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Data-driven Optimization of Giles Parameters of Super L-band Erbium Doped Fibers

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Abstract: *Precise modeling of super L-band erbium doped fibers (EDFs) is more challenging than conventional C-band EDFs. We demonstrated a data-driven Giles parameter optimization routine that leads to significant precision improvement of the simulated gain and noise figure. ©2022 The Author(s)*

Introduction

For several decades, C-band erbium doped fiber amplifiers (EDFAs) have achieved a great success in optical communication networks. Products that can provide 6 THz bandwidth and ~ 4 dB noise figures (NF) are commercially available. The technology of C-band EDFA is quite mature. The Giles model works quite well in the C-band [1], providing precise matching between the experiment and the simulations [2]. In order to further expand the system capacity, the L-band and even super-L band EDFAs have recently attracted the attentions from both academic and industrial societies [3-5]. However, the numerical simulation results of L-band EDFAs are much less accurate compared to that of the C-band EDFAs. This is mainly because, in L-band EDFAs, the C-band ASE light plays an important role. Both the C- and L-band Giles parameters need to be precisely measured. However, this would be quite challenging since in L-band EDFs, especially in super-L band EDFs (based on phosphor-silicate glass matrix), the magnitude of the C- and L-band Giles parameters are very much different, which requires an extremely large measurement dynamic range. In addition, the super L-band EDFs suffer from the effect of excited state absorption (ESA) beyond ~ 1580 nm.

To address this issue, we present in this paper a data-driven optimization routine that increases the accuracy of EDF parameters extracted from experimental measurements that are needed to feed numerical models for L-band EDFAs. The optimization study is performed on single as well as on two stage super L-band amplifiers that were built using in-house fabricated EDF engineered to provide L-band amplification beyond 1620 nm. By comparing results using optimized and un-optimized EDF parameters, we show that the proposed optimization routine significantly improves the agreement between numerically and experimentally obtained amplification results of L-band EDFA systems, and paves way for significant improvement of their amplification performance in the future.

Numerical model

The numerical model used for simulating L-band EDFAs is the well-known Giles model [1]. This model has shown excellent agreement with experimental data for C-band EDFAs when four parameters are provided, i.e. the absorption coefficient $\alpha(\lambda)$, the emission coefficient $g^*(\lambda)$, the background loss coefficient $l(\lambda)$ and the saturation coefficient ζ. Erbium ion clustering is also implemented in the numerical model following the approach outlined in [6] and its magnitude is determined by the paired ion ratio (k). Finally, ESA affecting L-band signals with wavelengths > 1580 nm is taken into account by using a distinct emission coefficient in the ionic rate equations ($g^*(\lambda)$) and the spontaneous emission ($g_{21}(\lambda)$) terms of the power evolution equations, in agreement with [7]. As such, the relationship between both emission coefficients is given by

$$g_{21}(\lambda) = g^*(\lambda) + \alpha_{ESA}(\lambda)$$
$$g_{21}(\lambda) = \alpha(\lambda)\exp\left(\frac{hc}{k_B T}\left(\frac{1}{\lambda_0} - \frac{1}{\lambda}\right)\right), \qquad (1)$$

where $\alpha_{ESA}(\lambda)$ is the excited state absorption spectrum, k_B and h are the Boltzmann and Planck constants, respectively, c is the speed of light, T the temperature and λ_0 is the cross-over wavelength.

Optimization procedure

Optimization of the EDF parameter values extracted from the experiments is accomplished by comparing the numerically calculated internal gain and internal noise figure (NF) spectra under various conditions, i.e. signal input powers, pump powers and EDF lengths. A total of 7 parameters were optimized simultaneously, i.e. $\alpha(\lambda)$ and $g^*(\lambda)$ from 1575 nm to 1626 nm, α_p at 976 nm, ζ, k, T and λ_0. The background loss coefficient $l(\lambda)$ as well as $\alpha(\lambda)$ and $g^*(\lambda)$ in the 1450 nm to 1575 nm wavelength range were not optimized and kept identical to the values deduced from spectral absorption measurement (see Experimental setup section for details). The cost function (F) supplied to the optimization algorithm is given by

$$F = F_G + F_{NF}$$
$$F_G = \sum_{i=1}^{n} \left| \frac{G_{sim}(i) - G_{exp}(i)}{n * G_{exp}(i)} \right| \tag{2}$$
$$F_{NF} = \sum_{i=1}^{n} \left| \frac{NF_{sim}(i) - NF_{exp}(i)}{n * NF_{exp}(i)} \right|,$$

where G_{sim} and G_{exp} are the simulated and experimental gain, respectively, NF_{sim} and NF_{exp} are the simulated and experimental noise figures, respectively, and n is the number of experimental gain and noise figure measurements used for the optimization.

