RIGA TECHNICAL UNIVERSITY
Faculty of Electronics and Telecommunications
Institute of Telecommunications

Ingrīda Lavrinoviča
Doctoral Student of the Study Programme “Telecommunications”

DEVELOPMENT AND ASSESSMENT OF THE NEW GENERATION RARE-EARTH DOPED OPTICAL FIBER AMPLIFIERS

Summary of the Doctorate Thesis

Scientific Supervisor
Professor Dr. sc. ing.
JURĢIS PORIŅŠ

RTU Press
Riga 2019

Lavrinoviča, I. Development and Assessment of the New Generation Rare-Earth Doped Optical Fiber Amplifiers. Summary of the Doctoral Thesis. Riga: RTU Press, 2019. 28 p.

Published in accordance with the decision of the Promotion Council “RTU P-08” of 4 April 2019, Minutes No. 44.

ISBN 978-9934-22-305-1 (print)
978-9934-22-306-8 (pdf)

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

To be granted the scientific degree of the Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defense at the open meeting of RTU Promotion Council on June 27, 2019 at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Azenes Street, Room 201.

OFFICIAL REVIEWERS

Professor Dr. sc. ing. Ģirts Ivanovs
Riga Technical University

Lead Researcher Dr. phys. Jānis Alnis
University of Latvia, Latvia

Professor Dr. phys. Valfrīds Paškevičs
University of Daugavpils, Latvia

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 Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Ingrīda Lavrinoviča ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of Introduction; 4 Chapters; Conclusions; 52 figures; 8 tables; 4 appendices; the total number of pages is 103. The Bibliography contains 110 titles.

TABLE OF CONTENTS

LIST OF ACRONYMS

A

ASE – amplified spontaneous emission

E

EDF – erbium doped fiber

EDFA – erbium doped fiber amplifier

EYCDFA – erbium-ytterbium co-doped fiber amplifier

EYDFA – erbium-ytterbium-doped-fiber amplifier

F

FOPA – fiber optical parametric amplifier

H

HDWDM – high density wavelength division multiplexing

I

ITU-T – International Telecommunication Union

L

LOA – linear optical amplifier

M

MOPA – master oscillator power amplifier

N

NRZ-OOK – non-return to zero on/off keying

R

REDFA – rare-earth-doped fiber amplifier

S

SDM – space-division multiplexing

SM-SCF – single-mode singlecore fiber

SNR – signal-to-noise-ratio

SOA – semiconductor optical amplifier

SSMF – standard single-mode fiber

T

TDM – time-division multiplexing

W

WDM – wavelength division multiplexing

Y

YDF – ytterbium doped fiber

GENERAL DESCRIPTION OF THE WORK

Topicality of the Subject Matter

Today, telecommunication industry is rapidly developing. Fiber optics transmission systems have been integrated into data transmission networks of different scale: corporate, access and regional networks, city and intercity lines, transcontinental networks. As can be seen in Figure 1., in the past four decades, the data rates of optical communication systems have experienced an astonishing increase from 100 Mbit/s per single-mode fiber in the 1970s, up to 24 Tbit/s and more in modern commercial systems [14].

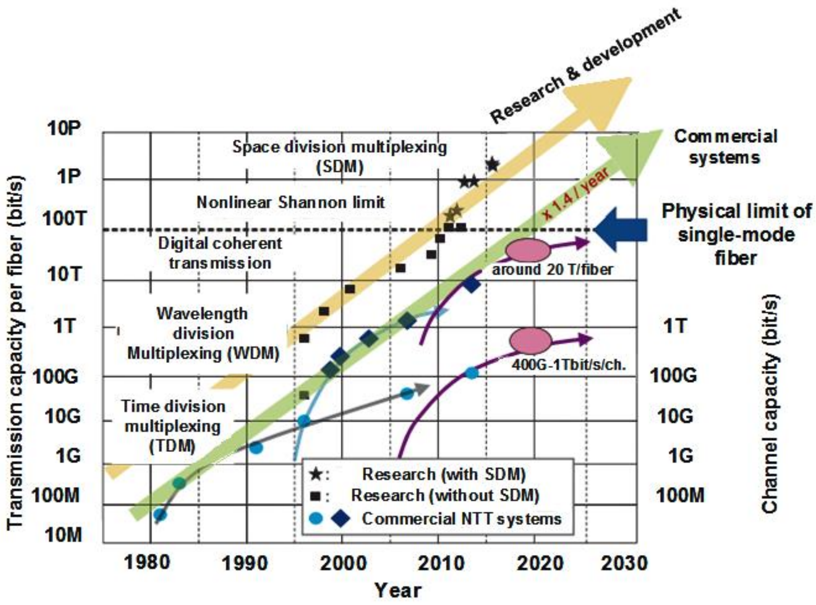

Fig. 1. Development tendencies of fiber optics transmission systems [10].

For large distances data transmission with attenuation rate less than 0.2 dB/km in fiber optics mostly C frequency band (1530–1550 nm) and L frequency band (1565–1625 nm) are used, in which the optical amplifiers' bandwidth is held within 40 nm (5 THz). In turn, around 2020, it is anticipated that it would be necessary to broaden total optical amplifiers' bandwidth up to 120 nm (15 THz), respectively, covering also S frequency band range (1460 nm to 1530 nm). Taking the above into account, the total capacity of transmission system tends to reach around 150 Tbit/s [11], [12].

Following the source [13] data, communication systems with transmission data rates over 100 Tbit/s have already been launched and are functioning using single-mode singlecore optical fibers SM-SCF (single-mode singlecore fiber) and combining up to 100 high-density (HDWDM) channels through application of time-division multiplexing (TDM) and space-division multiplexing (SDM) technology.

With increasing volume of transmitted data per channel, it is necessary to have greater optical capacities; therefore, in the process of optimizing the multichannel communication system, one faces two basic issues: bandwidth and input power increase [1].

Traditional communication theory states that the upper limit of spectral efficiency (communication capacity per band) with respect to a fixed signal-to-noise ratio (SNR) is defined by the maximum Shannon limit $\eta_{\max}$ [9]:

$$\eta_{\max} = \log_2\left(1 + \frac{RE_{\mathrm{b}}}{N_0 W}\right), (\mathrm{bit/s})/\mathrm{Hz}, \tag{1}$$

where E_{b} is energy amount for transmission of one bit;
R is system transmission rate, bit/s;
N_0 is noise power spectral density;
W is channel capacity, Hz.

With increase of optical signal power, interchannel crosstalk also increases, which is caused by impulse distortions under impact of non-linear effects [4], [7], [16]. Following the non-linear Shannon limit parameter, currently the potential of increasing spectral efficiency of transmission system is restricted approximately four times, if the current systems transmit 2 bits per symbol) [2]. Respectively, it is necessary to extend spectral bandwidth towards frequency band *L*.

Optical power losses are caused by attenuation in optical fibers, resulting from dispersal and absorption processes, and this is a topical issue when transmitting optical signal at large distances. In standard single-mode optical fiber SSMF (Standard Single-Mode Fiber) at the wavelength of 1550 nm, attenuation is around 0.2 dB/km. Once the length of optical communication line increases, after each 50–100 km signal is attenuated by 10–20 dB and needs to be restored [18]. Respectively, power reserves shall be provided, as, for maintenance of a bit stream, the transmitter should be given a more powerful signal, in other words – the signal must be amplified.

For this purpose, optical amplifiers are used. Unlike regenerators in modern commercial fiber optics transmission systems, they provide optical signal amplification without optically electrical conversion. Optical amplifiers are adjustable to transmission data rate and modulation format, as well as amplify several optical signals simultaneously within a certain frequency range.

From all the above mentioned, it can be concluded that rapid development of telecommunication sector and growth of transmitted data amount defines one of the most strategic directions, which is aimed at optimizing the usage of resources and increasing efficiency in the optical network. Such direction is the design of new-type optical amplifiers, which would ensure larger output power, as well as extend the range of amplification wavelength [8], [11], [17].

Aim and Tasks of the Thesis

Summarizing the above mentioned facts, **the aim of the Doctoral Thesis** was brought forward: to evaluate parameters of rare-earth-doped telecommunication optical fibers, as well as develop a solution for optical signal amplification range extension in wavelength division multiplexing communication system's frequency bands S (1460–1530 nm) and L (1565–1625 nm).

To reach this aim, the following **basic tasks** had to be performed.

