# Distributed Gain Measurements in Er-Doped Fibers with High Resolution and Accuracy Using an Optical Frequency Domain Reflectometer

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***Abstract*—For critical Erbium-doped fiber amplifier (EDFA) design, e.g., gain tilt optimization in WDM booster amplifiers, knowledge of the gain distribution within the active fiber can present a valuable information. Among the different techniques to evaluate the distributed gain in active fibers, the technique of optical frequency domain reflectometry seems most promising as it is a nondestructive measurement method well matched to the task due to its dynamic range, resolution, and range. Moreover, background light from ASE or residual pump light is strongly rejected due to the coherent detection scheme employed. Using different Erbium-doped fibers with strongly varying doping levels and confinements, we demonstrate the excellent accuracy and reproducibility of the technique.**

***Index Terms*—Fiber optics amplifiers and oscillators, metrology, nondestructive testing.**

## I. INTRODUCTION

THE ERBIUM-DOPED fiber amplifier (EDFA) is one of the key components for the tremendous, fast pace progress in optical telecommunication. Do to its high efficiency, large output power, low noise figure, and compactness, it found its way into diverse applications at different locations in the optical network [1].

In order to exploit the EDFA capabilities to a maximum, theoretical models were soon developed for further optimization of the EDFAs [2], [3]. Although these different models proved as a valuable tool for the proper tuning of parameters like the Erbium ion density and doping confinement, they are typically not capable of predicting important parameters like the distributed gain or optimum fiber length to better than 15% for a specific experimental configuration [2]. This point will be further addressed in the paper. The problem stems on one hand from the fact that models are never perfect as they frequently neglect some aspect of the gain dynamics for the sake of simplicity, e.g., inhomogeneous gain broadening, the number of levels, transverse space integrals, ASE spectrum, etc. [2]. The more important point, however, is that the input parameters for the models can frequently not be measured with a sufficient accuracy. Therefore, several methods to directly measure the gain distribution have been proposed and demonstrated. Cut-back methods are expensive and time consuming, and are not applicable for the measurement of the gain distribution in backward or bi-directionally pumped fibers. Nondestructive methods are consequently advantageous. Using an optical time domain reflectometer (OTDR) with additional ASE filtering, distributed gain curves were obtained [4]. However, the limited dynamic range and spatial resolution (due to the large minimum measurement distance in the order of a kilometer) of OTDRs make it a bad match to measure the gain distribution in typical Erbium-doped fibers (EDF) with lengths of some tens of meters.

Recently, we reported on distributed gain measurements using an optical frequency domain reflectometer (OFDR) [5]. The OFDR is ideally suited for this type of measurement, as its range, resolution, and dynamic range match well with the required values [6], [7]. Further, due to the coherent detection used in the OFDR, disturbing ASE light is largely rejected.

In this paper, an improved OFDR with better resolution, accuracy, and stability is used to give good quantitative results for the gain distributions in different types of EDF at 1550 nm. The reproducibility and accuracy of the distributed gain measurements are investigated carefully and compared to traditionally measured results using the cut-back method.

## II. CHARACTERISTICS OF THE IMPROVED OFDR

The OFDR technique (Fig. 1) is based on the detection of a beat signal between the distributed reflections from the fiber under test (Rayleigh backscatter, connectors, etc.) and a fixed Fresnel reflection (local oscillator). Using a specific linear frequency sweep of the laser source, one can straightforwardly map the measured beat frequencies on a distance scale, whereas the normed square power for a given beat frequency gives the reflectivity at the corresponding distance.

