Waveform Restoration in Semiconductor Optical Amplifier Using Fiber Loop Mirror

Kit Chan, Chun-Kit Chan, Wai Hung, Frank Tong, and Lian Kuan Chen

***Abstract*—In this letter, we present a simple and effective interferometric approach for waveform restoration in semiconductor optical amplifier (SOA) using a fiber loop mirror. Pattern-dependent distortion caused by gain dynamics of SOA can be compensated. With our scheme, enhanced input power dynamic range of 7 dB was achieved. For data sequence with different pattern lengths, both significant waveform and extinction ratio improvement were obtained.**

***Index Terms*—Inline amplifier, gain saturation, semiconductor optical amplifier.**

I. Introduction

THE SEMICONDUCTOR optical amplifier (SOA) has recently attracted much interest because of its wide application for inline optical amplification. Its attractive features, including broad gain bandwidth, compactness, and potentially low cost, make it a promising device for future lightwave networks. However, when the SOA is operated in saturation regime, its fast gain dynamics causes pattern dependent distortion, in such a way that the amplifier gain greatly varies with the waveform of the input signal. The amplified signal waveform suffers from severe distortion, and thus greatly hinders the deployment of SOA in real-life systems. Different schemes have been proposed to suppress such waveform distortion, including light injection [1], shifting the output wavelength [2], and gain clamping [3], yet these schemes had their own limitations in terms of complexity, gain consumption, and signal bit rate.

In [4], an interferometric approach was proposed to alleviate such waveform distortion in which the SOA was placed at one arm of a Mach–Zehnder interferometer (MZI). The 2-dB improvement in input power dynamic range was demonstrated using commercial integrated MZI with SOA (MZI-SOA). In this letter, we present an alternative interferometric approach using a fiber loop mirror, which not only has the advantage of simplicity and easy integration, but also is very effective in suppressing the excessive waveform distortion and thus greatly improves the input power dynamic range. In our experimental demonstration, we achieved 7.5-dB enhancement in input power dynamic range in 10-Gb/s single-wavelength signal amplification.

Manuscript received January 29, 2002; revised March 4, 2002.

K. Chan, C.-K. Chan, W. Hung, F. Tong, and L. K. Chen are with the Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China (e-mail: kchan0@ie.cuhk.edu.hk).

Publisher Item Identifier S 1041-1135(02)04608-6.

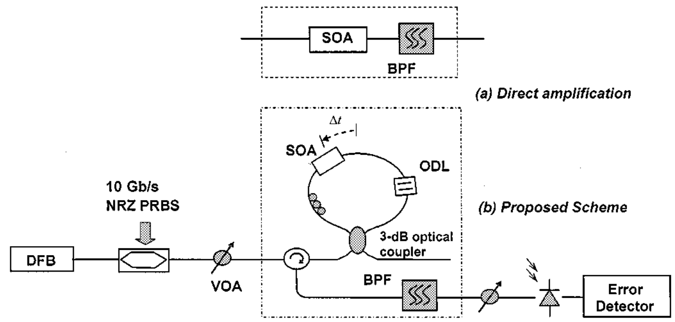

Fig. 1. Experiment setup. OVA: Optical variable attenuator. SOA: Semiconductor optical amplifier. ODL: Optical delay line. BPF: Optical bandpass filter.

II. Scheme and Principle

For an SOA operating in saturation regime, the decrease in carrier density results in gain suppression. The leading edge of each input nonreturn-to-zero (NRZ) pulse experiences relatively much larger gain than the other part of the pulse, thus intense spikes are resulted at the leading edges of the amplified signal. The output signal waveform is severely distorted. In addition, the signal extinction ratio is also degraded as a zero-bit experiences a much higher gain than a one bit. Concurrently, due to the fact that the output phase of the signal is dependent on the signal gain in the SOA, the difference in gain at the signal pulse's leading edge from the rest part of the pulse also results in respective phase difference [5]. In our proposed scheme, we make use of this relative phase difference phenomenon to suppress those intense spikes at the pulses' leading edges and to improve the signal extinction ratio by placing the SOA asymmetrically in a simple fiber loop mirror, as shown in Fig. 1. The input NRZ optical signal is equally split into clockwise (CW) and counterclockwise (CCW) propagating signals in the fiber loop mirror. When each of them passes through the SOA and combines again at the 3-dB coupler, interference between these two counterpropagating signals occurs. The overall signal gain, $G_{\text{overall}}(t)$, obtained at the reflected port of the fiber loop mirror can be generally written as [6], [7]

