All-Optical 2R Regeneration Based on a Compact Self-Seeded Fabry–Pérot Laser Diode With an Embedded Fiber Bragg Grating

Hung-Chang Chien, Chien-Chung Lee, Yu-Min Chen, Kai-Ming Feng, and Sien Chi

***Abstract*—A cost-effective method, based on the injection-locking technique of a compact self-seeded Fabry–Pérot laser diode with a 10-mm-long embedded fiber Bragg grating cavity, is proposed and experimentally compared with the two-mode injection-locked scheme for all-optical 2R regeneration at 10 Gb/s. Placing the presented all-optical 2R regenerator after a 50-km fiber significantly improves the transmission performance of a signal over 50- and 100-km fiber links. The power penalties at BER $= 10^{-9}$ are similar to those of the two-mode injection-locked scheme.**

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

I. Introduction

ALL-OPTICAL regeneration, a highly promising technology for all-optical networks, can restore signals degraded by the combined effects of noise accumulation, fiber dispersion, and fiber nonlinearities. The injection-locked semiconductor laser has attracted much attention as a 2R device with reamplification and regeneration capabilities [1], [2]. Additionally, all-optical 2R regeneration based on a sidemode injection-locked semiconductor laser has been analyzed. The relaxation oscillation frequency [3], [4] and injection-locking bandwidth [3], [5] can be enhanced by a stronger injected power required for a stable sidemode injection due to an increased threshold gain deficit, but they remain insufficient to meet the current needs of high-speed regeneration. All-optical 2R regeneration at 10 Gb/s, using a two-mode injection-locked Fabry–Pérot laser diode (FP-LD), has been recently presented [6]–[8]: An external probe laser was introduced to suppress the effect of relaxation oscillation. However, the complexity will increase for the two-mode injection-locked method. Therefore, this study demonstrates a new and economical technique for executing all-optical 2R regeneration at 10 Gb/s using a compact self-seeded FP-LD with an embedded fiber Bragg grating (FBG).

Manuscript received August 2, 2005; revised November 2, 2005. This work was supported in part by the National Science Council (NSC) of R.O.C. under Grant NSC 93-2752-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).

Y.-M. Chen and K.-M. Feng are with the Institute of Communications Engineering, National Tsing-Hua University, HsinChu, Taiwan 300, R.O.C. (e-mail: g925915@oz.nthu.edu.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.2005.863994

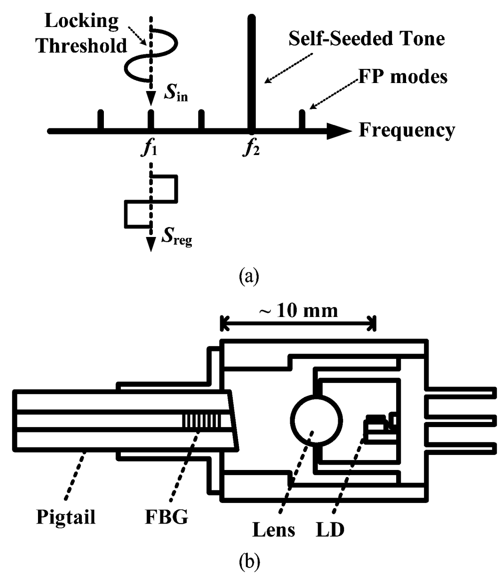

Fig. 1. (a) Principle of the proposed 2R regeneration. (b) Schematic diagram of the proposed self-seeded FP-LD.

II. Operating Principle

Fig. 1(a) depicts the operating principle of the proposed waveform reshaping scheme, which is based on the injection-locking technique using a self-seeded FP-LD. In the absence of the injected signal, the FP-LD is stable-locked by the self-seeded tone generated by the FBG cavity, and has a single-longitudinal-mode operation at frequency f_2. When an injected signal S_{in} at frequency f_1 has a power that exceeds the injection-locking threshold, which produces enough locking bandwidth to cover f_1, the FP-LD is injection-locked and begins to operate at f_1 with a constant power. The induced red-shift of the FP mode comb would lead to a frequency misalignment between the reflectivity maximum of the FBG and the closest FP longitudinal mode and help 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. The schematic diagram of the proposed self-seeded FP-LD is illustrated in Fig. 1(b). To achieve higher modulation bandwidth and lower polarization effect, a short FBG cavity length is needed. A

