Optical amplitude modulation extinction by a deep saturated ultra-long semiconductor optical amplifier

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Abstract: The recovery of an optical carrier with the deletion of its amplitude modulation is introduced using a deeply saturated ultra-long semiconductor optical amplifier (UL-SOA). The experimental results were achieved for input signal bit rates up to 12.5 Gbps with high extinction ratio (up to 13.9 dB). The influence of parameters such as UL-SOA bias current, optical bandwidth, signal input power, modulation depth and bit rate are analyzed including the carrier spectral broadening effects due to the self-phase modulation effect.

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1. Introduction

Optical-data extinction (ODE) is essentially the recovery of an optical carrier by erasing its amplitude modulated (AM) data. One of the first visualized ODE techniques was based on the semiconductor optical amplifier (SOA) saturation effect and proposed a cascade of deeply saturated SOAs to achieve adequate ODE [1,2]. Due to the saturation effect, the higher SOA optical gain is provided to lower amplitude components of the optical carrier; the lower gain to high power levels. Therefore, the optical signal modulation deepness decreases after subsequent passage through each cascaded SOA, eventually leading to ODE under proper conditions. In those proposals, optical routing devices were designed to support the bypass routing, the ODE operation and new modulation over the optical carrier (i.e., wavelength reuse) for applications in wavelength division multiplexing (WDM) networks [1]. The original idea intended to decouple the switching and routing functions, and so these actions can be performed concurrently instead of sequentially, leading to an increase in the effective bandwidth of the switch fabric [2]. The reduction to practice of SOA-based ODE was achieved using a cascade of 3 SOAs, attaining AM extinction ratio (ER) reduction from 5.4 dB to 2.9 dB at 70 Mbps for pseudo-random bit stream (PRBS) pulses; the setup was tested only up to few hundreds of Mbps [3].

The ODE approach has applications in wavelength division multiplexing passive optical network (WDM-PON), with centralized light sources (CLS) in fiber-to-the-home (FTTH) systems [4,5]. The CLS systems are promising technique for robust WDM networks without wavelength-controlled lasers at each remote node (RN) [6]. Many of the proposed WDM-PON networks use two wavelengths, one for the upstream and another for the downstream carrier [7]. However, the limited numbers of available wavelength channels reduce the total system capacity, making attractive the employment of ODE in the downstream signal to enable the wavelength reuse for the upstream channel, with no additional carrier required.

Other approaches have been proposed for ODE and the subsequent carrier reuse, such as based on use of: two modulators [8]; SOA with feed-forward gain control technique and optical modulator [3]; SOA as eraser and modulator [9]; reflective SOAs (RSOAs) [10]; interferometric filter with RSOAs [11]; among others. However, the achieved ODE is not substantial in most of those techniques, even more when considering PRBS signals with input ER greater than 8 dB, and/or when trying high bit rates (above 2.5 Gbps).

This paper analyses the process of ODE achievement using a deeply saturated ultra-long SOA (UL-SOA). We report ODE in PRBS coding, for data-rates from 2 to 12.5 Gbps using input ERs up to 13.9 dB. Greater than 10 dB ER reduction is obtained at 7 Gbps (from 11.6 dB to 0.77 dB), and for 2 Gbps (from 13.9 dB to 0.74 dB). The results obtained at 12.5 Gbps are similar. The ODE is analyzed for different parameters such as the input extinction ratio (ERin), UL-SOA bias current, bit rate and input optical power.

After proper ODE, the optical carrier is ready to be modulated once more as presented in [12] where wavelength reuse was achieved by the optical carrier remodulation at 3.3 Gbps, after attaining ODE at 7 Gbps. The results presented here can be the basis for ODE implementation in WDM-PON with CLS.

2. Experimental setup

The experimental setup is shown at Fig. 1. The optical carrier is provided by a continuous wave (CW) tunable laser (L1, λ = 1565 nm). The AM signal is achieved by a Mach-Zehnder...
optical amplitude modulator and a signal generator operating from 2 to 12.5 Gbps in non-return to zero (NRZ) PRBS with variable extinction ratio. The wavelength band was centered at 1565 nm with an excursion of ± 15 nm. The 1565 nm wavelength corresponds to the peak of the UL-SOA amplified spontaneous emission (ASE) spectrum – with so, the better gain saturation is obtained. After modulation, the optical signal is amplified by a linear SOA to reach the adequate power levels and saturate the UL-SOA. Polarization control before the UL-SOA is also provided to maximize the effect. The ODE is analyzed using a 40 GHz oscilloscope with optical input, and an optical spectrum analyzer (OSA).

