Ibn Al Haitham Journal for Pure and Applied Science

Journal homepage: http://jih.uobaghdad.edu.iq/index.php/j/index

Dynamics and its Effects on Saturation Region in Semiconductor Optical Amplifiers

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Article history: Received 20, July, 2020, Accepted 13,Augest, 2020, Published in October 2021.

Doi: 10.30526/34.4.2698

Abstract

We focus on studying the dynamics of bulk semiconductor optical amplifiers and their effects on the saturation region for short pulse that differ, however there is the same unsaturated gain for both dynamics. Parameters like current injection, fast dynamics present by carrier heating (CH), and spectra hole burning (SHB) are studied for regions that occur a response to certain dynamics. The behavior of the saturation region is found to be responsible for phenomena such as recovery time and chirp for the pulse under study.

Keywords: Semiconductor Optical Amplifier, Semiconductor Optical Amplifier Parameters, Parameters of ultrafast dynamics of SOA

1. Introduction

In a long distance optical communication system, when the signal force becomes low, we need to boost up it. So many amplifiers invented to make this happen from the bulk semiconductor-optical amplifier (SOA) [1]. Travelling wave- SOAis considered one of the most important devices because it has main characteristics, such as little size, highly gain, wide gain bandwidth, and the capability to be integrated in the cost effective way [2,3]. The bulk SOA origin began after evolution for the Fabry-Perot -cavity that utilized into an evolution of the lasers. A researcher's attention increased to SOA because it has a non-linear feature, we focus to one feature that included the study of the output power against input power which that clearly referred to the saturation power region under consideration. By utilizing its non-linear features, SOA could be utilized into a range of the optical applications such as optical routing, wavelength conversion, pulse compression, an optical-logic design, etc. [4,5]. SOAs are almost like semiconductor-lasers into which they need a gain area that is electrically pumped for supply electrons to the active area [6]. Also, it has two types: the first is Fabry-Perot amplifier and the second travelling-wave amplifier [7,8].SOA has many parameters like gain, the noise figure, saturation output power, gain bandwidth, and recovery time, and other parameters of ultrafast-dynamics such as CH and SHB, which are used to determine the performance of the amplifier and to control the output performance.These parameters have a signifcant influence on the saturation region[9,10,11,12]. The advantages of utilizing SOA as an essential gain-element into futurity of all the optical systems and the numerous results obtained give a lot of knowledge to the designers for possibility of utilizing SOA into a various optical system [13].

In this work, we used the Runge-Kutta fourth order method to solve numerically the rate equation that coupled with the propagation one to get a wider knowledge about the power shape and the relation between output power as a function of input power that refers to the saturation power region at which the gainreduced by 3dB or 50% relative to the unsaturated gain. The paper is regulated as follows. Into section 2 contains SOA parameters, Parameters of ultrafast dynamics of SOA are provided in section 3, Numerical Implementation presented into section 4, followed by results and discussion into Section 5, lastly, conclusions are drawn into section 6.

2. SOA Parameters

An important parameter to take into account is gain (G). This parameter is perhaps the most essential and can be considered as a parameter for OA operation [14].It directly effects the saturation region. The function of any optical amplifier is to increase the optical signal power. The increase of the input power when passed through SOA is called G. However, the gain of SOA is given by [15]:

$$G = \frac{P_{out}}{P_{in}} \quad (1)$$

whereP_{in} is power of input-pulse, the and P_{out} is the power of the out-put pulse. The above equation represents the main transfer function of the device in our work[15].Another parameter is defined as the out-put power for which amplifier gain is decreased by three Deci Bell from its unsaturated value; it is a "saturation power"[16]. The importance of the region (saturation region) at which the power is saturated can be used to refer to the upper boundary of SOA amplification to be linear. Also, it depends on P_{in} or is consistent with. Actually, when is saturated to be as high as possible. In this case, P_{out} can take the form according [14]

$$P_{sat,out} = P_{sat} \ln(2) = \frac{hv.wd}{\Gamma\, a_o \tau_c} \ln(2) \quad (2)$$

The energy of photon is represented byhv, $a_\circ$ is the coefficient of differential gain, $\tau_c$is the carrier lifetime, and Γ is the confinement factor[14]. To realize large $P_{sat,\ out}$, the gain medium must be pushed to the saturation depth where $a_\circ$is small [17]. The recovery time is the period of time which gain of the SOA needs for recover of (10 - 90%) of its final-value [18]. The accelerating of a gain recovery operation is essential in communication systems because it improves the out-put performance into the high-speed signal processing functions [19]. A gain recovery of the SOA happens on two various time scales. Firstly, on the scale of 1 picosecond, outcomes from intra-band effects like CH, two-photon absorption, and SHB. Secondly, in the order from 10 ps to 1 ns, results from the time taken by the traditional SOA to achieve a carrier density inversion, that is limited to long carrier lifetimes[20].The figure below shows packaged and schematic SOA.

