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Effects on Semiconductor Optical Amplifier Gain Quality for Applications in Advanced All-optical Communication Systems

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Abstract: Semiconductor optical amplifiers are strong candidates to replace traditional erbium-doped-fibre-amplifiers in future all-optical networks by virtue of their proven functional capabilities, in addition to gain. They are also smaller, cheaper and easier to integrate than fibre amplifiers. This study summarizes the gain quality of the semiconductor optical amplifier with varying effects such as input power, bias current and wavelength and data rate. The results reported herein show high quality gain, coupled with accept ably low noise figure values.

Keywords: Erbium-Doped-Fibre-Amplifier (EDFA), Noise Figure (NF), Quality factor (Q), Semiconductor Optical Amplifier (SOA)

INTRODUCTION

There has been an almost exponential growth in the deployment and capacity of optical fibre communication networks over the past 25 years (Connelly, 2003), made possible mainly by the development of new optoelectronic technologies utilized to exploit the enormous bandwidth of optical fibre. Today, systems are operational at bit rates well in excess of 100 Gb/s. Optical technology is the dominant carrier of global information and is also central to the realization of future networks that will have the capabilities demanded by a growing society. These capabilities will include virtually unlimited bandwidth to carry communication services of almost any kind, including full transparency that allows terminal upgrades in capacity and flexible routing of channels. Many of these advances in optical communication networks have been made possible by the optical amplifier.

The topic of interest in this study is an optoelectronic device called the Semiconductor Optical Amplifier (SOA), for applications in advanced optical fibre communication systems. As the incredible recent growth in data speeds is largely attributed to new photonics technologies that enable the enormous capacity of optical fibre to be exploited, next generation optical networks will therefore require advanced photonic devices/subsystems for high speed all-optical signal processing of narrow (picoseconds) optical pulses to allow for very large increases in data rates (100s Gb/s to Terabit/s). SOA-based subsystems have been proven to have the capability of implementing many all-optical signal processing functions and the technology has therefore been exposed to the world due to its vast commercial value and future high potential in fibre optic communication systems.

The two types of optical amplifier most used at present are the SOA and the Erbium-Doped-Fibre-Amplifier (EDFA). The latter device usually employs a rare-earth doped fibre gain medium, commonly erbium (Er^{3+}) and has tended to dominate conventional system applications for many years, functioning only as in-line amplification to compensate for fibre losses. However, SOAs are increasingly becoming of interest, not only as basic amplifiers, but as more functional elements in optical communication networks capable of providing all-optical signal processing; such as high speed optical switching (Mahad *et al*., 2010; Nakamura *et al*., 1994; Pleros *et al*., 2004; Aw *et al*., 2007), optical gating (Guo and Connelly, 2005), wavelength conversion (Leuthold *et al*., 2000; Vaughn and Blumenthal, 1997) and in-line detection. These functions, where there is no conversion of optical signals into the electrical domain, will be required in future transparent optical networks. SOAs are compact, less expensive and highly compatible devices easily installed into a communications link and can be a more favorable choice when compared to EDFAs due to the various attractive properties described above It therefore follows that SOAs may become a more promising choice of amplifier in the near future by virtue of their intrinsic characteristics-high gain, low input power requirements, small size, capability for large-scale integration, very short response times and multi-functional capabilities (Bogoni *et al*., 2004).

