An All-Optical 2R Regenerator Using a Compact Self-Seeded Fabry–Pérot Laser Diode Incorporated in a Bidirectional EDFA

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

***Abstract*—An all-optical 2R regenerator, based on a compact self-seeded Fabry–Pérot laser diode with a 10-mm-long embedded fiber Bragg grating cavity, and a bidirectional erbium-doped fiber amplifier, is proposed and experimentally demonstrated to execute all-optical 2R regeneration at 10 Gb/s. Compared with the conventional 1R regeneration, the proposed scheme has achieved significant 6.4-dB improvement of power penalty at bit-error ratio $= 10^{-9}$ in the transmission experiment over 100-km standard single-mode fiber.**

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

I. Introduction

ALL-OPTICAL 2R regeneration (reamplification and reshaping) plays an important role in future all-optical networks due to its outstanding ability for the high-speed restoration of signals degraded by the noise accumulation, fiber dispersion, and nonlinearities. All-optical 2R regeneration based on a sidemode injection-locked semiconductor laser has been analyzed [1]–[3]. These studies show that the operating bit rate has a limitation caused by the carrier-induced relaxation oscillation frequency. Recently, several research studies [4]–[6] using a two-sidemode injection-locked Fabry–Pérot laser diode (FP-LD) to execute 10-Gb/s all-optical 2R regeneration have been presented. The relaxation oscillation frequency was dramatically increased by introducing an external probe laser in this method. However, an extra probe laser is needed for this scheme. In addition, a stronger injection power for a stable two-sidemode injection locking and a high output level for fiber-link loss compensation will require two erbium-doped fiber amplifiers (EDFAs) placed at input and output sides of the FP-LD. Therefore, this study proposes and demonstrates a new and cost-effective 10-Gb/s all-optical 2R regenerator by using a compact self-seeded FP-LD incorporated in a bidirectional EDFA.

Manuscript received November 21, 2005; revised April 5, 2006. This work was supported in part by the National Science Council (NSC) of R.O.C. under Grant NSC 94-2752-E009-009-PAE, Grant NSC 94-2215-E-115-001, and Grant NSC 94-2215-E-115-003.

H.-C. Chien and C.-C. Lee are with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 300, R.O.C. (e-mail: money.eo91g@nctu.edu.tw; cdlee@cable-vision.com.tw).

S. Chi is with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 300, R.O.C., and also with the Department of Electrical Engineering, Yuan Ze University, Chung-Li, Taiwan 320, R.O.C. (e-mail: schi@mail.nctu.edu.tw).

Digital Object Identifier 10.1109/LPT.2006.877010

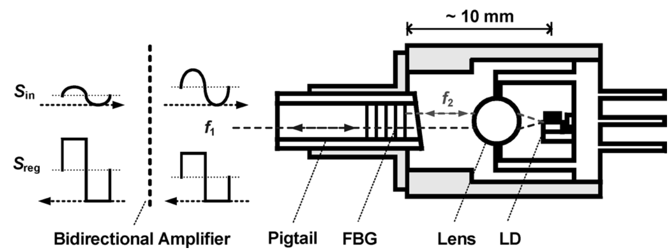

Fig. 1. Schematic diagram of the proposed 2R regenerator.

II. Device Description and Operating Principle

Fig. 1 illustrates the schematic diagram of this proposed 2R regenerator. A compact self-seeded Fabry–Pérot laser diode (SSFP-LD), which is composed of a 2.5-GHz commercial FP-LD without output isolator, and a integrated fiber Bragg grating (FBG), is combined with a bidirectional EDFA to form the new 2R regenerator. To achieve higher modulation bandwidth and lower polarization effect, the external feedback cavity of less than 10 mm is used. In addition, an EDFA with short erbium-doped fiber (EDF) is placed in front of this SSFP-LD to provide adequate bidirectional amplification for both the injected and reshaped signals. The operating principle is based on the ON–OFF thresholding nature of an injection-locked SSFP-LD to compress the accumulated noise over the zeros and ones. In the beginning, the SSFP-LD, stable-locked by the FBG-reflected light, has single-longitudinal-mode operation at frequency f_2. Then a distorted signal $S_{\rm in}$ at frequency f_1 is injected. When the amplified power level of $S_{\rm in}$ exceeds the injection-locking threshold, a sufficient locking bandwidth can be obtained to cover f_1, and the induced red shift of the FP mode comb would also help to quench the self-seeded tone at frequency f_2. Thus, at this moment, the SSFP-LD is stable-locked at f_1 with a constant output power. After passing through the amplified SSFP-LD and filtered out by an optical bandpass filter (OBPF), a wavelength-preserved and 2R-regenerated signal $S_{\rm reg}$ can be obtained.

