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PAPERS

Simulation of the optical erbium doped fiber amplification for performance analysis

Rastislav Róka[1]

In this contribution, innovations in the simulation of the optical transmission path are presented specifically, the dynamic performance analysis of erbium doped fiber amplifier (EDFA) properties for system applications is focused. Our EDFA simulation model is based on population equations of ions that can describe mutual relations between three states of ions in the EDFA amplifier. The presented numerical approach includes a signal gain and noise contributions to the single input channel amplification using the steady state modelling coming out of a dynamic model. The EDFA model in the steady state can be consequently applied for a purpose of advanced si mulations performed in the complete optical transmission path.

K e y w o r d s: the EDFA amplifier, population equations of ions, output EDFA characteristics, the steady state model, numerical simulations

1 Introduction

Ever increasing enduser requirements for higher capacity, lower cost, and lower energy consumption lead to increased demands for the data transmission speed and thus to the need to develop novel services and technologies used in optical communication networks. Recently, the focus has been paid to long-haul networks with capacity more than 100 Gb/s per one channel and with more flexible grid based on 12.5 GHz [1]. This increased network capacity and flexibility can be reached as well using advances in optical fibers, amplification and regenerations, high order modulation formats, multiplexing techniques such as the wavelength division multiplexing (WDM), advanced routing and spectrum allocation schemes [1–4].

The simulation allows increasing the data rate and the transmission range of deployed optical transmission systems using advanced signal processing techniques and allows designing a new optical transmission system with different optical fibers. Due to increased demands for transmission rates in the optical transmission medium, it is very important to avoid expensive practical demonstration and testing. Therefore, simulation platforms are increasing their role. However, it is important to search for a simulation platform that will be able to accurately describe behavior and limitations of the optical transmission system under various working conditions. After becoming acquainted with several various commercial simulation software products, we decided for designing and creating our own simulation platform based on the Matlab Simulink programming environment.

The beginning phase of our work was focusing on an optical transmission medium, primarily on linear and non-linear effects present in the single-mode optical fiber and on analyzing environmental negative influences on transmitted optical signals. Its summary presents the base of simulation tools for broadband optical networks [5]. The developing phase is focusing on another significant components of the optical transmission path with an emphasis placed on their specific features influencing transmitted optical signals.

Advances in optical amplifier research can have a very beneficial impact on data transport cost and energy efficiency in elastic optical networks. Optical amplifiers can compensate losses of optical signals in the optical transmission medium. Optical amplifiers are utilized in specific places of the optical transmission path to reach a required distance for the signal transmission regarding its losses. Received optical signals must achieve some measurable and detectable power level in the optical receiver for specification of bit error rates. In a developing process, it is very important to avoid expensive practical testing and demonstrations. Therefore, it is necessary realize experimental efforts in an appropriate simulation platform for the optical transmission system that can accurately describe a behavior of optical components at the signal transmission under varying working conditions.

This contribution presents innovations in the enhanced simulation tool for analyzing the performance of optical dopped fiber amplification techniques in the optical transmission path. These are representing an upgrade of the base of simulation tools including specific optical amplifiers suitable for transmitted optical signals associated with new multimedia broadband services and advanced applications provisioned in modern optical networks. Also, we present a mathematical methodology that can be used to model a behavior of the erbium doped fiber

[1] Slovak University of Technology, Faculty of Electrical Engineering and Information Technologies, Institute of Multimedia Information and Communication Technologies, Ilkovičova 3, 812 19 Bratislava, Slovakia, rastislav.roka@stuba.sk

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Table 1. Parameters for the simulation of output EDFA characteristics

Parameter	Unit	Extracted value
r	m	1.4
$\Gamma_{p(980)}$	-	0.64
$\Gamma_{p(1480)}$	-	0.43
Γ_s	-	0.4
ρ	ions/m^3	6.3×10^{24}
τ_e	ms	10
$\sigma_{1\text{-}2}$	m^2	2.4×10^{-25}
σ_{2-1}	m^2	3.8×10^{-25}
$\sigma_{1-3(980)}$	m^2	2.7×10^{-25}
$\sigma_{1-3(1480)}$	m^2	1.5×10^{-25}
λ_s	nm	1550
λ_{p1}	nm	980
λ_{p2}	nm	1480

amplifier (EDFA) under different operating conditions in the optical transmission path.

