Verification of the Physical Modelling Approach of Spectral Hole Burning in EDFA Based on Erbium Ion Groups

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Abstract: Our previously presented modelling approach for EDFA spectral hole burning has been extended to be valid at various operating points. It is successfully applied for three different input signals with strong local saturation. © 2024 The Author(s)

1. Introduction

For future optical networks a dynamical switching of wavelength channels may be desirable such that changing traffic patterns and energy efficient operation can be accounted for. Precise models for EDFA operating in saturation are therefore useful for a robust design. Especially the transients caused by EDFA operated in the saturation regime, which may increase for cascades of EDFA, can distort the signal. To fully model the transient domain first the stationary models have to be improved. An effect not yet considered in classic rate equation models is the spectral hole burning (SHB) [1] i.e. local inhomogeneous gain changes in the stationary regime due to the presence of a strong saturating signal. SHB is usually observed with the aid of the spectral subtraction technique. The gains of two operating points, which show the same gain at a wavelength far away from the saturating wavelength, are subtracted. The difference spectra form spectral holes surrounding the saturating channel. Empirical approaches to model the characteristics of these holes obtained by difference spectra have been presented [2]. However, the capability to model the inhomogeneous gain saturation due to SHB directly in the gain spectrum as well as independent of the specific operating points used for empirical description would be of great use for the precise prediction of EDFA behavior within optical networks.

Physically, the gain inhomogeneity is caused by an inhomogeneous broadening of the laser line. The broadening characteristics of individual erbium ions within a glass host and the characteristics of the overall ensemble of erbium ions differ. Within the glass host the doped Erbium ions may occupy a finite amount of different sites. Each site type may be characterized by individual emission and absorption cross section spectra. We proposed a modelling approach assuming a small number of groups of erbium ions, which independently contribute to the overall EDFA gain [4], similar to amplifiers with different gain spectra operating in parallel. The ions in each group all occupy the same site type and therefore show the same spectroscopic properties. These properties are cumbersome to characterize as there are uncertainties about the exact co-ordinations and proportional occurrences of the site types. Therefore, we proposed a derivation process of cross sections of possible erbium ion groups, which shows valid predictions for one operating point with strong local saturation [4].

In this contribution we show that it is possible to derive cross sections of individual erbium ion groups, which simultaneously give valid predictions at various wavelengths of a strong saturating channel, and therefore enable the modelling of spectral hole burning. The simulated results are compared to measurements and show good agreement.

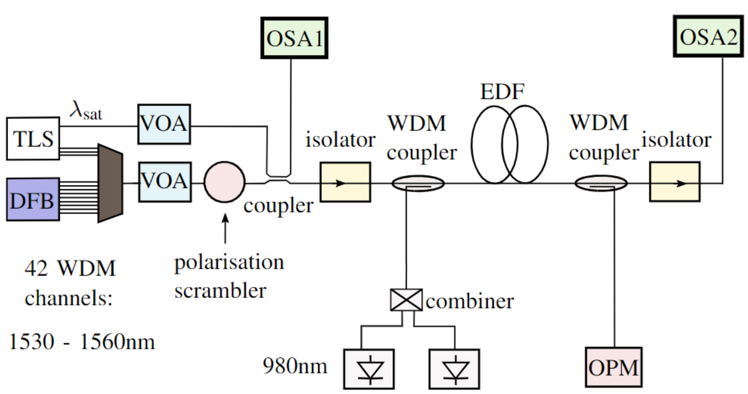


Fig. 1: Set-up for the measurement of gain spectra of a pumped erbium-doped fiber.

2. Measurements

The measurement set-up used for the results presented in this paper is based on the one previously published in [4], which uses a WDM signal comb to measure the EDFA gain shapes. In comparison to the set-up used in [4] we have altered the pump power supply. A pump combiner has been added such that the power of two pump power modules with polarization maintaining PANDA output fibers can be combined.

The input signal consists of a cw WDM signal comb with 42 channels in the 100GHz ITU grid and a channel power of -32 dBm starting from 1527.99 nm up to 1560.61 nm. An averaging over 260 gain measurements with random states of polarization is applied. This is used to mitigate the polarization dependent insertion loss of the components and the influence of polarization dependent gain changes. In order to investigate the inhomogeneous gain saturation, observed as spectral hole burning, operating points with a strong local saturation are chosen. Therefore, a signal with a high input power of about - 4.9 dBm is coupled to the WDM signal. The wavelength λ_{sat} of this saturating signal can be varied.

