EDFA Application in WDM CATV Systems

Lidia Jordanova[1] and Valentin Topchiev[2]

Abstract – **Research of the influence of the erbium-doped fiber length and optical input power on the gain spectrum and noise figure of EDFA, working with milti-wavelength signals, is conducted and the results are presented in this paper. The gain spectrum in full C-band when EDFA is pumped with laser at 980 nm and 1480 nm, is analyzed. The EDF length optimum value, when pumping at 980 nm, is defined so that maximum optical output power and gain flatness are attained. The influence of optical input power on the gain spectrum and noise figure is investigated and its maximum variation is determined.**

Keywords – **WDM CATV system, EDFA, EDF lengh, Gain flatness, noise figure.**

I. INTRODUCTION

Erbium-doped fiber amplifier (EDFA) is mostly applicable for signal amplification in C-band (1525-1565 nm) due to high signal gain, wide waveband, low noise figure (3-5 dB) and low price.

EDFAs are made by doping the silica fiber with erbium ions. These ions can absorb light energy injected from laser source and reemit it in the range of input signal wavelength, due to stimulated light emission. The highest quantum efficiency is attained when pumping at 980 nm or 1480 nm.

The EDFA is designed to operate in saturation when single-wavelength signal amplifies. This way, when the input signals level varies in wide range, the output power and noise figure remain stable. It is well-known that the average inversion population is very low (< 0.69) in saturation regime operation, which is precondition for maximum transformation from pump to signal power.

One of the main issues when EDFA amplifies multi-wavelength signal is the gain flatness in the used wavelength range. Researches show that maximum gain flatness is achieved when the average inversion population is in the range from 0.75 to 0.8 [1]. This means that EDFA, which operates in saturation, is not suitable to work in WDM systems. To ensure high gain flatness, it is necessary to retain high average value of inversion population. There are two ways to obtain that – by using higher pump power or shorter erbium-doped fiber. In the second case, this leads to gain decrease.

The goal of the researches in this paper is to optimize EDFA parameters in order to obtain high gain flatness and low noise figure when it operates in C-band. Since this amplifier is used in WDM CATV system, we are interested in the influence of the total input power on the amplifier characteristics.

II. MATHEMATICAL DESCRIPTION OF THE PROCESSES IN AN EDFA

EDFAs are designed to operate in three main pumping schemes – forward, backward and bidirectional. The forward pumping provides lowest noise figure (NF), while the backward – the highest saturated output power. As the parameter noise figure is one of the most important for EDFA, the researches are made using forward pumping only.

Fig. 1 shows simplified EDFA block scheme which consists of: pump laser, connected to EDF by wavelength division multiplexor (WDM), optical isolators for separation of the amplifier input and output, an optical waveband filter that decreases the pump and ASE noise power at the amplifier output.

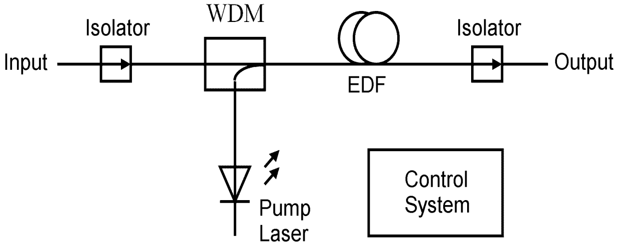


Fig. 1. EDFA Scheme

The processes in EDFA can be described by two types of mathematical equations – the rate equations, which define the transitions between energy states, and the propagation equations, which characterize signal (P_s), pump (P_p) and ASE (P_{ASE}) power evolution along the active fiber [2].