2 Equations for the EDFA model in the steady state

Erbium doped optical amplifiers are commonly used in commercial optical transmission systems due to their high optical amplification compared to costs against optical amplifiers utilizing other mechanisms for signal amplifying [6].

The signal gain in a doped fiber amplifier is achieved when a population inversion of erbium ions reaches a sufficiently high level. This can be achieved with available pump lasers. In real optical amplifiers with a doped fiber, the pump wavelength must provide a high power for reaching a high pump gain. In praxis, the 980 nm wavelength pump source is used due to its high gain coefficient up to 4 dB/mW. Differences between pump sources with 980 and 1480 nm wavelengths are caused above all by absorption and emission factors. A change in the EDFA signal gain can be achieved by changing the doped fiber's length, the pumping power and/or the pumping wavelength. Based on our previous research [7], we can confirm following conclusions. The first, the signal gain increases with increasing the erbium doped fiber's length only to a certain value. The second, the signal gain increases with increasing the pump power and is approaching asymptotically to its highest value. Furthermore, noises are also generated over the EDFA signal amplification. A dominant noise is the amplified spontaneous emission (ASE) noise. The ASE spectral range is too broad, *ie* 1530–1625 nm, it covers a gain spectrum of the amplifier and thereby it decreases an available signal gain [6]. The ASE level is increasing by repeated transitions through EDFA amplifiers and thereby it begins to saturate subsequent amplifiers and to decrease a total signal gain.

A complete list of parameters for the output EDFA characteristics and their extracted values [6], [7] is displayed in Tab. 1.

For time-depending population of erbium ions in the metastable state in the EDFA amplifier [8–11], a dynamic model was evolved based on nonlinear differential equations. We can distinguish three population states of erbium ions with a proper population density – the fundamental (or stable) state with N_1 population density, the metastable (or steady) state with N_2 population density and the excited state with N_3 population density. The basis of our EDFA model is presented by population equations for these three states of ions as follows [6],

– the stable state

$$\frac{\partial N_1(t)}{\mathrm{d}t} = - W_{1\text{–}3}N_1(t) - W_{1\text{–}2}N_1(t) + W_{2\text{–}1}N_2(t) + \\ + \frac{N_2(t)}{\tau_{2\text{–}1}} + W_{3\text{–}1}N_3(t) + \frac{N_3(t)}{\tau_{3\text{–}2}}, \tag{1}$$

– the steady state

$$\frac{\partial N_2(t)}{\mathrm{d}t} = W_{1\text{–}2}N_1(t) - W_{2\text{–}1}N_2(t) + W_{3\text{–}2}N_3(t) - \frac{N_2(t)}{\tau_{2\text{–}1}}, \tag{2}$$

– the excited state

$$\frac{\partial N_3(t)}{\mathrm{d}t} = W_{1\text{–}3}N_1(t) - W_{3\text{–}2}N_3(t) + W_{3\text{–}1}N_3(t) - \frac{N_3(t)}{\tau_{3\text{–}2}}, \tag{3}$$

where W values present transition rates between states of ions labeled as 1–2, 1–3, 2–1, 3–1 and 3–2 and τ denotes a florescence lifetime of ions between states.

The lifetime 2–1 of ions from the steady state to the stable state is longer than the lifetime 3–2 from the excited state to the steady state. It means that ions are accumulated in the metastable state and a population of ions in the excited state is negligible comparing to the short lifetime 3–1 of ions.

A dynamic model of the EDFA amplifier is focusing on high input power levels used in a multichannel optical network. In the dynamic EDFA model, a parameter of time is very important comparing to the EDFA model in the steady state. The time dependency is very important above all in an optical network with continually reconfigurable optical channels. Thanks to multichannel amplification and using the dynamic model, the EDFA signal gain can be predicted more precisely. One of advantages of the EDFA is its slow dynamics because of the long spontaneous lifetime of around 10 ms. This is also a reason why steady state models can play an important role in the dynamic analysis of EDFA properties for system applications. The aim of our simulation is acquiring values of the EDFA amplification irrespective of time, we prefer creating the EDFA model in the steady state for a single input channel. For multichannel amplification, this model can be easily modified. Following terms and equations are very similar with the EDFA modelling in the stable state, so some differences are emphasized [6],