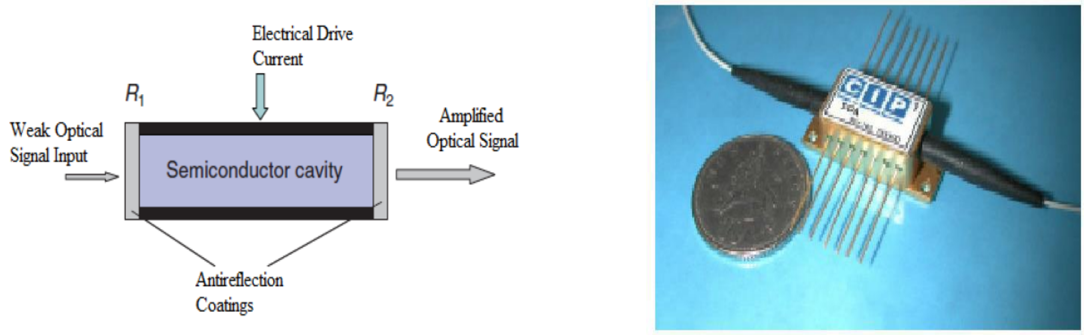

Figure 1 .SOA fully packaged (right), and SOA schematic (left) [12]

3. Parameters of Ultrafast Dynamics of SOA

The ultra-fast gain dynamics is mostly determined by utilizing the SHB, CH. **[21]**. So we will explain these parameters briefly:

3.1 Spectral Hole Burning

Before launching any optical pulse to SOA, which is forward-biased, the carriers of CB and VB, respectively, within each band are in thermal equilibrium, and also the Fermi-Dirac distribution will be followed. When a released pulse is within (a few ps) into SOA active region, electrons of CB will be depleted at the appropriate photon energies due to stimulated recombination. So, in energies of these photons, the number of carriers and then its gain is reduced. The spectral (almost symmetric) hole will be burned in the distribution of carrier; for this reason, this influence is known as SHB. It is an "ultrafast" impact on the temporal scale of a few fs[22].

3.2 Carrier Heating

If the carrier's equilibrium inner a band is destroyed by quick operations, the immediate carrier occupation probability cannot be described anymore using a "Fermi" function. Nevertheless, after refilling the vacant states left by means of SHB, the carrier occupation probability follows once more a Fermi distribution with an efficient (hot) carrier temperature greater than a lattice temperature. This process is known as "CH". By warming the carrier distribution, the gain is lowering, and the refractive index will increase. Later, the hot carriers cool (a carrier cooling), and the gain is relaxed again on a timescale up to picosecond the CH relaxing time [23].

4. Numerical Implementation

The propagation of the pulse down into SOA can be described by [24]

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

Whereϵ_m is the sum of compression due to CH and SHB and α is the loss factor that can be neglected for small it. The term g that is the gain produced for pulse passed through SOA active region and the equation that helps as for calculating g represented by the single differential equation included fast dynamics and ASE contribution [25]

$$\frac{dh}{d\tau} = \frac{1}{1+\epsilon_m P_{in}\, e^h}\left[\frac{h_o}{\tau_c} - \frac{h}{\tau_{eff}} - (e^h - 1)\left\{\epsilon_m p'_{in} + P_{in}\left(\frac{\epsilon_m}{\tau_{eff}} - \frac{1}{\tau_c\, P_{sat}}\right)\right\}\right] \quad (4)$$

