Investigation of SPM in WDM System with EDFA

Tomáš Ivaniga
Department of Electronics and Multimedia Communications, Faculty of Electrical Engineering and Informatics
University of Technology Košice
Košice, Slovakia
tomas.ivaniga@tuke.sk

Ľuboš Ovseník, Ján Turán
Department of Electronics and Multimedia Communications, Faculty of Electrical Engineering and Informatics
University of Technology Košice
Košice, Slovakia
lubos.ovsenik@tuke.sk; jan.turan@tuke.sk

***Abstract*—The article describes a nonlinear phenomenon SPM (Self Phase Modulation), which occurs in the all-optical communications systems. In the 21st century, the WDM (Wavelength Division Multiplex) system cannot be created without the software that simulates the system under real conditions. The most important WDM components include the EDFA (Erbium Doped Fiber Amplifier), in which amplification occurs at all wavelengths. The 10 Gbps optical line DWDM (Dense Wavelength Division Multiplex) system is created according to the ITU-T.G.694.1, in which the SPM phenomenon is observed.**

Keywords—EDFA; DWDM; OptSim; SPM

I. Introduction

In recent years, the emphasis on quantity, quality and speed of conveyed information increased. The awareness of the optical communication systems concept, which is the transmission of information through optical signals, rises. Each optical communication system comprises the transmitter and the transmission path from the receiver. The transmission medium is the optical fiber, which replaced metallic lines over time. Optical fiber is used mainly in the transmission of information over long distances. The single fiber can transmit from 10 Gbit.s^{-1} to 40 Gbit.s^{-1} data, if maximum transmission capacity is achieved. One of the options how to use the optical path more efficiently, is to apply the wavelength division multiplexing WDM.

An example is the use of 10 Gbit.s^{-1} rate transmission, where 100 spectral channels are created by using WDM and bit rate becomes 1 Tbit.s^{-1} through a single optical fiber [1], [2], [5], [6] and [16]. The limiting factor in the spread of optical radiation is the optical phenomena divided into the linear and the nonlinear phenomena. The linear phenomenon represents a deterioration of the transmission quality due to the attenuation of optical radiation and the nonlinear effects are subject to the radiation intensity. For transmissions at very large distances it is usually significantly better to use optical amplifier that amplifies an optical signal without conversion to electrical signals, which is a great advantage. Currently deployed computer simulations analyze the characteristics of the proposed communication system. There are many commercial software packages simulating the functions, deficiencies, or the maximum use of optical communication systems prior to the implementation in practice, which ultimately can save considerable funds.

II. WDM Communication System

The WDM is a technology that multiplexes many optical signals with different wavelengths into the one common signal. The single signal is transmitted through the transmission optical fiber, and finally demultiplexed to the original signal at the characteristic wavelength [1], [7]. The advantage of using WDM technology in optical communication systems is the increase of transfer speed via the single optical fiber by using WDM technology as the several channels are transmitted in one frequency channel. The disadvantage of WDM technology is necessary complexity of multiplexers and demultiplexers.

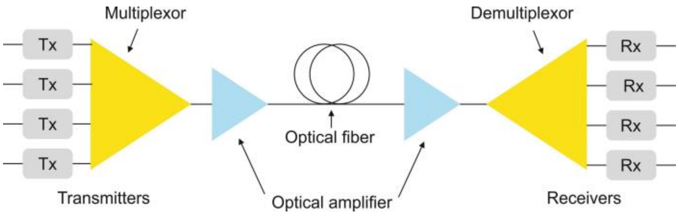

Fig. 1. The scheme of WDM technology

Fig.1 illustrates a scheme of the WDM technology, which consists of transmitters, receivers, and the optical fiber. One common signal is transmitted through the optical fiber which by using the multiplexer merges input signals into the one common signal. The demultiplexor function is the opposite, that is to divide the transmitted signal to original signals. The WDM technology is divided into two standards, the CWDM (Coarse Wavelength Division Multiplex) and DWDM (Dense Wavelength Division Multiplex).

