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Increasing Input Power Dynamic Range of SOA by Shifting the Transparent Wavelength of Tunable Optical Filter

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Abstract—Gain-saturation-induced self-phase modulation (SPM) leading to pulse distortion in a semiconductor optical amplifier (SOA) is overcome by shifting a tunable optical filter (TOF). A recovered or broadened pulse can be obtained after filtering the amplified pulse in the SOA even if the short pulse is only 2–3 ps long. The input power dynamic range (IPDR) can be strongly increased by shifting the TOF and the direction of the shifted transparent wavelength is different for 10 Gb/s return-to-zero (RZ) or nonreturn-to-zero (NRZ) signals. The transparent wavelength of the TOF should be shifted to a longer wavelength for RZ signals and to a shorter one for NRZ signals. 80-Gb/s optical time division multiplexing (OTDM) signal amplification in the SOA is demonstrated for the first time. We also demonstrate that a large IPDR for the 80-Gb/s OTDM signal can be obtained by shifting the TOF.

Index Terms—Gain saturation, input power dynamic range (IPDR), optical time division multiplexing (OTDM), self-phase modulation (SPM), semiconductor optical amplifier (SOA), tunable optical filter (TOF).

I. INTRODUCTION

THE SEMICONDUCTOR optical amplifier (SOA) is a promising candidate for cascaded optical fiber systems and optical gating because of the coverage of the entire fiber transmission window and the possibilities for integration and low cost [1]–[9]. However, an important issue for the SOA is extinction ratio (ER) degradation due to gain saturation at high input powers, which has a severe impact on the SOA cascadability [1]–[5]. A simple method to improve the ER is to use gain-clamped SOAs (GC-SOAs). GC-SOAs have attracted much interest because they exhibit high saturation input power resulting in superior cascadability for both single- and multiwavelength systems [2]. However, at bit rates of 10 Gb/s and beyond, the performance of GC-SOAs is limited by the relaxation frequency causing pulse pattern distortions. Reference [3] reported an optical filtering technique to suppress nonreturn-to-zero (NRZ) waveform distortion by use of a narrow Mach–Zehnder filter of 0.1-nm bandwidth; however, our experiment will show that a narrow filter is not suitable to recover NRZ signals when the SOA has a short carrier lifetime. In this paper, we will demonstrate that shifting the tunable optical filter having a 1.5-nm bandwidth can realize short pulse recovery and input power dynamic range (IPDR) improvement for both 10-Gb/s return-to-zero (RZ) and 10-Gb/s NRZ signals. However, the direction of the shifted transparent wavelength of the tunable optical filter (TOF) is different for RZ and NRZ signals. The TOF transparent wavelength should be shifted to a longer wavelength for RZ signals, but to a shorter one for NRZ signals. SOAs can be used for inline amplification in single or multichannel systems, as well. A number of multichannel or single-channel transmission experiments using SOA amplification have been reported [7]–[9]. However, to our knowledge, no 80-Gb/s or higher per-channel amplification in SOAs has been reported until now. In this paper, we will demonstrate 80-Gb/s optical time division multiplexing (OTDM) amplification in the SOA for the first time. In particular, we will demonstrate that IPDR for the 80-Gb/s OTDM can be improved by shifting the transparent wavelength of the TOF.

II. 10-GHz SHORT PULSES

The experimental setup is shown in Fig. 1. The short pulse source is a 10-GHz, 1560-nm erbium fiber ring laser (EFRL) that generates 2.3-ps full-width at half-maximum (FWHM) pulses. The SOA used in the experiment has a total length of 1200 μm. It has an unsaturated fiber-to-fiber gain of 18 dB at 130 mA [6], [7]. After a TOF with a bandwidth of 1.5 nm, the optical pulse is detected by a sampling oscilloscope (SO) with a bandwidth of 32 GHz set by the photodiode, an optical spectrum analyzer (OSA), or a second-harmonic generation (SHG) autocorrelator.

Figs. 2 and 3, respectively, show the waveforms and optical spectra for an input power of 0 dBm. Fig. 2(a) shows the op-
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Fig. 2. Waveforms for 0-dBm input power into the SOA. (a) Input pulse. (b) After the SOA without filter. (c) After shifting the TOF. (d) After fixing the TOF at the input signal wavelength.