The work done in this study explores and reports on the quality of the output amplified signal obtained

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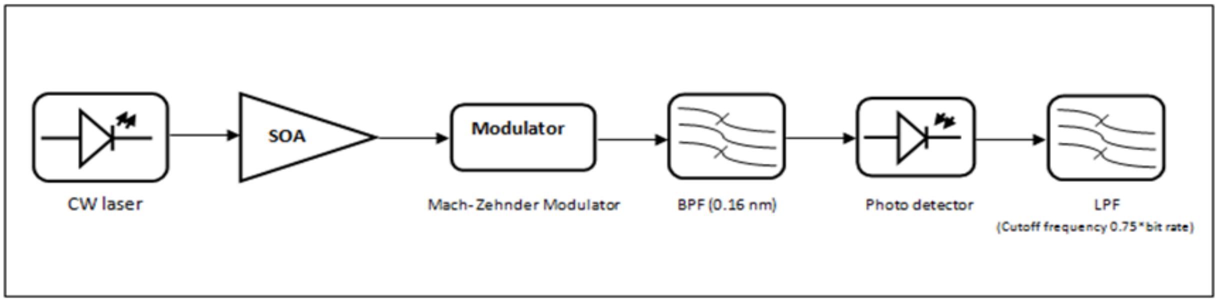

Fig. 1: Simulation set-up

from a semiconductor optical amplifier with the varying effects of input power, bias current, wavelength and data bit rate. The matrics used to assess this are the Q factor (dB) and Noise Figure (NF).

SYSTEM DESIGN

Using state-of-the-art design software, a test-bed was set-up as shown in Fig. 1. This consisted of a Continuous Wave (CW) laser source, bit rate generator, pulse generator, a SOA, an optical band-pass filter (centered at 1550 nm), a PIN photo detector and a low pass electrical filter. An optical power meter was used to measure the power of certain signals, while the electrical scope was used to measure the Quality (Q)-factor. The band-pass filter eliminated excess ASE outside the signal bandwidth. In our system, the CW laser was directly connected to the SOA and the output signal modulated by a Mach-Zehnder modulator at a certain Pseudo-Random Bit Sequence (PRBS). The SOA used in this system is a wideband traveling-wave type.

RESULTS

Input power: As shown in Fig. 2, the gain saturation characteristics of the SOA were determined when the input power was varied between -60 to 10 dBm. The SOA bias current was maintained at 0.3A and the wavelength at 1550 nm. In the flat unsaturated region, the SOA can operate as a constant gain amplifier without any non-linear effects. The maximum gain was seen to be around 32 dB. Then, as the input signal increases, the carriers in the active region become depleted leading to a decrease in the amplifier gain (Connelly, 2003). This gain starts to saturate at around-18 dBm input power and the input power at which the gain decreases by 3 dB is estimated from the curve to be around -22 dBm.

In order to verify the simulation results, a mathematical model was used as well. Figure 3 shows the variance between simulation results and mathematical results, the main difference being in the unsaturated region at low SOA input powers. Here, the software simulation package intrinsic algorithms

