Journal of Optoelectronics and Advanced Materials Vol. 6, No. 4, December 2004, p. 1207 - 1212

THE DETERMINATION OF THE SATURATION POWER FOR ERBIUM DOPED FIBER AMPLIFIER

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Here is presented a method for determination of the saturation power from the EDFA (Erbium Doped Fiber Amplifier). This method uses the analytical expressions in different approximations to obtain the saturation power of the EDFA. We have obtained the saturation power of EDFA by varying the wavelength in the interval $\lambda \in [1.45 \div 1.64]$ μm. Also, we have calculated the absorption and emission cross-sections for optical fiber with the germano-aluminosilicate. For these values we obtain the saturation power P_{sat} in the following interval $P_{sat} \in [0.1 \div 5]$ mW and the overlap-inversion factor Γ in the following interval $\Gamma \in [0.1 \div 0.8]$. Using these results we can optimize the EDFA performances and increase the capacity and distance for transmission in the optical networks.

(Received October 21, 2004; accepted after revision November 29, 2004)

Keywords: EDFA, Saturation power, Absorption and emission cross section, Overlap-inversion factor

1. Introduction

The EDFA is used in the optical transmission systems because it have the maximum gain and low pump power and its performances are better in comparison with other similar amplifiers. In the DWDM (Dense Wavelength Division Multiplexing) networks are used the EDFA to increase the distances and the capacity for transmission [1] and [2]. These parameters can be increased when we have determined the EDFA characteristics. One of these EDFA's characteristics is the saturation power [3]. The saturation power is used to optimize the EDFA's characteristics in the DWDM networks [4-6]. The saturation power for EDFA depends on the wavelength, mode area, and the overlap-inversion factor. Also, the saturation power depends on the absorption and emission cross-section.

The absorption and emission spectra for Er^{3+} can be obtained experimentally or theoretically using different approximation methods for the energy states [3]. These spectra are used to calculate different EDFA's parameters. The peak values from the cross-section spectra and the lifetime for transition $^4I_{13/2} \rightarrow {}^4I_{15/2}$ of Er^{3+} ions can affect the EDFA performance [7] and [8]. In the doped optical fiber these energy states are modified by the local electric field. Other doped elements for optical fibers can increase or decrease the variations from the electric field. This local electric field determinates the Stark splitting effect and gives the dynamic perturbations and homogeneous broadening. The charge distribution in the host glass generates a permanent electrical field, which induces the Stark effect with splitting of the energy levels.

2. Theoretical background

The absorption and emission cross-section for EDFA depends on the nature of the doped elements from the optical fiber core. Also, the absorption and emission cross-sections were obtained

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for Er^{3+}-doped optical fiber [3]. With these absorption and emission cross-sections we can get the loss spectra $\alpha(\lambda)$ and the gain spectra $g^*(\lambda)$ [3], [9] and [10]:

$$\alpha(\lambda) = \sigma_a(\lambda)\Gamma(\lambda)\rho_0 \tag{1}$$

$$g^*(\lambda) = \sigma_e(\lambda)\Gamma(\lambda)\rho_0 \tag{2}$$

where: λ is the wavelength, $\Gamma(\lambda)$ is the overlap-inversion factor or average of population inversion changed across the doped core, ρ_0 is the Er^{3+} ion density, $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ are absorption and emission cross-sections [3].

The absorption coefficient for the pump and the gain coefficient for the signal are wavelength dependent [9], [10] and [11]. For the characterization of the Er^{3+}-doped optical fiber, we need an accurate measured value for $\sigma_a(\lambda)$ and for $\sigma_e(\lambda)$ [3]. For this reason, we need to obtain a good precision at the measuring of these values. Also, for the bulk material, we can use different experimental methods to obtain the spectra and the values for ρ_0. For different approximations, it is used for Γ the unit value, $\Gamma = 1$ and we can obtain $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$. But this method is not used in the case of optical fibers when ρ_0 have a radius variation and when Γ have an integral form which is difficult to be determined.

