# Study of recombination's effect oncharacteristic and self -phase modulation in semiconductor optical amplifier

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**الخلاصة:**

في هذا البحث تم دراسة تاثير اعادة مجموعة تلقائية وتاثير اوجر على خواص التضخيم وتحوير الطور الذاتي في المضخم الضوئي من نوع شبه موصل ذات موجة الجوالة. إنّ التأثير مدروس على المكسب،قوة الأشارة الخارجة،تغيير الطور اللاخطّي للطيف و الشكل اشارة المضخمة لقيم مختلفة للتيارات الدافعة لشبه الموصل.
عندما يكون مقدار اعادة المجموعة قليلة فان المكسب وقوة الأشارة الخارجة يكون كبيرا وينتقل قمة الطيف نحو الأطوال الموجية الطويلة.

## Abstract

This paper presents a detailed simulation study of the spontaneous and auger recombination on amplification characteristic and self -phase modulation in travelling- wave (TW) semiconductor optical amplifier (SOAs). The effect is studied on the gain, output signal power, nonlinear phase shift spectrum, and shape of amplified pulse at a range of drive currents. For small value of recombination, gain and output signal power were large, and the peak spectrum shifts more to longer wavelengths.

Keywords: Auger recombination coefficient, amplified spontaneous coefficient, travelling wave semiconductor optical amplifier (TWSOAs), self phase modulation (SPM), spectral broadening.

## 1. Introduction

In future high-speed telecommunication systems, all optical signal processing techniques promise to play a prominent role in avoiding electro-optic conversions that may create data-flow bottlenecks. Semiconductor optical amplifiers (SOAs) have been widely used to perform a variety of all optical functions such as wavelength conversion [1], signal regeneration [2], and pulse reshaping [3].Travelling–wave (TW) semiconductor optical amplifiers (SOAs)will probably be one of the key component in the next generations of optical networks where they could be used either as linear amplifiers or in switching and wavelength conversion applications due to their strong nonlinearities.[4] Amplification of ultra-short optical pulses in SOA produces considerable spectral broadening and distortion due to the non-linear phenomenon of self-phase modulation. The physical mechanism behind SPM is gain saturation, which leads to intensity-dependent changes of refractive index in response to variations in carrier density. Signal-gain saturation in SOA is caused by a reduction of the population inversion in the active layer due to an increase in stimulated emission. Gain saturation characteristics are especially important in optical repeaters and multi-channel amplifiers which require high-power operation. [5,6,7] In this paper the effect of spontaneous recombination coefficient, and Auger recombination coefficient have been studied on SOA's characteristic and self phase modulation.

## 2. Simulation model

The rate-equation approximation has been used in which the electrical field is described by the wave equation and the carrier density by means of the rate equation. Such model is applicable to describe the amplification of continues wave (CW) and optical pulse signals. The material gain coefficient $g_m$ is related to carrier density N(t) by,

$$g_m(t) = A[N(t) - N_0] \quad \text{................1}$$

Where $N_0$ is the carrier density at transparency point and Ag is the differential gain coefficient [8].

The net gain coefficient (g) is related to the material gain $g_m$ by

$$g(t) = \Gamma g_m(t) - \alpha \quad \text{..................2}$$

Where α is an effective loss coefficient which includes scattering and absorption losses and Γ is the optical confinement factor defined as a fraction of the mode power within the active layer. It is also assumed that the amplifier supports a single wave-guide mode and it does not change the polarization state during the amplification. Linearly polarized input light is presumed. The group velocity dispersion in the SOA is neglected. The amplified spontaneous emission noise is not taken into account. In the framework of these assumptions, the gain G for a traveling wave SOA for a distance z is:

$$G(t,z) = e^{[g(t)z]} \quad \text{........................3}$$

The carrier density rate equation expresses the conservation of carriers inside the active layer. It takes into account the current density and the net rate of carrier generation and recombination averaged over the active layer. The recombination rate consists of spontaneous and stimulated recombination. The spontaneous recombination rate includes the radiative and nonradiative components. The nonradiative recombination takes into account the Auger recombination, which is generally the dominant nonradiative process in long wavelength lasers. The spontaneous recombination rate can be characterized by a quantity known as the carrier lifetime $\tau_S$ :

$$\frac{N(t)}{\tau_s} = R_A N(t) + R_B N^2(t) + R_C N^3(t) \quad \text{......................4}$$