For a good overview of the OFDR principles and limits, the reader is referred to [6]. In the device used for the measurements presented here, several important improvements have been implemented. First, a different laser source with a much higher coherence length (about 3 km, bandwidth of 10 kHz) is used [8]. The coherence loss leads to a drop in the Rayleigh backscattering level of only about 0.15 dB after 30 m, making a correction of the measured gain curves as in [5] unnecessary. The accuracy of the reflectivity values has been greatly increased by adopting a polarization diversity detection scheme. This assures that the measured reflectivities are independent of the state of polarization of the reflected light—which changes as a function

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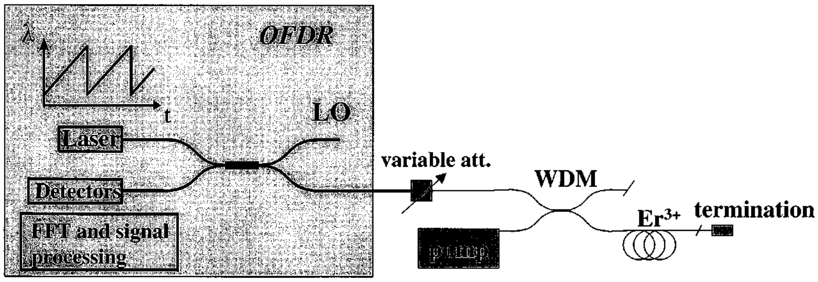


Fig. 1. Sketch of the experimental setup.

of the location of the reflector down the fiber and the fiber beat-length [9]—to within ±0.5 dB. Note that this value is an upper limit corresponding to the maximum signal deviation, observed when purposefully varying the polarization state in front of a reflector. Assuming a Gaussian probability distribution with a confidence level of 99% for the measured maximum deviation, the typical accuracy becomes $\sigma = 0.25$ dB. Further, the spatial resolution (FWHM of a distinctive reflection peak) was enhanced to 2 cm (30 m range), with a peak location accuracy of a mm.

The OFDR can easily measure the Rayleigh backscattering due to its sensitivity of $\sim -120$ dB, and the distributed gain in an EDF can be directly measured within 30 s. During the backward path of the reflected light, gain saturation is the same as during the forward path due to the extremely slow gain dynamics of the Erbium ions (~1 ms, [2]). The measured Rayleigh light therefore undergoes twice the gain (or loss), and the corresponding decibel-values have to be divided by two to get the physical quantity of interest. Note that if the single forward trip gain is to be measured, one has to be careful to avoid strong backreflections after the active fiber (which in an EDFA is ensured by the exit isolator), as the reflected light could saturate the gain. Using an analytic model for the EDF gain [10], we found that for a 25 dB gain, 30 m long fiber backreflections do not add to gain saturation in a significant way (gain reduction of less than 0.5 dB) as long as they are kept below $-40$ dB.

## III. EXPERIMENTAL RESULTS

In all the following measurements, a wavelength division multiplexer (WDM) was inserted between the OFDR test output and the EDF to feed the 1480 nm pump radiation into the active fiber. This corresponds to a forward pumping scheme, but the measurements could be done as easily for backward or bi-directional pumping. For the case of a large part of nonabsorbed pump light exiting the fiber, additional filtering might however be necessary for the latter pump set-ups to remove the backward travelling pump light. This is because noncoherent light reaching the OFDR can saturate its detectors and also leads to a somewhat enhanced noise background.

A standard fiber with a low end reflectance ($-65$ dB) was spliced to the output end of the active fiber in order to avoid backreflections into the EDF as much as possible.

In order to investigate the accuracy and reproducibility of the measured distributed gain curves from the OFDR we performed several measurements using different fibers and pump powers, and compared them with the gain values obtained from direct transmission measurements using the cut-back technique.

