Modeling of Yb3+-sensitized Er3+-doped silica waveguide amplifiers

Lester, Christian; Bjarklev, Anders Overgaard; Rasmussen, Thomas; Dinesen, Palle Geltzer

Published in:
Journal of Lightwave Technology

Link to article, DOI:
10.1109/50.387791

Publication date:
1995

Document Version
Publisher's PDF, also known as Version of record

Modeling of Yb^{3+}-Sensitized Er^{3+}-Doped Silica Waveguide Amplifiers

Christian Lester, Anders Bjarklev, Thomas Rasmussen, and Palle Geltzer Dinesen

***Abstract*— A model for Yb^{3+} sensitized Er^{3+}-doped silica waveguide amplifiers is described and numerically investigated in the small-signal regime. The amplified spontaneous emission in the ytterbium-band and the quenching process between excited erbium ions are included in the model. For pump wavelengths between 860 and 995 nm, the amplified spontaneous emission in the ytterbium-band is found to reduce both the gain and the optimum length of the amplifier significantly. The achievable gain of the Yb^{3+}-sensitized amplifier is found to be higher than in an Er^{3+}-doped silica waveguide without Yb^{3+} (18 dB versus 9 dB for a pump power of 100 mW). However, it is important to optimize the Yb-concentration according to the choice of pump wavelength.**

I. Introduction

SHORT amplifiers are currently attracting increased interest, especially for use in integrated optics. To make short high gain erbium-doped waveguide amplifiers (EDWA's), it is necessary to use high Er-concentrations, which involves interaction between neighboring erbium ions and result in a quenching process. The quenching process reduces the pump efficiency, and a full inversion cannot be reached [1]. To minimize quenching in the amplifier, the EDWA can be Yb^{3+}-sensitized. The Yb^{3+}-ions then absorbs most of the pump power, and cross relaxation between adjacent Er^{3+} and Yb^{3+}-ions allows the absorbed energy to be transferred to the erbium system [2]. This will result in a higher gain because more pump power can be absorbed and an improved inversion is obtained. The sensitization of erbium-doped fibers with ytterbium is also a well-established technique for increasing the choice of pump wavelength to range from 800 to 1100 nm [3]. We introduce a model for an Yb^{3+}-sensitized EDWA that includes the amplified spontaneous emission (ASE) in the ytterbium-band, and also takes the dissipative ion–ion interaction into account. We show the results of an analysis of an Yb^{3+}-sensitized EDWA, using the general model applied in the small-signal regime (signal input power less than −30 dBm). The influence of the ytterbium ASE on the small-signal gain and the optimum length of the waveguide as a function of the pump wavelength is demonstrated. Furthermore, we show how the optimum Yb-concentration depends on the choice of pump wavelength, and compare the results to measurements and calculations on an EDWA.

Manuscript received February 28, 1994; revised July 26, 1994. This work was supported by the Danish Technical Research Council and by the National Agency of Industry and Trade, Denmark.

The authors are with the Center for Broadband Telecommunications, Electromagnetics Institute, Technical University of Denmark, DK-2800 Lyngby, Denmark.

IEEE Log Number 9411013.

II. Model

The basic amplifier model for the EDWA is described in [1] and [4], where the model in [4] is developed for the description of light propagation in optical fibers, and has been changed in [1] to account for an EDWA. The destinctions for the planar waveguide are the rectangular core and the influence of the background loss, which is several decades larger than for fibers. The circular symmetric LP_{01} mode description used for fibers has been replaced with the fundamental E_{11}^{y} or E_{11}^{x} modes, calculated by an accurate optimized effective index method [5]. This method is a variational method, where the trial function is the product of two slab waveguide solutions, $X(x, n_x)$ and $Y(y, n_y)$, one for the x-dependency and one for the y-dependency. The slab waveguides have core width a, height b and core refractive indexes n_x and n_y, respectively. n_x and n_y is chosen so the integral