Fig. 3. Optical spectra for 10-GHz optical pulse for 0-dBm input power. Note: Optical power means relative power and resolution is 0.1 nm in all spectral figures.

Fig. 4 shows the experimental setup for 10-Gb/s optical signal amplification in an SOA. In this section, we add an LiNbO$_3$ modulator after the 10-GHz optical pulse source, and by modulating the input pulses with a pseudorandom bit sequence of $2^{31} - 1$, an optical RZ signal at 10 Gb/s is obtained. After the
SOA, the amplified RZ signal is filtered by TOF1, then amplified by a pre-EDFA. After filtering in TOF2, the signal is received by a standard 10-Gb/s NRZ receiver; then, the output signal from the receiver is amplified by a wide-band electrical amplifier (Picosecond Pulse Lab Mod: 5830) and, finally, the bit error rate (BER) is measured. In the following sections, TOF means TOF1.

Fig. 5 shows the eye diagrams for 0-dBm input power (10 ps/div). (a) Input signal. (b) Without filter. (c) Shifting the TOF.

In order to make a more detailed investigation, Fig. 7 shows the waveforms for an input power of 0 dBm. We modulate the signal by a PRBS of $2^7 - 1$ because of the trigger limitation of the sampling oscilloscope when measuring waveforms, as opposed to eye diagrams and BER measurement, where $2^{31} - 1$ was used, as mentioned earlier. Fig. 7(a) shows that the difference between “1”s and “0”s after the SOA is very small. We also see that the pattern effect is small because the carrier lifetime of the SOA is smaller than the bit duration time; hence, the carrier density is almost fully recovered when the next “1” arrives. Fig. 7(b) shows that the waveform is almost recovered after shifting the TOF. When the TOF transparent wavelength stays at the position of the original input signal, the waveform consists of the components of the amplified “0”s and the trailing edge of “1”s of the input signal. Fig. 7(c) shows the trailing edge of “1”s and amplified “0”s, and the “1”s are broadened.

Fig. 6. Optical spectra with input power of 0 dBm.

Fig. 4. Experimental setup for 10-Gb/s RZ signal amplified in an SOA. BER: bit error rate. MOD: LiNbO$_3$ modulator.
Fig. 7. Optical waveforms with 0-dBm input power (200 ps/div). (a) Without optical filter. (b) After shifting the TOF. (c) After fixing the TOF at almost the input signal wavelength.

Fig. 8 shows BER performance after shifting the TOF. The penalty at $10^{-9}$ after shifting is very small when the input power is $-15.5$ dBm; however, the penalty is about 1.2 dB when the input power is 0 dBm and the penalty is caused by the remaining pattern effect that can be seen in Fig. 7(b).

Fig. 9 shows the optimal transparent wavelength of the TOF as a function of the input optical power into the SOA. It is clearly seen that the larger the input power is, the longer the center wavelength of the TOF is, as well.

Fig. 10 shows that shifting the TOF is a very effective method to increase IPDR. Fixing the transparent wavelength of the TOF, the IPDR at 2 dB power penalty is 6 dB. The penalty at low input power is caused by a low signal-to-noise ratio (SNR), whereas the penalty at high input power is caused by ER degradation due to gain saturation. By shifting the TOF, the IPDR is strongly increased and the IPDR at 2 dB penalty is now larger than 32 dB. When the input signal power becomes large enough—for example, larger than $-4$ dBm—the penalty is increased; this is due to the fact that the pattern effect after the SOA will be increased and can no longer be eliminated completely by shifting the TOF as done in Fig. 7(b).
Fig. 11. Experimental setup for 10-Gb/s NRZ signals amplified in the SOA. ECL: external cavity laser.

IV. 10-Gb/s NRZ SIGNALS

Fig. 11 shows the experimental setup for 10-Gb/s NRZ signals. After the SOA, the amplified NRZ signal is filtered by TOF1, then amplified by a pre-EDFA. After filtering by TOF2, the signal is received by a standard 10-Gb/s NRZ receiver, and then the BER is measured. In the following sections, TOF again means TOF1.

