Parameter Estimation of Semi-Conductor Optical Amplifier Booster based on Digital Signal Processing

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Abstract: We propose a method for SOA characterization using conventional coherent transmission signals, including dual-polarization signals. Using 16QAM signals, we demonstrate that this method can be applied for several baudrates and wavelengths.

1. Introduction

Semiconductor optical amplifiers (SOAs) have been widely implemented, as transceiver booster amplification since they are compact and can operate under low power consumption [1]. Additionally, SOA noise figure can reach values below 5 dB [2]. Due to these characteristics, using SOAs as booster and thus compensating the transmitter loss is becoming common as for example in the case of HB-CDM transmitters [3]. When considering SOAs operating as booster, the distortion caused by SOA nonlinearities should also be considered. The nonlinear penalty can be assessed when considering the following SOA parameters: linewidth enhancement factor, carrier lifetime and saturation power as introduced in [4]. Several techniques have been introduced in order to characterize these SOA parameters. Methods based on Four wave mixing (FWM) require access to high resolution OSAs which might not be available in every lab [5]. Self-Phase Modulation (SPM) and spectral broadening of optical pulses is alternative technique that can be used to monitor the SOA [6]. The use of a coherent receiver and digital signal processing (DSP) makes the method of [7, 8] better than the other techniques since: i) It can be implemented without any additional equipment than a coherent transceiver ii) it could be implemented in HB-CDM in which the SOA is embedded into the transmitter and iii) it could be used for monitoring operating SOAs using offline processing. This method requires only knowledge of transmitted and received symbols (the transmitted symbols could be obtained from the decoded symbols in an operating SOA). In this paper, we use the same relation between received and transmitted symbols as in [7, 8] to calculate the linewidth enhancement factor while we propose an elliptical fitting for improving the accuracy of the estimation. Different than [7,8] which estimated the carrier lifetime by solving the Agrawal model, we here propose to use the spectral density of the power in order to calculate the effective carrier lifetime. Additionally, we propose a simple method to calculate the linewidth enhancement factor in a polarization-diverse SOA amplifying Dual Polarization (DP) signals without polarization control, consisting in taking into account the input SOP. Our experiments include the SOA characterization for different wavelengths and baud rates using 16QAM signals. Our results show that we estimate similar linewidth factor (3.5 vs 3.1) than FWM-based methods. We also show that the linewidth enhancement factor can be estimated for DP signals with estimated range values from 3 to 4 in a set of measurement with random input SOP.

2. SOA Parameter Estimation

The nonlinear model of an SOA is given by [4]:

$$E_{X,out} = E_{X,soa\,in} exp(g(t)/2(1+j\alpha)) \tag{1}$$

$$\tau_c \frac{dg}{dt} = g_0 - g(t) - (\exp(g(t))-1)|E_{in}|^2/P_{sat} \tag{2}$$

where $g(t)$ is the time dependent gain exponent, α is the linewidth enhancement factor, τ_c is the carrier lifetime, g_0 is the small signal gain and P_{sat} is the saturation power. P_{sat} can be easily measured by varying the input power to the SOA and observing the output power and gain compression. Thus we focus on a method to estimate both α and τ_c from a single characterization measurement of the SOA.

The effect of the nonlinear phase change due to α can be estimated from using only knowledge of transmitted and received symbols,

$$\boldsymbol{A} = g(1+j\alpha) = 2ln\left(E_{X,out}/E_{X,soa\,in}\right) \tag{3}$$

And thus α can be estimated as the ratio of the imaginary to the real part of $\boldsymbol{A}$. When considering noise, as shown in Fig. 1c, the complex PDF of A has an elliptical shape and thus α can be calculated as the arctangent of the angle the major axis of the ellipse makes with the x axis as in Fig. 1c. In the DP case and assuming polarization diverse SOA, shown in Fig. 1b, as the output is formed as:

$$E_{\ out} = \left[E_{X,soa,in}\exp\left(\frac{g_1}{2}(1+j\alpha_1)\right)\hat{x} + E_{y,soa,in}\exp\left(\frac{g_2}{2}(1+j\alpha_2)\right)\hat{y}\right] \quad (4)$$

where $E_{X,soa\ in}$, $E_{y,soa,in}$ are related to the transmitted signal x and y components by the polarization rotation

$$\begin{bmatrix} E_{x,soa,in} \\ E_{y,soa,in} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta)\exp(j\phi) \\ -\sin(\theta)\exp(-j\phi) & \cos(\theta) \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix} \quad (5)$$

Calculating the polarization angles, θ and ϕ is necessary to be able to use the aforementioned equation due to the polarization diverse scheme. In this paper we use a brute-force approach which aims to maximize the ratio between the major and minor axis of the ellipse calculated from rotating both the received symbols and transmitted symbol so that we obtained the input and output signals in the polarization frame of the SOA. As will be shown, when not applying this rotation, the estimation could fail. The effective carrier lifetime of the SOA depends on the P_{out}/P_{sat} ratio and is thus varying with Pin. The relationship between the τ_{eff} and the spectrum of the power at the output of the SOA is defined by the relation $P(f) = \frac{1}{1+2\pi\tau_{eff}f}$.