$$W_{1\text{–}2} = \frac{\Gamma_{\mathrm{S}}\sigma_{1\text{–}2}cP_{\mathrm{Sin}}}{h\lambda_{\mathrm{S}}A}, \tag{4}$$

$$W_{1\text{–}3} = \frac{\Gamma_{\mathrm{P}}\sigma_{1\text{–}3}cP_{\mathrm{Pin}}}{h\lambda_{\mathrm{P}}A}, \tag{5}$$

$$W_{2\text{–}1} = \frac{\Gamma_{\mathrm{S}}\sigma_{2\text{–}1}cP_{\mathrm{Sin}}}{h\lambda_{\mathrm{S}}A}, \tag{6}$$

where A presents a core area of the erbium doped fiber, h is the Planck constant, P_{Sin} is the input signal power, P_{Pin} is the input pump power, λ_{S} is a signal wavelength, λ_{P} is a pump wavelength, Γ_{S} is the overlap factor at the signal wavelength, Γ_{P} is the overlap factor at the pump wavelength, $\sigma_{1\text{-}2}, \sigma_{1\text{–}3}$ and $\sigma_{2\text{–}1}$ are absorption and emission factors at the signal (1–2, 1–3) and pump (2–1) wavelengths.

Input channels on various wavelengths have different values of the EDFA signal gain caused by the spectral dependency of absorption and emission cross-sections and by the overlap factor. Therefore, this presumption must be emphasized at the model's modification for multichannel amplification.

A signal gain increment along the EDFA amplifier is nonlinear and its exponential change is assumed, therefore the signal power P_{Sout} can be expressed as follows, [6]

$$P_{\mathrm{Sout}} = P_{\mathrm{Sin}} \exp\left(\frac{\Gamma_S(\sigma_{1\text{–}2} + \sigma_{2\text{–}1})}{A} N_2 - \Gamma_S\sigma_{1\text{–}2}\rho L\right), \tag{7}$$

where L presents a length and ρ presents the ion density of the erbium doped fiber.

The ASE noise is stochastic and can be modelled by generating complex spectral components with stochastic variables accomplishing a function of the Gaussian probability density with the P_{ASE} variance corresponding the average noise level. The ASE noise spectral power PASE can be estimated over a bandwidth Δf as follows

$$P_{ASE} = n_{\mathrm{sp}}(G-1)hf_S\Delta f, \tag{8}$$

where the bandwidth must be sufficiently wide and sensitive for the ASE detection in the 1480–1605 nm spectral range, G is a small signal gain amplification, f_{S} is a signal frequency and n_{sp} is the population inversion factor. For ASE noise modelling, a Gaussian wave with the ASE mean power and variance is used [6]. In our simulation, the ASE noise power is a main noise source and other noise sources are negligible [12, 13].

3 The EDFA model in the optical transmission path

The presented EDFA model is realized in the Matlab Simulink program environment because its simplicity and functionalities. The EDFA model represents a doped fiber amplifier with forward pumping and is created on principles for the steady state modelling with a single input channel. This EDFA model can be incorporated into a simulation platform of the optical transmission path created in the Matlab Simulink. The simulation platform consists of following functional blocks representing distinguished optical components:

- Bernoulli generator (green)
- DFB Laser (turquoise)
- Mach-Zehnder modulators (blue)
- Single mode optical fiber (red)
- EDFA (orange)
- Optical receiver (dark glue)
- Measurement units - eye and constellation diagrams (white)

The simulation platform is performed in the Matlab R2017B Simulink software based on previous works [5, 14–16]. In Fig. 1, there is presented a complete block scheme for the optical transmission path including main optical components. The Bernoulli Generator block stands for a random data stream that is used to control arms of the Mach-Zehnder modulators (MZM). This data stream is shaped as a Gaussian wave to maintain a shape of real generated data signals. The DFB Laser block represents the continuous-wave light stream produced by a distributed feedback laser on that is modulated information data stream using the MZM. The polarization beam splitter divides a signal from the DFB laser into two polarization planes that are entering MZM V and MZM H branches. The SMF block represents the transmission

