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IMPACT OF SIGNAL WAVELENGTH ON THE SEMICONDUCTOR OPTICAL AMPLIFIER GAIN UNIFORMITY FOR HIGH SPEED OPTICAL ROUTERS EMPLOYING THE SEGMENTATION MODEL

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ABSTRACT

This paper investigates the impact of a train of input Gaussian pulses wavelength on semiconductor optical amplifier (SOA) gain uniformity for high speed applications. In high speed applications, the linear output gain of the input pulses is necessary in order to minimize the gain standard deviation and power penalties. A segmentation model of the SOA is demonstrated to utilize the complete rate equations. The SOA gain profile when injected with a burst of input signal is presented. A direct temporal analysis of the effect of the burst wavelength on the SOA gain and the output gain standard deviation is investigated. The output gain uniformity dependence on the input burst power and wavelength within the C-band spectrum range is analyzed. Results obtained show the proportionality of the peak-gain conditions for the SOA on the nonlinearity of the output gain achieved by the input pulses.

1. INTRODUCTION

The relatively low switching speed of electronic devices limits the huge communication capacity of optical fibers in optical networks [1]. The future high speed telecommunication systems are expected to use all-optical technologies to avoid optical-electrical-optical conversions. Semiconductor optical amplifiers can be used to perform a variety of all-optical functions, such as wavelength conversion, add-drop multiplexing (wavelength and time), regeneration, optical logic signal processing and switching [1]. They have the advantage of a compact size, high stability, a low switching energy, a high integration potential, and fast and strong nonlinearity characteristics [2].

It is important to note that all-optical processing technology is not a replacement but is a complementary alternative to the electrical processing particularly at the back-bone optical layer where the data rate is extremely high. The temporal behaviour of the gain, carrier density and stimulation emission of an SOA following pump pulse propagation are the key characteristics. Mathematical models are required to aid the design of SOAs and to predict their operational characteristics. In gain dynamics studies including the pump propagation, a few models have been proposed [3]. In the literature, different research groups have proposed techniques to improve SOA gain recovery to avoid system power penalties [4] arising from bit pattern dependencies. At high data rate, fast gain recovery will result in a uniform output gain. Shortening of the SOA gain recovery time can be achieved varying the input pulse width or the SOA waveguide length [5]. However, the linearity of the output gain experienced by all input pulses has not been addressed. The SOA gain responses has been reported in the literature but without the considering the direct relationship to the operating wavelength and hence, the linearity of the output gain.

In this paper, we investigate the impact of the power and wavelength of a burst Gaussian pulse train on the SOA carrier density and its total gain. The output gain uniformity of the pulses is investigated using a proposed segmentation model. In order to achieve the maximum SOA gain uniformity, we optimize the SOA peak-gain wavelength. The SOA amplification process is explained in the following section. The proposed SOA segmentation model utilizing the third order rate equations is explained in section 3. In Section 4, we discuss the results obtained that highlight the conditions required for improving the SOA gain uniformity. A conclusion of this paper is presented in the final section.

2. SOA AMPLIFICATION PROCESS

The SOA is basically a semiconductor laser composed of an optical waveguide which amplifies input optical signals by stimulated emission [1]. The gain achieved is due to energy provided by an external source applied to the SOA waveguide. Stimulated emission occurs due to the collision of the incident optical beam with excited

electrons in the conduction band. An identical photon is then released to amplify the incoming signal.

The reduction of excited electrons in the conduction band (due to stimulated emission) will result in decreasing the SOA gain, since it is proportional to the carrier density. After the departure of the incident beam from the waveguide, the carrier density recovers by means of series of effects that will take place, namely, carrier-carrier scattering [6], two-photon absorption, the optical Kerr effects and quasi-equilibrium distribution [7].

3. MATHEMATICAL AND SEGMENTATION MODEL

We have developed a segmentation mathematical model of the SOA using Matlab™ where the waveguide length L is divided to five equal segments of length l each. The reason five segments were chosen is to match the required pulse width for the anticipated data rates of 10 Gb/s up to 160 Gb/s. In addition, the effect of the input pulse power and the operating wavelength on carrier density and the SOA total gain G can be investigated from one segment to another. Each pulse is with full pulse width of $l/v_g = 1.167$ ps where v_g is the group velocity of the signal inside the active region of the waveguide. The system incorporates a homogeneously broadened traveling-wave SOA, and the input signal is a single mode with a narrow linewidth. In order to study the operating wavelength and input power effects on the SOA gain, the complete rate equations are analyzed in small segments.

