RIGA TECHNICAL UNIVERSITY

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RESEARCH ON NEXT GENERATION FIBER OPTICAL AMPLIFIERS AND THEIR EVALUATION IN DENSE COMMUNICATION SYSTEMS

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 26 November 2021 at 14.00 at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Āzenes Street, Room 201.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Lilita Ģēģere …………………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of 6 chapters; Conclusions; 72 figures; 7 tables, 1 appendix; the total number of pages is 126. The Bibliography contains 175 titles.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

A

ASE – Amplified Spontaneous Emission

AWG – Arrayed Waveguide Gratings

B

BER – Bir Error Rate

BLS - Broadband Light Source

C

CD - Chromatic Dispersion

CW – Continuous Wave laser

D

DC – Double-clad

DCF – Dispersion Compensating Fiber

DEMUX – Demultiplexor

DFA – Doped Fiber Amplifier

DPSK – Differential Phase Shift Keying

DRA – Distributed Raman Amplifier

DWDM – Dense Wavelength Division Multiplexing

E

EBF – Electrical Bessel Filter

EDFA – Erbium Doped Fiber Amplifier

EF – Electrical Filter

EYE – Eye Diagram Oscilloscope

EYDFA – Erbium-Ytterbium Dopped Fiber Amplifier

F

FBG – Fiber Bragg Grating

FOPA – Fiber Optical Parametric Amplifier

FOTS – Fiber Optical Communication System

H

HNLF – High Non-Linearity Fiber

I

ITU-T – International Telecommunication Union – Telecommunication Standardization Sector

L

LRA – Lumped Raman Amplifier

M

MLR – Mixed Line Rate

MMF – Mixed Modulation Format

MZM – Mach-Zehnder Modulator

MUX – Multiplexor

N

NF – Noise Figure

NGPON – Next Generation PON

NRZ – Non-Return-to-Zero

O

ODN – Optical Distribution Network

OF – Optical Filter

OGF – Optical Gaussian Filter

OLT – Optical Line Terminal

ONT – Optical Network Terminal

ONU – Optical Network Unit

OOK – On-Off Keying

OSNR – Optical Signal-Noise Ratio

P

PIN – PIN photodiode

PP – Parametric pump

PON – Passive Optical Network

Q

QAM – Quadrature-amplitude Modulation

QPSK – Quadrature phase-shift Keying

R

RP – Raman pump

RX – Receiver

S

SMF – Single Mode Fiber

SOA – Semiconductor Optical Amplifier

SRS – Stimulated Raman Scattering

SS-WDM – Spectrum Sliced WDM

T

TX – Transmitter

W

WDM – Wavelength Division Multiplexing

GENERAL DESCRIPTION OF THE DOCTORAL THESIS

Topicality of the Theme

The sector of information technologies continues developing year by year, a sharp increase in the amount of transmitted data is observed. This is explained by the growing number of internet users, multimedia services and computing devices registered in the global web. Increasing amount of data is explained by a growing range of the offered online services, such as HD video streaming, video conferences, cloud computing, e-services, web browsing, file downloading, and M2M (*machine to machine*) applications. This conditions the growing demand for greater telecommunication network capacity. According to Cisco forecast data, by year 2022 the amount of global IP data will reach the level of 4.8 zettabits compared to year 2017. Figure 1 demonstrates that in 2022 IP traffic per month will reach 396 Exabits [1].
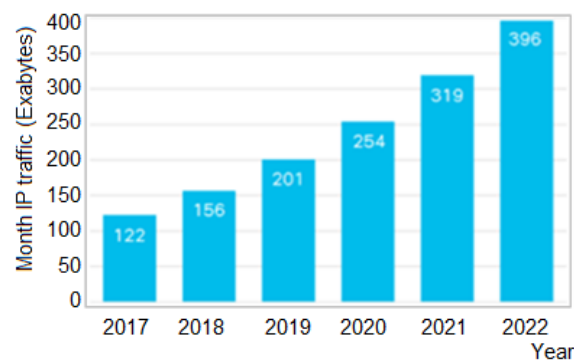

Fig. 1. Amount of IP traffic per month as forecasted by Cisco [1].

Over the last two decades optical communication technologies have shown the increase in the fiber throughput capacity, which has reached transmission rate of several Tbit/s. Optical amplification bandwidth is a significant limiting factor for long-range communication systems and networks. Currently, C-band (1530 nm to 1550 nm) or L-band (1565 nm to 1625 nm) are used for long-distance transmission at low signal loss (attenuation 0.2 dB/km), where bandwidth of each optical amplifier is around 40 nm (5 THz) [2]. Already now it is anticipated that optical amplifiers will cover S-band range (1460 nm to 1530 nm), where total optical amplification bandwidth can be up to 120 nm (15 THz) and total optical transmission system throughput capacity can reach 150 Tbit/s [3].

Optical power losses are caused by attenuation in optical fibers (standard single mode fiber (SSMF) attenuation is around 0.2 dB/km at 1550 nm wave length). Attenuation is not significant, but its effect is accumulated for every subsequent kilometer and reduces a transmitted signal in hundred- or thousand-kilometer-long communication systems. In every 50 to 100 km span, a signal is reduced by 10 dB to 20 dB and the optical signal needs to be restored or amplified [4]. To compensate for the accumulated signal attenuation, regenerators or optical amplifiers can be used [9]. The number of active elements in a system with regenerators present in the design scheme deteriorate significantly the system's availability in general [27]. Optical regenerators receive transmitted signals and convert them to electrical signals, then process them and regenerate using a transmitter. In WDM communication systems, the use of regenerators is an expensive and complex solution, as signal transmission channels need demultiplexing, detection, conversion to electric current, regeneration and, finally, conversion

of electric signals to optical signals [2]. Optical amplifiers are another solution for compensating attenuation. An optical amplifier is an optical device, which impacts FOCS (fiber optical communication system) development, as it can amplify optical signals in a specified frequency range and ensures amplification without the need for optical-electrical conversion [10]. Optical amplifiers amplify multiple transmitted channeled signals simultaneously. Amplification of optical signals is based mainly on energy transition from radiation pumping or other kind of energy to intensified optical radiation. In different types of optical amplifiers this process is implemented differently. The use of amplifiers has become available also in WDM systems, it also promoted introduction of optical switching [7].

Telecommunication systems use various types of optical amplifiers: semiconductor amplifiers (SOA), rare earth element-doped fiber amplifiers (xDFA), Raman and Brillouin amplifiers and parametric amplifiers (FOPA). Optical amplifiers use different effects to amplify signals [11].

More and more research on fiber optical communication systems (FOCS) has been conducted globally, which will allow increasing transmission rate and improving performance of the existing transmission systems. Novel transmitting optical fibers, novel transmission system technologies and optical amplifiers of the next generation, which will be able to transmit data over longer distances and at higher transmission rates, are being studied.

Aim and Tasks of the Doctoral Thesis

Summarizing the facts mentioned above, the **aim of the Doctoral Thesis** was set: to investigate and evaluate the operation of optical amplifiers in WDM communication systems, and to develop a new type of EYDFA optical device model with cladding pumping technology in a computer simulation program.

In order to achieve the above-mentioned aim, it was necessary to complete the following **general tasks**:

1. To analyze technical and scientific literature on the performance of the existing optical amplifiers in WDM communication systems.
2. To study and evaluate the performance of EDFA optical amplifier depending on the location of the amplifier in the optical line, changing the channel spacing in the communication system: 37.5 GHz, 50 GHz, and 100 GHz, and changing the amplification range: 75 km, 100 km, and 150 km.
3. To evaluate the performance of a 16-channel optical WDM-PON access system with a broadband ASE light source and DCM module.
4. To evaluate the implementation of the hybrid communication system in the 16-channel WDM-PON system using mixed modulation formats and mixed data transmission rates.
5. To research and estimate the performance of a discrete and distributed Raman amplifier.
6. To analyze the hybrid Raman-EDFA, Raman-SOA and Raman-FOPA performance in a WDM transmission system.
7. To develop an EYDFA fiber optic amplifier model in a computer simulation program and to evaluate the application of cladding pumping technology for signal amplification in the C-band.

Methods of Research

The Doctoral Thesis uses mathematical calculations, numerical simulations and experimental measurements in the analysis of the problems. Numerical simulations were made with the help of the fiber optical system modelling software (*Rsoft OptSim* and *VPIphotonics Design Suite*). The results of numerical simulations were acquired using nonlinear Schrödinger equation, direct and inverse discrete fast Fourier transform, and Monte Karlo method of evaluation of bit error rate (BER). The optical power values, power spectral densities and mesh diagrams, as well as bit error rate values were acquired and applied to optical amplifier configuration and parameter evaluation. The highest BER across all channels was used in the analysis of the quality of *WDM* transmission systems (the worst channel). Scientific experiments within this Doctoral Thesis were carried out at RTU ComTech Research Centre.

Main Results of the Doctoral Thesis

Scientific Novelty of the Doctoral Thesis:

1. A hybrid Raman-FOPA amplifier computer model for an S-band (1460–1530 nm) multichannel transmission system has been developed to ensure more uniform and broader amplification compared to the existing amplifiers.
2. A new type of EYDFA computer model with a cladding pumping technique has been developed, which would ensure amplification of up to 40 channels in C-band with low input signal power (~ -20 dBm/channel).

The following **main conclusions** have been made in the process of development of the present Doctoral Thesis:

1. Transmission systems with an EDFA amplifier where the channel spacing is below 100 GHz require pumping power above 60 mW to ensure the appropriate quality of the amplified signal and BER values below the specified level of 10^{-9}. If the spacing is below 50 GHz, spectrum interference of adjacent channels is inevitable and power penalty value is greater than 0.20 dB.
2. In EDFA systems with multiple amplification stages, a system with 3 EDFAs and a 100 km amplification range is the most efficient in terms of power consumption, as the total system pumping power is lower (105 mW) and 24 m long EDF fibers are sufficient to ensure the necessary signal quality, and the BER of the system would be below 10^{-9}. The power penalty for a WDM system with 3 EDFA amplifiers corresponding to a system without amplification is only 0.32 dB.
3. Using only one broadband ASE light source for all users and a DCM module for dispersion compensation, the studied 16-channel WDM optical access system ensures data transmission on a more than 20 km long line with high system performance with BER 10^{-10}. This solution is good for next-generation passive optical networks.
4. The assessment of hybrid configuration effects on spectral efficiency of a WDM-PON system showed that SE efficiency can be increased via optimization of channel spacings. For a system with unequal channel spacing and an MMF, the SE (0.62 (bit/s)/Hz) is 6.2 times larger than a typical 100 GHz 10 Gbit/s WDM-PON system. The spectral efficiency of the WDM-PON system with MMF and MLR is 0.27 (bit/s)/Hz and is 2.7 times higher than that of a typical system.
5. When installing a discrete and distributed Raman amplifier farther from a transmitter unit, which is at 125 km, 3 % lower pumping power is required to ensure the appropriate

quality of an amplified signal at BER 10^{-9} and also the channel amplification is above 21.5 dB. In the case of a discrete Raman amplifier, the pumping power (up to 500 mW) is on average 50 % lower than in the case of a distributed Raman amplifier (the minimum pumping power is 905 mW to 1020 mW depending on the location in the transmission line).

6. Hybrid Raman-FOPA computer model amplification is more uniform and reached 34.7 dB in a 16-channel 40 Gbit/s WDM system. Amplification of a hybrid amplifier is by 30 % (8.2 dB) higher than the total of both Raman and FOPA ones. Raman-FOPA - 3 dB amplification bandwidth is by 0.02 THz wider than that of a 682 mW FOPA and by 0.20 THz wider than an enhanced 660 mW FOPA, which is explained by direct signal amplification via a Raman pump source.

7. A cladding pumping EYDFA computer model amplifier ensured uniform and broad amplification (19.7 dB to 28.3 dB), low noise level (3.7 dB to 4.2 dB), and power penalty is lower by 0.1 dB. Transmission systems with such an EYDFA (7 m EYDF fiber, a 3W 975 nm directly driven pump source and $p_{input} = -20$ dBm per channel) are appropriate for WDM software applications.

Practical Significance of the Doctoral Thesis

- The Latvian patent application "Dispersion compensated spectrum sliced wavelength division multiplexed optical communication system" has been submitted. Patent application number: P-16-108. Patent number: LV15236B (publication/registration date: 20.12.2017).

- The results of the Doctoral Thesis are used for implementation of scientific research projects:

    1. ERDF project "Design of high-speed optical access networks and elements" (activity "Support of Science and Research"), No. 2010/0270/2DP/2.1.1.1.0/10/APIA/VIAA/002.

