EDFA-Free All-Optical 2R Regeneration Using a Compact Self-Seeded Fabry–Pérot Laser Diode

Hung-Chang Chien, Chien-Chung Lee, and Sien Chi

***Abstract*—This study presents an erbium-doped fiber amplifier (EDFA)-free all-optical 2R (reamplification and reshaping) regeneration scheme based on a compact self-seeded Fabry–Pérot laser diode. The proposed 2R regenerator achieves a straight line transmission at 10 Gb/s over 76 km without either the EDFA or the external probe laser, both of which are traditionally required. Additionally, device characteristics such as data-rate transparency, input dynamic range, amplified gain, and 2R regeneration performance are investigated experimentally.**

***Index Terms*—Fabry–Pérot (FP), reamplification and reshaping (2R) regeneration.**

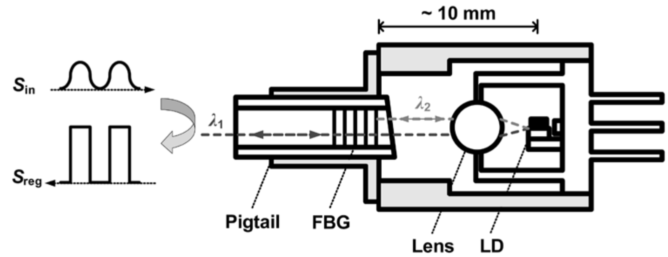

Fig. 1. Schematic diagram of the proposed compact SSFP-LD.

I. INTRODUCTION

ALL-OPTICAL 2R (reamplification and reshaping) regeneration, which can restore the signal degradation caused by the combined effects of noise accumulation, fiber dispersion, and nonlinearities, is a highly promising technique for future all-optical networks. Several techniques, including a sidemode injection-locked semiconductor laser [1]–[3] and a two-mode injection-locked Fabry–Pérot laser diode (FP-LD) [4]–[6], have recently been reported. Although the two-mode injection-locked method has significantly better reshaping and relaxation frequency performances than the one-sidemode scheme, it also has a higher device cost and complexity due to the introduction of an external probe laser. In addition, extra optical amplifiers, such as the erbium-doped fiber amplifier (EDFA), are needed to reamplify the signal and to compensate the loss of reshaping. In this letter, we propose and demonstrate a new and cost-effective technique to simultaneously execute all-optical 2R regeneration without the need for optical amplifiers by using a compact self-seeded FP-LD (SSFP-LD) with an embedded fiber Bragg grating (FBG).

II. DEVICE CHARACTERISTIC AND OPERATION PRINCIPLE

Fig. 1 illustrates a schematic diagram of the proposed SSFP-LD. An FBG is directly integrated into a 2.5-GHz commercial FP-LD without an optical isolator to form a ~10-nm-long feedback cavity. This FBG has a 70% reflectivity at central wavelength of 1550.8 nm, a bandwidth of 0.25 nm, and a grating length of 1 cm. In the absence of the injected signal, the FP-LD, which is self-seeded and stable-locked by the reflection tone at wavelength λ_2 generated by the FBG, has a single-longitudinal-mode operation. When a degraded signal S_{in} at wavelength λ_1, which has a power exceeding the injection-locking threshold, is injected into this SSFP-LD, the FP-LD is injection-locked and begins to operate at λ_1 with a constant power. The induced red-shift of the FP mode comb would lead to a wavelength misalignment between the reflectivity maximum of the FBG and the closest FP longitudinal mode, and helps to quench the self-seeded tone. The injection-locking mechanism is characterized by an ON–OFF threshold that can be exploited to reduce and compress the noise over the zeros and ones. In addition, the regeneratively amplified gain of injected signal S_{in} is limited by the spectral profile of the FP-LD. A positive gain of input signal can be achieved by arranging the signal wavelength in the main-peak mode area and the self-seeded tone far from the main-peak mode.

III. EXPERIMENTAL SETUPS

Fig. 2 indicates experimental setups for 10-Gb/s all-optical transmissions with the proposed 2R regenerator (block A) and a conventional EDFA module (reamplification (1R) device, block B). To provide an EDFA-free transmission, an SSFP-LD, which can provide 8.3-dB gain at 1560.12 nm, was placed between two 38-km standard single-mode fiber spans. A signal at 1560.12 nm, generated from a tunable laser, was externally modulated by an electrooptic modulator with $2^{31}-1$ pseudorandom binary sequence (PRBS) data stream at 10 Gb/s. The modulated signal propagated through the first 38-km fiber span, and then was injected into the SSFP-LD via an optical circulator and a polarization controller. The SSFP-LD was biased at 4.6 times its threshold current (10 mA) and had its temperature controlled at 17.35∘C to generate a self-seeded tone at 1551 nm with a sidemode suppression ratio (SMSR)

