RIGA TECHNICAL UNIVERSITY
Faculty of Electronics and Telecommunication
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Doctoral student of the programme "Telecommunications"

OPTICAL KERR EFFECT IN TELECOMMUNICATIONS FIBER MEASUREMENTS AND SIGNAL REGENERATION

Summary of the promotion work

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PROMOTION WORK
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The promotion work for a doctor's degree of engineering sciences (telecommunications) is to be defended publicly at 29th of May, 2014, at the Faculty of Electronics and Telecommunications of the Riga Technical University, 16/20 Azenes Str.

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CONFIRMATION

I confirm that I have developed this promotion work for a doctor's degree of engineering sciences which is submitted to consideration at the Riga Technical University. The promotion work is not submitted to any other university for receiving a scientific degree.

Andis Supe ……………………………. (Signature)

Date:

This promotion work is written in the Latvian language. It contains Introduction, 4 Chapters, Conclusion, and Bibliography, 5 appendices, 49 figures and illustrations, with the total number of 120 pages. The Bibliography has 105 titles.

GENERAL DESCRIPTION OF THE WORK

Topicality of the subject matter

The sector of information technologies is constantly developing. The quality of the existing services is being improved and completely new services are being introduced. Services related to remote access to various resources, such as cloud-computing or high-resolution video transmission via communications networks, are becoming ever more topical. The introduction of such services requires a stable broadband data flow. Therefore, there is an ever increasing demand for a higher data transmission rate in main and local data networks alike. Moreover, forecasts show that the demand for a high information transmission rate in communication networks will only keep increasing. According to a forecast by Bell Labs, the data transmission rate in backbone networks over the period until 2017 might increase by 3.2 times, whereas in metro networks – even by up to 5.6 times [6].

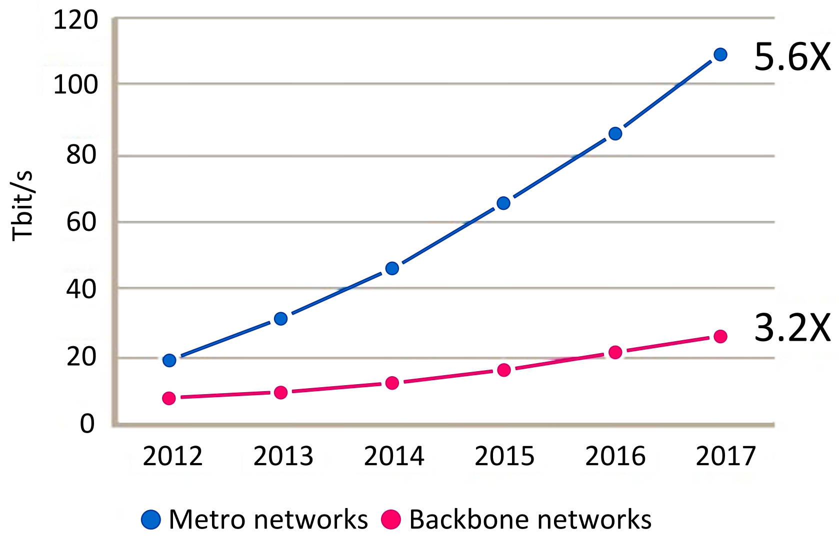

Fig. 1. Data transmission rate increase in metro and backbone networks [6].

It is the fiber-optic communication systems that are particularly suitable for ensuring high data transmission rates. Key advantages, compared to other technologies, include a very broad spectral range and low signal losses. Therefore, optical fibers are widely used in the construction of communications networks, in particular, over long distances.

To create fiber-optic transmission systems (FOTS) with high data transmission rate, it is crucial to know the parameters of fiber to be used. Firstly, it is the fiber attenuation and dispersion. However, in case of FOTS using wavelength division multiplexing, fiber nonlinear properties become important as well, because each system channel increases the power of the total signal to be transmitted via the fiber. Manifestations of nonlinear optical effects (NOE) in signal transmission are undesirable, as they introduce additional signal distortions.

Nevertheless, notwithstanding the adverse effect of NOE on signal transmission, various applications of these effects have been found in optical signal processing. Some of them include optical signal wavelength transformation, switching, multiplexing and demultiplexing, amplification, as well as signal regeneration. The last of the listed applications is a very topical field of research, because it is essential in high-speed communication systems that the necessary bit error ratio (BER) is ensured, which depends on the signal to noise ratio. Thus, NOE not only implies additional noise, but it can also be used for reducing the noises in the transmitted signal.

The aim and tasks of the work

Having regard to the above facts, **the aim of the doctoral thesis** was set forth: to evaluate the options of application of the optical Kerr effect in determining the nonlinear coefficient of telecommunication fibers, as well as in regenerating the shape of signal in an optical domain.

To achieve the set aim, the following **main tasks** were to be solved:

1. To analyse and evaluate the causes of nonlinear occurrences arising due to the optical Kerr effect in telecommunication fibers and their impact on signal transmission in wavelength division multiplexing systems;
2. To evaluate the effective area of an optical fiber, by employing the plane wave superposition method;
3. Measure the effective area of a single mode fiber and erbium doped fiber experimentally with the two-fiber transverse shift method at different wavelengths in the 3rd optical transparency window;
4. Perform experimentally and with the computer simulation software OptSim 5.2 optical fiber nonlinear coefficient measurements using the signal self-phase modulation and four wave mixing effects in the case of continuous and pulsed optical signal cases;
5. To research the optical signal regeneration principle, by employing the signal self-phase modulation or what is known as the Mamyshev type regenerator and factors affecting its functioning;
6. To obtain the regenerator transmission function and find the best possible combination of signal power and optical filter parameters for 40 Gbit/s RZ – OOK optical signal regeneration.

The methodology of research

To perform the tasks and analyse the problems set forth in the doctoral thesis, mathematical calculations, numerical simulations, and experimental measurements have been employed. The mathematical description of effective area calculations is based on interpretation of actual light distribution in a fiber as plane wave superposition obtained with the direct Fourier transform. Light far field distributions obtained in experimental measurements are recalculated to light near field distributions using the Hankel transform. In numerical simulations, the nonlinear Schrödinger equation, direct and inverted discrete fast Fourier transform, as well as the Monte Carlo method for bit error ratio evaluation is used. In measurements of nonlinear coefficient, two distinct measurement methods are used. The effective nonlinear coefficient characteristic curve is obtained with a two tunable lasers, optical polarisation rotator and spectrum analyser, by triggering a nonlinear four wave mixing effect in a fiber. For evaluation of the optical signal changes after the impact of nonlinear effects, measurements of optical power, power spectral density and eye pattern diagrams were used.

The results and scientific novelty of the research

The scientific novelty of the promotion work consists in the following:

1. With the nonlinear coefficient measurement scheme, which is based on four wave mixing, as known to author, for the first time highly nonlinear fiber effective nonlinear coefficient is evaluated, that shows a four four-wave mixing dependence on both: fiber nonlinearity and changes of light state of polarization.
2. Using computer simulations and experimentally, 40 Gbit/s RZ OOK signal shape regeneration was implemented completely in the optical domain with a Mamyshev type regenerator, by finding two distinct optical bandpass filter and amplifier parameter combinations, providing the best enhancement of signal to noise and extinction ratio for the regenerated signal.