A. *Dense wavelength division multiplex*

The DWDM multiplex uses minimal spacings between channels, which can implement dozens of wavelengths in the single optical fiber. It is necessary to ensure sufficient frequency stability and extremely narrow spectral line. The stability of the laser is provided externally by using spread feedback or by Bragg mirrors.

For the practical implementation, it is necessary to take into account that the impact of each channel will be various and consider the worst transmission properties of the same channel in the multiplex. The condition for the onset of DWDM systems to commercial deployment was developing of economically feasible production of key components such as the EDFA, multiplexor and demultiplexor units or narrowband laser transmitters [4], [6]. With the advancement in the field of development and production, but also due to the demand for the transmission capacity that occurred at the end of the 20th century, the deployment of DWDM systems in backbone transmission networks happened.

The recommendation ITU-T G.694.1 defines the different traffic channels at wavelengths, ranging from 1490 nm to 1620nm. It counts with the channel spacing 100 GHz with starting at 186 THz (spacing approximately 0.8 nm) or the double number of channels with the space 50 GHz (spacing approximately 0.4 nm) (Fig.2). Whilst transferring the DWDM, the requirement for the signal / noise spacing increases with the increasing transmission speed of the channel.

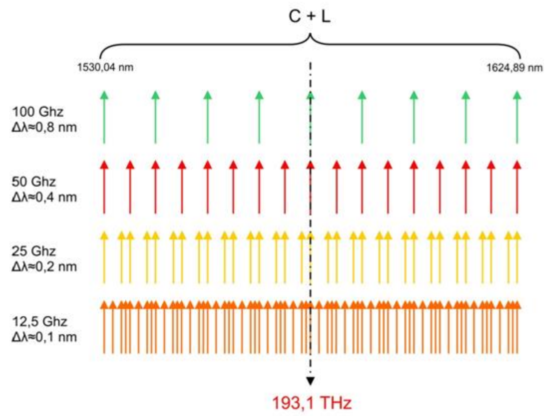

Fig. 2. The scheme of WDM technology

For example, for STM-16 (Synchronous Transport Module - 16) (2.5 Gbit.s^{-1}) is sufficient for quality transmit spacing SNR (Signal to Noise Ratio) 18 to 20 dB, STM-64 (10 Gbit.s^{-1}) requires about 22 dB and for STM-256 (40 Gbit.s^{-1}) is approximately 25 dB [4], [14]. For the transmission quality it is necessary that the actual wavelength of the channel (i.e. the wavelength of maximum power) does not deviate from the designed wavelength (i.e. nominal wavelength) by more than 0.2 nm. The actual wavelength for spacing 100 GHz should be within the ± 20 GHz (± 0.16 nm).

B. Coarse Wavelength Division Multiplex

CWDM was created as a cheaper option of DWDM. CWDM is a form of multiplexing, which uses larger spacing between channels than is possible with DWDM technology. The arrival of the fixed specification of individual wavelengths laid the foundations for the great development and rollout of this technology. ITU in 2002 issued a recommendation ITU-T G-694.2 where a standard G.694.2 defines the size of the channel spacing of individual wavelengths for use in CWDM. All wavelengths of CWDM technology (18 channels) can only be used with a fiber type '*Metro'* or the full spectrum according to the standard G.652.C or G.652.D. In normal cases of the construction of optical communications, is only the standard single mode fiber 9/125 µm, which corresponds to the standard ITU-T G.652, where there are 12 channels with wavelengths of 1290, 1310, 1330, 1350, 1470, 1490, 1510, 1530, 1550, 1570, 1590 and 1610 nm [3], [8].