$h = gz$ is the integrated gain coefficient for the section of SOA, h_o is the unsaturated value of $h = g_o\, z$, τ_{eff} is the carrier lifetime due to spontaneous emission. And, $p'_{in} = dP_{in}/\, d\tau$. The output power from the subsection can be expressed by [26]:

$$P_{out}\,(\tau) = P_{in}(\tau)e^{h(\tau)} \quad (5)$$

and the chirp can be written as :

$$\Delta v_{out}\,(\tau) = \Delta v_{in}\,(\tau) + \frac{\beta_{cdp}}{4\pi}\,(\frac{dh}{d\tau}) \quad (6)$$

where$\Delta v_{in}\,(\tau)$ is the input chrip of an input pulse [26]. It is obvious that if $\varepsilon = 0$, then equation(2) must be reduced to their compression to be free. Moreover, the neglecting ASE effects will change equations (2) to an equation that represents low dynamics [27]:

$$\frac{dh}{d\tau} = \frac{h_o - h}{\tau_c} - \frac{P_{in}(\tau)(e^h - 1)}{\tau_c\, P_{sat}} \quad (7)$$

MATLAB software is used as a tool to solve numerically equation (4) and equation (7) that refer to, respectively, the integrated gain for fast and slow dynamics. Range-Kutta four order method is employed to solve them and can be coupled with equation (3) for calculating output power (P_{out}) as a function input power (P_{in}) and from the curve data, one can get a figure the refers to the relation between G against P_{out} for slow and fast dynamics. After that, the gain that decrease by 3dB or 50% from the initial value. Also, the chirp $\Delta v_{out}\,(\tau)$ and gain recovery are calculated. The calculation is achieved for slow and fast dynamics.

5. Results and Discussion

In this section, simulation results of dynamics SOA and its effects on the saturation region for both cases are discussed. Parameters utilized in our work are recorded in **Table 1** below. For certain operating conditions, in other words, current concerning SOAs which are pumped-electrically, at little input power (P_{in}) levels, it is found that the G is independent of optical input power (P_{in}) as shown in **Figure 2**. It shows the relationship between the P_{out} as a function of P_{in}. P_{out} develops linearly as the P_{in} increases, to obtain enough great P_{in}, then, G begins to rely on the P_{in} signal and this occurs due to the low inversion level. After that causes saturation gain to be occurred [28]. In this work we have studied SOA dynamics in both cases, fast and slow dynamics. Therefore, we note that in the slow state, for figure 2, located on the left side, the saturation state (saturation region) starts when P_{in}=15dBm and

P_{out} =10 dB while in the fast state, which is on the right side, it starts when P_{in} =12dBm and P_{out} = 5dB.This difference in the saturation region is due to the recovery of gain as shown in **figure 5 (left side).**

Table 1 . Used parameters in the simulation

parameters	Symbol	Value and unit
Active region length	L	0.5 Ps
Width and height	w and d	3 and 0.8 μm
Confinement	Γ	0.3
Pulse width	τ_{FWHM}	0.5 Ps
Current	I	0.187 A
Carrier life time	τ_c	292 Ps
Effective gain recovery	τ_{eff}	100 Ps
Differential gain	a	$278 \times 10^{-20} m^2$
Carrier density	N_o	$1.4 \times 10^{24} m^{-3}$
Saturation energy	E_{sat}	4.7 PJ
Compression factors due to CH and SHB	ϵ_{CH} and ϵ_{SHB}	0,2 W^{-1}

We note from **Figure 2** that there is a difference in the gain (saturation region) for the fast state and slow one, which is a faster decrease and this, agree with that occurred in the SOA gains.

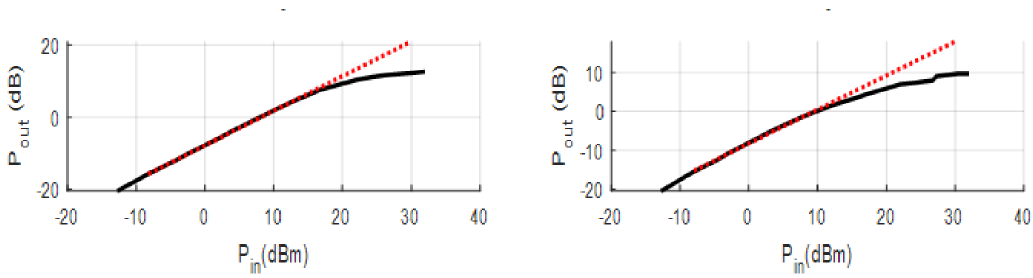

Figure 2: output power P_{out} versus input power P_{in} of SOA in slow (left) and fast (right) dynamic**.**

This depletion in G is due to the sudden reduction into carrier density which happens during a pulse spread along with SOA, and then G is recovered-back (get better) to reach its steady-state value [29]. We notice also that, there is the same unsaturated gain for both dynamics.

