Semiconductor Optical Amplifiers in Photonic Switching

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Abstract – **This paper presents the results and analysis of semiconductor optical amplifiers (SOA) as applied in optical nodes for Photonic switching in OPS/OBS future networks. By the same token detailed characterization is provided to investigate physical constraints of optical power, gain and noise figure of SOAs. By using external cavity tunable laser and DFB laser sources, we verify that although the SOA gain is not sensitive to input source a significant influence on the noise figure (NF) of the amplifier is observed. Different analytical expressions for NF are used and consequently lead to different results, illustrating different aspects of devices.**

Keywords **– photonic switching, optical amplifiers, noise figure.**

I- INTRODUCTION

Excellent devices as they are, semiconductor optical amplifiers [1-4] despite many possible functionalities in amplification, switching and lambda conversion, performance limitations may be revealed in system applications. Thus, the practical use of SOAs requires thorough understanding and characterization the devices, so that the interplay of various parameters and dynamic features can be evaluated. In particular, it is our interest to apply SOA devices as high performance photonic switches in optical packet (OPS) and burst (OBS) switching networks [3-5].

In the present work we investigate the combination of amplification and switching functions within the same scope. This includes ASE (amplified spontaneous emission) accumulation when multihopping over various optical nodes occurs in OPS/OBS networks. It will be clear that ASE and noise accumulation, not power budget, will limit the network's extension. In the next section we reproduce from [5] the operation of the photonic gates with very fast rise-fall times, excellent extinction ratio and relatively low noise. Then in sections III and IV we show a deeper insight into the SOAs characteristics, including spectral amplification and noise figures using different laser sources and variable input and operation powers. Results are discussed in detail, and several conclusions follow.

II- SOA SWITCHES

The advantages of SOAs in switching [5] at the optical network layer are not only compactness, energy efficiency and reliability, but also the possibility of integration with Ics for amplification/switching operation and control. We have applied them in an optical packet switching (OPS) node, to be used in metropolitan area networks, saving OE conversions and switching time, thus contributing to significantly reducing the network latency and increasing its throughput.

Fig.1 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 follow to main optical *switch* – which is set in bar or cross-state, according to packet preferred destination; the "second" packet will take the other port.

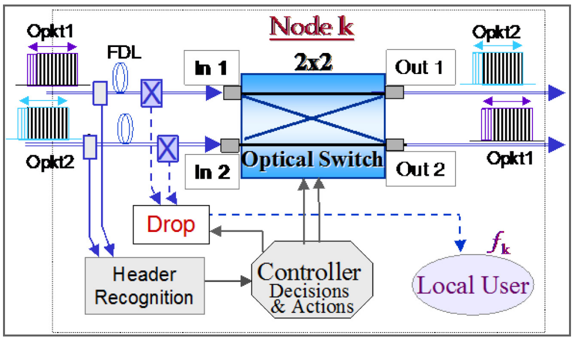


Fig.1 – Optical Packet Switching node.

In Fig.2 the optical packet time frames and the optical switch states can be seen; the two upper traces show the optical packets on-off rise-fall times and duration; the third (green) trace is the optical switch state: it is set when the first packet so demands; then, after the first packet frame ends a free empty interval allows re-setting of the main switch. If arriving packets would overlap, the DR protocol combined with the GCC automatically blocks the switch sending the first to its preferred outport and the second to the other port.

Fig.2 – Actuation of the GCC on the optical switch; rise-fall times <50ns (see text)for details); horiz. 2μs/div.

The gates with 2,5 µs duration accommodate optical packets of 2,4 µs, which in turn correspond to 500 bytes payload and 100bytes header in the present version. The SOAs themselves have on-off rise-fall times of ~0.2ns, but the GCCs have a total ~40ns on-off delay (time to process header information); therefore adjacent optical packets have a guard time ≥50 ns. The SOA optical switching function combined with amplification can easily be integrated into a compact and energy-efficient unit, consuming less than 500mW [CW-power (200mA@2V)]. In **Fig.3** the optical spectrum of the SOA operation is shown for three values of bias current: zero, 60mA and 160mA. This SOA has proper operation (optimal switching/amplification) in the range 150-200mA; in this condition the on-off extinction is above 50dB, rise-fall times are <200ps, and saturated signal amplification is ~10-12dB.

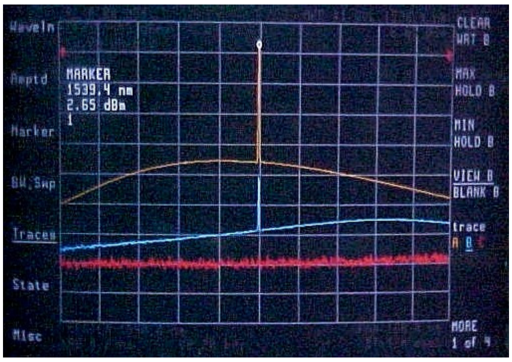


Fig.3 – Amplification and extinction of SOA (>40dB); horiz.1510-1570nm; vert.6dB/div).

