Relative intensity noise suppression in reflective SOAs

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ABSTRACT

The reflective semiconductor optical amplifier (RSOA) capability to compress the relative intensity noise (RIN) is well-known and widely exploited in wavelength division multiplexing passive optical networks (WDM PON). While this feature has been previously analysed using SOA theory, in this paper we show that RSOAs present specific gain saturation properties. According to the injected power, three nonlinear operation regimes can be highlighted: the first one, where RIN is moderately compressed, the second one, where RIN maximum compression takes place, and the final one, where RIN grows again, this last regime being RSOA specific. We focus on a spectrum-sliced WDM PON classical topology, evaluating the impact of the injection process and filtering. RSOA injection and optical filtering have opposite effects on the RIN: by injection into the RSOA the RIN is reduced, after filtering RIN increases. We experimentally evaluate RIN both in the time and in the spectral domain. A simple numerical model mainly based on the correct reproduction of the component gain behaviour is exploited to verify experimental results. Through our experimental analysis and by simulations, we identify the correct injected power range to best take advantage of the RSOA features.

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1. Introduction

The reflective semiconductor optical amplifier (RSOA) capability to compress relative intensity noise (RIN) has been widely exploited in wavelength division multiplexing passive optical network (WDM PON) both with externally injected topologies [1] and with high-bit rate self-seeding configurations [2]. The analysis of this capability has usually relied on the consideration on travelling wave semiconductor optical amplifiers (SOA) [3]. Nevertheless SOA theory alone is not sufficient to describe RSOA signal compression, which results from its specific gain saturation properties [4]. According to the injected power, three nonlinear operation regimes have been highlighted, where the modulation component of the signal is moderately bleached, exactly cancelled and inverted respectively [4]. In the last regime, which is specific of RSOAs, the co-presence of two waves locally competing for gain along the device length causes a strong depletion. The output power is lower for higher input power and signal inversion occurs. As the RSOA noise reduction capability arises from the compression of the optical intensity fluctuations associated to the signal, it relies on the same mechanism governing modulation bleaching.

This paper aims at highlighting the characteristic RSOA gain saturation behaviour with particular regards to noise reduction capability. We focus on a spectrum-sliced WDM PON classical topology [1], as shown in Fig. 1a: a broadband laser source (BLS), close to the optical line terminal (OLT), is sliced by the arrayed waveguide grating (AWG) at the remote node (RN) and injected into an RSOA. The impact of the injection process and subsequent filtering actions associated with the topology on the signal RIN are evaluated both experimentally and through simulations. Experimental measurements are made both in the time domain and in the spectral domain. Simulations exploit an RSOA simple model, which has been realized with commercial software, OptSim by RSOFT [5], and uses the data collected from the RSOA gain experimental characterisation.

2. Experimental setup

The experimental setup employed to measure both the RSOA gain and the RIN compression is shown in Fig. 1b. The BLS, that is an erbium doped fibre amplifier (EDFA) with no input signal, is sliced by a 0.43-nm athermal Gaussian AWG with 100-GHz channel spacing. The slice is centred at 1533.5 nm and is further optically amplified with an EDFA to ensure sufficient dynamic for the injected power. After the second EDFA, a large filter removes off-band optical power without affecting the slice RIN. A tap coupler monitors with a power metre the RSOA injected power, which is varied by means of a variable optical attenuator (VOA).

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The slice is then fed into the RSOA through a circulator. The RIN is measured in different point of the network, while varying the injected power, displayed both in Fig. 1a and b in order to clarify the meaning of the measurement. Point ① is immediately before injection, point ② is after RSOA injection, point ③ is after RN AWG filtering, and point ④ is after OLT AWG filtering, performed by a twin AWG. The RSOA by Alcatel–Thales III-V Lab used in the experiment [6] has a 3-dB modulation bandwidth in excess of 1.5 GHz and its polarisation dependent gain (PDG) is around 0.5–1 dB, being lower under saturated conditions. The optical signal is received with a PIN TIA with 125-MHz electrical bandwidth. The electrical signal is acquired with a real time oscilloscope, recording 2,000,000-sample sequences. The mean and standard deviation of the input electrical power are measured and used to evaluate the RIN, according to its definition [7].

Spectral RIN measurements have been performed replacing the receiver with a 10-GHz PIN photodiode followed by an electrical spectrum analyser.