Fig. 12 shows eye diagrams for an input power of −4 dBm. Because of gain saturation, the signal after the SOA is distorted and has a small ER, as shown in Fig. 12(b). After filtering by TOF, the signal is received by a standard 10-Gb/s NRZ receiver, and then the BER is measured. In the following sections, TOF again means TOF1.

In a further investigation, Fig. 14 shows the waveforms for an input power of −4 dBm. Fig. 14(a) shows the amplified waveform of “1100101000000011111101….” We can see that the leading edge of the first “1” of the 6 consecutive “1”s is amplified most, because the leading edge of the first “1” saturates the SOA and reduces the gain available for the following “1”s; this leads to an obvious pattern effect. In the frequency domain, the leading edge of the first “1” is shifted to both longer and shorter wavelengths. In order to eliminate the pattern effect, we should suppress simultaneously the red- and blue-shifted frequency components. Fig. 14(b) shows that the pattern effect is

Fig. 12. Eye diagrams for −4 dBm input power (20 ps/div). (a) Input signal. (b) Without TOF. (c) After shifting the TOF.
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Fig. 14. Waveform for input power of $-4$ dBm. (a) Without the TOF. (b) After shifting the TOF.

Fig. 15. Eye diagrams for input power of $-15$ dBm (20 ps/div). (a) Without the TOF. (b) After shifting the TOF.

Fig. 16. Power penalty as a function of input power.

![Graph showing power penalty vs. optical power](image)

The SOA has a short carrier lifetime, the “0”s are also amplified and distorted, as in Fig. 12(b). If we only use a narrow filter to eliminate the red- and blue-shifted part of the spectrum, and the transparent wavelength of the TOF still remains at almost the same wavelength as that of the input signal, as in [3], the distortion of “1”s can be eliminated. However, the center wavelength of the amplified “0” stays at the input signal wavelength; therefore, the ER cannot be improved because the distortion of “0”s cannot be recovered.

V. 80-Gb/s OTDM SIGNALS

The experimental setup is shown in Fig. 17. Two nonlinear optical loop mirrors (NOLMs) are used of which one is used to demultiplex the 80-Gb/s OTDM signal to 10 Gb/s in time domain. Because two narrow pulses are needed for all-optical
demultiplexing in NOLM2, but only one short pulse source is available, we use wavelength conversion based on cross-phase modulation in NOLM1 to obtain the narrow pulsewidth signal [10], [11]. The control pulse for the NOLM1 is generated by a 10-GHz, 1560-nm EFRL, and the FWHM pulsewidth is 2.3 ps. After adding the LiNBO$_3$ modulator, and modulating the control pulses with a pseudorandom bit sequence of $2^{31} - 1$, a control signal at 10 Gb/s is obtained. The continuous wave (CW) lightwave is generated by a tunable external cavity laser. The control signal is coupled into NOLM1 using a wavelength-independent 3-dB optical coupler. The length of the high-nonlinearity dispersion shifted fiber (HNL-DSF) in NOLM1 used for wavelength conversion is 1 km. The zero dispersion wavelength, dispersion slope, and nonlinear coefficient of the HNL-DSF are 1552 nm, 0.022 ps/nm$^2$/km, and 10.9 W$^{-1}$km$^{-1}$, respectively. A 1.6-nm bandpass tunable optical filter at the output of NOLM1 is used to suppress the control signal. The FWHM pulsewidth of the converted pulse at 1545.6 nm is 3 ps. Then, the 10-Gb/s converted signal is passively multiplexed up to 80 Gb/s using a fiber interleaver. After the 80-Gb/s OTDM signal is amplified in the SOA, NOLM2 is used to demultiplex the 80-Gb/s OTDM signal to a 10-Gb/s signal, and the control pulse is also obtained from the EFRL. NOLM2 consists of 3-km common DSF with zero dispersion wavelength of 1555 nm, dispersion slope of 0.06 ps/nm$^2$/km, and nonlinear coefficient of 2.6 W$^{-1}$km$^{-1}$.

