Black-box model for the complete characterization of the spectral gain and noise in semiconductor optical amplifiers

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Abstract: A Black Box Model for the quick complete characterization of the optical gain and amplified spontaneous emission noise in Semiconductor Optical Amplifiers is presented and verified experimentally. This model provides good accuracy, even neglecting third order terms in the spectral gain shift, and can provide cost reduction in SOA characterization and design as well as provide simple algorithms for hybrid integration in-package control.

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OCIS codes: (250.5980) Semiconductor optical amplifiers; (140.3280) Laser amplifiers

References and links

1. A. Rieznik et.al., “Spectral functional forms for modeling SOAs noise,” Proceedings of the SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference 2005 (Brasília, DF, Brazil).
2. K. Stubkjaer, “Semiconductor optical amplifier-based all-optical gates for high-speed optical processing,” IEEE J. Sel. Opt. Quantum Electron. 6, 1428-1435 (2000).
3. E. Conforti, C.M.Gallep, A.C. Bordonalli, “Decreasing Electro-Optic Switching Time in Semiconductor Optical Amplifiers by Using Pre-Pulse Induced Chirp Filtering,” Optical Ampl. Applications 2003 TOPS, J. Mark, and A. Srivastava ed.. (OSA Publications) 92, 111-116 (2003).
4. J. Leuthold et.al., “Novel 3R regenerator based on semiconductor optical amplifier delayed-interference configuration,” IEEE Photonics Technol. Lett. 13, 860-862 (2001).
5. N. C. Frateschi et.al., “Uncooled Performance of 10-Gb/s Laser Modules With InGaAlAs–InP and InGaAsP–InP MQW Electroabsorption Modulators Integrated With Semiconductor Amplifiers,” IEEE Photonics Technol. Lett. 17, 1378-1380 (2005).
6. C.Y. Tsai et.al., “Theoretical modeling of the small-signal modulation response of carrier and lattice temperatures with the dynamics of nonequilibrium optical phonons in semiconductors lasers,” IEEE J. Sel. Top. Quantum Electron. 5, 596-605 (1999).
7. C. M. Gallep and E. Conforti, “Reduction of Semiconductor Optical Amplifier Switching Times by Pre-Impulse-Step Injected Current Technique,” IEEE Photon. Technol. Lett. 14, 902 –904 (2002).
8. C. M. Gallep and E. Conforti, “Simulations on picosecond nonlinear electro-optic switching using an ASE-calibrated semiconductor optical amplifier model,” Opt. Commun.236, 131-139 (2004).
1. Introduction

Semiconductor Optical Amplifier (SOA) is a key device for nonlinear sub-systems implementation, enabling all-optical signal processing functionalities in Wavelength Division Multiplexing (WDM) networks [2]. SOA-based sub-systems can give feasible alternatives for wavelength conversion [2], switching [3] and pulse regeneration [4], among others. Also, SOA’s are essential for the development of small form factor, low power, uncooled high performance hybrid integrated optical systems [5]. In all these applications, simple models allowing reduction in testing time and resources for chip or package characterization are desirable, since this step is a costly one in the optoelectronic production chain. Also, simple algorithms covering the spectral gain and spontaneous emission over a large range of wavelengths and pump currents can enable the fabrication of tunable components for uncooled operation relying on simple in-package correction logic circuit.

Several different approaches to SOA modeling have been presented in the literature. While sophisticated models can provide design and analysis tools for the active region of the amplifiers [6], some simplified semi-empirical models are versatile for practical analysis [7].

We have recently proposed a Black Box Model (BBM) for the characterization of the gain and noise behavior of Semiconductor Optical Amplifiers (SOA) operating under CW conditions [1], i.e., a model that does not use any intrinsic device parameter and needs few experimental data points to map an entire range of SOA’s spectral properties. In this BBM three spectral gain or noise curves for different pump (bias current) condition are used to predict the SOA spectral response under any other bias condition, by knowing only two spectral points of the desired curve. In other words, the whole gain or noise spectrum of a SOA is predicted if only two spectral points of the curve are known and for this prediction we use three spectral functions that can be calculated from three gain or noise spectra. In this work, the BBM for SOAs operating under CW conditions is presented and experimentally validated to describe the spectral gain and amplified spontaneous emission (ASE) behavior. The derivation of the BBM for gain predictions is straightforward, while its application in ASE spectra modeling is not so obvious and deserves special attention. We discuss the conditions under which this BBM works for SOA gain and noise characterization and experimentally validate our results using a commercially available SOA.

