Experimental Demonstration of Pattern Effect Compensation Using an Asymmetrical Mach–Zehnder Interferometer With SOAs

Qianfan Xu, Minyu Yao, Yi Dong, Wenshan Cai, and Jianfeng Zhang

***Abstract*—In this letter, we proposed an asymmetrical interferometer to compensate the pattern effect in semiconductor optical amplifier (SOA) as an inline amplifier in dense wavelength-division-multiplexing (DWDM) system. In this letter, experiments are demonstrated with a commercial integrated Mach–Zehnder interferometer (MZI)-SOA. The experiments showed that in a 16 × 10-Gb/s DWDM system, the power penalty induced by the SOA decreased from 6.8 to 0.9 dB by the interference at 1 mW input power, and the input power dynamic range of the SOA was efficiently extended.**

***Index Terms*—Inline amplifier, optical communications, pattern effect, semiconductor optical amplifier.**

I. Introduction

The SEMICONDUCTOR optical amplifier (SOA) is very attractive as amplifier in dense wavelength-division-multiplexing (DWDM) systems for its wide gain spectrum, capability of integration with other devices, and potential low cost. Though a number of experiments have been performed to show its capability to be cascaded and used as inline amplifier in DWDM transmission systems [1], [2], the pattern effect caused by gain saturation still severely limits its implementation. When the SOA works in saturate state, the gain saturates and recovers along with the variation of the total optical power, which causes cross talk between symbols and channels and adds intensity noise to the signal of each channel. This phenomenon is called pattern effect. To avoid the pattern effect, the SOA is generally used in small signal state. However, the input optical power of each individual channel will be so small in such state that the noises will degrade the quality of the output signal. If the pattern effect can be compensated when the SOA is moderately saturated, the input power dynamic range of the SOA can be extended and the power penalty induced by SOA can be reduced.

Quite a few methods, including electronic feedback [3], compensation by saturable absorber, reduction of the carrier life time by the injection of continuous-wave (CW) light [2], and clamping of the gain by laser oscillation inside the device [4], [5], have been put forward to suppress the pattern effect in SOA.

However, these methods have not given a satisfied solution, mainly because of their speed limitation or large gain expense. The authors have proposed that the harmful gain change in saturation can be compensation by the accompanying phase change in an interferometric structure [6], [7]. This interferometric compensation approach has no speed limitation and is bitrate and waveform transparent, as long as only the interband processes are considered. In this letter, we demonstrate the compensate effect in both single channel and wavelength-division-multiplexing (WDM) system by using a commercial integrated Mach–Zehnder interferometer (MZI) with SOAs (MZI-SOA) to show the validity of this method.

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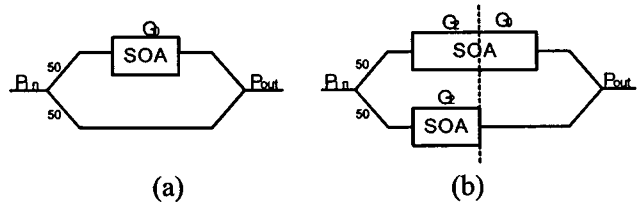

Fig. 1. The structures of the proposed device. The SOA is a semiconductor optical amplifier whose small signal gain equals G_0.

II. Principle of Compensation

Fig. 1(a) shows the schematic structure of the proposed device for inline amplification. One arm of the MZI contains the SOA for gain, and the other is a passive arm for compensation.

When SOA is saturated, the local gain of the SOA, defined as the ratio of the output power to the input power, is a function of the phase delay of the SOA [6]. When SOA is in small-signal state, i.e., SOA's local gain G equals its small-signal gain G_0, the phase-delay difference of the two arms of the MZI is made to equal π by adjusting the optical length of the compensate arm. So, the overall gain from the input port to the output port of the interferometer in small-signal state is

$$G_{t1} = \left(\sqrt{G_0} - 1\right)^2 / 2. \quad (1)$$

When the input optical power increases so that the SOA works in a saturated state and the phase delay of the SOA changes by π, the overall gain of the device will be

$$G_{t2} = \left(\sqrt{G_1} + 1\right)^2 / 2 \quad (2)$$

where $G_1 = G_0 \cdot \exp(-2\pi/\alpha)$ is the local gain of SOA in this saturated state, and α is the line-width enhancement factor of the SOA.

