The Er^{3+}-Fiber Gain Coefficient Derived from a Dynamic Gain Tilt Technique

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***Abstract*—We describe a new method to determine the Er^{3+}-fiber gain coefficient using a dynamic gain tilt technique. The method is based on attenuation measurement, gain measurements and crossover optimization of dynamic gain tilt. Results demonstrate that this method is very simple, highly accurate and especially useful for extended band erbium doped fiber amplifiers (EDFA's) design.**

***Index Terms*—Fiber measurement, optical amplifier.**

I. Introduction

THE absorption and gain coefficient play an important role in characterising the active properties of erbium-doped fibers. Accurate measurement of these data sets are required to predict the behavior of an erbium-doped fiber amplifier (EDFA) combined with a detailed and reliable numerical model [1]. This allows a more accurate EDFA design in conventional and extended band amplifier.

The physical parameters required to model and solve the nonlinear propagation equation are the absorption coefficient, the gain coefficient, the background loss and the saturation parameters.

The absorption coefficient and background loss can be determined accurately by attenuation measurement using a cutback technique and selecting different lengths to reduce the measurement errors.

The gain coefficient is more difficult to measure with the same accuracy even if different cut back techniques in the regime of full and uniform medium inversion have been proposed [2].

The saturation parameter can be derived from spectroscopy measurements or from saturation power measurements [3], [4].

Here, we present a new simple way to determine the E^{3+}fiber gain coefficient from a dynamic gain tilt (DGT) technique. The technique is based on accurate absorption and gain spectra measurement. These measurements allow to calculate the DGT from which we derive the gain coefficient. Results show that this method is very simple and highly accurate. The method is applicable to the conventional band but it is particularly useful for the extended band [5] where the gain coefficients are extremely low and very measurement sensitive. The method relies on the fiber and amplifier measurement including the deviation caused by signal excited state absorption (ESA), that isn't negligible beyond 1600 nm [6].

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The paper is organized as following. Section II focus on the input parameters required for the numerical modeling. Section III presents accurate attenuation measurements. Section IV focus on the current gain coefficient technique. Sections V and VI are related to the DGT definition and operative DGT definition. Before the conclusion, in Section VIII, Section VII reports the results of the modeling and experiment correlation.

II. Numerical Modeling

An accurate EDFA model provides useful length prediction of amplifier gain, gain and noise spectra. It uses a sets of nonlinear propagation equations to compute the inversion profile of the erbium ions and the evolution of signal, backward and forward amplified spontaneous emission (ASE) and pump wavelengths along the erbium length [1].

Modeling tools that provide useful predictions such as length dependence of an amplifier gain not only require convergence stability of the algorithm implemented (especially in the extended band as long fiber is required), but also accurate input data such as absorption [dB/m] and gain coefficient [dB/m] whose values in the extended band can be small and quite similar.

Accurate measurements are also required for Er^{3+} ions density [ions/m^3], doping radius of the Er-fiber [μm], spontaneous lifetime of the upper level [ms] and saturation power [m^{-1} s^{-1}].

Inaccuracy in the experiment and modeling correlation can be due prevalently to the absorption and gain coefficient measurement, saturation power measurement, pump power calibration. The simulation needs to be conform with the measurement technique used (e.g., time domain extinction technique).

III. Attenuation Measurement

The absorption coefficient, $\alpha(\lambda)$, can be determined accurately by attenuation measurement using a cutback technique. An incandescent white light source (-40 dBm) and an optical spectrum analyzer assures a reliable measurement with 0.1 nm resolution, wide dynamic range and high sensitivity.

Good accuracy can also be achieved using a spectral attenuation equipment as it is designed for fiber charaterization.

In case of high erbium concentration more care is needed to filter the cladding modes in order to reduce the power measurement error [2].

The accuracy for the absorption coefficient can be improved using several lengths as reported in Fig. 1, and removing the background loss. The length itself is correlated to the peak of absorption. A very short length for the absorption peak increases the accuracy.

Accuracy should be also taken in the 980 nm pump absorption measurement as the absorption band of erbium is relatively small.

As the accuracy of absorption measurement effects the inaccuracy of the results obtained in modeling, a repeated cutback measurements reduces drastically the experimental and modeling deviation.