1. To study rare-earth doped fibers used in fiber optics communication systems, and their features and possibilities of application in optical amplifiers.
2. To develop a model of multichannel communication system with data transmission rate up to 40 Gbit/s in computer simulation program to evaluate the performance of rare-earth doped fiber amplifiers.
3. Using computer simulation program, to evaluate amplification efficiency and noise factor depending on the length of doped fiber and pump power for erbium-doped fibers.
4. Using computer simulation program, to evaluate amplification efficiency and noise factor for ytterbium-doped fiber depending on the length of doped fiber and pump power.
5. Using the obtained simulation results, to experimentally evaluate the gain coefficient, noise factor and amplified spontaneous emission parameter for erbium and ytterbium doped optical fibers of different length.
6. Using transverse shift measurement method, to measure the effective area parameter for erbium and ytterbium doped optical fibers in order to evaluate the manifestation of non-linear optical effects in rare-earth doped fibers.
7. On the basis of the previous analysis and obtained results, to study the parameters of combined rare-earth doped optical fiber amplifiers for optical signal amplification range expansion within frequency bands S (1460–1530 nm) and L (1565–1625 nm) of wavelength division multiplexing communication systems and compare the acquired results.

Methodology of the Research

Implementation of tasks set within the Doctoral Thesis and problem analysis was performed with numerical simulations and experimental measurements. In numerical simulations, using calculation algorithm based on the non-linear Schrodinger equation, the parameters of erbium and ytterbium doped optical fibers such as gain coefficient and noise figure were evaluated. Experimental measurements of effective area for erbium and ytterbium doped fibers have been performed using transverse-shift measurement method with micro-positioner. During experimental measurements with transverse shift measurement technique, far field distribution is obtained, which is recalculated to the near field distribution with the Hankel transformation. Using MATLAB software, from the acquired near field distribution, we calculate the effective area of fiber A_{eff}.

Practical implementation of combined erbium and ytterbium doped fiber amplifier was performed using continuous wave laser as a primary source; excitation source, which has been set up to operate in forward and backward pumping configuration, as well as connecting together the segments of Er^{3+} and Yb^{3+} ions doped fibers of specific length. To evaluate the gain spectrum, a spectrum analyzer was used.

Main Results of the Doctoral Thesis

The scientific novelty of the promotion work is as follows:

- the transverse shift measurement method was developed and approbated for evaluation of effective area of rare-earth-doped optical fibers;
- experimentally, combining erbium and ytterbium doped fiber segments, amplification has been obtained within the wavelength range of 1000–1100 nm, which makes it possible to expand the erbium amplification band from 47 nm to 82 nm.

During the development of the Doctoral Thesis, the following **main conclusions** have been obtained.

1. Performing computer modeling of EDFA amplifier, it was stated that using counter-propagation pumping at 1480 nm with 30 m erbium fiber and 500 mW exciting source power, it is possible to obtain 40.7 dB gain coefficient, which is by 12 dB more than using an analogue fiber length with co-propagating EDFA configuration.
2. It was practically stated that using 15 m long HWT erbium fiber and bidirectional EDFA pumping configuration it is possible to ensure amplification by 14.4 dB with exciting source power of 21.3 mW. In comparison with one-way pumping excitation process requires 16 mW less power.
3. Using experimental transverse shift measurement method, it was defined that effective area values for erbium fiber at the wavelength of 1310 nm correspond to 36.5 μm^2, in turn, at the wavelength of 1550 nm, they increase up to 57.1 μm^2. The usage of ytterbium fiber shows a higher parameter of A_{eff}: at 1310 nm, A_{eff} is 106.2 μm^2 and at 1550 nm, A_{eff} equals to 129.2 μm^2. Respectively, it is more useful to apply ytterbium doped fibers in the development of combined optical amplifiers.
4. In the combined power amplifier of erbium and ytterbium co-doped fibers (EYCDFA), it is more useful to apply shorter ytterbium fibers, as with 10 m YDF, stable output power 36 dBm (5 W) is obtained.
5. With combined erbium and ytterbium doped fiber amplifier (EYDFA), applying counter-propagating setup at the wavelength of 980 nm, maximum gain value of 8.4 dB corresponds to the pump power of 13.3 dBm, while with 15.2 dBm pump power the gain attains about 5 dB. Thus, with counter-propagating EYDFA configuration power saving by 2 dBm is ensured.
6. Extended spectral band within 1000–1100 nm has been obtained experimentally, which may be used as excitation source pumping wavelength in further EYDFA research.

Practical Value of the Work

1. The results of the scientific studies within the Doctoral Thesis have been used in implementation of two Latvian scientific research projects.
2. Patent for effective area measurements of rare-earth elements doped optical fibers using transverse shift measurement method has been developed, submitted and published (patent application number P-16-103, date of publication 20.06.2018.).

3. Commercialization application “Measurement of Effective Area of Optical Fibers With Transverse Shift Method” has been developed and submitted.
4. As a result of the exploration of the combined erbium and ytterbium doped fiber amplifier (EYDFA) using ytterbium fiber, active excitation has been obtained with low pump source power within 13–15 dBm.
5. Experimental certification proves that, combining segments of erbium and ytterbium doped optical fibers, it is possible to expand amplification wavelength range within the band of 1000–1100 nm.

The Theses to be Defended

1. The usage of EDFA and combined EYCDFA amplifier in cascade within oscillator power amplifier configuration realizes a powerful light source with output power up to 35.6 dBm.
2. Ytterbium doped optical fibers require larger effective area A_{eff} than erbium doped optical fibers, to acquire higher optical amplification.
3. Using 5 m long erbium fiber and 5 m long ytterbium fiber in the combined EYDFA amplifier, with counter-propagating setup and 13.4 dBm pump power, it is possible to obtain experimentally 8.4 dB amplification with 2.5 dB noise factor.

Approbation of Results

The main results of the Doctoral Thesis were presented in 11 international scientific conferences, as well as in one publication in a scientific journal, eight publications in full-text conference proceedings, five publications in the conference books of abstracts and one Latvian patent application.

Reports **in international conferences**

1. **Lavrinovica I.**, Supe A., Udalcovs A., Ozolins O., Popov S. and Porins J. Exploration of Optical Amplifiers Based on Erbium (Er^{3+}) and Ytterbium (Yb^{3+}) Doped Fiber Segments and Their Emerging Applications// Progress in Electromagnetics Research Symposium (PIERS). **Japan**, Toyama, August 1–4, 2018 **(Invited)**.
2. Nazarovs V., Jelinskis J., Porins J. **Lavrinovica I**., Supe A. and Aispurs V. Architecture and research of M2M wireless mesh networks// Progress in Electromagnetics Research Symposium (PIERS). **Russia**, Saint-Petersburg, May 22–25, 2017.
3. Maharjan R., **Lavrinovica I.**, Supe A., Porins J. Minimization of FWM Effect in Nonlinear Optical Fiber using Variable Channel Spacing Technique// Advances in Wireless and Optical Communications (RTUWO). **Latvia**, Riga, November 3–4, 2016.
4. Shakya S., Supe A., **Lavrinovica I.**, Porins J. Different Optical Fiber Nonlinear Coefficient Experimental Measurements// 6th International Work Shop on Fiber Optics in Access Networks (FOAN). **Portugal**, Lisbon, October 18–20, 2016.
5. **Lavrinovica I.**, Porins J., Bruklitis E., Supe A. Evaluation of Effective Area and Nonlinearity Coefficient of Erbium-Ytterbium Doped Optical Fibers// Progress in Electromagnetics Research Symposium (PIERS), **China**, Shanghai, August 8–10, 2016.

6. **Lavrinovica I.**, Porins J. An improvement of EDFA efficiency by using Ytterbium co-doped optical fibers// IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom 2016). **Bulgaria**, Varna, June 6–9, 2016.
7. **Lavrinovica I.**, Porins J. Noise Figure Analysis of EDFA with different pumping configurations in 40 Gbit/s 8 channel DWDM transmission system// Advances in Wireless and Optical Communications (RTUWO). **Latvia**, Riga, November 5–6, 2015.
8. **Lavrinovica I**., Porins J. Estimation of EDFA performance in 40 Gbit/s 8 channel DWDM transmission system// Progress in Electromagnetics Research Symposium (PIERS). **Czech Republic**, Prague, July 6–9, 2015.
9. **Lavrinovica I.**, Porins J., Investigation of EDFA performance in 8 channel WDM transmission system// 11th conference Developments in Optics and Communications (DOC2015). **Latvia**, Riga, April 8–10, 2015.
10. Bajpayee P., Porins J., **Lavrinovica I.**, Investigation of PMD in 40 GBit/s Coherent QPSK Transmission System, 53rd Riga Technical University International Scientific Conference, Telecommunications Section. **Latvia**, Riga, 17th October, 2014.
11. **Lavrinovica I.**, Porins J., Supe A. EDFA amplification mode evaluation in 16 channel WDM communication system// Riga Technical University 54th Student Scientific Conference Telecommunications Section. **Latvia**, Riga, May 10, 2013.
12. Osipova K., **Lavrinovica I**., Parts R., ADSL adaptation ability // Riga Technical University 53th Student Scientific Conference Telecommunications Section. **Latvia**, Riga, April 17, 2012.

Publications in **scientific journals**

1. **Lavrinovica I.**, Porins J., Supe A. Experimental measurement of erbium-doped optical fibers characteristics for EDFA performance optimization// Latvian Journal of Physics and Technical Sciences. 2019. No. 2, pp. 1–10 (accepted for publication).