$$G_{\text{overall}}(t) = \frac{1}{4}(G_{\text{CCW}}(t) + G_{\text{CW}}(t)) + \frac{1}{2}\sqrt{G_{\text{CCW}}(t)G_{\text{CW}}(t)}\cos(\Delta\phi(t)) \quad (1)$$

$$\Delta\phi(t) = \frac{\alpha}{2}\ln\left(\frac{G_{\text{CW}}(t)}{G_{\text{CCW}}(t)}\right) \quad (2)$$

where $G_{\text{CCW}}(t)$ and $G_{\text{CW}}(t)$ are the signal gains in CCW and CW propagating signals, respectively; α is the linewidth confinement factor and $\Delta\phi(t)$ is the time-dependent phase difference between the CW and CCW propagating signals after they have returned to the 3-dB coupler of the fiber loop mirror. Suppose the SOA is placed with an offset to the left with a temporal delay of Δt from the center of the fiber loop, the CW propagating signal reaches the SOA at Δt earlier than the CCW propagating signal. Thus the leading edges of pulses in the former experience a small-signal gain (G_o), whereas that of the latter experience the saturated gain (G_S) with $G_o \gg G_S$. Therefore, the value of $\Delta\phi$ is large at the leading edges of the pulses as G_{CW}(leading edge) $\approx G_o$ and G_{CCW}(leading edge) $\approx G_S$. For the temporal region of the pulses other than the leading edges, both counterpropagating signals experience about the same saturated gain, that is $G_{\mathrm{CCW}} \approx G_S$, thus the induced $\Delta\phi$ between them is very small. When these two signals interfere at the 3-dB coupler, destructive interference takes place at the leading edges because of the existence of significant phase difference $\Delta\phi$ and this suppresses the overall gain at the leading edges. In contrast, constructive interference takes place over the temporal region other than the leading edges. As a result, at the reflected port of the fiber loop mirror, those intense spikes at the leading edges of the pulse stream are largely suppressed. Based on the same principle, the extinction ratio can also be enhanced as result of suppression of over-amplified zero bits. Thus, waveform distortion is alleviated.

III. Experiment

The experimental setup is shown in Fig. 1. Light from the DFB laser was modulated by a $LiNbO_3$ modulator using 10-Gb/s $2^{23}-1$ NRZ pseudorandom binary sequence (PRBS) data sequence. A variable optical attenuator (VOA) was used to control the transmitted optical power. The SOA was put in a fiber loop mirror with a temporal offset of Δt from the fiber loop center. In the experiment, we achieved this temporal adjustment by means of the optical tunable delay line (ODL). The reflected signal output from the fiber loop mirror was directed out via an optical circulator (OC). To filter out the amplified spontaneous emission (ASE) from the SOA, an optical bandpass filter (OBPF) was used before the receiver. For comparison, a direct amplification experiment was also performed as shown in Fig. 1(a). In the case of fiber loop mirror configuration, the input signal power was defined as the optical power sum of the two counterpropagating input signals entering the SOA. To ensure the input signal power used for both cases were identical, the optical power at the input of the fiber loop mirror was adjusted to be 4 dB higher than that in the direct amplification case, owing to the excessive insertion losses resulted from double passing the optical circulator and the 3-dB coupler.

Fig. 2 shows the waveforms of the amplified pulse train from the SOA for (a) direct amplification case and (b) our proposed scheme using fiber loop mirror for an optical input power of -12 dBm. Owing to gain saturation, it was found that the leading edges of ones experienced higher gain than the rest part of the optical pulses. Since the single bit duration was much larger than the carrier lifetime of the SOA, the SOA gain had enough time to be partially resumed, thus the zeros had higher gain than the ones, which resulted in significant extinction ratio degradation. In Fig. 2(b), with the help of the fiber loop mirror, the waveform was much improved as the over-amplified leading edges of ones were clamped by the destructive interference between two counterpropagating signals at the 3-dB coupler. Significant improvement in signal's extinction ratio was also observed, as the signal gain for zeros was suppressed.

