Analysis and characterization of Semiconductor Optical Amplifiers for application in Photonic Switching Networks

F. Rudge Barbosa, Decio Maia and E. Moschim
Faculdade de Engenharia Elétrica e Computação –FEEC, Unicamp
University of Campinas, SP, Brasil

ABSTRACT

Results and analysis of semiconductor optical amplifiers (SOA) are presented as applied to Photonic switching nodes in OPS/OBS future optical networks. Detailed characterization is provided to investigate physical constraints of optical power, gain and noise figure of SOAs. Two different lasers, one external cavity tunable laser and one DFB laser, verify that although the SOA gain is not significantly sensitive to input source a clear difference on the noise figure (NF) is observed. Another important result is that by limiting the average number of hops in the network accumulated ASE power from the amplifiers should not impair signal quality.

Keywords – photonic switching, optical amplifiers, noise figure.

I- INTRODUCTION

SOAs have been playing in the last decade an increasing role as functional devices in Optical Communication systems [1,2]. However, the effective utilization of SOAs requires a thorough understanding and characterization of device parameters and dynamic features so that their impact on system performance can be acknowledged. It is our interest to apply SOA devices as high performance photonic switches in optical packet (OPS) and burst (OBS) switching networks [3-5]; Fig.1.

Here the photonic switching application is looked at in detail and the combination of amplification and switching functions are investigated in the same context. Besides the excellent performance of SOAs as photonic switches, a concern exists that noise and ASE (amplified spontaneous emission) accumulation when multihopping over various optical nodes occurs in OPS/OBS networks [4-6]. On the other hand, by considering metro-access optical networks with as many as 36 optical nodes a limited average number of hops results [4,5], and noise accumulation may be mitigated and its impact on system performance controlled. This paper is organized as follows. In the next section, the operation of SOAs as photonic gates [5] is presented; in sections III and IV the SOAs characteristics are investigated, presenting results on gain, spectral amplification and noise figures with different laser sources. Discussions and conclusions follow.

Fig.1 – Photonic switching optical networks; backbone and metro-access.
II- SOA SWITCHES IN OPTICAL NETWORKS

The advantages of SOAs in switching in optical networks are not only compactness, energy efficiency and reliability, but also the possibility of integration with Ics for amplification/switching operation and control, which contribute more to these features. We have applied them in an optical packet switching (OPS) node, as in future OPS/OBS metropolitan area networks (Fig.1), which saves switching time, reduces the network latency and increases throughput, simply by avoiding OE conversions. But the operation has to be fast, reliable and low-noise.

Fig.2 shows the 2x2 switching node structure; optical packets arriving at node are split 10/90; 10% goes to OE conversion for header recognition; 90 waits at FDL (adjusted to the fixed header processing time); this header information activates the gate-control circuits (GCCs) which may drop the packet for local user or send to main optical switch –set in bar or cross-state, according to first packet preferred destination; the second packet will take the other port.

In Fig.3 the optical gates time frames (which contain the optical packets/bursts) and the optical switch states can be seen. The two upper traces show the optical gates rise-fall times and duration; and the third (green) trace is the optical switch state: it is set to bar or cross when the first packet so demands; then, after the first packet frame ends a free (empty) interval allows a possible re-setting of the switch, as shown. If on the other hand, arriving packets should overlap, the controller protocol combined with the GCC blocks the switch sending the first to its preferred outport, and the second is deflected to the other port. This guarantees that packets/bursts are not cut or lost.

The optical gates with 2.5 μs duration accommodate optical packets of 2.4 μs, which in this case (2.5 Gb/s transmission) correspond to 500 Byte payload and 10 Byte header. The SOAs have on-off rise-fall times of ~0.2ns (180ps), and the GCCs have ~40ms on-off delay time to process header information; therefore adjacent optical packets must have a guard time ≈50 ns. The SOA total switching function (amplification included) consumes less than 500mW.
In Fig. 4 the SOA optical spectrum is shown for three values of bias current: zero, 60mA and 160mA; best performance operation (optimal switching/amplification) lies in the range 150-180mA; in this condition the on-off extinction ratio can be in excess of 50dB, rise-fall times are <200ps, and saturated signal amplification is ~10-12 dB.

