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Noise effects relating to saturated region in semiconductor optical amplifier

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A B S T R A C T

Almost one is capable to change injected current into $SOAs$ easily, so, our simulation focuses on the effect of injected current on saturation power achieved with various fast dynamics included ASE, CH, and SHB. The NF effects at saturation power and its compression close saturation region are studied in the research. The association of input power or output power at which the noise start to be less has applications concerned traffic data in the data center.

Keywords: *Semiconductor Optical Amplifier, Saturation Region, Ultrafast Dynamics, Noise.*

1. Introduction

Due to their tiny size, integrability, low cost, and flexible bandwidth, semiconductor optical amplifiers (SOAs) with wavelengths of 1.3 and 1.55 μm are crucial components for high-speed transmission networks. [1]. Reducing the noise figure (NF) of SOA amplifier reduces the minimum input power required to amplify data signals. Minimizing NF requires factor of population inversion (n_{sp}) to be close 1. The latter can be accomplished by increasing the current injected into SOA as much as possible; the upper bound on input power is set by both phase and amplitude shifts in the data signal caused by gain saturation. Thus, large saturation input power (P_{in}^{sat}) *must be large, in this case* gain saturation can be avoided. The high limit of input power to amplified data signals into SOA can be increased via the choice of gain to be moderately high, however, this takes place if a modal cross section A/Γ is large which turn is achieved by doping the active region to decrease the effective carrier lifetime, also, a high injected bias current, and with a low differential gain ***[2]***. In addition, low alpha-factor, somewhat quick gain, and phase dynamics is preferred if gain saturation cannot be avoided.

The saturation regime offers several unique benefits for $SOAs$. Since it has nonlinear characteristics, they can be employed for optical signal processing, wavelength conversion, and optical regeneration. 2) Their ON/OFF commutation time is within the range of nanosecond, which could be desired and useful for optical packet switching. 3) the wide bandwidth (~80nm) which is centered in the range of $1200-1550\,nm$ **[3].**

The output efficiency of the amplifier is controlled by a number of SOA parameters, including gain, NF, output power at saturation area, bandwidth of gain, time of recovery, and other ultrafast-dynamics factors like CH and SHB. These variables have a big impact on the saturation region. **[5,6,7,8]**. NF is undesired consequence of saturated signal gain by amplified spontaneous emission (ASE) and the temperature dependent of intrinsic limitations of internal optical loss and population inversion factor. **[4]**.

In this work, we numerically solve the rate equation which it must couple with the equation of propagated pulse down into SOA to get a deeper understanding of the outpower against restarted time and, then, the relationship between output power as a function of input power. From the latter, it can be studied the saturation power region and since NF is expected to occur at saturation of signal gain by amplified spontaneous emission ASE , so, we focus NF close saturated region. Also, the dynamics which can occur depending on pulse passed with NF is studied in this research.

2. Methods and SOA Parameters

If population inversion takes place, SOA exhibits optical gain (G) in active region of SOA. Simply speaking, this indicates that the SOA output power (P_{out}) is higher than its input power. The level of input optical power (P_{in}) and the wavelength affect the gain of a SOA. As a function of signal power, G can be represented as **[9]**:

$$G = \frac{P_{\text{out}}}{P_{\text{in}}} = e^{h(\tau)} \tag{1}$$

where $h(\tau)$ is the integrated gain and can be obtained by numerically solving of the equation**[**10**]**

$$\frac{dh}{d\tau} = \frac{1}{1+\varepsilon P_{in} e^{h}} \{\frac{h_o}{\tau_{cdp}} - \frac{h}{\tau_{eff}} - (e^{h}-1)[\varepsilon \frac{dP_{in}}{d\tau} + P_{in}(\frac{\varepsilon}{\tau_{eff}} + \frac{1}{\tau_{cdp} P_{sat}})]\} \tag{2}$$

