Influence of SOA parameters on the nonlinear impairments experienced by QAM modulated signals

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Abstract: We propose an experimental method to tune SOA model parameters that yields good prediction abilities of nonlinear distortions induced on PCS-QAM signals. We show that reducing SOA nonlinearities is achieved by a trade-off between a high P_{sat} and a low α_H.

1. Introduction

Semiconductor Optical Amplifiers (SOA) have attracted lately some interest for amplification applications [1]. Contrary to an Erbium Doped Fiber Amplifier (EDFA), an SOA exhibits nonlinearities, and assessing their impact on a modulated signal is mandatory [2]. Accurately modeling SOAs is therefore of interest, in order to identify the dependency of these impairments on SOA parameters.

In this paper, we show for the first time to the best of our knowledge, that using only a continuous mode experiment, we can tune the parameters of the well-known SOA Agrawal model [3] to predict accurately the SOA nonlinear dynamics. Based on the model, we then show how each SOA parameter impacts Quadrature Amplitude Modulation (QAM) signals in a single-channel coherent transmission system configuration.

2. SOA model description and tuning

The Agrawal model emulates the impact of the dynamic behavior of the SOA on an optical signal, based on the set of parameters: small signal gain (H_0), saturation power (P_{sat}), linewidth enhancement factor (α_H) and carrier lifetime (τ_c) [3]. In order for the model to be realistic, these parameters should be found by fitting simulations on experimental measurements, which was done in two steps. First, the two parameters (H_0 and P_{sat}) were found using the basic amplifier gain characterization bench, by injecting a Continuous Wave (CW) laser to an SOA. The power of the signal at the output of the SOA was measured while varying the power of the CW laser. The gain was therefore obtained as a function of the input or output power of the SOA (Fig1.a-inset1). In our case, the model did not reproduce the static gain compression of our measurements. So, we introduced a correction to the model, in order to match experimental results. An example is shown on Fig1.a-inset1.

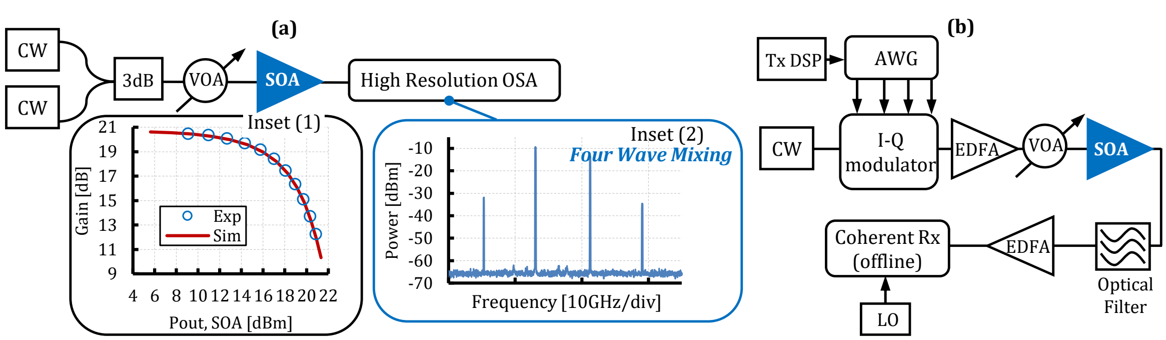

Fig. 1. Experimental setup of (a) the Four Wave Mixing, and (b) the SOA Back-to-Back.

Then, to find α_H and τ_c, we chose to setup an experiment (Fig1.a) that allows the measurement of the Four Wave Mixing (FWM) effects induced by the SOA in its saturated regime. We injected two CW lasers into an SOA, and swept the frequency spacing (f_{sp}) between these two lasers in a range from 150 MHz to 40 GHz. For each value of

f_{sp}, the spectrum was captured using a high resolution Optical Spectrum Analyzer (OSA) (Fig1.a-inset2). One can observe the two main frequencies ($f_{CW,i}$) of the two lasers (i=1,2), and two harmonics that appeared at frequencies $f_{CW,i} \pm f_{sp}$ due to SOA nonlinearities. We chose to quantify the FWM as a Peak-to-Peak difference (PtP_{Diff}) defined as: $PtP_{Diff} = (P_{CW,1} + P_{CW,2})/2 - (P_{Harm,1} + P_{Harm,2})/2$, where $P_{CW,i}$ is the power of the CW laser, and $P_{Harm,i}$ is the power of the generated harmonic. An example of the measured FWM PtP_{Diff} is shown on Fig2.a (blue squares) as a function of f_{sp}. Afterwards, the FWM PtP_{Diff} was computed by simulations when varying α_H and τ_c. It is worth mentioning that varying α_H results on a variation of the level of the whole curve, whereas varying τ_c results on a variation of the slope of the curve. A fine tuning accurately matched experimental measurements (Fig2.a, red dashed line on top of blue squares). We emphasis that once the fitting is done for one input power value to the SOA, the FWM PtP_{Diff} is then predicted for other values (Fig2.a, red line on top of blue circles). Moreover, the four Agrawal model parameters depend on the SOA, the wavelength (λ) and the injection current (I). After testing several SOAs while varying λ and I, we found interval of variations such as: $H_0 \in [18-22]$ dB, $P_{sat} \in [14-19]$ dBm, $\alpha_H \in [3-8]$, and $\tau_c \in [100-250]$ ps.