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} XY\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+n^2(x,y)k^2\right]XY\,dxdy \quad (1)$$

is maximum. By doping the EDWA with ytterbium, the pump light is mainly absorbed by the Yb^{3+}-ions. A energy diagram of the Er/Yb-doped system is shown in Fig. 1. Excited Yb^{3+}-ions transfer energy to neighbouring Er^{3+}-ions, whereby the Er^{3+} becomes excited, this is shown in the dashed square of Fig. 1. The decay from the metastable level in Er^{3+} is much faster than the backtransfer to the Yb^{3+} ground state; therefore, the backtransfer is neglected in the modeling. The equation for the inversion in the Yb^{3+}-system X_{Yb} then becomes

$$X_{Yb} = \frac{W_{PA}}{W_{PA}+W_{PE}+1/\tau_{Yb}+k_{tr}N_1^{ER}} \quad (2)$$

where N_1^{Er} is the Er-concentration in the ground state, W_{PA} and W_{PE} are the pump absorption and emission rates, respectively, both including the ASE. τ_{Yb} is the spontaneous emission lifetime for Yb^{3+}, and k_{tr} is the transfer coefficient for the energy transfer from the Yb-system to the Er-system. The transfer coefficient is largely independent of the Er-concentration, however, the dependence on the Yb-concentration is more complicated [6], [7]. Furthermore, k_{tr} depends on the host glass, typically values are in the range $2\cdot10^{-22}$ m^3/s to $5\cdot10^{-22}$ m^3/s [6]–[8]. For Yb-concentrations less than $1.0\cdot10^{27}$ m^{-3}, the transfer coefficient drops with the concentration, and for concentrations larger than $1.0\cdot10^{27}$ m^{-3}, k_{tr} is assumed constant, until crystallization sets in at $3.0\cdot10^{27}$ m^{-3} [6]. Because little information about the transfer coefficient between ytterbium and erbium

0733–8724/95$04.00 © 1995 IEEE

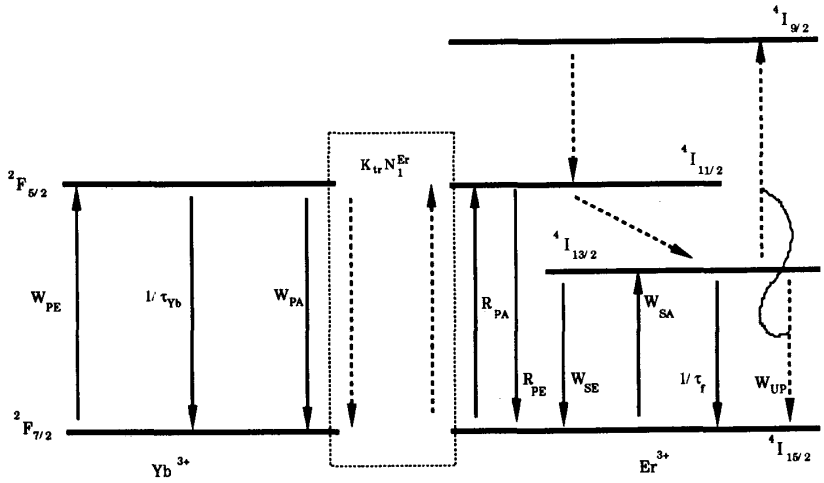

Fig. 1. Erbium-ytterbium energy level diagram. The dashed arrows corresponds to nonradiative transitions.

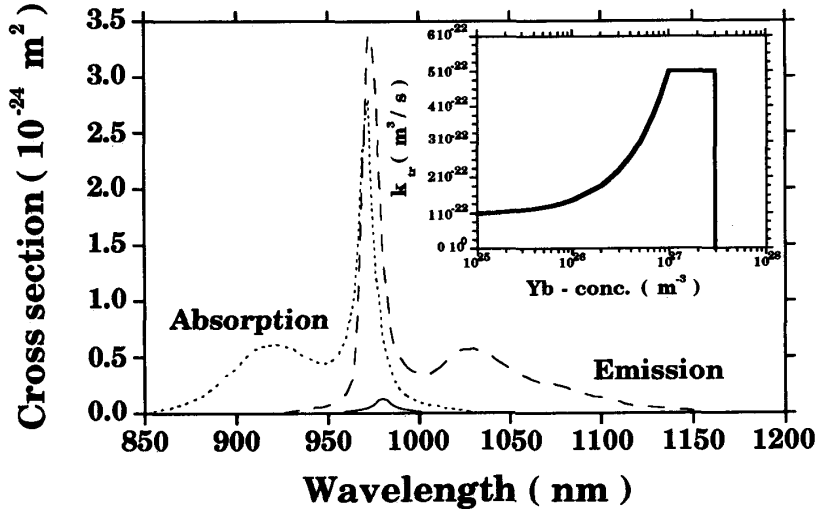

Fig. 2. Emission and absorption cross spectra for ytterbium in silica (dashed lines) and the absorption cross section for erbium in P-doped silica as a function of pump wavelength (solid line). The inset figure shows the transfer coefficient between ytterbium and erbium as a function of the Yb-concentration.