An insertion loss of 11 dB was measured between the laser output and the linear SOA input, with extra 2.5 dB loss from the linear SOA output to the UL-SOA entrance. Since the UL-SOA input optical power is a parameter to be analyzed, the linear SOA was biased from 120 mA to 210 mA, providing a gain variation from 4.3 dB to 10 dB. The UL-SOA has an active cavity of 8 mm divided in four sections: two center sections with 3 mm and two edge sections with 1 mm. The maximum total bias current is 2.7 A; in this work we report up to 450 mA in the center sections and up to 150 mA in the edge sections (total 150 + 450 + 450 + 150 mA = 1.2 A). By using an UL-SOA there is the benefit of operation based on the semiconductor’s fast nonlinear intraband effects, since the device is completely saturated after the first 1 mm in the active cavity, where the carrier density stays near the transparency condition. With so, slow interband effects are suppressed, as indicated in predictions for 4 mm-long UL-SOA, with net gain recovery time below 10 ps [13].

Due to the pronounced carrier injection, the UL-SOA presents deep gain saturation, enough to achieve the desired erasing behavior. Although, long active SOA cavities cause pattern dependence effects [14], which also might affect ODE.

Typical optical spectra are used at Fig. 1 to note the induced self-phase modulation (SPM) after the UL-SOA, and the ASE noise floor (−40 dBm) introduced by the linear SOA. These spectra are depicted for an input extinction ratio of 6.07 dB; further details are presented in Section 4.5.

3. Principle of operation

For a satisfactory ODE occurrence, the UL-SOA needs to operate in its saturation region - optical gain decreasing with the injected input optical power. Since the injected power at the “0” level of the downstream signal can be significantly lower than that at the “1” level, the SOA gain difference between the “0” and “1” levels results in the desired ER reduction for the output signal. The gain saturation is a consequence of the finite electrical carriers density [15], and the UL-SOA has the benefit to allow deep gain saturation, enabling the “0” level to be amplified up to powers very close to the “1” level, while this last one is slightly amplified. This UL-SOA behavior allows a good ODE even for carriers with high input ER.

The extinction ratio (ER) is defined as:
where $P_{\text{top}}$ and $P_{\text{base}}$ are the high and low AM signal power levels, respectively; $P_{\text{dark}}$ is the dark level noise. As mentioned before, the ODE is defined as $ER$ reduction after the UL-SOA. Thus, $ER$ of the input signal is called $ER_{\text{in}}$; we use the extinction ratio of the erased signal, $ER_{\text{out}}$, to quantify the ODE performance. The maximum suppression or ideal ODE would be achieved when $ER_{\text{out}} = 0$ dB.

Figure 2 shows typical eye diagrams for the downstream, AM carrier, and for the erased signal at 7 Gbps. At Fig. 2(a) the downstream signal presents a Q-factor = 9.14, optical input power = 5.4 dBm and $ER_{\text{in}} = 8.74$ dB; this signal was injected in the UL-SOA biased at 1.2 A (150 + 450 + 450 + 150 mA), obtaining the erased output of Fig. 2(b) – the amplitude modulation almost disappears: $ER_{\text{out}} = 0.63$ dB. The same occurs in the other case (Fig. 2(c) – 2(d), for lower $ER_{\text{in}}$ (2.74 dB) and Q-factor (5.3), obtaining an $ER_{\text{out}} = 0.27$ dB for input power of 6.8 dBm.

Note the eye-opening reduction, and that both the low and high input levels are amplified, with more gain to the lower levels - the data is erased but the optical carrier is kept similar.

The UL-SOA erases with good efficiency the downstream signals for bit rates from 2 to 12.5 Gbps, for diverse $ER_{\text{in}}$ and Q-factors. Numerous eye diagrams with ODE were obtained by varying the bit rate, the input optical power, the UL-SOA bias current, and the $ER_{\text{in}}$. The analysis of those experimental results is presented in the next section.