$\varepsilon = \varepsilon_{shb} + \varepsilon_{ch}$ which is called as the gain compression factor. h_o is the unsaturated gain $(h_0 = g_o z)$, the carrier lifetime is (τ_{eff}) that is due to spontaneous emission (SE). The others parameters occurred in the last equation will be explained in table (1) below. Integrating equation (2) with the propagation one **[**11**].**

$$\frac{\partial P(z,\tau)}{\partial z} = [g(1-\varepsilon P) - \alpha] P(z,\tau) \tag{3}$$

will give information about the relation between P_{out} versus restarted time (τ) at a certain P_{in}. For more P_{in} , one can get relations between P_{out} and P_{in}. from the latter is possible to get in saturated input and output power $(-3dB)$ or 50% with comparison unsaturated gain) [12]. Also, From the shape curve and for various input powers one can get the gain versus input or output power. For gain calculated, NF can be calculated as will explain in section 2 [13,14].

3. Noise figure in SOA

All amplifiers have noise; it cannot be avoided. Stimulated emission enables the amplification of incoming signal photons in any optically amplifying medium. However, a random and incoherent process known as carrier relaxation via SE will also take place [15,16]. Spontaneous emission events only add a detectable amount of noise power to the signal because they can emit a photon at any wavelength and in any direction or phase **[17]**. In electronics, an amplifier's noise properties are assessed using the noise NF. A helpful figure of merit is the NF. Its basic definition is a measurement of the signal-to-noise ratio degradation of a signal during transmission through the target device or system. Normally, it is expressed in decibels (dB) **[18]**. The shot noise, the signal-spontaneous beat noise, and the spontaneous-spontaneous beat noise are the three different types of noise. The following equation can be used to calculate the ASE noise's power within the SOA:

$$P_{ASE} = 2 \cdot n_{sp} \cdot h \cdot v \cdot (G-1) \cdot B_0 \quad (4)$$

whereas G is the gain at the optical frequency v, h symbolizes the Planck's constant, B_0 is the optical bandwidth, and n_{sp} represents the population inversion factor. In ideal amplifier, n_{sp} is equal to 1, equivalent the complete inversion of the middle. Although, in the usual case, the population inversion is partial and $n_{sp} > 1$. Noise can be represented by an equation containing the three types of noise [19**]:**

$$NF = \& \frac{1}{G} + 2 \cdot n_{sp} \cdot \frac{G-1}{G} + \frac{h \cdot v \cdot B_0 \cdot n_{sp} \cdot P_{in} \cdot (G-1)}{P_{\text{out}}^2} + \frac{h \cdot v \cdot (2B_0 - B_e) \cdot n_{sp}^2 \cdot P_{in} \cdot (G-1)^2}{2 \cdot P_{out}^2} \quad (5)$$

Due to the low ASE power in comparison to the signal power, the final two portions can be ignored in practice. Alternatively, the spontaneous-spontaneous beat noise can be decreased by adding an optical filter to the output. NF can be rewritten as follows **[20]:**

$$NF \approx \frac{1}{G} + 2 \cdot n_{sp} \cdot \frac{G-1}{G} \quad (6)$$

Since the spontaneous emission factor (n_{sp}) is always greater than 1, the smallest value of NF is obtained when $n_{sp} = 1$. Therefore, NF of an ideal optical amplifier is 3dB for large gain values $(G \gg 1)$ This is thought to have the least amount of NF. This implies that each time an optical signal is amplified, the signal to noise ratio is reduced by half.

