Nonlinearity Mitigation in a Semiconductor Optical Amplifier through Gain Clamping by a Holding Beam

Iosif Demirtzioglou, Romain Brenot, Abel Lorences-Riesgo, Trung-Hien Nguyen, Nayla El Dahdah, Antonin Gallet, Shuqi Yu, Sheherazade Azouigui, Yann Frignac, Gabriel Charlet

Huawei Technologies France, Paris Research Centre, Optical Communication Technology Lab, iosif.demirtzioglou@huawei.com

Abstract *We demonstrate the benefit of gain-clamping in mitigating SOA nonlinear noise through the use of an external optical beam. A nonlinear noise reduction of 2.3 dB is observed through extensive experimental SNR measurements. ©2022 The Author(s)*

Introduction

The use of Semiconductor Optical Amplifiers (SOAs) at the transmitter and receiver parts of an optical link is already commonplace[1,2]. As their design provides flexibility in the operation wavelength, they have proven to be suitable for applications in different optical communication bands, such as the C-band or the O-band[1]. Their operation in the L-band is equally proven useful for the transceivers in ultra-wideband transmission links that are increasingly considered in the recent efforts to boost the capacity of future networks[3,4,5].

The most significant limitation in the use of SOAs is their nonlinear behaviour at high output powers, which can manifest as both amplitude and phase noise on a data signal, as a result of gain saturation. Gain clamping has been proposed as a technique to fix the SOA to a constant state and thus mitigate nonlinearity. This has been implemented through modified structure designs, such as Distributed-Feedback-(DFB-) SOAs or Distributed Bragg Reflector-(DBR-) SOAs[6], as well as through modified operation schemes, such as the Holding Beam (HB) approach[2,7,8].

Indeed, a number of Holding Beam implementations have been demonstrated, mainly in the context of Dynamic Range extension for a Receiver amplifier in Access networks, where On-Off Keying (OOK) or Pulse Amplitude Modulation (PAM-4) are used[1,2,8,9]. In these cases, the Holding Beam significantly decreases the small-signal gain, effectively lowering the optical output power of operation. However, the advantage of the Holding Beam scheme has not been quantified when a given signal output power is required.

In this paper, the performance improvement due to the Holding Beam approach is quantified by extracting the nonlinear noise level from Signal-to-Noise Ratio (SNR) measurements of the amplified signal. An external Continuous Wave (CW) beam at 1530 nm is used to clamp a SOA amplifying a data signal at 1575 nm. The improvement in SNR and output saturation power is reported, while the effects of tuning the Holding Beam wavelength are also discussed. Finally, the SNR levels associated with nonlinear noise are extracted through modelling.

Experimental Setup

To experimentally evaluate the nonlinear noise at the output of the SOA when its gain is clamped

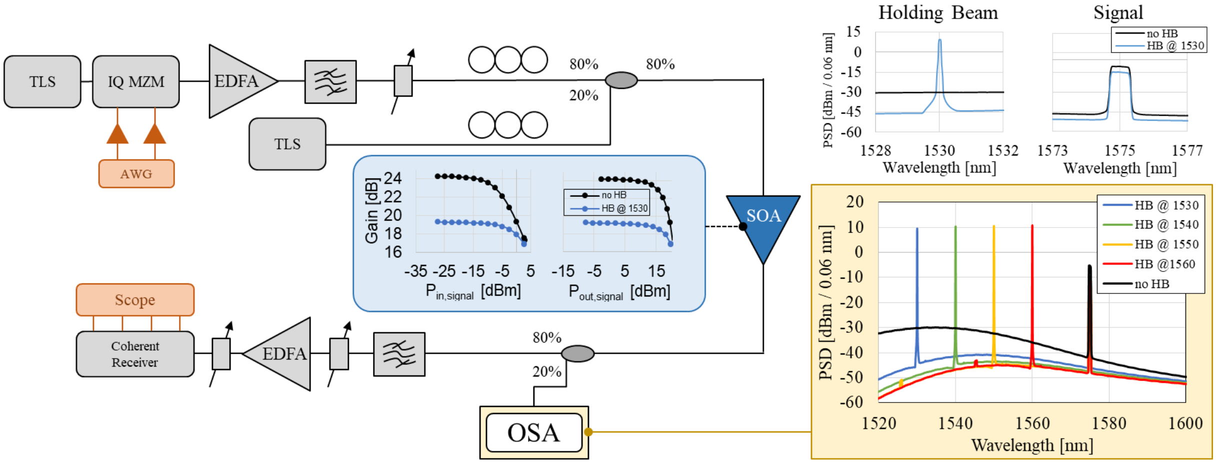

Fig. 1: Experimental setup built for the Gain Clamping scheme, Inset (left): Fibre-to-fibre signal Gain vs. signal input and output power, Inset (right): Optical Spectra at the SOA output for a signal input power of -10 dBm.