During the implementation of the promotion work the following **main conclusions** have been obtained**:**

1. Using the experimental transverse shift method, it was obtained that the EDF fiber A_{eff} in the wavelength range from 1470 to 1575 nm increases by 1.1 μm^2. However, in the case of a single mode fiber, it was obtained that A_{eff} increases by 4.4 μm^2 in the wavelength range from 1520 to 1580 nm which is due to the refractive index dependence on the wavelength. Therefore, it can be concluded that the optical fiber nonlinear coefficient decreases as the optical signal wavelength increases.
2. With the developed P-SPM method, a much broader spectral expansion was obtained than with the CW-SPM method for both G.652 D and G.655 C type fiber. Thus, the calculated coefficient γ for both fibers was higher ($\Delta\gamma$=0.07) in the case of P-SPM. It means that the pulsed type optical signal better triggers SPM emergence in a fiber. Moreover, in the case of CW-SPM method, one must take into account the impact of stimulated Brillouin scattering on the measurement process.
3. In the case of HNLF, just like with DSF, γ_{eff} changes, depending on the pumped and signal laser wavelength difference, are best described with a hyperbolic secant function. However the coefficients A_0 and T_0 differ at function argument $\Delta\lambda$, which in the case of HNLF is: A_0 =2.0 and T_0 =$1.56\cdot10^{-17}$.
4. The best optical signal regeneration result was obtained with the tunable optical filter at EDFA output power of 100 mW and optical filter throughput bandwidth of 0.625 nm, which is shifted from the signal central wavelength by 0.7 nm. The signal ER improvement by 5.2 dB and SNR improvement by 2.3 dB.

Practical value of the work

1. The results of scientific research of the doctoral thesis have been used in implementation of 3 international and 3 Latvian scientific research projects and in cooperation with Telecommunications Institute of the University of Aveiro were used in preparing the COST project application "Digital Signal Processing for Fiber Optic Communication Networks".
2. The measurement methods developed during the course of the work are intended for evaluating the nonlinear coefficient of optical fibers that are already being used and of new ones alike. Within the framework of a cooperation agreement, the topicality of the non-linear coefficient measurements in optical fibers is included in the assessment for VAS "Latvijas Valsts Radio un Televīzijas Centrs": "Assessment of backbone network technologies and main design trends" (EU fund project Nr.3DP/3.2.2.3.0/12/IPIA/SM/001 „Next generation electronic communications network development in rural regions").
3. A nonlinear coefficient measurement scheme patented in Latvia was developed, in which SPM is triggered with NRZ-OOK optical signal with the bit transmission rate of 10 Gbit/s, corresponding to the hierarchy level STM-64 of synchronous digital hierarchy data transmission rate (9953.28 Mbit/s).
4. Two European patent applications have been filed and approved for a new type screw shift structure optical fiber connector (patent application number EP12197706.0) and the measurement scheme of stimulated Brillouin scattering threshold power (patent application number EP13198258.9).

The theses to be defended:

1. With the developed measurement method, which is based on a two-fiber transverse shift, it is possible to determine the effective area of an optical fiber even if accurate fiber refractive index profile is not available. The measurement may be performed at various wavelengths in the entire 3rd optical transparency wavelength range with an accuracy up to +/-1 μm^2.

2. With the developed measurement method of pulsed signal self-phase modulation, it is possible to determine the optical fiber nonlinear coefficient, by employing amplitude manipulated, without return to zero impulses used in fiber optical transmission systems which gives 8% higher result than the continuous wave self-phase modulation measurement method.
3. The effective nonlinear coefficient of highly nonlinear fiber and dispersion-shifted fiber is described with a hyperbolic secant function with distinct coefficients at function argument, determining the oscillation range and period.
4. With an enhanced Mamyshev type regenerator, it is possible to regenerate 40 Gbit/s RZ-OOK optical signal shape in the optical domain, by increasing the extinction ratio by 5.2 dB and the signal to noise ratio by 2.3 dB, if an optical filter is used with the throughput bandwidth of 0.625 nm at -3 dB level, shifted by 0.7 nm from the signal central wavelength.

Approbation of the results of the research

The main results of the promotion work are presented at **12** international scientific conferences; these are reported in **5** publications in scientific journals, **6** publications in the full-text conference proceedings, **12** publications in the conference books of abstracts, and **2** Latvian patents and **2** European patent applications.

Reports at the **international scientific conferences**:

1. **Supe A.,** Poriņš J. ''Measurements of Nonlinear Coefficient in OS2 Optical Fiber'' // Electronics 2010, Lithuania, Kaunas, May 18.-20., 2010.
2. **Supe A.,** Poriņš J. ''Nonlinear Coefficient Determination for Telecommunications Optical Fibre'' // Optics & High Technology Material Science 2010, Ukraine, Kiev, October 21.-24., 2010.
3. **Supe A.**, Poriņš J. ''Optical Fibre Effective Area Measurements'' // Developments in Optics and Communications 2011, Latvia, Riga, April 28.-30., 2011.
4. **Supe A.,** Poriņš J., Ivanovs Ģ. ''Comparison of Different FWM Realization Methods in Optical Fibre'' // Electronics 2011, Lithuania, Kaunas, May 17.-19., 2011.
5. **Supe A.**, Poriņš J., Bobrovs V. ''Evaluation of effective area erbium doped fibers'' // 7th International Conference Advanced Optical Materials and Devices, Lithuania, Vilnius, August 29.-31., 2011.
6. **Supe A.**, Poriņš J. ''Optical Fibre Effective Area Measurements'' // 52nd RTU Scientific Conference, Latvia, Riga, October 13.-14., 2011.
7. **Supe A.**, Poriņš J. ''Estimation of Erbium Doped Optical Fibers Effective Area'' // IEEE Swedish Communication Technologies Workshop (Swe-CTW 2011)", Sweden, Stockholm, October 19.-21., 2011.
8. **Supe A.**, Poriņš J. ''Estimation of Erbium Doped Optical Fiber Nonlinear Coefficient'' // Optics & High Technology Material Science 2011", Ukraine, Kiev, October 27.-30., 2011.
9. **Supe A.,** Poriņš J. ''Estimation of Variables Affecting Parametric Amplification in Fiber Optics'' // Developments in Optics and Communications 2012, Latvia, Riga, April 12.-14., 2012.
10. **Supe A.**, Poriņš J. ''Research of Optical Radiation Intensity in Erbium Doped Optical Fibers'' // 8th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2012), Poland, Poznan, July 18.-20., 2012.
11. **Supe A.**, Poriņš J. "Optical Fiber Nonlinear Coefficient Measurements Using Four-Wave Mixing" // Swedish Communication Technologies Workshop (Swe-CTW 2012)", Sweden, Lund, October 24.-26., 2012.
12. **Supe A.**, Fernandes G.M., Muga N.J., Pinto A.N., Ferreira M.F.S. "Pump and Filtering Optimization in Mamyshev Regenerator" // 8th Iberoamerican Optics Meeting and 11th Latin American Meeting on Optics, Lasers and Applications (RIAO/OPTILAS 2013), Portugal, Porto, July 22.-26., 2013.

Publications **in scientific journals**:

1. Poriņš J., Ivanovs Ģ., **Supe A.** ''Measurements of Nonlinear Coefficient in OS2 Optical Fiber'' // Electronics and electrical engineering, -5. (2010) 53.-56. pp., ISSN 1392-1215.
2. Poriņš J., Ivanovs Ģ., **Supe A.** ''Comparison of Different FWM Realization Methods in Optical Fibre'' // Electronics and electrical engineering, -5. (2011) 37.-40. pp., ISSN 1392-1215.
3. Poriņš J., Bobrovs V., **Supe A.** "Evaluation of Effective Area of Erbium Doped Fibers" // Lithuanian Journal of Physics, Vol. 52, No.1, 19.-23. pp. (2012) ISSN 1648-8504.
4. Poriņš J., **Supe A.** "Methods for Estimation of Optical Fiber Non-linearity Using Self-phase Modulation Effect" // Latvian Journal of Physics and Technical Sciences, Vol. 48, No. 6/2011, 29.-40. pp., ISSN 0868-8257 (Print).
5. Poriņš J., **Supe A.** ''Interaction Between Electromagnetic Field and Optical Signal Transmission in Fiber Optics'' // Electronics and electrical engineering, No. 6(122), 2012., 83.-86. pp., ISSN 1392-1215.

