Amplification of the Multi-Wavelength Signal by Using EDFA with Constant Gain

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Summary

The paper deals with the results of EDFA simulation that has been carried out to study the modes of operation and to determine the amplifier parameters' values at which maximum flatness of the gain spectrum curve is obtained. The mathematical model applied is based on the propagation equations and known parameters of the erbium-doped fiber. Dependencies to determine the wavelength operation range, the fractional upper-state population and the length of the erbium-doped fiber are given. A formula to be used in engineering practice is proposed for the determination of the pump-power optimum value of EDFA with constant gain, the power level of the input multi-wavelength signal being taken into consideration. In order to estimate the accuracy of the EDFA simulation model its gain and noise spectrum characteristics have been compared to those of a real amplifier.

Key words:

EDFA, WDM system, gain flatness, constant gain, multi wavelength signal, dynamic range of input signal

1. Introduction

The wavelength division multiplexing (WDM) technology is applied to modern communication systems in order to make the optical channel more efficient. Thus the capacity of the optical channel implemented with a single optical fiber is increased many times and transfer rates higher than 120 Tbits/s are obtained.

On fig. 1 the block diagram of a typical optical communication system with WDM is shown. At the headend a large number of optical signals of different wavelengths are combined in the optical multiplexer (*MUX*) and are then transmitted to the end users over a single optical fiber. ADD/DROP modules (hubs) are included in the optical channel in order to provide for adding up or dropping out signals of some wavelengths to/from the total light flux respectively. Optical amplifiers (OA) are used to compensate for the signal attenuation along the optical channel.

WDM communication systems operate normally when the power level of the transmitted optical signals is within a preset range regardless of their number and wavelength. Hence, the gain spectrum of the optical amplifiers used must be wide enough; besides, a maximum flatness of their characteristics is required.

In now-a-days optical systems that transmit signals of only one wavelength the erbium-doped fiber amplifiers (EDFA) are preferred. At the same time expensive distributed Raman amplifiers are mainly used for amplification of multi-wavelength signals. Their most significant advantage is the possibility to provide a constant gain within a rather wide waveband when a large number of signals with unfixed values of optical power are transmitted over the optical channel. Yet, in most of the WDM communication systems operating in the C-band (1525-1565 nm) the less expensive EDFA can be used instead of the Raman amplifiers. Although EDFA have a rather narrow wavelength range of gain spectrum, they can provide large gain coefficient (above 30 dB), low noise figure (*NF*) of about 3 to 5 dB and a relatively high level of output power (more than 23 dBm).

The authors' aim was to investigate the possibility for implementation of EDFA that could be applied to amplify the C-band multi-wavelength signal transmitted over the cable distribution network of CATV systems.

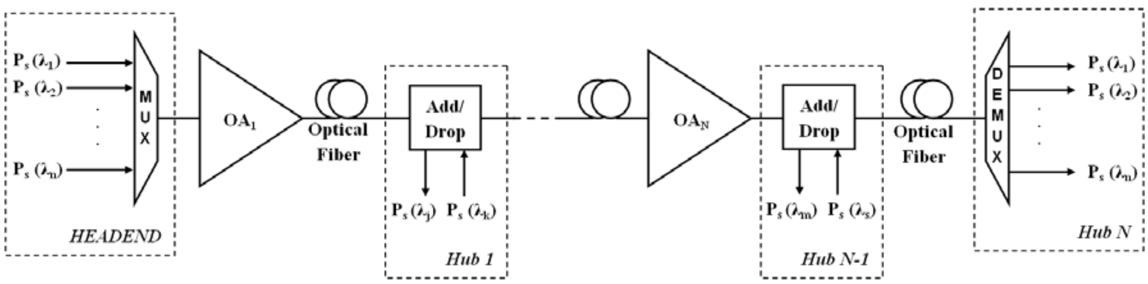

Fig. 1 Block diagram of WDM optical communication system

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2. Spectrum Characteristics of the EDFA Gain

Three basic circuits (forward, backward and bidirectional pumping) are used for the realization of EDFA. The forward pumping provides the lowest NF and the backward pumping provides the highest saturated output power. Investigations have shown that the highest efficiency is obtained when erbium ions are activated with laser source emitting at 980 or 1480 nm [1]. When the pump laser emits power at $\lambda_p = 980$ nm, a lower value of NF is obtained. When $\lambda_p = 1480$ nm a higher value of the output power is obtained [2].