    2. ERDF project "Design of effective cladding pumping based fiber optical amplifiers for telecommunication systems" (activity "Support of Science and Research"), No. 1.1.1.1/18/A/068.

    3. ERDF project "Passive fiber optical sensors for energy efficient health monitoring of transport infrastructure" (activity "Support of Science and Research"), No. 1.1.1.1/16/A/072.

Theses to be Defended in the Doctoral Thesis

1. Implementing the combined Raman-FOPA amplification computer model in the WDM communication system, a more even amplification is obtained compared to the parametric amplifier and –3 dB amplification bandwidth is by 0.20 THz wider.

2. Applying the developed computer model of optical erbium and ytterbium doped fiber amplifier, which initiates cladding pumping in the fiber, a stable amplification of up to 28.3 dB with a noise factor of 4 dB in the telecommunication C (1530 nm to 1565 nm) band is obtained.

Approbation of the Research Results

The main results of the Doctoral Thesis have been presented at six international scientific conferences, as well as published in five scientific journals, four publications as full texts in conference proceedings and one Latvian patent application.

Participation in International Scientific Conferences:

1. Kurbatska I., Bobrovs V., Gavars P., **Gegere L.** «Evaluation of the impact of parameters of transmission system on the performance of WDM-PON», Progress in Electromagnetics Research Symposium – Fall (PIERS-FALL). Singapore, Singapore, 19–22 November 2017.

2. Kurbatska I., Bobrovs V., Alsevska A., Lyashuk I., **Gegere L.** «Spectral effective solutions for mixed line rate WDM-PON systems», Progress in Electromagnetics Research Symposium – Spring (PIERS). Russia, St. Petersburg, 22–25 May 2017.

3. Kurbatska I., Alsevska A., **Gegere L.**, Bobrovs V. «Investigation of influence of Mixed Configurations on performance of WDM-PON», Electronics 2017. Lithuania, Palanga, 19–21 June 2017.

4. Olonkins S., Stankunovs I., Alsevska A., **Gegere, L.**, Bobrovs V. «Investigation of in-line Distributed Raman Amplifiers with Co and Counter-propagating Pumping Schemes», 2016 Progress in Electromagnetics Research Symposium (PIERS 2016 Shanghai): Proceedings, China, Shanghai, 8–11 August 2016.

5. Kurbatska I., Alsevska A., **Gegere L.**, Bobrovs V. «Comparison of modulation formats for use in the next generation passive optical networks», Progress in Electromagnetic Research Symposium (PIERS). China, Shanghai, 8–11 August 2016.

6. Spolitis, S., **Gegere L.**, Alsevska, A., Trifonovs, I., Porins, J., Bobrovs, V. «Optical WDM-PON Access System with Shared Light Source», Progress in Electromagnetics Research Symposium (PIERS 2015): Proceedings, Czhech Republic, Prague, 6–9 July, 2015.

Publications in Scientific Journals:

1. Supe A., **Gegere L.**, Zakis K., Redka D., Porins S., Spolitis S., Bobrovs V. «Ramana Assisted Fiber Optical Parametric Amplifier for S-band Multichannel Transmission System», Fibers2021, Volume 9, Issue 2, 9; doi: 10.3390/fib9020009.

2. Supe A., Olonkins S., Udalcovs A., Senkans U., Murnieks R., **Gegere L.**, Prigunovs D., Grube J., Elsts E., Spolitis S., Ozolins O., Bobrovs V. « Cladding-Pumped Erbium/Ytterbium Co-doped Fiber Amplifier for C-band Operation in Optical Networks» // Appl. Sci.20212021, Volume 11, Issue 4, 1702; doi: 10.3390/app11041702.

3. Kurbatska I., Alsevska A., **Gegere L.**, Bobrovs V. «Investigation of influence of mixed Configurations on performance of WDM-PON», Elektronika ir Elektrotechnika – 2017. Vol. 23 (2). pp. 74–78.

Publications in Full-text Conference Proceedings:

1. Kurbatska I., Bobrovs V., Gavars P., **Gegere L.** «Evaluation of the impact of parameters of transmission system on the performance of WDM-PON», Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL). - Singapore, Singapore – 2017, pp. 1370–1376.

2. Kurbatska I., Bobrovs V., Alsevska A., Lyashuk I., **Gegere L.** «Spectral effective solutions for mixed line rate WDM-PON systems», Progress in Electromagnetics Research Symposium – Spring (PIERS). St. Petersburg, Russia – 2017, pp. 1771–1777.

3. Kurbatska I., Alsevska A., **Gegere L.**, Bobrovs V. «Comparison of modulation formats for use in the next generation passive optical networks», Progress in Electromagnetic Research Symposium (PIERS). Shanghai, China – 2016, pp. 3783–3787.

4. Spolitis, S., **Gegere, L.,** Alsevska, A., Trifonovs, I., Porins, J., Bobrovs, V. «Optical WDM-PON Access System with Shared Light Source», In: *Progress in Electromagnetics Research Symposium (PIERS 2015): Proceedings*, Prague: The Electromagnetics Academy, 2015, pp. 497–501.

Scope and Structure of the Doctoral Thesis

The Doctoral Thesis comprises 126 pages. The Thesis consists of six chapters, conclusions, bibliography and appendix.

In Chapter 1, the working principles of optical amplifiers (SOA, rare earth-doped fiber amplifiers, Raman, Brillouin, hybrid, parametric) in transmission systems are evaluated by conducting the comparative analysis. The aim, tasks, scientific novelty, defendable theses of the Doctoral Thesis are formulated, the results are summarized and the areas of further research are outlined.

In Chapter 2, performance of erbium doped optical fiber amplifiers in a WDM communication system is studied. The research objective is to evaluate the optical signal quality depending on the location of an EDFA amplifier in the transmission line, channel spacing and gain range.

Chapter 3 is dedicated to the assessment of WDM-PON networks. Subchapter 3.1 studies the performance of a 16-channel spectrally sliced WDM-PON transmission system with a single broadband amplified spontaneous emission (ASE) light source and FBG-based continuous Dispersion Compensation Module. A SS-WDM PON optical system is energy-efficient and cost-effective, as one light source is shared by multiple users. A broadband ASE light source is based on two cascade-connected EDFA amplifiers. Another objective of Chapter 3 is to assess application of the integrated (MML and MLR) concept in a WDM-PON system to enhance its spectral efficiency.

Chapter 4 investigates Raman-based devices: performance of the distributed and lumped amplifiers in WDM communication systems. The objective is to find the radiant power of the minimum pumping, which would ensure pre-set BER values in all channels of the system.

In Chapter 5, hybrid optical amplification solutions in WDM transmission systems are studied. EDFA, SOA and combinations of Raman and FOPA amplifiers are analyzed. The hybrid Raman-EDFA amplifier has been developed not just to equalize the EDFA gain spectrum, but also to increase the length of the transmission line. But the hybrid Raman-SOA solution allows reducing SOA signal distortions. The hybrid Raman-FOPA amplifier is used in WDM systems as a pre-amplifier and amplifies the system channels uniformly.

The objective of Chapter 6 is to develop two rare earth doped cladding pump amplifiers, appropriate for applications in telecommunications. The intended area of application includes WDM optical transmission systems, underground access networks and hybrid passive optical networks of extended reach. In all these cases the main concern is power amplification configuration. Cladding pumping has various benefits compared to conventional core pumping.

Conclusions outline and justify the main conclusions of the Doctoral Thesis. The list of conferences, publications and projects is given in the appendixes.

OUTLINE OF THE CHAPTERS OF THE DOCTORAL THESIS

Chapter 1

Optical signals pass through optical fiber and attenuate. Regenerators are used to restore attenuated optical signals, which convert optical to electrical signals and electrical to optical. The number of active elements in transmission systems with regenerators in the design scheme significantly attenuates the system's availability in general [7]. Regenerators in WDM systems are rather complex and expensive. In order to compensate attenuation in transmission systems, optical amplifiers that amplify optical signals directly and without conversion of electric signals were introduced. Amplification of optical signals is based mainly on energy transition from pumping radiation or other kind of energy to amplified optical radiation. In each optical amplifier this process occurs in different ways. Amplifiers also became available for WDM systems [7].

Different physical principles corresponding to major types of optical amplifiers can be used for amplification of optical signals:

- Optical amplifiers, where the method of amplification is based on linear properties of materials: semiconductor amplifiers (SOA) and rare earth doped fiber amplifiers (xDFA).

- Optical amplifiers, the functioning of which is based on nonlinear optical effects: Raman amplifiers, Brillouin amplifiers and parametric amplifiers (FOPA).

An optical amplifier should ensure multichannel operation in a widest wavelength band possible, ensure uniform gain across the entire dynamic amplification range, have high saturation output power and low noise level. All these properties should be achieved while maintaining low energy consumption and appropriate size. This is why the types of optical amplifiers are compared in Chapter 1.

SOA is a cost-effective solution for signal amplification, it is simply connected to the already existing WDM transmission systems. A SOA is characterized by high levels of insertion ASE noise (7 dB to 2 dB), its amplification maximum is 30 dB, it is sensitive to polarization (~2 dB), and nonlinearity in a semiconductor material is observed [5]. All these shortcomings deteriorate the quality of transmitted signals, that is why SOAs are not widely used in WDM systems.

The most popular optical signal amplification solution is application of rare earth doped fiber amplifiers in communication systems. Mainly EDFA amplifiers are used. EDFAs can help achieve up to 54 dB gain in certain circumstances, but typical EDFA gain is equal approximately to 30 dB [12]. EDFA noise level is lower than in SOA amplifiers and NF value is approximately 5 dB to 6 dB, but for an ideal EDFA this value is equal approximately to 3 dB [6], [13]. Surely, EDFA amplifiers have some shortcomings: there is an expressed frequency-dependent amplification, a comparably narrow gain spectrum and a limited pass band. The gain spectrum is not uniform.

Optical amplifiers that use Brillouin scattering effect ensure high amplification efficiency and can amplify signals up to 30 dB, but the spectrum of amplification in these amplifiers is narrow (<100 MHz) and the offset between the pumping source and the amplification frequencies is approximately 10 GHz to 11 GHz [2], [8]. Amplifiers of this type are not widely used.

Raman amplifiers do not amplify optical signals in the way EDFAs do, but they have an advantage, as they produce much less noise and ensure gain in a wide frequency band, they can also change the gain spectrum.

This is why, along with emerging fiber optical transmission system technologies, it is possible to develop hybrid optical amplifiers for signal amplification purposes. Hybrid optical amplifiers are aimed to extend the gain spectrum or to obtain a higher amplification value at lower insertion noise values.

Fiber optical parametric amplifiers can ensure high-level amplification in a widest wavelength band possible, and due to their optimized configuration, they produce low noise levels compared to other types of lumped amplifiers.

Cladding pump technology contributed to the development of fiber optical amplifiers. Such amplifiers use co-doped fibers. With the help of co-doped fibers and cladding pump method applied in optical amplifiers, communication systems can operate in the range of all wavelength bands. Such kind of amplifiers would allow obtaining uniform amplification, would enhance system capacity and lower system's costs.

It is possible to use optical amplifiers in both active and passive optical networks. The presence of active elements in a transmission line is not allowed in the passive optical networks, but amplifiers can be placed in the central office of the operating company. Application of optical amplifiers allows increasing the length of WDM-PON transmission lines.

Chapter 2

During transmission over long distances optical signals are attenuated greatly, thus, optical signal amplification is needed to restore the optical power budget. In the variety of signal amplification methods for WDM systems, preference is given to EDFA amplifiers [14]. The main reason for such popularity of EDFA amplifiers is that these amplifiers are connected rather easily, their use is cost-effective, and they allow amplifying optical signals avoiding conversion to electrical signal and vice versa. Such amplifiers demonstrate low noise level and high energy efficiency (>50 %), and are almost insensitive to signal polarization [15]–[16]. EDFA systems need to have a customized amplifier configuration, which would ensure a better quality of transmitted signals, would not impair total system operation and allow achieving as long transmission distance as possible. EDFA performance depends on such amplifier parameters as input signal optical power, pumping radiation power, wave length and pumping distribution direction, EDF fiber length and the obtained erbium ion population inversion. These amplifier parameters affect the level of EDFA amplification, the gain spectrum shape and produced level of noise [13], [17].