Articles in **full-text conference proceedings**

1. **Lavrinovica I.**, Supe A., Udalcovs A., Ozolins O., Popov S. and Porins J. Exploration of Optical Amplifiers Based on Erbium (Er^{3+}) and Ytterbium (Yb^{3+}) Doped Fiber Segments and Their Emerging Applications// Progress in Electromagnetics Research Symposium (PIERS). Japan, Toyama, August 1–4, 2018, pp. 237–240. **(Invited)**
2. Nazarovs V., Jelinskis J., Porins J., **Lavrinovica I**., Supe A. and Aispurs V. Architecture and research of M2M wireless mesh networks// Proceedings of Progress in Electromagnetics Research Symposium (PIERS). Russia, Saint Petersburg, May 22–15, 2017, pp. 2500–2503.
3. Maharjan R., **Lavrinovica I.**, Supe A., Porins J. Minimization of FWM Effect in Nonlinear Optical Fiber using Variable Channel Spacing Technique// Proceedings of Advances in Wireless and Optical Communications (RTUWO). Latvia, Riga, November 3–4, 2016, pp. 1–4. Shakya S., Supe A., **Lavrinovica I.**, Porins J. Different Optical Fiber Nonlinear Coefficient Experimental Measurements// Proceedings of 6th

International Workshop on Fiber Optics in Access Networks (FOAN). Portugal, Lisbon, October 18–19, 2016, pp. 1–4.

4. **Lavrinovica I.**, Porins J., Bruklitis E., Supe A. Evaluation of Effective Area and Nonlinearity Coefficient of Erbium-Ytterbium Doped Optical Fibers// Proceedings of Progress in Electromagnetics Research Symposium (PIERS). China, Shanghai, August 8–11, 2016, pp. 3438–3441.
5. **Lavrinovica I.**, Porins J. An improvement of EDFA efficiency by using Ytterbium co-doped optical fibers// Proceedings of IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom). Bulgaria, Varna, June 6–9, 2016, pp. 1–3.
6. **Lavrinovica I**., Porins J. Noise Figure Analysis of EDFA with different pumping configurations in 40 Gbit/s 8 channel DWDM transmission system// Proceedings of Advances in Wireless and Optical Communications (RTUWO). Riga, Latvia, November 5–6, 2015, pp. 34–37.
7. **Lavrinovica I.**, Porins J., Ivanovs G. Estimation of EDFA performance in 40 Gbit/s 8 channel DWDM transmission system// Proceedings of Progress in Electromagnetics Research Symposium (PIERS). Czech Republic, Prague, July 6–9, 2015, pp. 502–505.

Articles in **conference books of abstracts**

1. **Lavrinovica I.**, Porins J., Supe A. Evaluation of effective area of ytterbium doped optical fiber// Developments in Optics and Communications (DOC 2016). Riga, Latvia, March 21–23, 2016, p. 49.
2. **Lavrinovica I.**, Porins J. Investigation of EDFA performance in 8 channel WDM transmission system// Developments in Optics and Communications (DOC 2015). Riga, Latvia, April 8–10, 2015, p. 59.
3. **Lavrinovica I**., Porins J., Ivanovs G. Estimation of EDFA performance in 40 Gbit/s 8 channel DWDM transmission system// Progress in Electromagnetics Research Symposium (PIERS) Book of Abstracts. Czech Republic, Prague, July 6–9, 2015, p. 576.
4. **Lavrinovica I.**, Porins J., Supe A. An estimation of EDFA amplification states in 16 channels WDM communication system// Riga Technical University 54th Student Scientific Conference Telecommunications Section. Riga, Latvia, May 10, 2013, p. 26.
5. Osipova K., **Lavrinovica I**., Parts R. ADSL system adaptivity// Riga Technical University 53rd Student Scientific Conference Telecommunications Section. Riga, Latvia, April 17, 2012, p. 48.

Latvian **patent applications**

Lavrinoviča I, Poriņš J., Supe A., Ivanovs Ģ. Rare-earth Doped Telecommunications Optical Fiber Effective Area Measurement System, P-16-103 (date of publication 20.06.2018).

Latvian scientific research projects

1. National research program "Cyberphysical systems, ontology and biophotonics for safe and smart city and society (SOPHIS)" project No. 4 – technology development for smart city development. Project agreement No.10-4/VPP-4/11, 2014- 2017.
2. Smart city technologies for life quality improvement, European Social Fund CPZ project No. 2013/0008/1DP/1.1.1.2.0/13/APIA/VIAA/016 2013-2015.

The Volume and Structure of the Work

The volume of the Doctorate Thesis is 103 pages. The work consists of Introduction, four chapters, bibliography and appendices.

The Introduction contains substantiation of the chosen topicality of research direction and defines the object of research of the Doctoral Thesis.

Chapter 1 of the Thesis deals with the current development directions of high-speed fiber optics transmission systems. Optical amplifiers used in fiber optic transmission systems are described and compared by their physical features, following such criteria as possibilities to obtain maximal amplification ratio with minimal noise ratio value and exciting source power consumption.

In Chapter 2, with computer simulations, as well as experimentally, dependence of basic parameters of erbium doped fiber amplifier EDFA – gain coefficient and noise figure on the doped fiber's length and power – was explored. The aim of the simulation was to assess amplification changes and define provisional optimal fiber lengths. The doped fiber length with which one can obtain the maximum gain coefficient, is accepted as the optimal criterion. Taking into account the simulation results, practical experiments were performed to assess the amplification efficiency.

Chapter 3 of the Thesis contains experimental measurement of the parameter of effective area A_{eff} for erbium and ytterbium doped fibers using transverse shift measurement method at two wavelengths: 1310 nm and 1550 nm.

Chapter 4 is devoted to a study of ytterbium-doped optical fibers (YDF) for EDFA efficiency improvement. The performed research has two stages. In the beginning, ytterbium fiber's physical features and stimulated emission process is explored, as well as the usage of YDF in amplification wavelength range expansion is analyzed. Using a computer program, master oscillator power amplifier MOPA is modeled to assess the combined amplifier's output power if co-doped double clad fiber containing both erbium and ytterbium ions is used. During the following stage, experimental implementation of combined erbium and ytterbium doped fiber amplifier EYDFA is performed to evaluate the possibilities of EDFA amplification and noise figure improvement by adding the section of Yb^{3+} doped fiber to erbium doped fiber.

The final part summarizes the basic conclusions of the Doctoral Thesis, as well as provides a short review of further research.

EXPOSITION OF INDIVIDUAL CHAPTERS OF THE THESIS

Chapter 1

In this chapter, different types of optical amplifiers are described and compared by their physical features. The choice of the research subject – rare-earth doped fiber amplifiers (REDFA) – arises from this.

The most significant parameters, which define the efficiency of optical fiber amplifier's performance, are gain coefficient, gain saturation, amplified spontaneous emission power and amplifier's noise figure. Depending on the physical processes, which initiate the stimulated emission process and optical signal amplification, the optical amplifiers used in fiber optics transmission systems are divided into the following groups:

- amplifiers based on non-linear optical effects such as Brillouin–Mandelstam and Raman scattering, as well as amplifiers based on four-wave mixing (FWM) effect (FOPA);
- rare-earth doped fiber amplifiers, where active medium is optical fiber doped with rare-earth element ions (REDFA);
- laser-type semiconductor optical amplifiers where photon emission is caused by spontaneous electron-hole recombination in a semiconductor material under electrical current instead of direct optical pumping (SOA, LOA).

Analyzing the operating principle of amplifiers of each group, rare-earth doped fiber amplifiers (REDFA) were selected as the object of research of the Doctorate Thesis. Compared to Raman's amplifiers and semiconductor amplifiers, they are polarization independent and stable by temperature, in turn, compared to parametrical amplifiers, it is easier to implement REDFA in practice. Respectively, the development of improved REDFA amplifiers is an actual topic, since combining doped fibers of different types makes it possible to get a wider amplification band, where possible benefit lays in around 35 nm depending on the specific dopant, as well as in higher gain coefficient without losing energy for heat draining.

Chapter 2

In this chapter, dependence of two basic parameters of erbium doped fiber amplifier (EDFA) – gain coefficient and noise factor on the length of the doped fiber and pump power –is evaluated. The performance of EDFA was studied according to the optimal criterion in relation to the amplification efficiency. Such criterion is formed by specific combination of erbium doped fiber length and excitation source power, which would ensure the maximal gain coefficient with low noise factor. The length of doped fiber shall be the one that provides the maximal amplification with the given rare-earth element ion concentration. In case, when the fiber is too long, signal absorption appears in the far ends. In turn, if the length is insufficient, pumping irradiation will not be used in full. The chosen doped fiber lengths are 10 m, 15 m, 20 m, 25 m and 30 m, but the corresponding excitation source power –

200 mW, 300 mW, 400 mW and 500 mW, respectively. Such excitation source power was chosen with an aim to get higher amplification values.