is available for Er/Yb-doped glasses, k_{tr} is kept constant at $5 \cdot 10^{-22}$ m^3/s for Yb-concentrations between $1.0 \cdot 10^{27}$ m^{-3} and $3.0 \cdot 10^{27}$ m^{-3}. For Yb-concentrations decreasing from $1.0 \cdot 10^{27}$ m^{-3} to $1.0 \cdot 10^{25}$ m^{-3}, the transfer coefficient k_{tr} is assumed to drop linearly from $5 \cdot 10^{-22}$ m^3/s to $1 \cdot 10^{-22}$ m^3/s, as shown in the inset of Fig. 2.

Because of quenching in the waveguide, described by the ratio W_{UP} in Fig. 1, the erbium inversion X_{Er} can be determined from a cubic equation [1]. By modifying this equation to account also for Yb^{3+}-sensitized EDWA's, the following equation is derived:

$$X_{Er}^3 + \{[R_{PA} + k_{tr}N_2^{Yb} + W_{SA} + R_{PE} + W_{SE}]\tau_0 + 1\} * \left(\frac{Q}{\rho}\right)^2 X_{Er} - [R_{PA} + k_{tr}N_2^{Yb} + W_{SA}]\left(\frac{Q}{\rho}\right)^2 \tau_0 = 0 \quad (3)$$

where N_2^{Yb} is the Yb-concentration in the excited state, R_{PA} and R_{PE} are the pump absorption and emission rates in erbium, respectively; W_{SA} and W_{SE} are the signal absorption and emission rates. Q is the quenching concentration which responds to the Er-concentration where the fluorescence lifetime is $\tau_f = 0.5 \cdot \tau_0$, and τ_0 is the fluorescence lifetime in the limit where the Er-concentration ρ approaches zero. Emission and absorption cross sections are for Er^{3+}- in P-doped silica [1], and for Yb^{3+} in pure silica [9] (Fig. 2 shows the spectra for Yb^{3+} and Er^{3+} around the pump wavelengths between 850 and 1200 nm).

The model takes into account the forward and backward ASE for both the pump and the signal. The ASE for the pump is mainly related to the ytterbium ASE, yielding two times 150 frequency slots from 850–1050 nm. The signal ASE is related to the erbium system, and is also represented by 2 times 150 frequency slots from 1400–1700 nm. The ASE, signal and pump propagation yield 602 coupled differential equations that are solved by numerical integration through the waveguide.

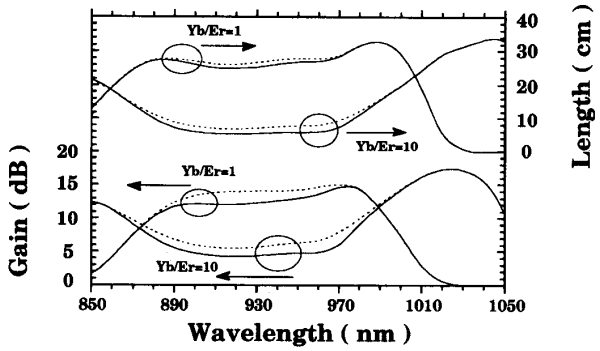

Fig. 3. Gain and optimized length as a function of pump wavelength for an Yb^{3+}-sensitized Er^{3+}-doped waveguide amplifier. The Yb-concentration is either the same as the Er-concentration or 10 times the concentration. The solid lines indicate when the ASE from the pump is included in the calculations, and the dashed lines indicate when the ASE from the pump is not included.

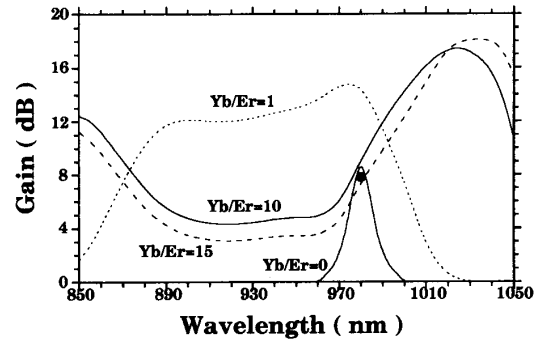

Fig. 4. Gain against pump wavelength for different ratios of the Yb-concentration and the Er-concentration. • is a measured value from [10] for an EDWA.