CWDM finds use in metropolitan optical networks and in solving the '*last mile*' optical fibers. In the access networks, xDSL (x Digital Subscriber Line) providers can use DLC (Digital Loop Carrier) for connection with the main panel [3]. The most commonly used CWDM is in two-point connections or ring topology up to four nodes. CWDM allows transfer Gbit.s^{-1} Ethernet within 80 km and at a speed STM-16 (2.5 Gbit.s^{-1}) is a range of about 50 kilometers. Fig.3 shows CWDM channels defined by ITU.

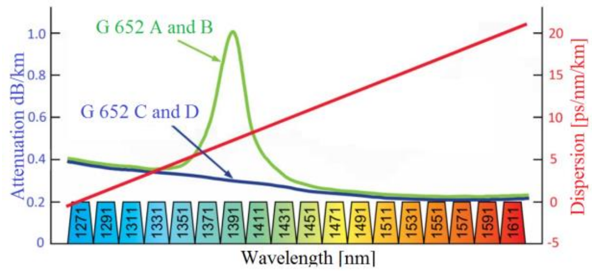

Fig. 3. CWDM channels defined by ITU – T G.694.2

III. Nonlinear Phenomenon SPM and the Related Kerr Effect

An interesting effect of the refractive index of the intensity of the light emitted in non-linear optical media occurs for self-phase modulation [7], [8] and [9]. It is a phenomenon which is characterized by enlargement of the spectrum of optical pulses and causes a phase shift of the pulses (Fig.4).

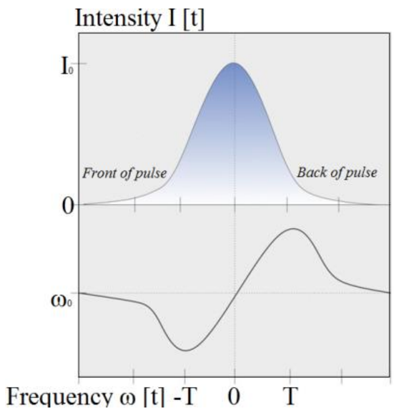

Fig. 4. Pulse frequency change due to SPM [8]

It is obvious that the frequency depends on the power, respectively the phase. We conclude that if the radiation power increases, there is a widening phase, and also can observe the frequency growth. This also applies vice versa. If there is a decrease of power radiation, the phase is also reduced and thus the value of the frequency decreases. The binary signal is characterized by two states, minimum and maximum output sate [8], [9]. Therefore, there is a phenomenon called frequency '*chirp*'. SPM is not a phenomenon that is unfavorable for us. It has several possible applications for example the soliton transmission. The transfer uses specially shaped signals, which due to SPM form themselves and they do not suffer from dispersion.

Optical Kerr effect is non-linear optical effect, which is present in the diffusion of light in crystals, glass, but also gases. Kerr nonlinear effect affects the folds of light in optical fibers which are SPM, XPM, and FWM and is given by:

$$n = n_0 + n_2 . | E |^2 , \quad (1)$$

where n_0 is the ordinary refractive index (intensity independent), n_2 is the index of refractivity, which depends on the intensity and E is the intensity of electric field [6], [9] and [10]. For SiO_2 the value of the Kerr effect is 0,6.10^{-22} V.m^{-1} for a large optical power, which is unbound:

$$P_0 = \frac{n_0 . | E |^2}{2Z_0} , \quad (2)$$

where Z_0 is the characteristic impedance in the material. A high intensity of the electric field that was formed is the predecessor of the phenomenon SPM. It occurs in environments where intensity of the input light beams depends on refractive index of the medium:

$$\Delta n = n_2 . I , \quad (3)$$

where n_2 is the nonlinear index of refractivity, and I is the optical intensity.

IV. Erbium Doped Fiber Amplifier

Fiber amplifier doped with Erbium - Er^{+3} (EDFA), which was invented in 1985, became a revolution in optical communications. EDFA are the most important amplifiers in the context of a long transmission path. They effectively amplify a light at wavelengths of 1.5 µm [11], [12]. On these bands communication optical fibers have minimal losses. It can enhance the optical signal not only on one wavelength, but a number of wavelengths and this is the main advantage. This fact enables saving of multiple photoelectric repeaters which would be needed for each wavelength. Currently, through the optical fiber can be transferred several tens Gbit.s^{-1} up to Tbit.s^{-1}.