Moreover, it can be shown that $\alpha(\lambda)$ and $g^*(\lambda)$ can be expressed as

$$\alpha(\lambda) = \gamma_1(\lambda) - n_2\left(\frac{\gamma_1 - \gamma_2}{n_1 - n_2}\right) + l(\lambda),$$
$$g^*(\lambda) = (n_2 + 1)\left(\frac{\gamma_1 - \gamma_2}{n_1 - n_2}\right) - \gamma_1 - l(\lambda), \tag{3}$$

where γ_i is the internal unitary gain provided by the EDF when operating at an inversion level n_i. The internal unitary gain is simply the total internal gain divided by the EDF length, i.e. $\gamma_i = G_i/L_i$. Equation (2) was used to reduce the optimization of $\alpha(\lambda)$ and $g^*(\lambda)$ at every signal wavelength, to optimizing only two constants, i.e. n_1 and n_2, using two gain spectra γ_1 and γ_2 from the experimental data set.

Experimental setup

The EDFA setup used to provide L-band gain and NF spectra to train and validate the optimization algorithm is depicted in Figure 1. It consists of 2 amplification stages built out of EDF manufactured at the Center d'optique, photonique et laser (COPL), Université Laval, Québec (Canada) and engineered to provide extended L-band amplification beyond 1620 nm.

The input signal is provided by a home-made sliced ASE comb source combined with to variable optical attenuator. The EDFs were pumped by several 976 nm single-mode semiconductor laser diodes in either the forward or bidirectional direction. Two rounds of measurements were conducted. The first round consisted of single stage measurements, both on the 25 m and the 48 m long EDFA stages, for signal input powers of -10 dBm and 0 dBm, and total pump powers ranging between 50 mW and 800 mW in the forward or bidirectional orientation. The second round of measurements was performed on the full EDFA shown in Figure 1. In this case, the 1st stage was forward pumped while the 2nd stage was pumped either in the forward or bidirectional orientation. It should be noted that an L-band gain flattening filter (GFF) and a C-band ASE filter (C/L filter) were inserted after the 1st stage to limit gain saturation of the 2nd stage.

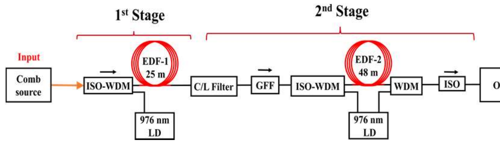

Fig. 1. Schematic of the 2-stage L- band EDFA. WDM-ISO: hybrid ISO-WDM; ISO: isolator; WDM: wavelength-division multiplexer, GFF: gain flattening filter; LD: laser diode.

Prior to numerical optimization, the EDF parameters were carefully measured. A cutback experiment was conducted on the fiber in order to determine $\alpha(\lambda)$ in the 1400 nm - 1650 nm range, α_p at 976 nm and the background loss coefficient l at 1200 nm, which was assumed to be constant for all wavelengths. The emission coefficient $g^*(\lambda)$ was measured using the amplified spontaneous emission method outlined in [7] while $g_{21}(\lambda)$ was calculated using Eq. (1) by fitting λ_0 so that $g_{21}(\lambda) = g^*(\lambda)$ in the 1520 nm – 1550 nm range. Finally, k and ζ were determined through a non-saturable absorption experiment using a high power laser at 1550 nm [8].

Results and discussion

Optimization of the EDF parameters was executed using measurements conducted on the single stage EDFAs. Figure 2 shows the measured (dashed lines) and optimized (solid lines) $\alpha(\lambda)$ and $g^*(\lambda)$, while the inset compares the other measured and optimized parameters (α_p, ζ, λ_0, T and k). The optimized $\alpha(\lambda)$ and $g^*(\lambda)$ values are higher compared to the measured values. Moreover α_p and T also

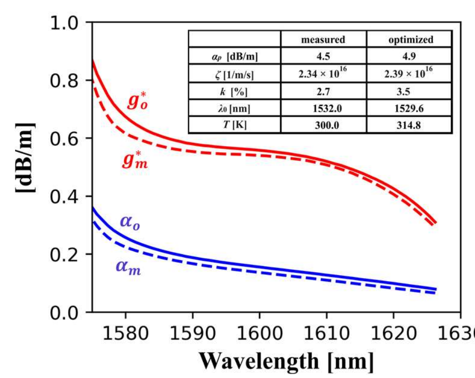

Fig. 2. Measured ($\boldsymbol{m}$) and optimized ($\boldsymbol{o}$) $\boldsymbol{\alpha(\lambda)}$ and $\boldsymbol{g^*(\lambda)}$ parameters. Inset: Comparison between measured and optimized values for other parameters.

display higher values, while other parameters remain fairly constant.