III. Experimental Setup

Fig. 2 illustrates the setups of transmission experiments for the proposed all-optical 2R (Block A) and the traditional amplifier modules (1R, Block B). The proposed 2R regenerator, comprising an optical circulator, a 3-m EDF with absorption of 4.5 – 5.5 dB/m at 980 nm, a 980/1550-nm wavelength-division multiplexer, a 980-nm pump laser operated at 14.6 mW, and an SSFP-LD, was placed between two 50-km standard single-

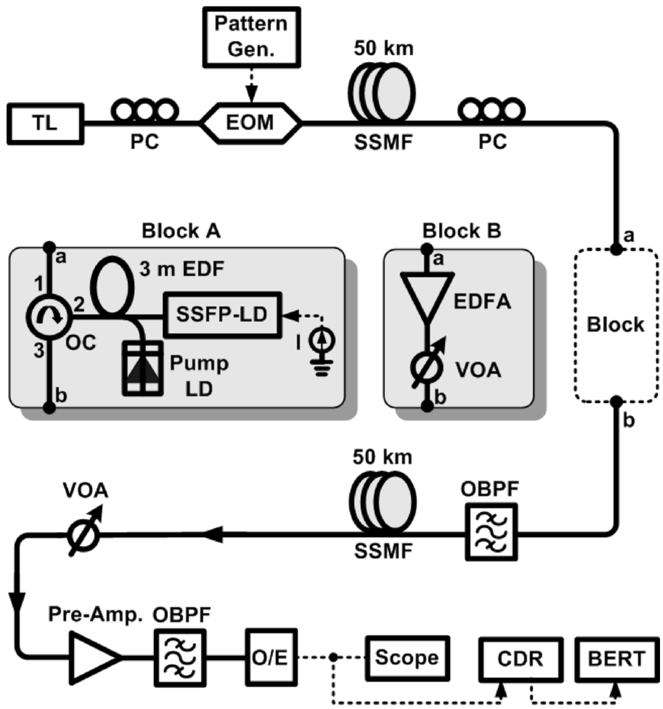

Fig. 2. Experimental setups for the proposed all-optical 2R (Block A) and the traditional 1R modules (Block B).

mode fiber (SSMF) spans. This SSFP-LD, composed of a commercial 2.5-GHz FP-LD and an embedded FBG, was biased at 4.28 times its threshold current and controlled at 16.67 °C to emit a self-seeded tone at 1550.76 nm with a sidemode suppression ratio larger than 40 dB. The embedded FBG has a central wavelength of 1550.68 nm, a grating reflectivity of 70%, and a bandwidth of 0.2 nm. A tunable laser was externally modulated via an electrooptic modulator with a $2^{31}-1$ psuedorandom binary sequence data format to generate a 10-Gb/s testing signal at 1555.32 nm. Such a signal was transmitted over the first fiber span of 50 km, and then was injected into Block A or B through a polarization controller. The transmission performance at 50 km can be measured right after Point b. To measure the performance of 100-km transmission, the regenerated signal, after being filtered out by an OBPF with the 3-dB bandwidth of 0.8 nm, was propagated through another 50-km fiber span and into a receiving module. This module includes a variable optical attenuator, an optical preamplifier, an OBPF, and an optical-to-electrical module. A 20-Gb/s digital scope for eye diagram measurement or a bit-error-ratio (BER) tester with a clock and data receiver for BER measurement is utilized after this receiving module. To prevent causing fiber nonlinearity, the average powers at each input port of 50-km spans were set at -8 dBm.

