Journal of the Optical Society of Korea, Vol. 10, No. 1, March 2006, pp. 11-15

All-optical Regenerator Using Semi-reflective Semiconductor Optical Amplifier

T. Y. Kim*, J. Y. Kim, and S. K. Han

Department of Electrical & Electronic Engineering Yonsei University Shinchon-dong,
Seodaemoon-ku Seoul 120-749, KOREA

(Received February 10, 2006 : revised March 3, 2006)

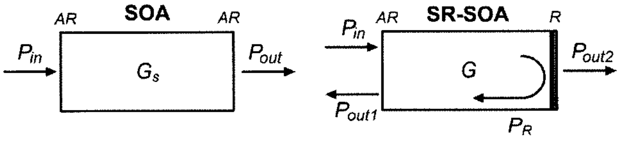
We have proposed and theoretically verified an optical regenerator using a single semi-reflective semiconductor optical amplifier (SR-SOA). To explain the operation characteristics and the operation condition of the proposed opticalregenerator, the simplified gain model for the SR-SOA is introduced and confirmed by comparing the result of the SOA simulation based on the transfer matrix method (TMM). The simulation results show that both extinction ratio (ER) enhancement and signal amplification can be achieved in the proposed regenerator.

OCIS codes : 060.4510, 250.5980, 230.4320, 230.3120, 000.4430

I. INTRODUCTION

In large-scale optical networks, all-optical regeneration will be one of the key techniques to suppress signal degradation induced by accumulation of noise and dispersion. Recently, several types of optical regenerator based on a semiconductor optical amplifier (SOA) have been proposed. Most of them use Mach-Zehnder interferometer (MZI) or Michelson interferometer (MI) structure with two SOAs [1,2,6]. In the optical regenerator based on MZI or MI structure, two SOAs should be controlled differently to satisfy the phase and amplitude condition of the interferometer.

In this letter, we propose a novel optical regenerator using a single SR-SOA which is an ideal reflective SOA (RSOA) with 2nd output port at the semi-reflection facet as shown in Fig. 1 (b). Due to the difference of pass length for amplification, the two output signals of SR-SOA experience different gain. By using this gain characteristic of the SR-SOA, we embody the optical regenerator with the interferometer structure like MZI or MI applying two SOAs. In the proposed scheme, we have achieved the high ER enhancement, signal amplification and negative chirp of the output signal. To explain the gain characteristics of the SR-SOA and the operation principles of the proposed regenerator, we represent a simplified gain model of the SR-SOA. Also, for the high speed operation, the adaptation of the CW holding beam is suggested.



(a) conventional SOA (b) SR-SOA

FIG. 1. Schematic diagram of SOAs.

II. SIMPLIFIED GAIN MODEL OF THE SR-SOA

Fig. 1 (a) shows the schematic diagram of a conventional SOA. The simplest gain model of a conventional SOA which explains the gain saturation phenomenon is given by [3]

$$G = \frac{P_{out}}{P_{in}} = \frac{G_0}{1 + P_{in}/P_{out}} \tag{1}$$

where G_0 is the unsaturated gain, P_{in} is the total input power, P_{out} is the output power, and P_{sat} is the saturation power, defined as that power at which gain reduces to half of G_0. Because the single pass gain of the SOA is equal in both directions at the steady-state, the signals in SR-SOA shown in Fig. 1 (b) can be expressed as

$$P_{in,total} = P_{in} + P_R = P_{in} + G_s R P_{in} = (1 + G_s R) P_{in} \tag{2}$$

$$G_s = \frac{G_{0,s}}{1 + P_{in,total}/P_{sat,s}} = \frac{G_{0,s}}{1 + (1 + G_s R) P_{in}/P_{sat,s}} \tag{3}$$

Where G_s is the single-pass gain of SR-SOA, $G_{0,s}$ is the unsaturated single-pass gain, P_{in} is the input power incident on anti-reflection (AR) coated facet of the SR-SOA, P_{out1} is the output power emitted from the AR coated facet, P_{out2} is the output power emitted from the far-facet which has non-zero reflectivity of R. Solving the Eq. (3) about single-pass gain G_s

$$G_s = \frac{-(P_{sat,s}+P_{in})+\sqrt{(P_{sat,s}+P_{in})^2+4RG_{0,s}P_{sat,s}P_{in}}}{2RP_{in}} \tag{4}$$

By using Eq. (4), two outputs of the SR-SOA can be expressed as the following simple equations.

