10 000-Hop Cascaded In-Line All-Optical 3R Regeneration to Achieve 1 250 000-km 10-Gb/s Transmission

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***Abstract*—We demonstrate 1 250 000-km 10-Gb/s return-to-zero transmission over 10 000 stages of in-line all-optical reamplification, reshaping, and retiming (3R) regeneration spaced every 125 km. The all-optical 3R regenerator incorporates a 10-GHz all-optical clock recovery module including a Fabry–Pérot filter and a semiconductor optical amplifier in a cascaded configuration for fast and stable response. Bit-error-rate (BER) performance measurements show less than 0.7-dB power penalty at the BER of 10^{-9} between 1 250 000- (Lap 10 000) and 125-km (Lap 1) transmission using pseudorandom bit sequence $2^{23} - 1$.**

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

I. Introduction

OPTICAL reamplification, reshaping, and retiming (3R) regeneration is an important function that provides scalability and robustness in future all-optical networks. Clock recovery is a key element of an optical 3R regenerator. It is desired to realize all-optical clock recovery without requiring high-speed electronics. Recent research has demonstrated a number of all-optical clock recovery techniques, involving synchronized mode-locked ring lasers [1], self-pulsating distributed feedback (DFB) lasers [2], and Fabry–Pérot filters (FPFs) [3], [4]. Among these techniques, the FPF-based technique can operate at a wide range of clock rates without involving active lasers [5]. This clock recovery technique also has the potential to work with nonreturn-to-zero [4] as well as return-to-zero (RZ) formats. In-line testing of optical 3R regenerators within a recirculation fiber loop is effective in evaluating the ultimate performance of the 3R regeneration technique. Previous studies have demonstrated 1 000 000-km soliton transmission at 10 Gb/s by synchronous modulation with a local clock (no clock recovery) [6], 1 000 000-km transmission at 40 Gb/s using highly nonlinear fiber (HNLF)-based 3R and electronic clock recovery [7], 1 000 000-km transmission at 40 Gb/s using HNLF, semiconductor optical amplifier (SOA)-based delay interferometer, and electronic clock recovery [8], 22 000-km transmission at 20 Gb/s using cascaded SOA-based Mach–Zehnder interferometers (SOA-MZIs) and electronic clock recovery [9], and 10 000-km transmission at 40 Gb/s using synchronous modulation with a recovered clock from a self-pulsating DFB laser [2]. Due to the polarization sensitivity of practical compact fiber FPFs [3], [4], the cascadability of FPF-based all-optical clock recovery has yet been fully explored in fiber recirculation loop experiments. This letter proposes a novel technique to circumvent the polarization sensitivity and to achieve stable FPF-based all-optical clock recovery for signal with polarization variation after fiber transmission. The fiber recirculation loop experiments incorporate in-line optical 3R regenerator with an FPF-based 10-GHz all-optical clock recovery module and demonstrate 10 000 stages 3R regeneration cascadability over a record distance of 1 250 000 km.

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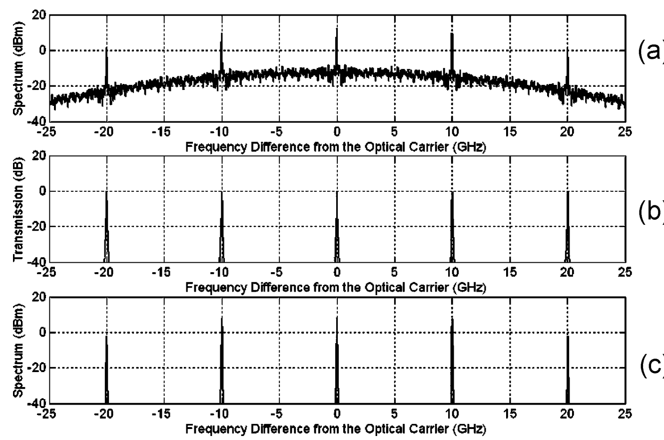

Fig. 1. Simulation results show the principle of all-optical clock recovery by narrow-band optical filtering with an FPF. (a) Optical spectrum of 10-Gb/s RZ signal with PRBS $2^{31} - 1$ sequences. (b) Frequency response of the FPF. (c) Optical spectrum of 10-GHz recovered clock.

