

Automated Characterization of Semiconductor Optical Amplifier Electro-Optic Response

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Abstract—This work presents an algorithm for the experimental characterization of the electro-optic response of semiconductor optical amplifiers (SOAs). An automation algorithm implemented in Python is proposed, using SCPI (Standard Commands for Programmable Instruments) commands for electrical signal generation and data acquisition. A method for minimizing spectral leakage in the discrete Fourier transform is investigated through the proper selection of the oscilloscope sampling rate and record length, i.e., the number of acquired points. For validation, measurements were performed using arbitrary frequency values that did not take into account the oscilloscope sampling rate or record length. The oscilloscope-based results are also compared with measurements obtained using an electrical signal analyzer. Using the proposed technique, a reduction in the maximum mean error from 0.404 to 0.114 was observed. Although this algorithm was developed for SOAs, it can also be applied to the characterization of other electro-optic devices, such as lasers and modulators.

Keywords—Electro-optical response, Semiconductor optical amplifier, Spectral leakage.

I. INTRODUCTION

Semiconductor optical amplifiers (SOAs) are electro-optic devices capable of providing optical gain. Light propagating through an SOA is amplified through stimulated emission driven by electrical pumping, i.e., current injection. When the injected current is low or zero, the SOA can operate as an absorbing device, in which incident photons are absorbed and converted into electrical signals. As the injected current increases, the stimulated-emission process becomes more pronounced [1].

In this context, SOAs can be employed in optical switching applications. For instance, in [2], several SOAs were integrated into a photonic integrated circuit to implement a 4×4 optical switch operating in the O-band. Another noteworthy contribution is presented in [3], which proposes an architecture based on optical add/drop multiplexers (OADMs) using semiconductor optical amplifiers and FPGA-based controllers to enable dynamic, low-latency operation suitable for applications with stringent latency and jitter requirements.

With the objective of reducing the switching time, the pre-impulse-step injected current (PISIC) technique, proposed in [4], stands out, as it significantly reduces the pulse rise time. Also relevant is the study presented in [5], which investigates ultrafast electro-optic switching with amplification using an SOA chip-on-carrier device; switching times as low as 115

ps were achieved using step-current injection with multiple pulses.

In [6], new approaches for ultrafast semiconductor optical amplifier switching based on artificial intelligence algorithms are developed and applied in both simulations and experiments. Effective switching, or stabilization, times of 542 ps are demonstrated with only 4.8% overshoot.

In [7], a study involving FIR filters and PID control for reducing optical switching time is proposed. The study was based on a numerical model fitted using the SOAs' S_{11} parameter. To extend the work presented in [7], we aim to develop algorithms to accelerate the switching time while also taking into account the electro-optic transmission response of SOAs.

In this context, the present work proposes an algorithm for the experimental characterization of semiconductor optical amplifiers. The algorithm accounts for spectral leakage arising from the fast Fourier transform (FFT) in the estimation of the SOAs' electro-optic response. Measurements were carried out using arbitrary frequency values, without accounting for spectral leakage; using frequency values selected according to the oscilloscope sampling rate and record length, thereby accounting for spectral leakage; and, finally, using an electrical signal analyzer. Using the investigated technique, a significant reduction in the discrepancy between the measurements obtained with the two instruments was demonstrated when spectral leakage was properly taken into account.

The algorithm, developed in Python using the SCPI (Standard Commands for Programmable Instruments) protocol, is provided for the control of sinusoidal-signal generation and data acquisition. The data measured using the proposed technique are also made available. Although this algorithm is intended for the experimental characterization of SOAs, it can also be applied to the characterization of other electro-optic devices, such as lasers and modulators. It is worth noting that, when using a signal generator and an oscilloscope, a large volume of data can be acquired, enabling a detailed characterization of SOA-induced distortions in each frequency component. Consequently, the use of experimental data to build numerical models that accurately represent the actual behavior of these devices becomes feasible.

This paper is organized into five sections. Section II describes the experimental setup and the main instruments used, while also highlighting details of the algorithm and the mea-

sured data. Section III presents the mathematical formulation of the investigated problem. Section IV presents the experimental results. Finally, Section V presents the conclusions of this work.

