Gain Profile Characterization and Modeling for Dual-Stage EDFA Abstraction and Control

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***Abstract*— Relying on a two-measurement characterization, in this work a simple and effective gain profile model for dual-stage optical erbium-doped fiber amplifiers (EDFAs) working under full spectral load conditions is presented and validated. Starting from the model of an ideal EDFA, the gain ripple profile is determined as the target parameters of the amplifier vary using a linear combination of two contributions. Being a consequence of the absorption/emission curves of erbium in the two stages, the first represents a characteristic of the specific device and reflects also the residual impact due to the gain flattening filter (GFF), while the second parameter accounts for a feature of the considered amplifier model, scaling according to the set tilt target. The proposed model faithfully reproduces the dynamics of EDFA by varying the total input power and the target gain and tilt parameters, as shown experimentally on a set of 14 devices divided into 4 different models from 2 vendors, of which 10 in C-band and 4 in L-band. The obtained error distributions present an unbiased peak shape with variability between the 25 and 75 percentiles below 0.2 dB for the worst case in C-band and 0.1 dB in L-band, respectively.**

***Index Terms*— Erbium-doped fiber amplifier, optical amplification, gain profile characterization and modelling.**

I. Introduction

MAXIMIZING the capacity of optical infrastructures is one of the main objectives of operators and service providers, with the aim of minimizing costs at the same time [1]. For this purpose, quality-of-transmission estimation (QoT-E) represents a fundamental aspect for both optical control and data planes and predicts the expected behavior of the system with a reasonable margin [2]. In this perspective, optical amplifiers are key network elements that allow signal power level to be restored at the cost of signal-to-noise ratio degradation. The characterization of optical amplifiers includes two main parameters that are critical in the search for the optimum operating point of the system: gain, g, and noise figure profiles. In general, a suitable description of the parameters of the frequency-dependent physical layer plays an important role in QoT-E, especially when considering wideband transmission scenarios [3]. Focusing on erbium-doped fiber amplifiers (EDFAs), an ideal gain profile can be expressed in decibels as:

$$g(f;G,T) = G + \frac{T}{B}(f - f_c) \tag{1}$$

where f is the optical frequency, G and T represent the target gain and tilt parameters set in the amplifier, f_c is the rotation pivot point of the tilt, and B is the EDFA bandwidth on which the target tilt is provisioned (Fig. 1). The latter should not be confused with the effective amplified bandwidth, which depends on the specifications of the device, such as minimum, f_{min}, and maximum frequency, f_{max}.

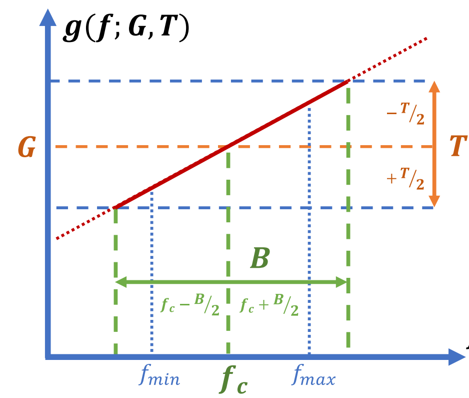

Fig. 1. Gain profile modelling representation of an ideal EDFA.

The accurate application of the tilt is important to compensate for stimulated Raman scattering (SRS) due to propagation through the fiber span [4]. Eq. 1 completely neglects the additional gain profile ripple due to the EDFA manufacturing and the physical behaviour. The design of the EDFA gain profile can be achieved through the evaluation of the dynamic gain tilt (DGT) parameter, evaluated as the normalized difference, with respect to a specific frequency of two different gain profiles [5]. Regarding the modelling of the EDFA gain profile, different machine learning (ML) strategies have already addressed the problem of accurately reproducing the gain ripple profile [6], [7], [8], [9], which requires relatively large data sets. ML solutions can also compensate for gain profile fluctuations induced by a varying spectral load, as shown in [10]. To the best of the authors' knowledge, no gain profile ripple modelling solutions have been presented that do not employ a massive number of measurements to characterize the behavior of an EDFA achieving a high degree of accuracy.

Manuscript received 1 August 2023; revised 3 October 2023; accepted 29 November 2023. Date of publication 30 November 2023; date of current version 15 December 2023. *(Corresponding author: Giacomo Borraccini.)*

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Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LPT.2023.3338482.

