Employing wavelength diversity to improve SOA gain uniformity

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In this paper, we propose a wavelength diversity technique for the semiconductor optical amplifier (SOA) to improve the gain uniformity for ultra-high speed optical routers. In such routers, fast SOA gain recovery is required to ensure the minimum gain standard deviation and thus leading to reduction in the system power penalty. The SOA is modeled using a segmentation technique and the detailed theoretical analysis for the model is presented. A direct temporal analysis of the impact of the signal wavelength on the SOA gain is investigated. The SOA gain profile when injected with a burst of input Gaussian pulses for a single wavelength and the proposed wavelength diversity technique are investigated. The operation principle is simulated and the results show a reduction in the gain standard deviation (at 1 mW input power) of 13.1, 11, 8.1, 6.2 and 4.8 dB for the data rates of 10, 20, 40, 80 and 160 Gb/s, respectively.

1. Introduction

Over the last decade, because of wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM), the overall capacity of the point-to-point optical fibre transmission systems has been enormously increased by high speed optoelectronic components. Accordingly, to overcome the speed and capacity bottleneck of optical-electrical-optical (OEO) conversion, there is a growing demand for ultra-fast photonic networks that rely on photonic signal processing [1]. The key element in all processes in all-optical switching is the SOA. The reason is that SOA has a small size, a low switching energy, high stability, fast and strong nonlinear characteristics, and seamless integration with other electronic and optical devices. Accordingly, ultra-fast all-optical switches based on SOA, such as Mach-Zehnder Interferometers (MZI) [2] are the most promising candidates for all-optical switching and processing applications [3].The gain recovery time defines, to a great extent, the performance of SOAs of any types. To that end, for many high speed applications, the SOA must have a fast gain recovery to avoid system penalties arising from bit pattern dependencies [4] and gain uniformity for high data rate input signals. The gain recovery of SOA is limited by the carrier lifetime [1]. Different approaches have been used to speed-up the recovery time by changing the cavity length of the SOA or by changing the input pulse width [5]. Number of researches proposed externally injection of an assist light at the transparency point of the SOA, which gives rise to very high speed operation at a current identical to conventional SOA [1].

In this paper, we investigate the effect of wavelength diversity on the SOA to improve the SOA gain uniformity (i.e. reducing the gain standard deviation). The wavelength diversity technique is introduced to an input burst of Gaussian shaped pulses at ultra-high speed data rates. We theoretically investigate the SOA total gain due to the injection of the input burst using a single wavelength and the wavelength diversity technique. The SOA operation principle based on the rate equations are shown in the following section. In section 3, the wavelengths required to the burst of input pulses in order to improve the SOA gain uniformity using the proposed wavelength diversity technique are investigated at different high speed data rates. A summary is presented in the final section to conclude the findings of this paper.

2. SOA Operation Principle and Mathematical Model

Semiconductor optical amplifier (SOA) is an optoelectronic device that amplifies an input light beam under suitable operating conditions. Electrons acquire higher energy when the SOA is biased with a direct current. Therefore, applying more bias current will result in a larger number of excited electrons in the conduction band which is known as the carrier density [4]. Stimulated emission process is a radiative mechanism within the SOA where amplification takes place. An input optical signal interacts with excited electrons to release an identical photon. Accordingly, the reduction of the carrier density results in decreasing the SOA gain, since it is proportional to the carrier density [4]. The carrier density is then recovered by means of number of effects, such as, carrier-carrier scattering, two-photon absorption [6], optical Kerr effects and the carrier temperature relaxation process [4]. We have developed a numerical model to analyze the impact of the input wavelength for a more uniform SOA gain. Changes in the carrier density and SOA gain can be described using the rate equations when an input optical beam enters the active region. The SOA is assumed to have a negligible reflectivity at the end facets. With Lorentzian and quadratic failing to replicate the gain at shorter wavelengths, the gain medium of the amplifier is described by the cubic equation which is the best fit to the real gain coefficient [7]. The material gain coefficient g which depends on the carrier density N and the input signal wavelength λ is given by [8]:

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

where a_1 is the differential gain parameter, a_2 and a_3 are, respectively, empirically determined constants that are chosen to fit the experimentally measured SOA gain curve at [7] to characterize the width and asymmetry of the gain profile, N_o is the carrier density at the transparency point, ε is the gain compression factor and P_{av} is the average output power. λ_N is the wavelength at which the gain has a peak value and is given by [8]:

$$\lambda_N = \lambda_O - a_4(N - N_O), \tag{2}$$

where λ_o is the peak gain wavelength at transparency and a_4 is the empirical constant that shows the shift of the gain peak. The carrier density change rate along the SOA length L is given by [8]:

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

where I is the bias current, q is the electron charge and V is the active volume of the SOA. The surface and defect recombination coefficient is defined by A. B and C are the radiative and Auger recombination coefficients, respectively. Γ is the confinement factor which is the ratio of the light intensity within the SOA to the total light intensity [8], h is the Plank's constant, and f is the input signal frequency.