On the base of the rate equations, a formula that calculates the number N_2 of the erbium ions in excited state can be written as:

$$N_2=\left(\sum_i\frac{\tau\sigma^a_{\nu_i}}{Ah\nu_i}\Gamma_sP_{s_i}+\sum_j\frac{\tau\sigma^a_{\nu_j}}{Ah\nu_j}\Gamma_{\nu_j}P_{ASE_j}+\frac{\tau\sigma^a_p}{Ah\nu_p}\Gamma_pP_p\right)N\text{ x}$$
$$\left[\sum_i\frac{\tau\left(\sigma^a_{\nu_i}+\sigma^e_{\nu_i}\right)}{Ah\nu_i}\Gamma_sP_s\left(\nu_i\right)+\sum_j\frac{\tau\left(\sigma^a_{\nu_j}+\sigma^e_{\nu_j}\right)}{Ah\nu_j}\Gamma_{\nu_j}P_{ASE}\left(\nu_j\right)+\right. \qquad (1)$$
$$\left.+\frac{\tau\left(\sigma^a_p+\sigma^e_p\right)}{Ah\nu_p}\Gamma_pP_p+1\right]^{-1},$$

where τ is the life time of electrons in exited state, σ^e and σ^a – emission and absorption cross section, A – effective area of erbium fiber, $h\nu$ – photon energy, Γ – overlap factor, N – erbium ions concentration and ν is the signal light frequency.

---

[1] Lidia Jordanova is with the Faculty of Telecommunications at Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, E-mail: jordanova@tu-sofia.bg.

[2] Valentin Topchiev is with the Faculty of Telecommunications at Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, E-mail: vtsc@mail.bg.

The indexes used in formula are refer to the signal (*s*), pump power (*p*), the number of the signal (*i*) and the ASE noise power (*j*) spectrum terms.

Since the EDF length usually does not exceed 20 m, the signal attenuation is neglectfully low and the propagation equations can be described as follows:

- about signal and pump powers:

$$\frac{dP(\lambda)}{dz} = \Gamma(\lambda) P(\lambda)\left[N_2\sigma^e(\lambda) - N_1\sigma^a(\lambda)\right], \quad (2)$$

- about ASE noise power:

$$\begin{aligned}\frac{dP^{\pm}_{ASE}(\lambda)}{dz} &= \pm\Gamma(\lambda) P^{\pm}_{ASE}(\lambda)\left[N_2\sigma^e(\lambda) - N_1\sigma^a(\lambda)\right] \\ &\pm \sigma^e(\lambda) N_2 \Gamma(\lambda) P_0(\lambda).\end{aligned} \quad (3)$$

The parameters used in the formulas given above are related to different wavelength *λ*. The number of erbium ions in ground state N_1 and the part of ASE noise power that propagates along with the signal, can be calculated by:

$$\begin{aligned}N_1 &= N - N_2\,, \\ P_0 &= 2hv\Delta v\,.\end{aligned} \quad (4)$$

When we calculate P_{ASE}, we take into consideration just the part of power that propagates to the signal direction P^{+}_{ASE}, which can be defined with the following expression:

$$P_{ASE} = n_{SP} hv(G-1)\Delta v\,, \quad (5)$$

where $n_{SP} = N_2/(N_2 - N_1)$ inversion population factor, Δv – waveband of optical filter и G – amplifier gain.

III. FIBER PARAMETERS AND PUMP POWER SELECTION

The simulation researches are conducted by using erbium-doped fiber, which has the following parameters: fiber type – Al-Ge-Er-SiO$_2$; erbium ions concentration N = 0,7.10^{-19} cm^{-3}; life time of electrons in exited state τ = 10 ms; overlap factor Γ(1535–1565) = 0.40, Γ(1480) = 0.43 and Γ(980) = 0.64.

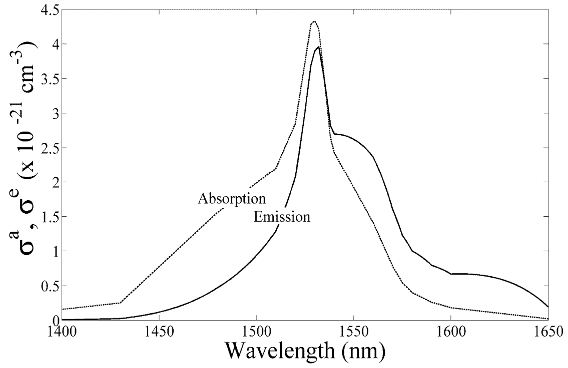


Fig. 2. Спектрални характеристики на σ^a и σ^e

On the Fig. 2 absorption (σ^a) and emission (σ^e) cross sections as a function of wavelength are presented. To create absorption cross section curve, experimental data is used [3], while the emission cross section is calculated by using McCumber equation [4]

$$\sigma^e = \sigma^a e^{\left(31.232 - \frac{48.007}{\lambda[nm]}\right)}. \quad (6)$$