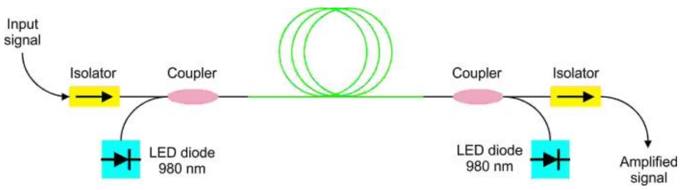

Fig. 5. The operating principle of a single EDFA

In Fig.5 is illustrated block scheme of EDFA. Single mode optical fiber core is doped with erbium is used as amplifying medium. The active fiber is pumped with the light from two laser diodes (bidirectional excitation), although one-way pumping - forwards or backwards is also very common. Pumping radiation whose wavelength is around 980 nm (sometimes 1450 nm) excites Erbia ions and thus increases the intensity of light at wavelengths of 1.5 µm. Parts of the EDFA are optical isolators, which are active at the input and at the output. Each isolator has a predefined role [10], [12] and [13]. The role of the input isolator is to prevent optical radiation that may occur during spontaneous emission. The role of the isolator is to prevent the output radiation of the laser beam, which should in theory be reflected back to the amplifier.

V. SPM Simulation for 2-Channel DWDM System According to ITU G.694.1 Using EDFA

OptSim is a programming environment that is used to design and simulate optical communication systems at the level of propagation. Conducting simulation in the programming environment OptSim is very convenient, especially for verification of functionality gaps, or suppression of undesirable phenomena during the transmissions. OptSim is comprehensive software for the simulation of communication systems prior to implementation in practice, which ultimately can save considerable funds. It is designed for professional research of WDM, DWDM, CWDM, time division multiplexing TDM (Time Division Multiplex), television access CATV (Community Access TeleVision), LAN (Local Area Network), parallel optical bus and other emerging optical systems [15], [17] and [18]. OptSim can create a fully optical communication system that represents interdependent set of blocks, each block represents a component or subsystem in a communications system. Each component could be customized according to their own requirements, users enter various numeric values, and the results could be checked with the virtual measurement instruments. In our case, for the DWDM system the '*Sample mode*' was used [19], [20]. In this mode, the data are transferred between components at any point in time during the entire simulation. These transfers are called samples and the advantage of this approach is that the simulation can be performed an unlimited number of times. In this mode, the signal processing is carried out only in the time domain. Design of optical communication system in this mode is easy, as each component is represented by its own icon. Non-linear phenomenon SPM was simulated to create a schema, which is shown in Fig.6. The DWDM communication system was also created based on the ITU-T G.694.1.

A. The transmitting part of DWDM system

It consists of two channels, each of which has its own data source generating a random bit sequence. These values pass to a block called power modulator, which use NRZ (Non-Return-to-Zero) encoding. The encoded signal is applied to an electrical filter, which then passes the signal to the amplitude modulator, to which also enter the light radiation from the excitation laser. Parameters of the random bit sequence and CW laser excitation are defined in the TABLE I.

TABLE I. Parameters of the Random Bit Sequence and CW Laser Excitation in the Simulation SPM

Component	Parameter	Channel 1	Channel 2
Source	*Bit rate [Gbit.s^{-1}]*	10	10
	Frequency [THz]	193.025	193.075
CW laser	*Wavelength [nm]*	1553.12762	1552.72541
	CW power [dBm]	-80	-10
		0	-10
		+80	-10