4. Experimental results and discussion

4.1 Bit Rate

The ODE performance was checked up to 12.5 Gbps. The results of Fig. 3 are presented for 2, 7 and 12.5 Gbps. The Fig. 3(a) shows $ER_{\text{out}}$ versus the UL-SOA total bias current for average
input power $P_{in} = 3.1$ dBm. The achieved ODE for 2 Gbps is better than for 7 Gbps carrier, even the first one having the highest $ER_{in}$. It is interesting to note that the $ER_{out}$ decreases with the increase of the total UL-SOA bias current; when it is driven at very high bias currents, the $ER_{out}$ is practically the same for all measured bit rates, approaching the ideal erasing ($ER_{out} = 0$). In Fig. 3(b), the $ER_{out}$ slightly changes with the input optical power, for a fixed UL-SOA bias current of 50 + 250 + 250 + 50 mA (I = 600 mA). Similarly to the results of Fig. 3(a), the signals at 2 Gbps achieved better ODE when compared with the signals at 7 and 12.5 Gbps signals. For all bit rates, the input optical power (>2 dBm) reveals minor influence in the $ER_{out}$.

Other cases with different $ER_{in}$ have also been studied with similar behaviors shown in Fig. 3(a) and (b). The higher erasure for lower bit rates reflects the UL-SOA relaxation time influence in relation to the bit time slot: the optical gain responds to the input power changes following this ratio. In an extreme situation, when the time slot is smaller than the relaxation time, the optical gain might not respond to changes in the input power. Thus, due to the time slot reduction the bit pattern suppression characteristic deteriorates as the bit rate increases [7]. However, the small $ER_{out}$ dependence on the bit rate (Fig. 3(b)) is an evidence that the UL-SOA relaxation time is still smaller than the time slot of 12.5 Gbps, and good ODE results may be achieved for even faster bit rates.

![Fig. 3. ODE for 2, 7, and 12.5 Gbps: (a) $ER_{out}$ versus UL-SOA bias current for $P_{in} = 3.1$ dB; (b) $ER_{out}$ versus $P_{in}$ for UL-SOA bias current of 50 + 250 + 250 + 50 mA.](image)

### 4.2 UL-SOA bias current

The UL-SOA gain saturation depends on its bias current ($I_{bias}$). The ODE performances for different combinations of bias currents in the UL-SOA sections versus the input optical power are presented in Fig. 4. It is shown that higher $I_{bias}$ provides deeper gain saturation and better ODE. The ODE for the larger $I_{bias} = 1.2$ A approaches the ideal value. Therefore, higher modulation suppression would be obtained by increasing the bias current.

Another parameter studied is the relation of the bias current in the central and in the edge sections of the UL-SOA active cavity, since non-homogeneous current injection might affect the UL-SOA behavior [16]. For several cases the relation 3:1 was kept between the current of the central and the edge sections in order to maintain the same current density in the active region. However, in Fig. 4 it is possible to note the similarities between the cases 0-240-240-0 mA and 60-180-180-60 mA, both with total current of 480 mA. From other similar tests performed in this work, it is possible to conclude that the proportion of the bias current between the central and edge sections makes less noticeable differences, indicating that carrier diffusion occurs quickly enough and what really matters is the total current injected into the UL-SOA. Therefore, we consider only the total current in the following sections. The same
behavior of Fig. 4 was noted for lower $ER_{in}$, but with the difference that even the case with lower total current achieved low $ER_{out}$, with its curve closer to the others. A similar behavior is maintained for bit rates from 2 to 12.5 Gbps.

**4.3 Input optical power**

The UL-SOA gain saturation depends on the input optical power ($P_{in}$) too, but from the results of Fig. 3(b) and Fig. 4 it can be noted that $P_{in}$ has no great influence on the ODE. The plot of Fig. 5 confirms this effect, observing the $ER_{out}$ versus the UL-SOA current for different values of $P_{in}$.

In this case, the $ER$ was obtained for a signal at 7 Gbps, $ER_{in} = 8.74$ dB and a Q-factor = 9.1. The $P_{in}$ influence is higher for low bias currents, since it is not enough to provide high saturated optical gain. As the bias current increases, this is the dominant parameter for the gain saturation and the influence of the input power decreases. For high bias currents, the saturation power is approached independently of the input signal power, not only for bit maxima but also for the bit minimum value (“0”) [14].