Publications **in the full-text conference proceedings**:

1. Poriņš J., Ivanovs Ģ., Bobrovs V., **Supe A.** ''Investigation of External Electromagnetic Disturbance in HDWDM System'' // Progress In Electromagnetics Research (PIERS 2012): Proceedings, Malaysia, Kuala Lumpur, March 27.-30., 2012. - 982.–986. pp., ISSN 1559-9450.
2. Poriņš J., **Supe A.** ''Research of Optical Radiation Intensity in Erbium Doped Optical Fibers'' // 8th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2012): Proceedings, Poland, Poznan, July 18.-20., 2012. - 1.-4. pp., Print ISBN: 978-1-4577-1472-6.
3. Poriņš J., Ivanovs Ģ., **Supe A.**, Cauņa G. "Investigation of Polarization Mode Dispersion Influence to Different Optical Signal Modulation Formats" // 7th International Conference on Broadband, Wireless Computing, Communication and Applications (BWCCA 2012): Proceedings, Canada, Victoria, November 12.-14., 2012. - 285.–288. pp.
4. **Supe A.**, Poriņš J., Ivanovs Ģ. "Optical Fiber Nonlinear Coefficient Measurements Using FWM" // Progress In Electromagnetics Research (PIERS 2013): Proceedings, Korea, Taipei, March 25.-28., 2013. - 339.–341. pp.
5. **Supe A.**, Fernandes G.M., Muga N.J., Pinto A.N., Ferreira M.F.S. "Pump and Filtering Optimization in Mamyshev Regenerator" // 8th Iberoamerican Optics Meeting and 11th Latin American Meeting on Optics, Lasers and Applications, Proceedings, Portugal, Porto, July 22.-26., 2013., Proc. SPIE 8785, doi:10.1117/12.2026288.
6. **Supe A.**, Fernandes G.M., Muga N.J., Pinto A.N., Ferreira M.F.S. "Experimental characterization of a highly nonlinear fiber" // 8th Iberoamerican Optics Meeting and 11th Latin American Meeting on Optics, Lasers and Applications, Proceedings, Portugal, Porto, July 22.-26., 2013., 87854D, doi:10.1117/12.2026182.

Publications **in the conference books of abstracts**:

1. **Supe A.**, Poriņš J. ''Nonlinear Coefficient Determination for Telecommunications Optical Fibre'' // Optics & High Technology Material Science SPO 2010: Scientific Works, Ukraine, Kiev, October 21.-24., 2010., publisher – Kiev university publishing house, p. 165.
2. **Supe A.**, Poriņš J. ''Optical Fibre Effective Area Measurements'' // Development in Optics and Communications 2011: Book of Abstracts, Latvia, Riga, April 28.-30., 2011., publisher – Institute of solid state physics, Riga, Latvia, pp. 38.-39.
3. **Supe A.**, Poriņš J. ''Optical Fibre Effective Area Measurements'' // Riga Technical University 52nd International Scientific Conference Section Electronics, Telecommunications and eSociety Abstracts 2011, Latvia, Riga, October 13.-14., 2011., publisher – Riga Technical university, Riga, Latvia, p. 23.

4. **Supe A.**, Poriņš J. ''Estimation of Erbium Doped Optical Fibers Effective Area'' // Swedish Communication Technologies Workshop (Swe-CTW 2011): Booklet of Abstracts, Sweden, Stockholm, October 19.-21., 2011., publisher – Royal Institute of Technology, ISBN 978-1-4577-1876-2.
5. **Supe A.**, Poriņš J. ''Estimation of Erbium Doped Optical Fiber Nonlinear Coefficient'' // Optics & High Technology Material Science SPO 2011: Scientific Works, Ukraine, Kiev, October 27.-30., 2011., publisher - Kiev university publishing house.
6. Poriņš J., Ivanovs Ģ., Bobrovs V., **Supe A.** ''Investigation of External Electromagnetic Disturbance in HDWDM System'' // Progress In Electromagnetics Research (PIERS 2012): PIERS book of abstracts, Malaysia, Kuala Lumpur, March 27.-30., 2012.
7. **Supe A.**, Poriņš J. ''Estimation of Variables Affecting Parametric Amplification in Fiber Optics'' // Development in Optics and Communications 2012: Book of abstracts, Latvia, Riga, April 12.-14., 2012., publisher – University of Latvia Institute of solid state physics, pp. 78.-79., ISBN 978-9984-49-518-7.
8. **Supe A.**, Poriņš J. ''Research of Optical Radiation Intensity in Erbium Doped Optical Fibers'' // Proceedings of the 8th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2012): Conference proceedings, Poland, Poznan, July 18.-20., 2012.
9. **Supe A.**, Poriņš J. "Optical Fiber Nonlinear Coefficient Measurements Using Four-Wave Mixing" // Swedish Communication Technologies Workshop (Swe - CTW 2012): Conference proceedings, Sweden, Lund, October 24.-26., 2012., p. 6.
10. **Supe A.**, Fernandes G.M., Muga N.J., Pinto A.N., Ferreira M.F.S. "Pump and Filtering Optimization in Mamyshev Regenerator" // RIAO/OPTILAS 2013: Abstract`s booklet, Portugal, Porto, July 22.-26., 2013.
11. **Supe A.**, Fernandes G.M., Muga N.J., Pinto A.N., Ferreira M.F.S. "Experimental Characterization of a Highly Nonlinear Fiber" // RIAO/OPTILAS 2013: Abstract`s booklet, Portugal, Porto, July 22.-26., 2013.
12. Ferreira M.F.S., **Supe A.**, Fernandes G.M., Muga N.J., Pinto A.N. "Effective Nonlinear Parameter Measurement Using FWM in a Highly Nonlinear Fiber" // 3rd Workshop on Specialty Optical Fibers and their Applications: Abstracts, Sweden, Stockholm, August 28.-30., 2013.

Latvian patents:
1. Telecommunications optical fiber nonlinear coefficient measurement scheme, LV-14296.
2. Screw type optical fiber connector, which design is based on shift and rotation movements, Nr. LV-14587.

European **patent applications**
1. Optical fiber connector assembly, EP12197706.0, 2013;
2. Method and system for stimulated Brillouin scattering threshold power measurement, EP13198258.9, 2013.

The results of the promotion work were used for realization of 3 International and 3 Latvian scientific research projects:

International scientific research projects:
1. „OSP-HNLF - Optical Signal Processing Using Highly Nonlinear Fibers", project ref. PTDC/EEA-TEL/105254/2008, European Union FEDER program;
2. „Steering of light in nonlinear waveguides with resonant interactions", project ref. PTDC/FIS/112624/2009 (CONLUZ), European Union FEDER program;

3. Strategic Project UI 44 - 2011 - 2012, project ref. PEst-C/CTM/LA0025/2011;
4. In cooperation with Telecommunications Institute of the University of Aveiro submitted COST project application ‘‘Digital Signal Processing for Fiber Optic Communication Networks’’.

Latvian scientific research projects:
1. „Optical signal state of polarization detection methods in FOTS”, Nr. ZP-2009/6, RTU;
2. „Investigation of nonlinear optical coefficient measurement methods in FOTS”. Nr. ZP-2010/10, IZM-RTU;
3. „Assessment of polarization changes and development of PMD compensator for optical wavelength division multiplexing communication systems”, Nr. ZP-2010/26, RTU.