To study EDFA gain coefficient and noise factor, 8-channel WDM communication system with data transmission rate 40 Gbit/s was designed in the computer program. Communication system has NRZ-OOK (Non-Return to Zero On/Off Keying) modulation format applied and 100 GHz interchannel interval, which was selected according to the ITU recommendation G.694.1 [6]. Respectively, the first channel frequency at 1554.9 nm corresponds to 192.8 THz and the eighth channel frequency at 1549.3 nm corresponds to 193.5 THz. In this system, EDFA operates as an in-line amplifier, because in-line amplifiers have no expressed non-linear effect impact.

Gain and noise factor values were measured in each communication system's channel using both co-propagating (980 nm) and counter-propagating (1480 nm) configuration. Block diagram of modeled communication system is represented in Figure 2.

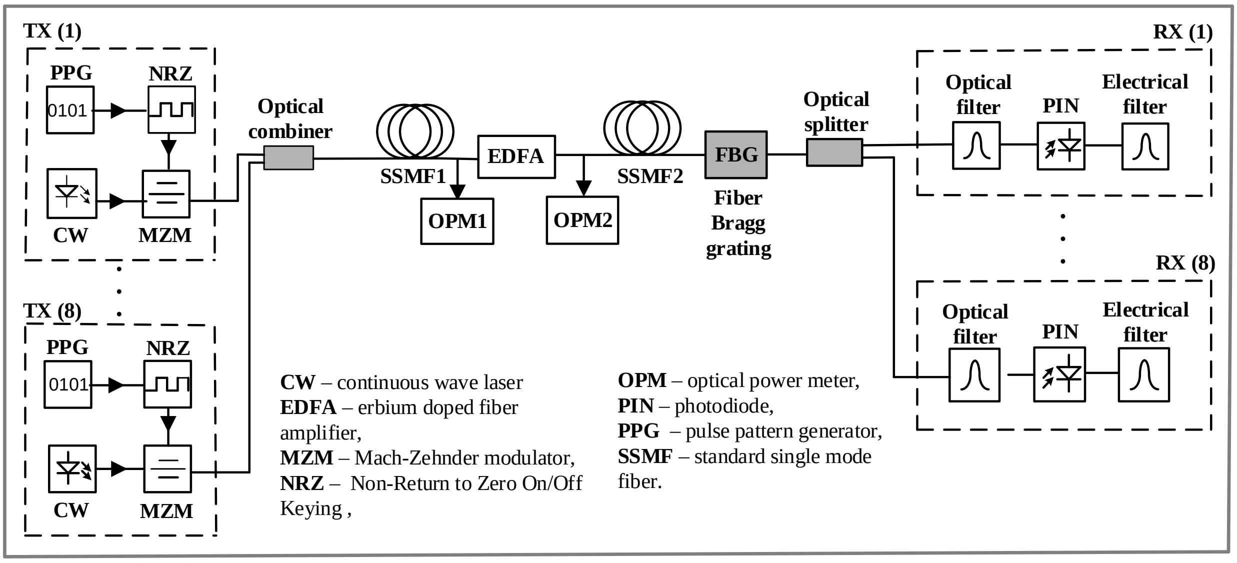

Fig. 2. 8-channel communication system's block diagram.

In case of co-propagating pumping at 980 nm with 15 m long erbium fiber (Fig. 3) and exciting source power 200 mW, 24 dB amplification was acquired, which was evenly distributed among all transmission system channels; the difference of gain coefficient in each channel was within 0.2 dB. The value of respective noise figure equals to 4.4 dB.

In case of counter-propagating EDFA configuration at 1480 nm (Fig. 4), the highest gain coefficient, which corresponds to 40.7 dB, was obtained using 30 m long doped fiber. In this case the noise factor values reach 9–15 dB, respectively, counter-propagating EDFA configuration increases the indicator of noise factor over 5 dB. Summarizing the results of EDFA computer modeling, it was concluded that amplification grows linearly; the lengths of doped fibers have been determined, which were later used for experimental EDFA investigation.

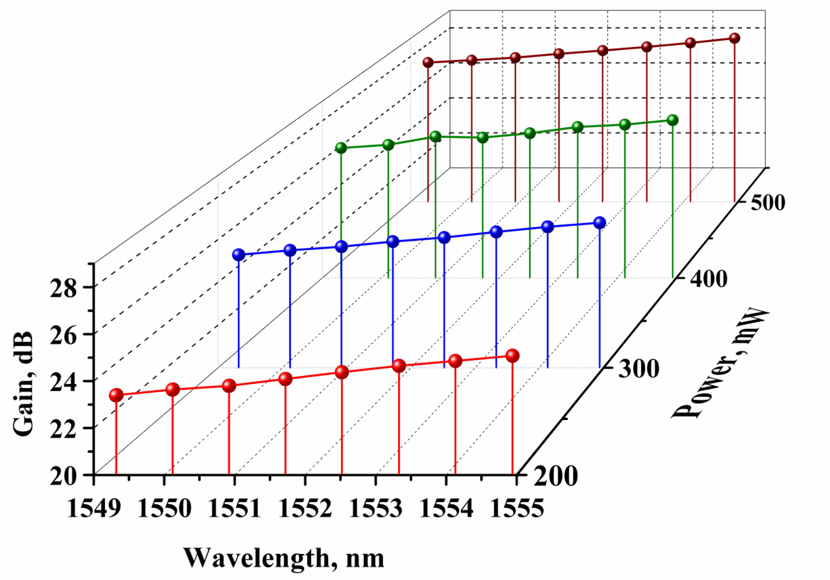

Fig. 3. EDFA gain depending on the pump power for 15 m long erbium fiber using co-propagating configuration.

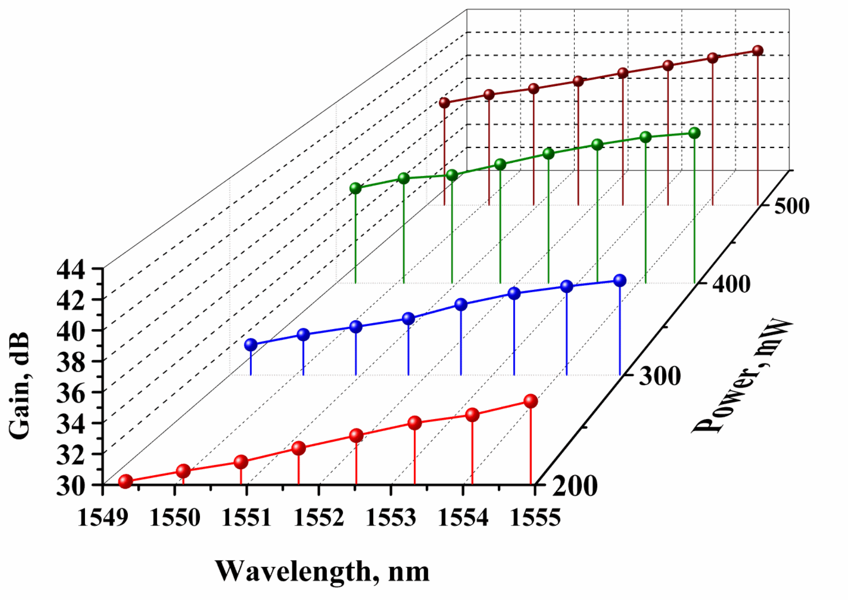

Fig. 4. EDFA gain depending on the pump power for 30 m long erbium fiber using counter-propagating configuration.

EDFA practical implementation has been performed using erbium-doped fiber samples of different length from two manufacturers: HighWave (HWT) and Fibercore. The usage of samples with different lengths is mandatory as it shows more precise dynamic of stimulated emission process depending on the power. The used erbium fibers have different geometrical parameters such as absorption coefficient, core radius and numerical aperture, and they have different active ion concentration. Thus, the range of excitation source power for each type and length of fiber also differs.

Specific values were obtained through middleware measurement by studying excitation process at various pump power levels till the optimal parameters were found – combination of fiber length and excitation source power, which could be used for the development of improved optical amplifier. The input signal level during all measurements corresponds to 13.2 dBm and pump power values are in the range from 21.1 mW to 54.1 mW. Experimental scheme with co-pumping and bidirectional pumping is represented in Figure 5.

