1000 Cascaded Stages of Optical 3R Regeneration With SOA-MZI-Based Clock Enhancement to Achieve 10-Gb/s 125 000-km Dispersion Uncompensated Transmission

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***Abstract*—We propose an optical 3R regenerator that incorporates a clock enhancement stage based on a semiconductor optical amplifier (SOA)-based Mach–Zehnder interferometer and a 10-GHz all-optical clock recovery module employing a Fabry–Perot filter and an SOA. The experiments assess the optical 3R regeneration technique using a fiber recirculation loop containing 125-km dispersion uncompensated large effective area fiber with a total chromatic dispersion of 531.25 ps/nm. The optical 3R regeneration achieves error-free 125 000-km dispersion uncompensated return-to-zero transmission at 10 Gb/s over 1000 optical 3R stages. The bit-error-rate (BER) measurements show that there is only 1.2-dB power penalty at 10^{-9} BER between 125 000-km (Lap 1000) uncompensated transmission and back-to-back using pseudorandom bit sequence $2^{23}-1$.**

***Index Terms*—All-optical clock recovery, dispersion uncompensated transmission, Fabry–Pérot filter (FPF), optical regeneration, semiconductor optical amplifier-based Mach–Zehnder interferometer (SOA-MZI), synchronous modulation, wavelength conversion.**

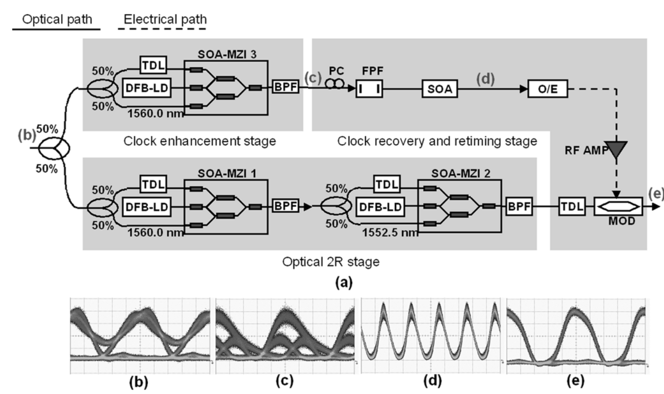

Fig. 1. (a) Setup of the optical 3R regenerator. TDL: Tunable optical delay line. DFB-LD: DFB laser diode. BPF: Optical bandpass filter. PC: Polarization controller. O/E: Optical-to-electrical converter. RF AMP: RF amplifier. MOD: $LiNbO_3$ optical modulator. (b) Eye diagram of signal after dispersion uncompensated transmission. (c) Eye diagram of RZ signal before all-optical clock recovery. (d) Recovered optical clock. (e) Eye diagram of RZ signal after 3R regeneration.

I. Introduction

OPTICAL 3R (reamplification, reshaping, and retiming) regeneration is a promising enabling technology that can overcome the physical limitations, extend the transmission distance, and improve the scalability of the next-generation optical networks. Previous studies have already demonstrated 1 250 000-km transmission at 10 Gb/s over 10 000 3R stages [1], and 1 000 000-km transmission at 40 Gb/s over 2500 3R stages [2], [3]. However, these works used dispersion-compensated fiber spans and ignored the CD's effect on the optical 3R regeneration. CD induces pulse-broadening, causes intersymbol interference, and adds complexity to clock recovery due to the radio-frequency (RF) fading of clock components [4]. Point-to-point uncompensated transmissions have been achieved with prechirping [6], duobinary modulation [7], and forward error correction coding [8]. Cascaded operation of optical 2R regeneration achieved 3600-km uncompensated transmission through single-mode fiber at 2.5 Gb/s [5]. Nevertheless, when retiming is absent, the accumulation of the timing jitter induced by CD limits the cascadability of the optical 2R regenerator to nine laps and restricts the operation data rate to 2.5 Gb/s [5]. The cascadability of optical 3R regeneration has not yet been fully explored in 10-Gb/s uncompensated fiber recirculation loop experiments. This letter proposes and demonstrates a 10-Gb/s optical 3R regenerator that employs a novel clock enhancement technique based on a semiconductor optical amplifier-based Mach–Zehnder interferometer (SOA-MZI) and all-optical clock recovery utilizing a Fabry–Pérot filter (FPF) and an SOA. The recirculation loop experiments achieve error-free, low penalty, dispersion uncompensated return-to-zero (RZ) transmission over a record distance of 125 000 km using 1000 cascaded optical 3R stages.