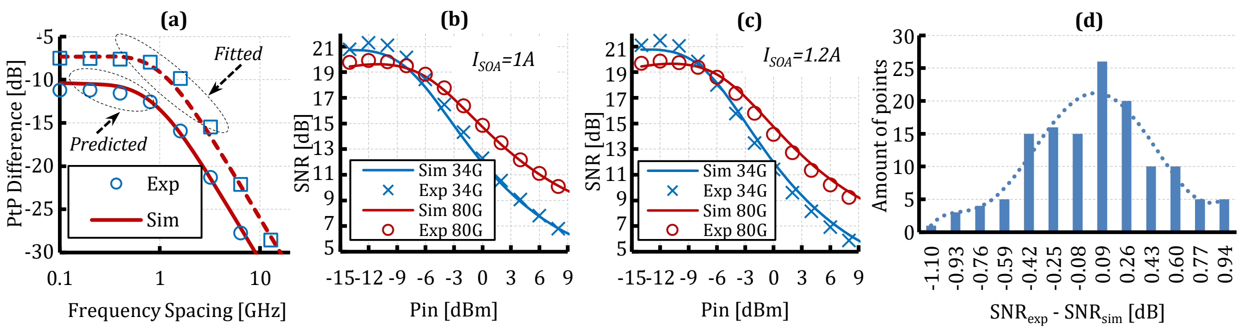

Fig. 2. (a) FWM PtP difference vs. f_{sp}, (b-c) SNR vs. $P_{in,SOA}$, (d) PDF showing simulations accuracy.

3. SOA model validation

In order to evaluate the accuracy of the nonlinear prediction ability of the SOA model, we chose to setup an offline experiment and measure the impact of the SOA nonlinear impairments on a modulated signal. The single-channel experimental setup is shown on Fig1.b, and consisted of a transceiver where a Probabilistic Constellation Shaped (PCS)-64QAM signal with an entropy of 5.5 bits/symbol (1 pilot-symbol each 32 data symbols), was loaded to a Digital-to-Analog Converter (DAC), and modulated at 34, 68 and 80 Gbaud. The signal was amplified using an Erbium Doped Fiber Amplifier (EDFA) into a Variable Optical Attenuator (VOA), which was used to sweep the power of the optical signal at the input of the SOA ($P_{in,SOA}$). The signal was then filtered, further amplified and sent into a coherent receiver consisting of a local oscillator, a coherent mixer, four 70 GHz bandwidth balanced photo-detectors and an Analog-to-Digital Converter (ADC). Received signals were then processed offline, where the Digital Signal Processing (DSP) consisted of clock recovery, carrier frequency estimation (CFE), 71-tap pilot-aided polarization demultiplexing and 41-tap pilot-based carrier phase estimation (CPE) algorithms. The results are shown with the Signal-to-Noise Ratio (SNR) metric. Note that the long CPE was chosen so that the phase noise induced by the SOA remains uncompensated. Fig2.b and c show the experimental SNRs as a function of $P_{in,SOA}$ for two values of injection current (1 and 1.2 A), and Baudrate (34 Gbaud in blue crosses, 80 Gbaud in red circles). Results show that increasing the Baudrate decreases SOA nonlinear impairments. Moreover, increasing the SOA injection current increases its nonlinear impairments, for instance, at 80 Gbaud and for $P_{in,SOA} = 8dBm$, the SNR equals 10.1 dB for I=1 A and 9.2 dB for I=1.2 A.

Using simulations, we reproduced the same experimental setup, and compared the results as shown on Fig2.b and c, where simulations (blue and red lines) are plotted on top of experimental results. The accuracy of the model was then quantified using a Probability Density Function (PDF) over the difference between the SNR values obtained from simulation and experiment. Measurements shown here were done for five injection current values (from 0.9 to 1.3 A), and three Baudrate values (34, 68 and 80 Gbaud), while sweeping $P_{in,SOA}$. Fig2.d shows an accuracy of $\pm 0.5\,dB$ SNR difference for more than 80% of the results, and a maximum of $\pm 1\,dB$ SNR difference for less than 5% of the results. Assuming that we observed a $\pm 0.3\,dB$ variations on the experimental SNR due to DSP algorithms, we can conclude that the model, with parameters extracted from experiments as described here, is accurate enough to conduct investigations on the impact of SOA impairments on modulated signals.