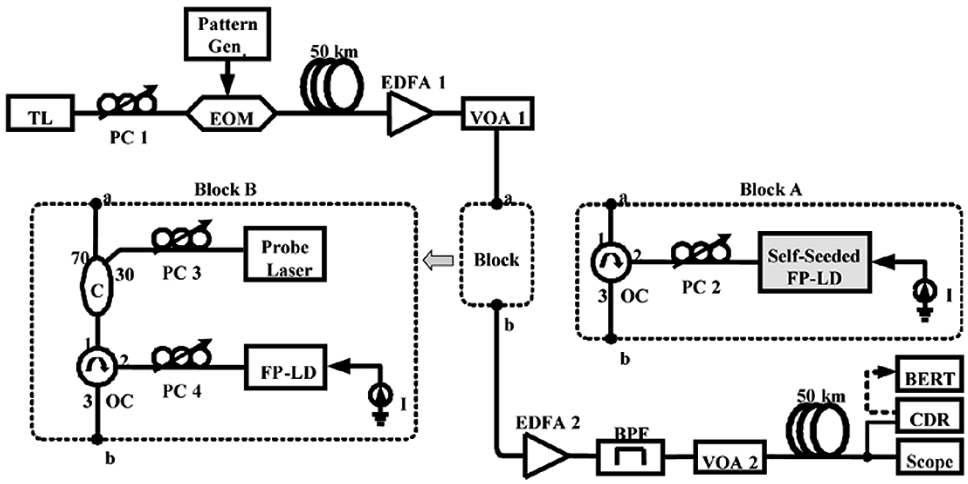

Fig. 2. Experimental setups for all-optical waveform regeneration of a distorted signal at 10 Gb/s.

2.5-GHz commercial high-power FP-LD without an output isolator is employed. An FBG is directly integrated into an FP-LD with a ~10-mm-long feedback cavity.

III. Experimental Setup

Fig. 2 displays the experimental setup for this proposed all-optical 2R regeneration at 10 Gb/s (with Block A). A self-seeded FP-LD for all-optical waveform reshaping was placed between two 50-km standard single-mode fiber (Corning SMF-28) spans. A 1548.39-nm transmission signal, generated from a tunable laser, was externally modulated by an electrooptic modulator with a $2^{31} - 1$ pseudorandom binary sequence data stream at 10 Gb/s. The modulated signal was propagated through the first 50-km fiber span, and was then injected into the self-seeded FP-LD via an optical circulator (OC) and a polarization controller (PC). The self-seeded FP-LD was biased at 3.14 times the threshold current and the temperature was controlled at 19.76 to generate a self-seeded tone at 1546.26 nm with a sidemode suppression ratio larger than 30 dB. Moreover, an FBG with a central wavelength of 1546.1 nm, a grating reflection of 9 dB, and a bandwidth of 0.2 nm, was packaged inside the FP-LD. After filtered out by a bandpass filter (BPF) with a 3-dB bandwidth of 0.8 nm, the regenerated signal was propagated through another 50-km fiber span and transmitted to a clock and data receiver to generate electrical clock and data for performance evaluation in a bit-error-ratio tester. A variable optical attenuator (VOA1) was used to adjust the input signal power at FP-LD, and VOA2 was employed to set the average powers at each input port of 50-km spans to 1 dBm to prevent fiber nonlinearity. Moreover, the functional Block B represents the all-optical waveform regenerator for the two-mode injection-locked method [6], [7]. In this case, a 1547.08-nm external probe laser with 0-dBm power and a 1549.28-nm transmission signal with -1.7-dBm average power were injected into the FP-LD via a 70 : 30 coupler, an OC and PCs for all-optical reshaping.

IV. Results and Discussion

Fig. 3(a) and (b) shows the optical spectra of the self-seeded FP-LD without and with the injection signal at 10 Gb/s, respectively. As shown in Fig. 3(b), a 1548.39-nm injection signal results in gain competition with the self-seeded tone at 1546.24 nm, and induces two four-wave mixing (FWM) tones. Such FWM tones can be negligible since they will be filtered out by the optical BPF. The inset is the optical reflection and transmission spectra of the FBG. Fig. 4 illustrates the received eye diagrams at 10 Gb/s with and without 2R regeneration. The average injection power into the FP-LD was kept at 1.3 dBm, and the distorted signal was injected at a frequency in one of the FP modes with a slight detuning of $+0.05$ nm from the central frequency in this mode. As a result, with regeneration, the eye diagram was still wide open after 100-km propagation, while the signal without regeneration was seriously distorted by the accumulation of chromatic dispersion. Fig. 5 shows the bit-error-rate (BER) performance of the proposed (P) scheme