3. Results and Discussion

Table 1. lists the parameters that were used in our simulation **[21]**

Table1: simulation parameters		
Parameters	Symbol	Value and unit
SOA region length *	LE from [**22**]	700 µm
Width	W	$3 \times 10^{-6}\, m$
Height	H	$80 \times 10^{-9}\, m$
Confinement factor	Γ	0.3
Pulse width **	τ_p from [**23**]	0. 84 psec
Current	I	varied
Carrier life time	τ_{cdp}	292 psec
Effective gain recovery***	τ_{eff} from [**24**]	20 psec
Differential gain	a	$2.78 \times 10^{-20}\, m^{-2}$
Carrier density at transparency	N_o	$1.4 \times 10^{24} m^{-3}$
Carrier density used	N	$3 \times 10^{24} m^{-3}$
Saturation energy	E_{sat}	3.74pJ
Compression factors due to CH	$\boldsymbol{\epsilon_{CH}}$	$0.2\, W^{-1}$
Compression factors due to SHB	$\boldsymbol{\epsilon_{SHB}}$	$0.2\, W^{-1}$
Nonradiative recombination coefficient	A	1.5×10^{8}
Bimolecular recombination coefficient	B	10×10^{-16}
Auger recombination coefficient	C	3×10^{-41}

For certain operating conditions, concerning with the current injected into SOA which is pumped- electrically, different values of the current were pumped for slow dynamic $\epsilon = 0$, fast dynamic $\varepsilon \neq 0$ without and in presence ASE factor (τ_{eff}). For mentioned dynamics, the value of P_{in} and P_{out} were calculated both versus profit values G. At certain values of the P_{in}, the value of the P_{out} begins to be almost a value where the amount of profit G remains a constant which is known as unsaturation gain. On the other hand, we calculated the NF for several values of the input power for more than one current value, as illustrated in Fig.(5). G is discovered to be independent of optical power at low P_{in} levels. It displays the relationship between P_{out} and P_{in} that is expressed as gain in dB as a function. of P_{in} and once of P_{out} . If P_{in} is high enough, P_{out} is linearly developed, and G then starts to rely on the P_{in} signal as a result of the low inversion level following those results in saturation gain as illustrated in Fig.1. The description is general for figures (1-4).

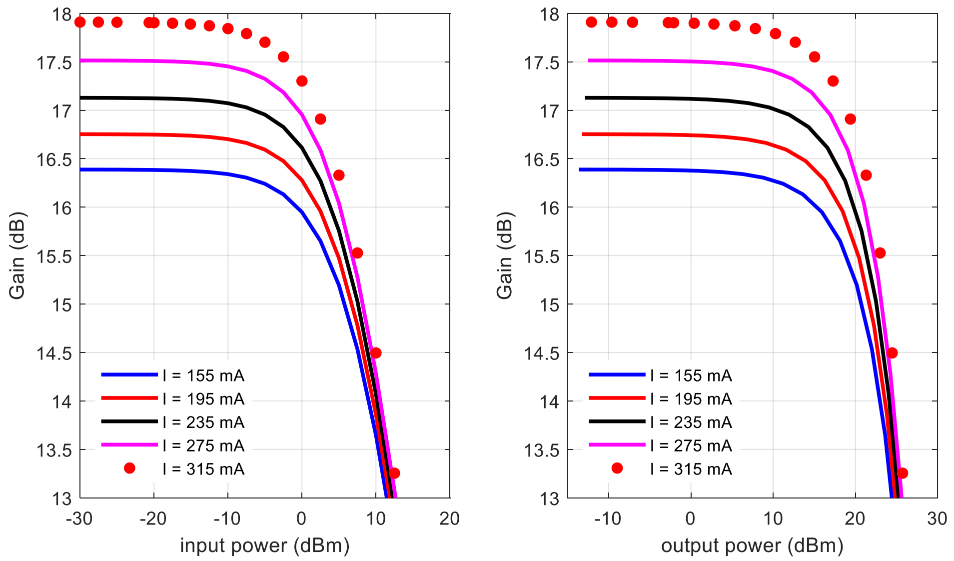

Figure 1. P_{in} and P_{out} vs G for slow dynamic without ASE

When entering ASE value in G calculation, it can be noted a decrease in the amount of G corresponding to each value of P_{in} with a slight change in the value of P_{out}. It is worth noting that the saturation region is further when taking into account ASE value, and this is evident in Fig. (2).