This problem is solved by the Landenburg-Fuchbauer equation (LF) and with this equation we can calculate the peak values for cross-sections through integration over entire spectra. The expression of the Landenburg-Fuchbauer equation is the following (see [3] and [12]):

$$\sigma_{a,e}(\lambda) = \frac{\lambda^4_{av,ev} I_{a,e}(\lambda)}{8\pi c n^2 \tau \int I_{a,e}(\lambda) d\lambda} \tag{3}$$

where: $\lambda_{av,\,ev}$ are wavelengths for peak values in the case of the absorption and the emission, τ is the lifetime of the metastable level, n is the refractive index of the optical fiber, c is the speed of light in vacuum, $I_{a,\,e}$ are absorption and emission spectra.

So, with the Landenburg-Fuchbauer equation we can determine the absorption and emission cross-section, but this determination has not a good precision.

For a better precision we must measure the loss spectra $\alpha(\lambda)$ and the gain spectra $g^*(\lambda)$. During the determination of the absorption and emission spectra it is not possible to establish the contributions of the linewidth for the homogeneous and the inhomogeneous broadening. This fact it is important because, it can have a significant role for pumping and for the saturation from the optical amplifier. A part of the Er^{3+} ions can exhibit low values for the absorption and emission cross-section at the pumping wavelength. Also, the total population inversion requires a high pumping power.

3. The determination of the saturation power for EDFA

For this method we used the analytical expressions for the saturation powers in different approximations. Today exist different approximate methods for the determination of the saturation power, but these methods are not discussed here.

Using the absorption and emission cross-section together with the parameter of the doped fiber optical, like laser ion density ρ_0, numerical aperture NA and core radius, we can calculate the saturation power $P_{sat}(\lambda)$ for EDFA.

In the followings, using the Eq. (3), we have obtained, with a good precision, the absorption and emission cross-section for germano-aluminosilicate, as is showed in Fig. 1 [3,12]. Using the Eq. (1), we can calculate the saturation power $P_{sat}(\lambda)$ as a function of the wavelength, mode area, lifetime of the metastable level and the overlap-inversion factor or average of population inversion changed across the doped core.

The saturation power has the following expression for the signal or for pumping [3]:

$$P_{sat}(\lambda) = \frac{h\nu A}{[\sigma_a(\lambda) + \sigma_e(\lambda)]\Gamma(\lambda)\tau} \tag{4}$$

where: h is the Planck constant, ν is the frequency for the signal or for pumping, λ is the wavelength for the signal or for pumping, A is the mode area and τ is the lifetime of the metastable level.

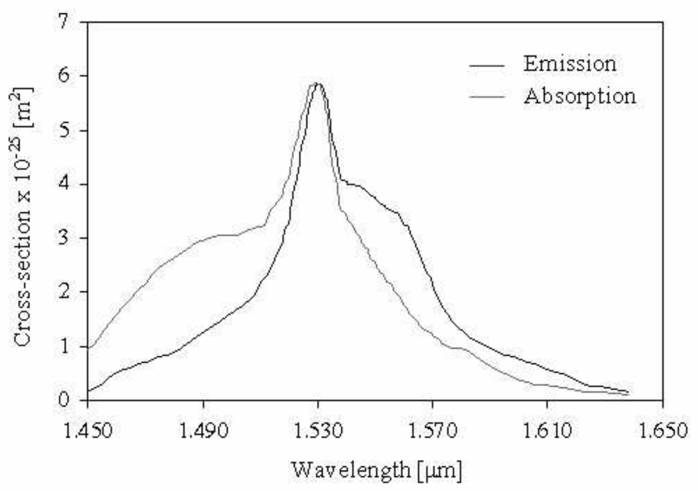

Fig. 1. The absorption and emission cross-section $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ as a function of the wavelength.

