Multi-wavelength signal amplification by using hybrid DRA - EDFA optical amplifier

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***Abstract**: The paper deals with the possibilities for expanding the operating wavelength range and improvement of the noise characteristics of hybrid fiber optic amplifier composed of erbium-doped fiber amplifier (EDFA) and distributed Raman amplifier (DRA). Mathematical models of EDFA and DRA, which allow research of their gain and noise figure spectrum characteristics, are presented. On the base of the results attained by conducted simulations, the parameters and operating modes of both co-amplifiers which provide maximum of gain flatness, minimum of noise figure and maximum of operation waveband are determined.*

***Key words:** EDFA, DRA, WDM system, gain flatness, noise figure*

1. INTRODUCTION

In now-a-days engineering, efforts have been mainly concentrated on three key aspects when building up long-haul terrestrial and submarine fiber optic networks – high channel capacity, long distance coverage and low price. Improvement of transmission channel performance has been successfully realized by integrating high-speed network devices and applying wavelength division multiplexing (WDM) technology. Due to DWDM, the capacity of the optical channel implemented with a single optical fiber is increased hundreds times and transfer rates higher than 12 Tbits/s are obtained.

WDM communication networks operate normally when the power level of the transmitted optical signals is within a preset range regardless of their number and wavelength. In order to compensate signal attenuation in long distance transmission systems, multi-wavelength signal is amplified by using optical amplifiers, adopted the wide operating wavelength range, flat gain spectrum, high gain and low noise figure.

Therefore Raman amplifiers are mainly used for DWDM signal amplification in long haul terrestrial and submarine optical transmission systems. 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 [1]. The main reason for their not wide deployment is too high price.

At the same time in most of the DWDM communication systems operating in the range from 1540 to 1560 nm the less expensive EDFAs can be successfully used. Although these amplifiers provide large gain coefficient (more than 30 dB), low noise figure (not exceed 5.5 dB) and output power can be more than 30 dBm [2], they have a rather narrow flat waveband.

The authors' aim is to investigate the possibilities for extension of the operating wavelength range of optical amplifiers applied in modern DWDM cable radio-communication systems. The main efforts in the paper are focused on designing of hybrid optical amplifier composed of less expensive erbium-doped fiber amplifier, which can provide high gain flatness only within the wavelength range from 1540 to 1560 nm [3], in combination with a distributed Raman amplifier which operating waveband can be set by adjusting the pump laser wavelength.

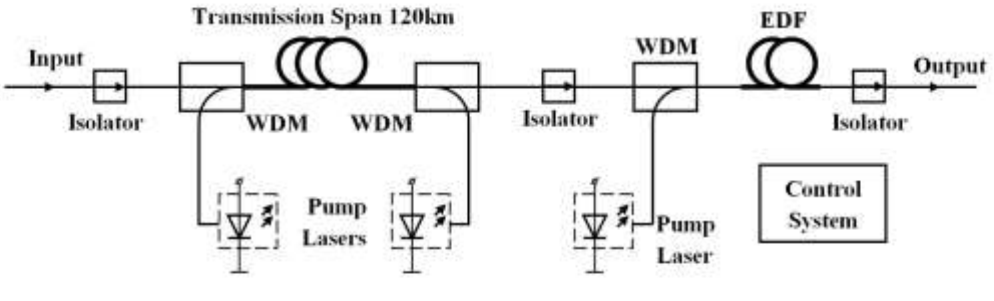

***Fig. 1.** Block diagram of hybrid optical amplifier, built up of distributed Raman amplifier and erbium-doped fiber amplifier.*

At the same time, by providing appropriate pump mode of the Raman amplifier and input optical power of the EDFA, significant improvement of the noise performance can be reached.

2. MATHEMATICAL DESCRIPTION OF HYBRID AMPLIFIER

A simplified block diagram of hybrid amplifier is shown on the figure 1. In the scheme both co-amplifiers are cascaded, where low noise Raman amplifier is applied as a pre-amplifier and high power EDFA is include as a booster amplifier.

Distributed Raman amplifier contains two pump laser sources, which have the same wavelengths and different optical powers. The scheme, known as bidirectional pumping, enables minimization of the optical noise power due to amplified spontaneous emission (ASE) and double Relay backscattering (DRB) by loading proper pump powers of both sides of the transmission span.

Since requirements such as low values of both the noise power and the intermodulation products of second and third order are essential for the cable radio-communication systems, the paper deals with EDFA circuit where pump light of 980 nm wavelength is propagated in the direction of the signal.

