Experimental Model of EDFA Spectral Hole Burning for WDM Transmissions Systems

Juliana Tiburcio de Araujo, Alexis Carbo Meseguer, Jean-Christophe Antona
Alcatel Submarine Networks, Nokia Paris Saclay, 91620 Nozay
juliana.tiburcio_de_araujo@asn.com

Abstract: We propose an empirical model to characterize the Spectral Hole Burning (SHB) of a chain of 200 EDFA in WDM transmission systems. Then we test it with 300 random input pre-emphases obtaining an average of root-mean-square error down to 0.5 dB. © 2022 The Author(s)

1. Introduction

Submarine systems may be operated in non-flat input WDM conditions, for instance to obtain an equalized signal-to-noise ratio (SNR) at the receiver-side [1]. To do so, the input WDM pre-emphasis can be as high as +/-5 dB. Since capacity of optical systems is evolving towards the zero-margin [2], a model of optical amplifier that considers the impact of the input pre-emphasis is desirable. Recently, an experimental model to predict the gain of Erbium-doped Fiber Amplifiers (EDFA) was proposed [3,4]: with a simple look-up table obtained experimentally to characterize an amplifier and the physical intuition provided by physical models such as [5,6], the homogeneous gain could easily be estimated with 0.05 dB root-mean-square error (RMSE), well below models based on machine learning techniques. This model was then tested in a cascade up to 12 EDFA with RMSE values < 0.15 dB. However, if it is extended for longer distances, the RMSE is compromised because inhomogeneous gain effects arise, becoming the main source of gain distortion. We show later in this paper that the contributions of inhomogeneous gain distortion can be as high as 12 dB in transpacific distances if WDM pre-emphases with +/-10 dB are considered. The goal of this paper is thus to find a similar approach to characterize in a non-complex manner gain distortions coming from inhomogeneous effects.

One of the main sources of inhomogeneous gain is Spectral Hole Burning (SHB). SHB has been studied for a long time and some models have already been proposed such as in [7]: this model permits to understand the physical nature of SHB. However, it is not practical from a system point of view since it relies on the knowledge of the so-called Giles parameters (erbium emission and absorption cross sections) and other not easily accessible parameters. On the other hand, experimental models to predict SHB in long WDM systems have been proposed. [8] shows a model assuming that SHB induced by multiple channels can be obtained by adding together individual channel contributions. With this model, SHB can be qualitatively characterized. Despite not shown, RMSE seems quite high because experimental measurements to train it are obtained using the two-tone subtractive technique [9]. With this technique, the SHB of a single EDFA is characterized using the Amplified Spontaneous Emission (ASE) noise generated for itself. This technique has some limitations because it assumes that input signal will suffer from SHB in the same way as ASE noise generated by the device. Furthermore, as shown in [3,4], when the input pre-emphasis of the optical amplifier changes, the population inversion of the EDFA slightly varies, which is translated to a homogeneous gain change. This distortion leads to an error in the SHB estimation. It is true that this error is very low for a single EDFA however, it becomes non-negligible when extrapolated to hundreds of amplifiers, since it is added systematically.

In this paper, we present a novel technique to estimate the impact of inhomogeneous gain of EDFAs in WDM systems based on a first calibration after a few EDFAs, the assumption of channel superposition as in [8], and an iterative process. Since the impact of homogenous gain is attenuated when EDFA are cascaded, the experimental characterization of each individual channel is performed for a chain of amplifiers (we tested from 5 to 20). Then, we assess it by predicting the inhomogeneous gain distortions induced by 300 random input pre-emphases (up to +/-5 dB excursions) in a cascade up to ~200 spans with 38-nm C-band amplifiers showing a mean RMSE error around 0.5 dB.