For different values of α, we can choose that

$$G_0 = 4[1 - \exp(-\pi/\alpha)]^{-2} \quad (3)$$

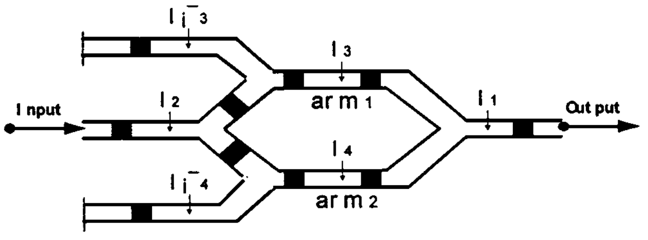

Fig. 2. Structure of the integrated MZI-SOA used for the pattern effect compensation. The white areas are active sections and the dark ones are insulated areas.

to make $G_{t1} = G_{t2}$, which means that the overall gain of the device can be held to its small-signal value even when the SOA saturates. So, in this approach, the gain variation due to the pattern effect can be compensated by the phase variation in the nonsymmetrical MZI-SOA.

If the overall gain of the interferometer is not large enough, a preamplifier can be added to each arm. In Fig. 1(b), the part at the left hand of the dashed line performs the function of preamplifier. And the whole device is an interferometer with SOAs of different lengths in its two arms.

III. Experimental Results

To verify the validity of this interferometric compensation method, experiments were done using a commercial integrated MZI-SOA manufactured by Alcatel Corporation (module MZ/S2/8). This device contained six SOAs with peak gain at 1530 nm and $\alpha \sim 11$. The structure of the device is shown in Fig. 2. Since this device is originally designed for wavelength conversion by cross-phase modulation, the structure and parameters are not optimized for compensating the pattern effect.

To form the asymmetry interferometer, the two arms of the MZI were driven at different bias currents. Compared with the asymmetry caused by different amplifier lengths in the original idea, the asymmetry caused by different currents may introduce different saturation powers and carrier lifetimes into the two arms, and makes it hard to achieve a complete compensation. However, the compensate effects was still evident.

In the first experiment, 10-Gb/s pseudorandom binary sequence (PRBS) $2^7 - 1$ nonreturn-to-zero (NRZ) coded data signal at 1553 nm was amplified by the MZI-SOA. Fig. 3 shows the waveforms and eye diagrams of the uncompensated and compensated output of the SOA, respectively. The uncompensated case is taken when the bias current of arm 2 is set to zero and the device acts as a single SOA. With the same bias current of the arm 1, optimal compensation can be achieved by adjusting the bias current of arm 2.

In the uncompensated case, we can see from the solid line in Fig. 3(a) that the overshoots exhibited at the leading edge of the initial "1"s, which is typically caused by the gain saturation effect. It was measured from the waveform that the peak power of "1"s following serial "0"s was about 1.88 dB larger than the power of "1"s following serial "1"s. The overshoots can be suppressed by compensation. In the compensated output, the highest power of "1"s was about 0.6 dB larger than the lowest power of "1"s.

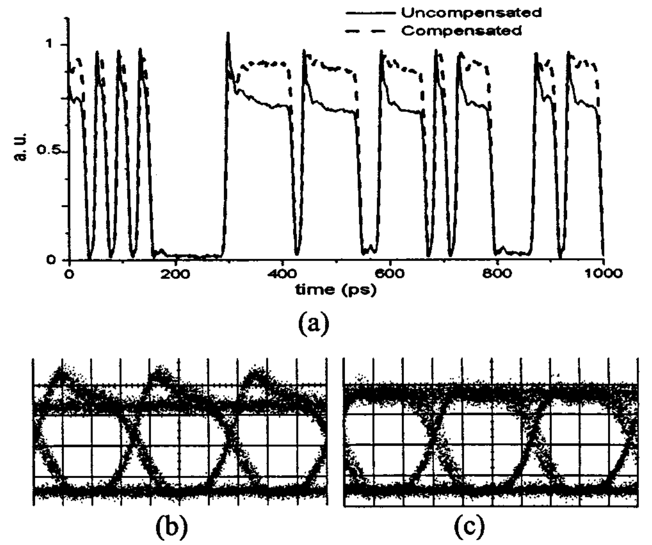

Fig. 3. (a) The solid line and dashed line are the uncompensated and compensated waveforms, respectively, and (b) and (c) are the uncompensated and compensated eye diagrams, respectively.

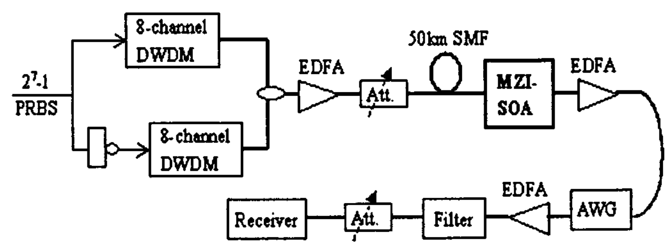

Fig. 4. Experimental setup for measuring the compensate effect in 16 × 10 -Gb/s DWDM system.

In the experiment, the drive current of the SOA at the output port (I_1) should be kept small and let the SOA work in transparent or weakly absorptive state to avoid the additional gain saturation effect at the output port.