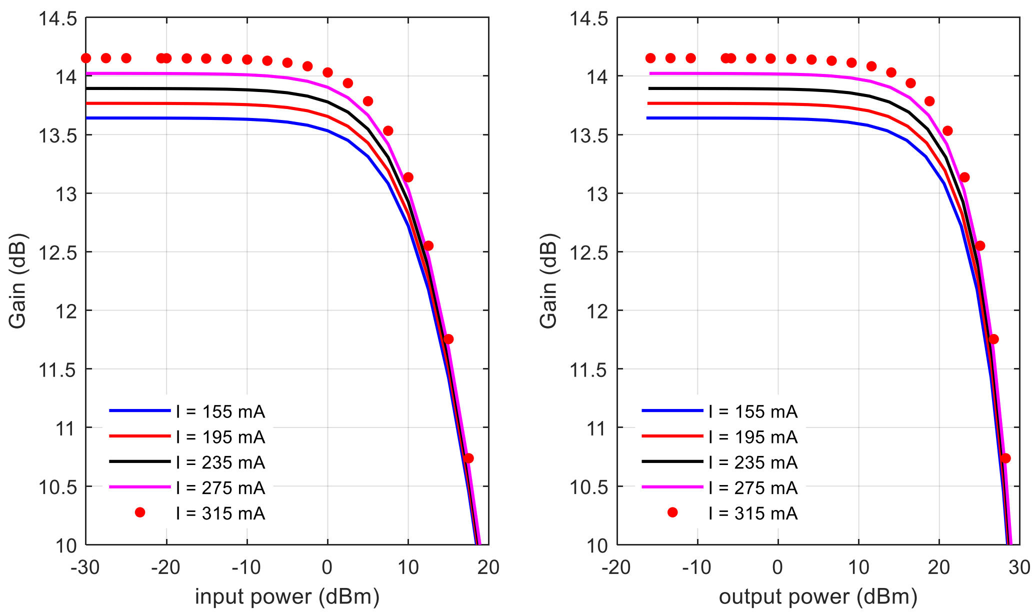

Figure 2. P_{in} and P_{out} vs G for dynamic presented by ASE only

It is also noted from Fig. (1) and (2) that when the pumping current is increased, the amount of gain increases, due to the increase of carrier's density, which contributes to the occurrence of stimulated emission and thus the gain increase.