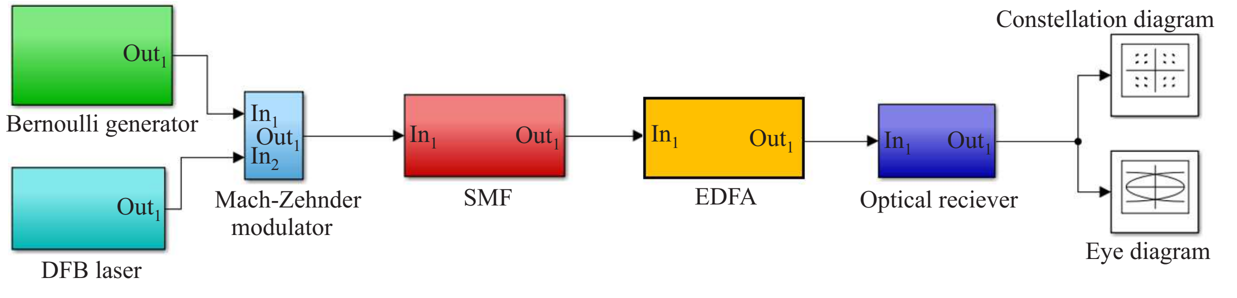

Fig. 1. The model of the optical transmission path with the EDFA block

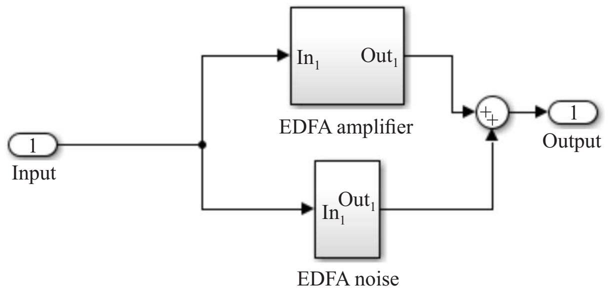

Fig. 2. The EDFA block scheme

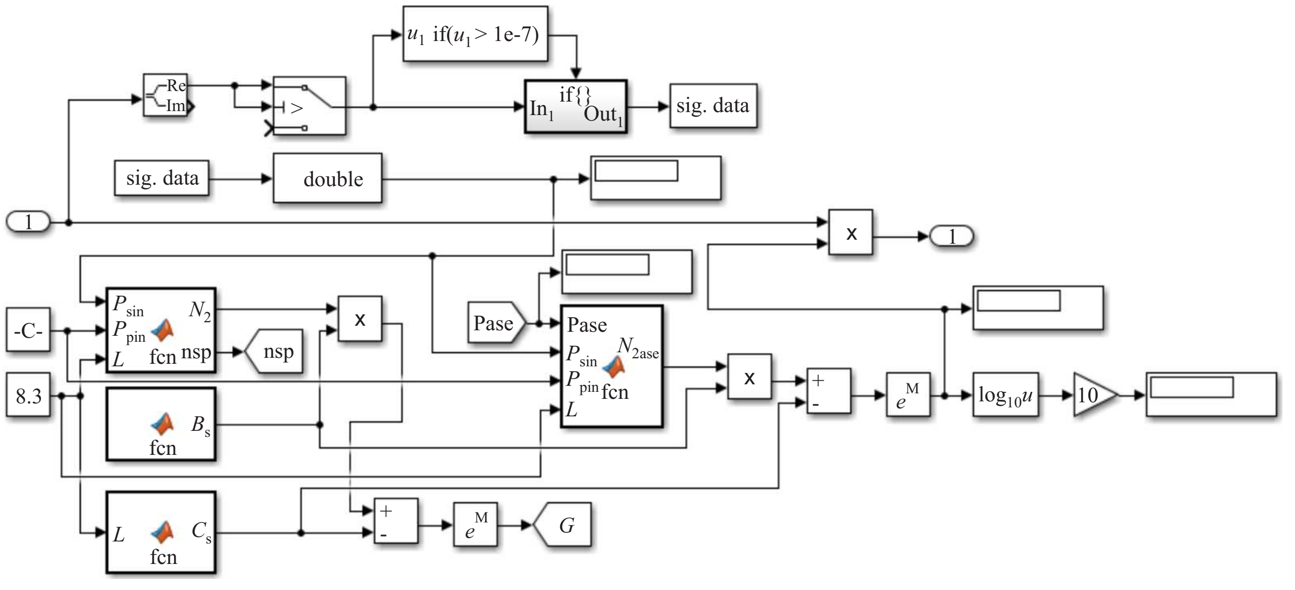

Fig. 3. The detailed scheme of the EDFA amplifier block

medium of the single-mode optical fiber including relevant environmental negative effects [17], [18]. The Optical Receiver block is represented by a preamplifier and the PIN diode with corresponding noise sources. The optical signal can be pre-amplified before the opto-electronic conversion by the EDFA block. Measurement units present Eye Diagram and Constellation Diagram blocks used for evaluating transmitted signals and for estimating BER values.