3. Modelling

The gain contributions of individual erbium ion groups to the EDFA gain are superposed according to the Ansatz presented in [3] and enhanced in [4]. The two-step optimization procedure explained in [4] is employed at various operating points in order to find the emission and absorption cross sections, $\sigma_{e,i}$ and $\sigma_{a,i}$, modelling the spectroscopic behavior of m distinct groups of erbium ions. In the first step, a rough estimate of the overall sums, $\sum_{i=0}^{m} \sigma_{e,i}$ and $\sum_{i=0}^{m} \sigma_{a,i}$, of the emission and absorption cross sections is fitted by an objective function consisting of a sum of Gaussian shaped elements. Those Gaussians are grouped to possible spectra of erbium ion groups and their simulated gains are evaluated with the aid of actual measurement results. In the first step the requirement of decent agreement is constrained to a small wavelength region and a plausible grouping is defined. In the second step the parameters of the grouped Gaussians i.e. the amplitude, center wavelength and the width are optimized for a decent agreement in the entire C-band. In [4] the optimization procedure is performed for a saturating wavelength with $\lambda_{sat} = 1545$ nm and applied for one operating point with $\lambda_{sat} = 1544.1$ nm.

In order to find a physically plausible fit of individual cross sections of the assumed erbium ion groups the derived cross sections should model the inhomogeneous gain behavior at various operating points i.e. different wavelengths of the saturating channel in the entire C-band. Therefore, an enhanced version of the two-step optimization procedure for the derivation of the emission and absorption cross sections of the individual erbium ion groups is proposed. Step 1 is evaluated at all operating points of interest to find a good grouping for a rough global fit. Step 2 is then performed for all operating points of interest and the best overall fit is chosen.

According to the findings of Robinson [5,6], which show evidence of four distinct erbium sites in erbium doped glasses, four erbium ion groups are selected to model the inhomogeneous gain characteristics i.e. m = 4. The Gaussian curve fitting of $\sum_{i=0}^{m} \sigma_{e,i}$ and $\sum_{i=0}^{m} \sigma_{a,i}$, from which the individual spectra are grouped, is performed with 24 Gaussian shaped elements. In Fig. 2 the four absorption (a) and emission (b) cross section spectra found are presented.

