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Enhanced Performances of an SOA over a Wide-Band Optical Wavelength by Holding Beam Injection at Transparency

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Abstract- We experimentally demonstrate the influence of a high power continuous wave (CW), as a holding beam (HB), injection into an SOA at the gain transparency wavelength on the device static and dynamic performances over a wide range of signal wavelength. Besides, the obtained results are exploited in an SOA based multi-channel transmission system to reduce the cross-gain modulation (XGM) induced inter-channel crosstalk pattern penalty between signals. Experiment shows that this crosstalk penalty can be considerably reduced by the HB injection at the gain transparency wavelength.

Keywords: Semiconductor optical amplifier (SOA), holding beam (HB), bit error rate (BER), inter-channel crosstalk penalty, saturation output power, dynamic gain recovery time.

I. INTRODUCTION

Semiconductor optical amplifiers (SOAs) are versatile attractive devices for future high-capacity all-optical telecommunication systems thanks to several features, such as compactness, integrability, low power consumption, low cost and a broad optical gain spectrum. Furthermore, their linear and nonlinear characteristics make them key components for optical access networks (OANs), optical local area networks (OLANs) and metropolitan coarse/dense wavelength division multiplexing (C/DWDM) transmissions. However, a high SOA 3-dB saturation output power is essential for employing this optical amplifier in high-capacity long-haul transmission applications. Moreover, when an SOA is used in a multi-channel telecommunication link, its transmission performance suffers from a signal distortion and inter-channel crosstalk pattern penalty caused by the cross-gain modulation (XGM) effects [1]-[2]. Therefore, improving the SOA gain linearity characteristics is an essential issue to deal with the increased growth of data rates in SOA based all-optical high-capacity multi-channel systems.

The XGM effects can be overcome by gain clamped semiconductor optical amplifiers (GC-SOAs) due to their improved gain linearity [3]. Unfortunately, the gain of these devices is fixed by the design and is low compared to that of the conventional SOAs. Moreover, due to the interaction with the internal laser and the amplified signal via the carrier density, relaxation oscillations and dark holes are present in the GC-SOAs. The SOA gain linearity characteristics can be enhanced by the injection of a high optical power continuous wave (CW) as a holding

beam (HB) into the SOA at its gain transparency wavelength. Here the transparency wavelength coincides with the left amplification region edge of the SOA gain wavelength spectrum. Such an injection of the HB inside the SOA has proven its efficiency to speed-up considerably its dynamic gain recovery time [5]-[12], to increase noticeably its 3-dB saturation output power [9]-[16] and to enhance the conversion efficiency in SOA based four-wave-mixing (FWM) wavelength converters [15]. Furthermore, the SOA small-signal gain has been maintained when the HB is close to the transparency wavelength [15]-[16]. Recently, an HB at the transparency point is used to improve the SOA noise figure [17].

To our knowledge, however, when employing an HB at the transparency wavelength, the SOA saturation output power and its gain recovery time improvement dependency on the signal wavelength has never been published yet. In this paper, experimental results concerning this improvement dependency over a wide band optical wavelength will be given and discussed in the next section. In addition, in section III, we exploit the obtained results, due to the HB injection, in an SOA based multi-channel WDM transmission system to reduce the XGM induced inter-channel crosstalk pattern penalty between signals traveling throughout the device. Conclusion will be given in section IV.

In [12], we have shown that employing an HB in counter-propagating scheme gives better results than those in a co-propagating one. Therefore, we use the first configuration in this work.

II. SATURATION OUTPUT POWER AND GAIN RECOVERY TIME IMPROVEMENT

Experimental static set-up is given inside Fig. 1. Experimental results are carried out on a 500 μm long low-polarization-sensitive (< 2 dB) bulk SOA with a ridge structure. Its optical confinement factor is about 0.3. This amplifier has a fiber-to-fiber gain of about 21.3 dB at a bias current of 200 mA for a low optical power signal incident at 1535 nm. A high optical power of 19 dBm at 1480 nm, obtained by an external pump laser, is used as an HB. It is injected into the SOA in counter-propagative scheme with respect to the optical input signal via an optical circulator.

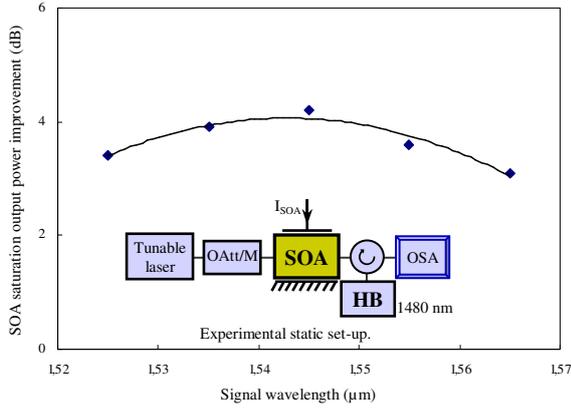


Fig. 1: SOA 3-dB saturation output power enhancement, due to the HB employment, dependency on input signal wavelength. Points present measurements and solid lines present polynomial approximation. (OAtt/M: Optical attenuator/monitor and OSC: Oscilloscope).