Where $R_A$ is the non-radiative coefficient recombination at defects and traps, $R_B$ is the spontaneous radiative recombination coefficient, and $R_C$ is the Auger recombination coefficient. Neglecting the carrier diffusion, the amplified spontaneous emission noise and the shot noise the equation for the carrier density N(t) is [3-4]:

$$\frac{dN}{dt} = \frac{J}{qd} - \frac{N}{\tau_S} A_g (N - N_0) \frac{I}{hf} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..5$$

Where (I) is the light intensity, (J) is the injection current density, (q) is the electron charge, (h) is the Planck's constant, f is the light frequency, (t) is the time, and (d) is the active layer thickness.
Equation 5 can be rewritten as:

$$\frac{dN}{dt} = \frac{I_P}{qV} - \frac{N}{\tau_S} - \Gamma A_g (N(t) - N_0) \frac{P(N,t)L}{Vhf} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots6$$

Where $I_p$ is the pump current (or injection current), V =( L w d) is the volume of the active region, and L, w and d are the length , the width and thickness of the amplifier respectively .

## 3. The effect of recombination on gain and out put signal power

*A-SPONTANOUS RECMBINATION EFFECT*

The software Optisystem is used for measuring the gain and output signal power of a weak continuous wave CW signal as a function of drive current using traveling wave SOA for different value of spontaneous recombination coefficient $R_B$ and Auger recombination coefficient $R_C$. Fig (1) shows the system setup, as input source 1550nm signal with 2-µw power lunched TWSOA to ensure that it does not saturate the amplifier. The values used in the simulations are displayed in table 1.

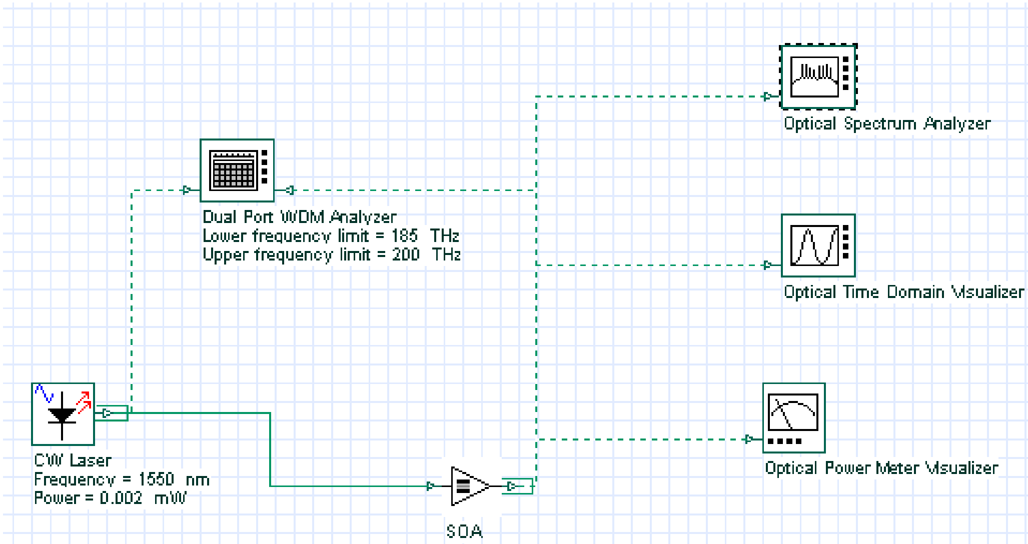


Fig .1. Set-up for the characterization measurements of the SOA.

Table 1
Model parameters used in the simulation of the device

| | | |
|---|---|---|
| L | SOA length | 0.0005 m |
| W | width | $3\times10^{-6}$ m |
| d | thickness | $8\times10^{-8}$ m |
| $\Gamma$ | Optical confinement factor | 0.4 |
| $\alpha$ | loss | 4000 $m^{-1}$ |
| Ag | Differential gain | $2.78\times10^{-20}$ $m^2$ |
| $N_0$ | carrier Transparency density | $1.4\times10^{24}$ $m^3$ |
| $R_C$ | Auger recombination | $3\times10^{-41} m^6/s$ |

It is evident from figure ( 2) that the continuous wave (CW) signal is amplified exponentially, and there is a cutoff gain for each value of spontaneous recombination ,it increases linearly for a certain value of current but this exponential growth is reduced dramatically at higher currents. This behavior is because of gain saturation induced by the increasing amplified spontaneous emission (ASE). Gain increases with decreasing the value of spontaneous recombination because the emitted photons from spontaneous recombination have a random phase and direction.