IV. Gain Coefficient

The gain coefficient, $g^*(\lambda)$, is more difficult to measure with the same accuracy than the absorption. There are two techniques commonly used. The first technique known as Emission measurement relies on measurements of emission spectra that assume a uniform longitudinal pump power distribution, cross-section independent of radial position and the right choice of fiber lengths [3], [4]. The second technique known as McCumber relation uses theoretical relationships to generate a gain coefficient from absorption coefficients [2]. Both methods produce good spectral shape information, but the limitation in accuracy concerns the relative scaling of $\alpha(\lambda)$ and $g^*(\lambda)$ spectra. To address this scaling problem: the first technique requires fluorescence measurements, while the second technique requires detailed knowledge of Stark level energies and degeneracies. Results of these techniques will be used for comparison. The technique that we propose addresses the scaling problem, optimizing the crossover wavelength using a numerical model. The gain coefficients are derived from measured gain spectrum using a dynamic gain tilt theory.

V. Dynamic Gain Tilt

Typically, the DGT is derived from two measured gain spectra, $g_2(\lambda)$, $g_1(\lambda)$, for the same fiber length at two different signal or pump levels as reported in Fig. 2, using the following relation:

$$\mathrm{DGT}(\lambda) = \frac{\Delta g(\lambda)}{\Delta g(\lambda_0)}$$

where $\Delta g = g_2(\lambda) - g_1(\lambda)$ is the measured gain difference and λ_0 is the reference wavelength for the DGT. It is defined as the ratio of the change in gain at a given wavelength, λ, to the change in gain at a reference wavelength λ_o.

From Fig. 3, 1 dB change in gain at $\lambda_o = 1570$ nm would give XdB change in the gain at any λ and therefore give a DGT of XdB/dB (e.g., 1 dB change in gain at $\lambda_o = 1570$ nm with more pump/signal power would give 1.9 dB change in the gain at $\lambda = 1550$ nm and therefore give a DGT of 1.9 dB/dB).

VI. DGT Theory

The DGT can be also defined as a function of the absorption and emission coefficients

$$\mathrm{DGT}(\lambda) = \frac{\alpha(\lambda) + g^*(\lambda)}{\alpha(\lambda_0) + g^*(\lambda_0)} \quad (1)$$

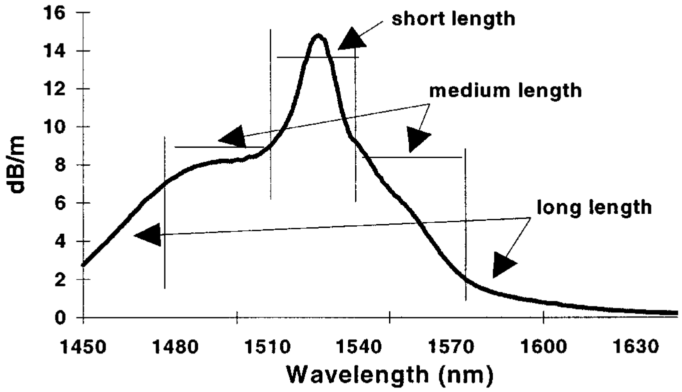

Fig. 1. Attenuation measurement.

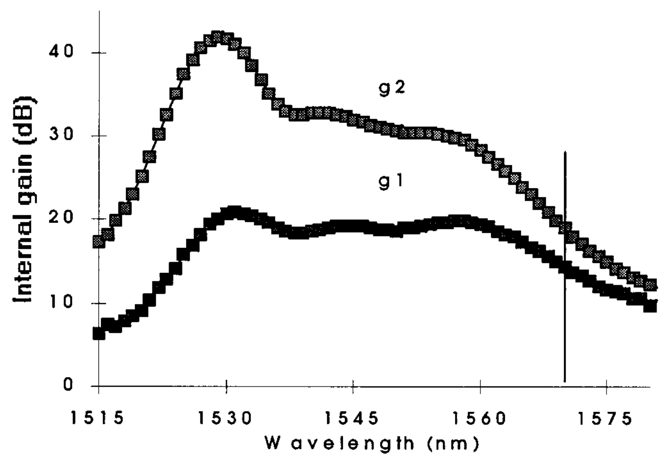

Fig. 2. Gain spectra measurement.