**4.4 Input extinction ratio ($ER_{in}$)**

The $ER_{in}$ is also another important parameter to be analyzed, since ODE can be sensitive to that. The tested values of $ER_{in}$ at 7 Gpbs were: 2.47 dB; 6.07 dB; 8.74 dB; and 11.6 dB. As
expected, the ODE is better for low \( ER_{in} \) values, as shown in Figs. 6(a) and 6(b) - we note higher difference for higher \( ER_{in} \). For the high bias currents, it is noted that \( ER_{out} \) tends to the ideal erasure (0 dB) independent of \( ER_{in} \). This behavior illustrates the influence of the bias current. In Fig. 6(b) it is used \( I_{bias} = 1.2 \) A with a variation of the input optical power; there is no pronounced difference in ODE results. This leads to the same behavior mentioned earlier: lower \( ER_{in} \) leads to lower \( ER_{out} \); for higher \( ER_{in} \) higher is the ER difference achieved.

Thus, the possibility of using the UL-SOA for ODE in high \( ER_{in} \) signals is highly desirable, since the downstream signal can so have an excellent quality (high Q) for system operation at low bit error rate (BER).

**Fig. 6.** \( ER_{out} \) for different \( ER_{in} \) as a function of: (a) UL-SOA bias current (\( P_{in} = 4.5 \) dBm); (b) input optical power (UL-SOA bias current of 1.2 A).

### 4.5 Optical spectra

As mentioned before, the output signal presents a spectral broadening effect due to the UL-SOA self-phase modulation (SPM) [17]. This non-linear effect is dependent on the \( ER_{in} \), and the spectral broadening is not visible for the low \( ER_{in} \) values. The performance is illustrated in Fig. 7, where the spectrum of the output signal (at 7 Gbps) for \( ER_{in} \) values of 6.07 dB and 11.6 dB is shown for a UL-SOA bias current of 480 mA and \( P_{in} \) of 4.74 dBm.

**Fig. 7.** Output ODE optical spectra (7Gbps) for different \( ER_{in} \) for the case with bias current and input optical power of 480 mA and 4.74 dBm, respectively.

In general, since good ODEs were obtained for signals with low \( ER_{in} \), the SPM is not associated to the erasure process per se, but it is an effect due to the UL-SOA gain saturation. Thus, the spectral broadening is a drawback of the technique presented here when the
downstream signal has very high input signal power. In addition, the UL-SOA bias current also exerts influence on the spectral broadening (not shown here), and a very large UL-SOA bias current might cause undesirable output spectral broadening. Anyway, the most extreme spectral broadening observed in our study was from 0.89 nm (input) to 2.32 nm (output).

The results presented above were obtained for the wavelength of 1565 nm corresponding to the peak of the employed UL-SOA ASE spectrum. This is the best wavelength to obtain the gain saturation, and so the better ODE. Results were also obtained for a wavelength variation of ±15 nm around 1565 nm as shown in Fig. 8, where it is shown the \( ER_{\text{out}} \) as a function of the wavelength for signals at 12.5 Gbps (bias of 1.2 A) for two different input extinction ratios (\( ER_{\text{in}} \) equal to 10.4 dB and 6.8 dB). For both \( ER_{\text{in}} \) it was obtained an almost flat behavior from 1557 to 1565 nm, with \( ER_{\text{out}} < 0.5 \) dB. The ODE results deteriorate outside this interval, but \( ER_{\text{out}} \) remain below 1 dB in the entire 30 nm band tested. Even so, the results for this band edge could be improved using higher current as well as high input optical power. With further lambda-detuning, the optical gain decreases fast and so the ODE deteriorates. In addition, the UL-SOA demonstrates to be sensitive to the optical polarization, a particular behavior of the employed UL-SOA.

**Fig. 8.** Output extinction ratio (\( ER_{\text{out}} \)) versus wavelength for two different input extinction ratio (\( ER_{\text{in}} \)) with UL-SOA bias current and bit rate of 1.2 A and 12.5 Gbps, respectively.

**5. Conclusion**

Results for ODE based on UL-SOA gain saturation were presented. The erasing of amplitude modulation for high input ER carriers was obtained for 2, 7 and 12.5 Gbps, preserving the optical carrier. The best results were achieved for high UL-SOA bias current, with slightly better results for lower bit rates. The drawback is the spectral broadening present when the input signal has high \( ER \) and high input power. However, the erased output signals obtained here are ready to be re-modulated [12]. As a conclusion, the employment of UL-SOA for wavelength reuse based systems is a promising technique, and its design needs to consider the input signal \( ER \), the input power range, the wavelength bandwidth efficiency, and the UL-SOA maximum bias current.

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