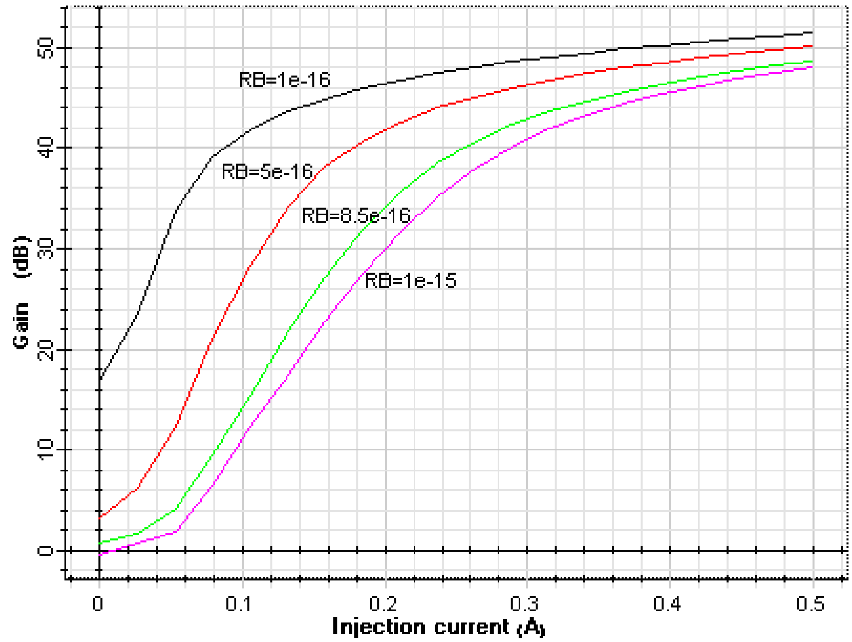


Fig.2. Gain as a function of drive current at different spontaneous recombination coefficient.

Figure .3 shows the calculated total output signal power as a function of drive current for different value of spontaneous recombination, the effects are small at low-drive currents and increase quickly; it is larger for low spontaneous recombination value.

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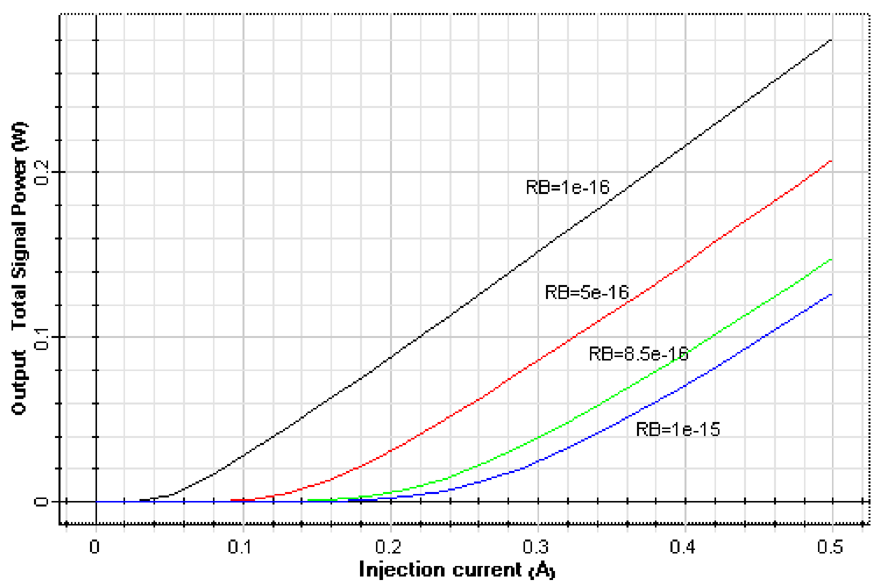


Fig.3 Output signal power as a function of drive current at different spontaneous recombination coefficients.