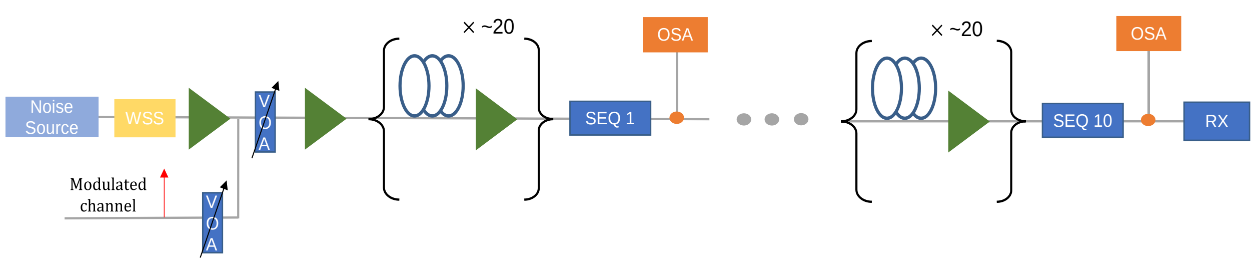

Fig.1 Experimental setup used to characterize the amplifiers inhomogeneous gain.

2. Experimental Setup and Inhomogeneous Gain Distortion Characterization

Fig.1 shows a schematic of the testbed used to characterize EDFAs inhomogeneous gain induced by each individual channel. The line comprises a chain of ~200 spans, each followed by a 38-nm C-band amplifier with a gain flattening filter (GFF). After a section of ~20 amplifiers, an additional spectrum equalizer (SEQ) is added to recover GFF design imperfections, under flat input spectrum assumption. Spectra after 5, 10 and 20 spans are accessed with an optical spectrum analyzer (OSA). Spans are fully loaded with a noise source equalized by a wavelength-selective switch (WSS). A 69 GBaud-PDM QPSK channel can eventually be inserted with a variable optical attenuator (VOA) to adjust its pre-emphasis. A grid of 75-GHz spaced channels is considered to emulate real system conditions. All amplifiers operate with constant gain so on average they show the same population inversion. We first enter the line with a flat input power, which is our reference case with no gain distortion. Then, a measurement of gain shape (i.e. link transfer function, in dB scale) $G_{shape,flat}(\lambda) = P_{ref,flat}(\lambda) - P_{in,flat}(\lambda)$ is performed to calibrate our system. P_{ref} stands for the power retrieved from the OSA at the point of interest (after 5, 10, 20 or after 200 spans) and P_{in} for the input power, both in flat conditions, in 0.2nm band. Then, we propose a perturbative approach to stimulate the inhomogeneous gain contribution coming for every individual channel. To obtain it, we first set the modulated channel in the channel under test (CUT) at λ_{CUT} with pre-emphasis Δp ranging up to $\pm$ 6 dB to locally saturate EDFAs. This saturation leads to a distortion in the gain shape: $G_{shape,\lambda_{CUT}}(\lambda) = P_{ref,\lambda_{CUT}}(\lambda) - P_{in,\lambda_{CUT}}(\lambda)$. The gain distortion attributed to these channels is expressed as: $GD_{\lambda_{CUT}}(\lambda) = G_{shape,\lambda_{CUT}}(\lambda) - G_{shape,flat}(\lambda)$. We vary the λ_{CUT} over all channels, to obtain the impact of the GD at all channels when applying a pre-emphasis at any λ_{CUT}. Gain distortion characterizations for the channel centered at 1536 nm is shown in Fig.2a), while for the rest of the channels only GD at $\Delta p = 6\ dB$ is plotted in order to facilitate figure comprehension. Later, the GD of a series of random WDM input pre-emphasis charged with the WSS is also characterized by following a similar procedure. Gain distortions associated to random pre-emphasis are estimated by $GD_{pre}(\lambda) = G_{shape,pre}(\lambda) - G_{shape,flat}(\lambda)$.

Normalizing to remove the dependency with Δp

We wish to have a unitary look-up table independently of the channel pre-emphasis. To do so, we characterize the evolution of the GD peak (GD at the saturation tone) with the applied pre-emphasis Δp_m in λ_{CUT}. Fig.2b) represents the GD peak versus Δp_m for different wavelengths. We observe little wavelength dependence. Then we fit it with a piecewise linear function that offers a good trade-off between accuracy and complexity for the aimed pre-emphasis +/-5 dB for this work. We define $NGD_{\lambda_{CUT}}(\lambda) = \frac{GD_{\lambda_{CUT}}(\Delta p_m,\lambda)}{\Delta p_m}$ as the normalized GD function for each channel. It is the vector that we store in the training look-up table. Specifically for 5 and 10 spans, amplifier averaging is not enough, and homogeneous gain distortions arise when pre-emphasis is applied. To illustrate it, Fig.2c) represents the NGD table measured after 5 spans. We observe non-negligible homogeneous GD. To remove it we assume that inhomogeneous effects only involve a transfer of energy between wavelengths and no extra gain is observed so a principle of energy conservation is applied. We can compute then the GD induced by any Δp_n, with $GD_{\lambda_{CUT}}(\Delta p_n, \lambda) = NGD_{\lambda_{CUT}}(\lambda) * f(\Delta p_n)$, where f is the fitted function in Fig.2b).