This chapter studies performance of EDFA amplifiers in various conditions of their operation. It is analyzed how the behavior of amplified signal quality changes when channel spacing (37.5 GHz, 50 GHz, 100 GHz), length of amplifying section (75 km, 100 km and 150 km) and EDFA location (power levels, lines and preamplifier) in a system are changed. EDFA configurations have been chosen to ensure BER lower than 10^{-9} in all channels of the system.

A 16-channel 10 Gbit/s WDM transmission system was designed in *OptSim* simulation software. Evaluating dependence of EDFA performance on the amplifier location in a system, the simulation model shown in Fig. 2 was used.
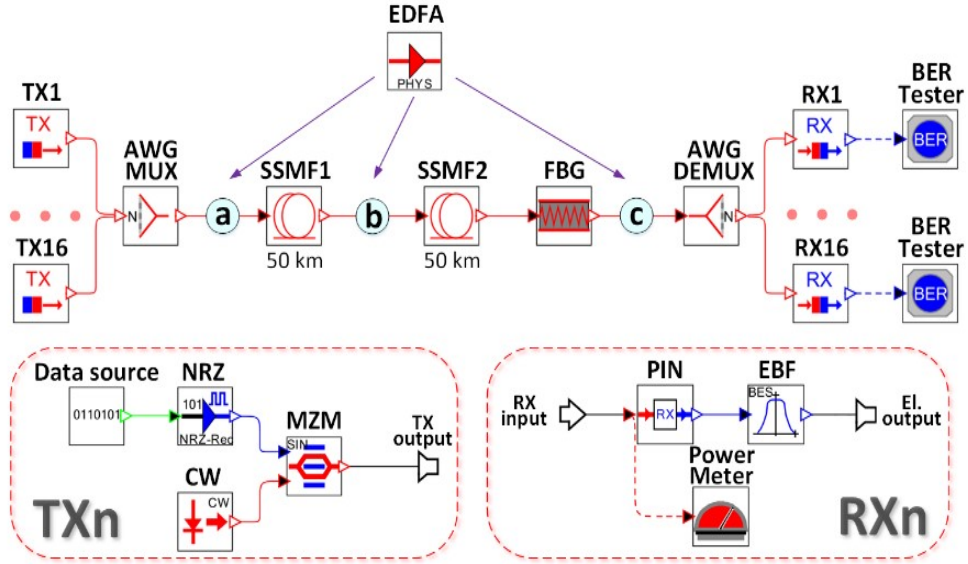
Fig. 2. Simulation model of a 16-channel 10 Gbit/s WDM transmission system with NRZ-OOK modulation format and various EDFA location scenarios: (a) – power amplifier; (b) – inline amplifier; (c) – preamplifier.

At the beginning of the research, the minimum pumping power and EDF fiber length for each amplifier were defined. In the case of a power amplifier, the lowest pumping radiation power that would ensure BER under 10^{-9} is 550 mW, which is observed in 8-meter long EDF fiber (gain: 12.74 dB – 12.94 dB and noise factor (NF): 5.03 dB – 5.19 dB). Inline EDFA needs 50 mW pumping radiation power and 8-meter long EDF (gain: 12.00 dB – 12.88 dB and NF: 5.12 dB – 5.30 dB). Preamplifier needs at least 4 mW pumping radiation power and 6-meter long EDF (gain: 12.43 dB – 12.66 dB and NF: 5.26 dB – 5.48 dB).

To evaluate the effect of EDFA location on the quality of amplified signals, for all three EDFA location scenarios BER value ratios in channels with the worst signal quality (highest BER values) from received signal power were calculated, and these results were compared with the results for an amplifier-free WDM system (Fig. 3).

For the power amplifier the power penalty of 0.92 dB was observed, for the inline EDFA – 0.26 dB, and for the preamplifier – 0.31 dB compared to the amplifier-free system. In all cases the main portion of the power penalty value is related to EDFA-induced amplified spontaneous emission (ASE) noise.

Considering the point of pumping energy consumption, it is preferable to use EDFAs as preamplifiers, but due to low input signal power, the achieved population inversion is not used as effectively as in the case of inline amplifiers. As a result, preamplifiers produce more ASE noise than the inline EDFA configuration. This produces additional power penalty compared to the amplifier-free system.
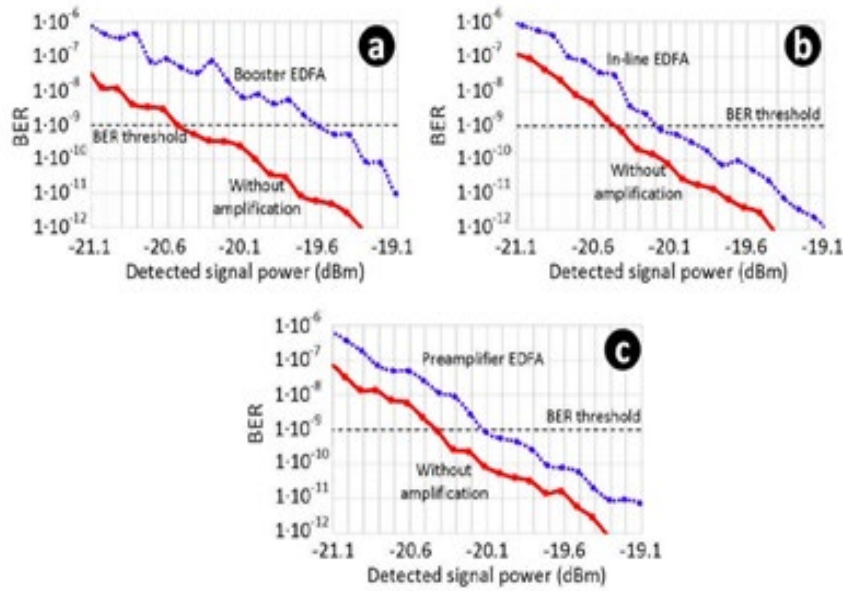
Fig. 3. BER value ratios for channels with the worst signal quality with respect to the received signal power in the amplifier-free system (solid line) and in the amp system (dotted line): (a) – power amplifier; (b) – in-line EDFA; and (c) – preamplifier.

Channel spacing also affects EDFA functions, and the research used a 16-channel 10 Gbit/s WDM transmission system with an inline EDFA simulation model (Fig. 2 (b)). The selected EDFA configuration: EDF fiber length – 12 m long for an EDFA with a single pump radiation source (such EDF length was chosen based on the research results [19]); 980 nm direct pumping [13], [19].
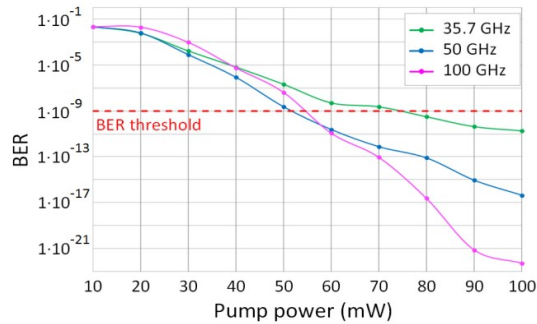
Fig. 4. Maximum system BER depending on 980 nm pumping radiation power.

The selected amplifier configuration ensured the following gain and noise figure (NF) values:

- System with 37.5 GHz channel spacing: 80 mW 980 nm direct pumping source ensures gain from 23.98 dB to 24.53 dB and NF – from 4.47 dB to 4.5 dB.
- System with 50 GHz channel spacing: 60 mW 980 nm direct pumping source ensures gain from 22.38 dB to 23.33 dB and NF – from 4.5 dB to 4.54 dB.
- System with 100 GHz channel spacing: 60 mW 980 nm direct pumping source ensures gain from 21.7 dB to 23.94 dB and NF – from 4.48 dB to 4.56 dB.

The system with 100 GHz channel spacing shows higher BER values than the one with 50 GHz channel spacing. This is connected with EDFA gain spectrum slope. In the 100 GHz

configuration, the range of transmission wavelengths is two times larger than in the case of 50 GHz spacing.
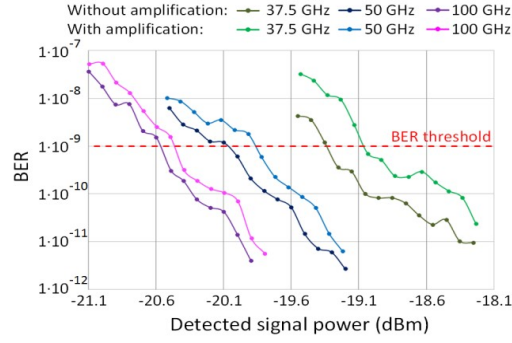

Fig. 5. Dependence of BER values on the received signal power in a WDM system with and without amplification.

As it may be seen in Fig. 5, in the EDFA WDM system with 100 GHz channel spacing the power penalty is 0.1 dB, in the system with 50 GHz channel spacing – 0.18 dB and in the system with 37.5 GHz channel spacing – 0.22 dB. The smaller the channel spacing, the larger is the power penalty.

In long-distance communication systems, application of different amplifying sections is inevitable, which results in attenuation of the transmitted signal quality. Selection of such amplified section lengths is a complex problem, when each transmission system needs individual approach. EDFA ununiform gain spectrum results into extra fiber nonlinearity in the channels with higher gain. Furthermore, every successive EDFA not only produces ASE noise, but also increases the preceding amplifying section noises. These two factors can dramatically attenuate the quality of the transmitted signal, thus limiting the transmission reach. If the number of amplifiers is reduced, but the amplifying section length is extended, an EDFA needs longer EDF fibers to ensure the required gain. This leads to larger ASE values and thus impairs the quality of the signal [13], [17].
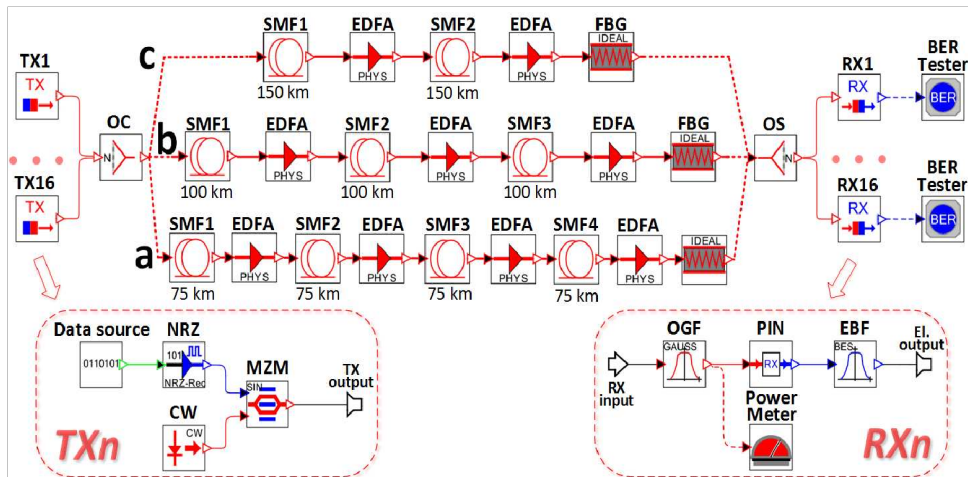

Fig. 6. Model of a 16-channel 10 Gbit/s WDM transmission system with 3 different amplifying section lengths: (a) – 75 km; b) –100 km; and (c) –150 km.

EDF length and pumping radiation power simultaneously increase (4 m to 15 m and 10 mW to 80 mW, respectively) for all EDFA amplifiers placed in the optical transmission line (Fig. 7).
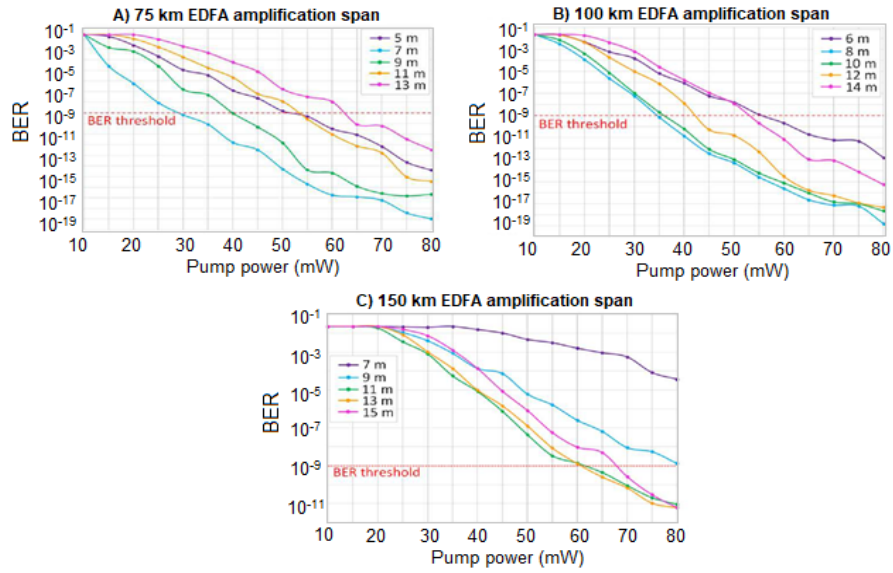
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Fig. 7. Dependence of the maximum system BER value on the pumping power at various EDF fiber lengths.