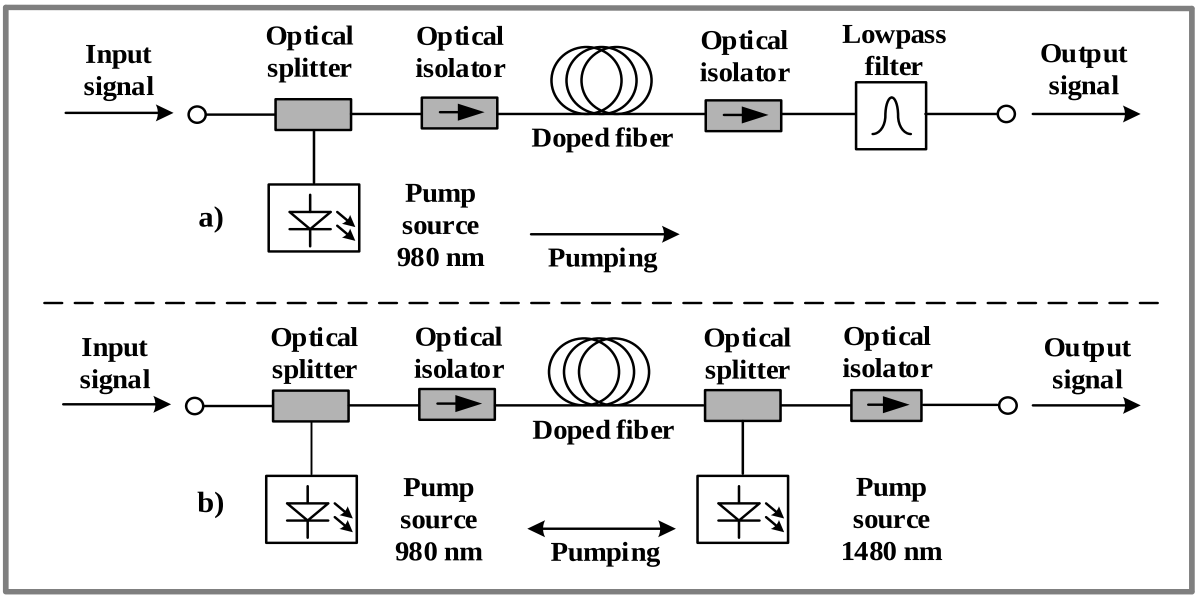

Fig. 5. EDFA experimental scheme with (a) co-pumping configuration and (b) bidirectional pumping.

The most significant results in this experiment were obtained with 15 m long HWT and 2 m long Fibercore fibers. As we can see in Figure 6, using 5 m long HWT fiber led to a faster reach of EDFA saturation regime: after an increase in pump power by about 8 mW (from 46.2 mW to 54.1 mW), the gain coefficient changed by 0.8 dB. Application of bidirectional pumping for such length of fiber shows that the minimal pump power of 21.3 mW corresponds to the gain coefficient of 14.4 dB. In comparison with the single-direction pumping scheme where the previously mentioned gain coefficient required pump power of 37.4 mW, it leads to energy preservation by up to 16 mW.

The maximum obtained amplification with 2 m Fibercore erbium fiber and bidirectional pumping (Fig. 7) is 9 dB at pump power of 54.1 mW. With an increase in fiber length to 5 m, maximum gain increment is 7.2 dB (the relevant gain coefficient equals to 17.1 dB).

The obtained results clearly show that using bidirectional EDFA configuration and Fibercore erbium fiber, it is possible to decrease the length of doped fiber, which is important for the construction of optical amplifier. During this study the optimal range of doped fiber length (5–20 m) have been obtained, which makes it possible to provide the gain within 16–20 dB at the pump power of 54 mW.

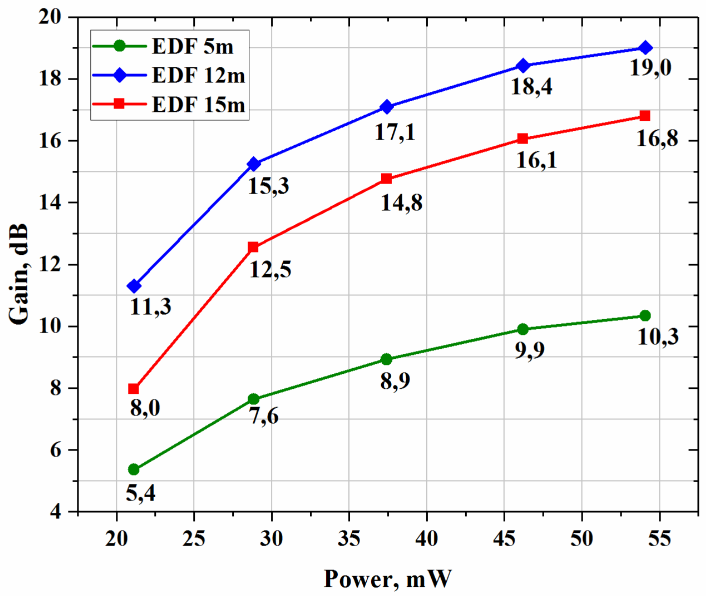

Fig. 6. EDFA gain at low signal for 5 m, 12 m and 15 m long HighWave erbium fibers using co-pumping configuration.

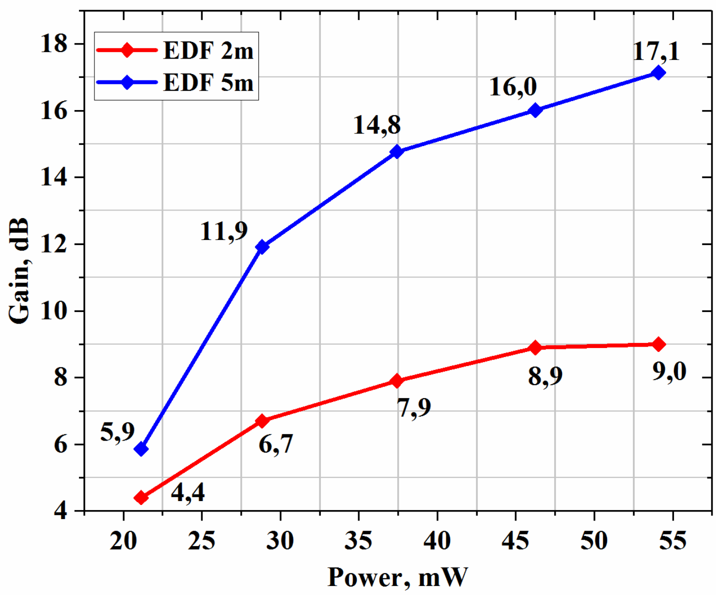

Fig. 7. EDFA gain at low signal for 2 m and 5 m long Fibercore erbium fibers using bidirectional pumping.

The effective area parameter A_{eff} is introduced with a purpose to evaluate non-linear effects from the obtained real optical intensity distribution in the fiber. Fiber's effective area depends on the fiber's geometrical parameters such as core radius and difference of core and cladding refraction coefficients. Effective area parameter has the determinative role in non-linear effect impact analysis, therefore when developing optical amplifiers, it is essential to define this value precisely. Distortions of optical signal under the impact of non-linear effects are described by the following expression:

$$kP_0L_{\text{eff}} = \frac{kP_0}{g}[\exp(gL-1)] = \frac{2\pi}{\lambda}\frac{n_2}{A_{\text{eff}}}\frac{P_0}{g}[\exp(gL)-1], \quad (2)$$

where
k is non-linear coefficient;
L_{eff} is fiber's effective length;
n_2 is refraction coefficient;
A_{eff} is fiber's effective area;
P_0 is average input power in each transmission system channel;
g is average amplification coefficient;
L is doped fiber length.

Tus, analyzing Expression (2), we see that by decreasing the non-linear effects one shall increase the effective area A_{eff} and the amplification ratio g [3].

Within the Doctoral Thesis, measurements of effective area for erbium and ytterbium doped fibers were performed using the transverse shift measurement method. Using this technique, we are concerned with the transfer of optical power from the source mode into the same mode of an identical fiber when their axes are parallel but laterally offset from each other. Unlike the interferometric transverse shift measurement method described in source [5], interferometer is not used, and determination of distribution of the far field is implemented using tunable laser light source, micro-positioner, optical power meter and spectral analyzer. Micro-positioner's full step size is 125 μm with a possibility to perform 1/8 of step (≈ 0.16 μm).
It ensures precise fiber shift in three different directions (coordinate axes x, y, z). The fiber is gradually shifted along one of the transverse shift axes and at the same time output optical power is fixed at the end of measured fiber. Power distribution measurements in the far field are performed at the wavelengths of 1310 nm and 1550 nm with two power levels P_1 and P_2. The usage of two power levels gives a benefit of receiving more information about the nature of optical irradiation distribution in the fiber under study.

Experimentally obtained far field power distribution for erbium (Fig. 8) and ytterbium (Fig. 9) doped fibers was recalculated to the near field distribution by processing the measurement results with calculation algorithm implemented in MATLAB program. The calculated A_{eff} values are summarized in Table 1.

The obtained maximum effective area value of the EDF fiber with 1310 nm corresponds to 36.5 μm^2, whereas with 1550 nm, it grows up to 57.1 μm^2. In case of ytterbium fibers, A_{eff}

parameter is higher than for the erbium fiber. With 1310 nm, it is 106.2 μm^2, but at 1550 nm, it is 129.4 μm^2. As shown in Table 1, the usage of two light source output power levels, result in different values of the fiber effective area. This difference for erbium fiber is up to 1 μm^2, but for ytterbium fiber – within 3 μm^2.