Fig. 18 shows typical eye diagrams. Fig. 18(a) is the back-to-back eye diagram at 10 Gb/s. Fig. 18(b) is the eye diagram after wavelength conversion in NOLM1 at 10 Gb/s; a very good eye diagram is obtained. Fig. 18(c) is the multiplexed signal at 80 Gb/s before the SOA. Fig. 18(d) is the amplified signal after the SOA for an input power of $-14$ dBm and after the TOF; there is no obvious difference between Fig. 18(c) and (d). Fig. 18(e) is the demultiplexed signal at 10 Gb/s, and a good eye diagram is obtained.

Fig. 19 shows BER performance. The penalty for the 80-Gb/s OTDM signal after demultiplexing to 10 Gb/s without the SOA, compared to the 10-Gb/s converted signal, is 3 dB. When the 80-Gb/s OTDM signal is amplified in the SOA with an input power of $-14$ dBm and demultiplexed in the NOLM2, the penalty at 10 Gb/s, compared to the 10-Gb/s converted signal, is 4.3 dB. The added penalty after the signal is amplified in the SOA is 1.3 dB; the added penalty is caused by SNR degradation after amplification in the SOA and by nonperfect filtering of the TOF.

Fig. 20(a) shows the optical spectra for the 80-Gb/s OTDM signal when the input power into the SOA is $-5$ dBm. In order to compare with a 10-Gb/s RZ signal, the optical spectra for the 10-Gb/s RZ signal are also shown in Fig. 20(b) and the input power into the SOA is also $-5$ dBm. Fig. 21 shows the shift in wavelength of the peak power as a function of the input power. It is clear that the shift in peak power is reduced for the 80-Gb/s OTDM signal. Because the duty cycle of RZ signals is very small, as shown in Fig. 10, the peak power is very large. The large peak power will lead to strong SPM in the SOA, and then the center wavelength of the signal after amplification in the SOA will be shifted to a very long wavelength. Therefore, the IPDR becomes very small when the transparent wavelength of the TOF after the SOA is kept fixed. For the 80-Gb/s OTDM, the peak power is small because the duty cycle is enhanced; therefore, the shift in wavelength of the peak power will be reduced. Furthermore, because the pulsewidth of the OTDM signal is smaller than the carrier lifetime, after amplification in the SOA, the pattern effect will be small, not like an NRZ signal.

Fig. 22 shows the power penalty as a function of the input optical power to the SOA. Keeping the transparent wavelength of the TOF fixed, the IPDR at 2-dB penalty is 10 dB. Comparing with the 10-Gb/s RZ signal and 10-Gb/s NRZ signal, the IPDR at 2-dB penalty is increased to 4 dB and 2.5 dB, respectively. Although the shift in wavelength of the peak power is reduced when the high-speed OTDM signal is amplified in the SOA, there is still some small change of the peak power as shown in Fig. 21. Therefore, it is necessary to shift the transparent wavelength of the TOF in order to obtain a very large IPDR. By shifting the TOF after the SOA, the IPDR is increased and the IPDR at 3-dB penalty is larger than 26 dB; in addition,
Fig. 18. Eye diagrams. (a) Back-to-back, (b) After wavelength conversion in NOLM1, (c) Input signal of 80-Gb/s OTDM, (d) 80-Gb/s OTDM after the SOA with input power of −14 dBm and the TOF, (e) After demultiplexing in NOLM2, (a), (b), and (e) are measured by a 32-GHz photodiode and shown in 20 ps/div, (c) and (d) are measured by a 50-GHz photodiode and shown in 10 ps/div.

Fig. 19. BER performance.

there is error-free operation even when the input power to the SOA is as high as 0 dBm.

The multiplexed signal at 80 Gb/s is launched into 44 km of conventional single mode fiber (SMF), passively dispersion compensated by 7-km wide-band dispersion compensating fiber (DCF). The total loss of the SMF and DCF is 12 dB, the input power into the SMF is −2 dBm, and the loss of the fibers is compensated by the SOA gain. BER performance is also shown in Fig. 19. Comparing the 80-Gb/s OTDM signal at 1545.6 nm before and after transmission, the penalty is seen to be small—approximately 0.5 dB.