Since requirements such as low values of both the noise power and the intermodulation products of second and third order are essential for the CATV systems, the paper deals but with EDFA circuit where pump light of 980 nm wavelength is propagated in the direction of the signal. A simplified block diagram of that type of EDFA is shown on fig. 2. It consists of a pump laser connected to the erbium-doped fiber through WD multiplexer, optical isolators at the amplifier input and output and an optical band-pass filter to suppress the pump light and to limit the spectrum of amplified spontaneous emissions (ASE) noise power.

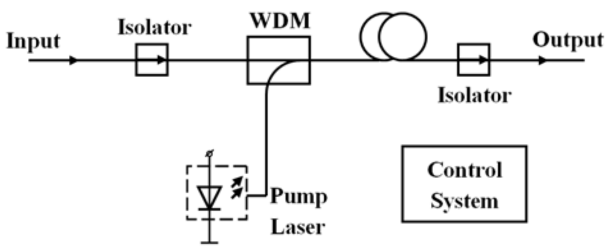

Fig. 2 Block diagram of EDFA

The mathematical model describing the operation of the EDFA includes two types of equations - the rate equations which define the transitions between energy levels, and the propagation equations which characterize the signal (P_s), the pump (P_p) and ASE (P_{ASE}) power variations along the active fiber [3] . The propagation equations referring to the signal and the pump are used to study the amplifier properties of EDFA:

$$\frac{dP_s(z)}{dz} = \Gamma_s \left[N_2(z)\sigma_s^e - N_1(z)\sigma_s^a \right] P_s(z) \quad (1)$$

$$\frac{dP_p(z)}{dz} = \Gamma_p \left[N_2(z)\sigma_p^e - N_1(z)\sigma_p^a \right] P_p(z), \quad (2)$$

where Γ_s and Γ_p are the overlap factors of the signal and the pump power, σ^e and σ^a are the emission and absorption cross-sections, $N_1(z)$ and $N_2(z)$ are the population densities of erbium ions on the ground and exited states.

The gain spectrum of the EDFA is obtained through integration of expression (1) along the EDF length and can be expressed with the formula:

$$G(\lambda)[\text{dB}] = 4.3\,\Gamma_s(\lambda)\left[\overline{N_2}\sigma_s^e(\lambda) - \overline{N_1}\sigma_s^a(\lambda)\right] L, \quad (3)$$

where L is the length of the erbium-doped fiber and $\overline{N_2}$ and $\overline{N_1}$ are the average values of the population density of erbium ions on the exited and ground states. They are defined as follows:

$$\overline{N_2} = \frac{1}{L}\int_0^L N_2(z)\,dz$$
$$\overline{N_1} = \frac{1}{L}\int_0^L N_1(z)\,dz. \quad (4)$$

For the case of several signals s_i, the population density N_2 could be presented as a function of position z along the fiber [4]:

$$N_2(z) = \left(\sum_{s_i} \frac{\tau\sigma_{s_i}^a}{Ahv_{s_i}} \Gamma_{s_i} P_{s_i}(z) + \frac{\tau\sigma_p^a}{Ahv_p}\Gamma_p P_p \right) N \text{ x}$$
$$\text{x}\left[\sum_{s_i} \frac{\tau\left(\sigma_{s_i}^a + \sigma_{s_i}^e\right)}{Ahv_{s_i}} \Gamma_{s_i} P_{s_i}(z) + \frac{\tau\left(\sigma_p^a + \sigma_p^e\right)}{Ahv_p}\Gamma_p P_p + 1 \right]^{-1}, \quad (5)$$

where τ is the lifetime of the electrons in excited state, A is the effective cross-section area of the distribution of erbium ions, hv is the photon energy. When the total population density N is known, $N_1(z)$ is easily determined as $N_1 = N - N_2$.

It is evident from (3) that the spectral distribution of the EDFA gain is determined by the term

$$G_1(\lambda) = 4.3\,\Gamma_s(\lambda) N \left[\frac{\overline{N_2}}{N}\sigma_s^e(\lambda) - \left(1 - \frac{\overline{N_2}}{N}\right)\sigma_s^a(\lambda) \right], \quad (6)$$

describing the amplification per unit length of the active fiber, expressed in dB/m. Parameter $\overline{N_2}/N$ in expression (6) represents the average value of the fractional upper-state population.