Fig. 2 shows the results for a fiber with a 2000 ppm Er doping level and a length of about 1 m. The lines correspond to the distributed Rayleigh backscattering as measured by the OFDR. The OFDR probe power was held constant at $-10$ dBm, whereas the pump power was gradually changed from no pump at all to $+15.2$ dBm. Due to the constant input signal, the Rayleigh level is about the same in front of the active fiber that starts at 7.9 m, in spite of the increasing level of backward ASE light. Note that the fluctuations in the backscattered signal is not due to a noisy measurement, but is caused by interference among the different Rayleigh scatterers ("coherent speckle"). The curves shown in Fig. 2 were smoothed by dithering the center frequency of the OFDR by ~0.5 nm and averaging (50 samples). As the fiber was not moved between the consecutive measurements, the remaining interference pattern should not change significantly, which was indeed the case as demonstrated by the figure. At the beginning of the active fiber, a distinctive jump of 8.7 dB in the Rayleigh level can be observed (unfortunately, it is somewhat covered by a Rayleigh peak). This is a known phenomenon due to the often larger numerical aperture (NA) of the EDF, leading to a larger capturing of the Rayleigh scattered light that is emitted in $4\pi$ sr (signal power $\propto \mathrm{NA}^2$ [2, ch. 5.8]. As a byproduct, the OFDR curves therefore give a good idea of the amount of possible NA mismatches, which lead to deteriorating internal reflections and losses that can increase the noise figure (input loss) or saturate the gain (reflections) and should consequently be avoided as much as possible.

Looking at the curve within the active fiber (7.9–8.8 m) for a switched off pump, one observes an exponential decay (linear on a decibel scale). It corresponds to the expected 1550 nm absorption of the Er ions in the active fiber, which is calculated from the slope to a value of $-62$ dB/m. For pump powers larger than about 9.6 dBm, the backscattered signal initially grows, indicating that the fiber is inverted leading to some gain. The figure shows that the location of the maximum gain strongly depends on the pump power. For a full pump of 15.2 dBm e.g., an amplification of 6.3 dB is obtained after 25 cm. After that distance, the fiber is no longer inverted because of pump depletion, and strong signal re-absorption takes place. For a distance of more than 70 cm, the remaining pump power is so small that the signal decays once more with a rate of about $-62$ dB/m.

A cut-back measurement was performed to obtain directly the transmission through different lengths of the active fiber. The same input signal power of $-10$ dBm and the same pump

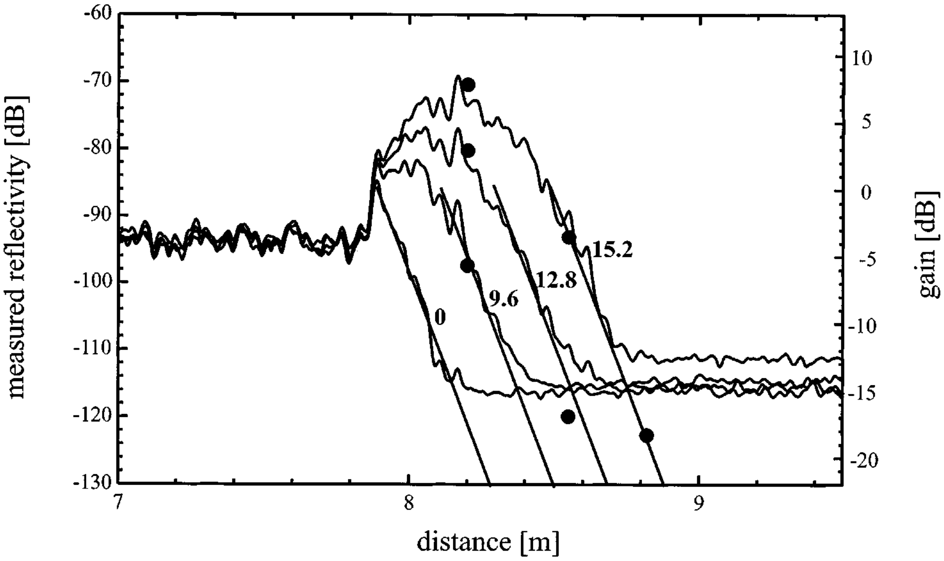


Fig. 2. Analysis of a forward pumped 2000 ppm Er-doped fiber with a length of 1 m. Solid lines: reflectivity traces as measured by the OFDR for pump powers from zero pump (bottom curve) to +15.2 dBm (top curve). Straight lines: guide to the eye of the linear absorption below the OFDR noise level. Dots: measured transmission values from traditional cut-back measures. The signal input power was held constant at −10 dBm.