2.1. Distributed Raman amplifier

The evolution of the signal (P_s) and the pump power (P_p) propagating along the silica fiber can be quantitatively described by differential equations called propagation equations [1], [4] and they can be expressed as:

$$\pm\frac{dP_p}{dz} = -\frac{\upsilon_p}{\upsilon_s} g_R P_p P_s - \alpha_p P_p \tag{1}$$

$$\frac{dP_s}{dz} = g_R P_p P_s - \alpha_s P_s \ , \tag{2}$$

where g_R is Raman gain coefficient of the fiber, α_s and α_p are the attenuation of the signal and the pump power in silica fiber, v_s and v_p – signal and pump frequencies. The signs of „+” or „–” correspond to forward and backward pumping.

Since $P_p >> P_s$, the first term in (1) is much lower than the second and its influence can be neglected.

In order to simplify the examination of Raman amplifier the pump powers of both lasers have been presented as $P_{P\,L1} = S\,P_p$ for forward pumping and $P_{P\,L2} = (1 - S)\,P_p$ for the backward respectively, where S is the splitting ratio showing the distribution of the total injected pump power P_P between both sides of transmission span. Therefore, to calculate the level of pump power at point z (3) can be used:

$$\begin{aligned} P_p(z) = S\,P_p \exp\left(-\alpha_p L\right) + \\ +\left(1-S\right) P_p \exp\left[-\alpha_p\left(L-z\right)\right]. \end{aligned} \tag{3}$$

When we are discussing the distributed Raman amplifier gain, two different values can be determined. The first one, named net gain (G_{NET}), is defined as a ratio between the signal power measured at the end of the transmission span and the level of input signal. It can be simply described by the expression:

$$G_{NET}\left(L\right) = P_s\left(L\right) / P_s\left(0\right). \tag{4}$$

Engineering practice is also interest in full gain (G_{DRA}) attained by DRA. For its calculation, signal attenuation due to transportation through the silica fiber is taken into consideration. Therefore, the final expression will be written as followed:

$$G_{DRA} = G_{NET} / \exp\left(-\alpha_s L\right). \tag{5}$$

2.2. Noises generated in DRA

The normal operation of Raman amplifiers is accompanied with unstimulated ion transitions from virtual excited state to vibration state which is the reason for spontaneous photon emission. Small fraction of generated photons is added to the signal as a noise power, known as amplified spontaneous emission (ASE). The process of ASE creating, amplifying and attenuating is modeled by differential equation (6) and corresponds to its first, second and third terms [5].

$$\pm\frac{dP_{ASE\_R}}{dz} = n_{sp} g_R P_p h \upsilon_{ASE\_R} \Delta\upsilon + \frac{g_R}{2} P_p P_{ASE\_R} - \alpha_s P_{ASE\_R} \tag{6}$$

where the signs plus and minus correspond to the forward and backward noise components. Parameter n_{sp} is defined by the expression:

$$n_{sp} = \left\{1 - \exp\left[-h\left(\upsilon_p - \upsilon_{ASE}\right) / kT\right]\right\}^{-1}. \tag{7}$$

When the signal propagates though the fiber, small part of light scatters in all directions due to small inhomogeneities or microscopic variation of the refractive index. Fraction of the scattered light couples back into the fiber medium and propagates in the opposite direction. The backscattered light amplifies along the fiber and creates new backscattered light which direction is the same as the signal and it is added to the signal as a noise power. This phenomenon is known as double Rayleigh backscattering (DRB) of the signals and the value of noise power depends on the pump and the signal power and is strongly correlated with the signal. The spectral terms of the DRB-noise are distributed in a narrow waveband around the carriers and they overlap with the signal [4], [6].

The phenomenon can be modeled by using the propagation equations (8) which represents the processes of Rayleigh backscattering and the DRB.

$$
\begin{aligned}
-\frac{dP_{BS}}{dz} &= \frac{\omega_p}{\omega_s} P_p P_{BS} - \alpha_s P_{BS} + \alpha_R s\left(P_s - P_{DRB}\right) \\
\frac{dP_{DRB}}{dz} &= \frac{\omega_p}{\omega_s} P_p P_{DRB} - \alpha_s P_{DRB} + \alpha_R s P_{BS}
\end{aligned} \tag{8}
$$

2.3. Erbium doped fiber amplifier

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 erbium doped fiber.