3. Results and Discussion

The above rate equations shown in section 2 are adapted to the proposed segmentation model, where the SOA is divided into five equal segments of length $l = L/5$ each to investigate the uniformity of the SOA gain using Matlab™. In this model, the system incorporates a homogeneously broadened travelling-wave SOA, and the input signal is single mode with narrow linewidths. The change of the carrier density from one segment to another depends on the input power and the carrier density of the previous segment. Five segments were chosen in order to match the desired pulse width for the intended data rate of up to 160 Gb/s. Then to investigate this input power effect on the change in the carrier density and the signal gain along the SOA. Each segment equates to a full pulse width of l/v_g (i.e. 1.167 ps), where v_g is the group velocity of the signal inside the active region of the waveguide. In this paper, the pulse power is the peak power of a Gaussian pulse. The SOA parameters adopted are obtained from [4, 8] and are given in Table 1.

Parameter	Value
Carrier density at transparency (N_0)	1.4×10^{24} /m^3
Wavelength at transparency (λ_0)	1605 nm
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
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

Table 1: SOA physical parameters.

The gain response of the SOA when a burst of ten 1 mW peak power Gaussian pulses with full-wave-half-maximum (FWHM) of 1.167 ps are launched into the SOA is depicted in Fig. 1. The pulses are separated by 100 ps (10 Gb/s) at 1540.6 nm. The rapid increase of gain until reaching the steady state value within ~ 1 ns is due to external biasing of 150 mA. Energy gained by a large number of electrons from the valence band will help them to overcome the energy gap, thus increasing the carrier density. When the first input pulse is applied to the SOA at t ~ 3 ns, a sudden gain depletion will occur due to the interaction of the input pulse with the excited electrons in the conduction band. Following exit of the first pulse from the SOA, the gain shows a slow recovery. To that end, the second pulse arrives before the full gain recovery. A further gain drop is introduced to the SOA gain due to the second pulse. As it can be seen from Fig.1, the injection of each pulse causes the gain to drop to a different level and achieve a different gain value (i.e. the gain depletion envelope is not uniform). The figure also shows that by injecting more pulses, the variation of gain depletion is negligible. Therefore, the injection of more than 10 pulses will not show a significant difference in our investigation. In this paper, the bit pattern of all ‘1’ is used in the simulation. The reason is because the bit pattern of all ‘1’s will give the least recovery time for the SOA which result in the worst case scenario for SOA gain uniformity. This scenario will therefore show the significance of the improvement achieved by the wavelength diversity technique.

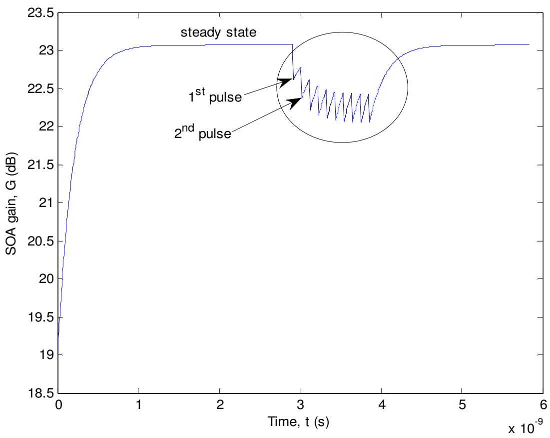

Figure 1: SOA gain response to a burst of Gaussian pulses.

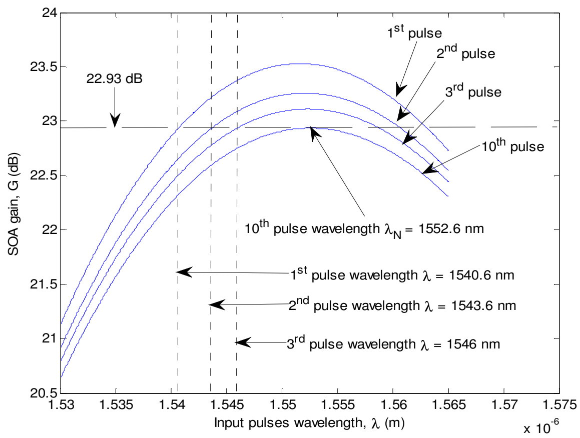

Figure 2: SOA gain response of a burst of Gaussian pulses against wavelength.