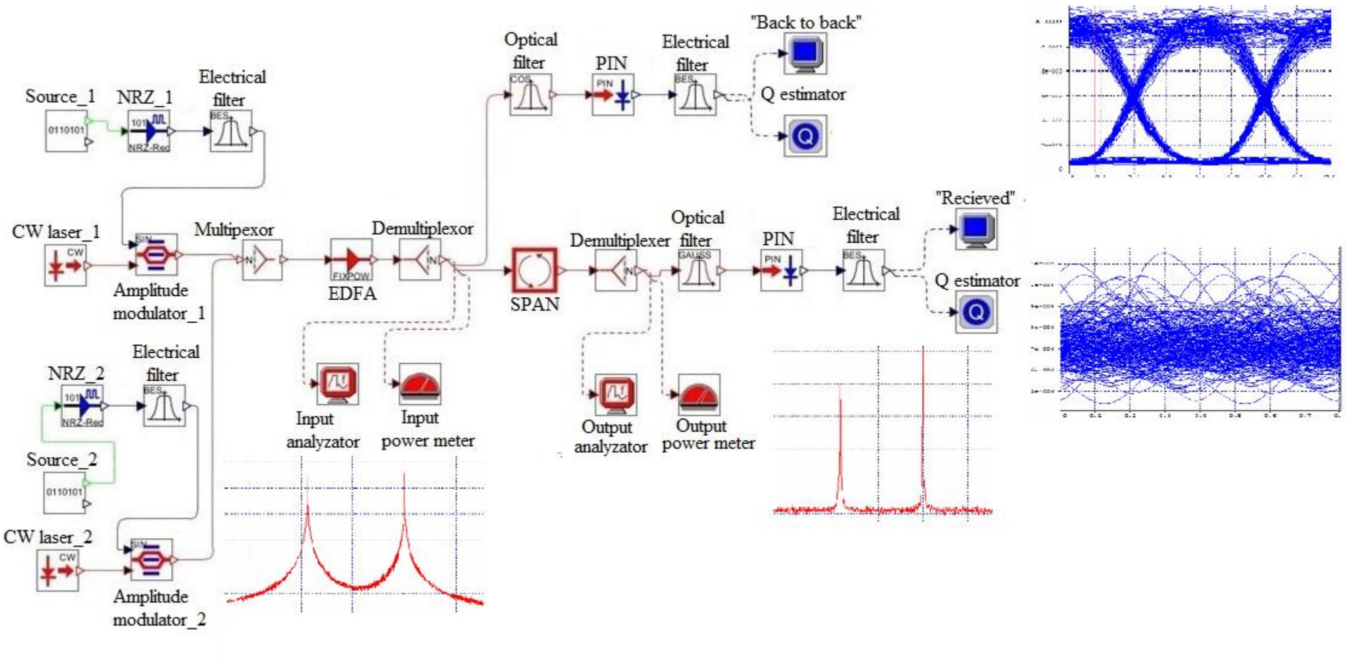

Fig. 6. The operating principle of a single EDFA

B. The optical part of DWDM system

The optical part of the signal transmitting section boosts power EDFA amplifier and then multiplexes the optical splitter. After demultiplexing, the signal moves to the input optical spectrum analyzer and also to the input optical power meter. The spectrum of this signal can be shown by simulation results. The next signal passes through the iterative loop that is performed 4 times. Iteration loop consists of the optical fiber, optical grating and in-line EDFA amplifier [21]. Furthermore, the signal passes through an optical splitter to an output optical spectrum analyzer and also the output optical power meter. Parameters used by power EDFA amplifier are changed to 80 dBm, 0 dBm and -80 dBm.

C. The receiving part of DWDM system

The signal after demultiplexing and passing optical splitter from transmitting section goes through the optical filter, PIN photodiode, an electrical filter to an electrical outlet *back_to_back* which after running simulation diplays the eye diagram. Output eye diagram displayed by *back_to_back* characterizes the converted electrical signal which was not coupled into the optical component that is the optical fiber. The signal that passes through iteration loop, and later through an optical splitter subsequently gets into electro-optical filter, where the PIN photodiode converts an electrical signal. This electrical signal is transferred to electrical outlet *received*. The electrical signal can be measured by probes and different simulation results could be observed – values of BER or Q factor.