3. Gain Flatness Conditions in Multi-wavelength Signal Amplification

Since the EFDA gain spectrum depends significantly on the parameters of the doped fiber applied, each specific case must be carefully investigated. The paper deals with results obtained for the standard Al-Ge-Er-SiO_2 optical fiber whose physical parameters are as follows: erbium ions concentration $N = 0.7\text{x}10^{-25}\ \text{m}^{-3}$, lifetime of ions in the upper state $\tau = 10$ ms; overlap factors $\Gamma_s(1525–1565) = 0.40$ and $\Gamma_p(980) = 0.64$.

On fig. 3 the spectrum shape of the emission (σ^e) and absorption (σ^a) cross-sections are shown. They are based on experimentally measured values of σ^a given in [5] and on the McCumber relationship [6] used to determine parameter σ^e:

$$\sigma^e = \sigma^a \exp\left(31.232 - \frac{48.007}{\lambda[nm]}\right). \qquad (7)$$

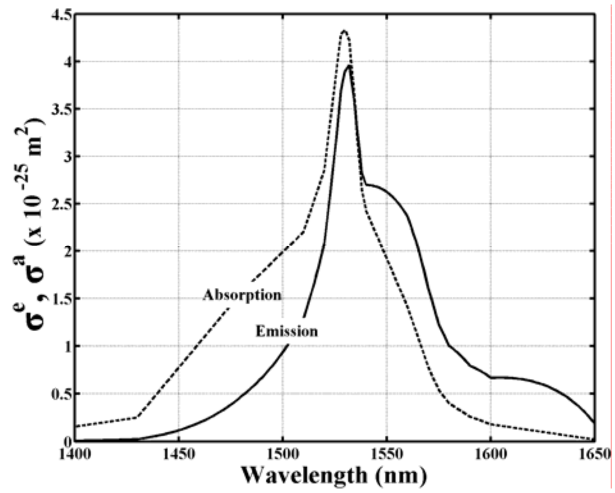

Fig. 3 Spectrum of σ^a and σ^e

3.1. Determination of the optimum value of parameter $\overline{N_2}/N$

The influence of the average value of the fractional upper-state population $\overline{N_2}/N$ on the amplification of multi-wavelength signals per unit length of the doped fiber can be estimated using the relationships shown on fig. 4.

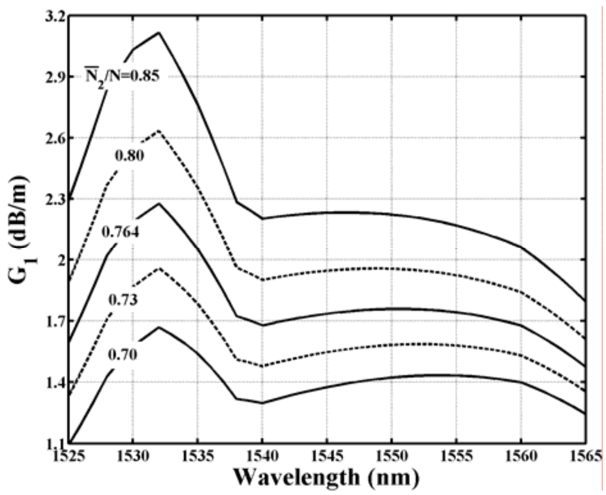

Fig. 4 Influence of the fractional upper-state population $\overline{N_2}/N$ on the gain spectrum

They are obtained through substitution of the fiber parameters in expression (6). The choice of the $\overline{N_2}/N$ values has been made taking into account the fact that optical amplification conditions are created when an inverse population occurs, i.e. $\overline{N_2}/N > 0.5$.

Analysis has shown that with the chosen erbium-doped fiber the gain spectrum characteristics does satisfy the requirement for maximum gain flatness within the wavelength range from 1538 to 1560 nm, the best results being obtained when the value of $\overline{N_2}/N$ is from 0.73 to 0.80. In the paper the value 0.764 is assumed to be the optimum. When choosing a value that is higher than the optimum the pump power should be increased but this will result in decreasing the quantum efficiency. Choosing a smaller value of $\overline{N_2}/N$ requires a longer active fiber that will increase both the ASE noise power and the nonlinearity of the EDFA transmission characteristics.

3.2. Dependence of the pump power P_p on the power of the input multi-wavelength signal $P_{s\,in}$

It can be concluded from expression (5) that the average value of the fractional upper-state population depends on both the parameters of the erbium-doped fiber and the signal and pump power. Therefore, it is of special interest for the engineering practice to determine the value of P_p that would provide the optimum value of parameter $\overline{N_2}/N$ for different power levels of the input signals [7].