In order to achieve a uniform output gain, the gain reduction due to each pulse should reach the same level. A direct temporal relation of the impact of the input signal wavelength on the SOA gain is shown in the cubic rate equation (1). Accordingly, we propose using wavelength diversity technique where each Gaussian pulse is assigned different wavelength in order to improve the output gain uniformity. Therefore, in order to choose the wavelengths of all pulses that would achieve the same output gain, the gain profile of each pulse at different wavelength must be investigated as shown in Fig. 2. The figure illustrates the SOA gain profile against the C-band wavelength range (1530 nm – 1565 nm) for a burst of input pulses. The gain profiles of each of the 10 pulses show a peak value at a wavelength λ_N as defined in (2). From Fig. 2, one can see that the same gain (i.e. uniform output gain) can be obtained by the input pulses at different wavelengths between 21.1 dB and 22.9 dB. Figure 2 shows the highest gain value (i.e. peak-gain value of the 10th pulse) that intersects with all pulses (dashed line) and the corresponding wavelengths (dotted line) that are used for the input Gaussian pulses in the simulation. These wavelengths are presented in Table 2. The output gain uniformity can be measured by calculating the gain standard deviation which is given by:

$$\sigma = 10\log_{10}\left(\sqrt{\frac{1}{np}\sum_{x=1}^{np}(G_x - G_{av})^2}\right), \tag{4}$$

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. Comparing the input burst at single wavelength (1540.6 nm) and the burst that uses the wavelength diversity technique, a significant improvement of 13.1 dB in the gain uniformity is achieved using the proposed wavelength diversity technique. The same burst of Gaussian pulses is launched to the SOA at higher data rates (20, 40, 80 and 160 Gb/s) and the corresponding gain profiles are illustrated in Fig. 3. The figure shows that at higher data rate, the output gain envelope is less uniform (see Fig. 3) when using a single wavelength. At all data rates, when the 1st input pulse is injected to the SOA, the gain depletion are similar, however, the time available for the gain to recover after the departure of the 1st pulse is halved in each case. Therefore, the 2nd input pulse enters the SOA at a lower gain level (compared to lower data rate), and results in further gain depletion (i.e. less gain is achieved). That explains the less gain uniformity achieved for higher input data rates as it can be seen in Fig. 3. Figure 4 displays the 2nd pulse gain profile against the C-band wavelength range at different input data rates. As expected, the higher the input data rate, less gain is achieved and hence less gain uniformity.

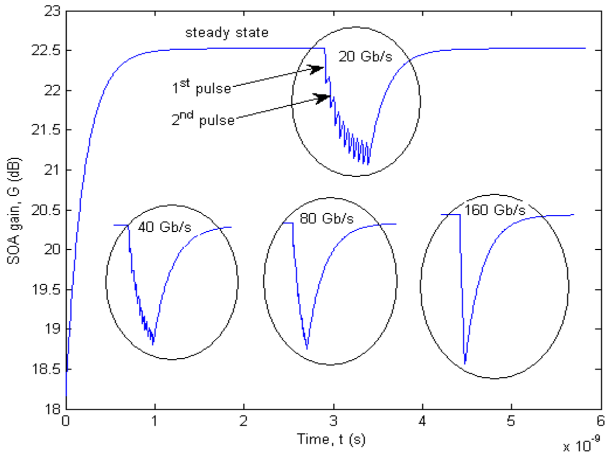

Figure 3: SOA gain responses to a burst of Gaussian pulses at different data rates.

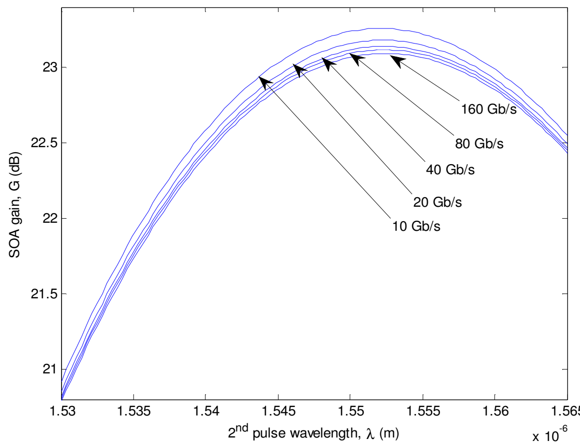

Figure 4: SOA gain profile of the second input pulse against the wavelength at different input data rates.