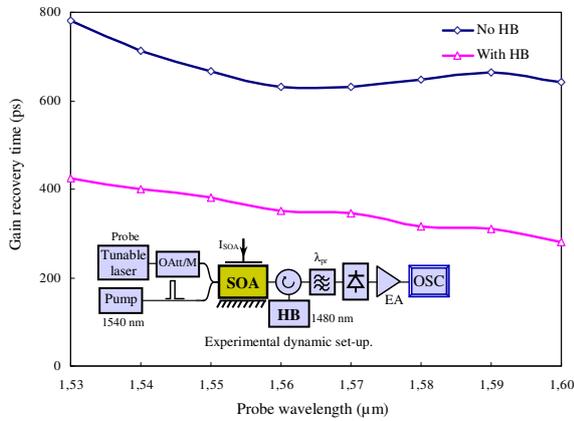


Fig. 2: SOA dynamic gain recovery time vs. probe wavelength in absence and in presence of an HB injection in the device cavity. (OM: Optical modulator and EA: Electrical amplifier).

We have measured the SOA gain saturation curves with and without HB injection for several signal wavelengths. Then, the SOA saturation output power improvement is derived for each signal wavelength. Fig. 1 shows the SOA 3-dB saturation output power enhancement dependency on the optical signal wavelength, due to the HB. This figure points out that the enhancement is optimal (4.2 dB) at the SOA gain peak wavelength (1545 nm). However, Fig. 1 reveals also that the SOA 3-dB saturation output power is increased by about 3.8 dB over a wide range of optical signal wavelength. This improvement almost covers our amplifier 3-dB gain window.

In addition, Fig. 2 demonstrates the SOA dynamic gain recovery time reduction dependency on the probe wavelength when an HB is used. Pump-probe measurements have been performed to characterize the SOA dynamic gain recovery time. The SOA gain recovery time is defined as the required time for the gain to recover from 10% to 90% of its steady state value. Here, the pump is a 5 ps pulse of about 275 fJ with a repetition rate of 454 MHz at 1540 nm. The probe signal is generated by a tunable laser at several wavelengths with a CW power of -12 dBm in order to leave the SOA gain unsaturated (small-signal regime). The detailed used set-up is dis-

played inside Fig. 2.

We have measured the SOA dynamic gain recovery time with and without HB injection for many probe wavelengths. Fig. 2 points out that the HB injection into the SOA speeds-up its gain recovery time over a large band of probe wavelength. It shows also that the SOA gain recovery time is reduced to about half its initial value by the HB and this reduction is almost constant for all probe wavelengths. As a result, for a probe wavelength of 1550 nm, a 19 dBm power as an HB injected inside the SOA reduces its gain recovery time to 382 ps, while it is around 667 ps without any HB.

From the above obtained results (Fig. 1 and Fig. 2), one concludes that the HB injection inside an SOA at the gain transparency, enhances its gain linearity characteristics over a broad band of signal wavelengths. This gain linearity enhancement is essential in an SOA based multi-channel WDM transmission system to overcome the XGM induced inter-channel crosstalk pattern penalty between signals.

III. MULTI-CHANNEL TRANSMISSION SYSTEM

A. Experimental set-up

The experimental set-up used to simulate an SOA based multi-channel WDM transmission system is depicted in Fig. 3. In this set-up, two optical input signals (signal₁ at 1535 nm and signal₂ at 1560 nm) can be modulated at 2.5 Gb/s by two separated Non-Return-to-Zero Pseudo-Random Bit Sequence (NRZ PRBS) generators with a word length of $2^{23}-1$ each and extinction ratios of about 13 dB and 10 dB respectively. Each optical input signal power can be controlled and monitored by an optical attenuator/monitor before being injected individually or together with the other signal into the SOA.

An optical filter of 1 nm bandwidth is used at the SOA output to select signal₁. The selected signal can be detected by a fast photodiode of 20 GHz bandwidth. The detected signal can be amplified by a large band-pass electrical amplifier of 20 kHz to 16 GHz bandwidth and then split up into two parts; the first one can be displayed on a 20 GHz bandwidth oscilloscope, the other supplied to a BER meter. The same HB presented in section II, has been used here and injected into the SOA in counter-propagative configuration as well.