The EDFA block (Fig. 2) consists of the EDFA Amplifier block modelled by equations presented in Section I. and the EDFA Noise block involving noise components present at amplification. Most of parameters for the EDFA amplifier is defined in Tab. 1. However, parameters can differ according to applied optical doped fibers, respectively to a material forming a core of the optical fiber. Also, some parameters can vary depending on various wavelengths of optical signals. Moreover, parameters for both pump wavelengths are different, [11],[19].

The EDFA Amplifier block (Fig. 3) realized in the Simulink is based on (7). It contains four main functions for calculation of amplified output signals. The first N_2 function presents a population density of erbium ions in the steady state with three required parameters (P_{Sin}, L, P_{Pin}). Together with B_{s} and C_s functions determining the exponent in (7), they allow to calculate the input signal gain amplification without noises. The last N2ASE function calculates a population density of erbium ions in the steady state with the ASE noise contribution.

The EDFA Noise block (Fig. 4) is realized on the equation (8) and includes only the ASE noise because contributions of other noise types are negligible, respectively incorporated into the total ASE noise [12, 13]. The Δf bandwidth is determined using a gain spectrum of the EDFA, from 1500 nm up to 1600 nm spectral range in our case.

A main limiting factor of the simulation is the input pump power because pump powers are limited to the 950 mW value in practice [20]. With higher pump power, the noise is also higher, but the pump-to-noise power ratio is changing just marginally. Another limiting factor is a length of the erbium doped fiber. With longer length, a population density of erbium ions is also increased. Subsequently, the noise power level is increased.

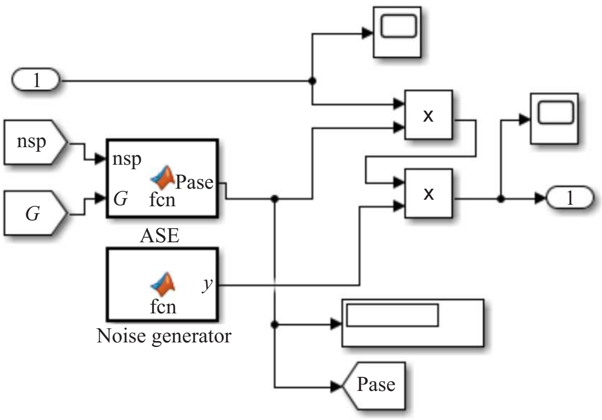

Fig. 4. The detailed scheme of the EDFA noise block

4 Results of the EDFA simulation

All simulations are realized in Matlab R2017B. Two steps of simulations are executed to obtain output characteristics of the EDFA amplification. The first step is focused on input signal gain and noise power characteristics for the 980 nm and 1480 nm pump wavelengths. Consequently, the second step is dedicated to comparing and analyzing acquired dependencies on input pump powers for both pump wavelengths.

First, results of the EDFA simulation for the 980 nm pump wavelength are presented.

In Fig. 5, we can see that an increment of the input pump power leads to increasing of the input signal gain, however only to the definite length of erbium doped fiber. With longer doped fiber's lengths, a population density of erbium ions is higher and therefore an input signal gain amplification is more sensitive to noises. With higher input pump powers, longer length of the erbium doped fiber is more suitable for utilizing to achieve a maximum gain amplification of input signals.

In Fig. 6, we can see that an exponential increment of the noise power is appearing around 10 m length of the erbium doped fiber. This value differs in regard of used input pump powers. With shorter doped fiber's lengths, noise power levels are very low and simultaneously an input signal gain amplification is very small. Therefore, a combination of input pump powers and doped fiber lengths is more suitable for utilizing to achieve higher gain amplification of input signals and larger signal-to-noise ratio. Also, with higher pump powers for the EDFA pumping, higher ASE noise power can be reached. However, critical noise values can be reached beyond 10 m lengths of the erbium doped fiber.