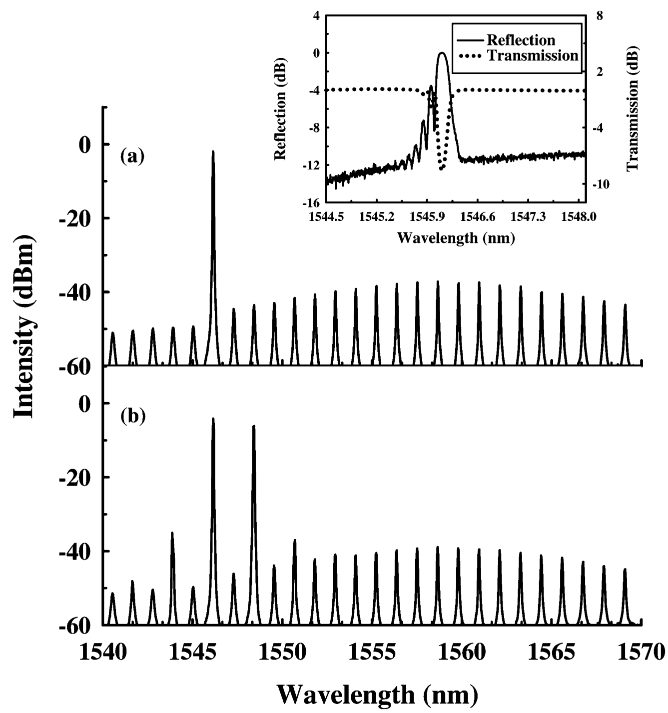

Fig. 3. Measured optical spectra of the self-seeded FP-LD (a) without and (b) with the injection signal at 10 Gb/s.

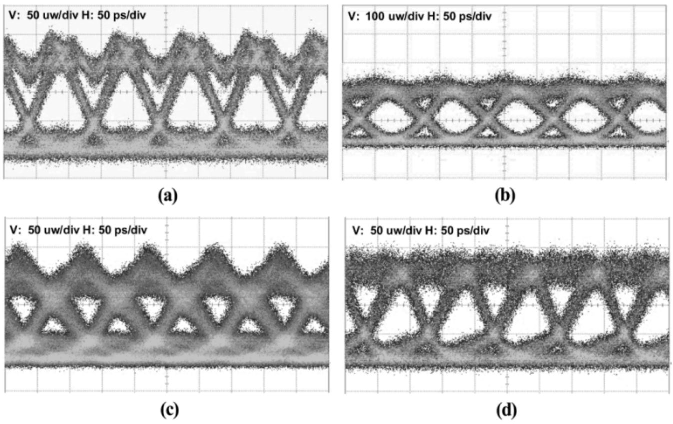

Fig. 4. Measured eye diagrams of the signal (a) after 50-km propagation without regeneration, (b) regenerated at 50 km, (c) after 100-km propagation without regeneration, and (d) after 100-km propagation with regeneration.

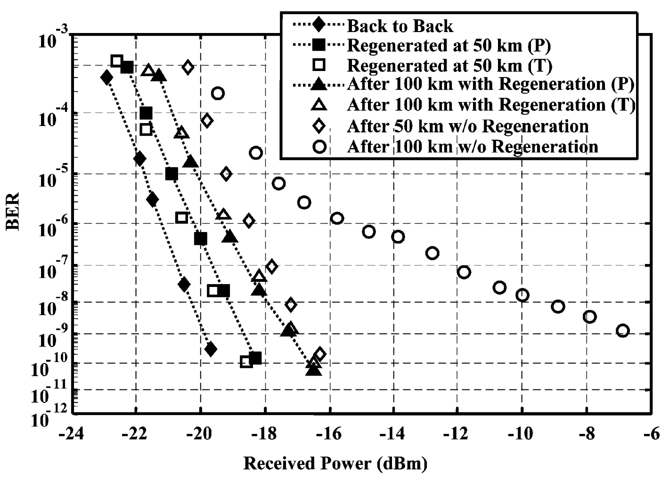

Fig. 5. BER performances with, and without the proposed (P) and the two-mode injection-locked (T) regeneration schemes, respectively.

and that of the two-mode injection-locked (T) method. The BER performance without using optical regenerators is also indicated in Fig. 5. For a fair comparison, the same FP-LD without an embedded FBG was employed as the slave laser and was driven under the same condition. When the proposed method was used, the power penalties, compared with the back-to-back case, are 1.3 and 2.5 dB after transmission over 50 and 100 km, respectively, at BER $= 10^{-9}$. Futhermore, with the two-mode injection-locked scheme, the power penalties are 1.1 and 2.6 dB after transmission over 50 and 100 km, respectively, at BER $= 10^{-9}$.

V. Conclusion

This work presents and experimentally demonstrates the feasibility of 10-Gb/s all-optical 2R regeneration via the injection-locking of a compact self-seeded FP-LD with an ultrashort feedback cavity of ~10 mm. In our experiments, it is proven that, by using the proposed self-seeded method, the BER performances can compete with those of the traditional two-mode injection-locked scheme. This self-seeded method is promising for the future applications in high-speed all-optical waveform reshaping.

References

[1] R. Lang, "Injection locking properties of a semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-18, no. 6, pp. 976–983, Jun. 1982.
[2] K. Weich, E. Patzak, and J. Hörer, "Fast all-optical switching using two-section injection-locked semiconductor lasers," *Electron. Lett.*, vol. 30, pp. 493–494, 1994.
[3] 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.
[4] 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.
[5] 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.
[6] 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.
[7] 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.
[8] 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.