II. Operation Principle

Fig. 1(a) shows the proposed structure of the optical 3R regenerator. Fig. 1(b) shows the eye diagram of 10-Gb/s RZ signal that has been transmitted through 125-km uncompensated large effective area fiber (LEAF) with a total CD of 531.25 ps/nm. The initial RZ pulses have a full-width at half-maximum (FWHM) of 35 ps and a modulation of pseudorandom bit sequence (PRBS) $2^{23}-1$. The CD-induced RF fading degrades the 10-GHz clock component in the signal spectrum [4] and limits the performance of the optical filtering-based all-optical clock recovery [9]. The clock enhancement stage includes an SOA-MZI in a push–pull operation, which injects the same optical signal into both interferometric arms of the SOA-MZI with a relative time delay [1].

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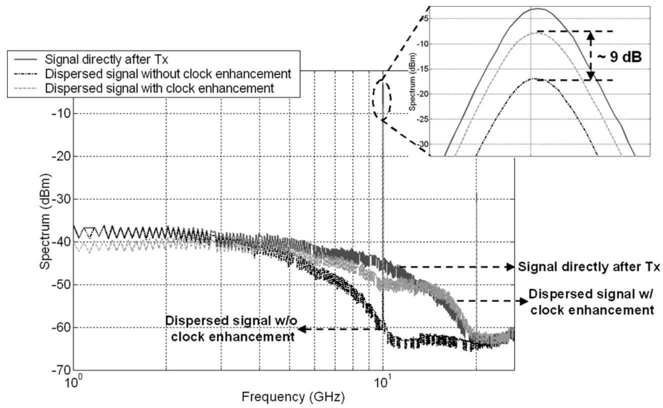

Fig. 2. RF spectrum comparisons of back-to-back signal before transmission, dispersed signal without clock enhancement, and dispersed signal with clock enhancement (the average optical power is fixed at 0 dBm in all cases).

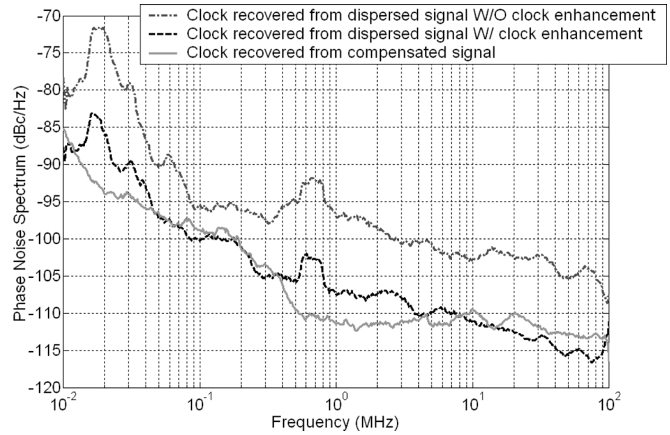

Fig. 4. Phase noise spectra of clocks recovered from dispersed signal without clock enhancement, dispersed signal with clock enhancement, and dispersion-compensated signal.

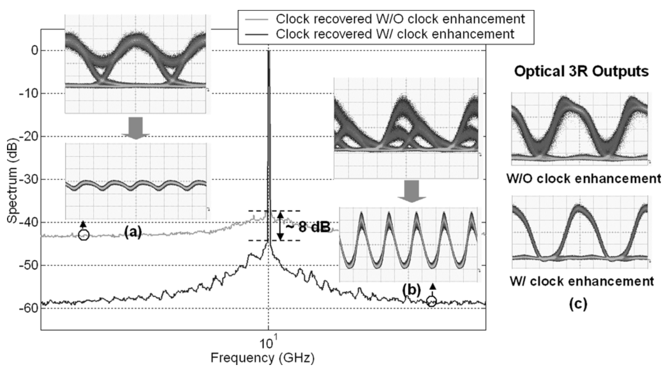

Fig. 3. RF spectrum comparisons of the 10-GHz clocks recovered with and without clock enhancement (the spectra are normalized to the peak power). (a) Eye diagrams of all-optical clock recovery without clock enhancement. (b) Eye diagrams of all-optical clock recovery with clock enhancement. (c) Eye diagrams of optical 3R outputs with and without clock enhancement.