On the base of the rate equations, a formula that calculates the number of the erbium ions in excited state (N_2) can be written as [2], [7]:

$$
\begin{aligned}
N_2 = &\left(\sum_i \frac{\tau\sigma^a_{v_i}}{Ahv_i}\Gamma_s P_{s_i} + \sum_j \frac{\tau\sigma^a_{v_j}}{Ahv_j}\Gamma_{v_j} P_{ASE_j} + \frac{\tau\sigma^a_p}{Ahv_p}\Gamma_p P_p\right) N \text{ x} \\
&\left[\sum_i \frac{\tau\left(\sigma^a_{v_i} + \sigma^e_{v_i}\right)}{Ahv_i}\Gamma_s P_s\left(v_i\right) + \sum_j \frac{\tau\left(\sigma^a_{v_j} + \sigma^e_{v_j}\right)}{Ahv_j}\Gamma_{v_j} P_{ASE}\left(v_j\right) + \right. \\
&\left. + \frac{\tau\left(\sigma^a_p + \sigma^e_p\right)}{Ahv_p}\Gamma_p P_p + 1\right]^{-1},
\end{aligned} \tag{9}
$$

where τ is the life time of electrons in exited state, σ^e and σ^a are emission and absorption cross section, A is effective area of erbium fiber, hv – photon energy, Γ – overlap factor, N – erbium ions concentration and v is the signal light frequency. The indexes used in formula 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 and the signal attenuation is negligible low, the propagation equations can be described as [2]:

- for signal and pump powers:

$$
\frac{dP(\lambda)}{dz} = \Gamma(\lambda) P(\lambda)\left[N_2\sigma^e(\lambda) - N_1\sigma^a(\lambda)\right], \tag{10}
$$

- for ASE noise power:

$$
\begin{aligned}
\frac{dP^{\pm}_{ASE\_E}(\lambda)}{dz} = &\pm\Gamma(\lambda) P^{\pm}_{ASE\_E}(\lambda)\left[N_2\sigma^e(\lambda) - N_1\sigma^a(\lambda)\right] \\
&\pm\sigma^e(\lambda) N_2 \Gamma(\lambda) P_0(\lambda).
\end{aligned} \tag{11}
$$

where N_1 is the number of erbium ions in ground state and P_0 is the part of ASE noise power that propagates along with the signal. The parameters used in the formulas given above are related to different wavelength λ.

When calculating P_{ASE}, we take into consideration just the part of power that propagates to the signal direction P^{+}_{ASE}, which is defined by the expression:

$$
P_{ASE\_E} = n_{SP} hv(G-1)\Delta v, \tag{12}
$$

where n_{SP} is inversion population factor of EDFA, Δv – waveband of optical filter and G is amplifier gain, which can be obtained by integration of the signal propagation equation (11) along the EDF length and is expressed with the formula:

$$
G_{EDFA}(\lambda)[\text{dB}] = 4.3\,\Gamma_s(\lambda)\left[\overline{N}_2\sigma^e_s(\lambda) - \overline{N}_1\sigma^a_s(\lambda)\right] L, \tag{13}
$$

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.

To estimate noise characteristics of EDFA, its noise figure (*NF*) described by the following relationship is used:

$$
NF(\lambda)[\text{dB}] = 10\,\text{lg}\left(2\,\bar{n}_{sp}(\lambda)\frac{G(\lambda)-1}{G(\lambda)}\right), \tag{14}
$$

where n_{sp} can be calculated as follows:

$$
\bar{n}_{sp}(\lambda) = \frac{\sigma^e_s(\lambda)\overline{N}_2/N}{\sigma^e_s(\lambda)\overline{N}_2/N - \sigma^a_s(\lambda)\left(1-\overline{N}_2/N\right)}. \tag{15}
$$

3. DESIGN OF EDFA WITH CONSTANT GAIN

In general case, EDFA operates in saturated mode and its output power remains constant even when input power varies with more than 10 dB. When we are designing hybrid amplifier we have to get into consideration the fact that Raman amplifier can work only in constant gain regime. Therefore, the condition for normal operation of hybrid amplifier is both co-amplifiers to work in constant gain mode.

Since the EFDA gain spectrum depends significantly on the parameters of the applied doped fiber, each 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 $N = 0.7\text{x}10^{-25}$ m^{-3}, ions lifetime in the upper state $\tau = 10$ ms; overlap factors $\Gamma_s(1525–1565) = 0.40$ and $\Gamma_p(980) = 0.64$. The used values of emission (σ^e) and absorption (σ^a) cross-section are reached from experimentally measured values of σ^a given in [8] and the McCumber relationship is used to calculate parameter σ^e.