The volume and structure of the work

The volume of the promotion work is 120 pages. The work consists of the introduction, four chapters, the list of literature sources used, and five appendices. In the introduction, the topicality of the carried out research is substantiated and the promotion work direction defined.

In the first chapter of the work, development trends of researches of optical fiber non-linear properties have been considered and a review of NOE observed in FOTS is offered. Parameters characterising nonlinearity of optical fiber and their physical importance are defined. The chapter is concluded with the formulation of aim and tasks of the doctoral thesis, its novelty, theses to be presented, and the key results are summarised.

The second chapter of the thesis is dedicated to research methods of measuring the optical fiber effective area A_{eff}. This parameter is measured because the optical radiation intensity depends on the area along which the majority of the optical signal propagates in a fiber. In the course of the studies, an experimental method for measuring A_{eff} was developed, based on mutual transverse shift of optical fibers, by using a micro-positioner. To assess the accuracy of the developed method, a comparison of the obtained measurement results with the calculated results was performed, by using a plane wave superposition method, as well as with measurement results achieved using the infrared radiation CCD camera. Furthermore, the evaluation of A_{eff} for erbium doped fiber was performed at various wavelengths in the 3^{rd} optical transparency window.

The third chapter covers a study of methods of measuring the optical fiber γ parameter based on nonlinear phenomena caused by the optical Kerr effect: self-phase modulation (SPM) and four-wave mixing (FWM). By conducting a study of SPM-based γ parameter measurement methods, a measurement scheme was developed and patented in Latvia, using a pulsed optical signal (P-SPM). To compare the obtained results, the measurement scheme was implemented also in the computer simulation software Synopsis RSoft OptSim 5.2. To determine the fiber γ parameter dependence on the state of optical radiation polarisation, measurement methods were studied, based on FWM triggering in the fiber under test. This study was conducted during the doctoral studies practice in cooperation with the Optical Communications and Photonics Scientist Group at the University of Aveiro, led by the professor Mario F.S. Ferreira and assoc. prof. Armando N. Pinto. By initiating FWM in the fiber and by making optical spectrum measurements, the effective nonlinear coefficient γ_{eff} in the highly nonlinear fiber (HNLF) was obtained.

In the fourth chapter a new type of optical signal regeneration method, by employing the SPM nonlinear effect or what is known as the Mamyshev type regenerator is examined. This type of signal regeneration completely in the optical domain is not yet used in commercial FOTS, but it is very promising, as it does not impose a restriction of the maximum data transmission rate of a signal, as it is in cases, when an electrical signal is restored, using optic-electric and electric-optic transition. The experimental part of the study was performed in cooperation with the Optical Communications and Photonics Group of the

University of Aveiro. By implementing 40 Gbit/s RZ OOK signal regeneration, a study was conducted regarding the impact of two distinct optical filters on the functioning of the regenerator. In the case of both filters, the best possible signal to noise ratio (SNR) and extinction ratio (ER) of the regenerated optical signal was found.

In the summary, the main conclusions are presented. In the appendices present lists of the conferences, the publications and the projects, the data on the Latvian patent, the recommendation about doctoral studies' practice and specification on used equipment.

DETAILED DESCRIPTION OF THE WORK'S CHAPTERS

Chapter 1

The first optical fibers made of SiO_2 back in 1960-ties had very high losses. An important breakthrough occurred in 1970, when scientists from the company Corning managed to significantly reduce the quartz glass fiber losses [18]. Soon after, the scientists working for Bell Laboratories used silicon dioxide fibers to study and demonstrate nonlinear optical effects [16, 35-38]. Thus, in 1972, studies were performed regarding stimulated Raman and Brillouin scattering processes in optical fibers [16, 35]. These studies promoted the study of other nonlinear phenomena as well, such as optically induced birefringence, parametric four wave mixing, and self-phase modulation [36, 38]. However, in actual FOTS, fiber nonlinearity practically did not affect signal transmission, because the optical signal power was relatively low (around 0 dBm), data transmission rates were measured in megabits and multichannel transmission using wavelength division multiplexing was not applied.

Studies of nonlinear fiber optics significantly expanded during the 1990-ties, when in the backbone fiber transmission lines began to use optical amplifiers. Moreover, single mode fibers (SMF) were ever more widely used in transmission systems, because it provides a much lower optical signal dispersion. However, the core size of such fibers is smaller than the previously used multi-mode fibers, therefore the optical signal intensity in the fiber is much higher. Therefore, nonlinear effects of optical fibers started emerging more markedly in optical transmission systems, along with their undesirable impact on signal transmission. It led to rapid development of the nonlinear fiber optics research, which continues also in the 21st century. The studies cover ways of how to reduce the impact of nonlinear effects and new methods of employing optical nonlinearities [2].

In optical fibers, nonlinearity is manifested in correlation between the medium polarisation and the electric field, $P = \varepsilon_0 \chi E$, where ε_0 is dielectric vacuum permittivity, χ is dielectric medium susceptibility and E is the electric field intensity [26]. Nonlinear dielectric medium is described by a nonlinear correlation between P and E, as shown in *Fig. 2*. Medium polarisation $P = Np$ depends on each individual dipole moment p, triggered by the electric field E, and dipole moment density N. Accordingly, medium nonlinearity depends on both p and N [9].

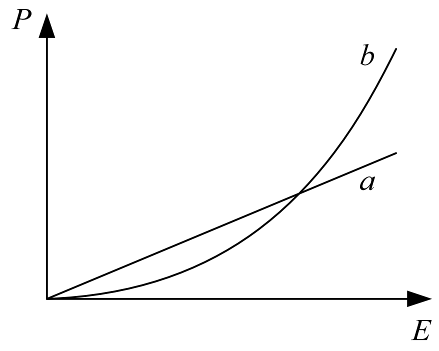

Fig. 2. Correlation between *P* and *E* in case of linear (a) and nonlinear (b) dielectric medium [9].

Any dielectric material reaction to light under influence of an intensive electromagnetic field becomes nonlinear and optical fibers are not an exception. Silicon dioxide as a material in essence is not a markedly nonlinear material, hence nonlinear optical phenomena occur only at relatively high light intensity, and they change the quality of the transmitted signal.

Taking into account the fact that the optical fiber attenuation is very low (typically for single mode fibers in wavelength ranges around 1310 nm and 1550 nm – respectively 0.5 dB/km and 0.2 dB/km), low power transmitters are used in transmission systems (the optical signal power for transmission of up to 100 km distance is typically up to 1 mW) [1]. However, the geometry of an optical fiber as a waveguide is formed in a way that light propagates only along its central part or the fiber core. The core size in single mode fibers is typically around 8–10 µm. If such a fiber is used for simultaneously transmitting multiple information flows or what are known as channels, using wavelength division multiplexing (WDM), then the total power in the fiber core depends on the total number of channels. Hence, in the case of multichannel WDM systems, the optical signal intensity in a fiber is high. Moreover, light in the fiber propagates without defocusing (without significant changes in the cross-sectional area) arbitrarily large distances. Nonlinear effects, in turn, increase in a linear manner depending on the fiber length. Nevertheless, due to attenuation, the optical radiation power is reduced, hence, to describe NOE, what is known as the effective fiber length is used or the area, in which nonlinear interaction is most intensive [3]

$$L_{eff} = \frac{1-e^{-0.23\alpha L}}{0.23\alpha}, \tag{1}$$

where L – total fiber length, α – attenuation coefficient, dB/km. The multiplier 0.23 is used to get the liner attenuation coefficient (the times by which optical signal power is reduced).

The aforementioned aspects (fiber core size and transmission line length) are the key reasons for why various nonlinear effects occur in quartz glass fibers, which must be taken into account when creating high-speed optical signal transmission lines, as NOE introduces undesirable signal distortions [2].