The SOA-MZI works in an over-modulated mode in which the device is driven across the minimum point on the transfer function. As shown in Fig. 1(c), a portion of the leading and falling edges of the bit “1” pulses can be flipped up and be extended into the adjacent bit “0” slots. This enhances the clock component by inserting pulses in the bit “0” slots. Fig. 2 shows the RF spectrum comparisons of the optical signals with the same average optical power at 0 dBm. The clock enhancement improves the 10-GHz clock component by approximately 9 dB. The FPF (free spectral range $=$ 10 GHz and finesse $=$ 100) and the gain-saturated SOA extract the 10-GHz clock component all-optically [1], [10]. As shown in Fig. 1(d), the all-optical clock recovery obtains 10-GHz optical clock pulses with an FWHM of 40 ps. Fig. 3 shows the RF spectra (1-MHz resolution bandwidth and normalized to the peak power) of the clocks recovered with and without clock enhancement. The clock enhancement improves the sidelobe suppression ratio of the recovered clock by approximately 8 dB. Without clock enhancement, the all-optical clock recovery has difficulty to properly extract the 10-GHz clock due to the fact that the CD-induced RF fading degrades the power of the clock component (as shown in Fig. 2). Thus, as shown in Fig. 3(a), the recovered clock shows low amplitude and a poor extinction ratio ($<$3 dB) that is not suitable for the following retiming using synchronous modulation, while the clock enhancement provides a clean clock with an extinction ratio of 10 dB [as shown in Fig. 3(b)]. Fig. 3(c) shows the 3R outputs with and without clock enhancement. Without clock enhancement, the 3R output exhibits a noisy eye diagram and is not qualified for retransmission. Fig. 4 shows the single-sideband phase noise spectra (10 kHz $\sim$ 100 MHz) of the clocks recovered from different signals. By integrating the phase noise spectra from 20 kHz to 80 MHz, we derived the upper-bound values for the timing jitter of the recovered clocks [10]. The estimated root mean square (rms) jitter values are 1.52, 0.60, and 0.52 ps for clocks recovered from dispersed signal without clock enhancement, dispersed signal with clock enhancement, and dispersion-compensated signal, respectively.

In the signal path, the optical 2R stage consists of two SOA-MZIs operating in the push–pull mode, which translate the signal wavelength from 1552.5 to 1560.0 nm, and vice versa. This configuration maintains the same wavelength in the loop and simultaneously enhances the nonlinearity of the regenerative power transfer function. A $LiNbO_3$ modulator takes the output of the optical-to-electrical converter and retimes the reshaped signal using synchronous modulation [1]. Fig. 1(e) shows the eye diagram of the signal after the 3R regeneration.

III. Experimental Setup and Results

Fig. 5 shows the fiber recirculation loop experiment setup. The bit-error-rate (BER) tester produces 10-Gb/s data using PRBS $2^{23}-1$. The two $LiNbO_3$ modulators in cascaded configuration generate a 10-Gb/s optical RZ signal at 1552.5 nm. The fiber loop consists of two uncompensated fiber spans with a total length of 125 km (65 km $+$ 60 km) LEAF fiber. The total CD of the fiber spans is 531.25 ps/nm at the operating wavelength 1552.5 nm. The inset of Fig. 5(a) shows the estimated dispersion curve of the fiber spans. After the optical bandpass filter with 1-nm 3-dB bandwidth, the distorted signal enters into the 3R regenerator in each loop.

The insets of Fig. 6(a) show the eye-diagram evolution at various loop numbers. Clear eye opening can be observed through Lap 1 to Lap 1000 (after 125 $\sim$ 125 000 km uncompensated transmission). There is a small amount of jitter accumulation from Lap 1 to Lap 1000 and the jitter peak-to-peak increases from 6 ps at Lap 1 to 16 ps at Lap 1000. Fig. 5(b) shows the zoom-in eye diagram of the recovered clock (20 ps/div) at Lap