2. Theory

2.1 Gain modeling

In many recent SOA models, the incremental material gain \( dG \) (for a spatial discrete step \( dz \) inside the amplifier active medium) as function of the wavelength \( \lambda \) is related to the electronic population density \( N(z) \) by using a direct linear term and indirect terms, second and a third order (spectral gain’s peak shift), being expressed as [8]:

\[
dG(\lambda) = \Gamma \left[ a_1 (N - N_{tr}) - a_2 (\lambda - \lambda_{sh})^2 + a_3 (\lambda - \lambda_{sh})^3 \right]
\]

where \( \lambda_{sh} = [\lambda_0 - a_4 (N - N_{tr})] \) is the shift in the central frequency \( \lambda_0 \), \( N_{tr} \) the transparency carrier density, \( \Gamma \) the confinement factor, and \( a_{1-4} \) are gain parameters [8]. Now, it is straightforward that the total amplifier gain in logarithmic scale can be approximated in the same way, but now with \( N \) being an averaged value of the electron-hole population density along the amplifier cavity. Thus,

\[
G(\lambda) = \Gamma \left[ a_1 (N - N_{tr}) - a_2 (\lambda - \lambda_{sh})^2 + a_3 (\lambda - \lambda_{sh})^3 \right]
\]
From Eq. (2) it is easy to show that \( G(\lambda) \) can be written in terms of \( N \) as:

\[
G(\lambda) = R(\lambda)N + S(\lambda)N^2 + T(\lambda)N^3 + W(\lambda)
\]

where \( R, S, T \) and \( W \) depend only on the SOA internal and intrinsic parameters and, obviously, on the wavelength \( \lambda \). Now, if the cubic term in Eq. (3) is discarded (i.e., \( T = 0 \)), Eq. (3) can be rewritten for three different wavelengths (\( \lambda, \lambda_1, \lambda_2 \)) and combined in order to eliminate \( N \) and \( N^2 \), hence obtaining

\[
G(\lambda) = F_1(\lambda, \lambda_1, \lambda_2)G(\lambda_1) + F_2(\lambda, \lambda_1, \lambda_2)G(\lambda_2) + F_3(\lambda, \lambda_1, \lambda_2)
\]

where the functions \( F_1, F_2, \) and \( F_3 \) depend on \( R, S, \) and \( W \), which are evaluated at \( \lambda, \lambda_1, \) and \( \lambda_2 \).

Equation (4) is the BBM fundamental equation and shows that the gain at any wavelength can be expressed as a linear function of the gain at the reference wavelengths \( \lambda_1 \) and \( \lambda_2 \) if the \( F \)’s spectral functions are known. The main advantage in the BBM interpolation process is that these three spectral functions (\( F \)s) can be easily obtained from the amplifier as a whole, including all penalties inherent to engineering mounts (packaging, gain polarization dependence, optical interconnections, etc). In fact, \( F_1, F_2, \) and \( F_3 \) are obtained from three complete spectral gain curves, each one measured under different SOA’s bias currents (say \( A, B \) and \( C \)). Writing Eq. (4) three times for these three different pump conditions, a set of equations are obtained which in a matrix form are:

\[
\begin{bmatrix}
G_A(\lambda_1) & G_A(\lambda_2) \\
G_B(\lambda_1) & G_B(\lambda_2) \\
G_C(\lambda_1) & G_C(\lambda_2)
\end{bmatrix}
\begin{bmatrix}
F_1(\lambda, \lambda_1, \lambda_2) \\
F_2(\lambda, \lambda_1, \lambda_2) \\
F_3(\lambda, \lambda_1, \lambda_2)
\end{bmatrix}
= \begin{bmatrix}
G_A(\lambda) \\
G_B(\lambda) \\
G_C(\lambda)
\end{bmatrix}
\]

Solving the system above, \( F_1, F_2, \) and \( F_3 \) are obtained and so the gain spectra at any different pump condition can be determined by Eq. (4) by measuring the optical gain just at the two reference wavelengths \( \lambda_1, \) and \( \lambda_2 \). If a reduction in device testing complexity is desired, one needs to measure the gain spectra for three bias currents and then, under any other operating condition, the optical gain at two fixed wavelengths to obtain the entire spectrum. In Section 3, experimental validation is presented. Now, it becomes important to evaluate an extension of the same approach to treat the ASE noise.