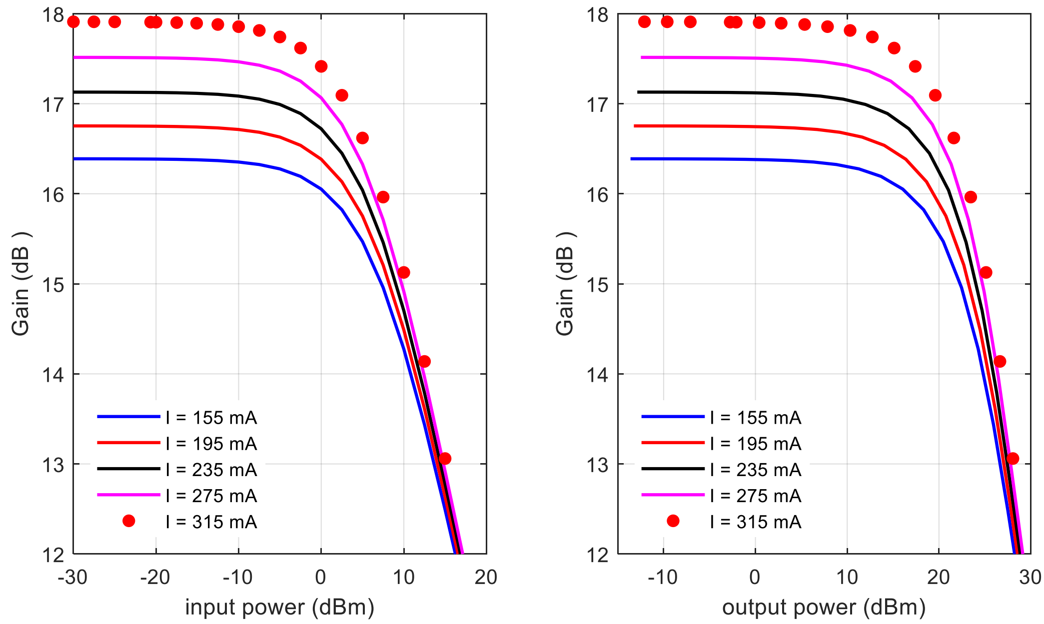

Figure 3. P_{in} and P_{out} vs G for fast dynamic presented by ϵ only

the relationship between G versus P_{in} and P_{out} taking into account compression factor with neglecting ASE for different values of bias current explained in Fig. (3). It can be noted G is linearly increased when P_{in} and associated P_{out} are low. If the letters increase more, G starts to be unsaturated. However, this behavior can be considered as indication for occurrence unsaturated case.

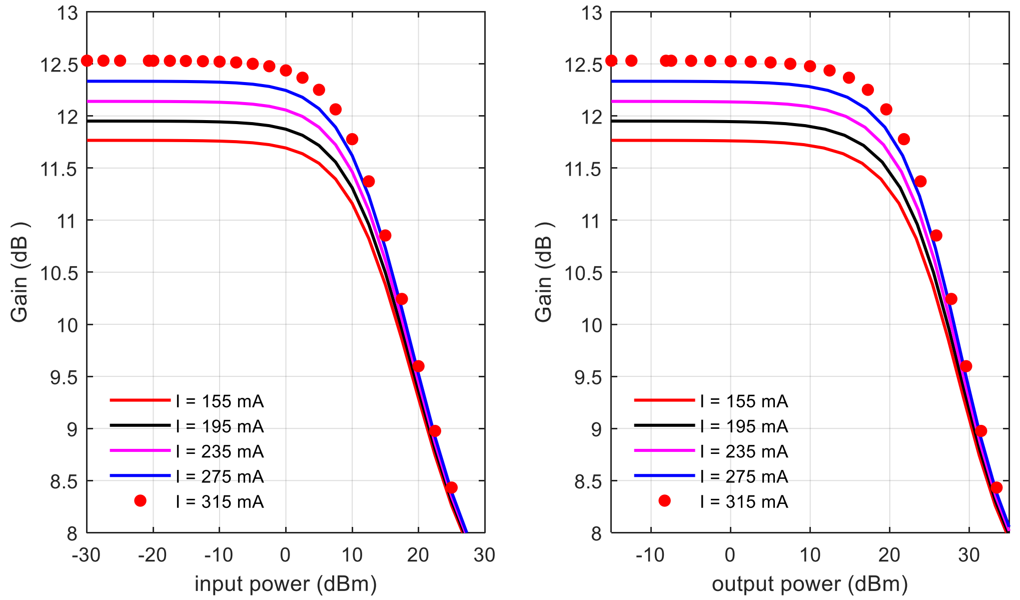

Figure 4. P_{in} and P_{out} vs G for fast dynamic presented by ϵ and ASE

There is a direct impact of applied current used for biasing the SOA on carrier density and gain. At higher bias current, the larger number of electrons that overcome the energy gap will lead to an increase the carrier density, thus leading to an increased SOA total gain. Also, one can note that SOA gain reduces with increasing the input signal power and this response appears at all bias current values. On the other hand, higher biasing current values achieve higher gain. The highest gain achieved is 17.91 dB at current 0.315 A while a decrease gain takes place at bias current of 0.15A and a gain of 16.39 dB.

In Fig. (4), entering the ASE value and $\boldsymbol{\epsilon}$ in the gain calculation attain a decrease in the calculated G value, where G = 12.35 dB at a rated current 0.315 A, because a huge portion of injected carriers are used in amplifying ASE. In the region with high gain, the ASE power is copropagating.