To define the pump laser power, the dependence of EDFA parameters (*G*, P_{ASE} and *NF*) on the pump power attained in [5], is used. On the base of made analysis, we obtain that the gain is higher than 17 dB, when the value of input signal is approximately 1 mW, and the needed pump power is at about 97 mW. For that reason, in researches conducted below, P_p is assumed to be equal to 100 mW.

IV. SIMULATION AND RESULTS

A. Gain Spectrum

In order to investigate the amplifier gain that is designed on the base of the described above erbium-doped fiber, multi-wavelength signal is launched in the amplifier input. This signal consists of 41 single-wavelength signals with channel spacing of 1 nm, placed on the wavelength range from 1525 to 1565 nm and each of them has – 16 dBm power (or total input power is equal to 1.025 mW). The numerical simulations are made with pump laser source having 100 mW output power in two cases: when λ_p = 980 nm and λ_p = 1480 nm.

The EDF length varies at about its optimum value that is attained in [5] in case the amplifier operates with 1550 nm single-wavelength signal. The main goal of this investigation is to define the optimum value of EDF length so that the gain is higher than 17 dB and the gain flatness is maximal in largest possible wavelength range.

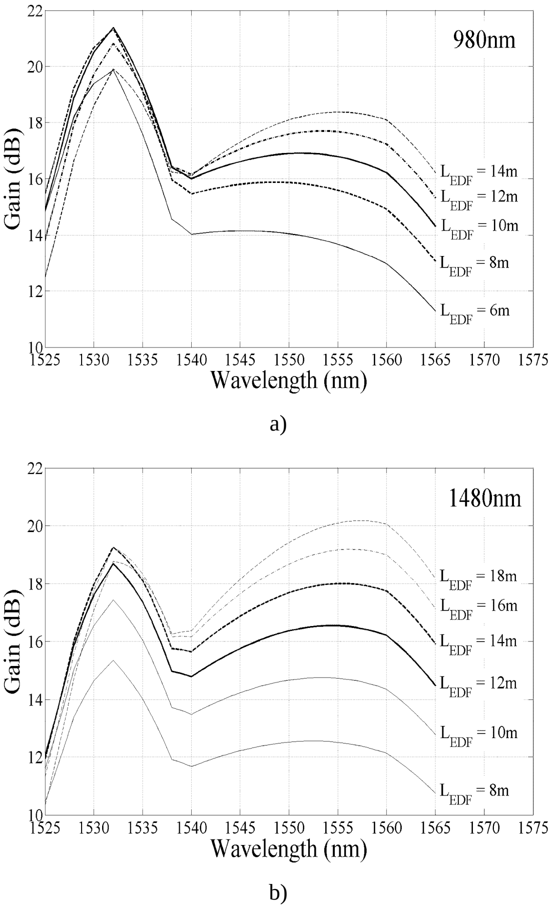
The amplifier gain can be calculated by the following expression:

$$G = P_s(L_{EDF})/P_s(0)\,, \quad (6)$$

where $P_s(0)$ and $P_s(L_{EDF})$ are input and output signal optical power calculated by using formula (2).

The results given on Figs 3a) and 3b) show that EDFA appliance in the range of 1525 to 1540 nm is not appropriate, because the gain flatness in not sufficient (about 8 dB). In the range from 1540 to 1560 nm, the gain spectrum is relatively flat, which is the reason for applying this amplifier in WDM systems. Furthermore, the shorter is L_{EDF}, the higher is the gain flatness. At the same time the gain value decreases too much.