In Fig. 7, we can see that shorter lengths of the erbium doped fiber are more suitable for utilizing to achieve lower input pump powers. Also, a length limit of the erbium doper fiber differs about input pump powers. Respectively, higher input pump powers are more suitable for utilizing to reach an optimum gain amplification of input signals for longer doped fiber's lengths. It can be verified that each input pump power has its own length limit, and its maximum efficiency can be reached on different lengths of the erbium doped fiber. The signal-to-noise ratio is largest at shorter doped fiber's lengths and gradually decreases. But the noise power is increasing exponentially for longer lengths of the erbium doped fiber.

In Fig. 8, we can see that a saturation of the erbium doped fiber amplifier is achieved at different values of the input signal gain and especially at various values of the input pump power for each length of the erbium doped fiber. So, we can reach smaller input signal gain amplification at lower input pump powers for longer lengths of the erbium doped fiber.

In Tab. 2, a maximum input signal gain for various erbium doped fiber lengths is presented depending on input pump powers at the 980 nm pump wavelength. The signal-to-noise ratio is approximately equal for each pump power, although a noise power level is increasing.

For the 1480 nm pump wavelength, we realized the same simulations as for the 980 nm pump wavelength. In Table 3, a maximum input signal gain for various erbium doped fiber lengths is presented depending on input pump powers at the 1480 nm pump wavelength.

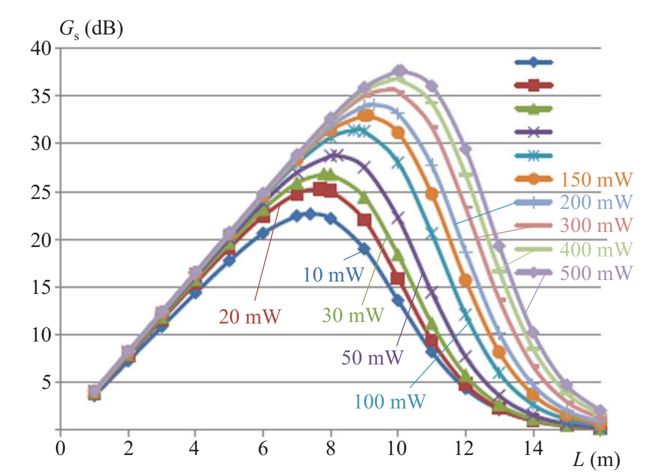

Fig. 5. Input signal gain dependencies on Er doped fiber lengths for various input pump powers at the 980 nm pump wavelength

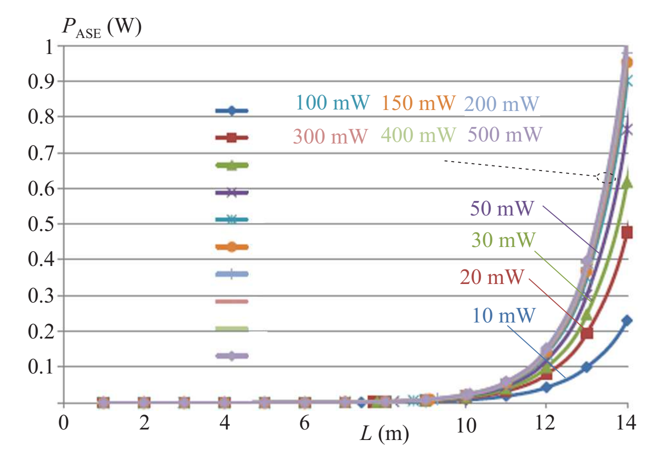

Fig. 6. Noise power dependencies on Er doped fiber lengths for various input pump powers at the 980 nm pump wavelength

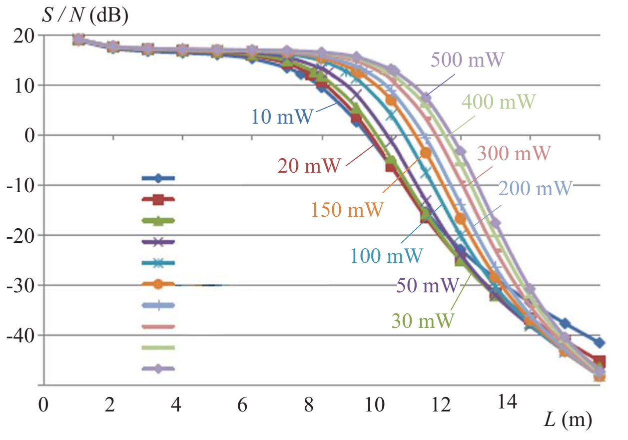

Fig. 7. Signal-to-noise ratio dependencies on Er doped fiber lengths for various input pump powers at the 980 nm pump wavelength