*B –Auger recombination effect*

To study the effect of Auger recombination on gain and output signal power the same values are chosen as shown in table 1,the value of spontaneous recombination is chosen to be $1\times10^{-16}$ $m^3/s$ .

As shown from figure (4) The value of cutoff gain is increased with decreasing Auger recombination, it increases linearly for low drive current and it saturates for high injection current because with increasing injection current carrier density increase until it reaches the saturation level which leads to gain saturation, but increasing Auger recombination's value decreases cutoff gain because it decreases carrier density.

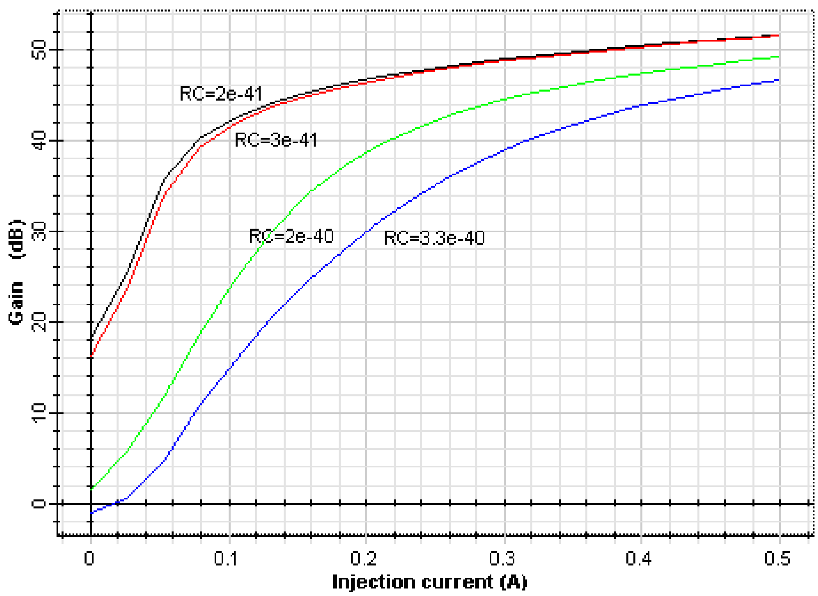


Fig.4 Gain as a function of drive current at different Auger recombination coefficients.

Figure (5) shows the effect of different Auger recombination effect on the output signal power at different value of injection current ,like figure(3) the effects are small at low-drive currents and increase quickly; it is larger for low Auger recombination value.

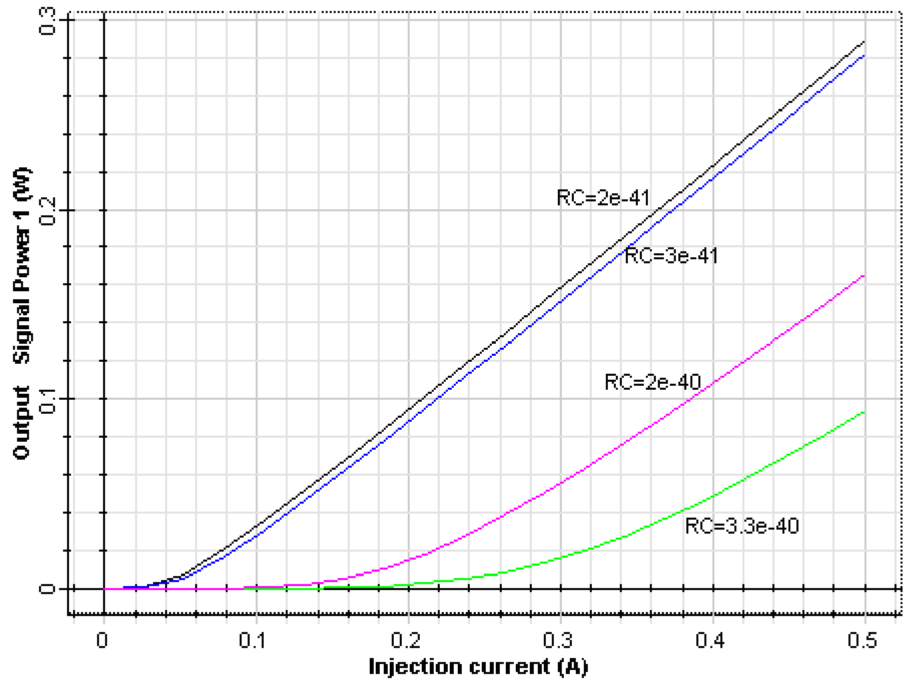


Fig.5 output signal power as a function of drive current at different Auger recombination coefficients