The description of nonlinear optical phenomena is typically formed by expressing polarisation *P(t)* dependence on the added electric field intensity *E(t)*. The reason for using polarisation in describing NOEs is that polarisation that changes over time can cause the occurrence of new electromagnetic field components, which is the key manifestation of nonlinear effects [10]. It is important to point out that SiO_2 is a symmetrical molecule, therefore the second order dielectric susceptibility tensor $\chi^{(2)}$ is very close to zero. Therefore, the main cause in quartz glass fiber nonlinearity is $\chi^{(3)}$. In optical fibers, the third order dielectric susceptibility is practically without any delay, therefore NOE manifests immediately and is observed also in cases of very short impulses.

All third order NOE are divided into two groups: elastic and inelastic. Nonlinear processes the cause of which is $\chi^{(3)}$, are elastic and such NOE are also referred to as parametric interactions. The origin of this terminology is obscure, but the word parametric has come to denote a process in which the initial and final quantum-mechanical states of the system are identical. Consequently, in a parametric process photon population can be removed from the ground state only for those brief intervals of time when it resides in a virtual level. Conversely, processes that do involve the transfer of photon population from one real level to another are known as nonparametric processes. One difference between parametric and nonparametric processes is that parametric processes can always be described by a real susceptibility, but nonparametric processes are described by a complex susceptibility [11].

In a parametric process photon energy is always conserved therefore waves of distinct frequencies can be subject to mutual energy transfer caused by the nonlinear properties of the medium, but the overall amount of energy remains unchanged. Since parametric processes are generally coherent they depend on the phase coherence [11, 21]. According to the american physicist Robert W. Boyd developed classification the intensity dependent refractive index (including optical Kerr effect) and new harmonic generation belongs to parametric processes [11]. The optical transmission systems most frequently feature the optical Kerr effect causing an intensity-dependent change in fiber index of refraction. It should be noted that the above mentioned is not the only NOE classification. For example, in the russian literature (Fain, Hanin) parametric NOEs refer to effects, in which phase relationship between the light waves play an important role. In this classification the optical Kerr effect is not parametric.

The second group includes nonlinear effects arising due to stimulated inelastic scattering, which are nonparametric nonlinear processes. Unlike the parametric processes, in this case, all quantum states of the physical system change. In this process, the optical wave transfers a part of the initial energy to the nonlinear medium. The nonparametric process group includes nonlinear scatterings related to initiation of vibrations in the quartz glass, as well as nonlinear absorption [2, 11]. From this group of nonlinear phenomena, the most frequently observed in optical fibers are the stimulated Brillouin and stimulated Raman scattering. However, the nonlinear absorption starts to arise at very high light intensity (nonlinear losses in telecommunication fibers rapidly increase at intensities starting at 10^{11} W/cm^2 [22]), which is not typical in optical communication systems.

The afore-described NOE classification is shown in *Fig. 3*. The most typical $\chi^{(3)}$ caused NOE in optical transmission systems are self-phase modulation, cross-phase modulation, and four wave mixing, as well as the stimulated Brillouin and Raman scatterings [14].

Since the optical Kerr effect causes fiber refractive index dependence on the electric field intensity, then the optical fiber refractive index can be described as

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

where $n_o=\sqrt{(1+\chi^{(1)})}$ is the linear part of the refractive index, which depends on the frequency, n_2 is the nonlinear refractive index, sometimes referred to as the second order refractive index, or the Kerr coefficient, which shows how rapid the nonlinear part of the refractive index increases depending on the optical wave electric field intensity square $|E|^2$ in the optical fiber [3]. The nonlinear part of the refractive index may be expressed also using the dielectric susceptibility tensor (SI system of units)

$$n_2 = \frac{3}{4}\frac{\chi^{(3)}}{c\varepsilon_0 n_0^2}, \quad (3)$$

where ε_0 is the vacuum dielectric permittivity and the optical field is assumed to be linearly-polarised so that only one component from the third order tensor $\chi^{(3)}$ is responsible for the refractive index. Parameters of the tensor $\chi^{(3)}$ also affect the light polarisation properties because they cause nonlinear birefringence [3, 14].

The optical fiber as a waveguide is also defined with a parameter nonlinear coefficient γ

$$\gamma = \frac{\omega n_2}{c_g A_{eff}}, \quad (4)$$

where ω is the angular frequency, c_g is the speed of light in the fiber, and A_{eff} is the effective core area of the fiber, which is typically slightly larger than the fiber core area. It means that a part of the light propagates also along the inner part of the optical fiber cladding. A_{eff} depends on fiber parameters, such as the core area, the difference between the core/cladding refractive index, and the fiber profile [3, 14]. The nonlinear coefficient describes the nonlinearity of the fiber which depends both on the material properties (n_2) and on the fiber structure (A_{eff}).

The optical fiber parameter γ can be determined only indirectly, by triggering one of NOE and evaluating the optical signal changes in the fiber output. It is important to point out that the nonlinear coefficient measurements are not yet standardised, therefore the question remains of which measurement methods would be the most suitable for it. Traditionally, in γ measurements, SPM-based method is used [38]. However, such measurements can be performed in various configurations, as well as by using other NOE, such as, four wave mixing (FWM). Since the work of development of a certain standard is still in progress, studies about n_2 and γ measurements are topical.

As mentioned before, NOE is one of the restricting factors in the high-speed (≥ 40Gb/s) optical transmission systems, however nonlinear effects could not be regarded as a solely undesirable occurrence. By using NOE, it is possible to realize signal processing completely in the optical division. Therefore, the high-speed functionality of a transmission system is no longer restricted with the potential of electrical components (mainly, the restrictive factor is the optical-electrical and electrical-optical transition in real time). However, NOE in an optical fiber occur nearly without any delay.

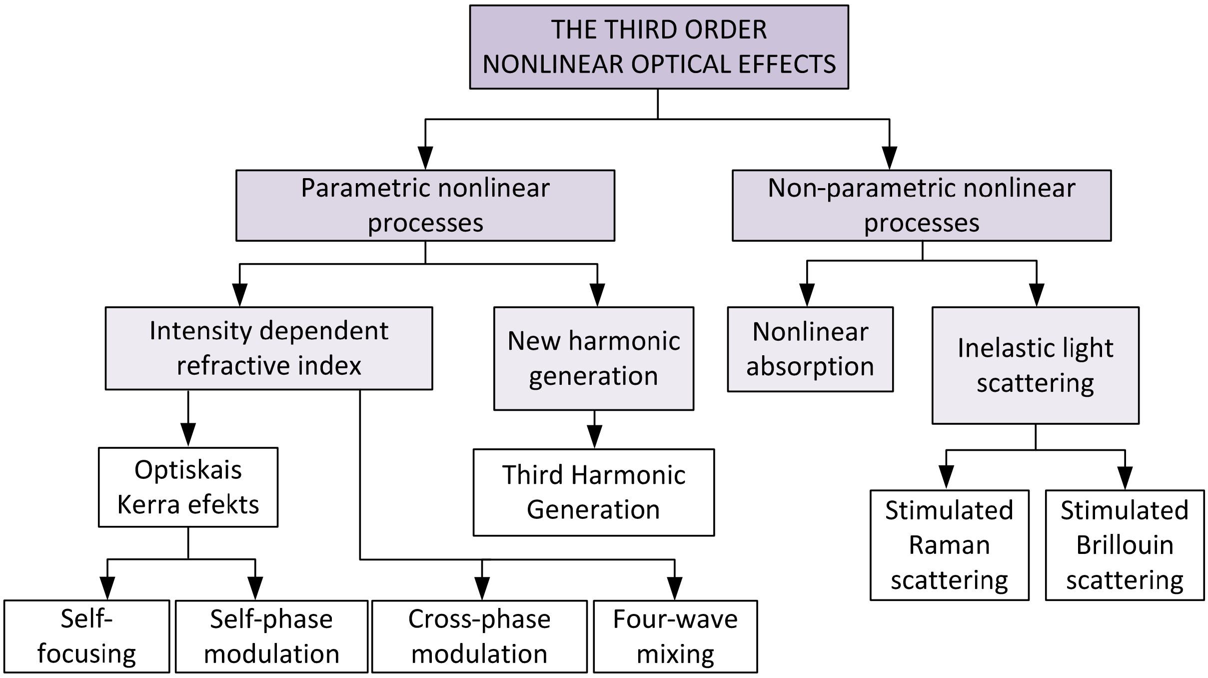

Fig. 3. Classification of third order NOE observed in optical fibers.