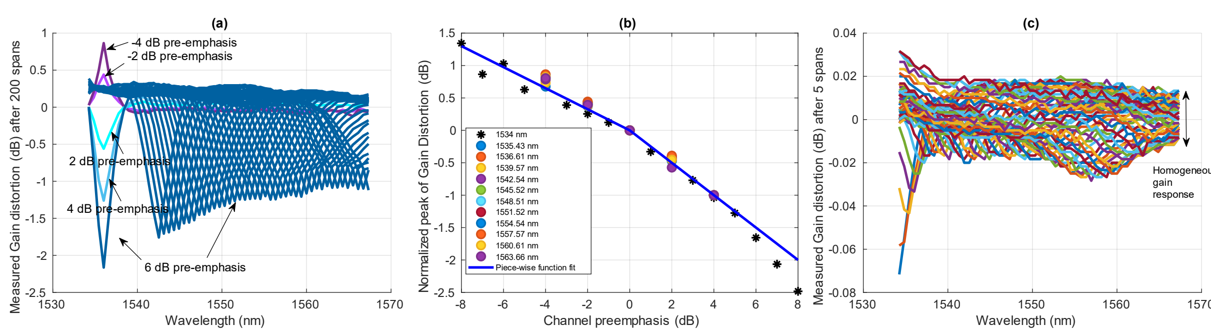

Fig.2 a) Measured GD at 1536 nm for pre-emphases from -4 to 6 dB and for some other channels with $\Delta P = 6\ dB$ after 200 spans. b) Normalized GD peak versus ΔP and for different λ_{CUT}. Dots: experimental measures. Solid line: piece-wise linear function fit. c) Measured NGD for all the channels using 5 spans without the energy conservation principle.

Superposition principle

Finally, we verify the superposition principle (also proposed in [8]) that states that the GD induced by multiple channels is the linear combination of the GD of every individual channel. To assess it, we pre-emphasize two channels at the input. We then predict the total GD at line output adding the individual contributions of each saturated channel which are stored in the look-up table $NGD(\lambda)$. Fig.3a) shows one example where channels at 1536.6 and 1541.4 nm are pre-emphasized by 4 and 3 dB respectively. We see a good agreement between the measurement and the prediction.

3. Model Description and Results

We propose an iterative model to predict the power evolution through the line using only the experimental characterization after a few amplifiers (in order to get rid of homogeneous GD). The number of iterations needed is given by the total number of amplifiers over the number of EDFAs used in the characterization (as mentioned before, here we tested after 5, 10 and 20 spans). It is based on the piecewise linear approximation as well as the superposition principle presented in the previous section. The power distortion due to the inhomogeneous gain with respect to the reference case at iteration k is given by: $\Delta p^{(k+1)}(\lambda) = \Delta p^{(k)}(\lambda) + \sum_{\lambda_i} NGD_{\lambda_i}(\lambda) \cdot f\left(\Delta p^{(k)}\right)$.
To illustrate the impact of inhomogeneous gain, Fig.3b) reports an example of input/output power spectral density (PSD) of a measured random pre-emphasis (solid line), as well as the model prediction (in dashed line) using the NGD after 20 spans. We see in Fig.3b) that when inserting a +/- 10 dB of pre-emphasis with respect to the averaged input power, we can have an impact in the output PSD as high as 12 dB around 1538 nm and a global RMSE of 5.6 dB if we are GD-unaware. Conversely the proposed model yields an RMSE of 0.33 dB in this case.