III. Results

The buried waveguide has a core of $8 \cdot 7\ \mu m^2$ and the Er-concentration is $48.8 \cdot 10^{24}\ m^{-3}$ as for the EDWA that was experimentally examined in [10]. The refractive index difference is 1.2%, the lifetime of the upper laser level in erbium τ_0 and ytterbium τ_{Yb} is 13.7 and 1.5 ms, respectively, the signal wavelength is 1535 nm, and the quenching concentration is $17.0 \cdot 10^{24}\ m^{-3}$ [1]. We assume that the amplifier is pumped from the same end at which the signal enters the waveguide. The absorption and emission cross section at the signal wavelength for erbium is $5.1 * 10^{-25}\ m^2$ and $5.6 * 10^{-25}\ m^2$, respectively. The background loss, which depends on the Er-concentration, is calculated to be 0.16 dB/cm for the signal and 0.2 dB/cm for the pump [1], [10]. The signal power is −40 dBm and the pump power is fixed at 100 mW.

The influence of the ASE in the ytterbium-band on the net gain and the optimum length of the waveguide is examined in Fig. 3 as a function of the pump wavelength. The Yb-concentration is either the same as the Er-concentration or 10 times the concentration. For pump wavelengths larger than 995 nm, the ASE from the ytterbium-band is seen to have no influence on the gain and the optimum length of the amplifier. This is due to the ratio between the absorption and emission cross section for ytterbium; when this ratio is substantially less than unity, the buildup of the ASE in the pump band will be suppressed [11]. The difference in gain is less than 0.01 dB and the ASE-power in the pump band is less than 0.2 mW. For pump wavelengths between 865 and 995 nm, the difference in the gain is between 0.6 and 1.8 dB, when the Yb-concentration is 10 times the Er-concentration (the ASE-power is more than 2.0 mW, when the gain is above 10 dB). When the amplification is reduced, the optimum length of the amplifier will decrease. The optimum length of the Yb^{3+}-sensitized EDWA is about 30 cm, when the gain is above 14 dB. A reduction of the Yb-concentration, to the same level as the Er-concentration, leads to a decrease of the ASE-power in the pump band, and thereby reduce the deterioration of the gain.

When changing the Yb-concentration, the gain is also changed (this is shown in Fig. 4) where the Yb-concentration is changed between no ytterbium and an Yb-concentration of 15 times the Er-concentration. The length of the waveguide is optimized with respect to gain. It is seen that the optimum Yb-concentration is changed with the pump wavelength. For pump wavelengths higher than 1.1 μm, the optimum Yb-concentration is approximately between 10 and 15 times the Er-concentration. For pump wavelengths around 980 nm and less, the optimum Yb-concentration is about the same as the Er-concentration. From Figs. 3 and 4, it is observed that the maximum gain for the Yb^{3+}-sensitized EDWA is not achieved at the pump wavelength with the highest absorption cross section (around 975 nm in Fig. 2). At high absorption cross sections and Yb-concentrations above 10 times the Er-concentration, the Yb^{3+} population of the excited ions builds above the population required to obtain the full Er^{3+} inversion, so losing energy to Yb^{3+} fluorescence. When comparing the performance of the Yb^{3+}-sensitized EDWA to the EDWA without Yb^{3+}, Fig. 4 illustrates that by sensitizing the EDWA with ytterbium the gain can be increased from 9–18 dB.

In [10], a measured gain of 7.8 dB for an EDWA, with the same parameters as used in Fig. 4, is reported. However, the length has not been optimized with respect to the gain. Besides the increasing gain, the Yb^{3+}-sensitized EDWA enhances the choice of pump wavelength. By optimizing the Yb-concentration according to the pump wavelength, in the range from 910–1040 nm, the gain can be kept between 15 and 18 dB. Furthermore, the Yb^{3+}-sensitized EDWA optimized according to the Yb-concentration and the length with respect to the gain, has a noise figure of approximately 4 dB, when the gain exceeds approximately 18 dB. For the optimized EDWA shown in Fig. 4, the minimum noise figure is 5.7 dB. The low noise figure for the Yb^{3+}-sensitized EDWA, results from the very high Er^{3+} inversion at the input end of the waveguide.