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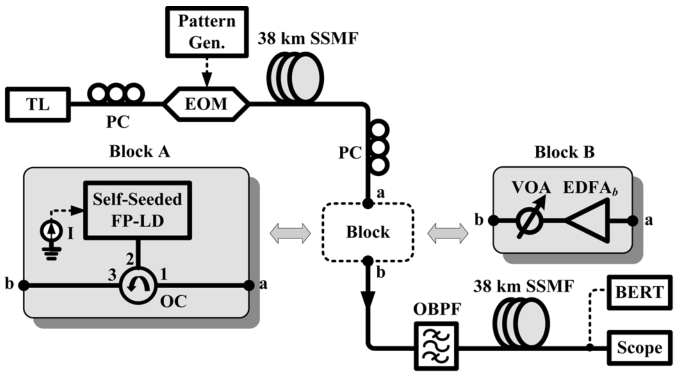

Fig. 2. Experimental setup for the proposed 10-Gb/s all-optical 2R regenerator in the transmission link.

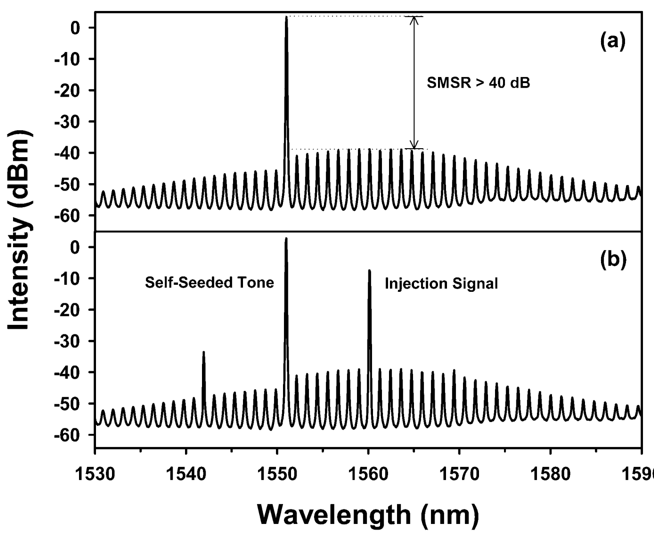

Fig. 3. Measured optical spectra of the SSFP-LD (a) without and (b) with the 10-Gb/s injection signal.

larger than 40 dB. After filtering out by a bandpass filter (BPF) with a 3-dB bandwidth of 0.8 nm, the regenerated signal was propagated through another 38-km fiber span, and transmitted to an optical receiver to investigate the bit-error-rate (BER) performance and the eye diagram. Average input powers of around −8 dBm were set at two 38-km spans to avoid or decrease the nonlinear effects such as self-phase modulation of fiber and four-wave mixing (FWM) of SSFP-LD.

IV. Results and Discussion

Fig. 3(a) and (b) illustrates the optical spectra of the SSFP-LD without and with the injection signal, respectively. As shown in Fig. 3(a), the free-running SSFP-LD have a 1551-nm self-seed tone with SMSR over 40 dB. In Fig. 3(b), when a 1560.12-nm degraded signal at 10 Gb/s was injected, the beating between the injection signal and the self-seeded tone led to two FWM tones at 1541.94 and 1569.42 nm, respectively. However, such redundant components can be eliminated by an optical BPF before being transmitted to the next span. Fig. 4 shows the testing results of data-rate transparency up to 10 GHz. The noisy signals at bit rates of 155 MHz, 2.5 GHz, and 10 GHz were input into the proposed 2R regenerator, and the outputs with clear eye diagrams come out. The data-rate transparency of the proposed

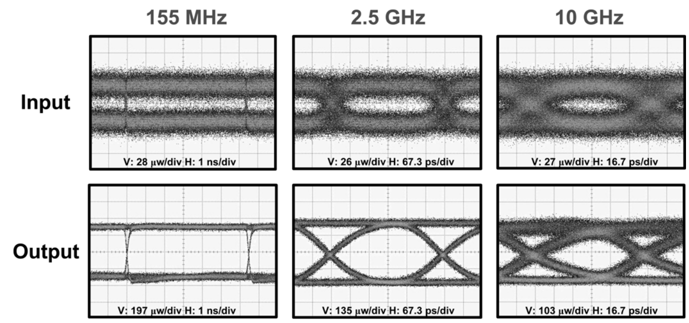

Fig. 4. Data-rate transparency up to 10 GHz of the proposed 2R regenerator.