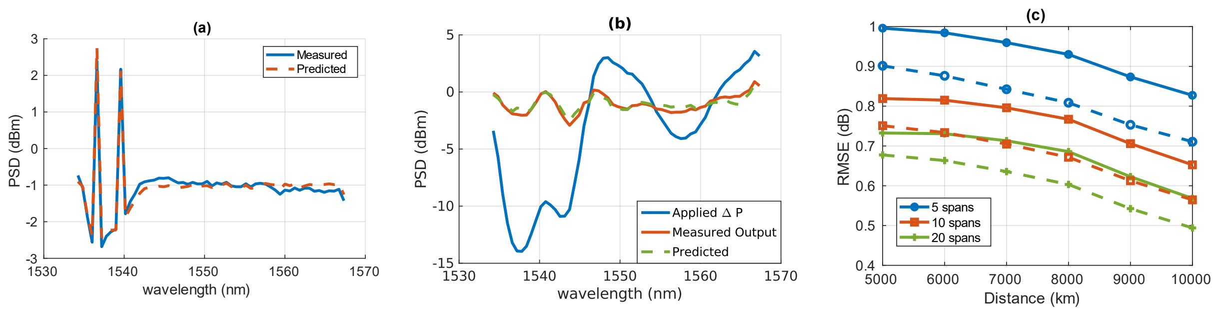

Fig.3 a) Measured (solid line) and predicted (dashed) link output PSD using the superposition principle. b) Measured and predicted Power Spectral Density after 10000 km compared with initial pre-emphasis. c) Root-mean-square error of model using 5, 10 and 20 spans in the training when extrapolated to distances from 5000 to 10000 km for input pre-emphasis with +/- 5 dB (dashed) and +/- 10 dB (solid).

Finally, we tested the model over 300 random pre-emphasis with excursions up to +/- 10 dB to really stress it and we computed the RMSE. Fig.3c) shows in solid lines the mean RMSE versus the predicted distance using the characterization of the 5, 10 and 20 spans. We obtained the lowest estimation error (0.56 dB) with a characterization after 20 spans that contrasts with the RMSE of 6 dB obtained if model is not applied (GD-unaware). Mean RMSE increases up to 0.65 and 0.82 dB respectively when 10 and 5 and spans are used to train the model because the arise of homogeneous GD effects. Then we tested only realistic excursions up to +/- 5 dB (dashed lines). PSD prediction at the output is done with 0.5, 0.56 and 0.71 dB of RMSE when using the NGD of 20, 10 and 5 spans, respectively.

4. Conclusion

An experimental model to predict the inhomogeneous gain distortion of EDFA amplifiers has been introduced which is based on the superposition of contributions of every individual channel in a 75-GHz spaced WDM grid. To obtain the gain distortion at each channel, the EDFA has been locally saturated with a pre-emphasis and the normalized response has been stored in a look up table. In order to get rid from homogeneous contributions an average of 5-10 and 20 spans has been considered together with a principle of energy conservation. Then we proposed an iterative model in order to predict the evolution of gain distortion for a chain of EDFAs. Finally, we tested our approach by predicting the gain distortion generated by 300 different random input WDM pre-emphases with +/-5 dB excursion in a submarine testbed with up to 200 C-band EDFA reaching a RMSE of 0.5 dB.

5. References

[1] E. Rivera, *et al*, “Design, Acceptance and Capacity of Subsea Open Cables,” JLT, vol. 39, no. 3, pp. 742-756 (2021).
[2] J. Pesic, “New Trends in Low Margin Optical Networks,” in ECOC 2022.
[3] A. Carbo, *et al.*, “Highly Accurate Measurement-Based Gain Model for Constant-Pump EDFA for non-Flat WDM Inputs,” in OFC 2021.
[4] V. Mathias *et al.*, “Extension of the Measurement-Based Gain Model for non-Flat WDM Inputs and various pump currents,” in ECOC 2021.
[5] A. A. M. Saleh, *et al.*, "Modeling of gain in erbium-doped fiber amplifiers," Photonics Technology Letters, vol. 2, no. 10, pp. 714-717 (1990).
[6] C. R. Giles and E. Desurvire, “Modeling of erbium-doped fiber amplifiers,” JLT, vol. 9, pp. 271–283 (1991).
[7] M. Bolshtyansky, “Spectral hole burning in erbium-doped fiber amplifiers,” JLT, vol. 21, no. 4, pp. 1032-1038 (2003).
[8] A. Pilipetskii, *et al.*, “Spectral Hole Burning Simulation and Experimental Verification in Long-Haul WDM Systems,” in OFC 2003.
[9] A. K. Srivarttava, *et al.*, “Room temperature spectral hole-burning in erbium-doped fiber amplifiers”, in OFC 1996.