## 4 .The effect of recombination on pulse shape and spectra

To illustrate the impact of recombination on the shape and the spectrum of the amplified pulse, 14 ps full width half maximum FWHM Gaussian pulse with pump power 50mW is considered. The Gaussian input pulse is amplified by the SOA at different drive current for two different value of Auger and spontaneous recombination coefficients.

Fig. 6 shows the output pulse shape for different value of drive current when ($R_B=1\times10^{-16}$ $m^3$/sec) and Auger recombination equal ($3\times10^{-41}$ $m^6$/sec).All other parameters are identical to table 1. The amplified pulse acquires an asymmetric shape with a leading edge sharper than the trailing edge. This occurs because the leading edge of the pulse experience full gain, but gain is reduced substantially near the trailing edge, the change in drive current influences the pulse shape, it increase with increasing drive current.

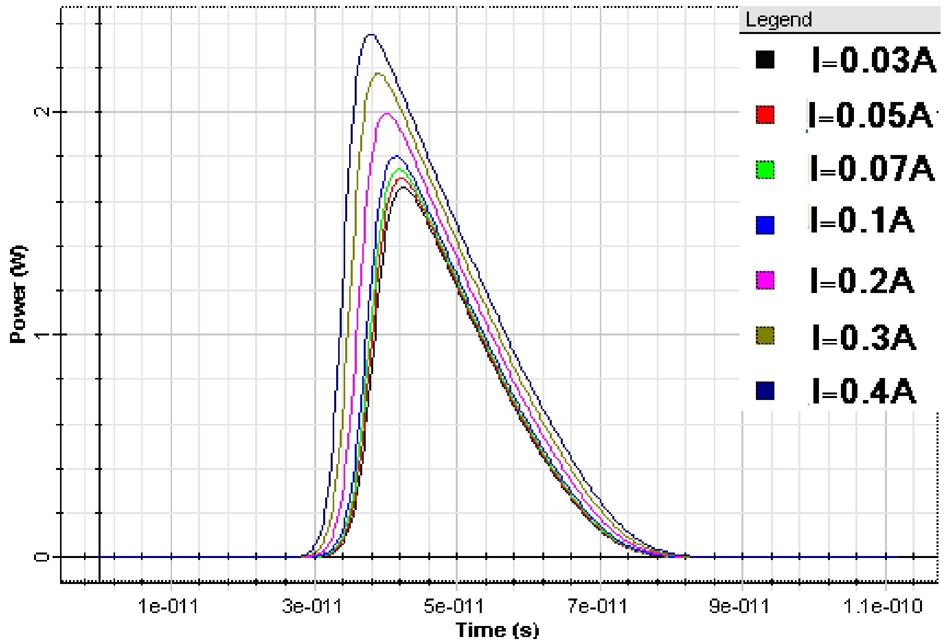


Fig.6 Output shape at (RB=$1\times10^{-16}$ $m^3$/sec) and Auger recombination (RC=$3\times10^{-41}$ $m^6$/sec).

Fig.7showes the output pulse shape at two different value of spontaneous and Auger recombination when they increased to $1\times10^{-15}$ $m^3$/sec and $3\times10^{-40}$ $m^6$/sec the value of out put power is decreased but the overall phase change remain the same.