Table 1

Effective Area Measurement Results for Erbium and Ytterbium Doped Fibers Depending on the Wavelength

Erbium doped fiber *HighWave HWT-FIB-EDF-EXC-BAND-002*					
Position	Power, dBm	Wavelength 1310 nm		Power, dBm	Wavelength 1550 nm
		A_{eff}, μm^2			A_{eff}, μm^2
P_1 (y axis)	–30.2	30.2		–27.7	42.7
P_1 (z axis)	–30.5	36.5		–27.1	57.1
P_2 (y axis)	–27,4	30.3		–26.9	43.5
P_2 (z axis)	–26.9	35.8		–26.5	56.9
Ytterbium doped fiber *LIEKKI Yb 1420-1560*, 15 %					
Position	Power, dBm	Wavelength 1310 nm		Power, dBm	Wavelength 1550 nm
		A_{eff}, μm^2			A_{eff}, μm^2
P_1 (y axis)	–30.9	106.2		–23.6	129.6
P_1 (z axis)	–33.6	76.6		–23.0	96.5
P_2 (y axis)	–30.7	105.3		–20.6	129.2
P_2 (z axis)	–30.3	74.1		–20.1	94.0

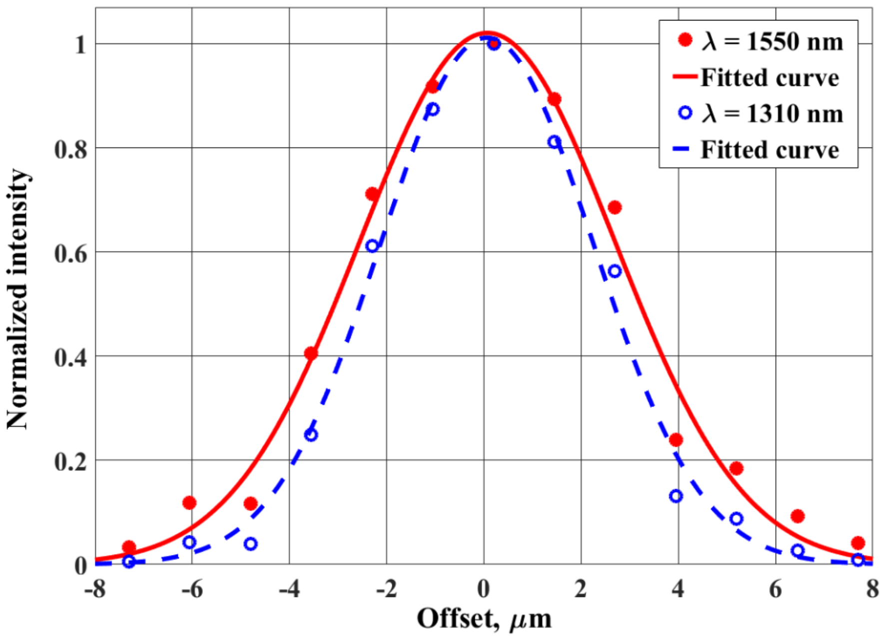

Fig. 8. Normalized optical radiation near-field distribution in fiber cross-section at wavelengths of 1310 nm and 1510 nm for erbium doped fiber.

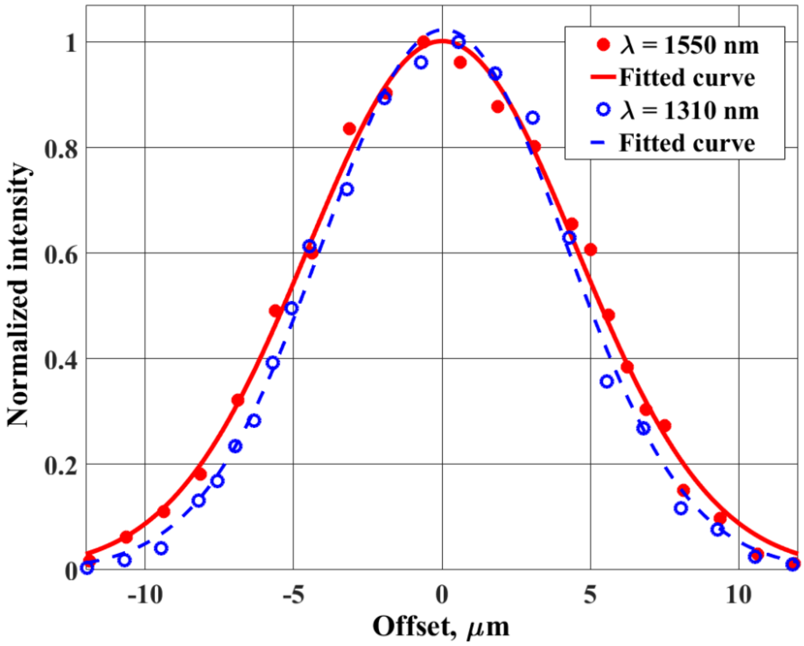

Fig. 9. Normalized optical radiation near-field distribution in fiber cross-section at wavelengths of 1310 nm and 1510 nm for ytterbium doped fiber.

The obtained results show that it is useful to apply ytterbium-doped fibers in the development of combined optical amplifiers, since they typically have larger effective area, but the specific nature of amplifier's use shall be noted. If the purpose is to improve the gain and excitation source power characteristic curve, mode field shall be decreased. In this case, fibers with the lowest A_{eff} indicators are preferable, because thus it is possible to combine different wavelengths of excitation source and input signal. In turn, if the priority is given to higher output powers, it is more effective to use fibers with the highest A_{eff}.

Chapter 4

Combining erbium (EDF) and ytterbium (YDF) doped fibers makes it possible to reduce an impact of the non-linear effects. Such a combined solution enables higher optical amplifier output powers since ytterbium ions absorb the maximum of the excitation source power due to larger cross-section area [15].

To assess the amplifier's output powers when erbium (Er^{3+}) and ytterbium (Yb^{3+}) co-doped fiber is used, a combined erbium and ytterbium co-doped fiber amplifier (EYCDFA) was modeled in the computer simulation program. It was implemented by connecting two optical amplifiers EDFA and EYCDFA in cascade, which is also called MOPA (master oscillator power amplifier), or oscillator power amplifier. MOPA is the most effective solution for power pulse generation, and it can be easily tuned, besides it ensures wide options for control and optimization (Fig. 10). In the model, double clad ytterbium fiber was used. Core diameter was 30 μm, internal cladding diameter was 650 μm and core profile was made by LP_{01} mode. Ytterbium fibers' length was changed from 10 m to 25 m with a pitch of

5 m. Output signal power was measured with optical power meter within the wavelength range 1550–1570 nm.

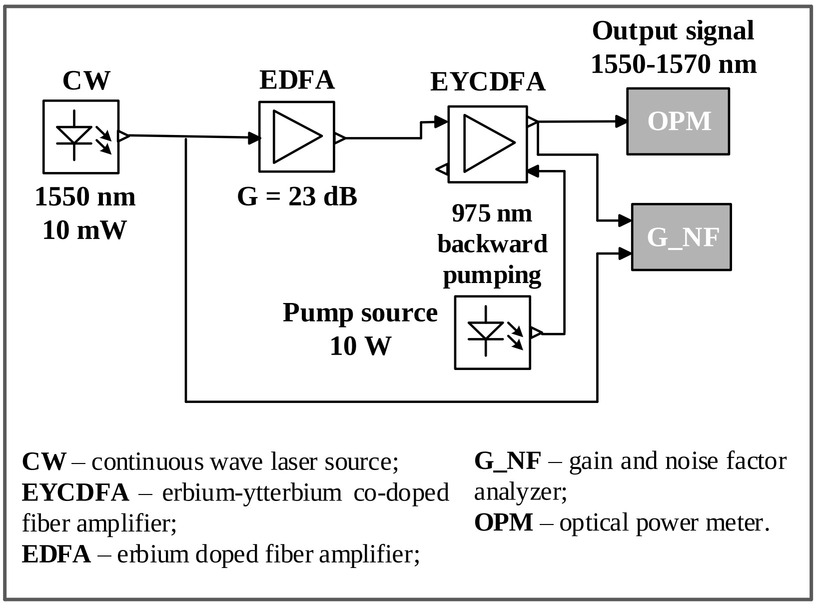

Fig. 10. Block diagram of a combined power amplifier.

The obtained results show that more stable characteristic curve of output power within the wavelength range 1550–1570 nm corresponds to 10 m long YDF fiber, where the combined amplifier's output powers are within 36 dBm (4–5 W) (Fig. 11). Extending ytterbium fiber up to 15 m within the range from 1555 nm to 1565 nm, the power increases, whereas staring with 1570 nm, EYCDFA reaches the saturation regime. Using 25 m long ytterbium fiber, the maximum value of EYCDFA's output power corresponds to 35 dBm (3.4 W). Thus by increasing the doped fiber's length, the results in output power decrease by 1 dBm.