In order to study gain spectrum profile and possibilities for wideband amplification of multi-wavelength signal (13) is circumstantially analyzed. It is clearly seen that gain magnitude G_{EDFA} is mainly determined by the EDF length whereas its profile entirely depends on the average fractional upper-state population $\overline{N_2}/N$. Therefore, simulation which shows dependence of gain profile on the parameter $\overline{N_2}/N$ is conducted. To eliminate influence of fiber length, parameter G_1 which describes the amplification per unit length of the active fiber, expressed in dB/m is used.

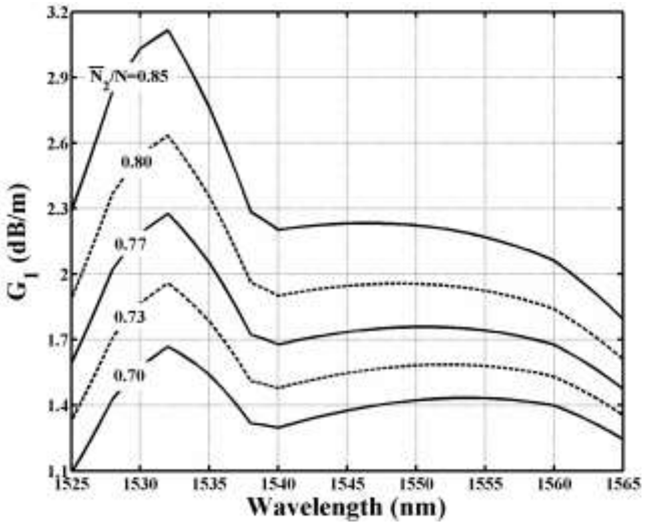

Fig. 2. *Influence of the fractional upper-state population on the gain spectrum*

On the base of the simulations results can be defined that the gain spectrum characteristic does satisfy the requirement for maximum gain flatness within the wavelength range from 1540 to 1560 nm, as the best results in the case are obtained when $\overline{N_2}/N$ is 0.77. Therefore, the main condition for gain flatness and operation with constant gain is maintaining a constant value of parameter $\overline{N_2}/N$ for each values of input power.

From the (9) can be concluded that the value of the parameter $\overline{N_2}/N$ depends only on the parameters of the erbium-doped fiber and the signal and pump powers. So it is of special interest for the engineering practice to determine the value of P_p that would provide the constant value of $\overline{N_2}/N$ for different levels of the input signals. The algorithm used by researchers to develop the needed relationship is based on the assumption that the value of EDFA gain (G_{EDFA} in dB) is preliminary set. Thus, the length L of the doped fiber can be determined from (13) in a way to provide the given gain when $\overline{N_2}/N = 0.77$. The calculated value

$$(16)\quad L = G_{EDFA}\left\{\frac{1.72N}{k}\sum_k\left[0.764\sigma_s^e(\lambda_k) - 0.236\sigma_s^a(\lambda_k)\right]\right\}^{-1}$$

is substituted into propagation equations (11) and as a result the following relationship can be obtained:

$$(17)\qquad P_p = P_{s\,in}\, G / E_q$$

where E_q is the quantum efficiency of the amplifier. On the base of the determined optimum values given above, the quantum efficiency is defined ~ 59 % when P_p > 100 mW. Then the final formula to calculate the pump power can be written in the form:

$$(18)\qquad P_p\left[\mathrm{dBm}\right] = P_{s\,in}\left[\mathrm{dBm}\right] + G\left[\mathrm{dB}\right] + 2.4\,.$$

This expression gives the proportional relation between input signal and pump powers which provide $\overline{N_2}/N = 0.77$. Therefore (18) can be considered as a condition to attain constant gain and maximum gain flatness in the researched range. This is physically realized by including control system which manages the pump laser current as a function of total input power.

4. SIMULATIONS AND RESULTS

In multistage amplifiers of great significance is the noise performance of the first-stage amplifier. Therefore the first step of improving amplifiers' parameters must be minimization of generated by the distributed Raman amplifier noise power.

4.1. Minimization of noise power of DRA

Analysis of (6) and (8) which describe the noise power from ASE and DRB shows that their magnitudes depend on the optical fiber length, pumped power and distribution of pumped power between both sides of transmission span. For the experiment, fiber length is fixed at L = 120km. Since the magnitude of the total pumped power defines amplifier gain, the simulation has been conducted with three values P_p = 600, 800 and 1000mW, which correspond to – 6,5 dB, 0 dB and 6,5 dB net gain.