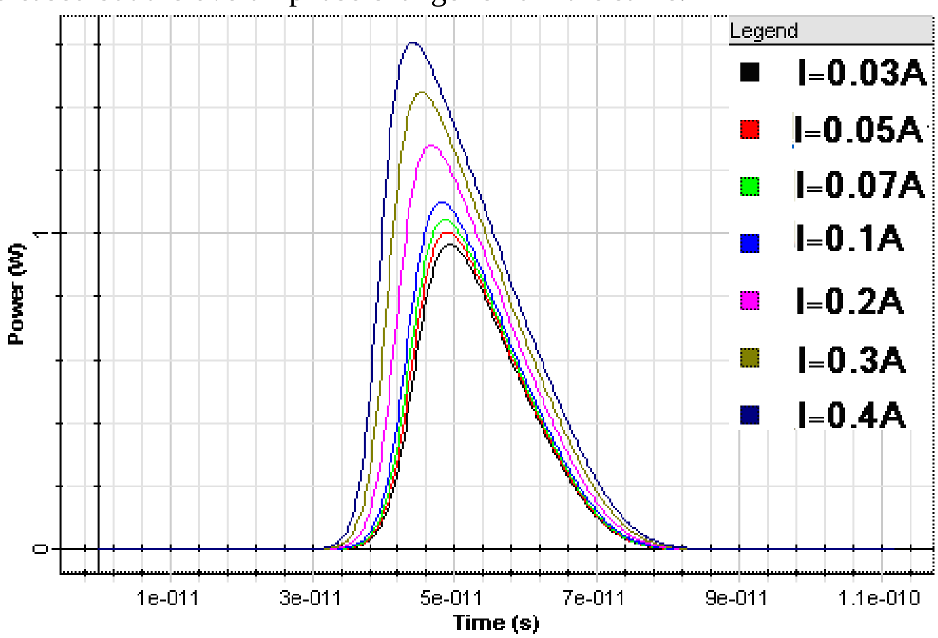


Fig.7 Output shape at (RB=$1\times10^{-15}$ $m^3$/sec ) and Auger recombination ($3\times10^{-40}$ $m^6$/sec).

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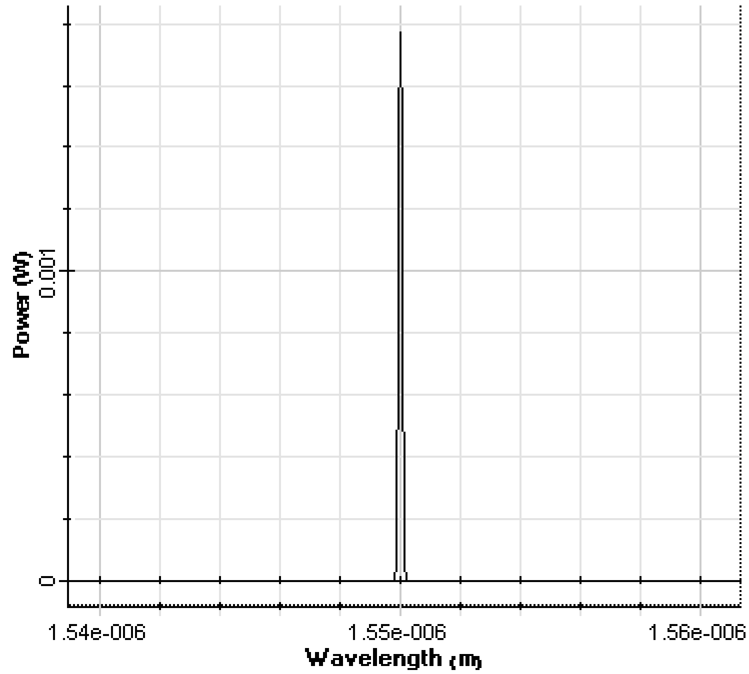


Fig.8 Input Gaussian pulse spectrum

Fig.8 and 9 show the input Gaussian pulse and out put pulse spectrum results for different drive currents value, the out put spectrum is highly asymmetric with most of pulse energy contained in a red shifted spectral, The spectrum develops a multi-peak structure. The dominant peaks shift toward longer (red) wavelengths as compared with the input Gaussian pulse.