IV. Results and Discussion

Fig. 3 shows the output spectra of the proposed 2R regenerator when the testing signal is injected. As shown in Fig. 3, the injected signal of 1555.32 nm is located in the fourth longitudinal mode counting from the self-seeded tone in the long wavelength direction. In order to optimize the regenerated signal, the average injection power into the proposed 2R regenerator is kept

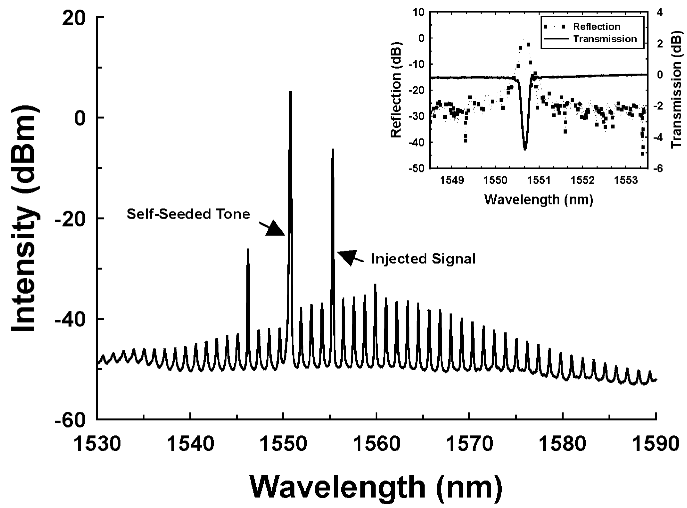

Fig. 3. Output spectra of the proposed 2R regenerator when a testing signal is injected. The inset is the optical spectra of the embedded FBG for the reflection and transmission.

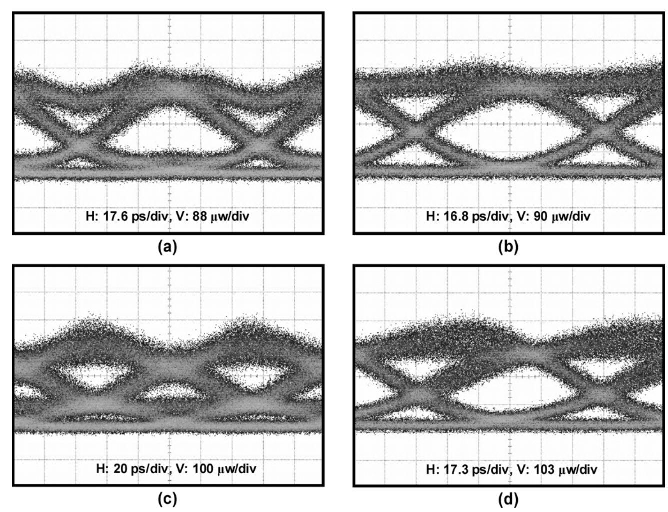

Fig. 4. Received eye diagrams of the 10-Gb/s testing signal for (a) 1R regenerated at 50 km, (b) 2R regenerated at 50 km, (c) 100-km propagation with 1R regeneration at 50 km, and (d) 100-km propagation with 2R regeneration at 50 km.

at -18.2 dBm with a slight wavelength detuning of $+0.03$ nm from the central frequency of targeted mode. The input power dynamic range of the proposed 2R regenerator ranges between -16.2 and -21.8 dBm, and the total signal gain provided by this proposed 2R module is about 10.2 dB. Moreover, two four-wave mixing tones generated by the injected signal and the self-seeded tone are observed in Fig. 3. The inset in Fig. 3 indicates the optical spectra of the embedded FBG for reflection and transmission. Fig. 4 illustrates the received eye diagrams at 10 Gb/s using proposed 2R and traditional 1R regenerations for 50- and 100-km fiber link transmissions. As shown in Fig. 4, the proposed 2R regeneration can provide a wide-opened eye after 100-km propagation, while the signal using 1R-only regeneration was seriously distorted by the accumulated chromatic dispersion over 100-km transmission. In addition, the measured input and output optical signal-to-noise ratio of the proposed 2R regenerator are 22.64 and 35.41 dB/0.1 nm, respectively. Fig. 5 shows the BER performances of the proposed 2R regenerator