Figure 3(left) shows the relationship between gains as function of P_{out} in SOA. We note when an output power is low, a gain is linearly increased, and when an output power increases, then a gain is decreased that refers to the start of a saturated case [30].

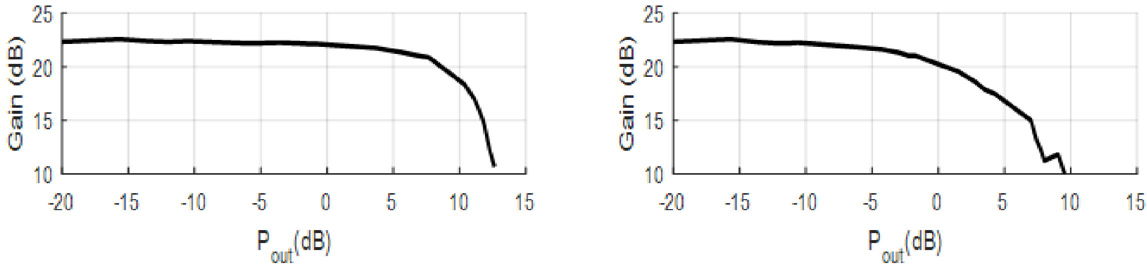

Figure 3 .Gain versus output power P_{out} of SOA in slow dynamic (left) and (right) fast dynamic.

In the case of fast, the gain begins to be fast decreased when the output power is close 2 dB, and it represents that the saturation output power ($P_{out,\ sat}$) (saturation region) will start. We can also note that the gain in the fast state seemed to decrease faster than the slow, due to the phenomenon of recovery of the gain in fast dynamics explained in figure 5 (left side).

Figure 4 illustrates P_{out} as function of relative time ($\tau/\tau_\circ$). From the **Figure** (left), we note that the pulse moves towards the left side the greater the relative time, the reason can be physically interpreted by noting **Figure 5** (right and red line) which shows that the chirp is negative only to reflect that the shifting will be towards the left.

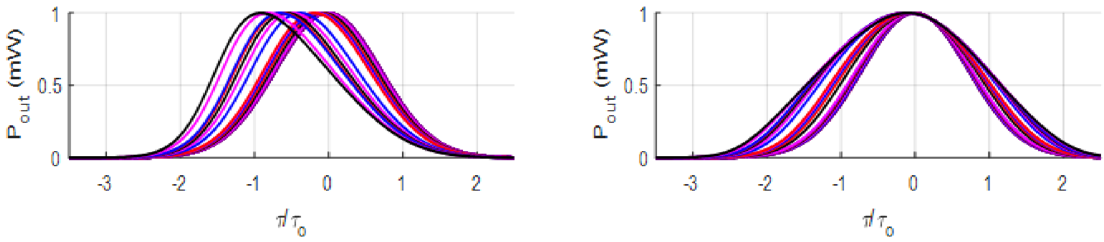

Figure 4 .output power P_{out} versus relative time ($\tau/\tau_\circ$) of SOA in slow (left) and fast (right) dynamic

As for the fast state in **Figure 4** (right), we note that the pulse is amplified in both sides only, as the relative time increases, and this happens because of the intra-band and the simultaneous operations such as the chirp when negative and positive this means that the shifting will be towards in both sides (left and right). **Figure 5** shows the relation of normalized material gain as a function of relative time ($\tau/\tau_\circ$). It is possible to note from the **Figure** that the recovery time for the fast state is greater than the slow state.