The rate of change of the carrier density, N within the active region of the SOA in the forward-propagating direction of the device is given by [8]:

$$\frac{dN}{dt} = \frac{I}{q \cdot V} - (A \cdot N + B \cdot N^2 + C \cdot N^3) - \frac{\Gamma \cdot g \cdot P_{av} \cdot L}{V \cdot h \cdot f}, \quad (1)$$

where I is the SOA bias current, q is the electron charge and V is the active volume of the SOA. A, B and C are the surface and defect recombination coefficient, the radiative recombination coefficient and the Auger recombination coefficient, respectively. Γ is the confinement factor which determines the ratio of the light intensity within the active region to the total light intensity [1], P_{av} is the average output power along the SOA, h is the Plank's constant and f is the light frequency. g is a 3rd order gain coefficient that depicts the gain medium of the SOA and depends on the carrier density and the input signal wavelength λ. With Lorentzian and quadratic failing to replicate the gain at shorter wavelengths, the cubic equation is the best fit to the real gain coefficient and is given by [8, 9]:

$$g = \frac{a_1(N - N_0) - a_2(\lambda - \lambda_N)^2 + a_3(\lambda - \lambda_N)^3}{1 + \varepsilon \cdot P_{av}}, \quad (2)$$

where a_1 is the differential gain parameter, a_2 and a_3 are, respectively, empirically determined constants that are chosen to fit an experimentally measured SOA gain curve at [9] to characterize the width and asymmetry of the gain profile, N_0 is the carrier density at the transparency point, λ_N is the wavelength at which the gain has a peak value and ε is the gain compression factor. The peak gain wavelength is given by [8]:

$$\lambda_N = \lambda_0 - a_4(N - N_0), \quad (3)$$

where λ_0 is the peak-gain wavelength at transparency and a_4 is the empirical constant that shows the shift of the gain peak. The net gain coefficient can be described by [10]:

$$g_T = \Gamma \cdot g - \alpha_{s,} \quad (4)$$

where α_s is the internal waveguide scattering loss. The SOA gain achieved by an optical input signal at any given location z is given by [10]:

$$G = e^{g_T \cdot z}. \quad (5)$$

Therefore, the average output power over the length L of the SOA can be expressed by:

$$P_{av} = \frac{1}{L}\int_0^L P_p \cdot G \cdot dz, \quad (6)$$

where P_p is the input signal peak power. Equation (6) can be rewritten as:

$$P_{av} = P_p \frac{e^{g_T \cdot L} - 1}{g_T \cdot L}. \quad (7)$$

4. RESULTS AND DISCUSSION

In Table 1 [1, 8], we present the SOA physical parameters used in our proposed model. In Fig. 1, the gain response of the SOA is displayed when a burst of input Gaussian pulses with a full-wave-half-maximum (FWHM) of 1.167 ps per pulse enters the active region of the SOA. The burst consists of 10 Gaussian pulses of 1 mW peak power and are separated by 100 ps (10 Gb/s). The rapid increase in gain (from zero to the steady state value) is mainly due to the biasing of the SOA.

A large number of electrons in the valence band will gain enough energy to overcome the energy gap thus increasing N and hence increasing the SOA total gain. The drop in the gain, 10% of the absolute gain, when the first input pulse enters the SOA at time t ~ 3 ns is because of the sudden decrease in N that occurs within 5.83 ps

(i.e. time for the propagation of the pulse along the active region). Due to the slow recovery of the SOA gain, the next pulse entering the SOA before its full recovery will introduce a further 8.6% (with respect to the steady state SOA gain) gain depletion. The third pulse will result in 7.9% gain depletion until the last pulse exits the SOA.

The depletion of the SOA gain, which depends on the input signal power is the gain achieved by input signals. The SOA gain is also directly affected by the wavelength of input signals as it can be seen from (2). The average burst signal gain as the function of the input peak power over a range of wavelengths is shown in Fig. 2.