The spectrum develops a multi-peak structure. The dominant peaks shift toward longer (red) wavelengths, the value of output pulse power increases with increasing current

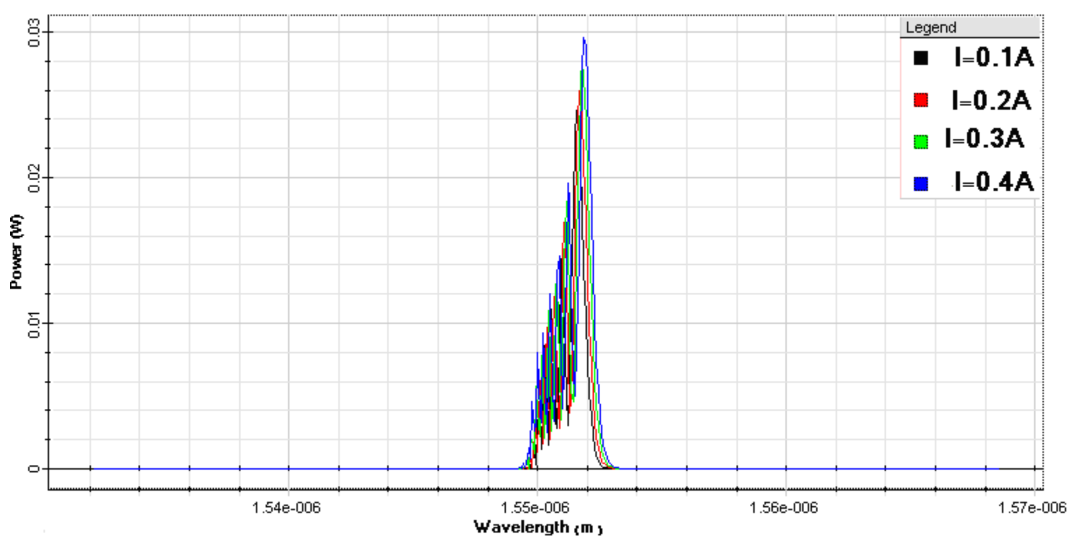

Fig.9 output shape at (RB=$1\times10^{-16}$ $m^3$/sec ) and Auger recombination ($3\times10^{-41}$ $m^6$/sec).

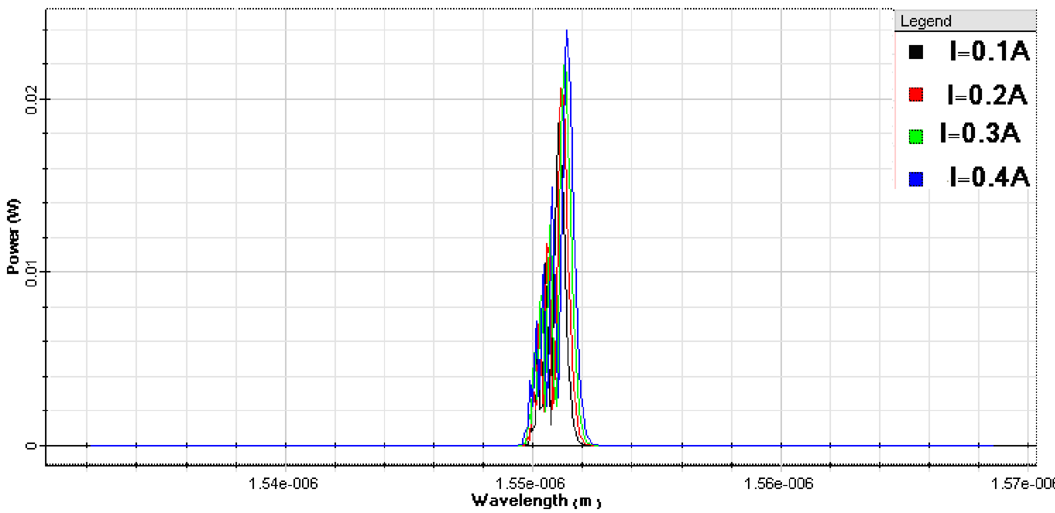


Fig.10 output shape at (RB=$1\times10^{-15}$ $m^3$/sec ) and Auger recombination ($3\times10^{-40}$ $m^6$/sec).

## 5. CONCLUSION

This paper has studied both spontaneous and auger recombination effect on SOAs characteristic, shape and spectral.

The gain and output signal power were calculated over a range of drive currents, gain increased with decreasing spontaneous and Auger recombination coefficients, and it saturates at a certain value of current.

The shape and spectrum of amplified pulse were calculated over a range of drive currents, for two different values of recombination factors, When the value of recombination are small the output power is large, and the peak spectrum shift toward longer wavelength for each value of the current.

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