Digital Object Identifier 10.1109/LPT.2023.3338482

In this work, a semi-analytical EDFA model is presented and validated, focusing on the accurate reproduction of the gain profile, including the gain ripple, in a full spectral load transmission scenario. This last condition is related to the response of erbium changes according to how the spectrum is populated, which requires a deeper study of the phenomenon as regards the modelling. On the other hand, the full spectral load condition has reference characteristics, representing both the worst case in terms of nonlinear effects in the fiber and the most stable condition in terms of transmission quality with respect to power transients that can suffer the channels.

Extending Eq. 1, the proposed methodology provides a low computational cost procedure for the evaluation of the ripple profile gain, promising for its precision and simplicity, which are fundamental features for efficient and agile QoT-E such as the GNPy physical layer model [11]. The implemented abstraction is composed of two different steps: first, the EDFA gain ripple parameters are characterized considering only two gain/tilt settings; then, the semi-analytical model enables an accurate estimation of the gain profile for any pair of gain/tilt settings, abstracting the behavior of the device.

II. Model

Without any loss of generality, an accurate EDFA gain profile modelling is described as follows:

$$g(f; G, T) = G + \frac{T}{B}(f - f_c) + r_T(f), \qquad (2)$$

where the term r_T refers to the gain ripple profile, which is mainly a consequence of the absorption/emission curves of erbium in the two stages, and it can be defined as the deviation between the real and ideal amplifier gain profiles [12].

In general, all gain ripple profiles, r_T, generated in a different tilt condition depend on the set tilt target parameter, T, which in this model is defined according to the frequency coordinate. By construction of the presented model, the gain ripple profile of a real EDFA evaluated when the tilt parameter is set to 0 dB represents a tilt-independent manufacturing footprint of the EDFA design procedure, also related to the gain flattening filter (GFF) of the specific device:

$$g(f; G, T = 0) = G + r_0(f). \qquad (3)$$

Bearing in mind the DGT-based EDFA design that describes the physical implementation of the tilt, it is possible to define a second tilt-independent parameter, K, defined as:

$$K(f) = \frac{r_T(f) - r_0(f)}{T}, \qquad (4)$$

which is a feature of the EDFA figure of merit, and r_T is derived from the gain profile measurement setting the tilt parameter at T. From Eq. 4, it is possible to evaluate a generic tilt-dependent gain ripple profile in function of the r_0 and K:

$$r_T(f) = r_0(f) + T\,K(f). \qquad (5)$$

Using Eq. 5, it is possible to obtain an accurate evaluation of a generic gain profile for a specific EDFA:

$$g(f; G, T) = G + \frac{T}{B}(f - f_c) + \left[r_0(f) + T\,K(f)\right]. \qquad (6)$$

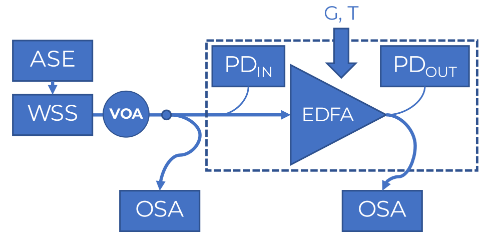

Fig. 2. Sketch of the experimental setup used to characterize a single device.

III. Experimental Setup

To validate the model, a complete experimental characterization of 14 devices is performed, divided into 4 models coming from 2 different vendors:

- **EDFA 1**: Vendor 1, C-band (x6);
- **EDFA 2**: Vendor 1, L-band (x4);
- **EDFA 3**: Vendor 2, C-band, low gain range (x2);
- **EDFA 4**: Vendor 2, C-band, high gain range (x2).