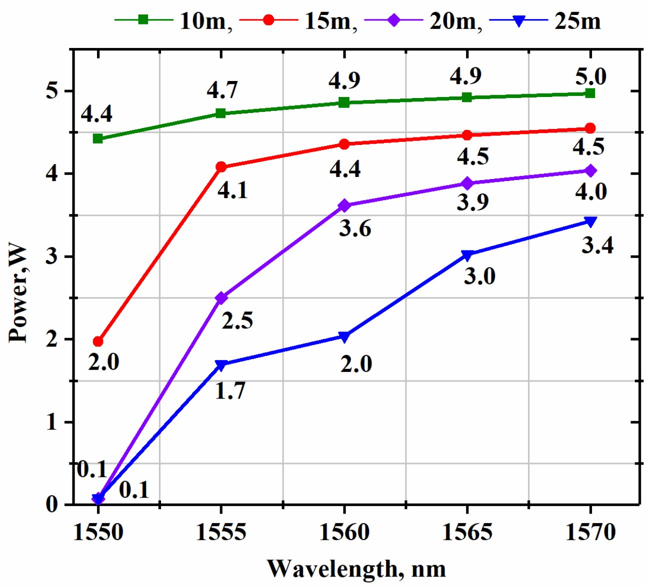

Fig. 11. EYCDFA optical power values for different ytterbium-doped fiber lengths.

The next phase of the combined solutions study is related to the possibilities of improving EDFA amplification and noise factor by adding to the erbium-doped fiber Yb^{3+} doped fiber's segment. This research was performed during the traineeship in the scientific laboratory of the Department of Materials and Nano Physics of KTH Royal Institute of Technology in Sweden.

A combined erbium and ytterbium doped fiber amplifier (EYDFA) was designed, which contains a 5 m long EDF section and a 5 m long YDF section. Application possibilities of this solution were assessed to amplify the optical signal in several spectral bands. Experimental diagram of the designed combined amplifier is shown in Figure 12.

Continuous wave laser (CW) with distributed feedback is used as a primary source, which initiates energy flow to the pumping supply. It has a low power of –30.6 dBm. EYDFA performance is studied using both pumping directions, hereby 980 nm pump laser is firstly set to forward pumping (a) and then to backward pumping (b) configuration. Erbium-doped fiber EDF HWT-FIB-EDF-EXC-BAND-002 has an absorption coefficient of 5.45 dB/m, 4.1 μm core radius, and 0.22 numeric aperture value (NA). The ytterbium-doped fiber YDF LIEKKI Yb1200-4/125 is of the same core radius and NA as EDF with 280 dB/m absorption coefficient and 15 % Yb^{3+} ion concentration. Gain and noise figure characteristics of EYDFA are estimated for variable pump power values in the range of 13.4 dBm to 17.0 dBm.

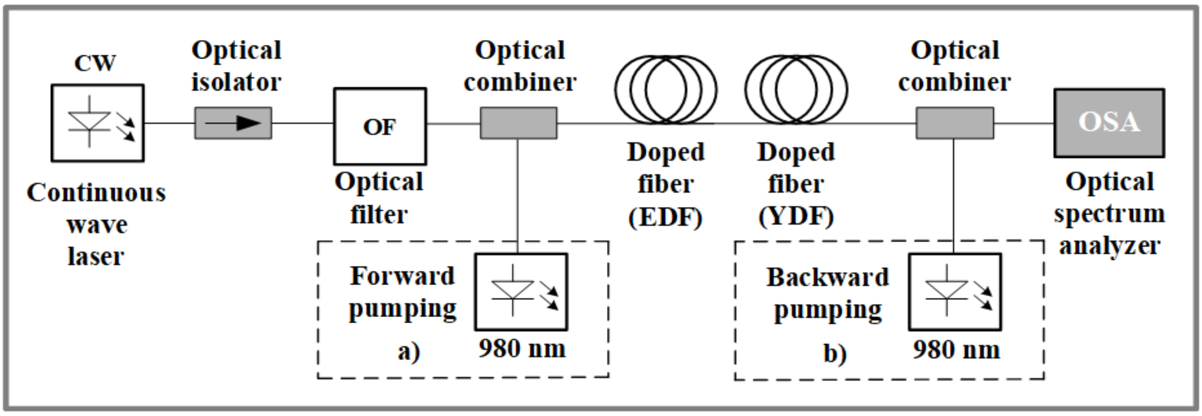

Fig. 12. Experimental setup of a combined erbium-ytterbium doped fiber amplifier with (a) forward pumping and (b) backward pumping configuration at 980 nm.

The maximum possible gain coefficient, which can be obtained with the combined erbium and ytterbium doped fiber amplifier using a co-pumping scheme at 980 nm is 6–7 dB. An application of EYCDFA counter-pumping configuration at 980 nm gives a maximum gain value of 8.4 dB at the pump power of 13.3 dBm, whereas with the power of 15.2 dBm, the gain coefficient is 5 dB (Fig. 13). This result leads to the conclusion that application of EYDFA backward pumping configuration makes it possible to obtain higher amplification with lower excitation source powers.

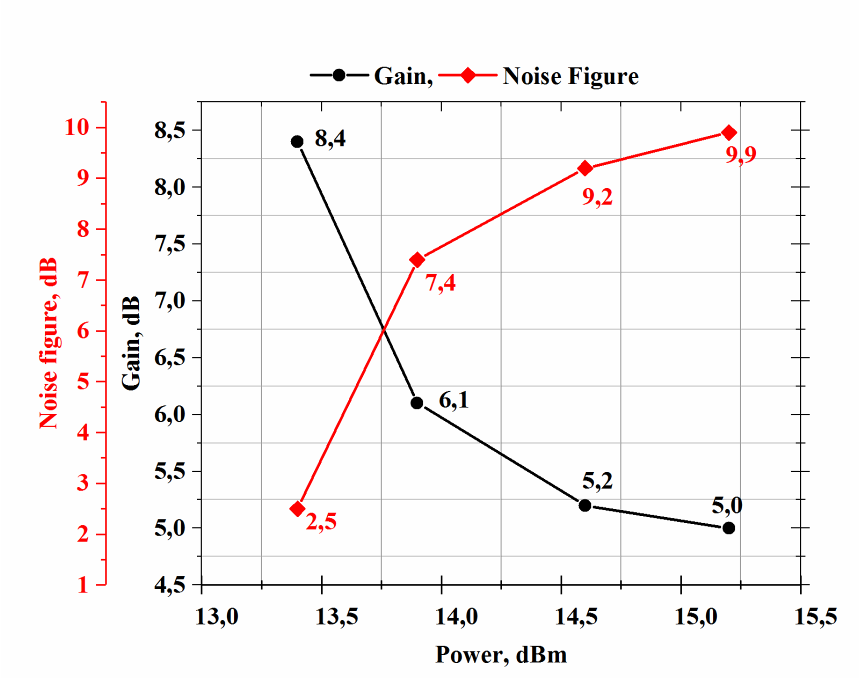

Fig. 13. EYDFA gain and noise figure using counter-propagating pumping.

Amplified spontaneous emission (ASE) spectrum of a combined erbium-ytterbium doped fiber amplifier is displayed in Figure 14. In this figure, it can be seen that stimulated emission from Yb^{3+} ions acts as an extra pumping source, producing amplification in the range of 1000–1100 nm. This means that using the combined solution with EDF and YDF fiber segments connected in a row, it is possible to expand erbium amplification band from the standard 47 nm to 82 nm, thus covering frequency bands C (1530–1565 nm) and L (1565–1625 nm) of the wavelength division multiplexing communication system.

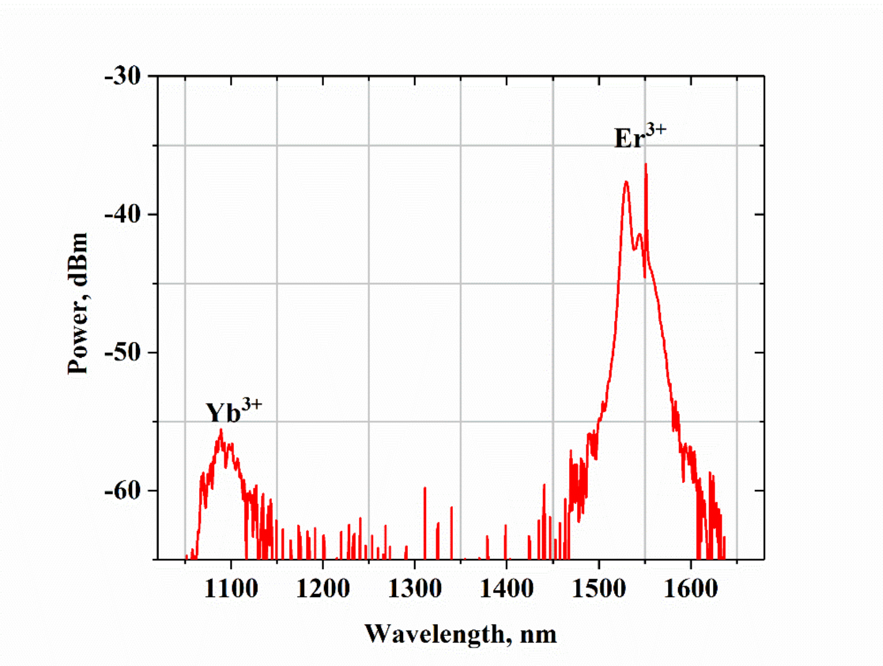

Fig. 14. Amplified spontaneous emission spectrum of EYDFA.