$$P_{out1} = RG_s^2P_{in},\ P_{out2} = (1-R)G_sP_{in} \tag{5}$$

To confirm the validity of the proposed gain model, we compared the proposed gain model with the simulation result of the SOA based on TMM. The detailed simulation method and the physical parameters of the SOA used in our simulation are represented in [4,5]. Fig. 2 shows the gain characteristics of the conventional SOA and SR-SOA. The length of the SOA is 600 um and the injected bias current is 35 mA. Its reflectivity is -10 dB. Through TMM-based simulation of the conventional SOA, we obtain the values of $P_{sat,s}$ and $G_{0,s}$ used in Eq. (1) and (5). As shown in Fig. 2, the gain values obtained from the proposed gain model agree well with those from TMM-based simulation results. Due to the simplicity of Eq. (1), the proposed gain model exhibits a little error at high input power which occurs at high gain saturation of the SR-SOA. But high input power is rarely used in an optical regenerator, therefore this error can be ignored. This gain model can be simply applied to predict the gain of the RSOA.

III. PRINCIPLES OF THE PROPOSED OPTICAL REGENERATOR

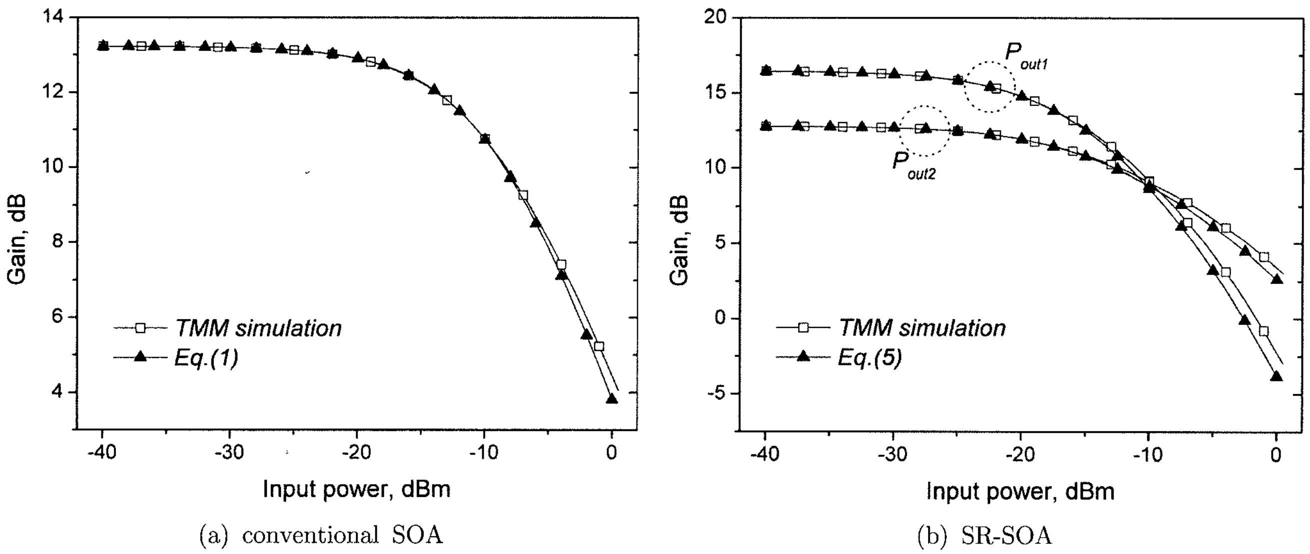
Two outputs of the SR-SOA have different gain characteristics (double-pass gain for P_{out1} and single-pass gain for P_{out2}) and can be modified as a function of G_s and R as represented in Eqs. (4), (5). It means that we can control the outputs of the SR-SOA similarly to the outputs of the two differently controlled SOAs used in previous SOA-based optical regenerator structures. By utilizing this characteristic of SR-SOA, we propose the novel optical regenerator. Fig. 3 shows the schematic diagram of the proposed optical regenerator. Each output of the SR-SOA is combined at the output port to configure interferometic structure. The optical phase shifter is used to optimize phase condition of the interferometer. By adjusting the single-pass gain or the reflectivity of the far-facet of the SR-SOA to satisfy Eq. (6) (it means P_{out1} and P_{out2} are equal in the unsaturated gain region), we can obtain the gain and phase difference curves which were utilized in the general optical decision circuit design [6].

$$\frac{P_{out1}}{P_{out2}} = \frac{R}{1-R}G_s \cong \frac{R}{1-R}G_{0,s} = 1 \tag{6}$$

Assuming the pass lengths of P_{out1} and P_{out2} are equal at the output port of the regenerator, the phase difference between P_{out1} and P_{out2} can be obtained from

$$\Delta phase = -\frac{1}{2}\alpha gL = -\frac{1}{2}\alpha \log G_s \tag{7}$$

where α is the linewidth enhancement factor, g is the modal gain of the SR-SOA, L is the length of the



(a) conventional SOA

(b) SR-SOA

FIG. 2. Gain characteristics of conventional SOA and SR-SOA. Proposed gain model is compared with TMM- based simulation result.