For each device, an experimental data set consisting of different gain profiles for a given combination of total input power, target gain, and tilt parameters has been collected. The experimental setup for the acquisition of the data set is depicted in Fig. 2. A commercial wavelength selective switch (WSS) is programmed in order to shape the amplified spontaneous emission (ASE) noise generating a wavelength division multiplexed (WDM) comb of 48 channels, 100 GHz spaced, each modulated at 32 GBd, to be provided at the EDFA's input (4.8 THz of total bandwidth). The created spectral load has a central frequency of 193.6 THz for all the C-band amplifiers and 188.5 THz for the L-band EDFA. Each amplifier can be controlled via the secure shell protocol (SSH), which has been exploited to set the gain and the tilt parameters, whereas its optical input power is changed acting on the variable optical attenuator (VOA) placed in front of it. The optical spectrum at both the input and output of the EDFA is captured using an optical spectrum analyzer (OSA). Each data set has been collected changing the total input power (dBm), target gain (dB) and tilt (dB) parameters as follows:

- **EDFA 1**: [−10:−4:+2], [12:27:+1], [−5:+3:+1];
- **EDFA 2**: [−4:−1:+1], [19:25:+1], [−5:+2:+1];
- **EDFA 3**: [−10:+0:+2], [10:20:+1], [−3:+3:+1];
- **EDFA 4**: [−10: __ : __], [17:30:+1], [−3:+3:+1];

where each triple of values corresponds to the minimum, maximum value, and step, for a total of 4,704 measured gain profiles considered. The total input power value ranges have been established so that the maximum value coincides with the difference between the maximum total output power supplied by the device and the maximum target gain, avoiding the case of saturation configurations. The target gain and tilt values fully cover the range of configurations set in real use cases. The tilt target parameter for commercial EDFAs, as also in the previous list, is generally considered according to the wavelength coordinate; therefore, this parameter is treated in the model by inverting the sign.

It is worth noting that the measured profiles are affected by the post-processing uncertainty of the measurement, as all gain profiles were obtained as a differential computation of the input/output power profiles, measured with the OSA, and scaled to the total power measured by the input (PD$_{IN}$), and output (PD$_{OUT}$) photodiodes of the EDFA, which suffer from an inaccuracy of ±0.1 dB. Given the experimental setup, to roughly estimate the error associated with each gain profile measurement it is reasonable to propagate the

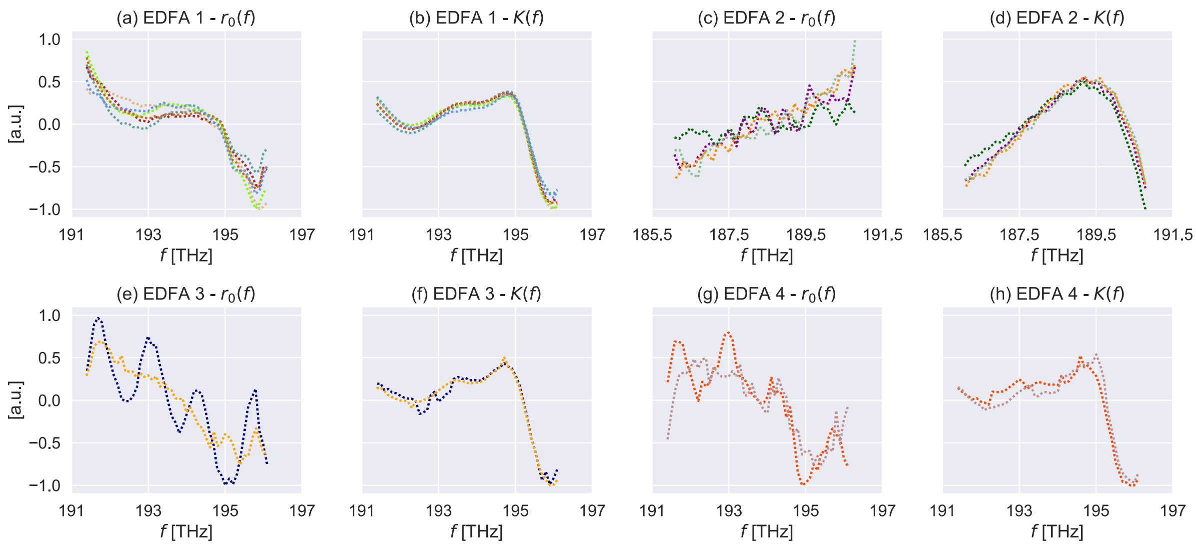

Fig. 3. Gain ripple profile with 0 dB tilt, r_0, and tilt-independent parameter, K, derived for each device under test, grouped and normalized by EDFA model.