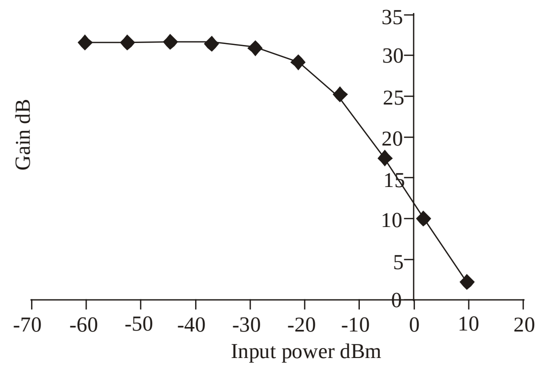

Fig. 2: SOA gain

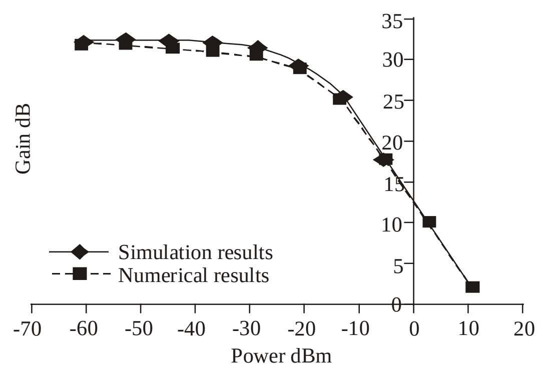

Fig. 3: Simulation and numerical result of SOA gain

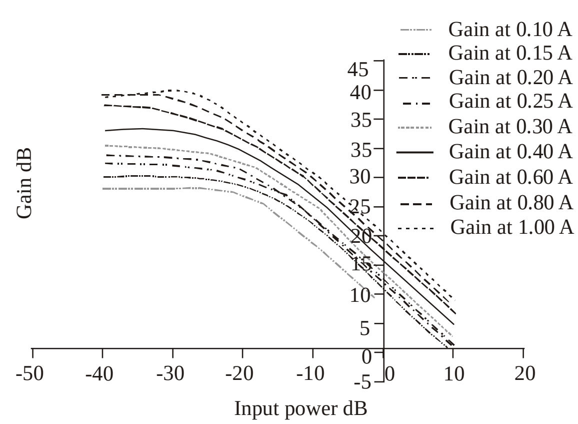

Fig. 4: SOA gain at different bias current

and iterations could not compete with the equivalent ultrafast saturation dynamics of the SOA.

Bias current: As shown in Fig. 4, the SOA gain was measured at different bias currents (between 0.1 and 1 A) and SOA input powers (between -40 and 10 dBm), whilst the wavelength was still 1550 nm. This shows the effect of increasing the injection current leading to an increase in the numbers of electrons in the valence band, subsequently causing sufficient gain energy to overcome the energy gap to cause high carrier density and hence increase the SOA gain. The SOA gain can easily be controlled by varying the bias current. From our earlier result, the best gain was 32 dB when the bias current was bounded to 0.3 A and the SOA gain began to saturate around -18 dBm input power when it went into the non-linear region. Here, at high bias current and low input power, the SOA can be seen to operate as an amplifier with over 40 dB gain.

Wavelength: Wavelength is another important parameter to be taken into consideration in any optical system design and it also affects the gain of the SOA. The SOA gain was examined at different wavelengths between 1500 and 1600 nm at four different input powers: -30, -20, -10 and 10 dBm, respectively. From the results shown in Fig. 5, we note the peak gains at all input powers occurs around 1544 nm. Also, the highest gain was at -30 dBm input power and was around 32 dB in the unsaturated region. The gain reduces at 10 dBm input power, where the SOA enters the deeper saturation region, the peak gain in this region was about 2.2 dB. The results clearly show the difference in the SOA gain due to different wavelengths of input pulse. The reason for this is that the higher input power causes an increase in the depletion carrier density which, in turn, reduces the material gain spectrum peak to shift to longer wavelengths, so decreasing the signal gain even further.

Figure 6 shows the SOA gain variations with input power in a different way to Fig. 5. The input power was bounded between -40 and 10 dBm, with a fixed bias current of 0.25 A These results show the gain characteristics of the SOA both in the saturation and unsaturated regions. Notice the gain at 1544 and 1550 nm was around 30.5 and 30.2 dB, respectively, which is close together.

Bit rate (speed): Figure 7 shows the effect of differing speeds on the gain of SOA, the bias current fixed at 0.25 A. The wavelength was 1550 nm, input power was -25 dBm and bit rate generator was at iteration between 1 to 100 Gb/s. The results show that the maximum SOA gain was around 27.5 dB, while the minimum gain was about 25.2 dB. The faster bit rates caused ripples in the gain spectrum and a reduction in SOA gain. This is because applying different short duration input optical pulses into the SOA will result in stimulated emission leading to the signal amplification and the SOA gain is relative to the population of carrier density, so the reduction of excited electrons in the conduction band will minimize the gain of SOA. Immediate mechanisms, for instance two-photon absorption and Kerr optical effects, will then effect on the SOA response.