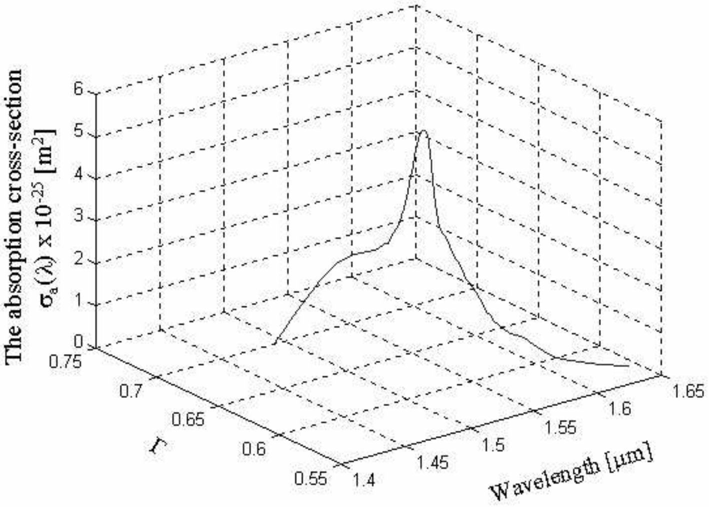

Fig. 2. The absorption cross-section $\sigma_a(\lambda)$ as a function of the wavelength λ and the average of population inversion changed across the doped core.

We calculated the saturation power using the Eq. (4) with the wavelength in the following interval $\lambda \in [1450 \div 1640]$ nm.

The overlap-inversion factor Γ or average of population inversion changed across the doped core takes values between -1 and 1. In the case of uniform doped optical fiber with the radius r for core and for a pumping with high value, the overlap-inversion factor has maximal value [13].

So, we have in this case Γ = 1 for ρ(r) = ρ_0 = constant. In practice, Γ < 1 for a high pumping. Also, it is possible to obtain the maximal inversion and the overlap between the laser and the signal mode. In the case of the uniform doped optical fiber and with the pumping off, we have a minimal value for Γ, Γ = -1. In the following we take some assumptions. Firstly, we vary the value of the Γ parameter between 0.65727 and 0.56460, which corresponds for the wavelengths between 1450 nm and 1640 nm. So, with the absorption and emission cross-section from Fig. 1, we can calculate the saturation power with the Eq. (4), as shown in Figs. 4, 5 and 6.

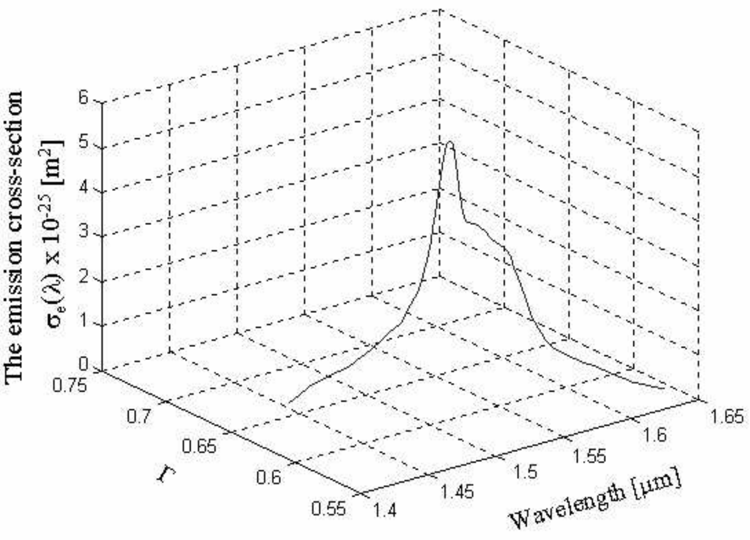

Fig. 3. The emission cross-section $\sigma_e(\lambda)$ as function of the wavelength λ and the average of population inversion changed across the doped core.