By plotting the FFT of the power of the received symbols and fitting the result to this function an estimate of τ_{eff} can be obtained [9]. This is demonstrated in Fig 1d. The relation between the τ_{eff} and τ_c can be found in [9] or could be estimated through numerical simulation using e.g. Agrawal model.

3. Experimental Results and Discussion

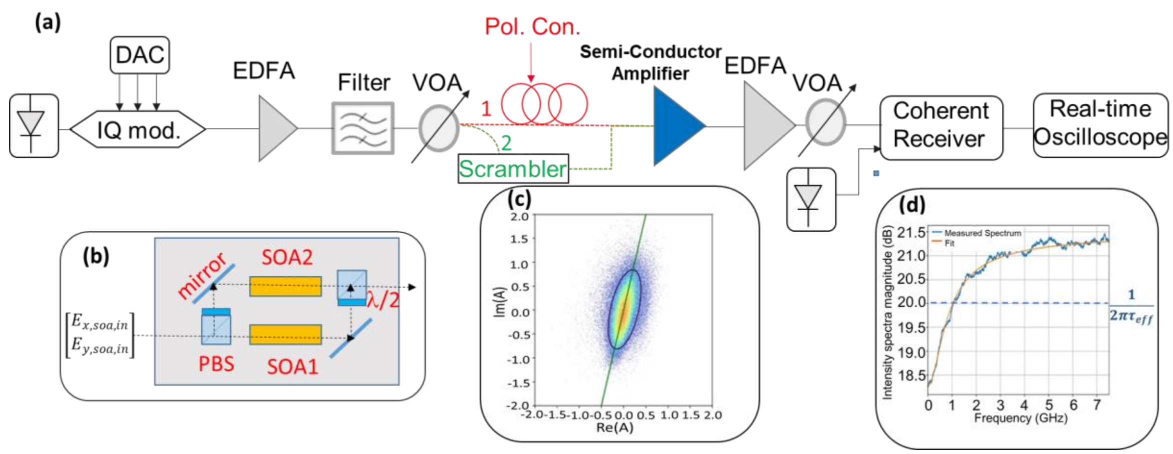

Fig. 1 (a) Experimental setup, (b) Structure of polarization diversity SOA (c) α estimation by ellipse fitting (d) τ_{eff} estimation by fitting power spectrum

The experimental setup is presented in Fig. 1a. One tunable laser source (TLS) is used at the transmitter. The single-carrier 16QAM signals are modulated onto the optical carrier by an IQ modulator and generated by a 120 GSa/s digital-to-analog converter (DAC). At the output of the IQ modulator, we use an erbium doped fiber amplifier (EDFA) to vary the SOA input power. The design of the semiconductor-based SOA is described in Fig. 1b, leveraging a polarization diversity structure and using two SOA chips. To remove the out of band amplified spontaneous emission (ASE), an optical band-pass filter is used after the EDFA. The SOA input powers are tuned using a variable optical attenuator (VOA). The SOA working temperature is equal to 30°C thank to a thermoelectric cooler. The current is 150mA per SOA chip. Then, the signal is amplified by a second EDFA in the receiver side just to protect the coherent receiver by keeping the input power constant. The coherent receiver is composed by a TLS local oscillator to mix the received signal and four balanced photodetectors to convert the signal to the electrical domain. A real-time oscilloscope operating at 256Gsample/s is used to sample the electrical signals.

3.1 *Single polarization SOA analysis*

The estimation of the linewidth enhancement factor and the carrier life estimation are done for different baud rates (16, 32 and 64 Gbaud) and different wavelengths in L-band (1575 and 1600 nm) and in C band (1550 nm) using a polarization diversity SOA (Fig. 1b) where only one branch is activated and also a single polarization 16QAM signal aligned along the SOA axis. Using FWM we estimated a linewidth enhancement factor of 3.1 at 1575 nm, using the proposed method we estimate around 3.5. The difference is below 15% is lay within the uncertainty of measurement of each method that is estimated to be slightly larger than 10%. When comparing different wavelengths, we find that the value of α decreases by decreasing the wavelength. For the same wavelength, we calculate slightly different α when varying the baud rate. We have found that the estimated value of τ_{eff} decreases by decreasing the wavelength. In addition, we have found, as shown in Fig. 2b and d, τ_{eff} decreases by increasing the output power which expected[9].