D. Resulting values of proposed DWDM system simulations

In Fig. 7, Fig. 8 and Fig. 9 are shown the simulation results for the non-linear phenomenon SPM for formed DWDM scheme. These 6 eye diagrams represent different ratios of CW laser power and CW output power of power EDFA amplifier.

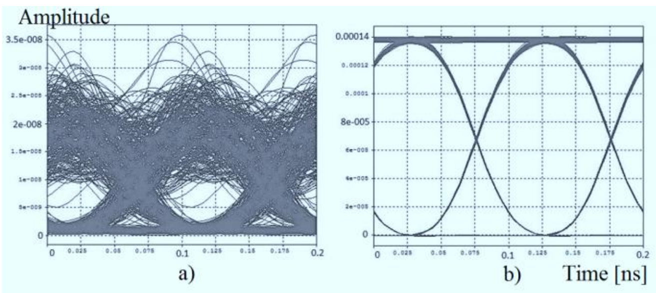

Fig. 7. The eye diagram for the simulation of SPM, CW laser power -80 dBm, CW power EDFA 80 dBm: a) *back_to_back* b) *received*

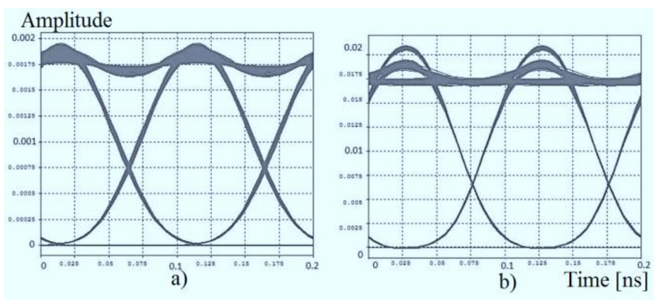

Fig. 8. The eye diagram for the simulation of SPM, CW laser power 0 dBm, CW power EDFA 0 dBm: a) *back_to_back* b) *received*

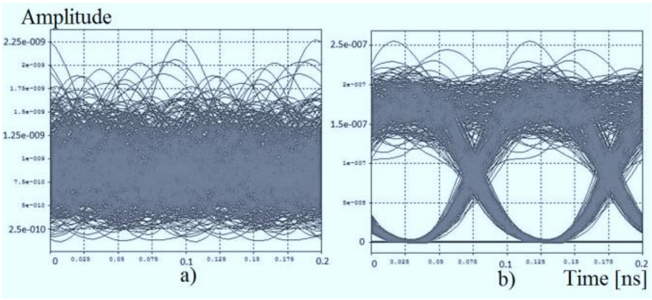

Fig. 9. The eye diagram for the simulation of SPM, CW laser power 80 dBm, CW power EDFA -80 dBm: a) *back_to_back* b) *received*

The observed values of BER and the Q factor are shown in TABLE II.

TABLE II. THE RESULTING VALUES OF BER AND THE Q FACTOR IN THE SIMULATION SPM

CW	**EDFA**	***Back_to_back***			***Recieved***		
CW výkon		*Q factor*		*BER*	*Q factor*		*BER*
[dBm]		[Lin]	[dB]	-	[Lin]	[dB]	-
-80	+80	3,45	10,757	0,0086	100	40	1.10^{-40}
0	0	32,8	30,324	1.10^{-40}	25,6	28,16	1.10^{-40}
+80	-80	2	6,0206	0,0227	8,147	18,22	$4{,}2.10^{-16}$

VI. CONCLUSIONS

For a phenomenon SPM was observed a bit error rate and transmission quality through eye diagrams and measured values. In the programming environment OptSim the eye diagram was designed for *back_to_back* output and also for the output *received*. *Back_to_back* characterizes the signal in the form of eye diagram, which is getting into the optical part. *Received* is output in the form of eye diagram, which has went through an optical fiber and was influenced by non-linear phenomenon SPM.