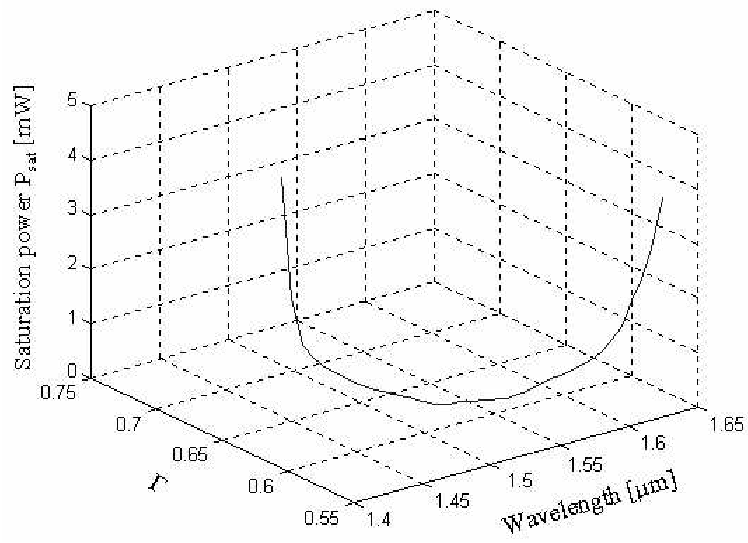

Fig. 4. The saturation power P_{sat} as function of the wavelength λ and the average of population inversion changed across the doped core.

The absorption and emission cross-section $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ are calculated with Eq. (3) [3]. For the lifetime of the metastable level we choose the value $\tau = 10$ ms, which is an average value of Er-doped fibers. Also, for the Er^{3+}-doped core radius we choose the constant value, $r = 1.2$ μm [3].

Also, in the following we suppose a uniform distribution, ρ_0 = constant in the case of doped optical fiber.

In the Fig. 2 and 3, are graphical showed the absorption and emission cross-section $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ as a function of the wavelength λ and the average of population inversion changed across the doped core.

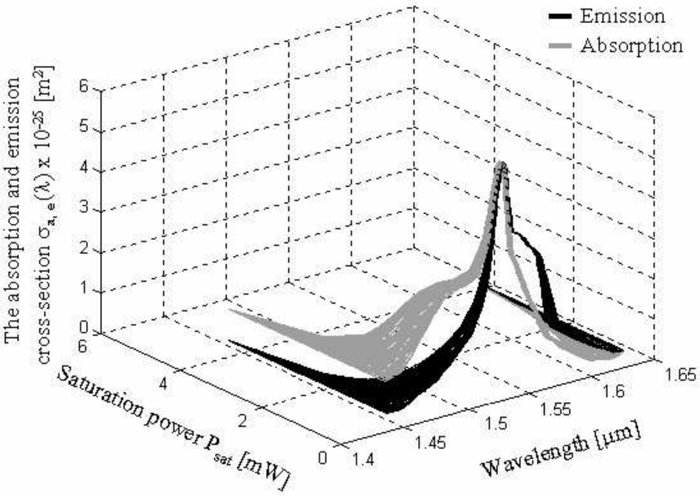

Fig. 5. The saturation power P_{sat} as a function of the wavelength λ, the absorption and emission cross-section $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$.

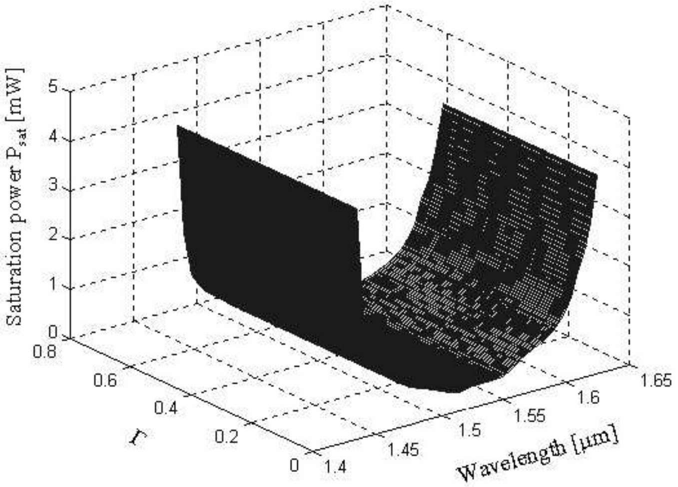

Fig. 6. The saturation power P_{sat} as a function of the wavelength λ and the average of population inversion changed across the doped core.