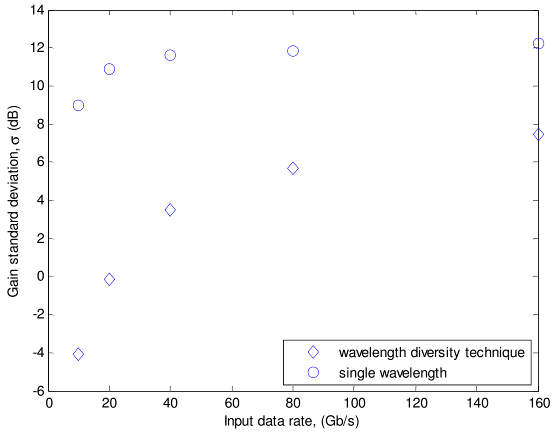

Figure 5: Gain standard deviation against input data rates for single wavelength and wavelength diversity technique.

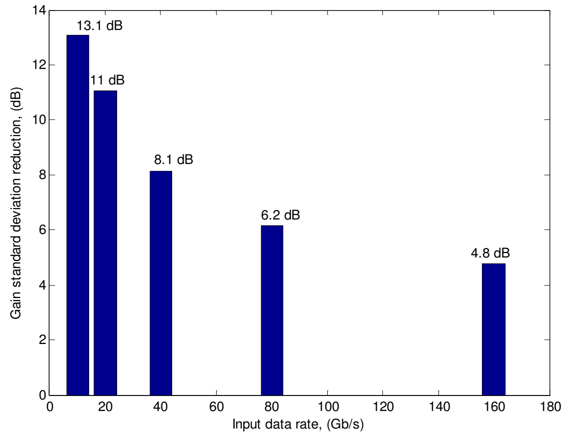

Figure 4: Bar chart showing the reduction of gain standard deviation when using the wavelength diversity technique.

The comparison of SOA gain uniformity between single wavelength and wavelength diversion at 10 Gb/s is repeated for higher data rates. Figure 5 plots the gain standard deviation of a single wavelength and wavelength diversity input pulses at different data rates. It is clear from the figure that the wavelength diversity technique results in lower σ values at any input data rate. Figure 6 depicts a bar chart to show the gain standard deviation reduction using the proposed technique (i.e. advantage of wavelength diversity over using a single wavelength) at different data rates.

Results show gain standard deviation reduction of 13.1, 11, 8.1, 6.2 and 4.8 dB at 10, 20, 40, 80 and 160 Gb/s data rates, respectively. In case of using the proposed wavelength diversity technique, the average σ improvement is 8.64 dB at data rates investigated in this paper which is 10, 20, 40, 80 and 160 Gb/s. At higher data rates, the fluctuation of σ is less perturbed. The reason is that at higher rates, spacing between input pulses are shorter and therefore, small gain differences. The wavelengths used for the proposed technique from the 1st to the 10th pulse at all input data rates are presented in Table 2.

Pulse wavelength (nm)	10 Gb/s	20 Gb/s	40 Gb/s	80 Gb/s	160 Gb/s
1st	1540.6	1536.5	1533.5	1531.5	1530
2nd	1543.6	1539	1535.6	1533.3	1530.7
3rd	1546	1541.3	1537.6	1535.3	1532.4
4th	1547.7	1543.3	1539.7	1537.3	1534.3
5th	1549	1545.2	1541.8	1539.4	1536.4
6th	1550	1546.8	1543.8	1541.6	1538.8
7th	1550.7	1548.3	1545.8	1543.9	1541.5
8th	1551.3	1549.6	1547.8	1546.4	1544.6
9th	1551.8	1551	1550.1	1549.4	1548.6
10th	1552.6	1553.5	1554.6	1555.6	1557.2

Table 2: Wavelengths for wavelength diversity technique at all data rates.

4. Conclusion

This paper has verified the ability to enhance the SOA gain uniformity utilizing the advantage of wavelength diversity characteristics for ultra-high data rates. The total gain response of an SOA model is simulated using a segmentation method. The paper has compared the gain uniformity using a single wavelength and a proposed wavelength diversity technique for the input burst. Results obtained showed an improvement of 13.1, 11, 8.1, 6.2 and 4.8 dB in the gain uniformity are achieved using the proposed method at 10, 20, 40, 80 and 160 Gb/s data rates, respectively.

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