by a Holding Beam, the measurement setup shown in Fig. 1 was constructed. Two Tunable Laser Sources (TLS) were used to provide the optical input to the SOA. One optical beam was modulated with data (from now on denoted as Signal), while the second one served as the CW Holding Beam, set to 1 dBm. The polarisation of both beams was carefully adjusted to match the SOA propagation mode, while the operation of the amplifier at a constant temperature of 20°C was ensured by the use of a Thermoelectric Cooler (TEC). The Holding beam wavelength was selected to be 1530 nm, where the SOA provides higher gain, while the signal beam was placed slightly outside the C-band at 1575 nm. A 120-GSa/s Keysight Arbitrary Waveform Generator (AWG) was used to generate the 68-GBaud 16-QAM signal that was pre-amplified in order to drive an I-Q Mach-Zehnder Modulator (MZM). The modulated output was then optically pre-amplified with an L-Band Erbium-Doped Fibre Amplifier (EDFA) in order to compensate for the MZM Insertion Loss, while a bandpass filter was used to remove all out-of-band Amplified Spontaneous Emission (ASE) noise.

At the receiver side, the SOA output was sent to a second wideband optical filter in order to isolate the signal beam, which was subsequently amplified by a second L-Band EDFA to be collected by the Coherent Receiver. Part of the SOA output was simultaneously monitored with an Optical Spectrum Analyser (OSA). Finally, the optical signal was collected by a Coherent Receiver, followed by four 70-GHz photodiodes whose output electrical signals were processed using a 256-GSa/s Real-Time Oscilloscope.

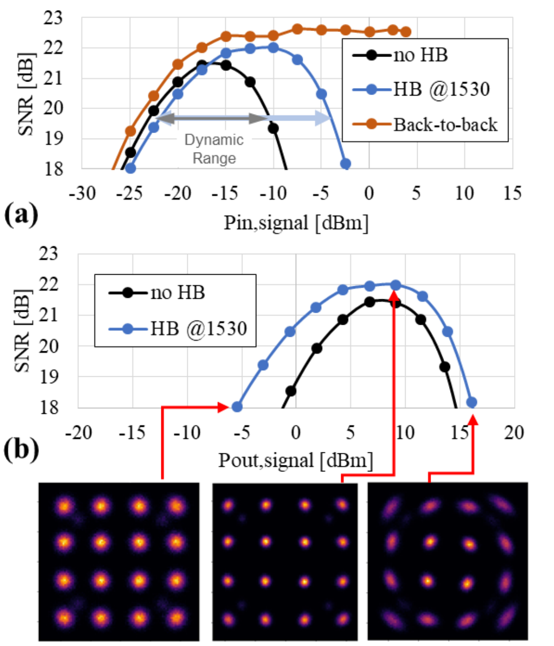

Fig. 2: SNR vs. (a) input and (b) output signal power. Inset: Received 16-QAM constellations for the gain-clamped case.

To compare the cases of gain-clamped and unclamped operation, SNR measurements were taken when the Holding Beam was turned on and off to analyse the link performance in the two cases. Examples of optical spectra at the SOA output for the two cases are shown in the inset of Fig. 1, where the signal clearly exhibits lower power when the gain is clamped. Figure 2a shows the “bell” curves with respect to the signal input power, as well as the curve for the back-to-back system. As expected, the Nonlinear Threshold (NLT) point shifts to higher input powers in the gain-clamping case, as a result of the decrease in signal gain which is illustrated in the inset gain plots of Fig. 1. This effectively extends the Dynamic Range of operation over a certain SNR threshold, as mentioned in a number of previous studies in the literature[8]. However, to accurately quantify the SNR improvement in the nonlinear region, it is necessary to plot the same measurements with respect to the signal output power (Fig. 2b), since the emergence of nonlinear effects mainly depends on the SOA output power. Figure 2b shows that for a given signal output power, an improvement in SNR, albeit smaller, is still present. The constellations of the recovered 16-QAM signal are also presented to illustrate the phase noise exhibited at high output powers due to the SOA nonlinearity.