The most typical optical signal processing methods that are implemented on NOE are: very high speed optical signal switching (R ≥ 1 Tb/s) [7], wavelength conversion, multiplexing and demultiplexing, optical signal amplification and regeneration [14]. The last of the enumerated methods is a very topical study subject, because in the high-speed communication systems, it is very important to ensure the necessary bit error ratio (BER), which depends on the signal to noise ratio (SNR) [30]. Hence, NOE not only implies signal distortions, but it can potentially be used in signal regeneration. To create a signal regenerator completely in the optical division, effective initiation of NOE must be achieved. In this case, fibres must be used with increased nonlinearity or what are known as highly nonlinear fibers (HNLF) [14].

Optical fiber nonlinearity becomes ever more topical, in particular in high-speed FOTS. Therefore, when choosing a fiber, it is important to evaluate its parameter γ. If the fiber is intended for optical signal transmission, then fibers with as low γ parameter as possible are preferable [28]. Whereas, when applying NOE in optical signal processing, fibres with enhanced nonlinearity are more suitable.

Chapter 2

To increase the optical fiber information throughput capacity, WDM systems are developed with enhanced spectral efficiency. Therefore, all WDM channels are arranged as densely as possible (at transmission rate of 10 Gbit/s in one channel, the inter-channel frequency spacing ≤50 GHz). Thus, it is possible to simultaneously transmit tens and even hundreds of optical signals with different wavelengths. Therefore, depending on the channel count, the total power of an optical signal to be transmitted in a single fiber and accordingly – also the optical radiation intensity increases. However, as it has been mentioned before, all nonlinear effects depend on the optical radiation intensity, which in the case of optical fibers depends on power and cross-section area, along which the optical signals propagates through the fiber.

In a single mode fiber, optical radiation along the cross section is not evenly distributed, moreover, it does not completely fill the entire fiber volume. It is greater at the central longitudinal axis of the fiber, but in the direction to the core/cladding bounding surface is reduced and partially penetrates also into the cladding. The light distribution on fiber cross-section depends on the fiber profile or structure, its dimensions and core/cladding light refractive indexes. If the fiber has the step index profile as defined in the ITU-T G.652 recommendation, then the optical radiation complies with the Gaussian distribution (see *Fig. 4.*). Light distribution in a fiber is described by two parameters: the mode field diameter (MFD) and the effective area A_{eff}. If the light in fiber cross-section features the Gaussian distribution, then the MFD is a fiber area diameter, where the optical radiation intensity reduces to $1/e^2$ from maximum intensity. In this case, the area, along which the majority of light is propagated is $A_{eff}=\pi w^2$. The effective area parameter was introduced to obtain the actual optical radiation intensity in the fiber in nonlinear effects calculations [17]. It is based on the model field distribution and generally it is

$$A_{eff} = \frac{2\pi\left(\int_0^\infty |E_a(r)|^2 rdr\right)^2}{\int_0^\infty |E_a(r)|^4 rdr} = \frac{2\pi\left(\int_0^\infty I(r)rdr\right)^2}{\int_0^\infty I^2(r)rdr}, \tag{5}$$

where $E_a(r)$ is the electric field intensity and $I(r)$ is the main mode near field intensity depending on the radius r (distance from the central longitudinal axis of the fiber) [8]. Integration is performed along the entire area of the cross-section.

The effective area can be calculated only in fibers with optical intensity with Gaussian distribution. According to ITU-T recommendation G.650.2 (07/2007), such fibres are the step-indexed or level-type profile fibers defined in recommendations G.652 and G.654, whereas it is not possible to accurately determine A_{eff}, using the above equation (5), in the case of G.653 dispersion shifted fibers. In such cases, A_{eff} measurements become relevant. Moreover, fiber manufacturers do not always indicate the MFD and A_{eff} parameters of the manufactured fibers. Therefore, to assess the nonlinearity of such fibers, the effective area measurements become relevant. In this chapter of the thesis, measurement of the effective area of optical fibers was carried out, using the two-fiber mutual transverse shift.

In the ITU-T recommendation G.650.2(07/2007), far-field scanning and variable aperture A_{eff} measurement methods are described. For using such methods, specific measuring equipment is necessary. Therefore, a measurement method for determining A_{eff} was elaborated in this part of the work, by employing the two fiber mutual transverse shift [27]. This method is based on far-field distribution determination, using a laser, micropositioner, and optical power meter. From the far-field distribution of optical radiation, the near-field distribution can be calculated, using the inverse Hankel transform. Consequently, from the near-field distribution, A_{eff} can be calculated using the above equation (5).

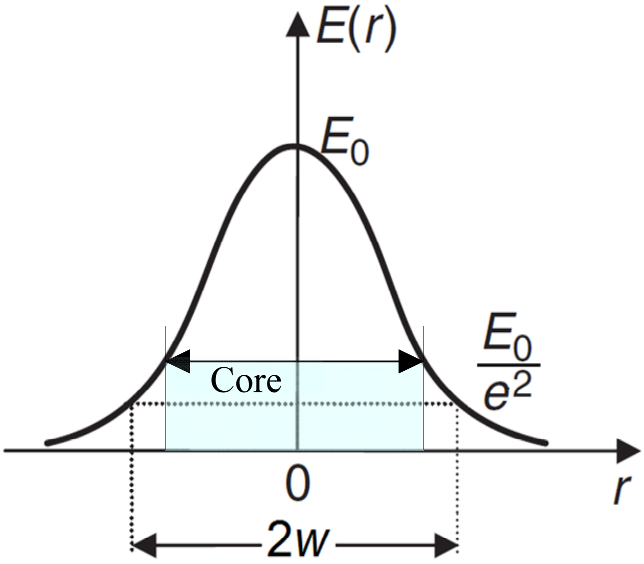

Fig. 4. Optical radiation in a single mode optical fiber with the Gaussian distribution. The mode field diameter is the function width 2w at level 1/e^2 [15]. The light blue denotes the fiber core diameter.

The transverse shift method differs from the far-field scanning method described in the ITU recommendation with the fact that the far-field power distribution is received with the optical fiber rather than with the PIN photodiode. Secondly, the receiver fiber longitudinal axis is always parallel to the longitudinal axis of the transmitting fiber, unlike the method mentioned in the recommendation G.650.2(07/2007), where the receiving PIN diode is moved along a curved trajectory at a certain distance from the end of the transmitting fiber. Thus, an angle deviation forms between the longitudinal axis of the transmitting fiber and the central axis of the receiver.