The algorithm used by researchers to develop the needed relationship is based on the assumption that the value G of the EDFA gain is preliminary set. Thus the length L of the doped fiber can be determined from expression (3) in a way to provide the given gain when $\overline{N_2}/N = 0.764$. The calculated value

$$L = G[\text{dB}]\left\{\frac{1.72N}{k}\sum_k\left[0.764\sigma_s^e(\lambda_k) - 0.236\sigma_s^a(\lambda_k)\right]\right\}^{-1} \qquad (8)$$

is introduced into propagation equations (1) and (2) and as a result the following relationship is obtained:

$$P_p = P_{s\,in}\,G/E_q \qquad (9)$$

where E_q is the quantum efficiency of the amplifier.

The EDFA quantum efficiency depends on the parameters of both the erbium-doped fiber and the power of the pump laser and can be determined using the propagation equations. On fig. 5 the results obtained for three of the most commonly used values of P_p (50, 100 and 150 mW) are given.

It is evident that when parameter $\overline{N_2}/N$ is at its optimum the EDFA quantum efficiency is 59 % for P_p = 150 mW, 57.5 % for P_p = 100 mW and 54 % for P_p = 50 mW respectively. Since the calculated values of the parameter under study appear to be very close an average value can be used, so we assume $E_q = 57.5$ %. Then the final formula to calculate the pump power can be written in the form:

$$P_p\left[\text{dBm}\right] = P_{s\,in}\left[\text{dBm}\right] + G\left[\text{dB}\right] + 2.4 \cdot \qquad (10)$$

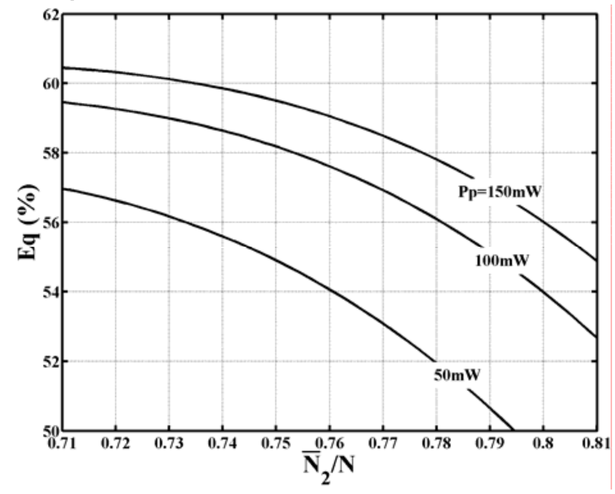

Fig. 5 Dependences to determine parameter E_q

3.3. Power level admissible limits of the input multi-wavelength signal $P_{s\,in}$

A peculiarity of the EDFA is the fact that gain depends on the input signal power level. On fig. 6 spectrum characteristics of the EDFA gain are shown. They are obtained by varying the power of the input multi-wavelength signal within the limits of – 10 dBm to + 10 dBm.

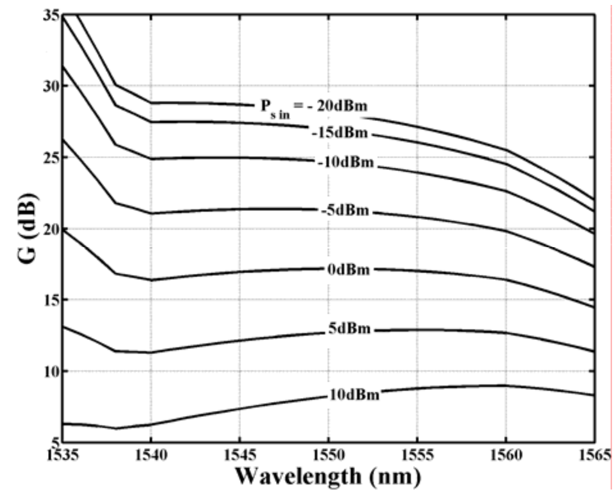

Fig. 6 Gain spectrum characteristics of the optical input power obtained for EDFA with parameters $L = 9.85$ m and $P_p = 19.4$ dBm.

As seen from the diagram, a higher gain level can be achieved at a low input signal power however this would worsen the gain flatness. Increasing $P_{s\,in}$ up to a level of 0 dBm will decrease the gain value but the gain flatness will be at its best. At higher levels of the input multi-wavelength signal the gain flatness will again start to worsen and the gain will drop to unacceptable value. When EDFA is applied in WDM systems the optimum limits of $P_{s\,in}$ variation are chosen according to the flatness requirement for the gain characteristics *G(λ)*.