MAIN RESULTS AND CONCLUSIONS OF THE DOCTORAL THESIS

1. Performing EDFA amplifier's computer modeling with co-pumping configuration at the wavelength of 980 nm, it was stated that with the excitation source power 200 mW for a 15 m long erbium the fiber gain coefficient value is 24 dB; and it is practically equal in all transmission system channels – the difference is only 0.2 dB. With an increase of pump power up to 400 mW and 500 mW, the gain values reach 27–28 dB. It is important to note that using a 15 m long fiber, the obtained gain is evenly distributed among all transmission system's channels. The noise figure value for such EDFA configuration is within 4.3 dB.
2. EDFA amplifier's performance modeling with counter-propagating pumping at 1480 nm results in a maximum gain coefficient of 40.7 dB, using a 30 m long erbium fiber. It means that from amplification efficiency perspective, this fiber length is optimal, as it ensures gain coefficient, which is by 12 dB higher, however, the noise figure indicator reaches 9–15 dB.
3. It was experimentally determined that in the low-signal amplification mode with a 15 m long HWT erbium fiber sample and bidirectional EDFA pumping, it is possible to obtain 14.4 dB amplification with minimum exciting source power 21.3 mW. Thus, in comparison with single-direction pumping, where an analogue gain coefficient was reached with a pump power of 37.3 mW, power saving up to 16 mW is ensured.
4. The values of effective area, that were measured using transverse shift measurement method for erbium doped fiber correspond to 36.5 μm^2 at the wavelength of 1310 nm, while at 1550 nm, they reach 57.1 μm^2. In case of ytterbium fibers, A_{eff} parameter is higher: at 1310 nm, A_{eff} is 106.2 μm^2, but at 1550 nm, it is 129.6 μm^2. It is important to note that performing A_{eff} measurements using two light source output power levels, result in different values of the fiber effective area. In the case of erbium fiber, the difference between A_{eff} indicators, which are measured at power levels P_1 and P_2, is up to 1 μm^2, whereas for ytterbium fiber – it is within 3 μm^2. This means that measurements of effective area with different powers give wider information about the nature of optical radiation distribution in the fiber under study.
5. In the course of study of combined erbium and ytterbium co-doped fiber amplifier (EYCDFA) it was determined that applying a 10 m long ytterbium fiber within the wavelength range of 1550–1570 nm, stable 36 dBm (5 W) output power is obtained. Using a 25 m long ytterbium fiber, the maximal EYCDFA power value corresponds to 35 dBm (3.4 W). Thus, extending the length of ytterbium fiber twice, the power decreases by 1 dBm.

6. Using counter-pumping configuration of combined erbium and ytterbium doped fiber amplifier (EYDFA) at 980 nm, the maximum obtained gain coefficient is 8.4 dB at the excitation source power 13.3 dBm. Increasing the excitation source power to 15.2 dBm, the maximum gain coefficient reaches only 5 dB. Thus with the counter-pumping EYDFA configuration, we ensure power saving by 2 dBm.
7. Analyzing the experimentally obtained combined EYDFA amplifier's spectrum, it has been determined that ytterbium ion stimulated emission functions as supplementary excitation source. Such process facilitates power growth and optical signal amplification within the wavelength range of 1000–1100 nm. The expanded spectral band may be practically used as a pumping wavelength of the excitation source for further study of a combined amplifier.

The results of the research of the Doctoral Thesis were used to implement two Latvian scientific projects: National research program "Cyberphysics systems, ontology and biofotonics for safe & smart city and society (SOPHIS)" Project No. 4 – technology design for smart city development. Project agreement No. 10-4/VPP-4/11, 2014–2017; Smart city technologies for life quality improvement, European Social Fund CPZ project No.2013/0008/1DP/1.1.1.2.0/13/APIA/VIAA/016 2013–2015.

Based on the results obtained in the present Doctoral Thesis, Latvian patent application No. P-16-103 "Rare-Earth Doped Telecommunications Optical Fiber Effective Area Measurement System" was prepared and published. The suggested measurement system enables acquiring practically useable effective area value for various rare-earth doped optical fibers.

In the conclusion it shall be emphasized that research on optical amplifiers is a perspective and effective direction in modern fiber optics transmission systems. The obtained results of the Doctoral Thesis may be used in further development of combined solutions, as, according to the current trends in the manufacturing industry of rare-earth doped optical fibers, thulium (Tm^{3+}) and bismuth (Bi^{3+}) fibers are under investigation. The author's further scientific work is aimed at the research of a possibility to apply these fibers in optical signal amplification.

LITERATURE

[1] Agrawal, G. P. Fiber-Optic Communication Systems, USA: John Wiley and Sons, 1997. 576 p.

[2] Agrell, E. et al. Roadmap of optical communications// Journal of Optics. 2016. Vol. 18, No. 063002. p. 40.

[3] Aiso, K., Tashiro, Y., Suzuki, T., Yagi, T. Development of Er/Yb Co-doped Fiber for High-Power Optical Amplifiers// Furukawa Review. 2001. No. 20, pp. 41–45.

[4] Bayvel, P., Maher, R., Xu, T., Liga, G., Shevchenko, N. A., Lavery, D., Alvarado, A, Killey, R. I. Maximizing the optical network capacity// Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2016. Vol. 74, No. 2062.

[5] Billington, R. Effective Area of Optical Fibres – Definition and Measurement Techniques// Centre for Optical and Environmental Metrology, National Physical Laboratory.

[6] ITU-T G. 694.1, Spectral grids for WDM applications: DWDM frequency grid// International Telecommunication Union. 2012. pp. 1–16.

[7] Foschini, G. J. and Gans, M. J. On limits of wireless communications in a fading environment when using multiple antennas// Wireless Personal Communications. 1998. Vol. 6, No. 3. pp. 311–335.

[8] Galdino, L., Edwards, A., Ionescu, M., James, J., Pelouch, W., Sillekens, E., Semrau, D., Lavery, D., Killey, R.I., Barnes, S., Bayvel, P. and Desbruslais. S. 120 Tbit/s Transmission over Single Mode Fibre using Continuous 91 nm Hybrid Raman-EDFA Amplification. arXiv:1804.01845 [physics.app-ph]. 2018. pp. 1–3.

[9] Materials for the course EE7950: Statistical Communication Theory: Shannon's Channel Capacity// University of Alberta, Faculty of Electrical and Computer Engineering.

[10] Miyamoto, Y. and Takenouchi, H. Metro Dense Space-division-multiplexing Optical Communications Technology for Petabit-per-second Class Transmission// NTT Technical Review Regular Articles. 2014. pp. 1–7.

[11] Morioka, T. New Generation Optical Infrastructure Technologies: EXAT Initiative Towards 2020 and Beyond// IEEE. 2009. pp. 1–2.

[12] Ono, H. Optical Amplification Technologies for Space Division Multiplexing// NTT Technical Review. 2017. Vol. 15, No. 6, pp. 1–6.

[13] Saitoh, K. Multicore Fiber Technology// Journal of Lightwave Technology. 2016. Vol. 34, No. 1, pp. 55–65.

[14] Semrau, D., Xu, T., Shevchenko, N., Paskov, M., Alvarado, A., Killey, R. and Bayvel, P. Achievable information rates estimates in optically amplified transmission systems using nonlinearity compensation and probabilistic shaping// Optics Letters. 2017. Vol. 42, No. 1, pp. 121–124.

[15] Shirakawa, A., Suzuki, H., Tanisho, M. and Ueda, K. Yb-ASE-Free Er Amplification in Short-Wavelength Filtered Er:Yb Photonic-Crystal Fiber// Proceedings of Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference (OFC/NFOEC). San Diego, USA, February 24–28, 2008.

[16] Tse, D. and Viswanath, P. Fundamentals of Wireless Communication - Cambridge: U.K., Cambridge University Press, 2006. 585 p.

[17] Zhu, B., Peckham, D., McCurdy, A. H., Lingle, R., Palsdottir, B., Yan , M. F., Wisk, P. W. and DiGiovanni, D. J. Large-Area Low-Loss Fibers and Advanced Amplifiers for High-Capacity Long-Haul Optical Networks [Invited]// OSA Journal of Optical Communications and Networking. 2016. Vol. 8, No. 7, pp. A55–A63.

[18] Никоноров Н.В., Шандаров С.М. Волноводная фотоника. Учебное пособие. Курс лекций – СПб: СПбГУ ИТМО, 2008, 143 с.