power levels we used for the OFDR measurements were applied to assure the same saturation behavior. As there is some part of ASE light in the active fiber output, we calculated the transmission values by comparing the input and output optical spectra on an OSA allowing for easy ASE subtraction. The obtained transmission values, doubled (decibel-values) and referred to the fiber input Rayleigh level and location, are shown as dots in Fig. 2. Lines were introduced to indicate the linear decay of the OFDR traces below the instrument noise floor of about −116 dB for better comparison to the measured cut-back transmission values. As can be seen, the correspondence of OFDR and transmission measurements is rather good, clearly demonstrating the proper working of the OFDR for distributed gain measurements. It has to be noted that the presented measurement is a rather rough test with power levels changing at a rate of up to −123 dB/m—nevertheless, the gain value correspondence is typically better than 1 dB.

Fig. 3 shows results for a 3.8-m-long fiber with a 500 ppm Er doping level. Note that the scales have been adjusted in such a way that 0 m/0 dB is located at the input of the fiber, and the measured gain values have been divided by half (in decibels) to give the correct single trip gain values. The solid lines give the OFDR curves obtained for different pump powers and an input power of −11 dBm, whereas the dashed set of curves was obtained for the same pump powers, but for an even larger input signal power of −5 dBm.

Although there is a small reflectivity peak at the beginning of the active fiber, there is practically no difference in the Rayleigh backscattering level at the standard fiber-active fiber transitions. Apparently, the active fiber NA closely matches the one of the standard fibers. The fiber attenuation is −8 dB/m, and for the maximum pump of 15.2 dBm an overall gain of 14.7 dB is obtained for an input signal of −11 dBm. Fig. 3 shows that the gain values obtained from the conventional transmission measurements (dots and triangles for −11 dBm and −5 dBm input signal power, respectively) are all in excellent agreement with the OFDR values. The agreement is better than 0.5 dB in the presented measurement, which is close to the accuracy of the OFDR—the mismatch is probably rather due to uncertainties in the traditional measures anyway.

The gain reduction due to the 6 dB signal input power increase is correctly predicted, demonstrating that the go and return path gain are indeed the same, allowing for exact OFDR measures in a strongly saturated gain regime.

The good reproducibility of the OFDR measurements is shown in Fig. 4. There, the distributed gain was first measured on a 300 ppm-doped Er fiber with a length of 6.3 m. The fiber was then cut down to 2.3 m, and the gain distribution was again measured for the same pump powers. As the figure demonstrates, the curves are overlying well. The attenuation for this fiber is −2.5 dB/m, and for an input power of −5.6 dBm, practically no gain saturation is observed for maximum pump power.

Comparing the attenuation rates of the three fibers [−62 dB/m (2000 ppm), −8 dB/m (500 ppm), −2.5 dB/m (300 ppm)], one observes that they do not scale with the doping level. One reason might be that different co-doping concentrations could have been used for the different fibers. More plausible however is that the confinement factor [2] of the Er doping was different. An indication for this is that the NAs, and with that the signal beam extent, were different in the different fibers as is illustrated by the different amounts of the Rayleigh backscattering: whereas it was enhanced for the 2000 ppm (Fig. 2) and the 300 ppm fiber (Fig. 4), the 500 ppm fiber (Fig. 3) showed about the same backscattering level as a standard fiber. Assuming a very low co-dopant concentration and step doping profiles, the confinement factor can be calculated straightforwardly for the different doping concentrations and attenuation rates [2]. It amounts to 0.65 (2000 ppm), 0.46 (500 ppm), and 0.31 (300 ppm). Apparently, in the fibers with a lower doping concentration, a stronger confinement of the Er-ions was used.