Fig. 4 – Amplification and extinction of SOA (>40dB); center 1540nm; (horiz. 5nm/div; vert. 6dB/div).

III- BASIC CONCEPTS AND PARAMETERS

The basic concepts and relevant parameters have been long established [1,2,7]. For the optical power, emission spectra and signal-to-noise ratio (SNR) of the semiconductor optical amplifier (SOA), we follow [2,7].

The objective of an amplifier is to provide gain to the input signal, thus increasing signal power at output. The total external gain is defined as,

\[ \text{Gain (dB)} = \text{[Output Optical Power]} - \text{[Input Optical Power]} \]  \hspace{1cm} (1)

The signal-to-noise ratio (SNR) can be written as [7],

\[ \text{SNR} = \frac{P_{\text{sig}G}}{n_{\nu}h\nu(\Delta\nu)(G-1)} \]  \hspace{1cm} (2)

where \( P_{\text{sig}} \) is the input signal power, \( n_{\nu} \) the spontaneous emission factor, and \( \nu \) the optical frequency. The amplified spontaneous emission (ASE), is regarded as noise in the optical amplifiers and considered as an average in both polarizations.

**Noise figure**

NF is interpreted as an indicator of quality of the amplifier; but attention is required – a low NF as in EDFAs [11] indicates a high-quality amplifier, as is needed for long-haul systems; whereas the higher NF of SOAs will be acceptable in metro-access.

NF can be evaluated as spectral NF (\( \text{NF}_{\text{spt}} \)) or as power NF (\( \text{NF}_{\text{pwr}} \)), and results can be different. The spectral noise figure \( \text{NF}_{\text{spt}} \), is calculated [7] as:

\[ \text{NF}_{\text{spt}} = 10 \log \left( \frac{\text{Pase}}{\frac{h\nu\Delta\nu G}{G+1}} \right) \]  \hspace{1cm} (3)

where, \( \text{Pase} \) is the amplified spontaneous emission integrated power, and \( G \) is the amplifier total external gain. Important to notice that we use \( \text{Pase} = 2n_{\nu} \) where \( n_{\nu} \) represents the spontaneous emission in each polarization (x and y).

The power ratio noise figure \( \text{NF}_{\text{pwr}} \) is the ratio signal-to-noise ratios at input and output [notice that in contrast with (1) it is input over output],

\[ \text{NF}_{\text{pwr}} = 10 \log \left( \frac{\text{SNR}_{\text{input}}}{\text{SNR}_{\text{output}}} \right) \]  \hspace{1cm} (4)
The ASE power is contained in the denominator of eq.(4); whereas it is explicit in eq. (3).

IV- MEASUREMENTS AND RESULTS

The experimental setup for optical power spectral analysis and gain measurements is depicted in Fig.5; it allows also the investigation of noise characteristics for input and output signals. The laser sources that were used are an external cavity tunable laser and a commercial butterfly package DFB laser. The external cavity laser has a sophisticated control unit which stabilizes the output for any setting of power and wavelength in the range studied. The DFB laser however, requires use of an external variable optical attenuator to maintain its spectral and power characteristics stable. The optical power output is measured as integrated in an optical receiver, or spectrally analyzed in an optical spectrum analyzer (OSA). The SOAs are hermetically packaged and have thermoelectric coolers to stabilize and control operation temperature. Needless to say that special care is taken to maintain the SOAs and lasers under well-controlled current and temperature conditions.

Although the gain is the most important feature of an amplifier, the quality of amplification is reflected in its noise figure. Therefore the noise figure of the amplifier must be evaluated also in accordance with the noise characteristics of the source, so that the system noise can be evaluated. We measured (at threshold) ASE power of –52 dBm for the external cavity (EC) laser in a spectral window of 0.2 nm; and ASE power of –38 dBm for the DFB laser.