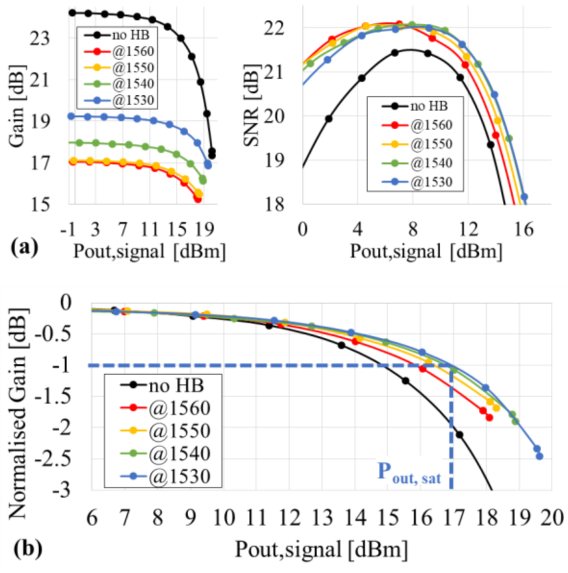

Fig. 3: (a) Fibre-to-fibre signal Gain (left) and SNR (right) vs. signal output power for various Holding Beam wavelengths, (b) Gain normalised to the Small-Signal Gain value vs. output signal power.

Next, to further investigate the impact of the Holding Beam wavelength on the SNR, the TLS frequency was swept across the C-band. For each case, the spectra recorded at the output of the SOA are presented in the inset of Fig. 1 for a signal input power of -10 dBm. The fibre-to-fibre signal gain and SNR measurements shown in Fig. 3a were taken for various levels of signal output power at different Holding Beam wavelengths. It is clear that shorter wavelengths provide a larger improvement in SNR in the nonlinear region, even though the gain reduction appears to be lower. This was also verified by the effect on the SOA output saturation power. Figure 3b shows the signal gain normalised to its small-signal value for all Holding Beam wavelengths. In the case of 1530 nm, the output power at 1 dB of saturation is 16.9 dBm, higher than the values for the other wavelengths. Indeed, the trend of the output saturation power confirms the conclusions on SNR improvement.

Results & Discussion

In order to precisely quantify the amount of noise that is associated with nonlinear effects, the SNR measurements were used in the Gaussian Noise (GN) model[10], described by the following formula:

$$\frac{1}{SNR} = \eta \frac{1}{OSNR} + \frac{1}{SNR_{TRx}} + \frac{1}{SNR_{NL}} \qquad (1)$$

which breaks the total noise down to three contributions: transceiver noise, ASE noise and nonlinear noise. In eq. (1), SNR represents the SNR at the Receiver, $OSNR$ represents the Optical Signal-to-Noise Ratio at the Receiver, based on the ASE level measured in the recorded spectrum, SNR_{TRx} is the maximum achievable SNR based on the limitations of the link Transmitter and Receiver and SNR_{NL} denotes the SNR associated with the nonlinear noise. η is a scaling factor to be calculated through fitting of the experimental values. In this approach, all effects are treated as uncorrelated additive Gaussian noise contributions. This model was applied to the SNR values estimated by the Receiver DSP algorithm for the optimum case of the 1530-nm Holding Beam (Fig. 2a).

To isolate the contributions, the back-to-back SNR measurement and the recorded OSNR values were used to calculate the η and SNR_{TRx} parameters of the model through fitting. Next, the SNR_{NL} parameter was extracted by fitting the curves of Fig. 2a to the model of eq. (1). The three noise contributions were thus estimated and Fig. 4a illustrates their trend with respect to signal output power. In this graph, the noise terms are presented in the form of a Noise-to-Signal Ratio (NSR) metric to facilitate the comparison of their relative levels, as the sum of the three NSR quantities represents the total NSR. As expected, the nonlinear noise is dominant at high output powers, whereas the transceiver noise is dominant close to the NLT point.

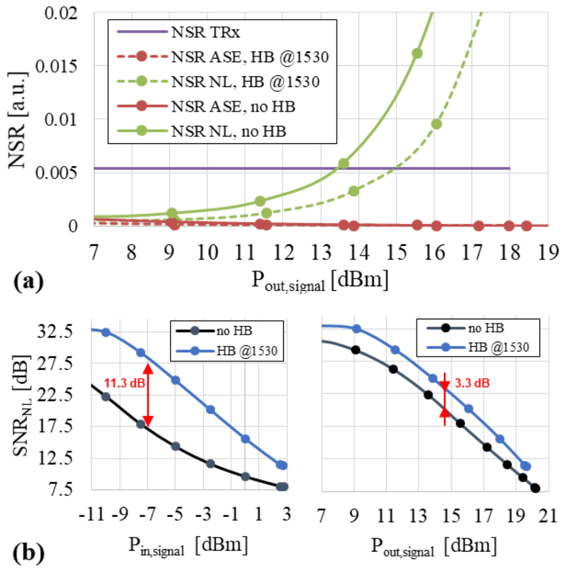

Fig. 4: (a) Noise Contributions vs. output signal power, (b) SNR associated with nonlinear noise vs. (left) input and (right) output signal power.

