; BPF: Optical band-pass filter; PC: Polarization controller; FPF: Fabry-Perot filter; SOA: Semiconductor optical amplifier; O/E: Optical-to-electrical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

Experimental Results

Fig. 4 shows the experimental results of the field trial experiments. For the 3R case, the eye-diagrams remain almost unchanged through Lap 1 to Lap 1,000 (264 ~ 264,000 km field transmission), and the eye opening is clear at Lap 1,000. In comparison, the eye-diagrams of the 1R scheme (EDFA only without 3R regeneration) become closed and noisy at Lap 6. The BER measurement results indicate that the optical 3R scheme achieves error-free operation (BER < 10^{-9}) at Lap 1,000. For 3R Lap 1 to Lap 200, the BER curves are overlapping with that of the back-to-back signal before transmission. After 264,000 km, only 1.5 dB power penalty at 10^{-9} BER is observed relative to the back-to-back case. 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. The experiment results indicate stable operation of the optical 3R regenerator.

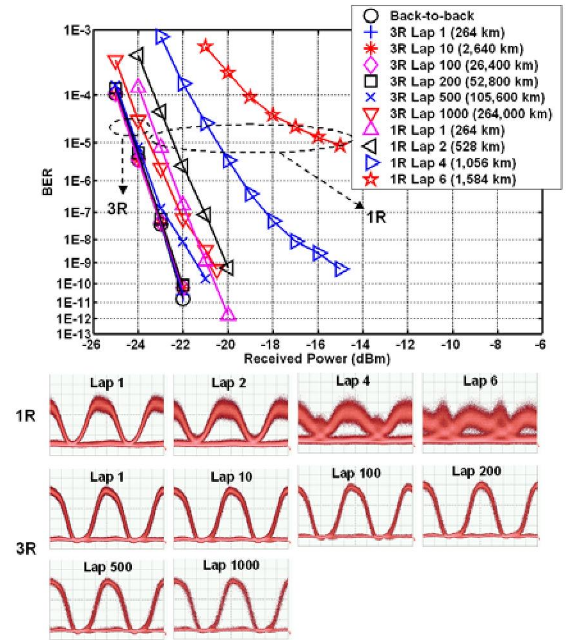

Fig. 4 BER results and eye-diagrams

Summary

We proposed and demonstrated a 10 Gb/s all-optical 3R regenerator in field trial experiments. The experiments evaluated the 3R regenerator using a fiber recirculation loop built with 264 km SSMF fiber in field. With an input OSNR of 23.5 dB, the 3R regenerator achieved 2 dB negative power penalty 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.

References

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