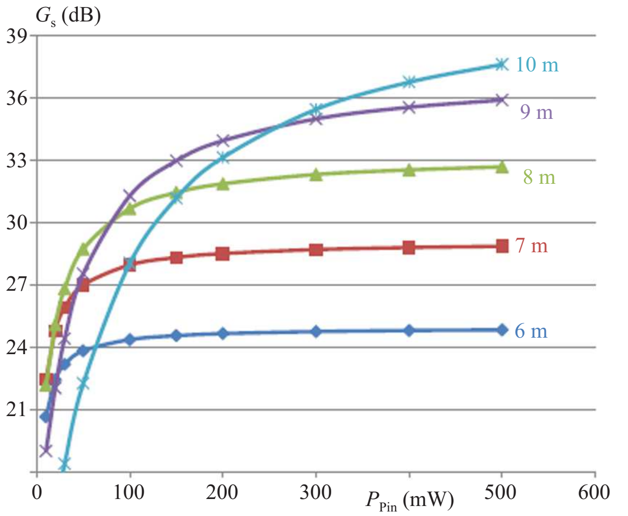

Fig. 8. Input signal gain dependencies on input pump powers for various Er doped fiber lengths at the 980 nm pump wavelength

For comparison, we prepared simulations executed for the 8 m erbium doped fiber length and some graphs presented in Fig. 9. A maximum input signal gain that can be reached at the 980 nm pump wavelength is around 2 dB/mW higher than at the 1480 nm pump wavelength. Our results verify assumptions introduced in [6, 21].

By comparison of Tab. 1 and Tab. 3, we can see that noise powers at the maximum input signal gain for optimum lengths of the erbium doped fiber are lower by using the 1480 nm pump wavelength. However, the 980 nm pump wavelength is still preferable option for achieving a maximum input signal gain amplification because the signal-to-noise ratio is balanced in both cases of pump wavelengths.

In Fig. 10, we can see that noise powers at the 980 nm pump wavelength are higher than at the 1480 nm pump wavelength for each pump power. Higher ASE noise power levels at the 980 nm pump wavelength are caused by a fact that a population density of erbium ions in the steady state is higher than at the 1480 nm pump wavelength. A main reason is that absorption and emission factors and an overlap factor are higher at the 980 nm.

Based on acquired simulation results, we can confirm that a forward pumping of the EDFA is the most suitable at the 980 nm pump wavelength because it reaches a maximum input signal gain around 2 dB/mW higher than at the 1480 nm pump wavelength regarding the doped fiber length and input pump powers. Noise power levels are higher at the 980 nm pump wavelength however, the signal-to-noise ratio is nearly balanced The efficiency of the erbium doped fiber is decreasing behind 10 m lengths depending on used input pump powers. For larger input pump powers, longer length of the erbium doped fiber is more effective for utilizing to achieve higher efficiency of a gain amplification of input signals.

Table 2. Maximum signal gain values for input pump powers and erbium doped fiber lengths at the 980 nm pump wavelength

P_{Pin} (mW)	L (m)	G_{S} (dB)	P_{ASE} (mW)	S/N (dB)
10	7.4	22.65	0.909	12.1
20	7.7	25.30	1.69	12.
30	7.8	26.84	2.11	12.6
50	8.2	28.79	3.43	12.5
100	8.7	31.43	6.03	12.7
150	9.1	32.99	9.1	12.4
200	9.3	34.10	11.3	12.6
300	9.7	35.67	16.7	12.5
400	9.9	36.78	20.4	12.7
500	10.1	37.65	24.8	12.7

Table 3. Maximum signal gain values for input pump powers and erbium doped fiber lengths at the 1480 nm pump wavelength

P_{Pin} (mW)	L (m)	G_{S} (dB)	P_{ASE} (mW)	S/N (dB)
10	7.5	20.37	0.614	11.5
20	7.5	23.11	1.07	11.9
30	7.5	24.66	1.32	12.5
50	7.8	26.61	2.08	12.5
100	8.3	29.24	3.85	12.4
150	8.6	30.79	5.39	12.5
200	8.8	31.89	6.70	12.7
300	9.2	33.45	10.1	12.4
400	9.4	34.56	12.4	12.7
500	9.6	35.43	15.1	12.7

For the erbium doped fiber with longer lengths than 10 meters, only the noise is transmitted because a high population density of erbium ions amplifies ASE noise components, not input signals. Moreover, a saturation of the EDFA is achieved for extra high pump powers. Therefore, a higher power of the input signals is necessary for applying to counterbalance ASE noise contributions and available lengths of the erbium doped fiber.