The second experiment was to demonstrate the compensation in a 16 × 10-Gb/s DWDM system. The experimental setup is shown in Fig. 4. The DWDM transmitter was built by 16 integrated distributed feedback (DFB) + electroabsorption (EA) lasers with 0.8-nm wavelength spacing, in the range of 1548–1560 nm. The data signals were injected into the MZI-SOA after transmission over 50-km standard single-mode fiber (SMF). The third channel at 1550.11 nm was demultiplexed from the 16 channels by an arrayed-waveguide grating after passing through the MZI- SOA, and bit-error-rate (BER) curves were measured for compensated and uncompensated case, respectively, when the total optical input power of the SOA was 1 mW, as shown in Fig. 5. For comparison, the BER performance for back-to-back was also measured and shown in Fig. 5. The power penalty (at 10^{-9} BER) was significantly decreased from 6.8 dB in uncompensated case to 0.9 dB in compensated case. Since the power penalty was caused by cross talk induced intensity noise, it would increase with the decrease of target BER [8]. So, the slopes of the BER curves were different in author inconsistent with math variables. Fig. 5. When the signal was PRBS $2^{31} - 1$ coded, we observed

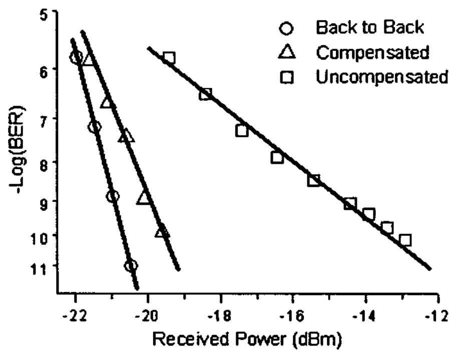

Fig. 5. BER curves of the compensated and uncompensated output signal of the device. The back-to-back curve is measured when the device is bypassed. The input optical power is 1 mW.

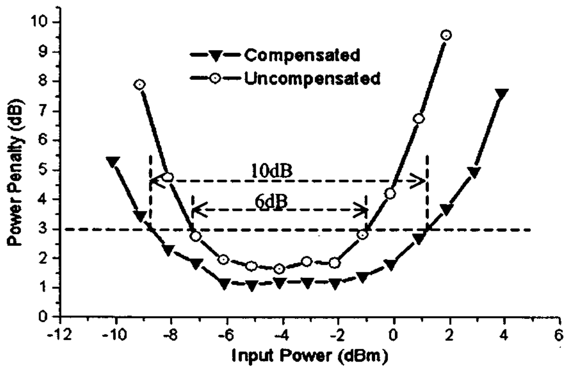

Fig. 6. Power penalty versus input power of the device in compensated and uncompensated states.

similar compensation effect with about 1-dB increase of power penalty in both compensated and uncompensated output.

Thirdly, we tested the power penalties under different input powers. The system setup was the same as that shown in Fig. 4 with slightly different operation condition of the device. As shown in Fig. 6, the dynamic range of the input power was obviously extended in the compensated case. As mentioned in Section I, the performance of the device was limit by amplified spontaneous emission (ASE) noises at low input signal power, and by the pattern effect induced cross talk at high input power. In the compensated case, lower power penalty at high input power side was achieved due to the compensation of pattern effect by the interference. From Fig. 6, we can see that the maximum input power at 3-dB power penalty increased more than 2 dB. At low input power side, where the signal to ASE noise ratio was low, the BER characteristic of the system was most influenced by the power of the lower "1"s, which was the "1"s experienced lower gain because of gain saturation effect. In compensated amplifier, the lower "1"s experienced constructive interference and had higher output power and signal to noise ratio than uncompensated amplifier, so lower power penalty was also achieved at low input power.

We noticed that the extension of the dynamic range at the high input power side was below the theoretical anticipation of about 9 dB [6], [7]. One reason is the structural difference between the commercial device and the proposed interferometer as mentioned above. The other is the high noise figure caused by low bias current of part of the six SOAs. The ASE noise affects the performance of the device even when the input power is high and SOA starts to saturate. So, part of the expected compensation effect is overwhelmed.

Finally, we should note that this commercial integrated MZI-SOA is not suitable to be directly used as inline amplifier in DWDM system, due to the large gain reduction caused by fiber to device coupling loss and absorption at the output port of the device. This gain reduction prevents the device from achieving the high gain for a practical amplifier. However, the experiments have verified the validity of the compensation method. And we believe, with hybrid integration of SOA and lossless passive waveguide, high gain and more ideal compensation can be realized.

IV. Conclusion

We experimentally demonstrated the compensation of pattern effect in SOA inline amplifier in DWDM systems with a commercial MZI-SOA. Obvious compensation effects were shown, and the methods to improve the performance of the device as an amplifier were discussed.

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