EDFA configurations:

➤ 7-meter long EDF fiber and 30 mW pumping power selected for the system with 4 EDFA amplifiers (each amplification span is 75 km long);

➤ 8-meter long EDF fiber un 35 mW pumping power selected for the system with 3 EDFA amplifiers (each amplification span is 100 km long);

➤ 11-meter long EDF fiber and 65 mW pumping power selected for the system with 2 EDFA amplifiers (each amplification span is 150 km long).

The same trends were observed in all three cases – when EDF lengths were shorter or longer than those in the selected configurations, a larger pumping radiation power is needed to ensure the required gain and appropriate quality of the signal.
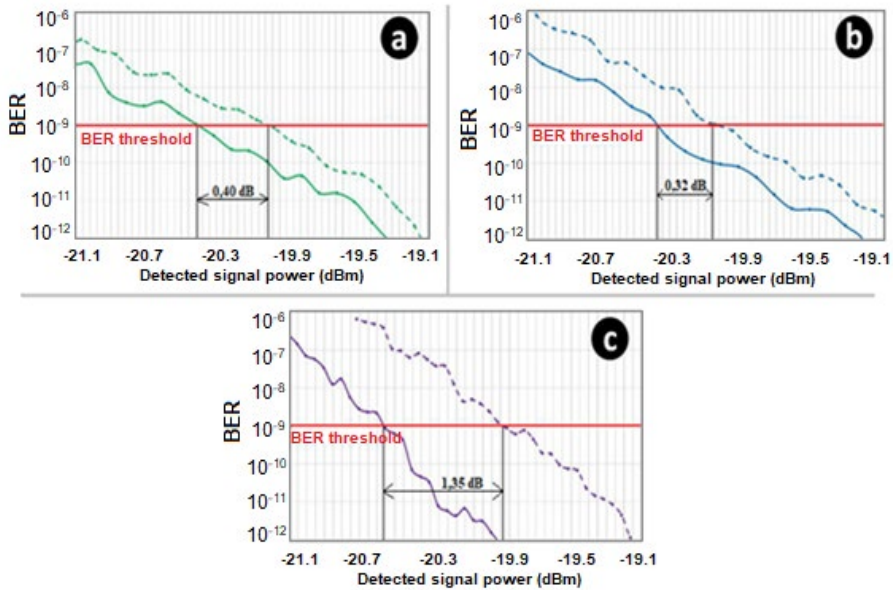

Fig. 8. Dependence of BER value on the received signal in the amplifier-free system without (solid line) and in the amp system (dotted line) at the length of the amplifying section (a) 75 km, (b) 100 km, and (c) 150 km.

Figure 8 compares BER value dependence on the power of the received signal in WDM systems with and without amplification, and defines the system power penalty.

Considering energy consumption, the system with 3 EDFA amplifiers and 100 km long amplifying section (105 mW pumping power and 24 m EDF) is the most efficient; it ensures the required quality of the signal. In the system with 75 km long amplifying section and 4 EDFA amplifiers, the total pumping power and EDF total length is 120 mW and 28 m, respectively, and in the one with just 2 EDFA amplifiers (150 km long amplifying section) – 130 mW pumping power and 22 m EDF. The option with 3 amplifiers produces the lowest amplified signal distortions. The power penalty of a 100 km long amplifying section is by 0.08 dB lower than in the system with 75 km long amplifying section and by 1.03 dB lower than in the system with 150 km long amplifying section. Every successive amplifier not only produces its ASE, but also increases the ASE noise from the preceding EDFA, therefore, in the system with four EDFA, the total ASE value at the receiver input is larger, as there are more amplifiers in the system. High power penalty value in the system with two EDFAs appears due to fiber nonlinearity mismatches caused by the optical line during transmission in connection with the total amplifier signal power at the first EDFA output.

Summarizing the above-mentioned results, it can be concluded that EDFA amplifier performance is affected by different operation conditions, so EDFAs have to be reconfigured in order to make their use as efficient as possible.

Chapter 3

The presence of active elements in the transmission lines is not allowed in the passive optical networks, but amplifiers can be placed in the central office of the operating company. Application of optical amplifiers allows increasing WDM-PON network capacity and performance.

A spectrally sliced wavelength division multiplexing passive optical network is a very promising technology that would satisfy the growing band width requirements globally. The advantage of this technology is that it allows placing electronic and optical elements in the central office (CO) and simplifying NG-PON network architecture, as well as using only one broadband light source (BLS) for all the users [27], [39], [30]. SS-WDM-PON optical system is energy saving and cost-effective, as one light source is shared between multiple users, instead of individual light sources for each of them [31]. SS-WDM-PON transmission system operation is limited with chromatic dispersion (CD) [30], [32]. Dispersion causes distribution of optical signal impulses and loses its shape while travelling along the optical fiber. Thus, it limits the transmitted signal quality, maximum data transmission rate and transmission system reach [2], [33]. Dispersion compensating fiber (DCF) or Fiber Bragg Grating (FBG) can be used in NG-PON systems [32].

In an intensively modulated 16-channel SS-WDM-PON system with NRZ linear code and direct detection, transmission rate (2.5 Gbit/s) is limited due to intensive noise, which is produced by a non-coherent ASE source [28], [34]. BER threshold value is $<10^{-10}$. The SS-WDM-PON system (Fig. 9) has just one BLS light source (ASE) co-exploited by all ONTs.

In the SS-WDM-PON system under research, the earlier developed [35] ASE broadband light source with +23 dBm (200 mW) output power and uniform output spectrum in the frequency range of 192.3 THz to 194.0 THz will be used. A uniform ASE light source was

developed based on two cascade EDFA amplifiers, because this technique allows obtaining more uniform ASE output spectrum.
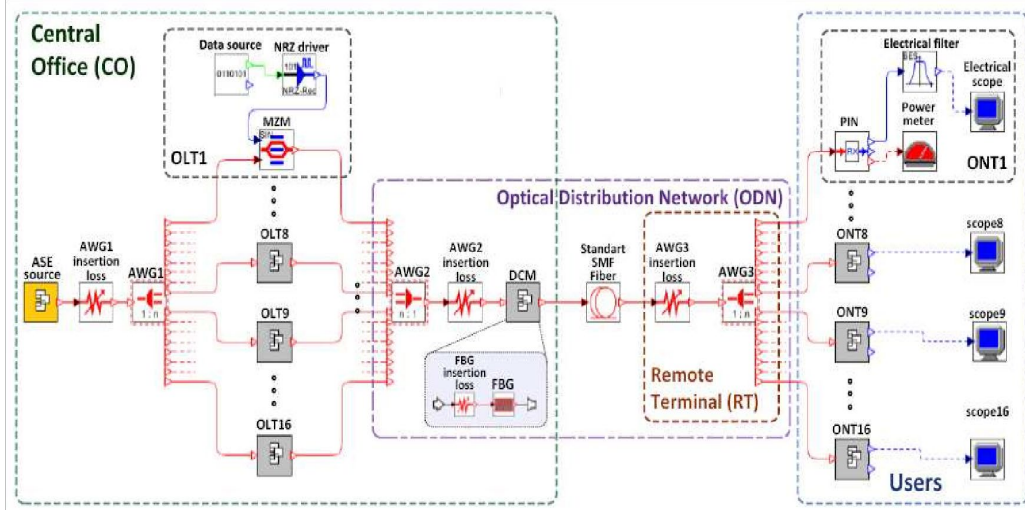

Fig. 9. Simulation model of a 16-channel SS-WDM-PON network with spectrally sliced broadband ASE light source and a dispersion compensation module.

The SS-WDM-PON system demonstrates signal distortions, and the Fiber Bragg Grating dispersion compensating module was used for CD compensation. It was found that the optimal CD amount to be compensated by FBG DCM in a 20 km SMF fiber range is 310 ps/nm at 1550 nm wave length.

Optical signal attenuation in the 16-channel SS-WDM-PON system with BER $<10^{-10}$ after 20-km transmission and CD compensation by FBG DCM is 1.9 dB. Such attenuation is caused by ASE broadband light source crosstalk, dispersion and noise-like pulse.
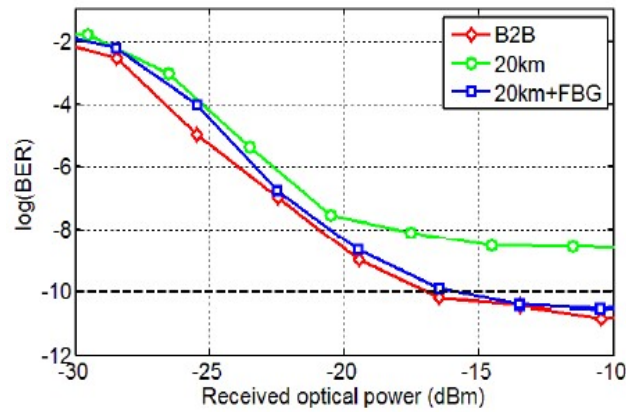

Fig. 10. BER values measured for the 16-channel SS-WDM-PON system compared to the average received signal optical power.

The arranged SS-WDM-PON 16-channel transmission system under research uses NGPON technology. The system ensures data transmission over more than 20 km fiber range to provide a higher system performance with BER $<10^{-10}$, the access system was equipped with a DCM module (with Fiber Bragg Grating) for chromatic dispersion compensation.

Transmission network data capacity can be increased by increasing transmission rate or reducing the channel spacing. However, none of these solutions can be applied if conventional optical signal modulation formats are used, for example NRZ-OOK [37]. Though change to the

modulation format means change to the equipment and consequently the costs for an internet service provider.

One of the most frequently studied solutions of how to enhance the total capacity of a WDM transmission system is to increase its spectral efficiency (SE) [36], [48]. A hybrid transmission system is an effective solution of SE issue. In case of a hybrid transmission system, new data transmission rates or modulation formats can be applied only to a part of channels that would ensure lower costs. This ensures percentage changes in the channels with high data rates, different modulation format or minimum channel spacing. Thus, a hybrid WDM system can be considered as an intermediate stage in gradual transition to a higher data transmission rate system as well as in transition to a different modulation format. The necessity to use transmission in the channels with mixed modulation formats (MMF) or mixed line rates (MLR) motivates internet service providers to develop transmission network infrastructure [38], [39].

In the course of research presented in Sub-section 3.2, co-existence of MMF and MLR, which are used as an intermediate stage to ensure higher data transmission rate at lower costs, was evaluated. The ways MMF, MLR and unequal channel spacings affect operation of a WDM-PON transmission system were studied by comparing the operation of a hybrid configuration system with the operation of a WDM-PON transmission system with equal channel spacing. The spectral efficiency in a hybrid WDM-PON system was analyzed comparing it to WDM-PON with uniform modulation formats, data transmission rates and channel intervals in all channels.

Duobinary (DB) intensity modulation format is applied as another modulation format. DB coding selection for implementation of hybrid solutions is also based on the previous research. A large number of studies demonstrate that DB modulation format is a promising solution ensuring higher data transmission rate and narrower channel spacing because it shows high resistance to chromatic dispersion and limited spectral width. For example, the authors of [41] found out that DB showed its primacy comparing to other analyzed intensity formats (NRZ, RZ, CSRZ), by reaching the minimum channel spacing of 12.5 GHz with a 10 Gbit/s WDM system. DB is also more efficient than the formats with 40 Gbit/s transmission rate. Further in the statement report [42], the authors specify that DB showed high SE level comparing to NRZ, RZ and CSRZ high-speed data system with unequal channel spacing and MMF. In addition, DB parameter is much simpler compared to modern modulation formats. It is also important to note that DB does not require changing the receiver, because it allows using the existing receiver, same as in the case of NRZ coding.

The findings show that Q-factor from the worst NRZ channel in the hybrid transmission system with unequal channel spacings (equal to 18.3 dB) is higher than Q-factor from the worst channel in the 10 Gbit/s NRZ transmission system with 18.75 GHz channel spacing (18.01 dB). Q-factor coming from the worst NRZ channel in a MLR transmission system (18.28 dB) is higher than 18.01 dB Q-factor found in the reference system. This allows concluding that application of either of the above-mentioned concepts does not impair WDM-PON performance and even increases it.