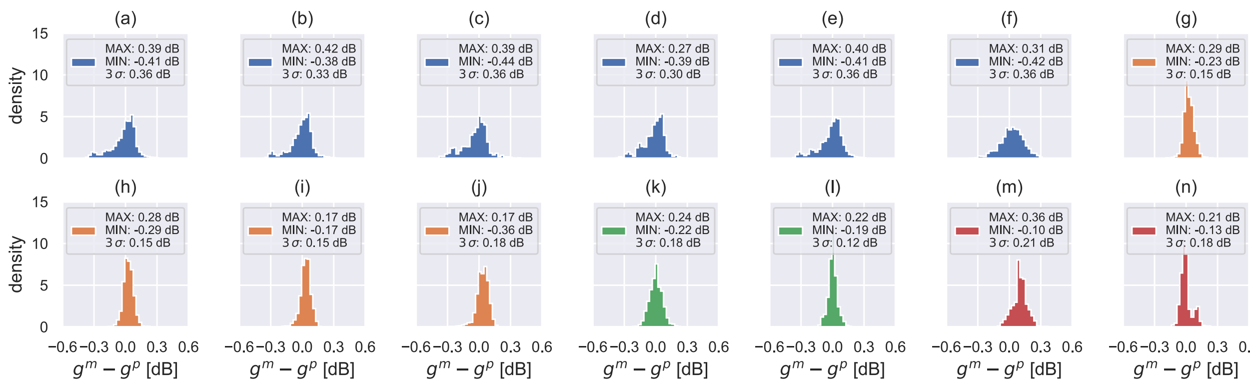

Fig. 4. Normalized error distribution in the form of a histogram for each EDFA tested. Each color represents a different amplifier model. In particular: (a–f) EDFA 1; (g–j) EDFA 2; (k–l) EDFA 3; (m–n) EDFA 4.

uncertainty associated with each photodiode measurement and add an assumed maximum term of 0.05 dB for the OSA measurements, for a total error of 0.30 dB.

IV. Characterization

The model presented is derived for each device under test. The 0 dB tilt target gain ripple profile, r_0, is derived by subtracting the gain target value from the corresponding measured gain profile. Although the conditions for target gain and total input power are arbitrary, in this work the measured gain profile is chosen with the target gain parameter set to mid-dynamic range and at minimum input power. To evaluate K, two gain profiles are considered: one with a target tilt of 0 dB and another with a higher positive target tilt parameter considering the frequency coordinate. The selection of the second gain profile is arbitrary; however, empirical evidence shows that higher tilt leads to lower relative measurement error. Furthermore, considering the non-zero target tilt parameter, the tilt pivot point, f_c, is evaluated when the linear regression of the measured gain profile assumes the value of the target gain parameter. The EDFA tilt bandwidth, B, is estimated by considering the same linear regression so that the set target tilt parameter value agrees with the estimate.

V. Results

For each device under test, all pairs of parameter profiles, r_0 and K, derived from the two-measurement characterization procedure are represented in Fig. 3, grouped and normalized according to the maximum absolute value of the specific set of profiles by EDFA model. The gain ripple profiles, r_0, show significant variability even between devices belonging to the same amplifier model. On the other hand, it is evident how the profiles of the tilt-independent parameter, K, have a clear similarity for devices of the same model, representing in fact a property of a specific model of amplifiers. To corroborate this, it is worth noting that K is characterized starting from r_0. Therefore, to obtain an accurate representation of the behavior of each individual amplifier, it is sufficient to measure the value of r_0 for each amplifier of the same model and maintain the profile K derived from a single amplifier. It is important to underline that the curves extracted depend on the bandwidth used, 4.8 THz in this case, and that the K profile, derived by differential measurement, describes a characteristic of *erbium-doped fiber* amplifiers.

Fig. 4 provides a complete view of the effectiveness of the model, showing the distribution of the difference between the performed experimental measurements described in Sect. III, g^m, and the corresponding predictions using the presented EDFA model, g^p, for each device tested across all combinations of total input power, gain and tilt values. Leaving aside the semi-analytical nature of the proposed model, it is assumed to be error-free leading to a more stringent comparison with respect to measurements, in which it is evaluated whether the model estimate is compatible, or falls within the measurement range. The distributions obtained have a dominant peak centered around 0 dB,