From Fig. 3a) we can easily define that when L_{EDF} is approximately equal to 10.5m, a gain at about 17 dB is obtained so that the gain flatness is lower than 1 dB in the range from 1540 to 1560 nm. If the pump laser operates at 1480 nm the required gain value of 17 dB can be achieved at $L_{EDF} \approx 14$ m. In this case the gain flatness is too low (2.5 dB). Therefore such amplifier is not appropriate for multi-wavelength signal amplification and further researches are conducted just in case λ_p = 980 nm.



a)

b)

Fig. 3. Gain Spectrum, when multi-wavelength signal is amplified and 100 mW with 980 nm a) and 1480 nm b) is pumped

B. Defining of L_{EDF} and G optimal values

In the previous simulation more than 70 % of the pump power is used for amplification of the input signals at about 1530 nm. Therefore, the optimum values of the L_{EDF} and G in the range of 1540 to 1560 nm cannot be determined. For that reason it is necessary a second simulation to be performed and the input signal spectrum is limited to the range that is interesting for us.

The results shown on Fig. 4 are attained by launching EDFA input with 21 single-wavelength signals with channel spacing of 1 nm, placed on the wavelength range from 1540 to 1560 nm and each of them has – 13 dBm power (or total input power is equal to 0 dBm).

It can be clearly seen that the maximum gain flatness is obtained when L_{EDF} is equal to 10 m. Then the gain is 17.2 ± 0.4 dB and the quantum efficiency of the optimized amplifier is approximately 59 %, which is a typical value for EDFA applied for single-wavelength amplification.

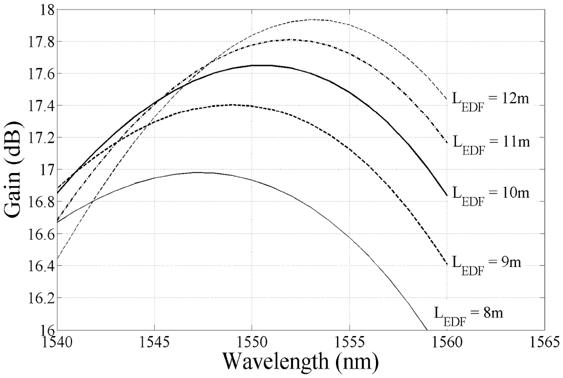


Fig. 4. Gain Spectrum when pump 100 mW with 980 nm and L_{EDF} is from 8 m to 12 m

B. Influence of the optical input power

The results till now show that when a chosen erbium-doped fiber is used, then EDFA in the range from 1540 to 1560 nm can be designed. When the pump laser operates at 980 nm and its output power is equal to 100 mW and the total input power is 0 dBm, the gain flatness remains lower than 0.4 dB.

When the amplifier operates in real WDM CATV system, the optical input power usually differs from the optimized value. To clarify the EDFA behavior, when the total input power changes, a research with multi-wavelength signal containing 21 single-wavelength signals within the optimized range, is conducted. The power of each single-wavelength changes by step of 3 dB in the range of – 19 до – 7 dBm, therefore the total input power of the amplifier is respectively: – 6, – 3 , 0, 3 and 6 dBm.

The obtained results of the simulation are presented on Fig. 5. It can be seen that any deviation of the optical input power from the optimum ($P_{in\,1}$ = – 13 dBm, respectively. P_{in} = 0 dBm), leads to decrease of the gain flatness. This can be explained by the deviation of the average level of inversion population from its optimum value (N_2 = 0.75), that can be calculated by formula (1). Nevertheless, even if the total level of input signals changes twice, i.e. P_{in} = ± 3 dBm, the gain changes in the examined range not more than 1 dB.

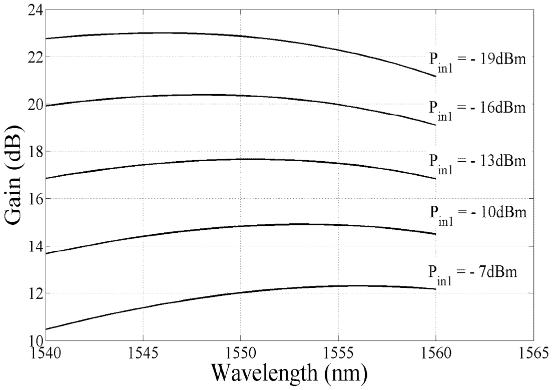


Fig. 5. Gain Spectrum when pump 100 mW with 980 nm and $P_{in\,1}$ is from – 19 dBm to – 7 dBm

The analysis of the obtained results show that the total output power remains almost constant. This guarantees a stable output level (± 0.5 dB), which allows easier calculations of the optical channel budget.