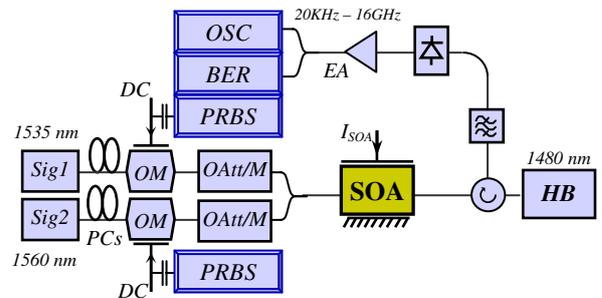


Fig. 3: Experimental set-up for measuring the signal BER in multi-channel transmission system. (PCs: Polarization controllers, OM: Optical modulator, OAtt/M: Optical attenuator/monitor, OSC: Oscilloscope and EA: Electrical amplifier).

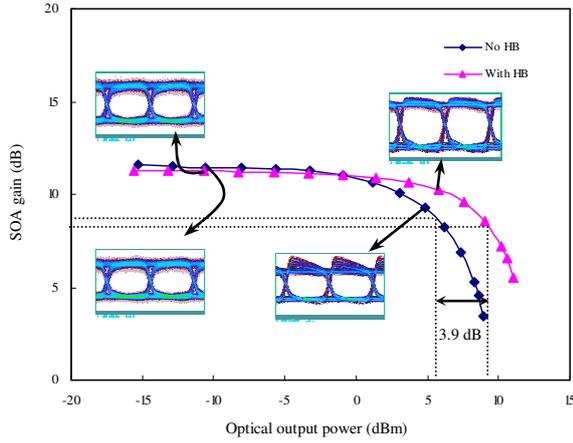


Fig. 4: SOA saturation curves of signal₁ and its optical eye diagrams obtained in dynamic regime, in presence and in absence of the HB. The SOA drive current is 120 mA.

In this set-up, our SOA has been biased at 120 mA. At this current, it has a fiber-to-fiber gain of about 11.6 dB for a low optical power of signal₁ (1535 nm). This gain is not changed by the injected HB (1480 nm) which is considered, in this case, situated at the gain transparency wavelength of our device. Fig. 4 shows the SOA gain of signal₁ against its output power and the output signal₁ eye diagrams obtained with and without HB. These SOA saturation curves confirm that the HB use improves the SOA saturation output power (3.9 dB in our case) while maintaining its unsaturated gain level (Fig. 4). Moreover, our HB does not influence the SOA output eye diagrams obtained in the dynamic regime for low input powers of signal₁. On the other hand, for high powers, a gain overshoot appears in the SOA output eye diagrams without the HB (Fig. 4). However, this gain overshoot is suppressed and the eye has become more open when the HB is employed.

B. Inter-channel crosstalk in presence of HB

In our experiment, the effect of a multi-channel transmission is simulated by a relatively high average power of signal₂ (-7.5 dBm). In fact, this power of signal₂ brings our SOA gain around the 3-dB gain saturation point, which corresponds to the worst case of the device use. In order to evaluate the influence of the HB injection into the SOA on the inter-channel crosstalk penalty caused by signal₂, the signal₁ BER is measured for signal₁ in three situations: signal₁ alone (Sig1), with signal₂ (Sig1&Sig2) and finally with signal₂ and an HB (Sig1&Sig2&HB). In this measurement, our SOA has been biased at 120 mA to have our HB wavelength (1480 nm) at the transparency one.

Fig. 5 points out that when the signal₂ is injected together with signal₁ into the SOA, without the HB, the signal₁ BER is degraded. This degradation indicates that an inter-channel crosstalk pattern penalty has appeared due to the XGM effect between the two signals. As results, a penalty of 5.3 dB of input power is imposed on signal₁ for a BER of 10^{-9} when signal₁ and signal₂ are injected together to the SOA (case Sig1&Sig2 in Fig. 5). However, this imposed penalty is reduced down to 2.4 dB when the HB is added to signal₁ and signal₂ (case Sig1&Sig2&HB in Fig. 5). In fact, signal₂ saturates the SOA gain in such a

way that its spectrum is shifted toward longer wavelengths. Consequently, the HB wavelength is no more at the transparency one but in the absorption region. The HB photon-absorption generated carriers enhance the SOA gain and restore its spectrum, which reduces the imposed XGM induced crosstalk penalty between the signals.