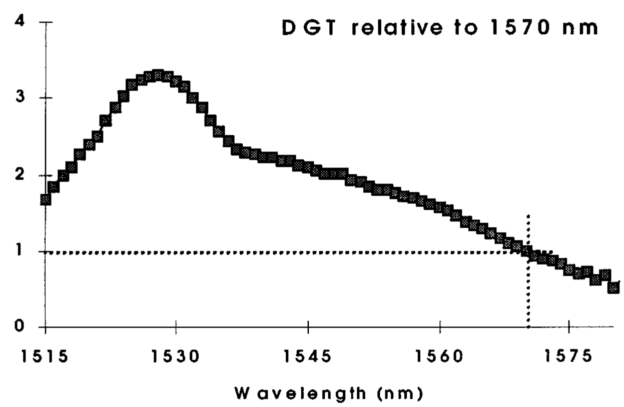

Fig. 3. Dynamic gain tilt relative to 1570 nm.

where $\alpha(\lambda)$, $g*(\lambda)$ are the absorption and gain coefficients and, λ_0 is the DGT reference wavelength. A similar correlation can be drawn in terms of absorption and emission cross-section.

The gain coefficient can be determined by manipulating the previous relation (1):

$$g^*(\lambda) = \mathrm{DGT}(\lambda)[\alpha(\lambda_0) + g^*(\lambda_0)] - \alpha(\lambda)$$

leading to

$$g^*(\lambda) = 2\frac{\mathrm{DGT}(\lambda)}{\mathrm{DGT}(\lambda_{xo})}\alpha(\lambda_{xo}) - \alpha(\lambda)$$

where DGT(λxo) denotes the DGT at the crossover wavelength, λxo, where the gain coefficient has the same value as the absorption coefficient

$$\alpha(\lambda_{xo}) + g^*(\lambda_{xo}) = 2\alpha(\lambda_{xo}).$$

An optimized value of λxo is obtained by iterating the EDFA spectral model until the gain matches with one of the previous measurements.

The relation (1) has been tested using measured DGT, $\alpha(\lambda)$, and $g^*(\lambda)$ as shown in Fig. 4. The agreement between the emission data and the measured DGT is highly accurate with a maximum absolute difference of only 3%–4% using two different erbium fiber, with high and low erbium dopant.

The crossover wavelength is typically within the range 1520–1527 nm and does not depend on the cutoff wavelength. Fig. 5 indicates that the crossover wavelength changes the gain shape and gives high inaccuracy with the measured gain data.

An optimized technique needs accurate gain measurements, DGT calculation and crossover wavelength optimization.

The pump mediated in-homogeneity for the gain spectrum measurements is negligible in the extended band region but needs to be considered and filtered out in the conventional-band [7].

VII. Results

The previous technique has been applied to a fiber with the following physical properties: mode field radius 3.11 μm @ 1550 nm-1.77 μm @ 980 nm, refractive index variation $\Delta n = 0.024$, cut-off wavelength 924 nm, composition $Er^{3+} Al_2O_3$, an absorption peak of 14.7 dBm @ 1529 nm.

The consistency of the DGT theory has been verified using measured and calculated data. The DGT spectrum deduced from McCumber relations differs significantly at the spectrum peak as reported in Fig. 4. In Fig. 6, it is shown the measured absorption with the emission coefficient spectrum generated from DGT. The emission coefficient spectra measured directly and calculated using McCumber relation are also shown for comparison.

Measured and simulated gain spectra for conventional band, using short fiber length, are shown in Fig. 7. The McCumber generated data overestimate the EDFA gain, while the DGT generated data gives the best estimate on the EDFA gain and the measured emission coefficient underestimates the gain.

The DGT gives also the smallest deviation in terms of noise figure compared to the previous methods as reported in Table I. In general within ± 0.5 dB the noise figure is very well predicted.

For extended EDFA's, the direct measurement of the gain coefficient is difficult due to the small value of the gain coefficient. The accuracy cannot be increased by using a longer length of EDF as a high inversion cannot be obtained along the full length. The DGT technique is therefore especially useful for obtaining data for long wavelength including ESA that is dominant beyond 1625 nm.

In Fig. 8, a summary is reported of the method presented in this paper.