To precisely define the limits of the $P_{s\,in}$ variation a mathematical simulation has been carried out for three values of EDFA gain (13 dB, 17 dB and 20 dB). The goal was to determine how $P_{s\,in}$ affects the average fractional upper-state population $\overline{N_2}/N$. The lengths of EDF and pumping powers (calculated for the case when the level of the input signal is 0 dBm) used at the research are result of equations (8) and (10). They have the following values: $L = 7.55$ m and $P_p = 15.4$ dBm ($G = 13$ dB), $L = 9.85$ m and $P_p = 19.4$ dBm ($G = 17$ dB) and $L = 11.6$ m and $P_p = 22.4$ dBm ($G = 20$ dB).

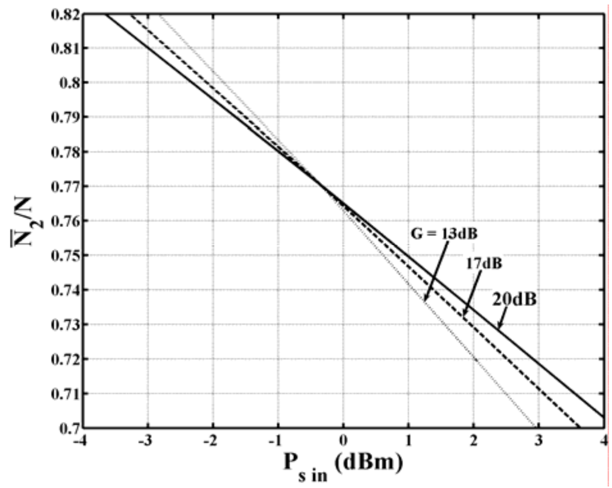

Fig. 7 Dependence of the fractional upper-state population on the optical input power

The total power of the input multi-wavelength signal (21 single-wavelength optical signals of equal amplitude, displaced from one another by 1 nm in the range from 1540 to 1560 nm) varies from – 4 dBm to + 4 dBm. The obtained results are shown on fig. 7.

Taking into consideration that a maximum flatness of the gain characteristics is provided when the values of $\overline{N_2}/N$ are within the range from 0.73 to 0.80, the $P_{s\,in}$ variation range can be determined from the dependences on fig. 7 for three cases as follows:

- from − 1.45 dBm to + 1.55 dBm, $G = 13$ dBm;
- from − 1.85 dBm to + 1.95 dBm, $G = 17$ dBm;

- from − 2.40 dBm to + 2.35 dBm, $G = 20$ dBm.

Hence, with a constant pump power the admissible gain flatness of the EDFA to properly amplify multi wavelength signals in the range of 1540 to 1560 nm is attained within rather narrow limits of the input signal power level.

In order to widen the dynamic range of the EDFA input signal a control module must be included in the circuit to meet condition (10). A small part of the input multi wavelength signal is passed to that module through a directional coupler. The electrical signal obtained at the module output is used to control the pump laser current i.e. its power.

4. Accuracy Estimation of the Simulation Method

To evaluate the accuracy of the described method for EDFA design a comparison is made between the theoretically and experimentally obtained characteristics of an amplifier whose gain is equal to 17 dB in the wavelength range from 1540 to 1560 nm. A package of 21 single-wavelength signals of equal amplitude (displaced from one another by 1 nm in the investigated range) is loaded to the amplifier input. The power level of the input signal is 0 dBm, i.e. each of the signals is of power – 13.2 dBm.

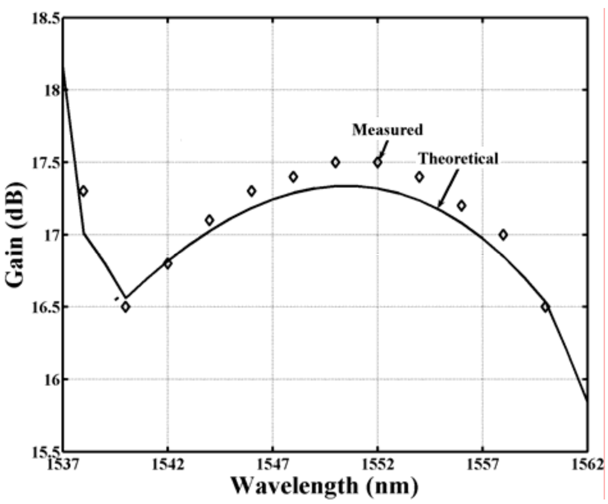

Fig 8 Comparison of the gain spectrum characteristics of the synthesized and real EDFA

In the case, it follows from (8) that the optimum length of the erbium-doped fiber of the synthesized model is $L = 9.85$ m, and it follows from (10) that the pump power P_p is equal to 19.4 dBm. The EDFA gain spectrum described by dependence (3) is shown on fig. 8.