II. ELECTRO-OPTIC RESPONSE

The experimental setup investigated in this work is schematically shown in Figure 1. Figure 1a presents the configuration based on the PSG Analog Signal Generator E8257D and the DSO-X 96204Q oscilloscope. Figure 1b schematically depicts the arrangement used to characterize the electro-optic response of the SOAs. Considering the two experimental configurations shown in Figure 1, two frequency sweeps were performed: a non-coherent sweep, using arbitrary frequency values without accounting for the oscilloscope sampling rate and record length, i.e., the number of acquired points; and a coherent sweep, using frequency values selected according to the oscilloscope sampling rate and record length.

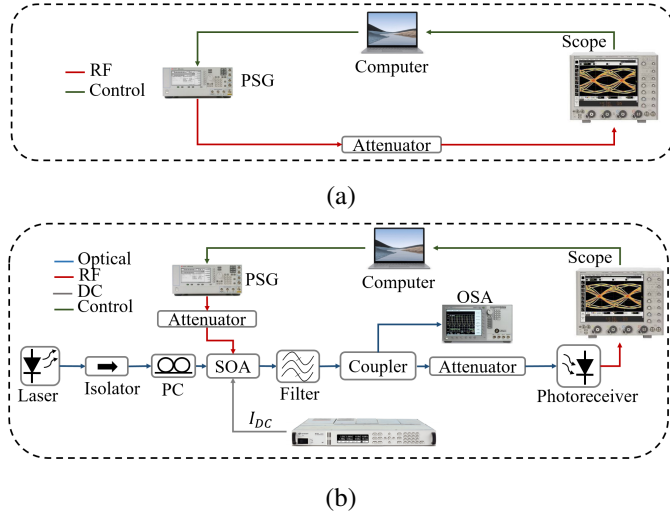


Fig. 1: Experimental setup: (a) configuration comprising a PSG signal generator and an oscilloscope, both computer-controlled; (b) configuration used for the experimental characterization of the electro-optic response of a SOA.

The equipment-control algorithm was developed in Python using the SCPI protocol. The algorithm sets the amplitude and frequency of the signal generator and acquires the time- and frequency-domain signals measured by the oscilloscope. The algorithm and the experimental data used in this paper are available in [8].

In the configuration shown in Figure 1a, the signal-generator output power was set to 0 dBm, and a 20 dB RF attenuator was used. In the configuration shown in Figure 1b, an N6700B current source was used to drive the CIP-L-OEC-1550 SOA with a bias current of 120 mA. The PSG output power was fixed at 15 dBm. For optical signal generation, a RIO Orion laser was used, biased at 50 mA with a thermistor resistance of 11191 Ω , producing approximately 0 dBm of optical power. An optical isolator was used to protect the laser from backward-propagating optical signals, such as the SOA amplified spontaneous emission (ASE). The polarization

controller (PC) was employed because SOAs are polarization-dependent devices. A SANTEC OTF-350 tunable filter was used to suppress the SOA ASE; a 90/10 optical coupler was used for spectrum monitoring; and an optical attenuator and an RXM42AF photoreceiver, with a bandwidth of 42 GHz, were employed. The optical power at the photoreceiver input was approximately -6.5 dBm.

For comparison, additional experiments were carried out using the two configurations shown in Figure 1 with an EXA N9010B signal analyzer operating from 10 Hz to 44 GHz, with RBW = 20 kHz and VBW = 200 kHz.

III. SPECTRAL LEAKAGE

When analyzing the discrete Fourier transform (DFT) of a sampled sinusoidal signal, periodic variations in the amplitude of the spectral components are commonly observed when the signal frequency does not exactly coincide with one of the discretized DFT frequencies, commonly referred to as frequency bins. This behavior is associated with incoherent sampling and with the phenomenon known as spectral leakage.