III- BASIC CONCEPTS AND PARAMETERS

The basic concepts and relevant parameters have been long established and have had excellent reviews [1,2]. For the optical power, emission spectra and signal-to-noise ratio (SNR) of the semiconductor optical amplifier (SOA), we follow [2,6]:

$$SNR = \frac{PsigG}{n_{sp} h\nu(\Delta\nu)(G-1)} \qquad (1)$$

where P_{sig} is the input signal power, n_{sp} the spontaneous emission factor, ν is the optical frequency, and G is the total external gain.

The objective of an amplifier is to increase the output power. The SOA external gain is defined as

$$G(dB)=[OpticalSignalPower]_{output}\ (\text{dBm}) - [OpticalSignalPower]_{input}\ (\text{dBm}) \qquad (2)$$

The amplified spontaneous emission (ASE), regarded as noise in the optical amplifiers will be considered [2,6] as the average power in both polarizations.

Noise figure

In order to evaluate the dynamic behavior of an amplifier, the noise figure (NF) must be known; NF can be interpreted as the *quality* of the amplifier gain. Furthermore, it can be evaluated as spectral NF or as power NF, and results can be quite different for non-ideal systems. The *spectral noise figure* NF|spt , is calculated [6] as :

$$NF_{spt} = 10\ \log\left(\frac{Pase}{\text{h}.\upsilon.\Delta\upsilon.\text{G}} + \frac{1}{G}\right) \qquad (3)$$

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

The *power* ratio noise figure *NF|pwr* is the definition itself [2,6]: the ratio signal-to-noise ratios at input and output (notice that it is *input* over *output*),

$$NF_{pwr} = 10\ \log\left(\frac{[SNR]\ input}{[SNR]\ output}\right) \qquad (4)$$

The ASE power is contained in the denominator of eq.(4); by contrats 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.4;** 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 □ho 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 na external variable optical attenuator to maintain its spectral and power characteristics stable. The optical power output is measured as integrated in na optical receiver, or spectrally analyzed in na optical spectrum analyzer (OSA). The SOAs are hermetically packaged and have thermoelectric coolers to stabilize and control operation temperature. Needles 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 an spectral window of 0.2 nm; and ASE power of –38 dBm for the DFB laser.

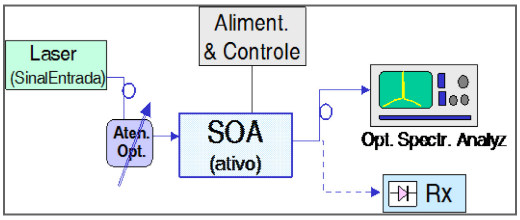
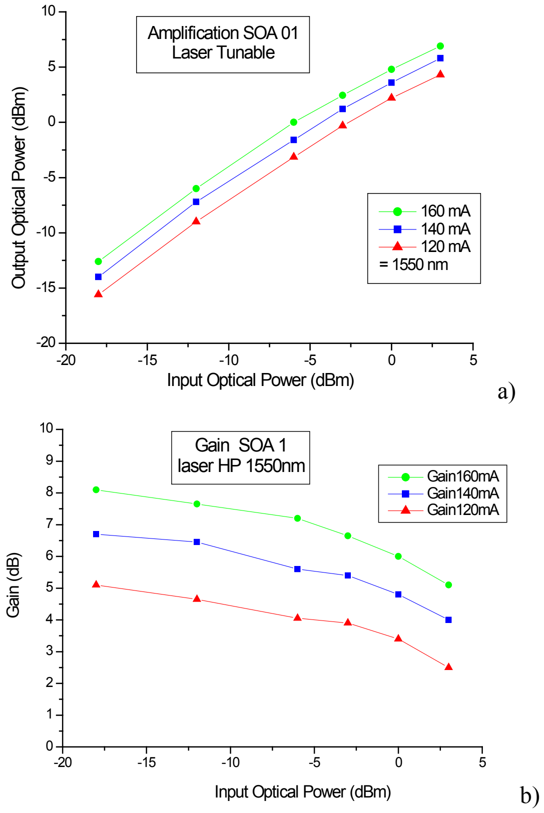


Fig.4 – Experimental setup for SOA characterization.

Amplification and gain

Fig.5 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).