3. RSOA characterisation and compression measurements

The results of RSOA output power versus input power are displayed in Fig. 2 for the 180 mA and the 100 mA. Both curves show the RSOA highly nonlinear behaviour discussed in [4]. The modulation cancellation dynamic range (MCDR) is from –10 dBm to –5 dBm both at 180 mA and at 100 mA. Input signal marks and spaces in this range results in an output signal whose marks and spaces have the same level. This MCDR thus identifies the region of operation for signal modulation bleaching, and it is thus fundamental for the definition of the link power budget, i.e., the maximum allowable reach. The output power versus input power curves have been also obtained through simulations with commercial software, which uses an RSOA model with a reservoir approach as in [8,9]. The parameters used in the simulations are listed in Table 1. The simulated curves displayed in Fig. 2 show a very good agreement with experiments.

The RIN measurements demonstrate that this region also corresponds to maximum RIN compression. The RIN experimental measurements in the time domain are shown in Fig. 3a and plotted versus RSOA injected power in the different measurements points highlighted in Fig. 1b. Open diamonds and squares represent respectively the RSOA RIN, which is –116.7 dB/Hz, and the 0.43-nm slice RIN, which is -106.54 dB/Hz. The full-square curve describes RSOA RIN compression at point ②, that is immediately at RSOA output. For low injected-power (lower than –30 dBm) the RSOA output optical signal to noise ratio (OSNR) is quite low, that is to say that a significant amount of unfiltered ASE is present. The measured RIN is thus lower than for higher injected power, compare the datum at –35 dBm injected power with the following taken at –30 dBm. The RIN decreases, when the injected power increases beyond –25 dBm. As can be seen from Fig. 2, for input powers higher than –25 dBm gain saturation is clearly noticeable. A minimum of the compressed RIN value is reached between –10 dBm and –5 dBm, in this range, which corresponds to the MCDR [4], the output power is almost constant, independently of the input power fluctuations, as Fig. 3b schematics show. The RIN value within this MCDR is improved of almost 8 dB with respect to the slice RIN. For injected powers higher than –5 dBm, the RIN starts rising again. In this highly-depleted regime, which corresponds to the signal inversion [4], for growing input power signal fluctuations increase as well, as Fig. 3c schematic shows.

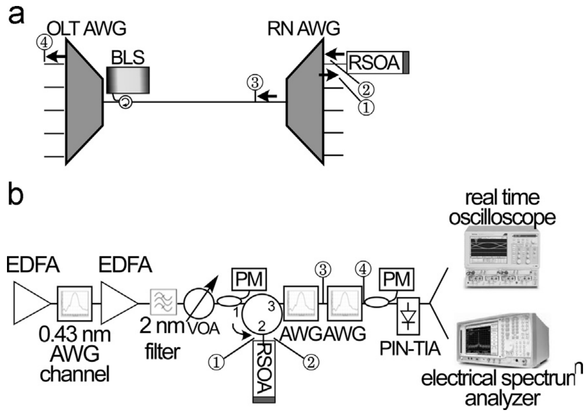

Fig. 1. (a) Typical WDM PON topology based on spectrum-sliced broadband laser source and (b) experimental setup for RIN measurements.

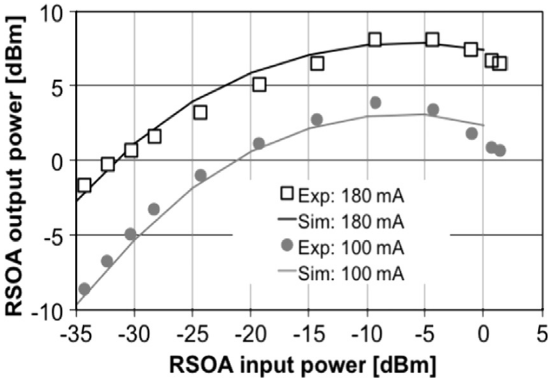

Fig. 2. Measured (dots) and simulated (continuous lines) RSOA output power versus input power at 180-mA (black) and 100-mA (grey) bias current.

Table 1
RSOA simulation parameter.