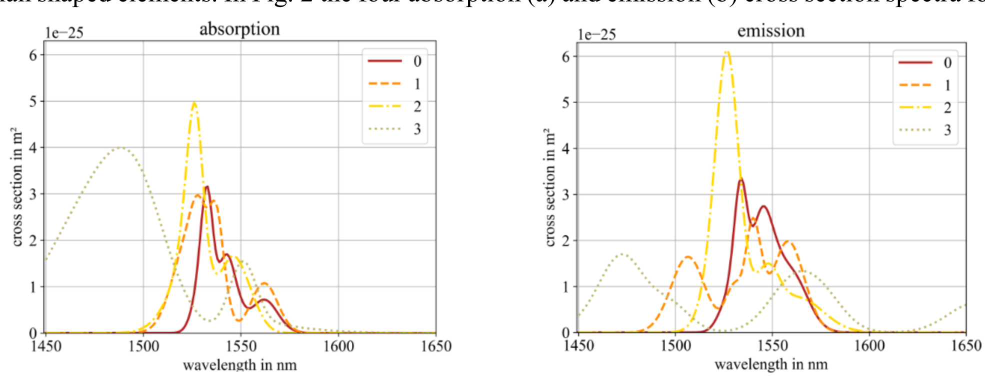


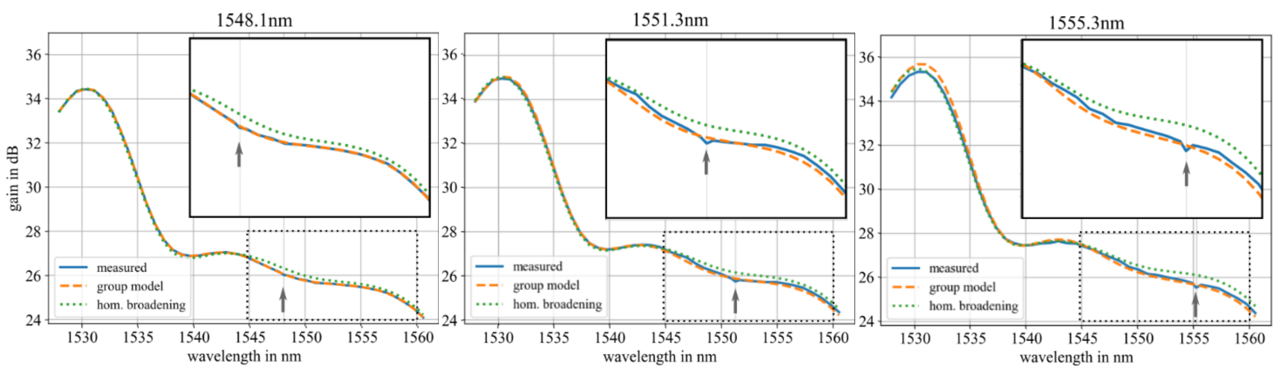
Fig. 2: Optimized absorption (a) and emission (b) cross sections, $\sigma_{a,i}$ and $\sigma_{e,i}$, for the erbium ion group model Ansatz according to [5] assuming m = 4 erbium ion groups and 24 Gaussian shaped elements fitting $\sum_{i=0}^{4} \sigma_{e,i}$ and $\sum_{i=0}^{4} \sigma_{a,i}$.

4. Results

Fig. 3 represents the final results obtained for the erbium ion group modelling approach (--) with the derived cross sections after step 2 presented in Fig. 2 and a simulated pump power of about 440 mW. The results are evaluated for three operating points in the upper C-band and compared to measured gain spectra (-). The operating points have a saturating channel at $\lambda_{sat} = 1548.1$ nm (a), $\lambda_{sat} = 1551.3$ nm (b), and $\lambda_{sat} = 1555.3$ nm (c), respectively. The saturating channels of the operating points are placed in the middle of two surrounding ITU WDM channels. In the upper C- band the operating points with saturating wavelengths close to each other often show similar gain shapes. Therefore, operating points, which show significant differences in the gain shapes, have been chosen.

The model with homogeneous gain characteristics (..) in the saturated regime has been scaled to best fit the measured gain shapes by adjusting the simulated pump power. For each operating point its results clearly show a derivation of up to about 0.5 dB in the wavelength region surrounding each saturating channel. This is in the range of the inhomogeneity expected by spectral hole burning for a single EDFA. As expected this observation shows that the common EDFA rate equation model with a homogeneous broadening characteristic does not represent the inhomogeneous gain characteristics due to an inhomogeneous line broadening behavior.

On the other hand the results of the presented group model approach (--) do follow the inhomogeneous spectral gain shape especially in the region of the saturating wavelength channel for all operating points presented. Therefore, it can be concluded that it is possible to find cross sections modelling erbium ion groups, which account for individual contributions to the gain spectrum and thereby enabling SHB modelling. For a saturating wavelength of $\lambda_{sat} = 1555.3$ nm the simulated results show derivations from the measurements in the lower wavelengths region surrounding the gain peak at about 1530 nm. These derivations have to be subject of further investigations. Slight adjustments of the derived cross sections will be necessary in order to reduce this derivation. Besides, further operating points should be investigated. The emission and absorption cross sections, $\sigma_{a,i}$ and $\sigma_{e,i}$, would then account for the SHB characteristics of the investigated type of erbium-doped fiber. Although SHB might be considered to have a small influence on gain spectra of a single EDFA it can significantly deteriorate the gain shape predictions of EDFA cascades.



(a) (b) (c)

Fig. 3: Gain spectra for signal loads with a saturating channel with $\lambda_{sat} =$ 1548.1nm (a), $\lambda_{sat} =$ 1551.3nm (b) and $\lambda_{sat} =$ 1555.3nm (c). The measured gain spectra (-), the simulated and adjusted gains of the reference model with homogeneous broadening characteristics (..) and the simulated gain spectra considering inhomogeneous broadening characteristics by employing the erbium ion group Ansatz (--) are presented.

5. Conclusions

We have extended a previously presented EDFA model accounting for the inhomogeneous gain changes due to a strong locally saturating channel. The enhanced model is able to accurately simulate the gain inhomogeneity surrounding the strong saturating signal for operating points with saturating wavelengths of 1548.1 nm, 1551.3 nm and 1555.3 nm. This verifies our previously presented modelling approach since it shows that one set of individual cross sections can be found to account for different gain contributions of erbium ion groups i.e. spectral hole burning.

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6. References

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