IV. Conclusion

A comprehensive model for an Yb^{3+}-sensitized erbium-doped waveguide amplifier is presented. The amplified spontaneous emission in the pump band is seen to reduce the amplifier gain, when the pump wavelength is between 860 and

995 nm. Calculation based on actual erbium-doped waveguide parameters shows an increase in the gain of approximately 9 dB, when Yb^{3+}-sensitizing the Er^{3+}-doped waveguide. Furthermore, the dependence between the Yb-concentration and the choice of pump wavelength has been characterized.

ACKNOWLEDGMENT

The authors thank E. Nicolaisen for fruitful discussions.

REFERENCES

[1] O. Lumholt, T. Rasmussen, and A. Bjarklev, "Modelling of Extremely High Concentration Erbium-doped Silica Waveguides," *Electron. Lett.*, vol. 29, no. 5, pp. 495–496, 1993.
[2] W. L. Barnes *et al.*, "Er^{3+}- Yb^{3+}- and Er^{3+}-doped fiber lasers," *J. Lightwave Technol.*, vol. 7, pp. 1461–1465, 1989.
[3] J. D. Minelly *et al.*, "Diode-array pumping of Er^{3+}/Yb^{3+} co-doped fiber lasers and amplifiers," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 310–303, 1993.
[4] B. Pederse *et al.*, "Detailed theoretical and experimental investigation of high-gain erbium-doped fiber amplifier," *IEEE Photon. Technol. Lett.*, vol. 2, pp. 863–865, 1990.
[5] T. Rasmussen *et al.*, "Detailed comparison of two approximate methods for the solution of the scalar wave equation for a rectangular optical waveguide," *J. Lightwave Technol.*, vol. 11, pp. 429–433, 1993.
[6] V. P. Gapontsev and N. S. Platonov, "Migration-accelerated quenching in glasses activated by rare-earth ions," in *Dynamical Processes in Disordered Systems*,W. M. Yen, Ed. Switzerland: Aedermannsdorf, 1989.
[7] V. P. Gapontsev *et al.*, "Erbium glass lasers and their applications," *Opt. Laser Technol.*, pp. 189–196, 1982.
[8] X. Zuelu and T. Izumitani, "Excitation energy transfer of Nd^{3+}–Yb^{3+}–Er^{3+} in several glasses," *Ceramic Soc. Japan*, vol. 101, no. 1, pp. 84–88, 1993.
[9] J. Nilson, P. Scheer, and B. Jaskorzynska, "Modelling and optimisation of short Yb^{3+}-sensitized Er^{3+}-doped fiber amplifiers," submitted to *IEEE Photon. Technol. Lett.*, Sept. 1993.
[10] T. Kitagawa *et al.*, "Amplification in erbium-doped silica-based planar lightwave circuits," in *Opt. Amplifiers Appl. Tech. Dig.*, Santa Fe, NM, 1992, paper PD-1.
[11] P. R. Morkel, "Modelling erbium/ytterbium-doped fibre amplifiers," in *Opt. Amplifiers Appl. Tech. Dig.*, OSA, Washington, DC, 1992, vol. 17, pp. 206–209.

Christian Lester was born in Copenhagen, Denmark, on March 13, 1967. He received the M.Sc. degree in electrical engineering in 1993 from the Electromagnetics Institute, Technical University of Denmark.

He is presently working at the Center for Broadband Telecommunications, Electromagnetics Institute on active optical waveguides.

Anders Bjarklev was born in Roskilde, Denmark, on July 2, 1961. He received the M.Sc. degree in electrical engineering from the Electromagnetics Institute, Technical University of Denmark, in 1985, and the Ph.D. degree from the Technical University of Denmark, in 1988.

His research interests are primarily within the field of characterization of active and passive optical waveguides. Presently he is employed as associate professor at the Electromagnetics Institute, Technical University of Denmark. In 1993 he authored a book entitled *Optical Amplifiers: Design and System Applications.*

Thomas Rasmussen was born in Copenhagen, Denmark, on November 3, 1965. He received the M.Sc. degree in electrical engineering from the Electromagnetics Institute, Technical University of Denmark, in 1991.

He is presently working at the Center for Broadband Telecommunications, Electromagnetics Institute, on integrated optics.

Palle Geltzer Dinesen, photograph and biography not available at the time of publication.