2.2 Noise modeling

It is well-known that the ASE output power of a SOA, in a bandwidth \( B \), is given by:

\[
\text{ASE}^L(\lambda) = N_{sp}(\lambda)B(G^L(\lambda) - 1) \approx N_{sp}(\lambda)B G^L(\lambda)
\]

where the superscript \( L \) indicates linear scale are used, \( N_{sp} \) is the so called noise factor where the rightmost term in Eq. (6) is valid for \( G^L \gg 1 \), as is usually the case in SOAs. Now, one can write Eq. (6) in logarithmic scale and use Eq. (3) with \( T = 0 \) to obtain:

\[
\text{ASE}(\lambda) = \text{Seq}^{dBm}(\lambda) + G(\lambda) = \text{Seq}^{dBm}(\lambda) + R(\lambda)N + S(\lambda)N^2 + W(\lambda)
\]

where \( \text{Seq}^{dBm} \) is equal to \( N_{sp}(\lambda)B \) in logarithmic scale (dBm), called ‘equivalent input noise term’ in order to stress that the ASE output power could be expressed as the amplification of this equivalent input noise. Now, \( \text{Seq}^{dBm} \) depends on \( N \), the carrier population density, and so it can be expanded as a power series of \( N \). Assuming this expansion up to the quadratic term and rearranging the terms proportional to each power of \( N \) in Eq. (7), one can proceed as in the derivation of Eq. (4) and write Eq. (7) for three different wavelengths, combining them to eliminate \( N \) and \( N^2 \):

\[
\text{ASE}(\lambda) = F_1^{\text{ASE}}(\lambda, \lambda_1, \lambda_2)\text{ASE}(\lambda_1) + F_2^{\text{ASE}}(\lambda, \lambda_1, \lambda_2)\text{ASE}(\lambda_2) + F_3^{\text{ASE}}(\lambda, \lambda_1, \lambda_2)
\]

Therefore, a similar approach as described in Section 2.1 can be, in principle, employed for the ASE characterization in amplifiers. One should observe that the main approximation
in the Eq. (8) construction is the dispose of third and higher order terms in both \( \text{Seq}^{\text{dBm}}(\lambda) \) and \( G(\lambda) \) in Eq. (7). Thus, Eq. (8) is an even more limited solution for the ASE output power than Eq. (4) is for the gain of the SOA. Nevertheless, as shown in the next Section, this equation provides excellent theoretical predictions for the ASE output power of a commercially available SOA.

3. Experimental validation

ASE and optical gain measurements were used to validate the BBM. The gain and ASE spectra of a commercially available SOA (Corning Inc.) were measured with an Optical Spectrum Analyzer (Anritsu, MS96A), using 400-point discretization for the acquired spectral span. The optical signals were directly collected from the SOA module with single-mode fiber cables with FC-APC (angled) connectors, avoiding spurious reflections. The SOA bias current was varied, in 50-mA steps, from 100mA to 450mA, and the typical ASE spectra are presented at Fig. 1(a).

With the experimental data collected, the BBM proceeds as follow: first, three ASE spectra are used in Eq. (5) to calculate the \( F_s \) spectral functions. Then, at different pump conditions (bias currents), the ASE power is measured at the two chosen reference wavelengths, \( \lambda_1 \) and \( \lambda_2 \), to predict the whole spectra through Eq. (8). In this example the curves corresponding to bias currents of 100mA, 250mA and 400mA were chosen to calculate...
the $F_j$ functions, and $\lambda_1 = 1450$ nm and $\lambda_2 = 1550$ nm as the reference wavelengths. The calculated curves are shown in Fig. 1(b). To better visualize the BBM accuracy, the relative error \((P_{exp} - P_{BBM})/ P_{exp}\) was calculated and is presented at Fig. 2, with good agreement between the BBM reconstruction and the experimental within 2% in all cases.