Consider a sampled sinusoid

$$x[n] = A \sin\left(2\pi f \frac{n}{F_s}\right), \quad n = 0, 1, \dots, N-1, \quad (1)$$

where A is the amplitude, f the frequency (Hz), F_s the sampling rate (Hz), and (N) the number of points used in the DFT; and, using the identity $\sin(\phi) = (e^{j\phi} - e^{-j\phi})/2j$, we have:

$$x[n] = \frac{A}{2j} \left(e^{j2\pi \frac{f}{F_s} n} - e^{-j2\pi \frac{f}{F_s} n} \right). \quad (2)$$

It is known that the complex DFT at bin k is defined by [9] - [10],

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-j2\pi \frac{k}{N} n}. \quad (3)$$

Substituting (2) into (3), we obtain

$$\begin{aligned} X[k] &= \frac{A}{2j} \sum_{n=0}^{N-1} \left(e^{j2\pi \frac{f}{F_s} n} - e^{-j2\pi \frac{f}{F_s} n} \right) e^{-j2\pi \frac{k}{N} n} \\ &= \frac{A}{2j} (S_1 - S_2), \end{aligned} \quad (4)$$

where,

$$S_1 = \sum_{n=0}^{N-1} e^{j2\pi \left(\frac{f}{F_s} - \frac{k}{N} \right) n}, \quad S_2 = \sum_{n=0}^{N-1} e^{j2\pi \left(-\frac{f}{F_s} - \frac{k}{N} \right) n}. \quad (5)$$

The complex geometric sum has a closed-form expression:

$$S(\theta) = \sum_{n=0}^{N-1} e^{j2\pi \theta n} = e^{j\pi(N-1)\theta} \frac{\sin(\pi N\theta)}{\sin(\pi\theta)} \quad (6)$$

The ratio $(\sin(\pi N\theta)/\sin(\pi\theta))$ is known as the *Dirichlet kernel* (in magnitude it exhibits a 'sinc-like' shape). Assuming:

$$\theta_1 = \frac{f}{F_s} - \frac{k}{N}, \quad \theta_2 = -\frac{f}{F_s} - \frac{k}{N}, \quad (7)$$

we have $S_1 = S(\theta_1)$ e $S_2 = S(\theta_2)$, therefore

$$X[k] = \frac{A}{2j} (S(\theta_1) - S(\theta_2)). \quad (8)$$

The magnitude of $X[k]$ is dominated by the behavior of the term $\sin(\pi N \theta) / \sin(\pi \theta)$. When $\theta \approx 0$ the denominator $\sin(\pi \theta)$ becomes small, so the fraction increases, producing a peak. In particular, if the frequency f coincides exactly with a DFT bin, i.e.,

$$\frac{f}{F_s} = \frac{k}{N} \quad (9)$$

for some integer k , then $\theta_1 = 0$ and

$$S_1 = \lim_{\theta \rightarrow 0} S(\theta) = N, \quad (10)$$

while S_2 tends to zero (the negative component lies outside the positive bin). Thus

$$X[k] = \frac{A}{2j} N \Rightarrow |X[k]| = \frac{AN}{2}. \quad (11)$$

Applying the single-sided normalization $\text{mag}[k] = (2|X[k]|)/N$, we obtain $\text{mag}[k] = A$: the bin magnitude is exactly the signal amplitude when the frequency is coherent with the DFT grid.

When f does not coincide with a bin, $\theta_1 \neq 0$ and $|S(\theta_1)|$ follows a sinc-like shape — i.e., spectral leakage occurs. The term S_2 (negative-frequency component) also contributes, but in the neighborhood of the positive bin of interest S_1 typically dominates the response.

A well-known approach to reduce spectral leakage is the use of windows (Hann, Blackman, etc.), as discussed in [11]–[12]. However, in this work we propose an algorithm for generating frequencies that respect the DFT discretization; that is, once the sampling rate and the DFT length are known, one can generate frequencies for which the DFT magnitude faithfully represents reality, thereby minimizing artifacts caused by spectral leakage.

A. Coherent technique

From Eq. (12), the spectral resolution of the Fourier transform can be defined by considering two adjacent frequencies f_a e f_b .

$$f_a = \frac{F_s k_a}{N}, \quad f_b = \frac{F_s (k_a + 1)}{N} = \frac{F_s (k_a)}{N} + \frac{F_s}{N} \quad (12)$$

Then, the spectral resolution of the DFT is given by:

$$f_b - f_a = \Delta f = \frac{F_s}{N}. \quad (13)$$

The sampling is said to be coherent when there exists an integer k such that, with f being the frequency of the sinusoid in Eq. (1):

$$f = k \Delta f = k \frac{F_s}{N}. \quad (14)$$

In this case, the sinusoid coincides exactly with an FFT bin, and all the signal energy appears concentrated in a single spectral bin.