In the Fig. 4, it is graphically shown the saturation power P_{sat} as a function of the wavelength λ and the average of population inversion changed across the doped core for a constant value of the quantity $hcA/\tau = 0.8687124 \times 10^{-9}$. With the Eq. (4), we calculated the saturation power P_{sat}.

In the Fig. 5, it is graphically shown the saturation power P_{sat} as a function of the wavelength λ, the absorption and emission cross-section $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$.

Also, in the Fig. 6, it is graphical showed the saturation power P_{sat} as function of the wavelength λ and the average of population inversion changed across the doped core. Generally, if we use the integral form for Γ and the numerical calculation for Γ, we get accurate values for the saturation power [3].

For the Fig. 5 and 6, we consider a family of functions with the constant value between 0.1 and 1 for the constant previous factor hcA/τ from the Eq. (4):

$$0.1 \leq hcA/\tau \leq 1 \tag{5}$$

Also, we can use the approximate methods to determine the saturation power, e.g. we can calculate the absorption and emission cross-section with numerical computations instead of Eq. (3).

4. Conclusions

This work presents the determination of the EDFA saturation power for wavelengths in the interval $\lambda \in [1450 \div 1640]$ nm. For this determination we used different approximations, which provides the same values for EDFA saturation power as the experimental values [3].

The approximations used here reduce the numerical computations for the determination of EDFA characteristics.

With the previous method, we have modeled the EDFA saturation power and we could improve the EDFA characteristics. The saturation power values for EDFA obtained with the method used here are in agreement with experimental values of EDFA saturation power [3].

The EDFA saturation power is used to obtain the signal gain and to determine the optimum fiber optic length for EDFA [2,3].

Using several methods to calculate the saturation power for the EDFA we can optimize the performances of the EDFA [5] and increase the distances and capacity for transmissions. EDFA works in the optical window situated at 1550 nm where the optical fiber attenuation is minimum [14].

In the actual networks, the required lengths of the optical fiber are expensive and for one additional gain we must increase the network cost [2]. Also, in present with EDFA we can develop a new type of optical fiber and to optimize the optical parameters from the network [4,6].

References

[1] F. I. Vasile, P. Schiopu, SPIE Proceedings **4068**, 198 (2000).
[2] F. I. Vasile, P. Schiopu, IEEE Proceedings **2002**, 142 (2002).
[3] E. Desurvire, Erbium Doped Fiber Amplifiers: Principles and Applications, A Wiley-Interscience Publication, New York, (1994).
[4] E. Desurvire, D. Bayart, B. Desthieux, S. Bigo, Erbium-Doped Fiber Amplifiers: Device and System Developments, A Wiley-Interscience Publication, New York, (2002).
[5] P. C. Becker, N. A. Olsson, J. R. Simpson, Erbium-Doped Fiber Amplifiers: Fundamentals and Technology, Academic Press, New York, (1997).
[6] A. Bjarklev, Optical Fiber Amplifiers: Design and Systems Applications, Artec House, London, (1993).
[7] E. Lacot, F. Stoeckel, M. Chenevier, Physical Review A, **49**(5), 3997 (1994)
[8] A. W. T Wu, A. J. Lowery, IEEE Journal of Quantum Electronics, **34**(No 8), 1325 (1998).
[9] T. Pfeiffer, H. Bülow, IEEE Photonics Technology Letters, **4**(5), 449 (1992).
[10] A. A. M. Saleh, R. M. Jopson, J. D. Evankow, J. Aspell, IEEE Photonics Technologies Letter, **2**(10), 714 (1990).
[11] F. F. Ruhl, Electron Letter **28**(3), 312 (1992).
[12] C. R. Giles, E. Desurvire, IEEE Journal of Lightwave Technology, **9**(2), 271 (1991).
[13] P. Schiopu, F. I. Vasile, The Hyperion Scientific Journal **3**(2), 159 (2002).
[14] F. I. Vasile, P. Schiopu, METRA Proceedings **3**, 11 (2002).