The same procedure applied to the ASE data was done to the SOA optical gain. In this case, however, due to the limited bandwidth of our CW tunable laser, the model was tested in a much narrower band, from 1520 to 1570 nm. The optical power injected in the SOA by the tunable laser was –10 dBm. The SOA bias current was varied in 50 mA steps and a computer controlled Optical Spectral Analyzer measured the output optical power. The net SOA optical gain, considering the back-to-back link losses, is presented at Fig. 3(a).

![Fig. 3. SOA optical gain spectra for eight bias current levels: (a) experimental and (b) predicted by BBM.](image)

In this case, the gain curves corresponding to the bias currents of 100mA, 200mA and 400mA were chosen to calculate the $F_j$ functions, and the wavelengths 1530 nm and 1555 nm as the reference wavelengths. The BBM prediction for the SOA optical gain is presented at Fig. 3(b). A good accuracy was obtained as shown by the relative error presented in Fig. 4, as done before for the ASE case, where relative errors within 4% are shown. The 10% relative error point (out of the figure span) at the 150 mA curve was due to an experimental fluctuation in the laser optical power at 1520 nm. Therefore, the accuracy is similar for both ASE and gain.

Two observations are relevant here. First, in Figs. 2 and 4 the BBM interpolation mechanism gives the exact result when predicting the gain (ASE) curves used to calculate the
Fs functions or when predicting the gain (ASE power) at the reference wavelengths. This happens by construction and is natural, since these measured curves are used to interpolate the other spectra. For instance, if in the right side of Eq. (5) \( \lambda = \lambda_1 \) is used, one will obtain \( F_1(\lambda_1, \lambda_1, \lambda_2) = 1 \) and \( F_2(\lambda_1, \lambda_1, \lambda_2) = F_3(\lambda_1, \lambda_1, \lambda_2) = 0 \). Similarly, if \( \lambda = \lambda_2 \) is used, one will obtain \( F_2(\lambda_2, \lambda_1, \lambda_2) = 1 \) and \( F_1(\lambda_2, \lambda_1, \lambda_2) = F_3(\lambda_2, \lambda_1, \lambda_2) = 0 \). In the same way, substituting in Eq. (4) the expression for the Fs curves as a function of the measured gains A, B and C, given by the solution of Eq. (5), it is straightforward to show that Eq. (4) gives the trivial relations \( G_{A,B,C}(\lambda) = G_{A,B,C}(\lambda) \).

The second observation is that the noise over experimental data propagate during BBM interpolation mechanism, as can be seen in Fig. 1 around the region of 1.40 \( \mu \)m. The noisy characteristic of this region in Fig. 1(b) is a consequence of the fluctuations also observed in the spectral curves used to calculate the Fs functions (Fig. 1(a)).

To guarantee that the probe signal (–10 dBm) used to measure the SOA gain is not saturating the amplifier, the optical gain versus optical input power response were measured for four bias currents (50 mA, 100 mA, 250 mA and 500 mA, not shown) and optical input powers from –30 dBm up to 3.8 dBm, with less than 2 dB of gain depletion. This guarantee that linear gain regime was used.

4. Discussion and conclusion

The validity of a simple BBM has been experimentally demonstrated for ASE and optical gain data. Since we have neglected all cubic and higher order dependences on average carrier density for the model, we can conclude that these terms do not significantly affect SOA gain and ASE behavior in the C-band.

Interestingly, the result presented here concerning the linear relation between the gain at three different wavelengths, has been first shown to correctly predict Thulium-Doped Fiber Amplifiers (TDFAs) with good experimental accuracy [9]. But, while in the case of SOAs the linear relation between gain at three different wavelengths arises from the fact that the cubic terms of the electronic population density can be neglected in its modeling, in the T DFA case it arises from the fact that three energy levels are involved in the amplification process. The BBM presented in [9] is an extension for a tree-level system of a model originally presented for erbium-doped amplifiers, i.e., for a two-level system [10].

Acknowledgments

The authors wish to acknowledge Thiago Branciforti (technical support for data acquisition) and FAPESP (Fundação de Amparo a Pesquisa do Estado de São Paulo) projects -CEPOF (www.ifi.unicamp.br/loton) and KyaTera (www.kyatera.fapesp.br). We also thank Corning Inc. for supplying the SOA for this work.