We also measured the SOA input power dynamic range (IPDR) for both cases and the results were depicted in Fig. 3. The receiver sensitivity was obtained at a bit-error rate (BER)

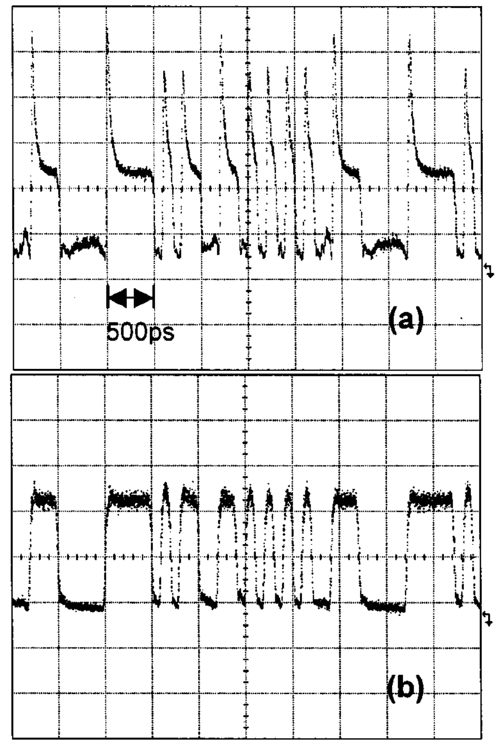

Fig. 2. Optical waveform with -12-dBm input signal power for (a) direct amplification and (b) proposed scheme using fiber loop mirror.

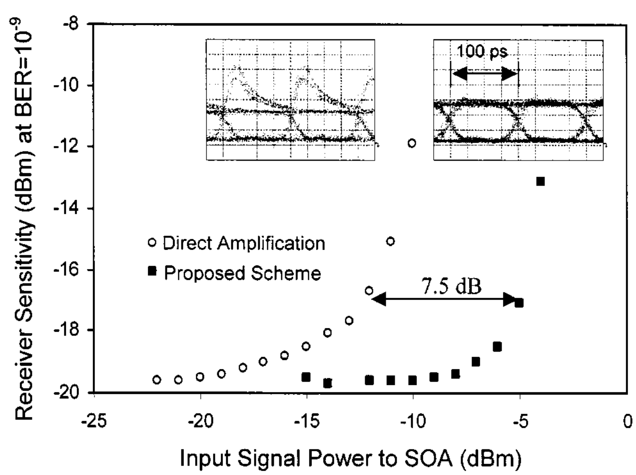

Fig. 3. Receiver sensitivity at BER of 10^{-9} as a function of input signal power for 10-Gb/s signal amplification. Insets show the respective eye diagrams for direct SOA amplification and SOA in a fiber loop mirror when input signal power is -12 dBm.

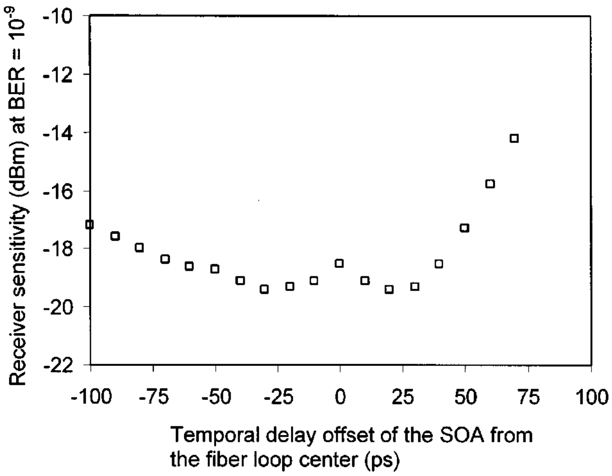

Fig. 4. Receiver sensitivity at BER of 10^{-9} as a function of temporal delay offset of the SOA from the fiber loop center for 10-Gb/s signal amplification.