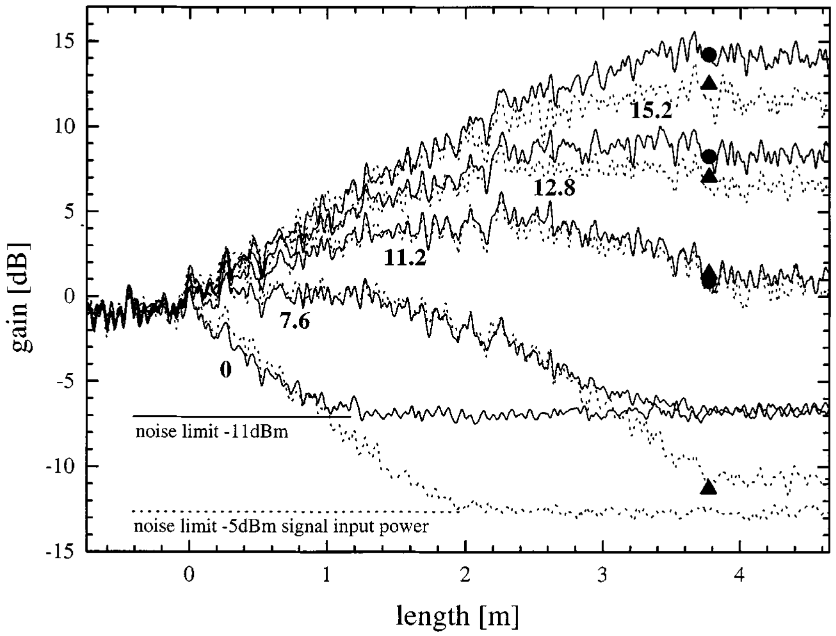


Fig. 3. Distributed gain curves in a 500 ppm Er-doped fiber for pump powers from zero pump (bottom curves) to +15.2 dBm (top curves). Lines: distributed gain calculated from OFDR traces for a signal input power of −11 dBm (solid line) and −5 dBm (dotted line), solid dots and triangles: directly measured transmission values through the Er-fiber. Note that because the gain (and not signal power) is shown, the apparent OFDR noise limit is increased by 6 dB for the set of lower signal input power (lower SNR).

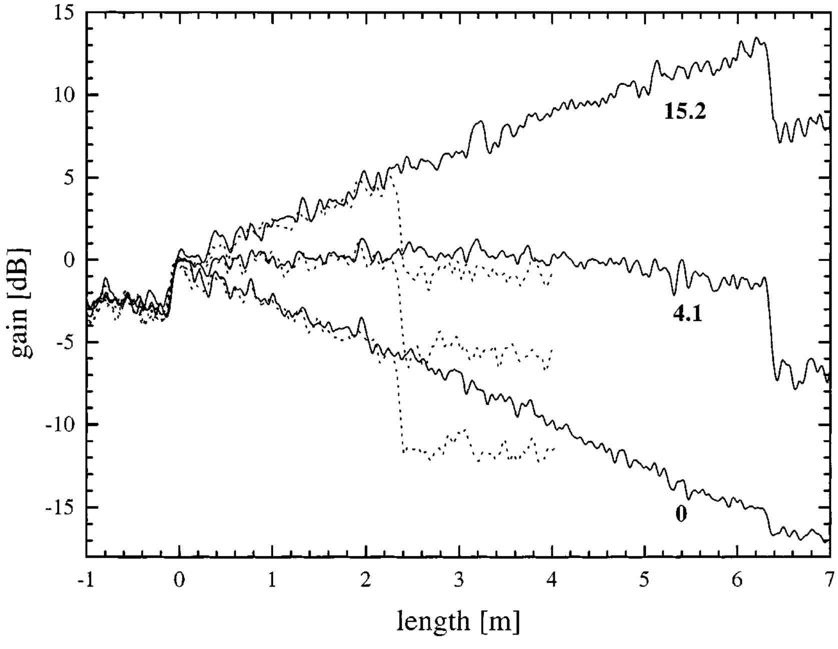
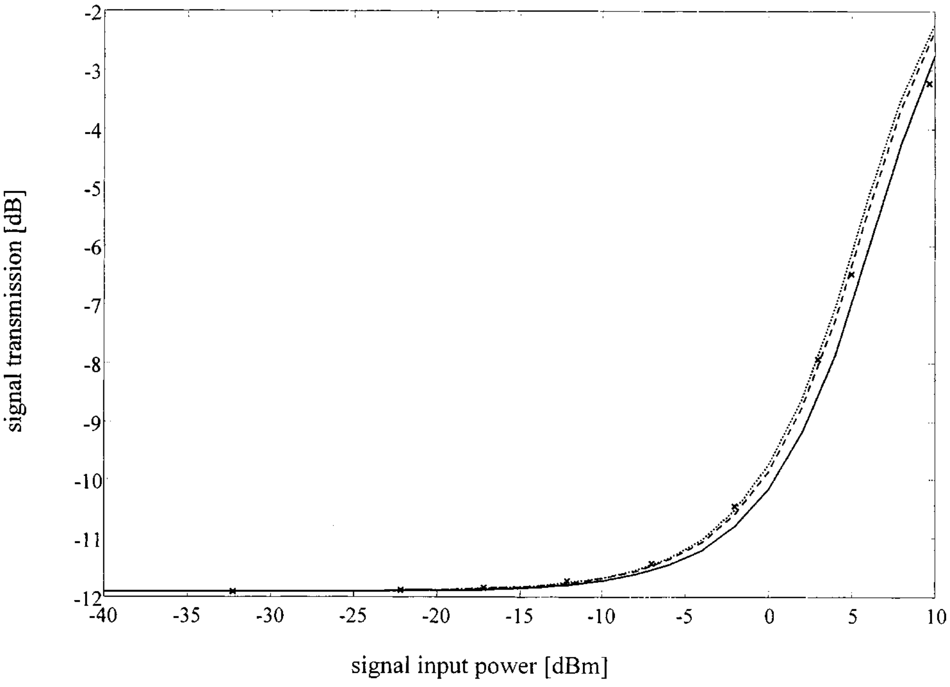