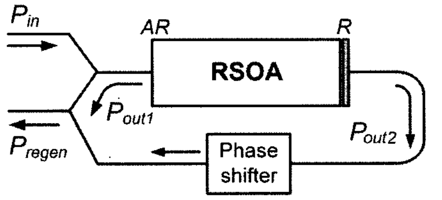


FIG. 3. Schematic diagram of proposed optical regenerator.

SR-SOA. To operate as regenerator, the phase shifter in the proposed regenerator should be tuned to satisfy the destructive interference condition for P_{out1} and P_{out2} in the unsaturated gain region. At this phase condition, increased input power enhances the construction interference of P_{out1} and P_{out2} and results in increased output power. The required amount of phase shift can be calculated by unsaturated single pass gain $G_{0,s}$

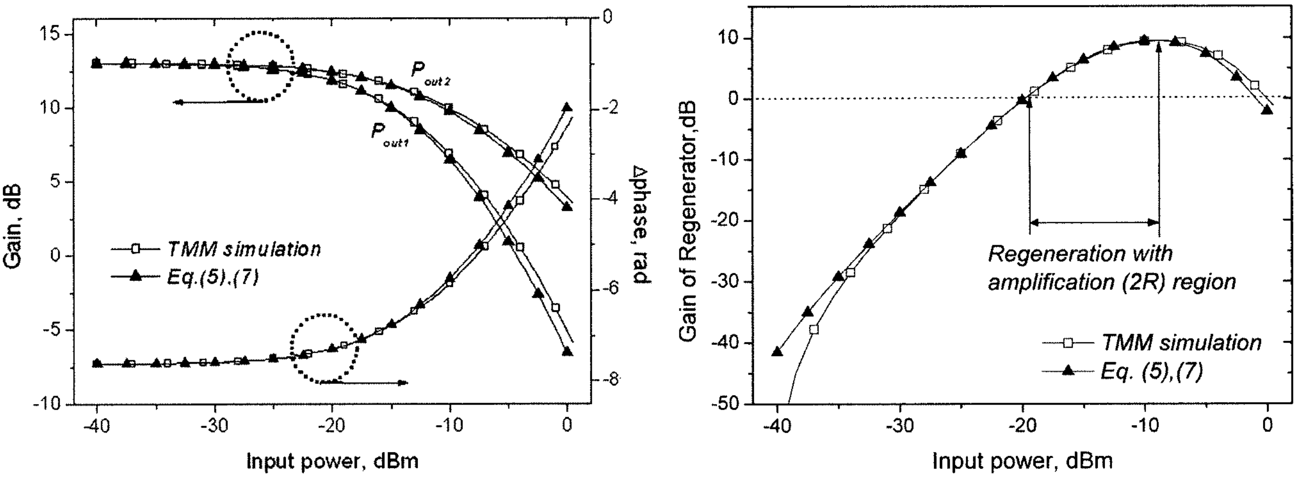
$$\begin{aligned} \mathit{Phase\ shift} + \Delta \mathit{phase} &= \mathit{Phase\ shift} - \frac{1}{2}\alpha \log G_{0,s} \\ &= (2n+1)\pi \end{aligned} \qquad (8)$$

where n is integer. Fig. 4 (a) shows the gain and phase difference between P_{out1} and P_{out2} versus input power. The parameters used in modeling are same as parameters used in Fig. 2 except for reflectivity. To match the amplitude condition of the regenerator simply, we adjust the reflectivity to -13.43 dB. In a real device with fixed reflectivity, controlling bias current to change the single-pass gain is preferred. The gain of regenerator versus input power is shown in Fig. 4 (b). When input power is below -20 dBm, only ER enhancement is expected. But when input power is -20 dBm~-9 dBm, the regenerator output signal attains the positive gain with regeneration. Fig. 5 shows performance of the proposed regenerator at the bit rates of 622-Mbps. ER enhancement of 6.5 dB, gain of about 6 dB and the negative chirp are observed.