Fig. 6 displays the SOA output eye diagrams of signal₁ obtained for the three situations: signal₁ alone (Sig1), signal₁ with signal₂ (Sig1&Sig2) and signal₁ with signal₂ and the HB injection at the gain transparency wavelength (Sig1&Sig2&HB). These eye diagrams are centered by the large band-pass electrical amplifier (see Fig. 3). Here the optical input average power of signal₁ is -15 dBm and that for signal₂ is -7.5 dBm. Fig. 6 shows obviously that the signal₁ eye diagrams have become less open and an XGM induced inter-channel crosstalk penalty has appeared on signal₁ when it is injected together with signal₂

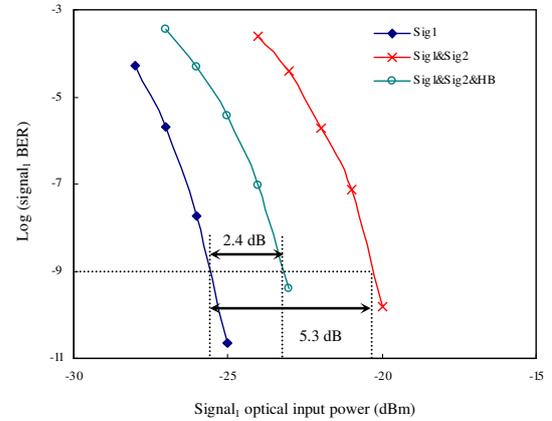


Fig. 5: BER of signal₁ vs. its optical input power for signal₁ (1535 nm) in three cases: alone (Sig1), with signal₂ (Sig1&Sig2) and with signal₂ and the HB at the transparency wavelength (Sig1&Sig2&HB). The SOA drive current is 120 mA.

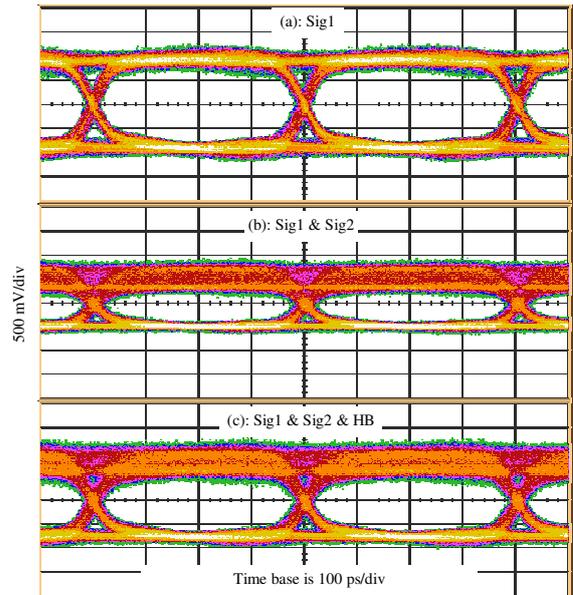


Fig. 6: SOA output eye diagrams of signal₁ in three situations: (a) alone (Sig1), (b) with signal₂ (Sig1&Sig2) and (c) with signal₂ and the HB at the transparency (Sig1&Sig2&HB). The optical input average power of signal₁ (1535 nm) is about -15 dBm and that for signal₂ (1560 nm) is around -7.5 dBm. The SOA bias current is 120 mA.

to the SOA without the HB, (see case Sig1&Sig2 in Fig. 6). On the other hand, under the same conditions, the signal₁ XGM induced crosstalk is significantly reduced and the their eye diagrams are improved when the HB, having an optical power of 19 dBm at wavelength of 1480 nm, is injected into the SOA at the transparency condition (see case Sig1&Sig2&HB in Fig. 6). Let's note that the bit rate of 2.5 Gb/s used in this experiment was limited by the available PRBS signal generators. The eye diagrams in Fig. 6 and the reduction in the gain recovery time (Fig. 2), due to the HB use, indicate that the performance of our technique would not be degraded before reaching a significantly higher bit rate.

IV. CONCLUSION

The impact of a high power continuous wave (CW), as a holding beam (HB), injected into an SOA at the gain transparency wavelength on its gain linearity performance is investigated over a broad range of signal wavelengths. We have shown an improvement in the SOA saturation output power (~3.8 dB) and its dynamic gain recovery time (almost speeded-up by a factor of two over a wide band optical wavelength covering the SOA gain window, when an HB of 19 dBm at 1480 nm is used. In addition, the obtained results have been exploited to reduce the XGM induced inter-channel crosstalk pattern penalty between two signals in an SOA based multi-channel transmission system. Consequently, we have shown a considerable reduction in the crosstalk penalty, imposed on signal₁ by signal₂, in this transmission system from 5.3 dB down to 2.4 dB for a BER of 10^{-9} due to the HB employment at the transparency wavelength.

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