The findings show that partial use of WDM-PON channels with 40 Gbit/s data transmission rate increases Q-factor of these channels compared to the one with full use of channels in the system with 40 Gbit/s data transmission rate. Q-factor from the worst 40 Gbit/s DB channel in the MLR system is equal to 17.78 dB compared to 17.64 dB demonstrated by the system using

all 40 Gbit/s DB channels. Based on these results it can be concluded that 40 Gbit/s data rate promotes compliance to WDM-PON performance requirements only in some channels.

The analysis of the effect of hybrid configuration on WDM-PON spectral efficiency revealed that both the system with unequal channel spacing and the MLR system demonstrate increase in SE compared to the systems with equal channel spacing. SE in the suggested 10 Gbit/s system with unequal channel spacing is 0.62 bit/s/Hz, which is 6.2 times higher than SE in a typical 100 GHz 10 Gbit/s WDM-PON system (equal to 0.1 bit/s/Hz). However, application of the fixed, yet minimum possible channel spacing equal to 18.75 GHz, allows achieving the SE only a bit worse than that in the hybrid configuration (equal to 0.61 bit/s/Hz). This means that the increase in SE is ensured by optimization of channel spacing. Spectral efficiency in the studied MLR system is equal to 0.27 bit/s/Hz, which is 2.7 times higher compared to a 10 Gbit/s WDM-PON (0.1 bit/s/Hz). Furthermore, the sufficiently high value of MLR system Q-factor (equal to 17.78 dB) allows concluding that it is possible to increase the system's SE by reducing channel spacing, which still complies with the minimum Q-factor requirements.

WDM-PONs can successfully use mixed line rates, mixed modulation formats and ununiform channel concepts. However, in order to achieve a higher level of SE in WDM-PONs it is necessary to carry out the research on simultaneous application of these concepts.

Chapter 4

Raman gain was one of the optical amplifier technologies, which debuted at slow pace but afterwards became used widely, along with increasing optical network requirements. Raman gain is based on Raman effect, which is non-linear. Raman amplifiers are the first large-scale non-linear optical devices in the telecommunications and are positioned to be one of the most promising of all optical signal amplification solutions. Raman gain features a comparatively broad amplification spectrum, which can be shaped according to the pumping parameters and is known to produce low distortion to amplified signals, for example, compared to EDFA. This is the reason why Raman amplifiers are commonly connected to optical transmission systems [21], [22].

Apart from the above-mentioned advantages, Raman amplifiers have one significant shortage – poor pumping efficiency at low input signal power levels. There are two types of Raman amplifiers: lumped (LRA) and distributed Raman amplifiers (DRA). A lumped Raman amplifier is a module containing high non-linearity fiber (HNLF) or dispersion compensating fiber (DCF). DCF or HLNF fibers are used as the amplification medium because they ensure higher efficiency of Raman gain than common single mode fibers. Distributed amplifiers use the fiber itself as the amplification medium (transmission line). Distributed amplifiers are used mainly due to better performance parameters. Distributed amplifiers have a better signal-noise ratio, as the amplifier does not allow the fiber level to fall too low [23], [43], [55]. Due to lower effective area of HNLF and DCF core, as well as a higher non-linearity ratio, LRA needs lower pumping power to achieve the certain input signal gain level of certain power than DRA. But, if reversal pumping is used, in the case with DRAs a signal gain begins closer to the transmitter than in the case with LRAs, which means that the signal is amplified more efficiently [24], [25].

This chapter studies Raman amplifier performance in WDM communication systems with reversal pumping configuration at different input signal power values. Using the *OptSim* software, a simulation model of a 16-channel 10 Gbit/s DWDM transmission system with NRZ-

OOK (Fig. 11) was generated. Each of these transmitters functions in its own frequency range from 193.0 THz to 193.75 THz with a 50 GHz channel spacing and output power of 2 mW (3 dBm).
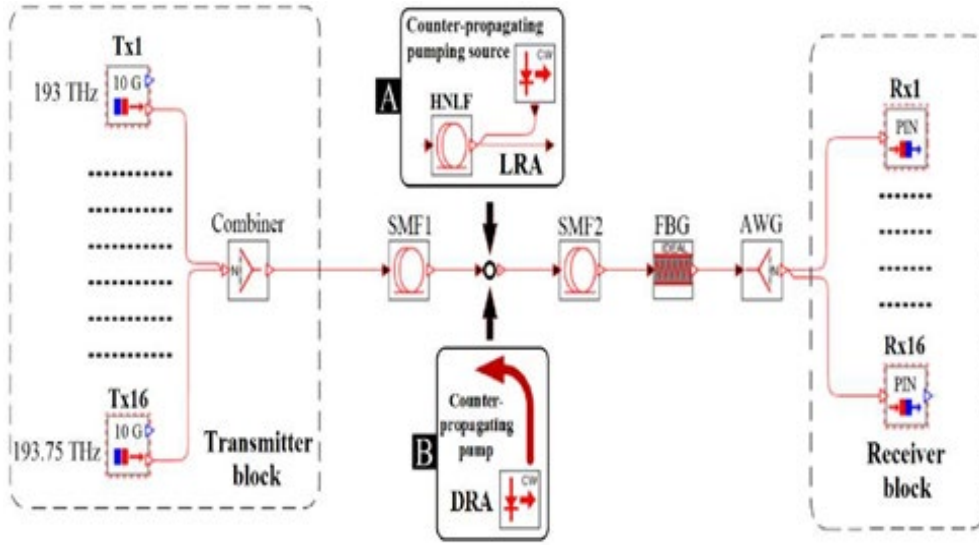

Fig. 11. Simulation model of a 16-channel 10 Gbit/s DWDM transmission system with an inline LRA (A) and inline DRA (B) amplifier.

Distributed Raman amplifiers produce lower noise, although such type of amplifiers demonstrates poor pumping efficiency at low input signal power levels, therefore lumped Raman amplifiers (LRA) can be used instead. LRA amplifiers are used mainly to boost optical fiber network capacity. LRA use highly non-linear fibers (HNLFs) as amplification media. When choosing the HNLF length, two main factors have to be taken into account: firstly, the longer HNLF is, the lower pumping power is needed to ensure the certain amplification level, but secondly, the longer HNLF is, the more essential are amplified signal inconsistencies caused by fiber non-linearity. Thus, it is essential to find equilibrium between amplification efficiency and the amount of amplified signal distortions. Finally, it was decided to use 3 km long HNLF in the existing system [44]. In the system with a DRA amplifier, SMF1 fiber was used as an amplification carrier.

Three different SMF1 and SMF2 fiber length combinations were used, keeping the total transmission distance of 150 km: 75 and 75 km, 100 and 50 km, and 125 and 25 km. This way it is possible to determine the amplifier performance at different input signal power values. Pumping wave length was chosen so as to ensure as high gain as possible and as little amplification gap across all 16 channels as possible. Such gain may be obtained if gain spectrum maximum is placed between two central channels. Pumping radiation wave length is equal to 1452.096 nm (206.455 THz).

First, it is necessary to find the minimum pumping power for each fiber length combination, which would provide appropriate signal quality and BER values under 10^{-9}.
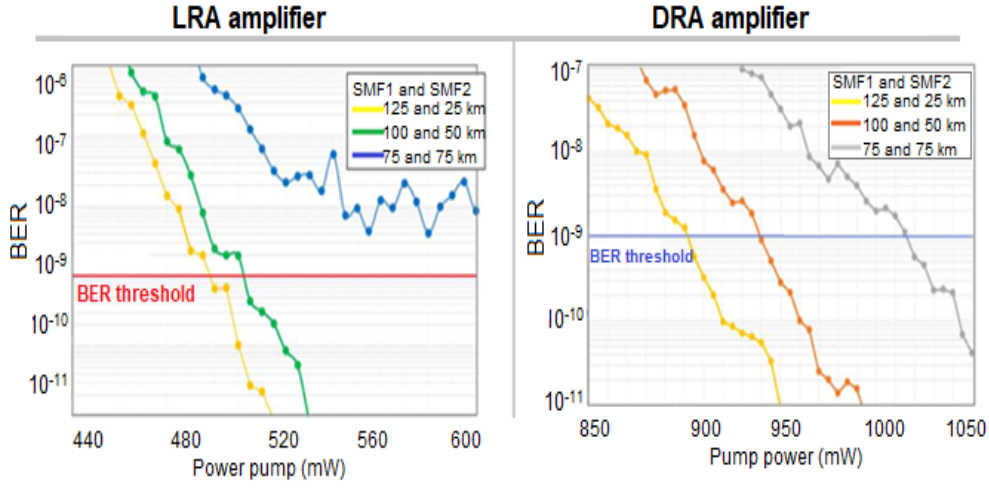
Fig. 12. Dependence of LRA and DRA system BER on pumping power for three different SMF1 and SMF2 lengths.

LRA pumping power:

- 490 mW, if LRA is placed 125 km away from the transmitter (gain: 21.43 dB to 21.56 dB);
- 505 mW, if LRA is placed 100 km away from the transmitter (gain: 21.58 dB to 21.71 dB);
- LRA connection 75 km away from the transmitter does not allow achieving the desired signal quality and thus is not considered any longer.

DRA pumping power:

- 905 mW, if DRA is placed 125 km away from the transmitter (gain: 19.96 dB to 20.08 dB);
- 940 mW, if DRA is placed 100 km away from the transmitter (gain: 20.32 dB to 20.44 dB);
- 1020 mW, if DRA is placed 75 km away from the transmitter (gain: 20.71 dB to 20.83 dB).

In the system with a DRA amplifier such large difference in pumping power at approximately the same gain level is explained by the fact that amplification of the most powerful signal at a certain dB level needs a larger pumping power.

In the DRA-equipped system, to ensure the required signal quality, the gain of around 1.2 dB times lower was needed compared to the LRA-equipped system. This is due to the fact that in LRA case, in addition to the attenuation accumulated during the transmission, the gain also had to compensate HNLF insertion losses, but DRAs use transmission fiber as the amplification medium. DRA need two times more powerful pumping to ensure approximately the same gain. This is explained by the fact that SMF fiber is much more resistant to non-linearity than HNLF fiber. Higher fiber nonlinear resistance explains why a DRA-equipped system achieved appropriate signal quality if the amplifier was placed 75 km away from the transmitter but an LRA-equipped system could not achieve it.

In order to evaluate the operation of both Raman amplifiers with the selected configuration, the determined BER value dependence on the received signal power was compared to the values of those in the same system without amplification (Fig. 13).
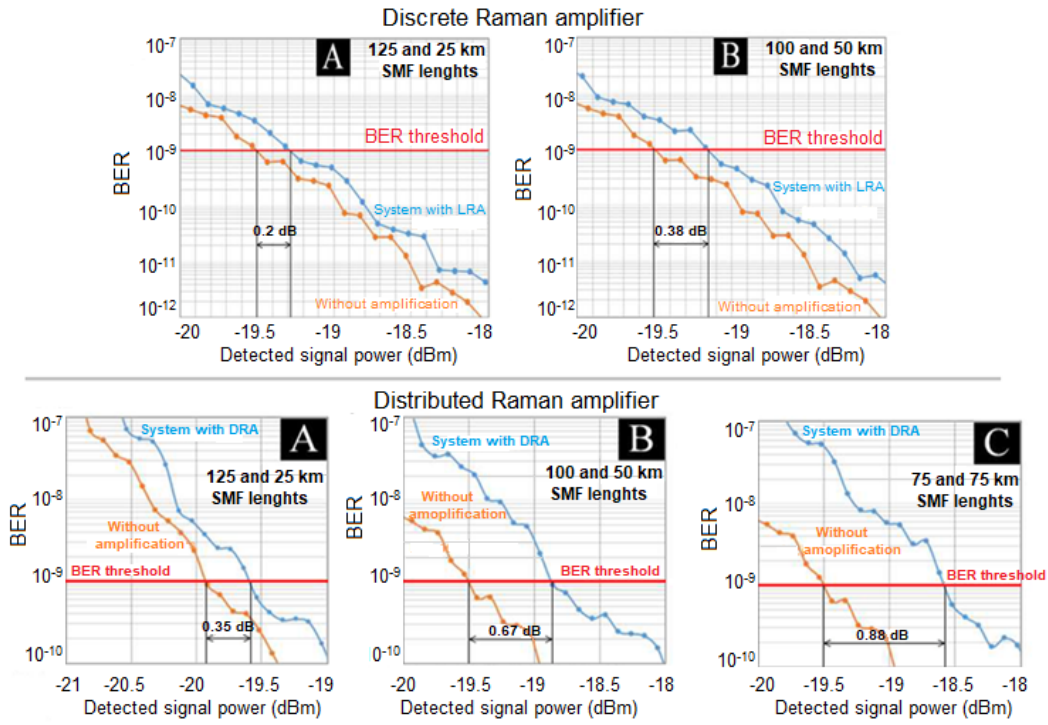
Fig. 13. Dependence of the system BER on the received signal power for LRA (above) and DRA (below) amplifier.