Figure 3 (a), (b), (c) and (d) compare a subset of gain and noise figure spectra obtained experimentally and produced through simulations using the optimized and the measured EDF parameters. Moreover, Figure 4 (a) and (b) present the histogram of average gain and NF difference, respectively, between the experimental data and the simulated data before and after parameter optimization for all the 53 recorded data sets. It is apparent that the optimized parameters produce better agreement in terms of gain and NF. The average gain difference is well below 0.5 dB (most curves show < 0.2 dB discrepancy) for the optimized case, while it varies significantly for the measured case. Similarly, the NF remains below 0.25 dB for the optimized case in all 53 data plots, whereas it can reach 1 dB in some cases for the measured case.

Finally, the accuracy of the EDF parameters that were obtained were validated on the experimental data measured on the two-stage EDFA, i.e. the EDF parameters optimized using the single stage measurements were taken as is without prior optimization on the two-stage experimental data. Figure 4 (c) and (d) present the histogram of average gain and NF difference, respectively, between experimental and numerically obtained data for the two-stage EDFA. Similarly to the single stage measurements, the average gain and NF difference decreases when using the optimized parameters (24 gain and NF spectra were taken experimentally), which is not the case using measured parameters. Overall, the results clearly demonstrate that the optimized parameters allow a better fit of the experimental data. On the other hand, experimentally measured fiber parameters could provide a good trend but are limited in terms of accuracy.

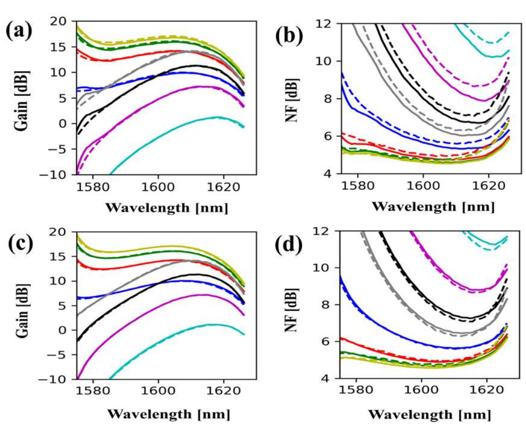

Fig. 3. (a) Measured single stage gain and (b) NF (dash lines), simulated using measured parameters (solid lines) (c) gain and (d) NF measured (dash lines), simulated using optimized parameters (solid lines).

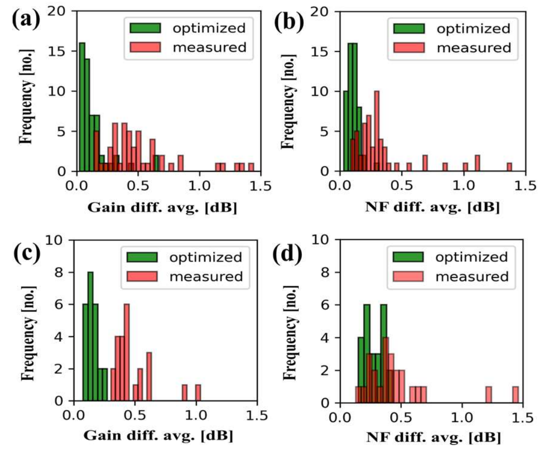

Fig. 4. Histograms of average gain and NF difference between experimental data and simulated data. For single stage EDFA (a) and (c) (total 53 data plots), two stage EDFA (c) and (d) (total 24 data plots), using measured (red) and optimized (green) parameters

We believe that the large discrepancy between numerically modeled results, using the measured fiber parameters, and the experimental results stems from the accuracy of the measured fiber parameters. Indeed, small experimental uncertainties, i.e. EDF length, measurement setup level stability, etc., can lead to non-negligible uncertainty on EDF parameters. Furthermore, the accuracy of several EDF parameters (for example g^*) is further degraded by propagation of uncertainty since they require knowledge of other EDF parameters (in this case α) that possess an uncertainty. Finally, the accuracy of the measured EDF parameters is also limited by the fact that the physical assumptions used to extract them from the measurements were not completely fulfilled.

Moreover, it should be noted that the optimized parameters might only yield accurate modeling results for certain EDFA designs. Indeed, they have been optimized using experimental L-band gain and noise figure results provided by an EDF operated within a bounded range of signal powers, pump powers and lengths and therefore parameters outside the range of the training set remains to be validated.

Conclusion

We have shown that using an optimization routine to extract EDF parameters improves the agreement between numerically calculated and experimentally measured amplification results of super L-band EDFAs. This optimization routine is another step in improving the accuracy of numerical models for L-band EDFAs, and will be used to scale the performance of these systems similar to their C-band counterparts.

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