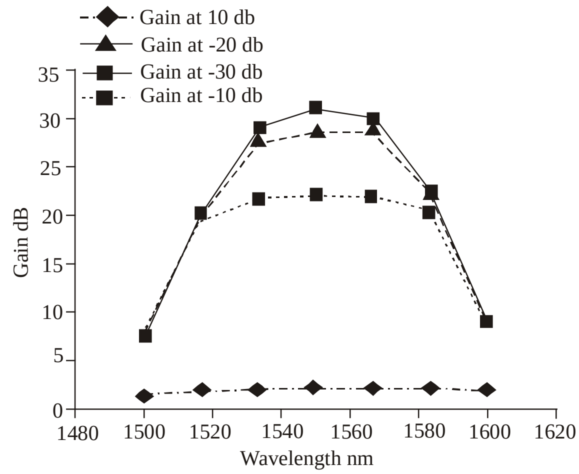

Fig. 5: SOA gain for different input power

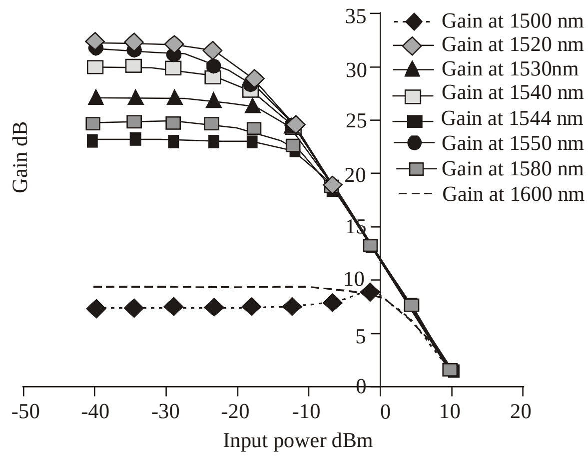

Fig. 6: SOA gain at different λ (nm)