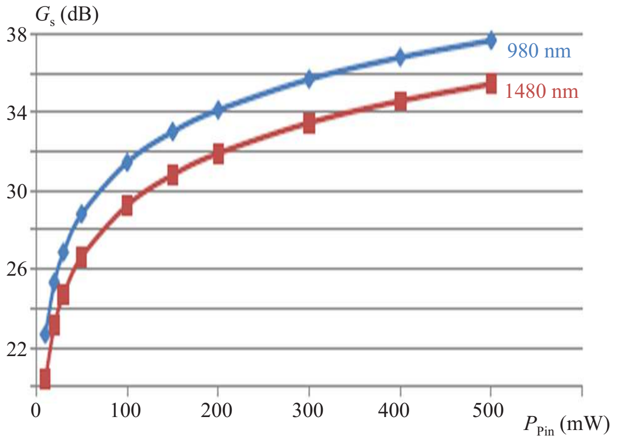

Fig. 9. Input signal gain dependencies on input pump powers for both pump wavelengths at the 8 m doped fiber length

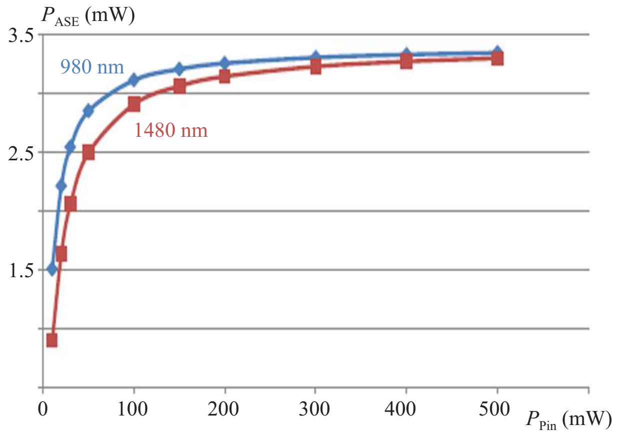

Fig. 10. Noise power dependencies on input pump powers for both pump wavelengths at the 8 m doped fiber length

5 Conclusions

This contribution presents high-innovations in the application and simulation focused on analyzing the performance of optical erbium doped fiber amplification techniques in the optical transmission path. Presented simulation results can confirm that the created EDFA model in the steady state presents a possible way for avoidance of expensive acquisition of optical technologies. It allows a software setting of necessary parameters for presentation of possible utilization under different operational conditions in real system applications.

The created EDFA model is expandable by a simple configuration of functions in the Matlab Simulink program environment. For providing more precise values and estimations of input signal gain amplifications, the presented EDFA model in the steady state is possible to upgrade for dynamic modelling and for multichannel amplification. The dynamic EDFA model is depending on a time and on a signal propagation through the erbium doped fiber and allows utilizing various input transmission channels, respectively signals working on different wavelengths. The created EDFA model in the steady state can be extended for backward pumping and/or for dual pumping by adding appropriate blocks in the simulation environment. Other possibility for the model extension is an observation for changes of output EDFA parameters regarding changes of input signals.

The enhanced simulation tool is representing an upgrade of the base of simulation tools including specific optical amplifiers suitable for transmitted optical signals associated with new multimedia broadband services and advanced applications provisioned in modern optical networks. Ultimately, this simulation tool can be adapted also for another types of doped fiber amplifiers using corresponding parameters.

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Rastislav Róka (M00SM16) became a Member (M) of IEEE in 2000, a Senior Member (SM) in 2016. (Assoc. Professor) was born in Šaľa, Slovakia on January 27, 1972. He received his MSc and PhD degrees in Telecommunications from the Slovak University of Technology, Bratislava, Slovakia in 1995 and 2002.