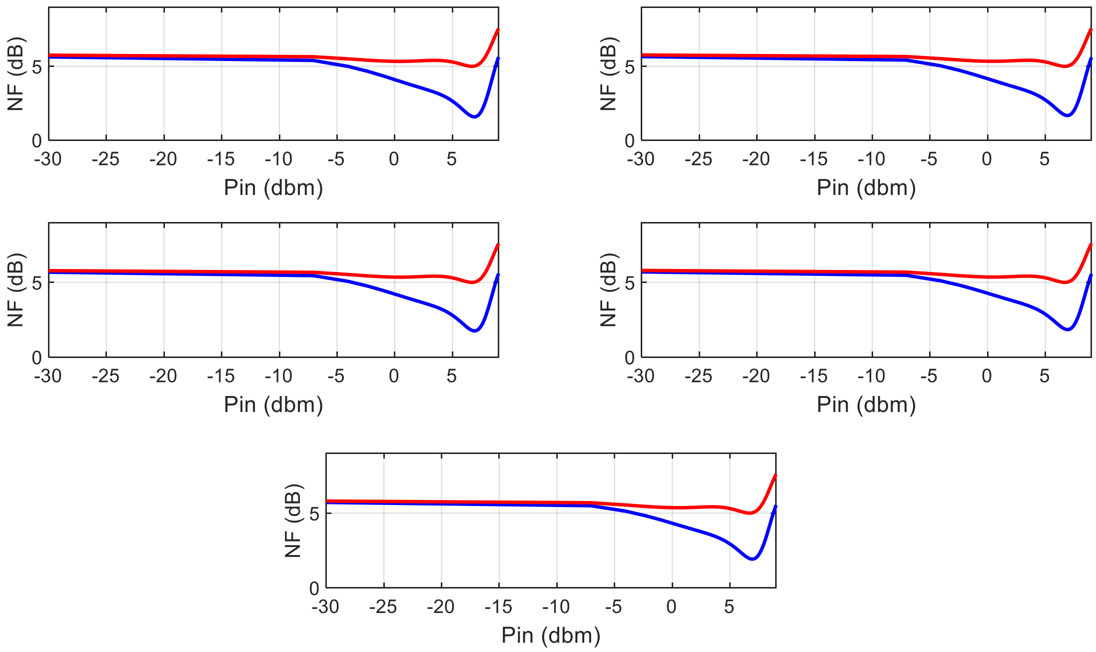

Figure 5. NF vs P_{in}. Presence ASE only (red), ASE in addition to ϵ (black) for: $I = 155\ mA$ upper left, $I = 195\ mA$ upper right, $I = 235\ mA$ middle left, $I = 275\ mA$ middle right, $I = 315\ mA$.

Fig. 5 shows NF versus $\boldsymbol{P_{in}}$ in presence ASE (red) only, ASE and $\boldsymbol{\epsilon}$ together. The NF of ASE dynamics is less than fast dynamic included ASE and $\boldsymbol{\epsilon}$ together. NF does not show any significant dependence on the current or $\boldsymbol{P_{in}}$. On the contrary, the NF in presence of ASE dynamic decreases with increasing input power and tow curves of all figures have the same behavior when $P_{in} \cong 7dBm$ because SE is dominant with comparison stimulated emission. The NF in presence ASE only is dependent on rapidly changed for G in Fig. (1). The NF reduction is then consistent with mentioned change for all injected current used in our simulation. The minimum of NF ranged from $1.6\ dB$ at $I = 150\ mA$ to $1.93\ dB$ at $I = 315\ mA$ as shown in Fig. (5). that's good prediction concerning on noise reduction close the saturation point $(-3\ dB)$ from unsaturated gain.

5. Conclusion

In order to illustrate dynamics (fast and slow) in SOA and their effects on the saturation area with some parameters basically focused on injected current. The fast dynamics that CH and SHB in addition to ASE and their influence on the saturation power region are investigated. Each chart has significant rapid feature concerned with change type of G function. NF is dependent on G change, in accurately expression, the rapid change of G. Therefore, the choice of suitable parameters and used dynamics assist us for estimating the performance of NF performance close saturation region and the control on noise as factor is a main aim because it cannot be removed.

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