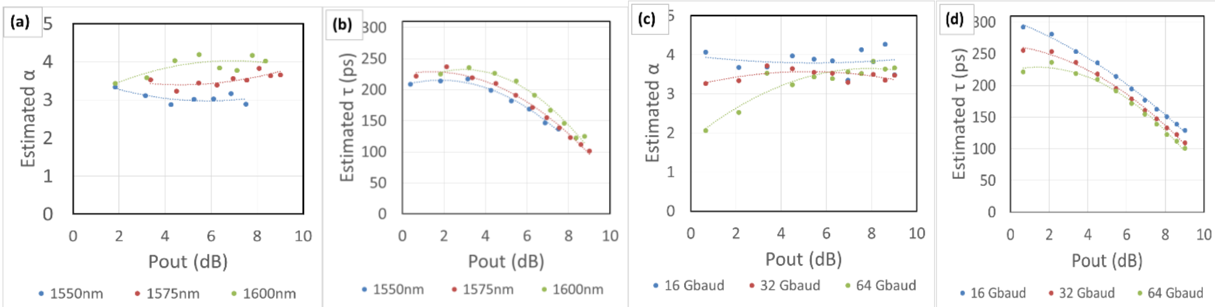

Fig. 2 (a) Estimated α for different wavelengths, (b) Estimated τ_{eff} for different wavelengths,(c) Estimated α for different baudrates and (d) Estimated τ_{eff} for different baudrates

3.2 *Dual polarization SOA analysis*

In the DP case the method for estimating α can still be used given that the received and reference signals are rotated to the SOA reference SOP before the estimation process, as explained in section 2. Fig. 3c and d, show the constellation to α estimation by ellipse fitting without and with rotation before the estimation (as mentioned the rotation maximizes the ratio between the ellipse axis). This is demonstrated in Fig. 3a where the SOP of the signal is randomized by 25 combinations before entering the SOA at 1550nm and 0dBm P_{out}. It can be seen that after this rotation process the estimation in DP converges to the values obtained in Fig. 1a for the same wavelength. As we have found in single polarization SOA case, that the estimated value of τ_{eff} decreases by increasing the baudrate (Fig. 2b).

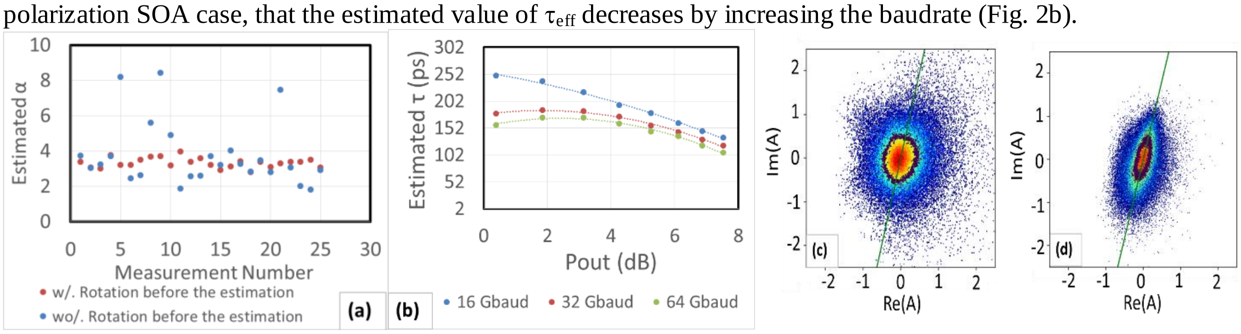

Fig. 3 Dual polarization estimation for (a), α Vs. P_{out}t, (b) τ_{eff} Vs. P_{out} ,(c) the complex PDF of A without rotation before the estimation and (d) the complex PDF of A with rotation before the estimation.

4. Conclusions

We have demonstrated a method to quickly estimate the linewidth enhancement factor and effective carrier lifetime of a semiconductor optical amplifier requiring only a coherent transmitter and receiver. The estimation method is suitable for use in both single and dual polarization setups. We also show the dependence of the estimated parameters on wavelength as well as the impact of baud rate utilized in the measurements. Since these parameters determine the strength of the SOA-induced nonlinear penalty, this method could find applications in SOA-booster characterization as well as monitoring.

5. References

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