Fig. 4. Demonstration of the reproducibility of the OFDR measurements using a 300 ppm Er-doped fiber, an input signal power of −5.6 dBm, and different pump powers. Lines: distributed gain calculated from OFDR traces for fiber lengths of 6.3 m (solid line) and 2.3 m (dotted line).

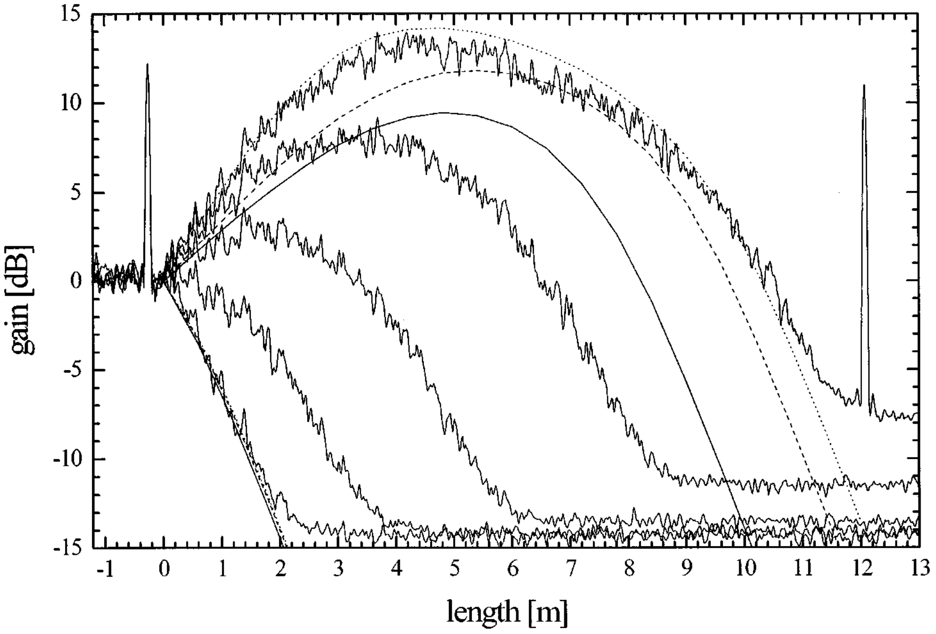
## IV. A WORD ON THE MODELING OF THE GAIN DISTRIBUTION

In the introduction, it was mentioned that the accuracy of models for the gain distribution is typically not very good due to a lack of knowing precisely enough the diverse parameters involved. Having seen the excellent precision and repeatability of the OFDR measurements of the distributed gain, we can now illustrate this point more concretely.