Power penalty between the amplifier-free system and the LRA-equipped system, when LRA is placed 125 km away from the transmitter unit, is 0.2 dB. When LRA was placed 100 km away from the transmitter unit, it was 0.38 dB.

Power penalty between the amplifier-free system and the DRA-equipped system is only 0.35 dB, with SMF1 length of 125 km. When SMF1 fiber length was 100 km, the penalty power reached 0.67 dB and when SMF1 length was only 75 km – 0.88 dB. Same as in the LRA-equipped system, in the case of DRA, the increase of power penalty with the amplifier pumping source placed closer to the transmitter unit is explained by fiber non-linearity – the closer the pumping source to the transmitter unit is, the longer is SMF2 fiber length and the stronger is its optical attenuation, and the higher should be the amplified signal power at SMF1 output, which expresses fiber non-linearity more explicitly.

Chapter 5

This chapter studies hybrid amplification solutions based on SOA, EDFA, Raman and FOPA amplifier combinations. Application of hybrid Raman-EDFA and Raman-SOA solutions in a 16-channel WDM transmission system was analyzed and compared. Due to excessive amount of SOA-induced signal distortions and strong EDFA-induced gain dependence on wave length, implementation of the hybrid EDFA-SOA solution has not been considered. The hybrid Raman-FOPA amplifier in a WDM system was also studied in this chapter.

For investigation of signal distortions from Hybrid Raman-SOA and Raman-EDFA amplifiers a 10 Gbit/s 16-channel DWDM transmission system with NRZ-OOK modulation and 50 GHz channel spacing was developed (Fig. 14). The transmission system functions in the frequency range of 193.05–193.8 THz. Firstly, a signal is transmitted over 72 km single mode

25

fiber (SMF1) with 0.2 dB/km attenuation and 16 ps/nm/km chromatic dispersion. SMF length is determined by the required optical signal power at the input of the optical amplifier, which is essential due to saturation effect, particularly, if a SOA is used. For EDFA this parameter also is significant, as it is upgraded to a semiconductor amplifier. Weak signal power level for each channel at the amplifier input is approximately 22.4 dBm, so the signal is amplified by inline SOA or EDFA.
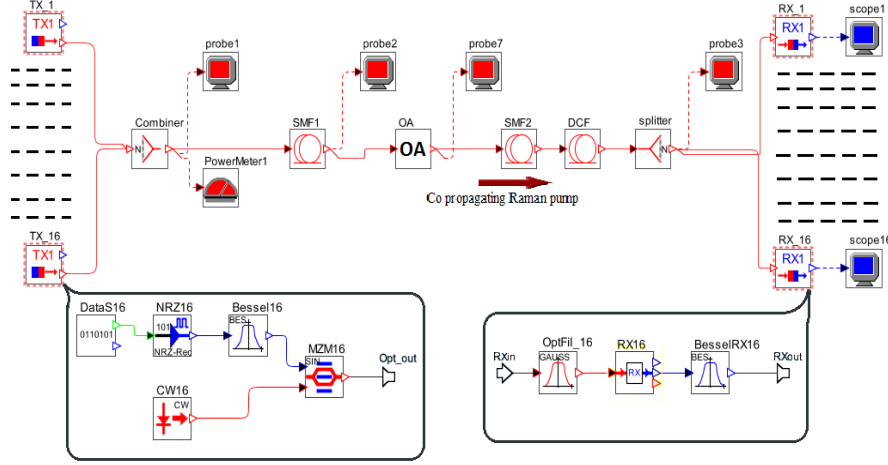

Fig. 14. Simulation model of a 16-channel 10 Gbit/s DWDM transmission system with a hybrid optical amplifier.

SOA pumping current was optimized to reduce signal distortions caused by the amplifier. EDFA parameters were selected so that the power spectrum non-uniformity could be compensated easily by one Raman pumping source. Next, the amplified signal enters the second SMF fiber to be boosted by a low-power DRA whose power allows achieving the maximum signal gain avoiding excessive non-linear distortions. The second SMF length is variable to allow obtaining the maximum transmission distance possible. At the end of the optical line, the signal enters the 17 km long DCF fiber.

First, Raman-SOA and Raman-EDFA configuration that allow obtaining the maximum transmission distance were found. The SOA amplifier pumping current is 370 mA because along with its increase the SOA gain decreases and the maximum level of population inversion is achieved. 5 m long EDF fiber with 10 dBm 980 nm direct and 16 dBm 1480 nm reversal pumping source was selected for a hybrid Raman-EDFA. EDFA gain varies from 12.93 dB to 13.1 dB and noise factor – from 5.33 dB to 5.49 dB in the range of wave lengths from 1547 nm to 1553 nm. Ununiform EDFA gain is equalized using one Raman pumping source. The EDFA configuration was not optimal, still the obtained noise factor is lower than that of the theoretical SOA.

Hybrid Raman-EDFA and Raman-SOA amplifiers were studied using a direct 1453.1 nm Raman pump source with the pumping power of 350 mW, as through the power increase FWM-induced crosstalk exceeds the permissible value and attenuates the total system performance.

As SMF2 fiber is a DRA amplification medium, SMF2 length should be determined (Fig. 15). For Raman-SOAs, the maximum SMF2 length is 52 km (the total transmission distance is 124 km), which ensures the system BER value of $<10^{-12}$. For Raman-EDFAs, fiber length is 54 km (the total distance is 126 km). It is important to note that the maximum transmission distance was reached for the system, which did not use amplification and was

69 km long. This means that Raman-SOA combination can increase this distance by 55 km and Raman-EDFA – by 57 km.
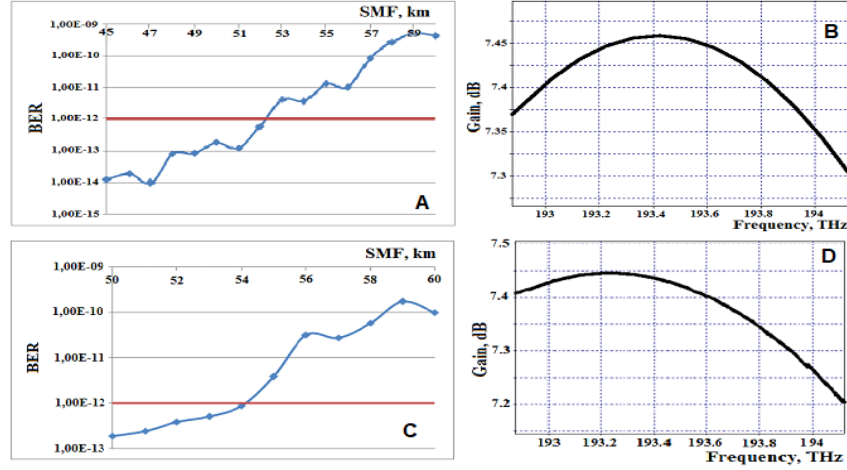

Fig. 15. Dependence of the system BER on SMF2 length (A, C) and resulting DRA gain spectrums for Raman-SOA (B) and Raman-EDFA (D).

To identify the factors that limit transmission in each of the three cases, mesh diagrams of the channels with the worst BER were analyzed (Fig. 16).
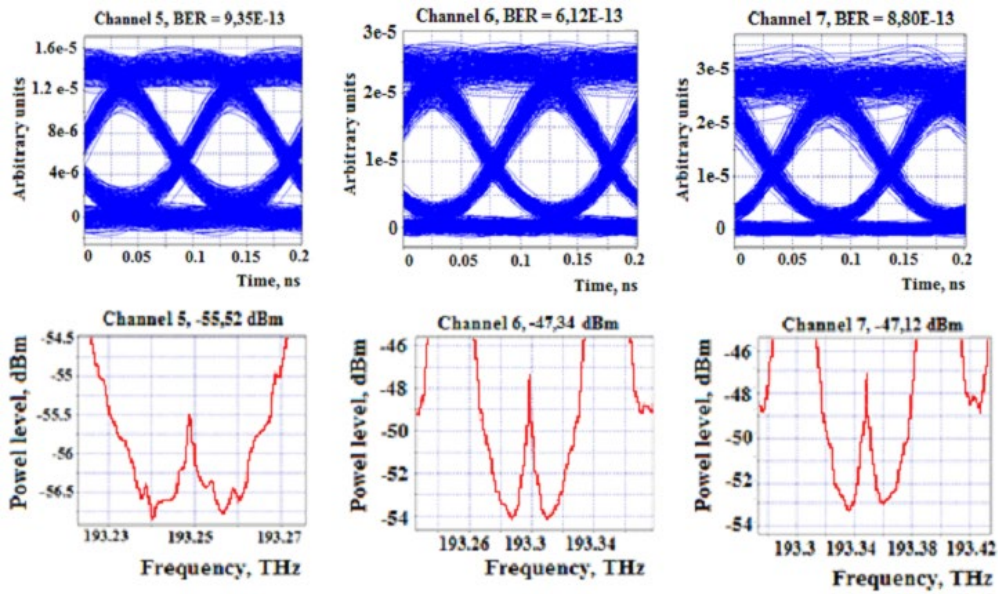

Fig. 16. Mesh diagrams of the channels with the worst BER value (above) and crosstalk in the relevant channels (below).

Based on the research results, the following conclusions have been made.

Introduction of the hybrid amplification can ensure uniform gain. In the case of Raman-EDFA combination EDFA parameters were corrected to obtain the gain spectrum, which could be easily equalized using one Raman pumping source. The introduced EDFA configuration ensured the gain margin of 0.17 dB, but after the EDFA was added with a DRA, the gain spectrum where the maximum gain margin is just 0.05 dB was achieved.

Even a non-optimally configured EDFA shows fewer signal distortions than a SOA. Input signal power was especially customized to the SOA, thus the EDFA was not optimally configured, still the Raman-EDFA showed better results and ensured transmission in a longer

optical line than the Raman-SOA amplifier (126 and 124 km respectively). The Raman-SOA ensured the average gain of 19.6 dB and the Raman-EDFA – 20.4 dB.

Since the EDFA showed fewer signal distortions, the Raman-EDFA solution ensured better gain quality than the Raman-SOA. In both cases FWM produced channel-to-channel crosstalk is the main limiting factor of transmission.

A hybrid Raman-FOPA amplifier is the second research objective of this chapter. Both of these amplifiers allow changing the band width using appropriate pumping sources. It is necessary to study combinations of both amplifiers in a 16-channel 40 Gbit/s WDM transmission system, which operates in the S-band portion (Fig. 17). Channels were transmitted over 150 km long NZ-DSF (ITU-T G.655) fiber, as the comparison between SMF and NZ-DSF fibers did not show any evident differences. The main objective was to find a Raman-FOPA configuration that would allow amplifying a very weak optical signal, while maintaining as low power margin as possible, as well as amplifying ununiformly all channels and keeping the system BER lower than 10^{-9}. The suggested Raman-FOPA setup was compared to FOPA amplifier of one pumping source with the same value of output signal power in order to assess improvements in performance after connection of a Raman amplifier to the system. The performance of the hybrid amplifier was determined through analysis of the gain curve, received WDM OSNR and BER values.
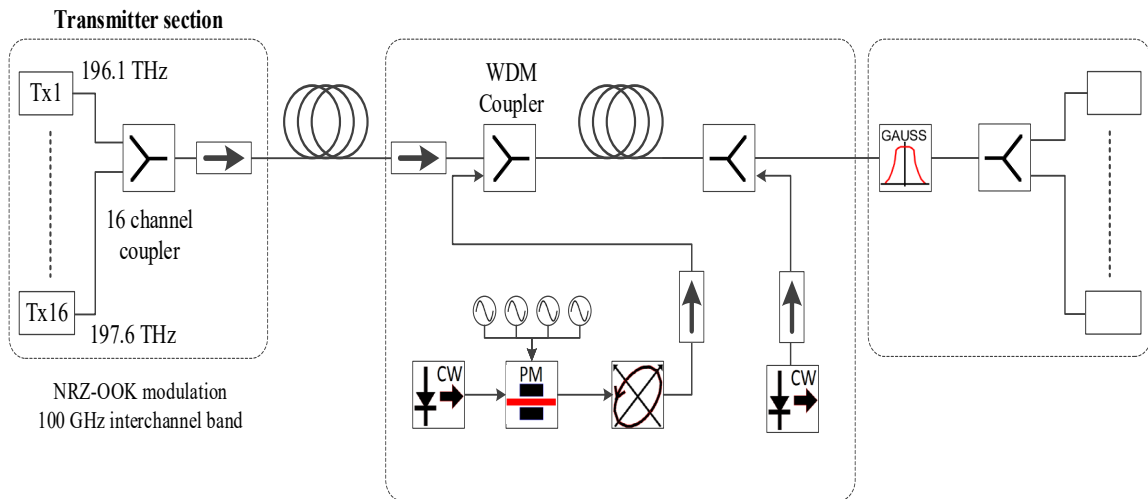

Fig. 17. Simulation diagram of the hybrid Raman-FOPA amplifier which functions as a preamplifier in a 16-channel WDM system.