To satisfy the amplitude condition of the regenerator represented in Eq. (6), the reflectivity of the SR-SOA constrains the gain of the SR-SOA. The reasonable values of reflectivity require a small gain of the SR-SOA. As shown in Fig. 5, the operation of the SR-SOA at low bias current limits the phase modulation speed which determines output pulse shape of the regenerator.

IV. HIGH SPEED OPERATION OF THE REGENERATOR

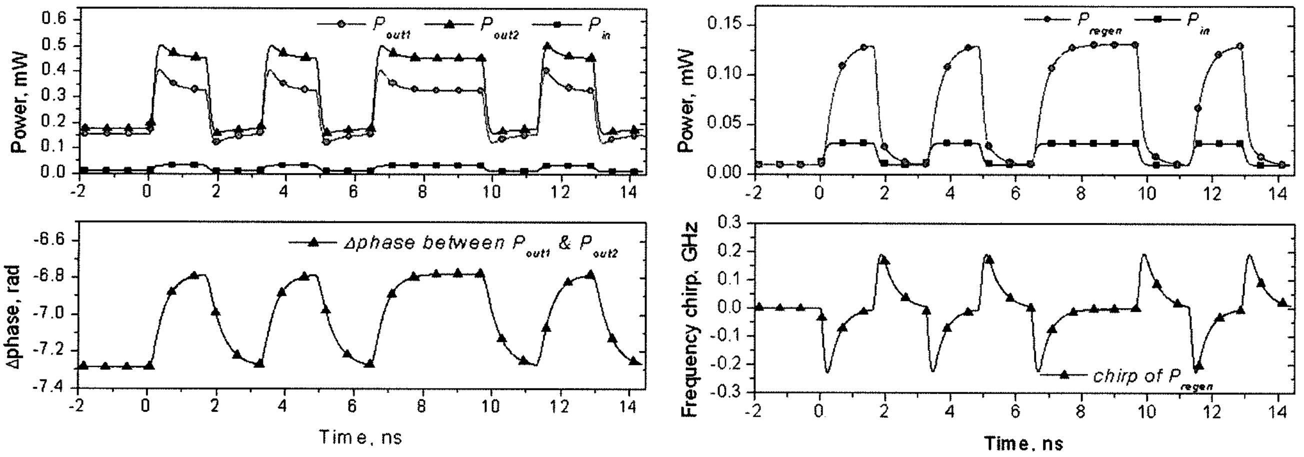
In order to increase operation speed of the SR-SOA in the proposed regenerator while maintaining small gain, we simulated the use of CW holding beam among many speed-up techniques for SOA [7]. Fig. 6 (a) shows the gain characteristics curve of the regenerator with bias current of 65 mA and the reflectivity of -15.45 dB. A CW holding beam of -3 dBm was used at 1530 nm. We choose the bias current and reflectivity of the SR-SOA and power of the CW holding beam considering the amplitude condition of the regenerator. Under the influence of the CW holding beam, 2R (reshaping and reamplification) region is shifted to higher input power compared to the regenerator without CW holding beam as shown Fig. 4 (b). The input and output pulses of regenerator and frequency chirp at 2.5-Gbps are shown in Fig. 6 (b). ER enhancement of 5 dB, about 5 dB gain and the negative chirp are observed. Because the use of CW holding needs additional optical source and optical filter, it makes the structure of the regenerator complex. Modifying internal structure of the SR-SOA like that of the gain-clamped SOA or linear optical



(a) Gain and phase of SR-SOA

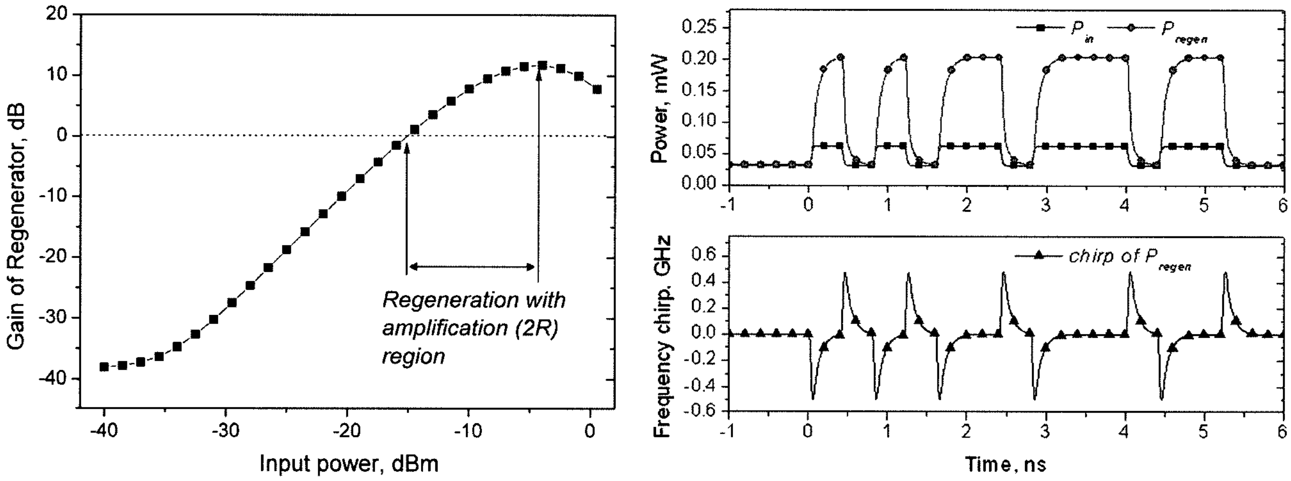
(b) Output gain of the proposed regenerator