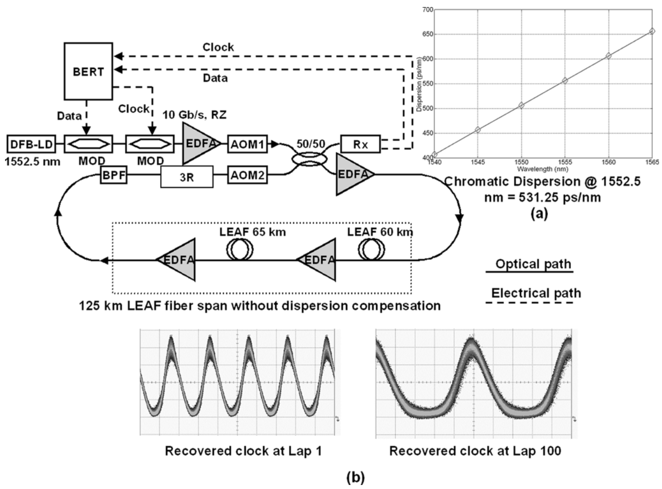

Fig. 5. Experimental setup for evaluating the optical 3R regenerator in a 125-km uncompensated fiber recirculation loop. DFB-LD: DFB laser diode. Mod: $LiNbO_3$ optical modulator. BERT: BER tester. EDFA: Erbium-doped fiber amplifier. AOM: Acoustic optical modulator. BPF: Bandpass filter. Rx: 10-Gb/s optical receiver. (a) Estimated dispersion curve of the fiber spans. (b) Eye diagram of recovered clocks at Laps 1 and 100.

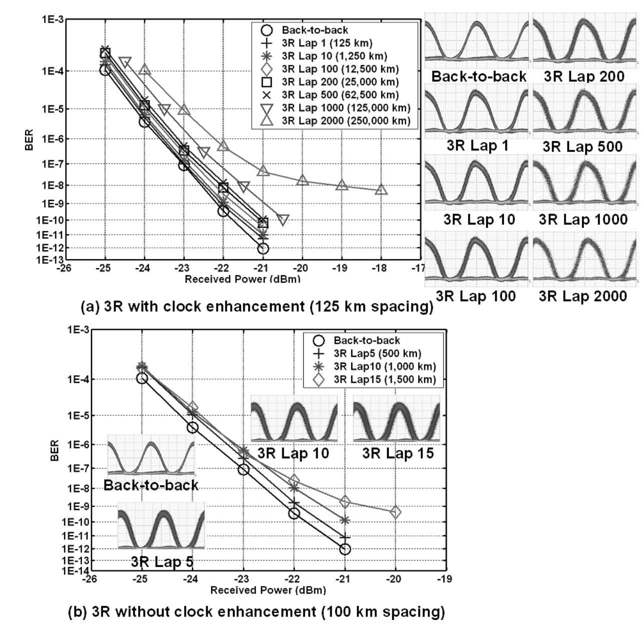

Fig. 6. BER and eye-diagram measurement results for (a) back-to-back and 3R Lap 1 to Lap 2000 with clock enhancement (125-km spacing). (b) Back-to-back and 3R Lap 1 to Lap 15 without clock enhancement (100-km spacing).

100, which indicates jitter accumulations with an increased number of loops for increasing loop circulations. Fig. 6(a) plots the BER of the signals at back-to-back and 3R Lap 1, 10, 100, 200, 500, 1000, and 2000 versus average receiver power. There is only 1.2-dB penalty at 10^{-9} BER for transmission over 125 000 km (Lap 1000) relative to the back-to-back case without transmission. All of the BER curves have no error floor, except for the one at Lap 2000, which has an error floor around 10^{-8}. The error floor is from the jitter accumulation mentioned above. As a comparison, Fig. 6(b) shows the BER curves and eye diagrams of optical 3R without clock enhancement, when the fiber recirculation loop only consists 100-km uncompensated LEAF fiber with a total CD of 425 ps/nm at 1552.5 nm. Due to the RF fading of the clock components, the 3R outputs exhibit much faster jitter accumulation and the BER curve at Lap 15 (after 1500-km uncompensated transmission) starts to bend, indicating an error floor around 10^{-10}.

IV. Summary

We proposed and demonstrated a 10-Gb/s optical 3R regeneration technique that incorporated an SOA-MZI based clock enhancement stage to strengthen the system's immunity to fiber CD. Error-free, uncompensated RZ transmission at 10 Gb/s over a record distance of 125 000 km was achieved using the in-line operation of the proposed 3R regeneration at every 125 km ($\mathrm{CD} = 531.25\ \mathrm{ps/nm}$). The BER performance evaluation using PRBS $2^{23} - 1$ showed that after 125 000-km uncompensated transmission, the power penalty at 10^{-9} BER is only 1.2-dB relative to the back-to-back case.

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