In measurements using the transverse shift method, the micropositioner is the main component allowing accurate performance of transverse shift of two-fiber ends. In this study, a micropositioner *Standa 8MT173* was used with the basic step of 1.25 µm, with an option to perform the shift at a half step (0.625 µm). The measurement scheme uses also a tunable ECL

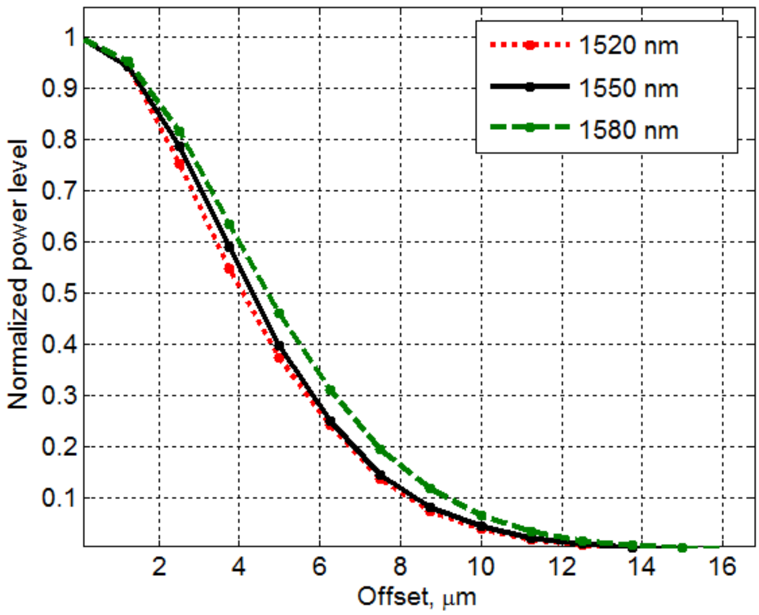

Fig. 5. Normalized optical radiation near-field distribution in fiber cross-section at wavelengths of 1520, 1550, and 1580 nm, depending on the mutual shift of fiber ends.

type laser and an optical power meter. With the two-fiber transverse shift method, the optical radiation distribution in the far field is obtained, because two fiber end surfaces are placed at a distance of ~2 mm from each other [27].

The optical radiation distribution obtained in measurements after the recalculation to the near-field distribution for a single mode fiber SMF-28 at wavelengths of 1520, 1550, and 1580 nm is provided in *Fig. 5.* The power on the *y* axis is normalized according to the maximum power, as in some measuring sessions, slightly different maximum power levels were obtained.

To verify reliability of results obtained with the developed measurement method, A_{eff} evaluation was performed for the single mode fiber SMF-28, using three different methods: calculations with the plane wave superposition method, measurements with the transverse shift method, and measurements with the infrared range CCD camera (measuring equipment BeamOn USB Measurement system, Version 4.01CCD S/N: 4634D). Table 1 offers a summary of all obtained results at the wavelength of 1520 nm.

Table 1.

Standard single mode fiber (SMF-28) A_{eff} measurement results and calculated MFD depending on the method used.

Single-mode fiber SMF-28	Calculations with the plane wave superposition method	Experimental measurements with transverse shift method	Infrared CCD camera
Mode field diameter, µm	9.60	9.53	9.55
A_{eff}, µm^2	72.40	71.40	71.63

All three methods yield very similar results. The dispersion of the obtained results ΔA_{eff} = 1.00 µm^2 and ΔMFD = 0.07 µm. Precision of measurements depends on the micropositioner's step (+/-5 %) and the power meter accuracy (+/-0.5 dB). Assuming the worst case scenario, when both parameters are shown with the highest deviation, the measurement error is +/-1 µm^2. Hence, all results fall within the measurement error interval. Therefore, it can be concluded that the results obtained with the developed A_{eff} measurement scheme are credible.

The developed A_{eff} measurement method was also used in the measurements of erbium doped fiber (EDF) effective area to assess its applicability options in development of EDFA amplifier. In this case the manufacturer of EDF under test has not indicated the A_{eff} and MFD. As a result of measurements, it was obtained that the A_{eff} of EDF fiber in the wavelength range from 1470 to 1575 nm increases from 22.6 µm^2 to 23.7 µm^2 (ΔA_{eff} = 1.1 µm^2) [29]. However, in the case of the single mode fiber SMF-28, it was found that A_{eff} increases from 71.4 µm^2 to 75.8 µm^2 (ΔA_{eff} = 4.4 µm^2) in the wavelength range from 1520 to 1580 nm [39]. Since the determined EDF A_{eff} is by ~3 times smaller than that of a single mode fiber, then it can be concluded that the optical radiation intensity in the EDF fiber will be three times higher than that of the SMF-28 fiber. The results show that as the wavelength increases, the A_{eff} change differs for various fibers.

Chapter 3

The third chapter of the thesis is dedicated to a study of methods for measuring the optical fiber γ parameter, based on the nonlinear phenomena caused by the optical Kerr effect: signal self-phase modulation (SPM) and four-wave mixing (FWM). The chapter is divided into two sections, with the first describing the measurements with SPM, whereas the other – with FWM.

It has already been mentioned that the fiber nonlinear coefficient can be determined only via indirect measurements, by triggering one of NOEs. However, as of now, no standardised γ measurement method has been created. For instance, the ITU-T recommendation *G.650.2*(07/2007) remarks that the nonlinear coefficient measurement methods are still being researched. The same remark can be found in the ITU-T recommendation G.652. The measurement method based on the pulsed self-phase modulation (SPM), is an experimental measurement method of ITU-T organisation. Whereas, the continuous wave (CW) method is an experimental measurement method of *Telecommunications International Association* (TIA) [44], which is suggested for reviewing also at the ITU organisation [43]. Another relevant issue is the accuracy of various measurement methods and which method provides the most suitable nonlinear coefficient assessment specifically in optical transmission systems [5, 13, 20].

Measurements with the P-SPM method

When analysing various γ measurement methods, a measurement scheme was developed based on SPM, by using the pulsed signal self-phase modulation (P-SPM) [23]. Unlike other methods, where P-SPM is used, in the developed measurement scheme, the pulsed optical signal is obtained with pseudo-random impulse sequence with a pulse repetition frequency of 10 GHz, which corresponds to the data transmission rate hierarchy level of synchronous digital hierarchy STM-64 (9953.28 Mbit/s) and is often used in multichannel wavelength division multiplexing systems as a data transmission rate of a separate channel. Therefore, γ measurements are performed under realistic optical signal transmission conditions [24]. A Latvian patent No. LV – 14296 has been obtained for the developed measurement scheme (see *Fig. 6.*). It consists of the transmitter part, the fiber under test, and the receiver part. The Transmitter part consists of an electric signal or pseudo-random bit pattern generator, NRZ coder, which obtains the no return to zero code, laser with an external resonator, and tunable wavelength in the range from 1465 to 1575 nm and wavelength resolution of 1 pm, 125 MHz at 1550 nm and external modulator of the optical signal, which is a Mach–Zehnder modulator on $LiNbO_3$ crystal base.

At the transmitter output, EDFA optical amplifier is connected with adjustable output signal power ranging from 10.5 to 23.5 dBm. After the transmitter part, the fiber under test follows, with its output connected to the optical spectrum analyser (OSA). The fiber parameter γ is determined by performing signal spectrum measurements and linearly approximating the dependence of the output signal spectral width on the fiber input signal

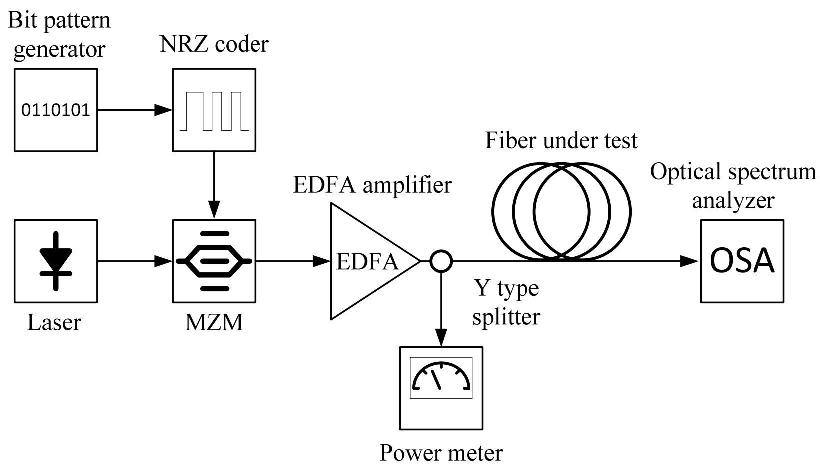

Fig. 6. Simulation and experimental P-SPM nonlinear coefficient measurement scheme based on the use of SPM nonlinear effect.