II. Operation Principle

Fig. 1 illustrates the operation principle of the FPF-based all-optical clock recovery. Fig. 1(a) shows the simulated optical spectrum of a 10-Gb/s RZ signal consisting of continuous spectral components from data modulation and line spectral components from the clock (10 GHz) and its harmonics. All-optical clock recovery can be achieved through extracting the clock spectral components with narrow-band optical filtering. An FPF with a free-spectral range (FSR) matched to the data rate and a relatively large finesse (typically >20) works effectively for this application [3], [5]. Fig. 1(b) shows the simulated frequency response of an FPF with FSR $=$ 10 GHz and finesse $=$ 100 (full-width at half-maximum (FWHM) of

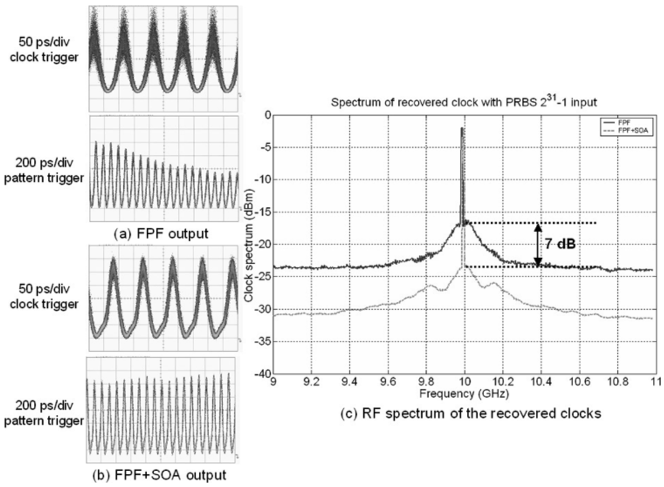

Fig. 2. Experimental results of all-optical clock recovery for 10-Gb/s RZ signal with PRBS $2^{31}-1$ sequences. (a) Recovered clock directly after the FPF (clock-triggered and pattern-triggered screens). (b) Recovered clock after the FPF and gain-saturated SOA (clock-triggered and pattern-triggered screens). (c) RF spectrum comparison of the recovered clocks with and without the gain-saturated SOA.

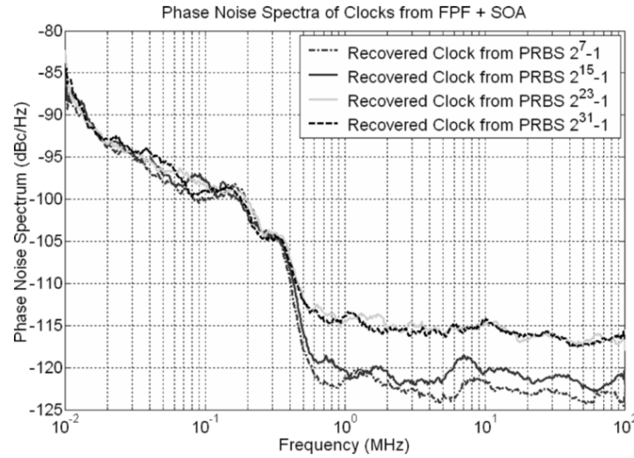

Fig. 3. Phase noise spectra of recovered clocks after FPF and SOA for 10-Gb/s RZ inputs with different PRBS sequence lengths.

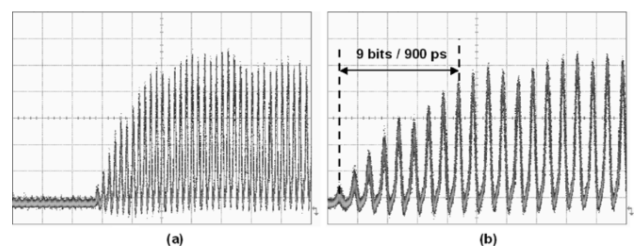

Fig. 4. Leading edge of the recovered burst-mode clock pulses after FPF and SOA with a screen resolution of (a) 500 and (b) 200 ps/div.