The average gain reduces with increasing the input burst pulse peak power for all wavelengths. This response is expected due to the interaction of a larger number of excited electrons in the conduction band with the higher power input pulse causing more depletion to *N*. In the C-band, the minimum average burst gain is observed at the wavelength of 1530 nm. The figure also shows that at peak power values of 0.9 mW and 4.8 mW, the same average gain is achieved for different wavelengths.

In order to understand the intersections in Fig. 2 of the gain responses at different wavelengths, we plot the average burst gain as the function of the input burst wavelength for a range of power levels. For all input power levels, the gain display peak values at a wavelength λ_N as defined in (3). At a wavelength of 1530 nm the average gain achieved is the minimum for all input power values compared to the C-band wavelengths. The intersections shown on both Figs, 2 and 3 are because of the variations of the peak-gain wavelength at different input burst power levels.

Figure 4 depicts these variations and shows a linear shift in the peak-gain wavelength against the input burst power. Higher input powers result in more depletion of the SOA gain and thus resulting in increased peak-gain wavelength as observed from (3). At 1 mW of input pulse power the peak-gain wavelength is ~ 1551.665 nm.

Table 1 Physical SOA.

Parameter	Value
Carrier density at transparency (N_0)	1.4×10^{24} /m^3
Wavelength at transparency (λ_0)	1605 nm
Initial carrier density (N_i)	3×10^{24} /m^3
Differential gain (a_1)	2.78×10^{-20} m^2
Gain constant (a_2)	7.4×10^{18} /m^3
Gain constant (a_3)	3.155×10^{25} /m^4
Gain peak shift coefficient (a_4)	3×10^{-32} m^4
SOA length (L)	500 µm
SOA width (W)	3 µm
SOA height (H)	80 nm
Confinement factor (Γ)	0.3
Surface and defect recombination coefficient (A)	3.6×10^{8} 1/s
Radiative recombinassions coefficient (B)	5.6×10^{-16} m^3 /s
Auger recombination coefficient (C)	3×10^{-41} m^6 /s
Gain compression factor (ε)	0.2 /W
Applied bias current (I)	150 mA

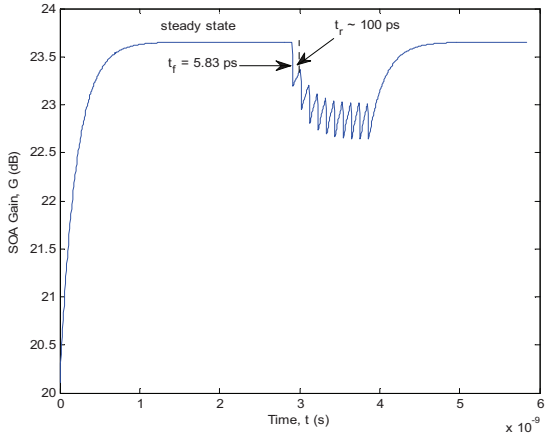

Figure 1 SOA gain response when injected with a burst input pulse trains.

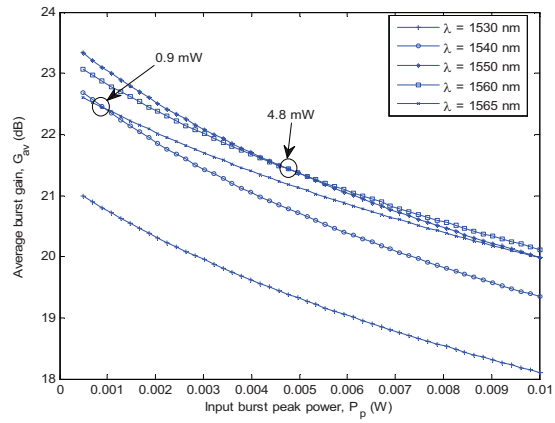

Figure 2 Average burst gain response to the input burst peak power at different wavelengths.

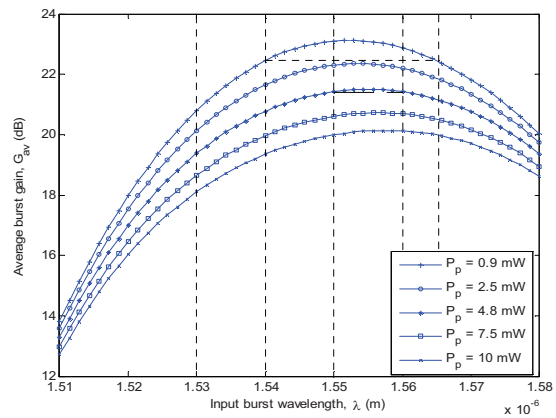

Figure 3 Average burst gain response against the input burst wavelength for a range of input burst peak powers.