The results plotted on the figure 3 show that minimum of total noise power can be obtained when:

- P_p = 600 mW, S = 0.82 – P_n = – 55.40 dBm;
- P_p = 800 mW, S = 0.58 – P_n = – 48.65 dBm;
- P_p = 1000 mW, S = 0.51 – P_n = – 41.85 dBm.

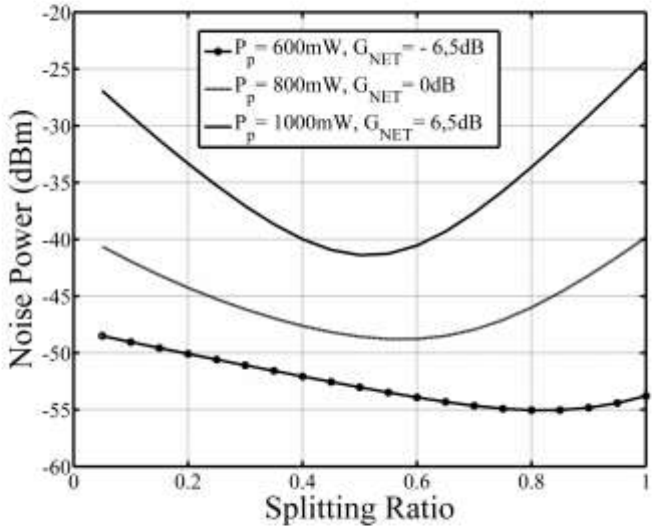

Fig. 3. *Dependence of noise power on splitting ratio*

From the results easily can be determined that the increasing of noise power is almost proportional to the variation of G_{NET} . This simulation is essential because it gives values of the splitting ratio, respectively pumping mode, which ensure noises minimization. These values reached above are considered as optimal and are used in the next simulations.

4.2. Noise Figure

The parameter noise figure is calculated as difference (in dB) between *CNR* at the EDFA output and *CNR* at beginning of the transmission span. In order to obtain real value of *NF* the calculated results are decreased with the value of attenuation which signals and noise power have received while being carried over an optical channel. Reducing of noises while they are propagating is one of the most significant advantages of distributed Raman amplifiers.

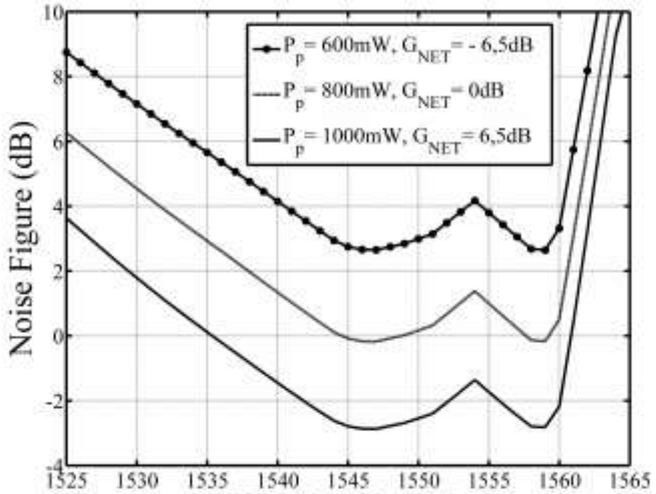

Fig. 4. *Noise Figure Spectrum*

On the figure 4 the spectral distribution of noise figure for the three optimized cases is presented. It is clearly seen that the *NF*-spectrum shape follows the inverted G_{NET} spectrum profile, shown on figure 5, due to proportional dependence between net gain and signal power loaded at the input of EDFA. The relation between *NF* and EDFA input power is also confirmed by analysis of the three cases simultaneously. It is clear that the increasing of G_{NET} with 6.5 dB leads to improvement of the whole spectrum curve of *NF* with 2.6 dB. This proportionality is retained even net gain is more increased and the additional plotted curves do not give more information. On the other side endless increasing of net gain leads to the impermissible high levels of the carried signals which causes significant influence of nonlinear phenomena such as stimulated Brillouin scattering, four-wave mixing etc.

4.3. Gain Spectrum

In order to reach maximum gain flatness and maximum waveband of aggregate characteristic is necessary to know both amplifiers gain behavior. On the figure 5 gain spectrums of Raman amplifier (G_{DRA}), EDFA (G_{EDFA}) and total gain of hybrid amplifier (G_{HYBRID}) are shown.