Figure 4b plots the SNR_{NL} parameter for the two cases in logarithmic scale, where two graphs are used in order to highlight the two possible definitions of SNR improvement. For applications which are indifferent to the SOA output power, an input signal at a given power level (e.g. -7.5 dBm) can benefit from a SNR_{NL} improvement of up to 11.3 dB at the SOA output. However, it must be noted that this value represents the combined effect of the gain reduction and nonlinearity mitigation as the SOA is operated at lower output powers when it is gain-clamped. To isolate the effect on the inherent SOA nonlinearity only, the improvement was calculated for a given signal output power. In this case, the SNR_{NL} increase was estimated to be from 2.3 to 3.3 dB for output powers ranging from 7 to 19 dBm.

Conclusions

We have investigated the impact of an external CW Holding Beam on the nonlinear noise generated by a SOA at high output powers. Contrary to previous investigations, the analysis has focused on quantifying the nonlinear noise mitigation for a given signal output power, thus evaluating the Holding Beam configuration as a means of SNR improvement, rather than a gain tuning scheme. The analysis has been performed using a Gaussian Noise model to quantify the nonlinear noise term and a SNR_{NL} improvement of 2.3 dB was estimated for a SOA output power as high as 19 dBm. The results demonstrate the added value of the Holding Beam scheme as a technique to enhance performance in transmitter amplifier applications where a specified target output power is required, while the gain can be engineered separately at a design level.

References

[1] Cheng, N., Liao, Z., Liu, S., & Effenberger, F. (2011, March). Gain-clamped semiconductor optical amplifiers for reach extension of coexisted GPON and XG-PON. In *National Fiber Optic Engineers Conference* (p. NTuD7). Optical Society of America. DOI: 10.1364/NFOEC.2011.NTuD7

[2] Chan, T. K., & Way, W. I. (2015, March). 112 Gb/s PAM4 transmission over 40km SSMF using 1.3 μm gain-clamped semiconductor optical amplifier. In *Optical Fiber Communication Conference* (pp. Th3A-4). Optical Society of America. DOI: 10.1364/OFC.2015.Th3A.4

[3] Cantono, M., Schmogrow, R., Newland, M., Vusirikala, V., & Hofmeister, T. (2020). Opportunities and challenges of C+L transmission systems. *Journal of Lightwave Technology*, *38*(5), 1050-1060. DOI: 10.1109/JLT.2019.2959272

[4] Demirtzioglou, I., Bendimerad, D. F., de Jauregui Ruiz, I. F., Le Gac, D., Lorences-Riesgo, A., El Dahdah, N., ... & Charlet, G. (2021, June). 107.6 Tb/s GMI Throughput over 220 km SSMF using Discrete C-and L-Band Amplification across> 12 THz. In *2021 Optical Fiber Communications Conference and Exhibition (OFC)* (pp. 1-3). IEEE. DOI: 10.1364/OFC.2021.W6A.28

[5] Le Gac, D., Bendimerad, D., Demirtzioglou, I., Ruiz, I. F. D. J., Lorences-Riesgo, A., El Dahdah, N., ... & Charlet, G. (2021, September). 63.2 Tb/s Real-time Transmission Through Discrete Extended C-and L-Band Amplification in a 440km SMF Link. In *2021 European Conference on Optical Communication (ECOC)* (pp. 1-4). IEEE. DOI: 10.1109/ECOC52684.2021.9605986

[6] Brenot, R., Kerboeuf, S., Bouché, N., Mallecot, F., Colson, V., Gauthier-Lafaye, O., ... & Thédrez, B. New low-chirp and high power semiconductor amplifier for 10 Gbit/s metropolitan transmission. *Proceedings ECOC, Th*, *3*(3).

[7] Crottini, A., Salleras, F., Moreno, P., Dupertuis, M. A., Deveaud, B., & Brenot, R. (2005). Noise figure improvement in semiconductor optical amplifiers by holding beam at transparency scheme. *IEEE photonics technology letters*, *17*(5), 977-979. DOI: 10.1109/LPT.2005.846757

[8] Tan, H. N., Matsuura, M., & Kishi, N. (2010). Enhancement of input power dynamic range for multiwavelength amplification and optical signal processing in a semiconductor optical amplifier using holding beam effect. *Journal of Lightwave technology*, *28*(17), 2593-2602. DOI: 10.1109/JLT.2010.2055040

[9] Yoshino, M., & Inoue, K. (1996). Improvement of saturation output power in a semiconductor laser amplifier through pumping light injection. *IEEE Photonics Technology Letters*, *8*(1), 58-59. DOI: 10.1109/68.475777

[10] Poggiolini, P., Bosco, G., Carena, A., Curri, V., Jiang, Y., & Forghieri, F. (2013). The GN-model of fiber non-linear propagation and its applications. *Journal of Lightwave technology*, *32*(4), 694-721. DOI: 10.1109/JLT.2013.2295208