C. Noise Figure

On Fig. 5 are given results of the simulation which show how changes in the input power and its wavelength affect the noise figure (NF). The value of this parameter can be determined by the following formula:

$$NF\left(\lambda\right)=\frac{2P_{ASE}\left(\lambda\right)}{G\left(\lambda\right)h\nu\Delta\nu}. \qquad (7)$$

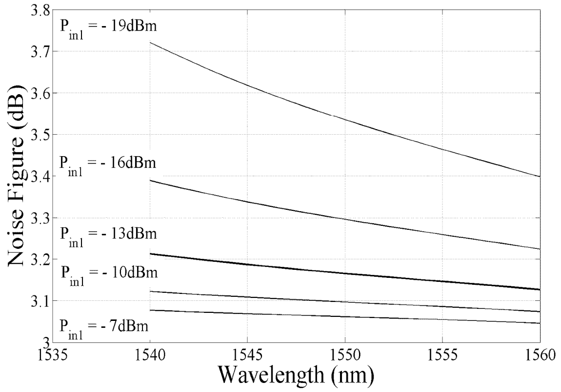


Fig. 6. Noise Figure Spectrum when pump 100 mW with 980 nm and P_{in1} is from – 19 dBm to – 7 dBm,

It is obvious that the investigated parameter slightly exceeds the quantum level of 3 dB and its value remains lower than 3.8 dB even in the most unfavorable case. The higher level of noise in the short wavelengths of the examined range is due to the higher values of gain cross section and the tendency of the erbium ions to emit photons spontaneously in this spectrum range, respectively.

V. CONCLUSION

The performed simulations show that the researched EDFA scheme can ensure flat gain of the optical signals at wavelengths from 1540 nm to 1560 nm. When an EDFA is launched with 21 single-wavelength signals with channel spacing of 1 nm, placed on the wavelength range from 1540 to 1560 nm and each of them has – 13 dBm power (or total input power is equal to 0 dBm), then the obtained amplifier gain is 17.2 ± 0.4 dB. In the same time the gain flatness remains approximately ± 0.5 dB, even if the total input power changes twice. This ensures stable output level (± 0.5 dB) and noise figure lower than 3.8 dB.

REFERENCES

[1] P. Becker, N. Olsson and J. Simpson, “Erbium-Doped Fiber Amplifier – Fundamental and Technologies”, Academic Press. 1997.

[2] N. Suong and Ph. Hop, “Simulation of the Gain Characteristics of EDFA”, ISEEE 2005, Conference Proceeding, pp. 37-41, HCM City, Vietnam, 2005.

[3] E. Desurvire, C. Giles, J. Zyskind and all of N.J., “Erbium-Doped Fiber Amplifier”, US Patent 5027079, 1991.

[4] N. Mohan, “Erbium-Doped Fiber Amplifier: Modeling and Simulation Using VHDL-AMS”, Course Project Report ECE-770, Ontario.

[5] L. Jordanova and V. Topchiev, “Optimizing the Parameters of Amplifiers used in the Optical Channel of CATV Systems”, Telecom 2008, Conference Proceedings, pp. 206-211, Varna, Bulgaria, 2008.

[6] “Optical Amplifier: EDFA”, EECS 290Q, CCH Lecture 3, September 25, 2001.

[7] St. Pinter, J. Jiang and X. Fernando, “A Dynamic Multi-Wavelength Simulink Model for EDFA”, Conference Proceedings, CCECE 2004 - CCGEI 2004, Niagara Falls, May 2004.

[8] Li Qian, “Experiment on Erbium-Doped Fiber Amplifiers”, Advanced Labs for Special Topics in Photonics (ECE 1640H), University of Toronto, April, 1998.