A simple analytical model that neglects excited state absorption (which is absent for 1480 nm pumping) and gain saturation caused by ASE is used [10]. It is applicable for moderate gains up to about 20 dB. The model is therefore perfectly applicable for the measurement using a 12 m long 500 ppm Er-doped fiber, which gives a maximum gain of 13 dB for full pump power [Fig. 5(b)]. In order to obtain the necessary model parameters, the small signal absorption and input saturation power were measured both at the pump and signal wavelengths. This can be done on any length of the same active fiber used for the OFDR measurements [10]. Fig. 5(a) shows such a measurement for the signal wavelength of 1550 nm. Using the measured parameters



(a)



(b)

Fig. 5. Modeling of measured gain distributions from a 12-m long 500 ppm Er-doped fiber. (a) signal transmission measurement through an unpumped, 1.5-m long piece of the same fiber for model parameter determination. Crosses: experimental values, lines: calculated transmission using different sets of model parameters (see text for details). (b) Gain distribution. zig-zag lines: measured, smooth lines: modeled using the same sets of parameters as in (a).

and the signal and pump input power used in the OFDR measurements, a gain distribution as shown in Fig. 5(b) for full and zero pump power can be calculated in an easy and rapid way.

The problem however is that the obtained gain distribution strongly depends on the measured parameters. The three different gain distributions for maximum pump power shown in Fig. 5(b) were obtained in the following way. For the solid line, a point measure of the small signal attenuation and saturation power [i.e. measuring the attenuation for a low input power, and measuring the input power for which the absorption is bleached by a factor e (4.34 dB)] has been used. For the dashed line, a fit to the transmission measurements [shown in Fig. 5(a) for the signal wavelength], was used. Finally, the dotted line is a "fit" to the measured OFDR gain curve obtained by manually varying the small signal absorption and saturation values entering the model. As can be seen from Fig. 5(a), where the calculated transmission curves using the three mentioned sets of parameters is shown, all three sets match well with the measured data (crosses), and the differences between the sets are quite small (even smaller for the pump wavelength not shown in the figure). Nevertheless, these small differences lead to predictions of the gain distribution with strongly varying maximum gain (9.4–14.2 dB) and maximum gain locations (4.7–5.3 m). Moreover, for the curve that matches best, there is still some difference in the shape of the modeled gain distribution to the real one as measured by the OFDR, demonstrating the difficulty to find the correct input parameters for the model.

To predict the maximum gain and especially the maximum gain location in a concrete, critical EDF set-up, it is therefore very useful to have a tool like the OFDR to accurately measure these parameters in a simple and rapid way.

## V. CONCLUSION

Using optical frequency domain reflectometry, distributed gain measurements in Erbium-doped fibers have been performed. The OFDR used is ideally suited for this type of measurement due to its sensitivity ($-120$ dB), resolution (2 cm at 30 m), and range (150 m). The coherent detection leads to a high background light suppression, and ASE from the active fiber is efficiently rejected. The accuracy and reproducibility of the measured gain distributions has been demonstrated using EDF with strongly varying doping levels and doping confinements. The results were found to be in excellent agreement with traditional cut-back measurements, typically to within the OFDR accuracy of about 0.25 dB. As a byproduct, possible mismatches between the NA of the active fiber and the preceding/following fibers are detected.

Comparison of the measured OFDR curves with an adequate gain model is confirming the difficulty in reproducing the exact gain distribution for a specific situation due to a lack of accuracy in the model input parameters. This clearly points out the importance of being able to accurately measure gain distributions in a rapid and nondestructive way.

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