Amplification and gain

Fig.6 a & b present results of optical amplification and gain; they have been obtained with the EC laser at 1550nm (further measurements at various wavelengths in the SOA spectral window 1520-1570nm, have yielded quite similar results, within less than 2dB margin).
Fig. 6 – Optical amplification (a) and gain (b) for SOA-1; with EC laser @1550 nm.

Fig. 7 (a & b) shows the results obtained with the DFB source. The results have the same qualitative behaviour, but significant differences appear in noise figures and will be discussed.

Fig. 7 – Optical amplification (a) and gain (b) for SOA-1; with DFB laser @1550 nm.
Noise Figures

Fig. 8 a & b, depict the results of the noise figures for both laser sources, as calculated with the spectral (Spt) and power ratio (Pwr) expressions, eq. (3) and (4). Again, the sets of curves represent the noise figures for three different pump currents (120, 140, 160mA) of the SOA. Fig. 9 depicts the results of SOA spectral gain and noise figure, for EC laser @-20dBm.

Fig 8 – Spectral (Spt) and Power ratio (Pwr) SOA-1 Noise figures, for: a) EC tunable laser; b) DFB laser with attenuator.
IV- DISCUSSION OF METHODS AND RESULTS

The noise figures shown represent expression of eqs. (3) & (4) with experimental data. Results from eq. (4), the power noise figure (NF|pwr), reveals more clearly the experimental data of power ratios. On the other hand, the spectral noise figure (NF|spt) in eq.(3) assumes that the source is noiseless, and only the output noise power is considered as the spectral density of noise, which is not considered in NF|pwr. This idealized situation may not be occurring in practical systems. Therefore, it is instructive to keep both methods, even if NF results appear different. For ideal systems the noise figures from eq. (3) and (4) should be the same. However, in real noisy systems significant differences may arise. This situation occurs in Fig.7. The SOA noise figure depends on the laser source and shows different behavior for the two lasers.

Nevertheless, the signal-to-noise ratio of the lasers does not seem to be affected by the fact that the external cavity (EC) tunable laser is very narrow (~1MHz) and the DFB laser not so narrow (~100MHz); that is, in Fig.3 both NF|spt are qualitatively and quantitatively quite similar.

On the other hand, the NF|pwr which is nearly constant for the EC laser, rises markedly from higher input to lower input; we interpret this as due to the optical attenuator used in the SOA measurements with the DFB laser. In other words, it appears that the EC laser can keep the S/N ratio constant over spectral and power ranges studied; whereas in the DFB case, to keep operation stable SOA bias current was fixed and optical power was controlled with an attenuator; this seems to be the reason why NF|pwr appears to increase markedly at lower powers, as in Fig.8b.

We observe that the gain is not very sensitive to the laser source being used, but the noise figure of the SOA tends to vary significantly with the nature of the signal, and is relatively high (~12dB). This is an issue for attention because different sources may share the same amplifiers in networks.

Finally, Fig.9 shows that the noise figure is quite flat (within ~1dB) throughout the better part of the wide operating spectral range of the SAO (1490-1570nm), with gain profile matching the emission spectrum of Fig.4, as expected.

V- CONCLUSION

A thorough study of SOA amplification and noise has been presented, anticipating their application as optical switches in OPS/OBS photonic networks. We confirm in this work that gain measurements alone do not express enough information on the amplifiers and their system. The noise figure must always be investigated, and we propose that two approaches have to be considered to give a better picture. These approaches are designated as power noise figure (NF|pwr) and spectral noise figure (NF|spt).

By using different sources such as external cavity tunable laser and fixed singlemode DFB laser, different behavior of the SOA can be investigated. However, for high quality SOA devices, NF|spt tend to coincide (between 14-16)
revealing the expected high noise figure of SOAs but with stable behaviour. In contrast, NF\(pwr\) may lead to very different and conflicting results depending on the methodology adopted. To keep spectral stability we used optical attenuator and kept DFB current constant; this gave a surprising behaviour, decreasing NF as power increased. Therefore, depending on the source behaviour and on the mathematical model adopted, a different behaviour may be revealed in the noise figure evaluation, not necessarily due to the amplifier itself.

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