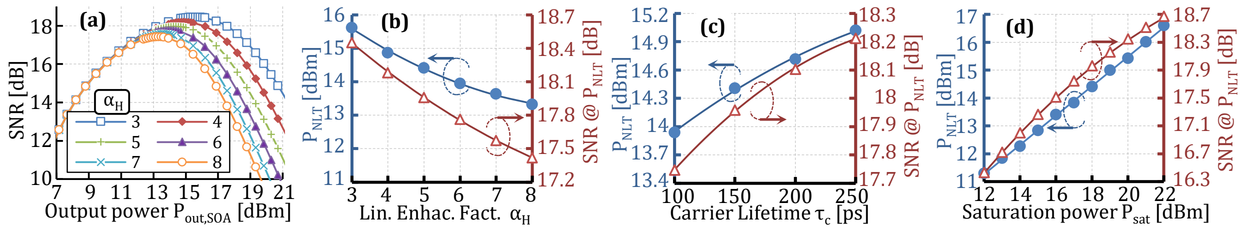

Fig. 3. (a) SNR vs. $P_{\mathrm{out,SOA}}$ for several α_H, P_{NLT} and $\mathrm{SNR}_{\max}$ evolution vs. (b) α_H (c) τ_c and (d) P_{sat}.

4. SOA impairments on a modulated signal

We then used the model to investigate the impact of the three parameters: P_{sat}, α_H and τ_c on a modulated signal. Using the simulator that matched the experimental offline setup with the same modulation formats and at a Baudrate of 68 Gbaud, we varied the SOA model parameters one by one. When not swept, the parameters of the model considered in the simulations were: $\alpha_H = 5$, $\tau_c = 150\,ps$ and $P_{\mathrm{sat}} = 18\,dBm$, while H_0 was always fixed to 20 dB. Note that we conducted the same investigation for a Baudrate of 34 Gbaud, and we found the same conclusions. Results when varying α_H are shown on Fig3.a, as SNR versus SOA output power ($P_{\mathrm{out,SOA}}$). From these Bell-curves, we extract the output power of the SOA for which the SNR reaches its maximum value (P_{NLT}), and the maximum SNR value ($\mathrm{SNR}_{\max}$). The extracted values are then shown on Fig3.b, where we can observe, as known in the literature [4], that increasing α_H increases SOA nonlinear impairments, and therefore decreases P_{NLT} as well as $\mathrm{SNR}_{\max}$. For instance, doubling the value of α_H yields a decrease of P_{NLT} and $\mathrm{SNR}_{\max}$ by $\sim$1.5 dB and $\sim$0.7 dB, respectively. For τ_c, as shown on Fig3.c, increasing it increases the SOA time response. The SOA becomes less sensitive to fast power variations and therefore impairs less a modulated signal. For instance, doubling the value of τ_c increases P_{NLT} and $\mathrm{SNR}_{\max}$ by 0.8 dB and 0.4 dB, respectively. When comparing the impacts of τ_c and α_H, one can emphasis that the latter has a higher impact on SOA induced physical nonlinearities.

Regarding P_{sat}, one has to keep in mind that changing it changes the saturation regime and the maximum output power of the SOA, hence, a high value is always desired. However, because designing an SOA to have a higher P_{sat} might result at the same time on an increased α_H (both parameters are inversely proportional to the SOA differential gain [4, 5]), it is still important to quantify its impact. It can be observed on Fig3.d that increasing P_{sat} by 3 dB increases the P_{NLT} by 1.6 dB, and the $\mathrm{SNR}_{\max}$ by 0.5 to 0.8 dB, depending on the value of P_{sat}. The P_{NLT} gain is therefore comparable to the one of α_H, but the $\mathrm{SNR}_{\max}$ gain might be lower. This is an important point, as increasing P_{sat} is key to increase the total output power of the SOA chip, however, when the targeted value of the latter is reached, one needs to check first the impact of an increased P_{sat} on α_H, in order to mitigate the nonlinear impairment of the SOA on modulated signals.

5. Conclusion

We have shown an experimental method to tune the SOA Agrawal model parameters. We have experimentally demonstrated the efficiency of the method, making the model accurate enough to use its prediction ability to evaluate the impact of the SOA on modulated signals. Then, we have used the model to quantify the amount of SOA impairments on a modulated signal, emphasizing the impact of each parameter separately. We have concluded that finding a trade-off between a high P_{sat} and a low α_H is the best approach, while increasing the τ_c should not be the main focus.

References

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