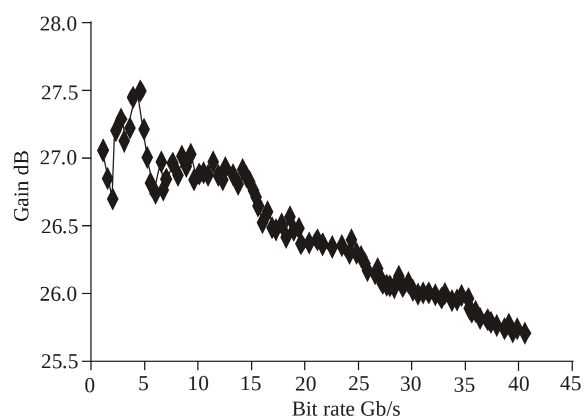

Fig. 7: SOA gain at -25 dBm

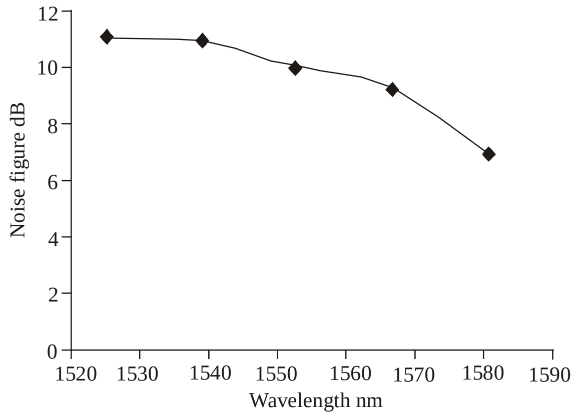

Fig. 8: Noise figure vs. wavelength

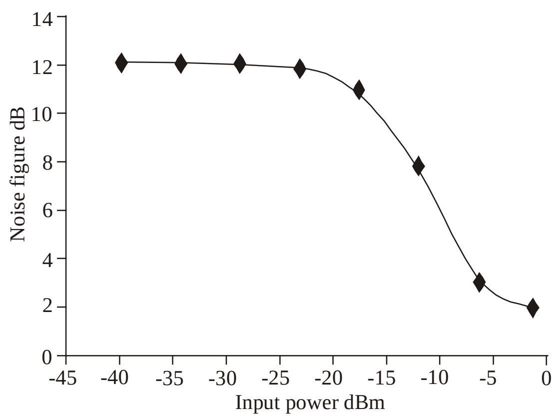

Fig. 9: SOA unsaturated noise figure

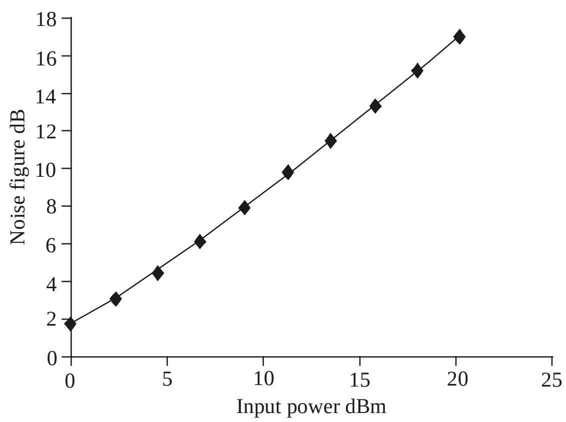

Fig. 10: SOA noise figure at saturated region

Noise Figure (NF): The effective NF was analyzed in our system. This is defined as the ratio of the Optical Signal-to-Noise Ratio (OSNR) at the output versus the OSNR at the input. Figure 8 shows the noise figure spectrum obtained for the unsaturated SOA, where the input power was -25 dBm and bias current was 0.25A and the wavelength was between 1525 and 1580 nm. The noise figure was seen to be around 11 dB at

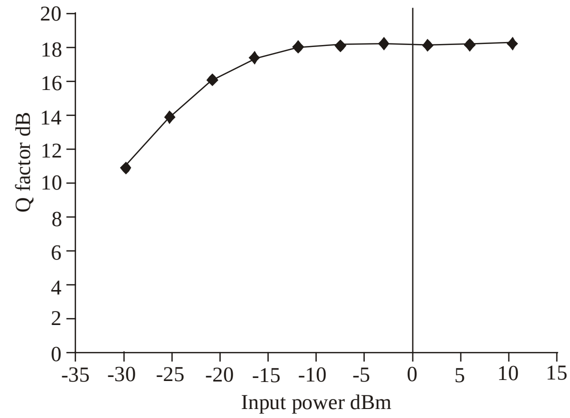

Fig. 11: Q factor as a function of input

1525 nm, decreasing to around 6.8 at 1580 nm. The NF is therefore clearly dependent on the operating wavelength over the rang.

Figure 9 shows the noise figure readings obtained at 1550 nm, the bias current fixed to 0.25 A and mainly in the unsaturated region. The NF is seen to be high at the higher input powers. Here, the SOA is frequently affected by spontaneous emission-the random phase and polarization of photons are added to the amplified signal causing a decrease in the OSNR at the output of the SOA.

When the SOA was saturated, the noise figure increased, as shown in Fig. 10. This is due to the extra noise added to the signal in the deep saturated region.

Quality factor (Q): The performance of the SOA at different input powers using the Q-factor as metric was analyzed at a bias current of 0.25A, 1550 nm wavelength and 2.5 Gb/s, as shown in Fig. 11. The Q initially increases with the SOA input power, but then plateaus out in the saturation region. The optimum Q is therefore obtained in the saturated region and the signal quality does not seem affected by the SOA non-linearity.

CONCLUSION

In this study, we have quantified the merits of using the SOA as the main gain element in future all-optical systems. We have characterized the gain of the SOA by investigating the varying effects of input power, bias current, wavelength and data rate. The many results we have reported will give designers much knowledge of the potential of using the SOA in their system. The SOA generally shows high quality gain, coupled with accept ably low noise figure values.

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