Raman-FOPA performance depends on rather complex interaction between different non-linear effects, it has to be found out what parametric pump (PP) and Raman pump (RP) parameters should be chosen to achieve the required gain properties. It was stated that Raman-FOPA WDM channel gain is uniform if a parametric pump of 192.918 THz and 440 mW output power and a Raman pump of 206.13 THz and 500 mW output power are combined.

The average 16-channel WDM gain in the case of Raman-FOPA is 34.7 dB, which is on average by 8.2 dB higher than the total Raman and FOPA gain.

Raman-FOPA amplifier operation will be compared to single pump FOPA amplifiers (PP – 682 mW and 660 mW). Figure 18 shows that for all three amplifiers the gain is approximately the same, but the gain of the hybrid solution is more equalized and broader. Raman-FOPA 3 dB gain band width is by 0.02 THz broader than for FOPA at 682 mW and by 0.20 THz broader

than optimized FOPA at 660 mW, which partly can be explained by direct signal amplification through Raman pumping.
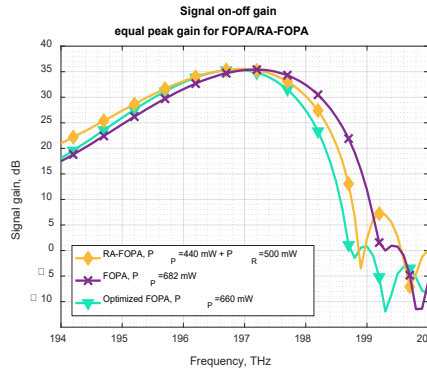

Fig. 18. FOPA and Raman-FOPA signal gain curves.

The hybrid Raman-FOPA amplifier provides uniform output power. When comparing BER distribution, it can be seen that channel 16 showed the worst performance, which is related to the steep FOPA gain curve and results in lower channel power values. The signal OSNR was acquired (calculated at 0.01 THz resolution). Respectively, the average and standard OSNR deviation makes: for Raman-FOPA 18.57±0.53 dB, for FOPA 18.52±0.45 dB and for optimized FOPA 18.59±0.61 dB. This means that as soon as the received signal power is equalized, all three amplifiers produce approximately the same amount of noise. It needs to be noted that both single pump FOPAs are equipped with significantly more powerful parametric pump lasers to achieve equal output power and OSNR level.
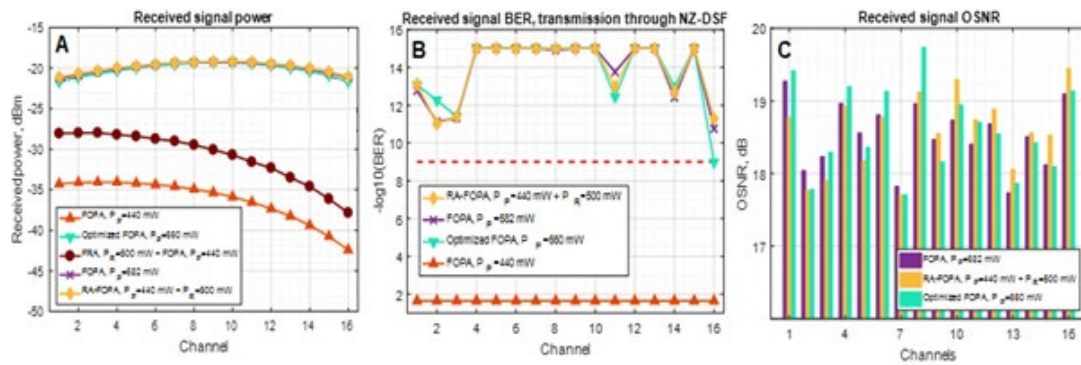

Fig. 19. WDM channel power (A), BER (B) and OSNR (C) distribution.

In the Raman-FOPA configuration, the single pump FOPA power (PP=682 mW) is less by 38 % compared to total pumping power (PP=440 mW and RP=500 mW). The required FOPA pumping power is higher than for each individual Raman-FOPA pump laser by 36 %. High power of one pumping source is related to its introduction issues, for example, thermal dissipation, efficiency and SBS induced start-up power limitations.

The hybrid Raman-FOPA amplifier shows essential advantages in WDM transmission systems and in application of hybrid solutions is aimed at significant enhancement of existing FOPA amplifier operation.

Chapter 6

The significance of optical amplifiers is related to the fact that optical transmission systems

are developing fast, since the amount of transmitted data is increasing and higher rates of data transmission are required. This poses new challenges which include optical signal gain.

The objective of this chapter is to develop a two rare earth doped amplifier based on the cladding pump technology. Such kind of amplifiers would allow achieving high and uniform gain. The intended area of application includes WDM optical transmission systems, underground access networks and hybrid passive optical networks to extend the reach.

The combination of two rare earth doped elements improves pumping efficiency which is essential in the case of cladding pumping. Ytterbium (3+) has been chosen as the second element because Yb has a much larger absorption cross section than Er and ensures Er emission in the absorption band.

An essential component of the cladding pump technique is a specialized connector which couples the signal and the pumping light so that the signal propagates in a doped fiber core but pumping radiation – in the cladding. Cladding pumping can use multiple connectors depending on their physical appearance. One of the cone shaped fiber bundle techniques has drawn attention. Application of this technique makes the production of fiber connectors less complex.

The cladding pump based EYDFA operation in various conditions has been studied to evaluate its suitability for the municipal optical transmission network access segment. To carry out the evaluation, a simulated system (Fig. 20) was developed using *VPIphotonics Design Suite* [48]. The amplifier model was generated based on the characteristics of the commercially available Er/Yb doped fiber Fibercore CP1500Y. To generate a realistic EYDFA model, experimental CP1500Y fiber cladding ratios and absorption cross sections to be introduced into the EYDFA model were obtained. The amplifier performance was determined taking into account its gain, noise factor, which is ASE noise level caused by amplification, and pumping power conversion efficiency.
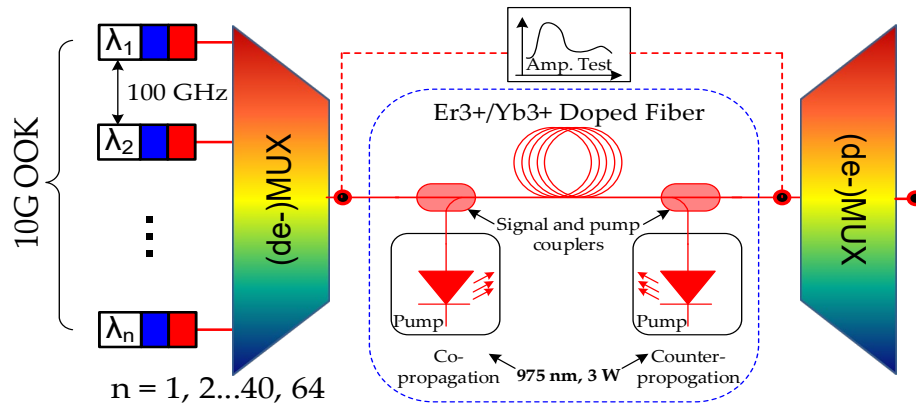

Fig. 20. Simplified simulation model of cladding pump based EYDFA.

Simulated system parameters: 10 Gbit/s NRZ-OOK, 1 to 64 channels, 191.6 THz to 195.5 THz operation range, 100 GHz channel spacing, –25 dBm/channel to –10 dBm/channel.

EYDFA pumping source parameters: 975 nm wave length, 3W pumping power, direct and reverse propagation.

Doped fiber parameters: up to 10 m fiber length, 1×10^{25} m^{-3} Er^{3+} concentration, 2×10^{26} m^{-3} Yb^{3+} concentration, 1×10^{-22} m^3/s Er/Yb cross-relaxation ratio.

EYDFA configuration was chosen having achieved the gain and NF at different amplification medium lengths both for direct and indirect spreading. In order to obtain these

results, EYDFA was included into the model of a 40 channel WDM transmission system with the input signal power of 20 dBm/ channel.
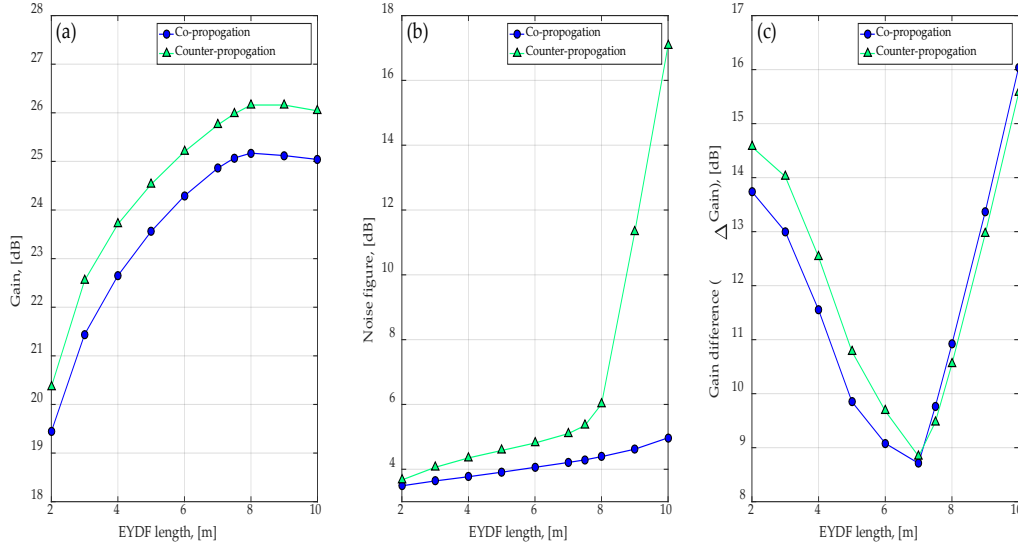

Fig. 21. (a) – average gain, (b) – average noise factor, and (c) – maximum gain margin between channels depending on EYDF fiber length.

Figure 21 (a) shows that enlargement of amplification medium length causes average gain growth only until 8 m EYDF and then the gain decreases slightly. NF values obtained from an 8 m long EYDF at most do not exceed 6 dB, but after that NF increases, especially in the case of reverse pumping (Fig. 21 (b)). The gain margin reaches the minimum level both for direct and for reverse pumping source solutions when EYDF fiber length is 7 m. The reverse pumping source ensured higher average gain, but the direct one – lower NF values. As soon as a lower noise factor has the priority over a higher gain, the single-core cladding pumped EYDFA will use a 3W 975 nm direct pumping source and 7 m EYDF fiber.

Figure 22 shows signal and noise spectrums at the amplifier output, as well as gain and noise factor spectrums.
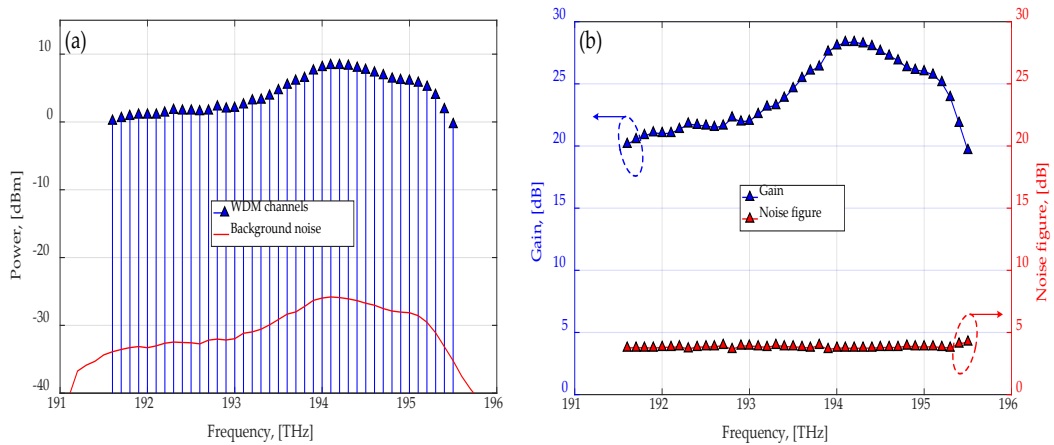

Fig. 22. (a) – optical power spectrum and (b) – average gain and NF in the system with 40 WDM channels.