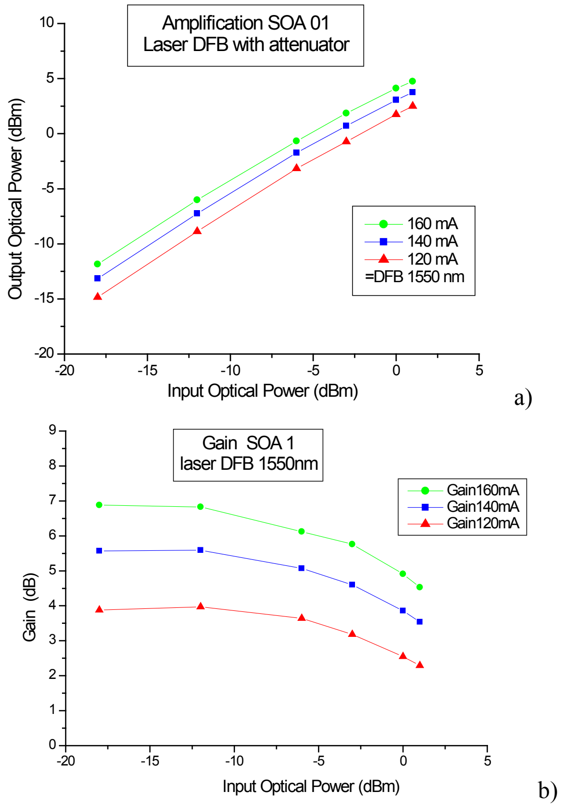


a)

b)

Fig.5 – Optical amplification (a) and gain (b) for SOA-1; with EC laser @1550 nm..

Fig.6 (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.



a)

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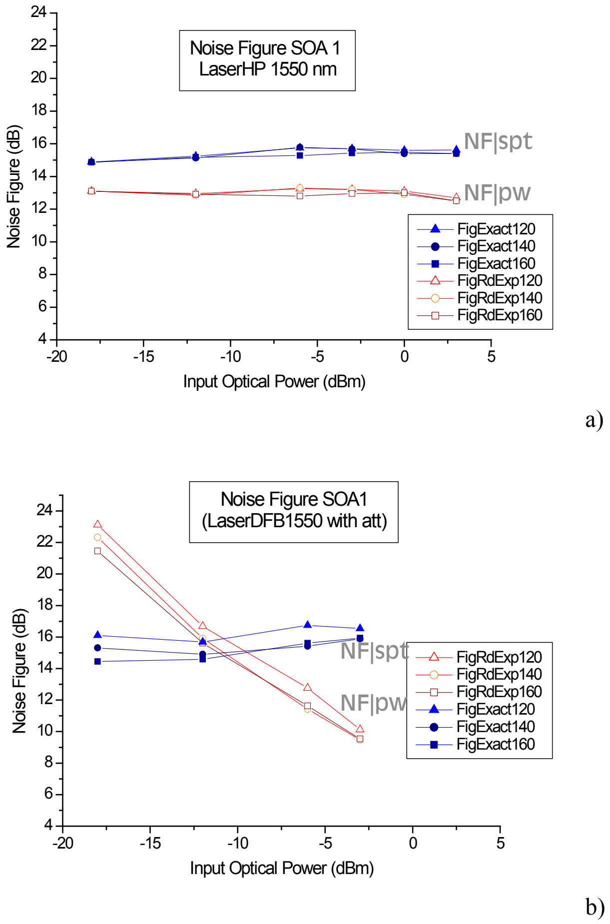
Fig.6 – Optical amplification (a) and gain (b) for SOA-1; with DFB laser @1550 nm..

Noise Figures

Fig.7 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.



a)

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Fig 7 – Spectral (Spt) and Power ratio (Pwr) Noise figures, for): a) EC tunable laser; b) DFB laser source 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. This idealized situation may not be occurring in practical systems. However, eq.(3) gives an account of the spectral density of noise, which is not considered in NF|pwr. Therefore, it is instructive to always keep both methods of calculation, even if NF results appear different.

For ideal systems the noise figures from eq. (3) and (4) tend to be similar and results approximate each other. However, in real noisy systems significant differences may arise between NF|pwr and NF|spt. This situation is clearly seen in **Fig.7.** The SOA noise figure is clearly dependent 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 even 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, the sophisticated EC laser can keep the S/N ratio constant over spectral and power ranges studied; the DFB by contrast, in order to keep the spectral characteristics stable we decided to use tha attenuator, which in turn impacts on the S/N ratio of the DFB laser over the range studied.

Therefore we see that although the gain is not sensitive to the laser source being used, as demonstrated here, the noise figure of the SOA, tends to be relatively high (~12dB), and is sensitive to the nature of the signal. Then, care must be taken because different sources may share the same amplifiers in networks.

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 behaviour 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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