B. Non-coherent technique

When the ratio between the signal frequency (f) and the spectral resolution (Δf) is not an integer, the sinusoid does not coincide with a DFT bin. Consequently, its energy spreads across several adjacent bins, which characterizes spectral leakage. The individual magnitudes of those bins are smaller than A , but are distributed around the frequency f .

C. Conservation of energy

Energy conservation in the DFT is guaranteed by Parseval's theorem. For a single-sided normalized spectrum, it holds:

$$\sum_{k=0}^{N/2} \text{mag}[k]^2 = A^2. \quad (15)$$

Or, equivalently, the signal's average energy is: $E = A^2/2$. Therefore, the physically conserved quantity is the sum of the squares of the magnitudes, not the linear sum of the amplitudes.

D. Case study

To illustrate spectral leakage, the FFT of a single-frequency sinusoidal signal was computed, as shown in Figure 5a, by varying N while keeping F_s fixed. In this example, the signal frequency was set to 1 GHz. Figure 2b highlights the spectrum around the signal frequency.

From the spectrum highlighted in Figure 2b, three important differences between the curves can be identified: magnitude, spectral width, and peak frequency. It can be observed that, under coherent sampling, i.e., when FFT bin 100 coincides with the signal frequency, the normalized magnitude is equal to 1 at the signal frequency, 1 GHz, and zero at the other frequency bins, as expected. Under non-coherent sampling, the maximum magnitude, which occurs at bin 102, is approximately 0.75 at 996.09 MHz. In this case, there is no FFT bin exactly at 1 GHz, since k would be non-integer, namely $k = 102.4$. Notably, as shown in Figure 2b, the signal energy spreads across the spectrum under non-coherent sampling, producing artifacts at other frequencies and increasing the apparent spectral width of the signal.

IV. EXPERIMENTAL RESULTS

The oscilloscope real-time channels were used with the sampling rate fixed at 160 GSa/s and a record length of 1,048,576 points. In this context the oscilloscope capture time is approximately 6.5536 μ s. A frequency sweep of 1,000 points was performed, distributed between 200 MHz and 10 GHz.

For the non-coherent acquisition, the frequencies were generated by specifying a minimum and maximum value and the number of frequency values. For the coherent acquisition, the first frequency value was chosen so that the frequency satisfies $f = k F_s / N$; the first coherent frequency was approximately 200.04 MHz.

The signal period at 200 MHz is 5 ns, so more than 1,310.72 cycles were captured, with over 800 samples per cycle. With coherent generation (≈ 200.04 MHz) 1,310.98 cycles of the

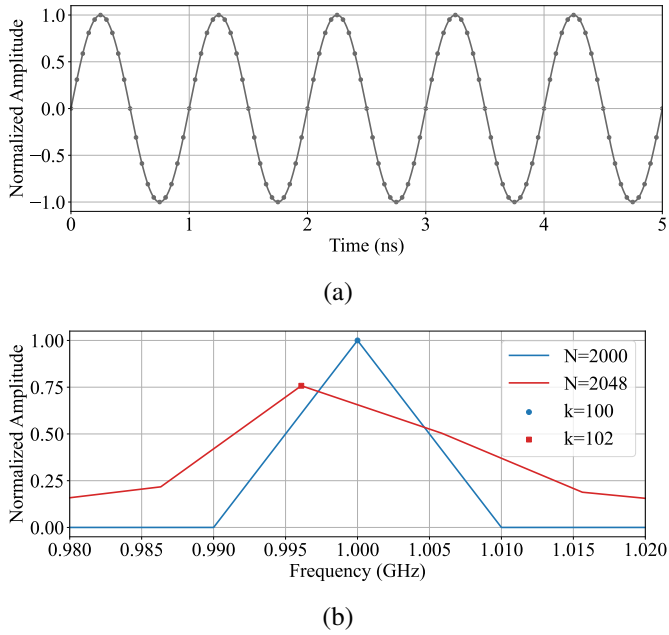


Fig. 2: Computational implementation of the FFT. (a) Time-domain signal; (b) FFT of the signal, zoomed view around 1 GHz.

signal were captured, which brings the number of cycles closer to an integer. Obviously, the higher the signal generator's frequency accuracy, the closer the generation is to being fully coherent.