For comparison, experimentally obtained G values of the Hi-Tech HT-OA-20 optical amplifier, whose erbium-doped fiber parameters and operation behavior (pump power, input signals) are much the same as those of the simulation model, are shown on the same diagram. During the measurement 10 DWDM SFP modules whose output power is 0 dBm have been used as a signal source. Their output signals whose wavelength is changing at a step of 2 nm are combined in the WDM. To adjust the power level of the total multi-wavelength signal at the EDFA input a variable optical attenuator is used.

As seen from fig. 8, the deviation between theoretical and experimental results does not exceed 3.7 %. Thus a conclusion can be drawn that the proposed mathematical model describing the process of multi-wavelength signal amplification in the EDFA is accurate enough for the engineering practice.

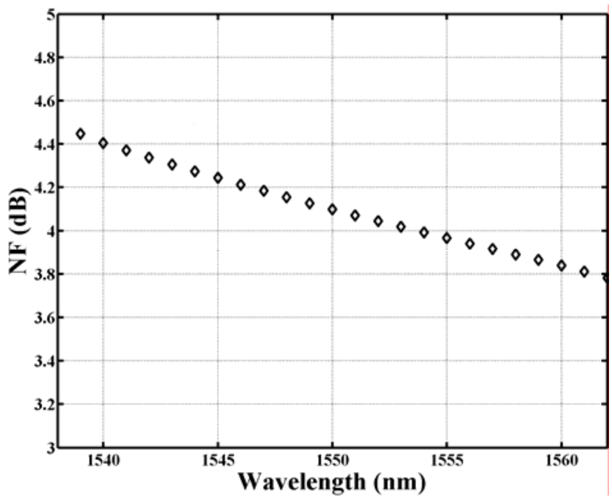

Fig. 9 NF spectrum

Since with the mathematical description of the amplification process in EDFA the ASE noise power is not taken into consideration the NF and its spectrum in the range from 1540 to 1560 nm should be defined. For that purpose, the following relationship is used: [3]

$$NF(\lambda)[\mathrm{dB}] = 10\lg\left(2\,\bar{n}_{sp}(\lambda)\frac{G(\lambda)-1}{G(\lambda)}\right), \tag{11}$$

where n_{sp} is the inversion population factor that can be calculated as follows:

$$\bar{n}_{sp}(\lambda) = \frac{\sigma_s^e(\lambda)\overline{N}_2/N}{\sigma_s^e(\lambda)\overline{N}_2/N - \sigma_s^a(\lambda)\left(1-\overline{N}_2/N\right)}. \tag{12}$$

On fig. 9 the NF spectrum of the investigated EDFA model is shown.

The results show that in the wavelength range here considered the NF values vary within the limits of 3.8 to 4.4 dB. Higher levels of noise in the short-wavelength range are due to the greater transition cross-section causing higher spontaneous emission. Comparing the simulation results with the *NF* value measured for HT-OA-20 (max $NF = 4.5$ dB) an error less than 2.3 % is observed.

5. Conclusion

As seen from the investigations, the maximum gain flatness of the designed EDFA in the wavelength range from 1538 nm to 1560 nm can be obtained if three basic requirements are met. According to the first one the average value of the fractional upper-state population must be equal to the optimum value, i.e. $\overline{N_2}/N = 0.764$. The other two refer to the erbium-doped fiber length and the pump power whose choice is based on expressions (8) and (10).

As simulation and experiments have shown, when EDFA with constant pump power is used the power level of the input multi-wavelength signal affects both the gain value and the gain flatness of the spectrum shape. In result, the dynamic range of the input signals turns out to be limited, so an additional control module should be applied.

When comparing the spectral characteristics (gain and noise figure) of the designed EDFA with those of a real one (HT-OA-20) the deviation does not exceed 3.7 %. The conclusion is that the mathematical model here described is well applicable in designing EDFA whenever multi-wavelength signals must be amplified and requirements such as maximum gain flatness and minimum NF in the operating wavelength range must be satisfied.

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