100 MHz). Fig. 1(c) shows the simulated optical spectrum of the RZ signal transmitted through the FPF, which transmits the clock spectral components while suppressing the data modulation components. Fig. 2 shows the experimental results of all-optical clock recovery at 10 GHz using an FPF with FSR $=$ 10 GHz and finesse $=$ 100. The input is a 10-Gb/s continuous RZ optical signal with $2^{31}-1$ pseudorandom bit sequence (PRBS) pattern. Fig. 2(a) shows the recovered clock directly after the FPF. The FPF removes most of the data modulation and provides periodic optical clock pulses matching the FSR (i.e., data clock) frequency. However, when long sequences of repeated zeros occur, the recovered clock amplitude decays, resulting in significant pattern-dependent amplitude variations [5]. These pattern-dependent amplitude variations can be reduced by exploiting the limiting amplification property of a gain-saturated SOA [4]. The SOA has an amplified spontaneous emission peak wavelength at 1540 nm and its noise figure is 7.8 dB at 1550 nm. Fig. 2(b) shows the recovered clock after the saturated SOA. The amplitude variation is effectively suppressed. After the saturated SOA, optical clock pulses with an FWHM of 40 ps can be obtained. As shown in Fig. 2(c), the radio-frequency (RF) spectra of the recovered clocks, measured by an RF spectrum analyzer with a 3-MHz resolution bandwidth, confirm that the limiting amplification in the SOA enhances the recovered clock's sidelobe suppression ratio by 7 dB to approximately 21 dB. Fig. 3 shows the single-sideband phase noise spectra (10 kHz$\sim$100 MHz) of the recovered clock signals for input PRBS sequences 2^7-1, $2^{15}-1$, $2^{23}-1$ and $2^{31}-1$. By integrating the single-sideband phase noise spectra (20 kHz to 80 MHz), we derived the upper-bound values for the timing jitter of the recovered clocks [4]. The estimated maximum root mean square (rms) jitter values are: 0.19, 0.22, 0.34, and 0.34 ps for PRBS sequences 2^7-1, $2^{15}-1$, $2^{23}-1$ and $2^{31}-1$, respectively. In addition to the large sidelobe suppression ratio and small rms jitter values, an additional requirement on the all-optical clock recovery module for optical burst and packet switching networks is a short lock-in time that enables burst-mode clock recovery of bursty incoming signals with rapid clock-phase jumps. Fig. 4 shows the response of the FPF followed by the saturated SOA to packetized input. Both the packet and the guard-time lengths are 25.6 ns/256-bit and the packet is encoded with PRBS pattern 2^7-1. The recovered clock pulses rise from 10% to 90% of the peak amplitude within 9 bits duration (900 ps) that indicates its potential application in 10-Gb/s burst-mode clock recovery. Note that due to the fact that this clock recovery technique is based on pulse-reflection inside the FPF cavity [5], the clock lock-in time can be longer if long sequences of repeated zeros occur at the beginning of the input packets.

III. Experimental Setup and Results

Fig. 5 shows the experimental setup with a 125-km fiber recirculation loop. The bit-error-rate tester (BERT) produces 10-Gb/s $2^{23}-1$ long PRBS sequences. The two $LiNbO_3$ modulators in cascaded configuration generate the 10-Gb/s optical RZ signal at 1552.5 nm. The fiber recirculation loop consists of two fiber spans with a total length of 125-km (65 + 60 km) large effective area fiber (LEAF) [$D = +3.6$ ps/(nm $\cdot$ km)]. The signal launch power into each LEAF fiber span is 5.4 dBm. To offset the self-phase-modulation effect which induces negative chirp in the signal, the chromatic dispersion of the LEAF fibers is compensated 90.4% instead of 100% by introducing 4-km-long dispersion-compensating fibers (DCF) with the dispersion parameter $D = -101$ ps/(nm $\cdot$ km). The optical 3R regenerator consists of two optical 2R stages and one retiming stage with synchronous modulation. Each 2R stage consists of an SOA-MZI operating in differential mode with 35-ps delay between the two arms, and it translates the signal from 1552.5