Parameter	Value
Reflectivity	0.3
Length	1.2 mm
Width	2.8 μm
Thickness	0.2 μm
Confinement factor	0.325
Linewidth enhancement factor	5
Linear recombination coefficient	$1.43 \times 10^{-8}\ \mathrm{s}^{-1}$
Quadratic recombination coefficient	$10^{-16}\ \mathrm{m}^3\ \mathrm{s}^{-1}$
Auger recombination coefficient	$3 \times 10^{-41}\ \mathrm{m}^6\ \mathrm{s}^{-1}$

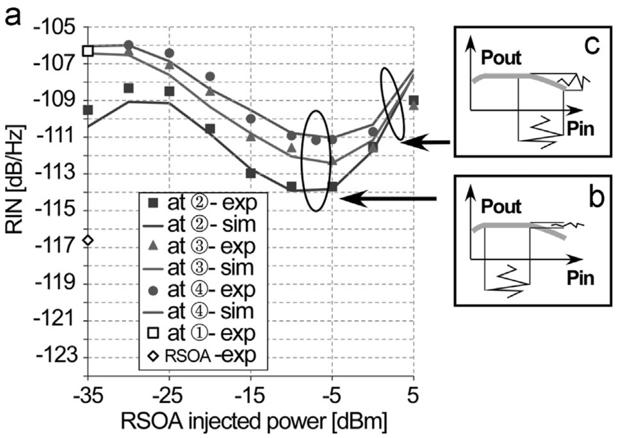

Fig. 3. (a) RIN compression versus injected power, experiments (dots) and simulations (continuous line), (b) schematic of RIN compression in the exact bleaching regime, and (c) schematic of RIN compression in the signal inversion regime.

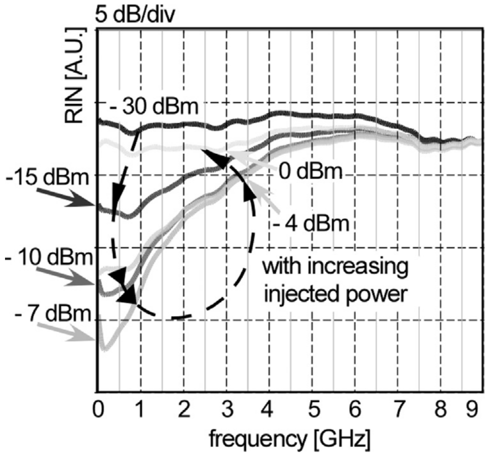

Fig. 4. RSOA slice RIN spectra for different injected power at 180 mA.

The full-triangle curve in Fig. 3a describes the RIN after RN AWG filtering, at point ③. The AWG filters the added ASE at low-injected power, thus the RIN at −35 dBm and -30 dBm is quite the same and the effect previously noted in point ② on the full-square curve is not present. When input power approaches the saturation value, the RIN decreases and a minimum is found again between −10 dBm and −5 dBm. When also OLT filtering is applied, at point ④, the full-circle curve in Fig. 3a is obtained. The overall behaviour of the three RIN versus injected power curves is similar, evidencing the three nonlinear regimes already highlighted in [4]. RN AWG filtering causes a 2-dB deterioration of the RIN, as expected [3], while the additional OLT AWG filtering worsens the RIN of 0.3 dB. Fig. 3a also presents the simulated RIN results (continuous-line curves) using the developed RSOA model, as can be seen the three nonlinear regimes are also evident: the RIN moderate compression, the maximum RIN compression and the RIN re-growth. It is noteworthy that the good agreement with the experimental results has been achieved by targeting the RSOA model to fit the gain curve.

The RIN spectra at point ②, at the RSOA output, have been also measured and the results are shown in Fig. 4 for various injected powers, exploring the linear region as well as the three nonlinear regimes. The different spectra have been obtained at fixed power at the receiver and by subtracting the photodiode noise spectrum. At low injected power, −30 dBm, the RIN spectrum is almost flat. As the injected power is increased up to −7 dBm the low-frequency components are compressed, as expected [3]. The maximum compression bandwidth approximately corresponds to the 3-dB modulation bandwidth, and is around 2 GHz. For increased injected power, the RIN spectrum low-frequency deep reduces and at −4 dBm power it is similar to −10 dBm. At −4-dBm injection level the RSOA operates in the third nonlinear regime, where the measured RIN grows again. It is also interesting to note that at higher injected power, 0 dBm, the RIN spectrum is quite flat again.

4. Conclusion

The experimental data shown in this letter demonstrate the peculiar behaviour of RSOA with respect to SOA in terms of RIN compression. The three nonlinear regimes, already reported in [4] in relation to signal modulation compression, have been highlighted in relation to RIN reduction stemming the importance to operate in the MCDR to take advantage of both RIN suppression and signal modulation bleaching. By means of a model based on RSOA gain fitting the experimental results have been confirmed with simulations. For the first time to the best of our knowledge, it has been shown spectrally that the RIN spectral behaviour is significant altered when operating in the highly nonlinear regime.

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