VI. DISCUSSION

We have demonstrated that IPDR for 10-Gb/s RZ, 10-Gb/s NRZ, and 80-Gb/s OTDM signals can be improved by shifting the transparent wavelength of the TOF in the case of single-channel input. Considering multiple-channel input, when the input signal of each channel is large enough—for example, larger than −10 dBm—there will be strong cross-gain modulation (XGM) when the wavelength division multiplexing (WDM) signals are amplified by the SOA, and crosstalk between different channels will be generated. The larger the input power of each channel, the larger the crosstalk. However,
the crosstalk cannot be eliminated by shifting the transparent wavelength of the TOF; therefore, the IPDR cannot be improved. For amplifying WDM signals in SOAs, we believe that holding light injection is a suitable method to improve the IPDR of each channel; the crosstalk of different channels caused by XGM will be reduced because of the presence of strong holding light [6], [12]. However, the gain of each channel will also be reduced because the power of the holding light is always larger than the power of each channel.

VII. CONCLUSION

Gain-saturation-induced SPM leads to pulse distortion when the signals are amplified in an SOA. We have experimentally demonstrated that shifting the transparent wavelength of the TOF is a very effective method for short pulse recovery and IPDR improvement for both RZ and NRZ signals.

The short pulse can be recovered or broadened by shifting the TOF, even if the short pulse is only 2–3 ps long. When the transparent wavelength of the TOF is shifted to a longer wavelength, the pulse is recovered. When the transparent wavelength is shifted to the input signal wavelength, the pulse becomes broadened to approximately 25 ps, mainly determined by the carrier lifetime.

For 10-Gb/s RZ signals, because the optical spectrum of the leading edge of the “1”s is fully shifted to a longer wavelength and the falling edge of the “1”s and “0”s will remain at the original wavelength, the leading edge of “1”s can be obtained by shifting the TOF. Thus, the transparent wavelength of the TOF is shifted to a longer wavelength. Keeping the center wavelength of the TOF fixed, the IPDR at 2-dB power penalty is 6 dB. However, shifting the TOF to a long wavelength, the IPDR at 2-dB penalty becomes larger than 32 dB.

For 10-Gb/s NRZ signals, the optical spectrum is broadened to both the red and blue side, and the red-shifted part of the spectrum is larger than the blue-shifted part. The TOF is used to reduce the red-shifted part stemming from the gain-saturation-caused SPM; therefore, the transparent wavelength of the TOF is shifted to a shorter wavelength. Because the blue-shifted part of the spectrum caused by SPM cannot be suppressed, the pattern effect cannot be eliminated fully. However, even though the blue-shifted part cannot be eliminated, the IPDR is strongly improved. When the transparent wavelength of the TOF is fixed, the IPDR at 2-dB power penalty is 7.5 dB; however, when the TOF is shifted, the IPDR at 2-dB penalty is 16.5 dB.

80-Gb/s OTDM signal amplification in the SOA has been demonstrated for the first time. For 80-Gb/s OTDM signals
having the same average power and pulsewidth as the 10-Gb/s RZ signals, because the peak power of the signal is reduced, the shift in wavelength of the peak power will also be reduced. Furthermore, because the pulsewidth of the OTDM signal is smaller than the carrier lifetime, after amplification in the SOA, the pattern effect will be small in contrast to an NRZ signal; therefore, the IPDR is increased. The IPDR at 2-dB penalty is 10 dB. Keeping the transparent wavelength of the TOF fixed, and compared with a 10-Gb/s RZ and 10-Gb/s NRZ signals, the IPDR at 2-dB penalty is increased by 4 and 2.5 dB, respectively. However, although the shift in the wavelength of the peak power is reduced when the high-speed OTDM signal is amplified in the SOA, there is still some change of the peak power. Therefore, it is necessary to shift the transparent wavelength of the TOF to obtain a much larger IPDR. Shifting the TOF, the IPDR is increased and the IPDR at 3-dB penalty becomes larger than 26 dB; there is error-free operation even when the input power to the SOA is as high as 0 dBm.

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