At 10 GHz the period is 0.1 ns, so 65,536 cycles were captured, with 16 samples per cycle. In this case, for the oscilloscope sampling rate and record length used, the number of cycles at 10 GHz is an integer.

It is important to emphasize that, in both scenarios (coherent and non-coherent), the Nyquist-Shannon sampling theorem, which states that the sampling rate must be at least twice the highest frequency present in the signal to ensure proper digitization, was satisfied. [9], [10].

Figure 3a shows the oscilloscope capture for a 200 MHz signal generated by the signal generator. Figure 3b was obtained when a signal of approximately 200.04 MHz was generated. It is observed that coherent generation minimizes spectral leakage. Note that the signals were normalized for the purpose of comparing spectral spreading; therefore the influence of spectral leakage on amplitude cannot be assessed here. Nevertheless, it is evident that the signal with greater spectral spreading exhibits a lower peak amplitude.

Considering the first test configuration shown in Figure 1a, the results presented in Figure 4 were obtained. Emphasis is placed on the comparison of results using coherent signal generation, non-coherent generation, and measurements performed with the EXA signal analyzer. For each of the 1000 frequencies set on the signal generator, one oscilloscope trace was acquired. The coherent and non-coherent results correspond to the maximum values for their respective frequencies. For the EXA, the results were obtained using the instrument's "Max Hold" function. It is also worth noting that the traces corresponding to the coherent and non-coherent measurements

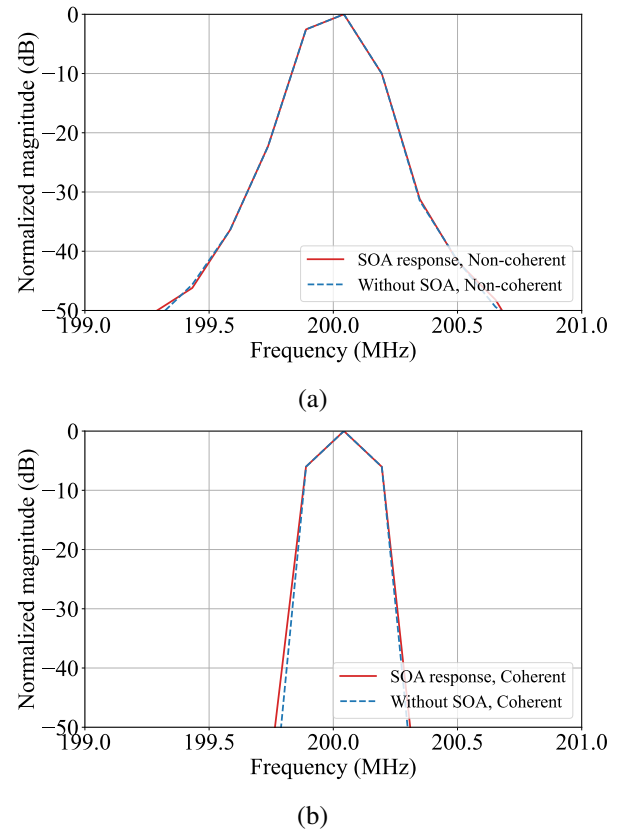


Fig. 3: FFT measurement of a single-frequency signal: (a) Non-coherent; (b) Coherent.

contain the same number of points.

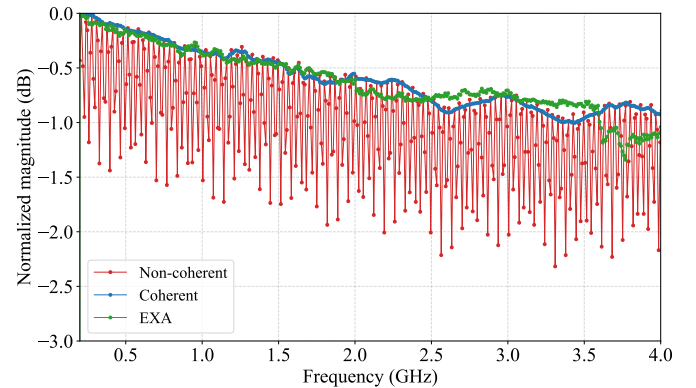


Fig. 4: Experimental result considering the setup without SOA.