FIG. 4. Characteristics of proposed regenerator. Assumed bias current and reflectivity are 35mA and -13.43dB, respectively.



(a) Output pulses of SR-SOA and phase difference (b) Input and output pulse of the proposed regenerator and frequency chirp

FIG. 5. Performance of the proposed regenerator at 622Mbps.



(a) Output gain of proposed regenerator (b) Input and output pulse of the proposed regenerator and frequency chirp

FIG. 6. Performance of the proposed regenerator with CW holding beam at 2.5Gbps.

amplifier (LOA) will be recommended for high speed operation of the regenerator without CW holding beam.

V. CONCLUSION

We have proposed and theoretically verified the optical regenerator using single SR-SOA. The simplified gain model for the SR-SOA is represented to explain its operation characteristics and to derive the amplitude and phase conditions of the regenerator. The validity of the proposed gain model was confirmed by comparing the result of TMM-based SOA simulation. The simulation results of proposed regenerator show that ER enhancement and signal amplification can be achieved simultaneously in the proposed scheme. We show that high-speed regeneration is possible in the proposed regenerator with a SOA speed-up method using CW-holding beam.

Proposed simplified gain model of SR-SOA will be useful of intuitive understanding of gain characteristics of SR-SOA and RSOA. Although some limitation of operation speed remains, the proposed simple regenerator can be applied to enhance the performance of SOA based optical devices like wavelength converter in the form of co-integration.

*Corresponding author : reborn@yonsei.ac.kr

REFERENCES

[1] D. Wolfson, P. B. Hansen, A. Kloch, and K. E. Stubkjaer, "All-optical 2R regeneration based on interferometric

structure incorporating semiconductor optical amplifiers," *Electron. Lett.*, vol. 35, no. 1, pp. 59-60, 1999.

[2] J. De Merlier, G. Morthier, P. Van Daele, I. Moerman, and R. Baets, "All-optical 2R regeneration based on integrated asymmetric mach-zehnder interferometer incorporating MMI-SOA," *Electron. Lett.*, vol. 38, no. 5, pp. 238-239, 2002.

[3] S. I. Pegg, M. J. Fice, M. J. Adams, and A. Hadjifotiou, "Noise in wavelength conversion by Cross-Gain Modulation in a semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 11, no. 6, pp. 724-726, 1999.

[4] H. L. Lee, H. J. Yoon, Y. G. Kim, and J. C. Jeong, "Theoretical study of frequency chirping and extinction ratio of wavelength-converted optical signals by XGM and XPM using SOA's," *IEEE J Quantum Electron.*, vol. 35, no. 8, pp. 1213-1219, 1999.

[5] Y. S. Jeon, J. M. Kang, T. Y. Kim, S. K. Han, and S. Lee, "Investigation of input power dynamic range enhancement of a cross-phase modulation wavelength converter by pre-amplification," *Microwave Opt. Technol. Lett.*, vol. 36, no. 2, pp. 131-134, 2003.

[6] G. Morthier, J. Sun, T. Gyselings, and R. Baet, "A novel optical decision circuit based on a mach-zehnder or michelson interferometer and gain-clamped semiconductor optical amplifiers," *IEEE Photon. Technol. Lett.*, vol. 10, no. 8, pp. 1162-1164, 1998.

[7] K. I. Chung, T. Y. Kim, and S. K. Han, "Analysis of all optical cascaded XGM wavelength converter using CW-holding beam," *Optical and Quantum Electron.*, vol. 34, no. 10, pp. 937-950, 2002.