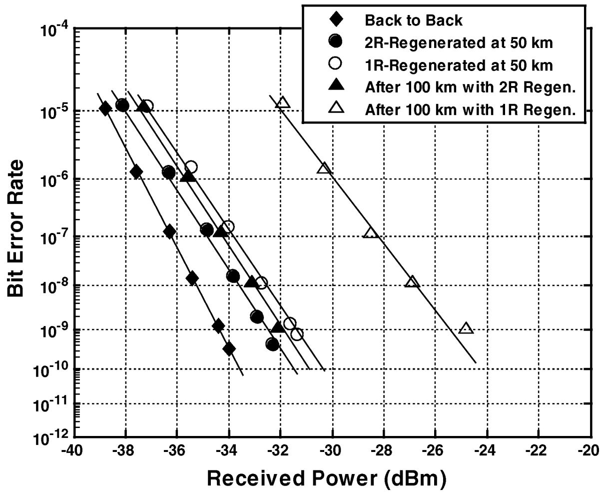

Fig. 5. BER performances of the proposed 2R regenerator and the conventional 1R module for 50- and 100-km fiber transmissions.

and the conventional 1R module for 50- and 100-km fiber transmissions. For the proposed 2R regenerator, the power penalties of BER $= 10^{-9}$, referring to the back-to-back case, are 1.9 and 2.5 dB after 50- and 100-km transmissions, respectively. However, larger power penalties of 3 and 8.9 dB are observed for 1R-only regeneration after transmitting over 50 and 100 km. Therefore, compared with conventional 1R regeneration, this proposed 2R regeneration can obtain 6.4-dB improvement of power penalty at BER $= 10^{-9}$ for 100-km SSMF propagation.

V. Conclusion

This work proposes and experimentally demonstrates a new and economic 10-Gb/s all-optical 2R regenerator consisting of a compact SSFP-LD with an ultrashort feedback cavity of $\sim$10 mm, and a bidirectional EDFA. The BER performances of using the proposed scheme, compared with the one of 1R-only regeneration, can be significantly improved. The elimination of external probe laser and utilization of a bidirectional EDFA can highly simplify the all-optical 2R regeneration. This method is promising on the applications of future optical networks.

Acknowledgment

The authors would like to thank C.-T. Lin for LD packaging.

References

[1] Y. Hong and K. A. Shore, "Locking characteristics of a side-mode injected semiconductor laser," *IEEE J. Quantum Electron.*, vol. 35, no. 11, pp. 1713–1717, Nov. 1999.

[2] A. Kuramoto and S. Yamashita, "All-optical regeneration using a side-mode injection-locked semiconductor laser," *IEEE J. Sel. Topics Quantum Electron.*, vol. 9, no. 5, pp. 1283–1287, Sep./Oct. 2003.

[3] J. M. Luo and M. Osinski, "Stable-locking bandwidth in sidemode injection locked semiconductor lasers," *Electron. Lett.*, vol. 27, no. 19, pp. 1737–1738, 1991.

[4] J. Hörer and E. Patzak, "Large-signal analysis of all-optical wavelength conversion using two-mode injection-locking in semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 33, no. 4, pp. 596–608, Apr. 1997.

[5] L. Xu, W. H. Chung, L. Y. Chan, L. F. K. Lui, P. K. A. Wai, and H. Y. Tam, "Simultaneous all-optical waveform reshaping of two 10-Gb/s signals using a single injection-locked Fabry–Pérot laser diode," *IEEE Photon. Technol. Lett.*, vol. 16, no. 6, pp. 1537–1539, Jun. 2004.

[6] S. Yamashita and J. Suzuki, "All-optical 2R regeneration using a two-mode injection-locked Fabry–Pérot laser diode," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1176–1178, Apr. 2004.