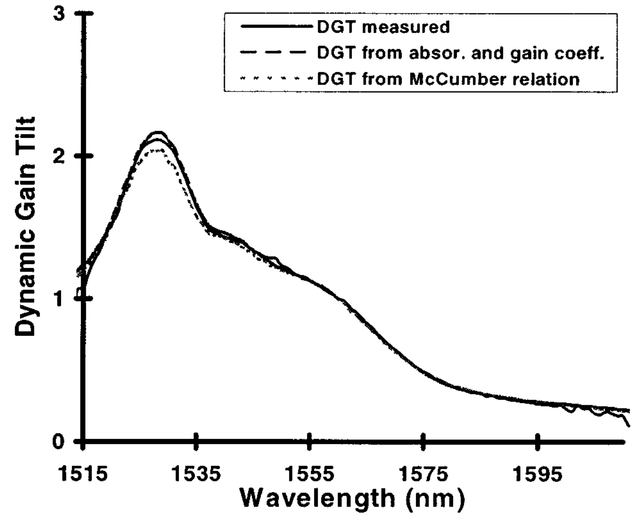

Fig. 4. Dynamic gain tilt spectra.

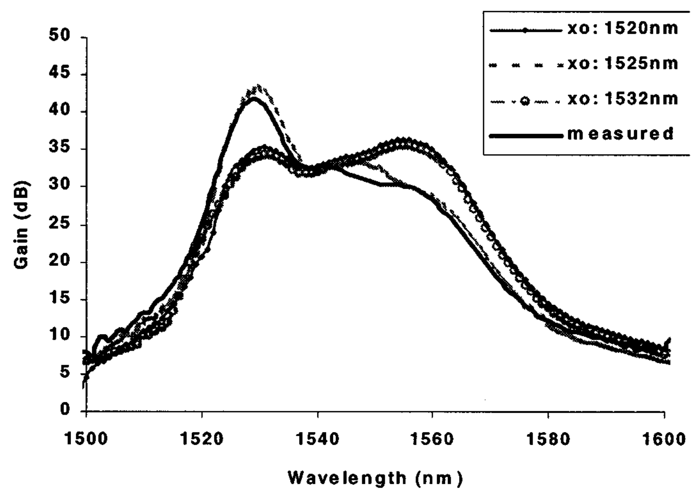

Fig. 5. Gain spectra depending on crossover wavelength.

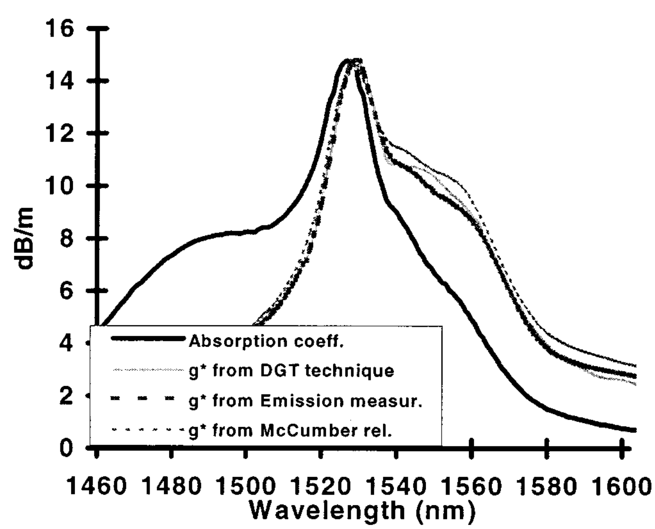

Fig. 6. Absorption and emission coefficient spectra.

VIII. Conclusion

The work has shown that Er^{3+}-fiber gain coefficient can be determined easily from dynamic gain tilt technique. The