Subsequently, the second configuration (Figure 1b) was implemented. The results are shown in Figure 5. From these results, it can be observed that the coherent technique exhibited better agreement with the measurements performed using the EXA signal analyzer. This convergence between the curves is highlighted in Figure 5b.

From the results presented in Figures 4 and 5a, the maximum absolute error (MAE) was calculated, defined as the absolute value of the difference between the reference value and the approximated value. The signal variance was also computed as a measure of the dispersion of the signal

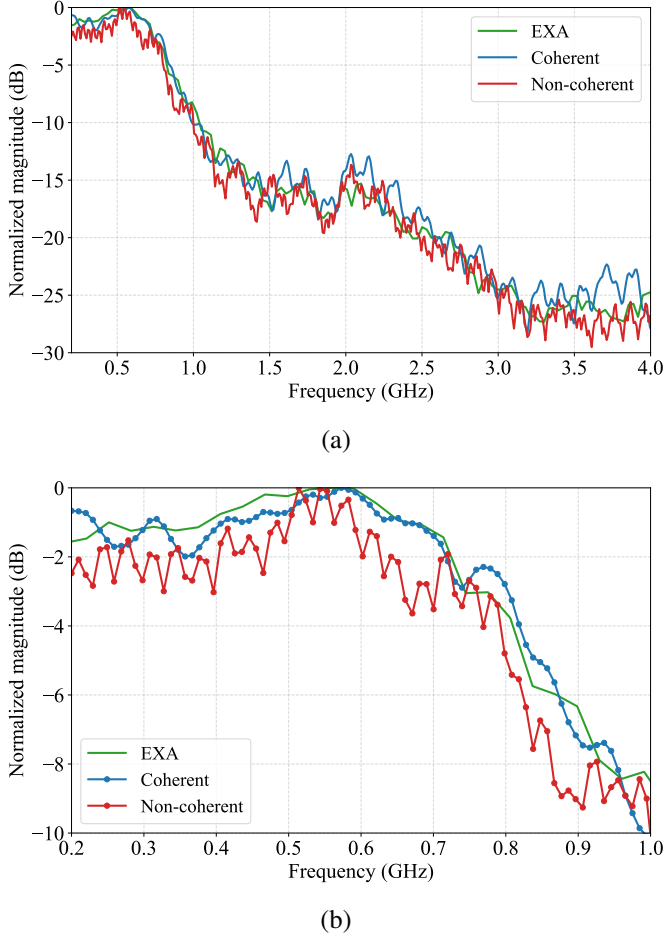


Fig. 5: Comparison of the electro-optical responses of SOAs considering (a) 0.2 to 4 GHz; (b) 0.2 to 1 GHz.

magnitudes. It is observed that the signals obtained with coherent generation exhibit lower MAE and lower variance, thus highlighting the impact of spectral leakage in the context of the devices' electro-optical responses.

TABLE I: Comparison between the proposed techniques.

Setup	Frequency vector	MAE	Variance
Without SOA	Non-coherent	0.404	0.190
	Coherent	0.114	0.013
With SOA	Non-coherent	1.13	1.87
	Coherent	1.11	1.50

V. CONCLUSIONS

This work proposes an algorithm for signal generation and acquisition to characterize electro-optical responses, with the goal of minimizing spectral leakage. The algorithm was implemented and experimentally evaluated, reducing spectral leakage at a sampling rate of 160 GSa/s and with approximately 1.04 million points. Using the proposed technique, it was observed that, in the worst-case scenario, the maximum mean error decreased from 0.404 to 0.114. A reduction in signal variance was also observed, from 0.190 to 0.013. As future work, numerical models with electro-optical responses

consistent with measured results will be proposed, also taking into account the device step/impulse response. From these models, techniques for pre-compensation of the electrical drive signal of the SOAs (semiconductor optical amplifiers) will be explored to increase SOA switching speed while ensuring low overshoot.

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