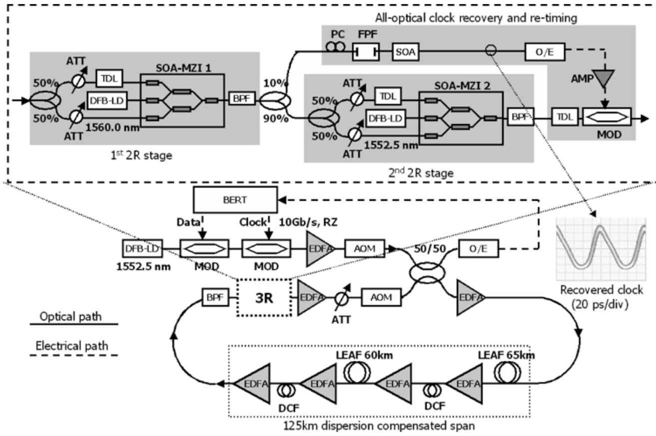

Fig. 5. Experimental setup for evaluating the optical 3R regenerator in a 125-km fiber recirculation loop. DFB-LD: DFB laser diode. Mod: $LiNbO_3$ optical modulator. AOM: Acoustic optical modulator. O/E: O/E converter. DCF: Dispersion-compensating fiber. BPF: Bandpass filter. ATT: Variable attenuator. TDL: Tunable delay line. PC: Polarization controller. AMP: RF amplifier.

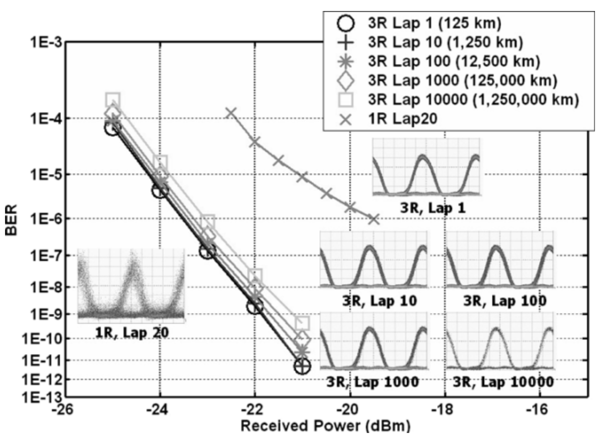

Fig. 6. BER measurement results and eye-diagram evolution for transmission distance from 125 to 1 250 000 km with 3R regeneration and 2500-km transmission with 1R regeneration.

to 1560.0 nm in the first stage, and *vice versa* in the second stage, to maintain the same wavelength (1552.5 nm) in the fiber loop. The first 2R stage removes polarization variations from fiber transmission and provides a signal with a fixed polarization state to the polarization-sensitive FPF through the polarization controller. The FPF and the saturated SOA all-optically recover the clock. The recovered optical clock drives an optical-to-electrical (O/E) converter and an RF amplifier (AMP) that supplies synchronous modulation clock to the $LiNbO_3$ modulator for retiming. This configuration delineates the reshaping and the retiming functions and simplifies 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. 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 insets of Fig. 6 show the eye-diagram evolution. The eye diagrams remain almost unchanged through Lap 1 to Lap 10 000 (125~1 250 000-km transmission) and clear eye openings can be observed throughout 1~10 000 loops. As a comparison, the eye diagram of the signal that goes through 20 fiber loops without 3R regeneration (1R by erbium-doped fiber amplifier (EDFA) only) becomes noisy. Fig. 6 also plots the bit-error rate (BER) of 10-Gb/s signal at Lap 1, 10, 100, 1000, and 10 000 versus received optical power. There is less than 0.7-dB power penalty at 10^{-9} for transmission over 1 250 000 (Lap 10 000) relative to 125 km (Lap 1). The BER of signal after 1 250 000-km transmission is 4.23×10^{-10} at a received power of -21 dBm. It is worth noting that the measurement duration to obtain enough bits for measuring certain BER increases proportionally with the loop numbers, this constrains the BER measurements for a large number of loops. To benchmark the effectiveness of the 3R regeneration, Fig. 6 shows that the BER curves of the signal passing through 20 loops (2500 km) without 3R (1R only) has an error floor around 10^{-6}. The experimental results prove that the all-optical clock recovery module is very stable and the optical 3R regenerator built with it can be cascaded up to 10 000 stages.

IV. Summary

We achieved 10-Gb/s RZ transmission over a record distance of 1.25 million kilometers (10 000 loops) using in-line all-optical 3R regeneration that incorporated all-optical clock recovery with an FPF and a saturated SOA. The proposed optical 3R technique successfully circumvented the polarization sensitivity of the FPF and achieved a stable operation. The all-optical clock recovery worked effectively at 10 Gb/s for PRBS sequences of length up to $2^{31} - 1$ and only required a very short lock-in time (~900 ps). BER performance evaluation using PRBS $2^{23} - 1$ showed that the power penalty between 1 250 000- (Lap 10 000) and 125-km (Lap 1) transmission was less than 0.7 dB for a BER of 10^{-9}.

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