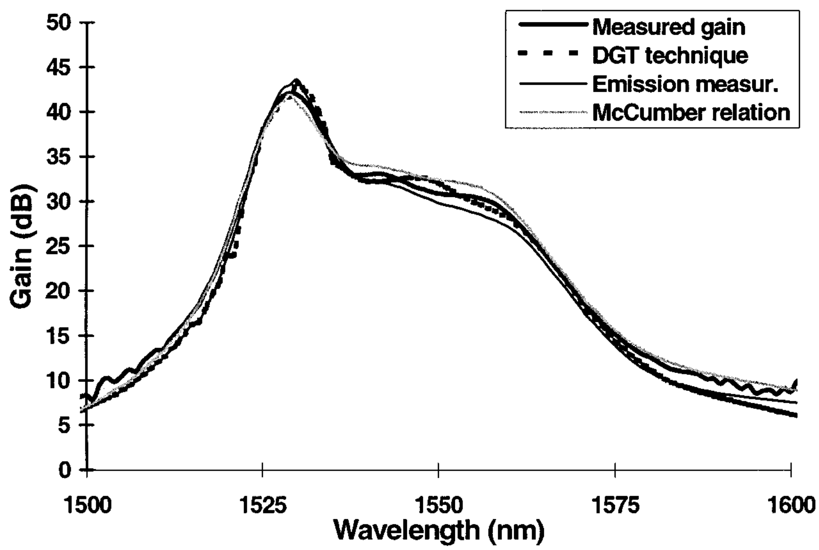

Fig. 7. Spectral gain in the conventional band.

TABLE I
NOISE FIGURE COMPARISON AT 1550 nm

	Simulation Results				Deviation from measurements		
	McCumber	Emission	DGT technique	Measured	McCumber	Emission	DGT technique
Gain (dB)	32.45	29.84	31.95	30.91	1.54	-1.07	1.04
Noise Figure (dB)	5.74	5.84	5.65	5.27	0.47	0.57	0.38

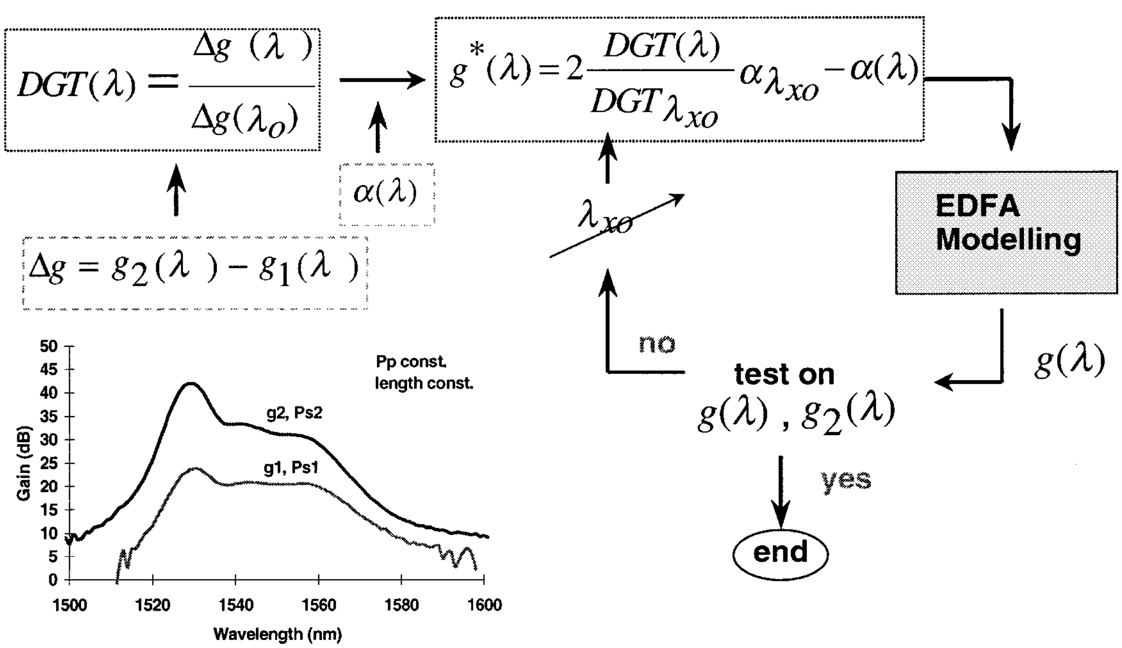

Fig. 8. Flow chart of the method used starting from the bottom left corner going around to the right corner. 1) Gain measurement at constant power due to the wiggle effects in C-band, 2) DGT calculation—using the attenuation measurement and estimated crossover wavelength a first estimation of gain coefficient is obtained, and 3) the optimum crossover wavelength is obtained by iterating the EDFA spectral model until the gain matches one of the previous measurements.

accuracy is high in comparison to the traditional McCumber and emission measurement. A comparison of theoretical and measured gain gives very good agreement. The method gives good agreement using fiber with high erbium concentration and fiber length. The method can be applied to conventional band EDFA's but is especially useful for long wavelength EDFA's, where accurate measurement of gain coefficient is more difficult.

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