The signal power varies from 0.1 dBm to 8.3 dBm (Fig. 22 (a)). This was achieved using the EYDFA gain ratio, whose spectrum is shown in Fig. 22 (b) and varies from 19.7 dB to 28.3 dB. Noise factor values of 40 amplified channels change from 3.7 to 4.2 dB.

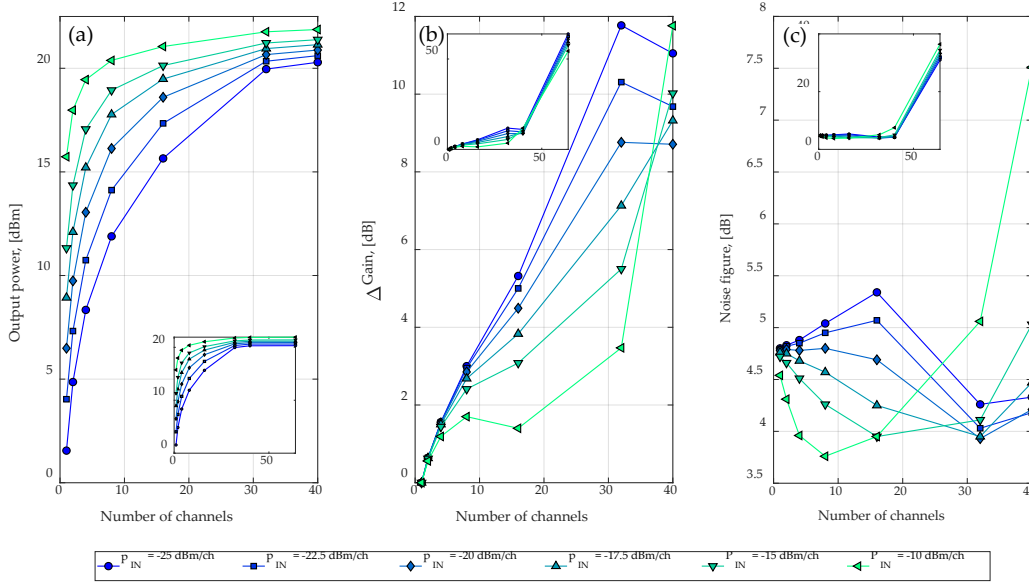EYDFA response to changing channel number and amplifier input power was considered.

Fig. 23. (a) output power, (b) maximum gain margin and (c) maximum noise factors compared to WDM channel number and input power.

The larger is the number of channels, the lower is different output power for different signal power values at the amplifier input. Furthermore, the amplifier output power gain becomes insignificant when increasing the number of channels from 40 to 64, regardless of the EYDFA input signal power. If the input signal power is –25 dBm/channel and the number of channels is increased from 16 to 32, a higher ASE noise level is observed. If the number of channels is increased from 32 to 40, the amplifier output power increases only by 0.3 dB, and it remains unchanged if the number of input channels is increased from 40 to 64. This shows that at this moment the amplifier is already working in a saturation region. Based on the results shown in Fig. 23 (a) it can be stated that with the selected configuration the EYDFA output power is limited to approximately 22 dBm.

When the number of channels was up to 32, the higher input signal power featured lower maximum gain margin between the channels. But when the number was increased up to 40, the situation became fully opposite, the gain margin at the input signal power –25 dBm/channel became lower than at the power of –10 dBm/channel.

Similar tendency may be observed in Fig. 23 (c), the increased number of channels, firstly, caused the achieved NF reduction at the amplifier input, but afterwards, when the number of channels achieved the certain value, average NF values started increasing. The gain margin and average noise factor values dramatically grew when the number of channels was increased from 40 to 64 because the amplifier with such configuration was unable to ensure amplification over the whole range of frequencies used by 64 channels and channels transmitting higher frequency signals were absorbed in the amplification medium.

Limitation of the output power is mainly related to physical properties of the amplification medium, which characterizes transmission rates in the whole fiber, consuming the pumping

radiation and transmitting it to amplified signals. As soon as EYDF Yb^{3+} ions are responsible for fast absorption of the pumping radiation and for partial transfer of its energy to Er^{3+} ions, through manipulations with Yb emission and absorption cross section characteristics it becomes clear how Yb^{3+} ion characteristics affect EYDFA operation. The obtained experimentally Yb emission and absorption cross sections were multiplied by the ratios 0.7 and 1.3 and the gain, the NF and ion excitation percentage dependence on the fiber axial state were determined (Fig. 24).
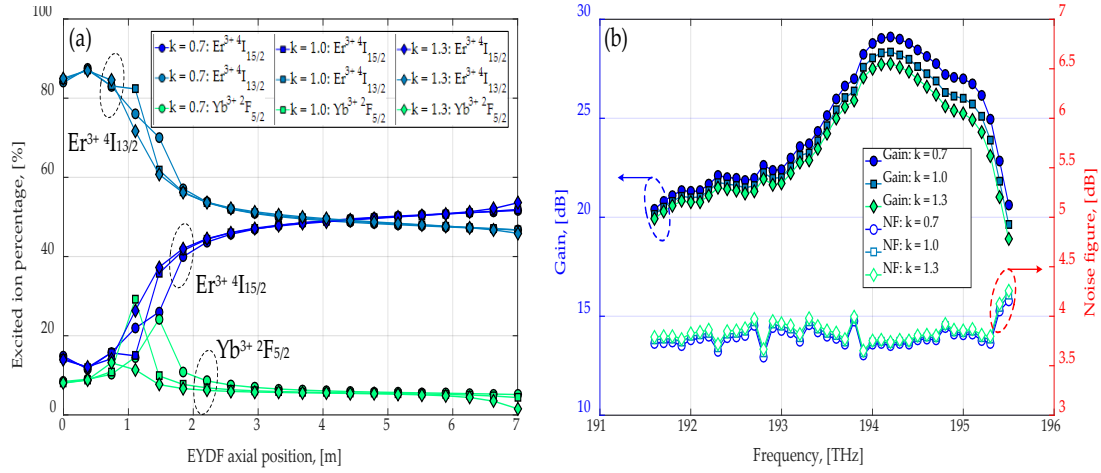

Fig. 24. Sensitivity analysis that shows the impact of Yb^{3+} absorption and emission cross section on excited ion coefficient $k = 0.7, 1.0, 1.3$: (a) – percentage of stressed ions related to the fiber axial state; (b) the average EYDFA gain and the maximum NF in a WDM system with 40 channels.

If cross section values decrease by 30 %, the peak value of excited Yb ion percentage will decrease by 5 % and will move deeper into the amplification medium: 1.1 m to 1.5 m long EYDF (Fig. 24 (a)). This lengthens the EYDF supporting the signal amplification herein, which results in a higher gain (by ~0.7 dB) and lower NF (by ~0.1 dB). The opposite situation is observed if Yb emission and absorption cross sections are increased by 30 %, the maximum Yb population inversion is observed at the distance of 0.74 m from the EYDF output (by 0.36 meters closer). As the result, the achieved average gain decreased by 0.5 dB and the average NF increased by 0.05 dB.

BER performance has been assessed for a 40 channel DWDM system configuration with an EYDFA and without amplification (Fig. 25). As the result, the power penalty is lower than 0.1 dB at BER=10^{-9}. Such level of distortions may be considered negligible. Still, the gain spectrum would need to be flattened using, for instance, gain flattening filters or multiple amplification stages to start effective application of such amplifiers for compensation of optical losses in WDM transmission systems.

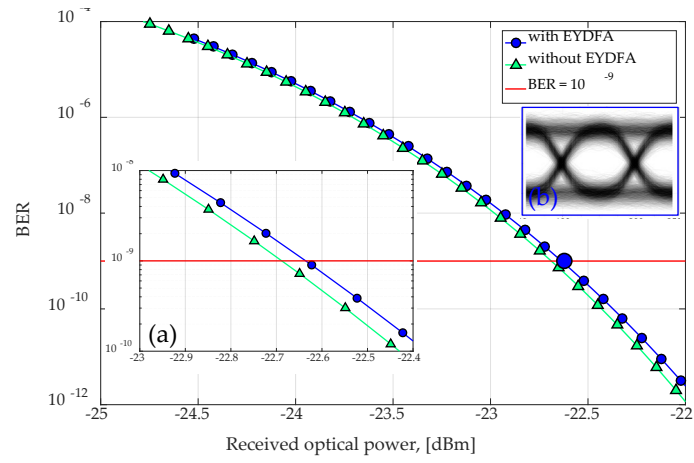Fig. 25. Dependence of the worst BER on the received signal power in a 40-channel WDM system with and without EYDFA amplifier, where (a) is closer to BER=10^{-9} and (b) is mesh diagram which is limited to the amp configuration at BER$\cong 10^{-9}$.

The amplifier characteristics found and determined during the research are paramount for further experimental development and testing of the cladding pump EYDFA amplifier.

MAIN RESULTS OF THE DOCTORAL THESIS

In the process of completion of the defined tasks, a number of **results and conclusions of the Doctoral Thesis have been obtained**.

Transmission systems with an EDFA amplifier where the channel spacing is below 100 GHz require pumping power above 60 mW to ensure the appropriate quality of the amplified signal and BER values below the specified level of 10^{-9}. If the spacing is below 50 GHz, spectrum interference of adjacent channels is inevitable and power penalty value is greater than 0.20 dB.

In EDFA systems with multiple amplification stages, a system with 3 EDFAs and a 100 km amplification range is the most efficient in terms of power consumption, as the total system pumping power is lower (105 mW) and 24 m long EDF fibers are sufficient to ensure the necessary signal quality and the BER of the system would be below 10^{-9}. The power penalty for a WDM system with 3 EDFA amplifiers corresponding to a system without amplification is only 0.32 dB.

Using only one broadband ASE light source for all users and a DCM module for dispersion compensation, the studied 16-channel WDM optical access system ensures data transmission on a more than 20 km long line with high system performance with BER 10^{-10}. This solution is good for next-generation passive optical networks.

The assessment of hybrid configuration effects on spectral efficiency of a WDM-PON system showed that SE efficiency can be increased via optimization of channel spacings. For a system with unequal channel spacing and an MMF, the SE (0.62 (bit/s)/Hz) is 6.2 times larger than a typical 100 GHz 10 Gbit/s WDM-PON system. The spectral efficiency of the WDM-PON system with MMF and MLR is 0.27 (bit/s)/Hz and is 2.7 times higher than that of a typical system.

When installing a discrete and distributed Raman amplifier farther from a transmitter unit, which is at 125 km, 3 % lower pumping power is required to ensure the appropriate quality of an amplified signal at BER 10^{-9} and also the channel amplification is above 21.5 dB. In the case of a discrete Raman amplifier, the pumping power (up to 500 mW) is on average 50 % lower than in the case of a distributed Raman amplifier (the minimum pumping power is 905 mW to 1020 mW depending on the location in the transmission line).

Hybrid Raman-FOPA computer model amplification is more uniform and reached 34.7 dB in a 16-channel 40 Gbit/s WDM system. Amplification of a hybrid amplifier is by 30 % (8.2 dB) higher than the total of both Raman and FOPA ones. Raman-FOPA -3 dB amplification bandwidth is by 0.02 THz wider than that of a 682 mW FOPA and by 0.20 THz wider than an enhanced 660 mW FOPA, which is explained by direct signal amplification via a Raman pump source.

A cladding pumping EYDFA computer model amplifier ensured uniform and broad amplification (19.7 dB to 28.3 dB), low noise level (3.7 dB to 4.2 dB), and power penalty is lower by 0.1 dB. Transmission systems with such an EYDFA (7 m EYDF fiber, a 3W 975 nm directly driven pump source and $p_{input} = -20$ dBm per channel) are appropriate for WDM software applications.

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