In order to measure the gain uniformity of the output pulses, the gain standard deviation is introduced which is given by:

$$\sigma = \sqrt{\frac{1}{np}\sum_{x=1}^{np}(G_x - G_{av})^2}\ , \qquad (8)$$

where np is the number of successive input pulses launched into the SOA, G_x is the gain achieved by each input pulse and G_{av} is the average gain of all input pulses. Figure 5 compares the gain standard deviation σ against the power of the input pulse train (at a data rate of 10 Gb/s) at different wavelengths. As it is expected, σ increases with the power of the input signal due to the further depletion of the SOA gain by each input pulse, thus resulting in a reduced amount of gain uniformity. At higher power levels, the fluctuation of σ is less perturbed. The reason for such response is that the gain has lower values at higher input power as seen Fig. 2 and therefore, gain differences in (8) decreases. As explained earlier in this section, the SOA gain has a peak value at λ_N (see Fig. 3). Correspondingly, σ maximum value is at the peak-gain wavelength, thus explaining the highest and lowest gain uniformities at 1550 nm and 1530 nm wavelengths, respectively as shown in Fig. 5. From Fig. 5 at a power level of 4.5 mW, the 1540 nm and 1560 nm wavelengths have the same gain standard deviation of 12.61 dB. This intersection is due to the variations of λ_N corresponding to the input power as explained in Fig. 4. At 1 mW input power level, the maximum gain standard deviation is 9.8 dB at 1550 nm, while the best gain uniformity of the output pulses is achieved at 1530 nm with only ~ 6.6 dB.

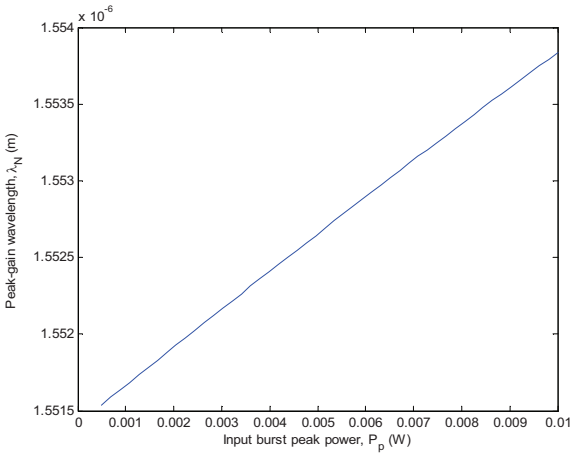

Figure 4 Peak-gain wavelength corresponding to input pulse power.

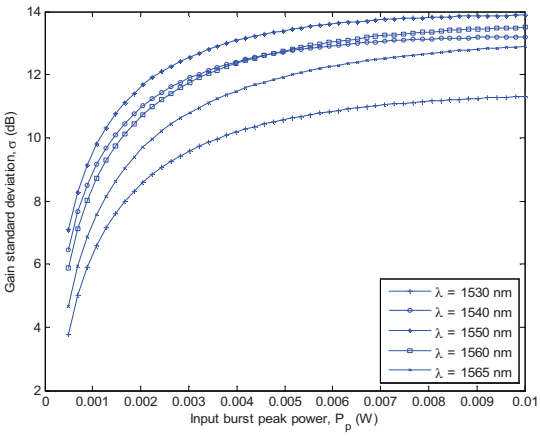

Figure 5 Gain standard deviation against the input pulse power for a range of wavelengths.

5. CONCLUSIONS

In this paper the impact of the input power and wavelength of a burst of input Gaussian pulses on the SOA carrier density and gain are investigated. The gain standard deviation was used to measure the output gain uniformity of the 10 Gb/s input pulses employing the proposed segmentation model. The direct effect of the propagating wavelength on the SOA gain and the gain uniformity was investigated. Results obtained showed that the least gain uniformity is at the peak-gain wavelength while the best uniformity is achieved at 1530 nm within the C-band. It was shown that at 1 mW of input power the minimum gain standard deviation achieved is ~ 6.6 dB at 1530 nm.

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