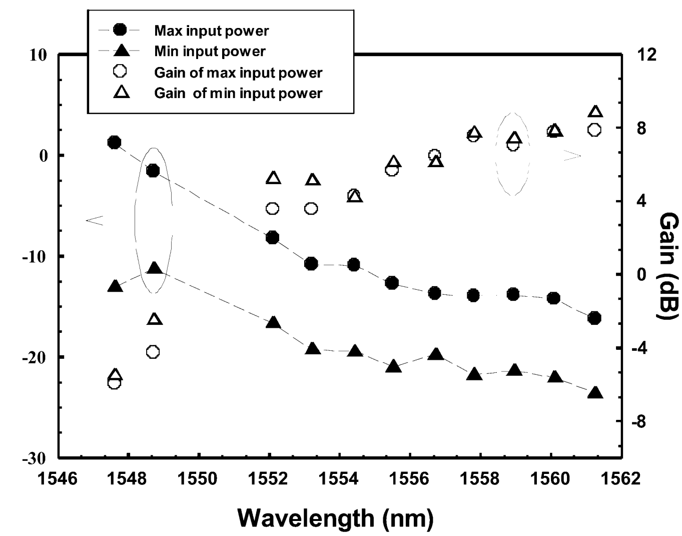

Fig. 5. Dynamic range and gain of the injection signal for the proposed SSFP-LD as a function of operating wavelengths.

scheme has been successfully proven. Fig. 5 depicts the dynamic range and amplified gain of the injection signal for the proposed SSFP-LD as a function of the operating wavelengths to achieve successful waveform reshaping. Clearly, a higher signal gain and lower injection power level can be obtained if the operating wavelength approaches the free-running main mode of the FP-LD (∼1562 nm). Fig. 6 shows the 10-Gb/s BER performance of the proposed 2R regenerator and the 1R EDFA module in the setup of Fig. 2. The insets show the measured eye diagrams of the signal: (a) 2R-regenerated at 38 km; (b) 1R-regenerated at 38 km; (c) after 76-km propagation with 2R regeneration; and (d) after 76-km propagation with 1R regeneration. By using the proposed method, the power penalties, compared with the back-to-back case, were 0.65 and 0.9 dB after transmission over 38 and 76 km, respectively, at BER $= 10^{-9}$. However, the 1R-only transmission has larger power penalties of 1.5 and 3.4 dB after transmitting over 38 and 76 km, respectively, at BER $= 10^{-9}$. To optimize the regenerated signal, the average injection power into the FP-LD was kept at −14.58 dBm, and the degraded signal was injected at the wavelength which is located within one of the FP modes and has a slight detuning of +0.04 nm from the central wavelength of this mode. As a result, by using this proposed SSFP-LD, a distorted signal was successfully reamplified and reshaped, and the eye diagram was still wide open after 76-km propagation without the assistance of an

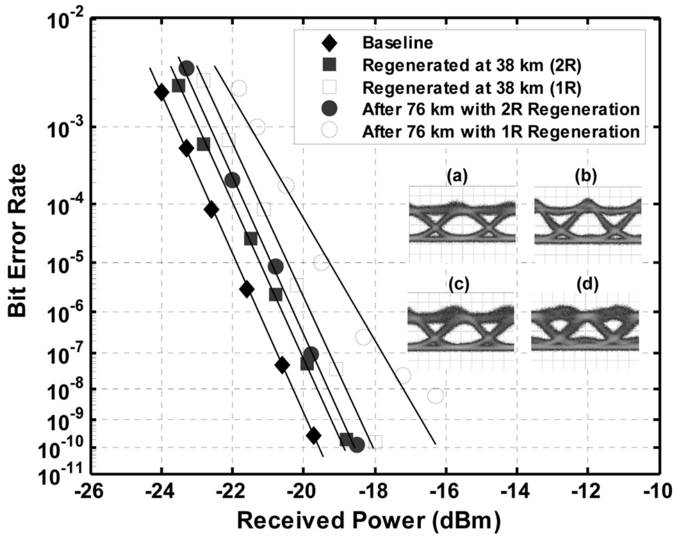

Fig. 6. BER performances and eye diagrams of the proposed 2R and 1R regenerations at 10 Gb/s in a transmission link, respectively.

EDFA. On the contrary, the signal in 1R-only transmission was seriously distorted due to the accumulation of chromatic dispersion.

V. Conclusion

This work demonstrates the feasibility of an EDFA-free and all-optical 2R regeneration by using a compact SSFP-LD with an ultrashort feedback cavity of ~10 mm. The experiments reveal that external probe lasers and additional EDFAs for the traditional two-mode injection locked scheme are not required when utilizing the proposed approach. This self-seeding method is promising for the future applications on high-speed all-optical 2R regeneration.

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