Results of the simulations were three pairs of eye diagrams that represent various ratios of CW laser power and CW power EDFA amplifier. Based on the values we note that all results from the output were sufficient and transmitting information in optical communication systems. The value of a bit error rate was very low and the value of the transmission quality was sufficient.

From the measured values it is seen that the BER has at the output *back_to_back* in two cases value 1.10^{-40}, which transmits the information with a very small bit error. The BER value was established at a ratio of -80 dBm and 80 dBm, at 0 dBm and 0 dBm, where the first value of the pair is the CW laser power and the second value of the pair is the EDFA amplifier power. Q factor values, the transmission quality, are in the best performance ratio -80 dBm and 80 dBm, 0 dBm and 0 dBm. The values of the BER and Q factor at outlet *received* are significantly better than at the outlet *back_to_back*. Except where CW laser power is 80 dBm, CW power EDFA amplifier is -80 dBm. In this case, a value of the order of a lower BER and the other BER value is equal to 1.10^{-40}.

All BER values are favorable for transmission of information. The values of Q factor are slightly better than on a leaving *back_to_back*, especially in a ratio of -80 dBm, and 80 dBm.

ACKNOWLEDGMENT

This work was supported by Cultural and Educational Grant Agency (KEGA) of the Ministry of Education, Science, Research and Sport of the Slovak Republic under the project no. „006TUKE-4/2014 - The Use of TUKE PON Experimental Model in Teaching.

This publication arose thanks to the support of the Operational Programme Research and development for the project "(Development of the Centre of Information and Communication Technologies for Knowledge Systems) (ITMS code 26220120030), co-financed by the European Regional Development Fund".

REFERENCES

[1] I. Rasheed, M. Abdullah, S. Mehmood, M. Chaudhary ,"Analyzing the non-linear effects at various power levels and channel counts on the performance of DWDM based optical fiber communication system," Emerging Technologies (ICET), 2012 International Conference, vol.1, no.5, Oct. 2012, pp. 8-9.

[2] P. Ivaniga, L. Mikúš, "Measuring of Block Error Rates in High-Speed Digital Networks", Advances in Electrical and Electronic Engineering, ISSN 1804-3119, vol. 5, 2011, pp. 35-36.

[3] ITU-T, G.694.2 (2013) Spectral Grids for WDM Applications: CWDM Frequency grid.

[4] ITU-T, G.694.1 (2012) Spectral Grids for WDM Applications: DWDM Frequency grid.

[5] G. P. Agrawal, "Fiber-Optic Communication Systems, 4th Edition", ISBN: 978-0-470-50511-3, 2010, 626 pp.

[6] J. Smieško, J Uramová,."Access node dimensioning for IPTV traffic using effective bandwidth, 2012, komunikacie, vol.14, no.2, ISSN: 1335-4205 pp. 11-16.

[7] S. Kumar, M. J. Deen , "Fiber Optic Communications: Fundamentals and Applications" Wiley-IEEE Press, ISBN: 978-0-470-51867-0, 2014, 572 pp.

[8] T. Ivaniga, Ľ. Ovseník, J. Turán , "Influence of Self-Phase Modulation on 8 and 16- Channel DWDM System with NRZ and Miller Coding", 2015, Carpathian Journal o Electronic and Computer Engineering, vol.8, no.1, ISSN: 1844-9689, pp. 17-22.

[9] Tang et al., "The Multispan Effects of Kerr Nonlinearity and Amplifier Noises on Shannon Channel Capacity of a Dispersion Free Nonlinear Optical Fiber,"Journal of Lightwave Technology, vol. 19, no.8 , 2001. pp. 1110-1115.

[10] O. Arora, A. K. Garg, S. Punia,"Symmetrical Dispersion Compensation For High Speed Optical Links", ISSN: 1694-0814, IJCSI International Journal of Computer Science Issues, vol. 8 ,no. 1, 2011, pp. 371-376.