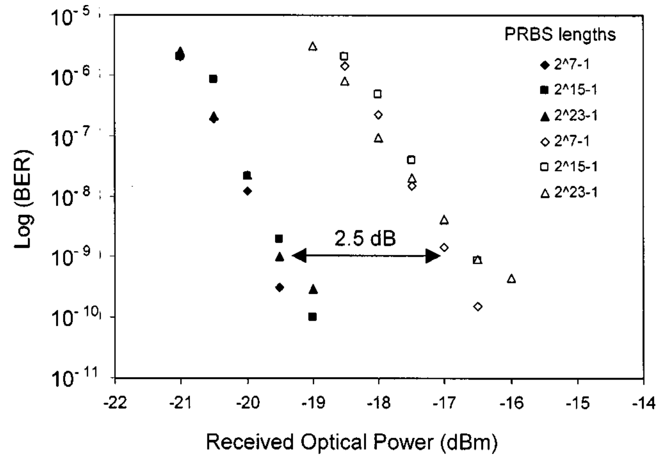

Fig. 5. Bit error rate (BER) measurement of 10-Gb/s PBRS with lengths of $2^7-1, 2^{15}-1$ and $2^{23}-1$. Solid symbols: Proposed scheme using SOA in fiber loop mirror. Open symbols: Direct SOA amplification.

of 10^{-9} against different input signal powers. For the case of direct amplification, the rapid increase in the power penalty was attributed to the distorted waveform and degraded extinction ratio due to gain saturation. It was shown that our proposed scheme has extended the input power dynamic range by more than 7 dB, at a power penalty of 3 dB. The eye diagrams in the insets were captured at an input signal power of -12 dBm.

Fig. 4 shows the measured receiver sensitivity at a BER of 10^{-9} for different temporal delays introduced by the optical delay line. As the fiber loop mirror was structurally a symmetric device, there exhibited two local minima at 25 ps and -25 ps, which basically corresponded to the temporal offset of SOA's location from the center on either side of the fiber loop. These symmetric values were related, in principle, to the finite SOA's gain recovery time and the rise time of the leading edge of the pulse stream.

Fig. 5 shows the BER performance in both direct amplification and our proposed waveform restoration scheme. It is clearly shown that, for several PRBS lengths of $2^7-1, 2^{15}-1$ and $2^{23}-1$, about 2.5-dB reduction in power penalty was achieved by using our proposed scheme. Moreover, the data points (for PRBS lengths of $2^{15}-1$ and $2^{23}-1$) in the case of direct amplification clearly exhibited error floors at low BER values, demonstrating the pattern-dependent distortion in a conventional SOA. Correspondingly, such error floors were alleviated in the case of using our proposed scheme. This proved that our scheme effectively suppressed the pattern-dependent distortion in SOA.

IV. Summary

A simple and effective interferometric approach for pulse waveform restoration in SOA was proposed and demonstrated. By placing the SOA in a simple fiber loop mirror configuration, significant improvement in both waveform and extinction ratio were achieved. Experimental results showed that the input power dynamic range of SOA was improved by over 7 dB and the pattern dependent distortion in SOA was also suppressed.

References

[1] K. P. Ho, S. K. Liaw, and C. Lin, "Reduction of semiconductor laser amplifier induced distortion and crosstalk for WDM system using light injection," *Electron. Lett.*, vol. 32, pp. 2210–2211, 1996.

[2] J. Yu and P. Jeppesen, "Increasing input power dynamic range of SOA by shifting the transparent wavelength of tunable optical filter," *J. Lightwave Technol.*, vol. 19, pp. 1316–1326, Sept. 2001.

[3] L. F. Tiemeijer, P. J. A. Thijs, and T. V. Dongen *et al.*, "Reduced intermodulation distortion in 1300 nm gain-clamped MQW laser amplifier," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 284–286, May 1995.

[4] Q. Xu, M. Yao, and Y. Dong *et al.*, "Experimental demonstration of pattern effect compensation using an asymmetrical Mach-Zehnder interferometer with SOAs," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 1325–1327, Dec. 2001.

[5] G. P. Agrawal and N. A. Olsson, "Self-phase modulation and spectral broadening of optical pulses in semiconductor optical amplifiers," *IEEE J. Quantum Electron.*, vol. 25, pp. 2297–2306, Nov. 1989.

[6] K.-L. Deng, I. Glesk, K. I. Kang, and P. R. Prucnal, "Unbalanced TOAD for optical data and clock separation in self-clocked transparent OTDM network," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 830–832, June 1997.

[7] M. Eiselt, W. Pieper, and H. G. Webber, "SLALOM: Semiconductor optical amplifier in a loop mirror," *J. Lightwave Technol.*, vol. 13, pp. 2099–2112, Oct. 1995.