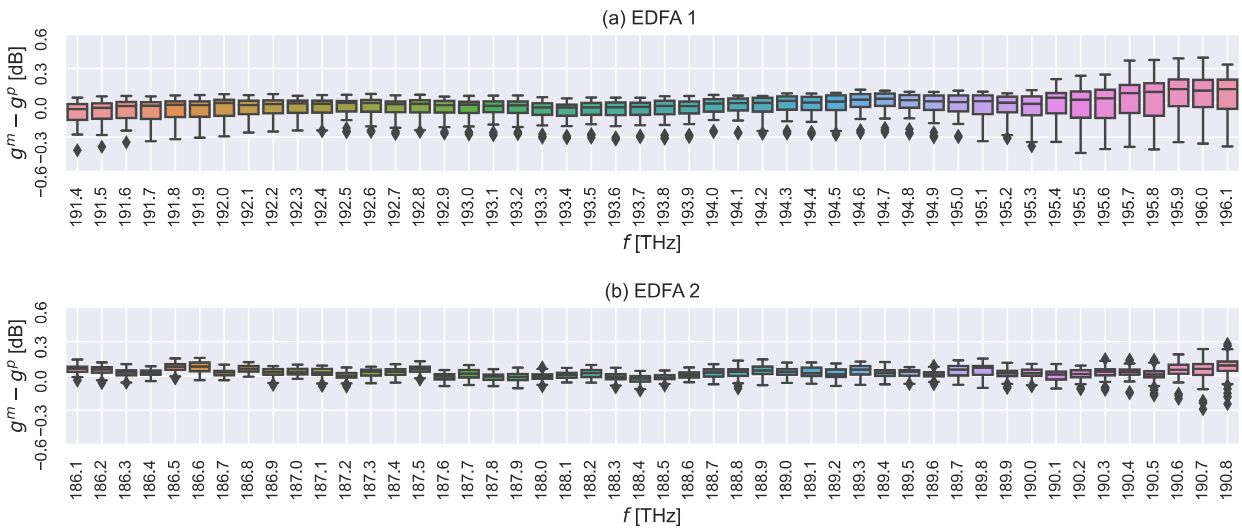

Fig. 5. Box plot summarizing the distribution of error with respect to frequency. The worst cases obtained for an amplifier model in C-band, (a) EDFA 1, and in L-band, (b) EDFA 2, are presented.

demonstrating an unbiased estimate. Taking into account for each distribution a large confidence interval such as three times the standard deviation, σ, the worst cases record an estimated error of 0.36 dB for the C-band and 0.18 dB for the L-band, demonstrating that the model is compatible with the measurements made. As also considered in the proposed model, the experimental evidence shows that the variation of the input power does not influence the shape of the gain profile.

Fig. 5 represents in the form of a box plot the distribution versus frequency for the two worst cases in the C and L bands. It is relevant to note that the range between the 25 and 75 percentiles is limited to ± 0.2 dB for the C-band and ± 0.1 dB for the L-band, highlighting the effectiveness of the proposed methodology. Furthermore, it is noted that in the high-frequency region, especially for C-band EDFA, the error distribution is wider than in the rest of the spectrum. Even if the resulting phenomenon of spectral hole burning (SHB) [13] in full spectral load conditions is taken into account in the model through the measures necessary for the characterization, the high variability shown is mainly due to the post-processing phase performed on the measured data, affecting also the model. The reconstruction of the gain profile for each configuration clearly depends on the two measured input/output power profiles. The fact that the two profiles have faster local variations in frequency leads to a less accurate estimation of the nominal gain profile, as is the case in the high-frequency region EDFA. Then, when the measured and predicted profiles are compared through the subtraction operation, this variability becomes evident resulting in a thickening in the specific region of the box plot.

VI. Conclusion

A gain profile model for dual-stage EDFA working under full spectral load condition is proposed, showing its effectiveness and accuracy through experimental verification on a set of EDFAs from 2 different vendors, both in the C and L band. In particular, through the two-measurement characterization of two invariant profiles, K and r_0, and two parameters that describe how the tilt is applied on the gain profile, f_c and B, all gain profiles for all combinations of input power, target gain and tilt parameters can be obtained with a semi-analytic expression. Given the low complexity of the characterization procedure, it can be performed by both vendors and final users, and device-specific characterization can be easily stored or shared.

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Open Access funding provided by 'Politecnico di Torino' within the CRUI CARE Agreement