The results presented on the figure 5 are attained for the third case where the total pumped power of DRA is 1000 mW distributed of ratio 0.51 / 0.49 between the first and the second laser, which emit at 1546nm. EDFA is designed with G_{EDFA} = 17dB and L_{EDF} = 9.49m. At the beginning of the transmission span 41 equal signals with level of − 13 dBm placed by step of 1 nm in the range from 1525 to 1565nm are loaded.

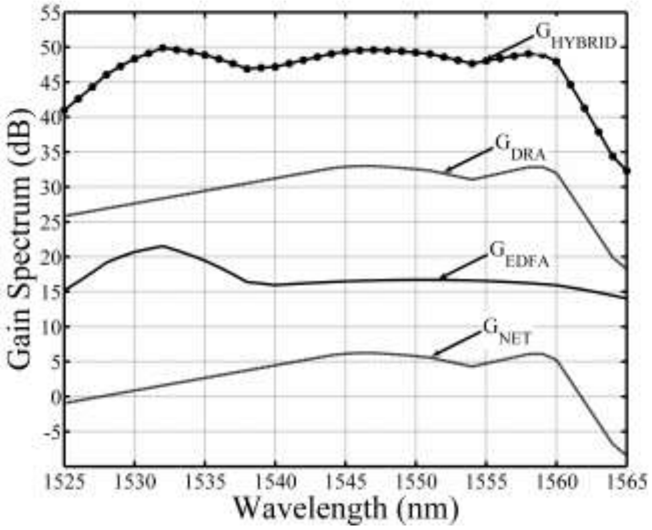

Fig. 5. *Signal Gain Spectrum*

In the G_{NET} spectrum can be marked three ranges: up to 1545 nm, between 1545 and 1560 nm and above 1560nm. Special interest for engineering practice has the middle range which is relatively flat for 15 nm. It is noteworthy that this range is not fixed with concrete value of wavelength and can be moved on wavelength axis.

Examination of EDFA gain spectrum shows availability of two main ranges – flat gain from 1538 to 1560 nm and gain pick from 1525 to 1538 nm. It is convenient, because the relatively lower gain on the first range of DRA could be compensated by the gain pick from EDFA gain spectrum. Therefore, conditions of successful combining are available.

The method used in this paper is based on equalization of total gain values in several specific wavelengths such as the region around the EDFA gain pick at 1532nm and both maximums from the DRA gain curve. This is realized by changing the wavelength of DRA pump lasers and adjusting the gain coefficients of both amplifiers.

From the characteristics plotted on the figure 5 can be defined that separated application of EDFA ensures maximum of gain flatness into the range from 1538 to 1560nm and EDFA gain is equal to 17 ± 0,5dB. Regarding Raman amplifier, its gain spectrum is relatively flat for 20nm and when pump laser wavelength is 1446nm flat gain spectrum is obtained in the range from 1540 to 1560nm. Averaged gain value in the same range is 32dB and maximum deviation is 1dB.

When both amplifiers work simultaneously, the operation waveband is extended from 1529 to 1560nm and total gain of hybrid amplifier G_{HYBRID} reaches 48.4 ± 1,45 dB. It is obvious that the deviation from the average value is maximum when $\lambda = 1538$nm due to impossibility for full compensation of the high slope of EDFA gain spectrum in the range from 1532 to 1538nm.

5. CONCLUSION

As seen from the investigations, the maximum gain flatness and minimum noise figure of the designed hybrid amplifier, composed of distributed Raman amplifier and EDFA, in the wavelength range from 1529 nm to 1560 nm can be obtained if several requirements are met. The first, minimum level of noise power can be reached when the total pump power is distributed between both lasers in optimum ratio, which in case when total P_p of DRA is 1000 mW, is 0.51% / 49%.

To be provided constant gain and maximum gain flatness in EDFA the average value of the fractional upper-state population must be equal to the optimum value, i.e. $\overline{N_2}/N = 0.77$. This is ensured as the erbium-doped fiber length and the pump power are calculated by expressions (17) and (18).

The third correspond to fixing a Raman amplifier pump laser wavelength at 1446nm in order to reach maximum of total gain flatness 48.4 ± 1,45dB and maximum of operation waveband (31 nm) from 1529 to 1560nm.

The designed hybrid amplifier combines the advantages of both co-amplifiers such as: low noise figure and wavelength-adjustable gain coefficient of Raman amplifier and high output power and low price of EDFA, respectively. Moreover, by setting appropriate operating mode of the hybrid amplifier its waveband is extended with 50 % in comparison with the cases when EDFA and Raman amplifier are used separately.

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