[11] E. Desurvire, "Erbium-Doped Fiber Amplifier: Principles and Applications", John Willey & Sons, Inc., ISBN: 0-471-58977-2, 1994, 749 pp.

[12] P. Ivaniga, "Hodnocení chybovosti ve vysokorychlostních digitálních sítích", Žilina,EDIS-ŽU, ISBN 978-80-8070-771-2, 2007, 87 pp.

[13] D.R. Zimmerman, L.H. Spiekman, "Amplifiers for the Masses: EDFA, EDWA, and SOA Amplets for Metro and Access Applications", Journal of Lightwave Technology, ISSN: 0733-8724, vol. 22, no. 1, 2004, pp.63-70.

[14] W. Steingartner, A. Poláková, P. Prazňák, V. Novitzká, "Linear Logic in Computer Science", Journal of Applied Mathematics and Computational Mechanics, vol. 14, no. 1, 2015, pp. 91-100.

[15] D. R. Anderson, l. Johnson, F. G. Bell, “Troubleshooting Optical-Fiber Networks: understanding and using your optical time-domain reflectometer “, ISBN: 0-12-0586614, 2004, 433 pp.

[16] J. Ružbarský, Ľ. Ovseník, J. Turán, “Optical AddDrop multiplexers for all-optical fiber communication”, In: MIPRO 2015-Rijeka MIPRO,2015,ISBN 978-953-233-083-0, pp. 1885-1889.

[17] P. Ivaniga, L. Mikuš: “ The Relationship Between G.826 Error Performance Objectives And Equivalent Ber“, Journal of Information, Control and Management Systems, vol. 2, no. 1 2007, pp. 39-44.

[18] K. Thyagarajan, A. Ghatak, ”Fiber Optics Essentials”, ISBN 978-0-470-09742-7, 2007 ,John Wiley & Sons, Inc. Hoboken New Jersey, 239 pp.

[19] Rsoft Design Group,Inc: “OptSim User Guide”, 2009, 454 pp.

[20] Rsoft Design Group,Inc: “Manual of OptSim Models Refernce Volume 1 Sample Mode”, 2009, 543 pp.

[21] ITU-T.G.652 – “Characteristics of a single-mode optical fibre and cable”, [online],[cit. 01.10.2016]. ITU-T, November 2009. Available on the internet: http://www.itu.int/rec/T-REC-G.652-200911-I.

BIOGRAPHIES

Tomáš Ivaniga (Ing.) received Ing. (MSc.) degree in 2014 at Department of Electronics and Multimedia Telecommunications, Faculty of Electrical Engineering and Informatics of Technical University of Košice. Since September 2014 he has been at University of Technology, Košice as PhD. student. His research interests include Mitigation of degradation mechanizm in all optical WDM systems.

Ľuboš Ovseník (doc., Ing., PhD.) received Ing. (MSc.) degree in radioelectronics from the University of Technology, Košice, in 1990. He received PhD. degree in electronics from University of Technology, Košice, Slovakia, in 2002. Since February 1997, he has been at the University of Technology, Košice as Associate Professor for electronics and information technology. His general research interests include optoelectronic, digital signal processing, photonics, fiber optic communications and fiber optic sensors.

Ján Turán (Dr.h.c., prof., RNDr., Ing., DrSc.) received Ing. (MSc.) degree in physical engineering with honours from the Czech Technical University, Prague, Czech Republic, in 1974, and RNDr. (MSc.) degree in experimental physics with honours from Charles University, Prague, Czech Republic, in 1980. He received a CSc. (PhD.) and DrSc. degrees in radioelectronics from University of Technology, Košice, Slovakia, in 1983, and 1992, respectively. Since March 1979, he has been at the University of Technology, Košice as Professor for electronics and information technology. His research interests include digital signal processing and fiber optics, communication and sensing