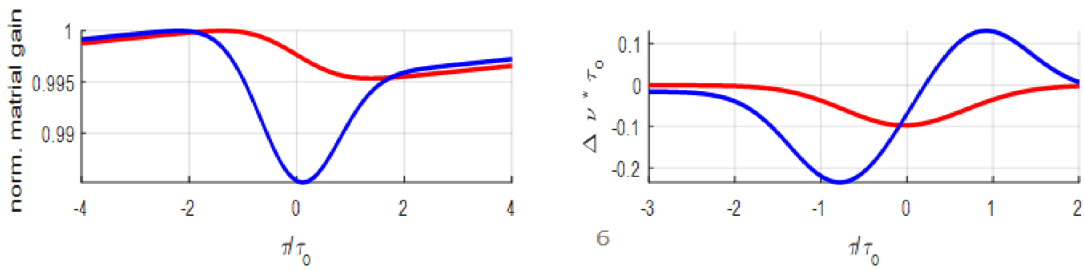

Figure 5: (Left)norm. material gain versusrelative time ($\tau/\tau_\circ$) for slow dynamics (red color) and for fast dynamics (blue color) . (Right) chirp versus relative time ($\tau/\tau_\circ$) forslow dynamics (red color) and for fast dynamics (blue color). norm. refers to normalized word

And the reason for this is due to the occurrence of several operations that are fast carrier depletion, fast carrier recovery via CH and SHB, and slow carrier recovery via electrical pumping. This makes the gain in slow dynamic less than fast dynamic. Thus, the gain increases because of the exponential relationship between gain and material gain. **Figure 5**(right) is used in this paper to physically determine the trend of pulses shape in **Figure 4** when it is destroyed by the slow and fast dynamics.

6. Conclusion

In conclusion, this paper presented four various diagrams illustrating both fast and slow dynamics in SOA and their effect on the saturation region with some parameters. Fast dynamics present by CH and SHB and its effects on saturation power region are studied. Each chart has unique features, and we can conclude from this work that time recovery for fast state is better than the slow due to the effect of SHB and CH. Also, we used the chirp figure to determine the reason for spreading pulse shape.

References

1. Raju, S.; Arunachalam, M**.;**Survey on various perspectives of Raman amplifiers, *3C Tecnología. Glosas de innovaciónaplicadas a la pyme*, 2020**,** 247-259.
2. Amada, M.;Noise in Semiconductor Optical Amplifiers (SOA), *IEEE 6th International Conference on Photonics (ICP)*, **2016**.
3. Ong, Y.; Kharraz, O.; Sulaiman, A.; Abdullah, F.; Yusoff, N.; Characterization of Wideband Semiconductor Optical Amplifiers Based on OptiSystem and MATLAB, *International Journal of Integrated Engineering* , **2018**, *10* , *7*, 263–272.
4. Malik, D.; Kaushik, G.; Wason, A.; Performance of Optical Amplifiers for High-Speed Optical Networks, *J. Opt. Commun* ,**2020**, *42*, *1*, 15–21.
5. Agarwal, V.; Agrawal, M.; Characterization and Optimization of Semiconductor Optical Amplifier for ultra-high speed applications: A Review, *Conference on Signal Processing And Communication Engineering Systems (SPACES)*, **2018**, 215-218.
6. Mark, J. All-optical signal processing using semiconductor optical amplifiers for next generation optical networks. Ph.D .Thesis. University College Cork.**2014**.
7. Wartak, M. chapter 9. Semiconductor optical amplifiers (SOA); 1st ed. Publisher: Cambridge University Press, **2013**,223-239.
8. Yusuf, M.; Bhandari, V.;Enhancement in the Gain of EDFA in Fibre Optic Communication, *International Journal of Engineering and Advanced Technology (IJEAT)* , **2019**, *9*, *2*,411-417.

9. Alquda, E.; Matarneh, A.; Comprehensive Investigation Modeling For Semiconductor Optical Amplifier (SOA), *Jordanian Journal of Computers and Information Technology (JJCIT)*, **2015**, *1, 1*,51-66.
10. Ab-rahman, M.;A review of the configuration and performance limitation parameters in optical amplifiers, *OpticaApplicata*, **2014**, *44, 2*,251-266.
11. Kharraz, O.; Harith, H.; Forsyth, D.; Dernaika, M; Mohammad, A.; Zulkifli, M.; Ismail, M.; Supa, at A.; Four-wave mixing analyses for future ultrafast wavelength conversion at 0.64 Tb⁄s in a semiconductor optical amplifier, *Optical Engineering* ,**2014**, *53,11*,1-8.
12. Mohammed, A.; Hemed, A.; Ultrafast Dynamics Effect in Presence of Different Pulse Width in Semiconductor Optical Amplifier, *Journal University of Kerbala*, **2017**, *15, 1*,40-48.
13. Johni, R.; Forsyth, D.; Tariq ,K.; Effects on Semiconductor Optical Amplifier Gain Quality for Applications in Advanced All-optical Communication Systems, *Research Journal of Applied Sciences, Engineering and Technology*, **2014**,*7,16*,3414-3418.
14. Aziz, A.; Ng, W.; Ghassemlooy, Z.; Aly, M.; Ngah, R.; Chiang, M.; Characterization of the Semiconductor Optical Amplifier for Amplification and Photonic Switching Employing the Segmentation Model, *IEEE*, **2008**, 1-6.
15. Hamze, M. Study of different SOA structures impact on the transmission of IMDD OOFDM signals. Ph.D .thesis.University of Bretagne Occidental.**2015**.
16. Malik, Y. Gain Control in Semiconductor Optical Amplifier. M.Sc. Thesis. University of Glasgow School of Engineering.**2014**.
17. Kaur, A.; Performance Analysis of Gain Characteristics of Semiconductor Optical Amplifier, *International Journal of Innovative Research in Computer and Communication Engineering*, **2016**, *4, 4*,7184- 7187.
18. Juodawlkis, P.; Plant, J.; Loh, W.; Missaggia, L.; O'Donnell, F.; Oakley, D.; Napoleone, A.; Klamkin, J; Gopinath, J.; Ripin, D.; Gee, S; Delfyett, P.; Donnelly, J.; High-Power, Low-Noise 1.5-μm Slab-Coupled Optical Waveguide (SCOW) Emitters Physics, Devices, and Applications,*IEEE Journal of Selected Topics in Quantum Electronics*, **2011**, *17, 6*,1698- 1714.
19. Singh, K.; Kaur, G.; Singh, M.; Enhanced performance of all-optical half subtracter based on cross-gain modulation (XGM) in semiconductor optical amplifier (SOA) by accelerating its gain recovery dynamics, *Photon NetwCommun*, **2017**, *34*,78-80.

20. Baveja, P.; Xiao, Y.; Arora, S.; Agrawal, G;, Maywar, D.; All-optical semiconductor optical amplifier-based wavelength converters with sub-mW pumping, *IEEE Photonics Technol. Lett*, **2013**, *25,1*,78-80.
21. Lee, H.; Effect of Amplified Spontaneous Emission on the Gain Recovery of a Semiconductor Optical Amplifier, *Korean Journal of Optics and Photonics*, **2018**, *29*, *1*, 32-39.
22. Wang, L.; Tao, S.; Liu, L., Picosecond Gain Recovery Dynamics in Semiconductor Optical Amplifiers and Three-Wavelength Devices, *Symposium on Photonics and Optoelectronics*,**2012**.
23. Venghaus, H.; Grote, N.; Fibre Optic Communication Key Devices, *Springer*, **2012**.
24. Marculescu, A.; Ó Dúill, S.; Koos, C.; Freude, W.; Leuthold, J.;Spectral signature of nonlinear effects in semiconductor optical amplifiers, *OPTICS EXPRESS*, **2017**, 2*5, 24*.
25. Ueffing, M.Direct Amplification of Femtosecond Pulses. Ph.D. thesis.Munchen.**2018**.
26. Duill, S.; Barry, L.; Improved reduced models for single-pass and reflective semiconductor optical amplifiers, *Optics Communications*, **2015**, *334*, 170-173.
27. Dutta, N.; Wang, Q.; Semiconductor Optical Amplifiers; 1st ed.; World Scientific Publishing Co. Pte. Ltd., **2006;** ISBN 981-256-397-0.
28. Marculescu, A. Semiconductor Optical Amplifiers: Modeling, Signal Regeneration and Conversion. Ph.D .thesis.ETH ZURICH.**2018**.
29. Schmeckebier, H. Quantum-Dot-Based Semiconductor Optical Amplifiers for O-Band Optical Communication. Ph.D. thesis.Technical University of Berlin.**2017**.
30. El Aziz, A. Characterisation and Optimisation of the Semiconductor Optical Amplifier for Ultra-High Speed Performance. Ph.D. thesis.University of Northumbria.**2011**.
31. Silveira, T. All-optical processing systems based on semiconductor optical amplifiers. Ph.D. Thesis.Universidade de Aveiro. **2011**.