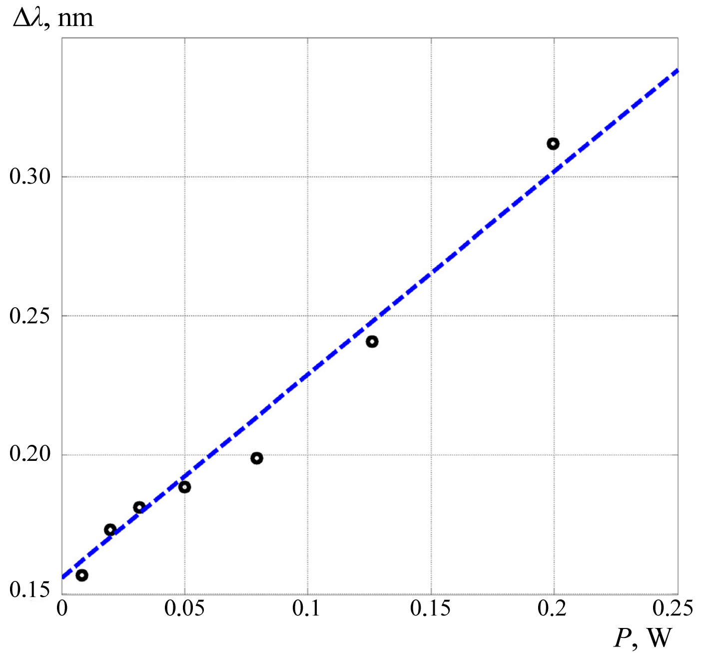

Fig. 7. Measurement results obtained with the P-SPM method and their linear approximation (the blue dotted line) for G.652 D type fiber.

power (see *Fig. 7.*). The parameter γ is accordingly the slope coefficient of the line obtained with the linear approximation [24].

In measurements of the nonlinear coefficient, two different fibers were used corresponding to ITU-T G.652 D and G.655 C recommendations. G.652 D type fiber is a standard single-mode fiber with reduced optical attenuation at OH- group absorption wavelength of 1383 nm. Whereas, G.655 C is the dispersion shifted fiber (DSF). The zero dispersion wavelength is shifted to 1550 nm wavelength.

To evaluate the results obtained with the developed P-SPM measurement method, measurements of the aforementioned fibers parameter γ were also performed by applying the CW-SPM method, as well as computer simulations with the software Synopsis RSoft OptSim 5.3. Table 2 shows the obtained results both from the experimental and simulation data.

Table 2.

Results obtained experimentally and from computer simulation

	Experimental results	
Fiber type	**CW-SPM** γ, ($W^{-1}km^{-1}$)	**P-SPM** γ, ($W^{-1}km^{-1}$)
G.652 D	0.88	0.95
G.655 C	0.91	0.98
	Computer simulations results	
Fiber type	**CW-SPM** γ, ($W^{-1}km^{-1}$)	**P-SPM** γ, ($W^{-1}km^{-1}$)
G.652 D	0.97	1.00
G.655 C	1.02	1.04

The best conformity between the simulation data and the experimentally obtained γ values was achieved with the P-SPM method. The result difference for the G.652 D type fiber is $\Delta\gamma$=0.05 $W^{-1}km^{-1}$ and in the case of G.655 C – $\Delta\gamma$=0.06 $W^{-1}km^{-1}$. In turn the measurements obtained with CW-SPM and the simulation results for the G.652 D type fiber differ by $\Delta\gamma$=0.09 $W^{-1}km^{-1}$ and for the G.655 C type fiber by $\Delta\gamma$=0.11 $W^{-1}km^{-1}$. The results show that the γ parameter results obtained with computer simulations and experimentally are very close (difference of 5 %). A bigger discrepancy between the results is observed in the case with the CW-SPM method (a difference of 10 %), which is related to a higher result dispersion.

Upon comparing the results obtained with the CW-SPM and P-SPM method, it is evident that the CW-SPM method in all cases gives a lower γ value. It could be explained with the fact that in the case of CW-SPM, continuous wave light is used. In such cases, the stimulated Brillouin scattering (SBS) is observed in the fiber, leading to the scattering of input light. Therefore, a part of the optical radiation does not reach the fiber output, but by means of scattering starts propagating in the opposite direction towards the beginning of the fiber. Therefore, the optical wave intensity in the fiber is lower than in the case of a pumped signal, when the SBS impact is effectively reduced.

Measurements with FWM method

Measurements with SPM triggering in the fiber allows determining the optical fiber parameter γ, but these are not the only measurement methods. Application options of other NOE in determining the fiber γ are also studied. A very promising is the measurement method based on FWM initiation because this NOE depends not only on the parameter γ, but also on the fiber birefringence properties [4, 13, 20, 31, 33, 34]. Thus, FWM depends not only on the power of the triggering optical waves, but also on their mutual state of polarisation [25].

A study on the opportunities of FWM application in the optical fiber γ measurements was performed during the doctoral practice in cooperation with the Optical Communications and Photonics scientists group of the University of Aveiro at the "Optical transmission system components" laboratory, led by the professor Mario F.S. Ferreira and assoc. prof. Armando N. Pinto. During the measurements, HNLF fiber parameter γ_{eff} was obtained.

If two optical waves of different wavelengths are fed into the fiber and one wave is markedly more powerful (pump) than the other (signal), then the newly created FWM component in the case of low pump power is described by the equation

$$P_3(L) = \left(\gamma P_1(0) L_{eff}\right)^2 P_2(0) \left|\frac{\sin(kL)}{kL}\right|^2 e^{-\propto L}, \tag{6}$$

where $P_3(L)$ is the FWM generated component power depending on the fiber length. $P_1(0)$ and $P_2(0)$ is the initial pump and signal laser power, α is the fiber attenuation coefficient, L is the fiber length, L_{eff} is the effective fiber length, whereas k is the parametric amplification [34]. From the above equation (6) it is possible to express γ depending on $P_3(L)$. Thus, an experimental measurement scheme was developed to initiate FWM in the fiber and to measure the power of the nonlinear mixing generated component.

The developed measurement scheme, which was used for nonlinear coefficient measurements of the HNLF fiber, by using the FWM nonlinear effect, is given in *Fig. 8*. The pump and signal component is generated, using two tunable lasers, which are operating in a continuous wave radiation mode. Both laser output power levels were selected so as only one FWM-generated interaction would form and accordingly only one newly created spectral component in the fiber output would be observed [40].

The pumping laser output is connected to EDFA amplifier, in the output of which an optical filter is connected to reduce the noise level in the pumping radiation spectrum caused by the amplifier. Then the pump and signal waves are fed through polarisation controllers PC-1 and PC-2, to be able to mutually adjust their state of polarisation. It is controlled by using a linear polariser after the optical signal combiner. Since the polariser fully let through only signals with a specific state of polarisation, then the polarisation controllers are used to turn the pump and signal component state of polarisation until the maximum optical power is obtained at the polariser output. The pump and signal wave polarisation control is very important, because FWM is sensitive to changes in the state of polarisation. Both optical

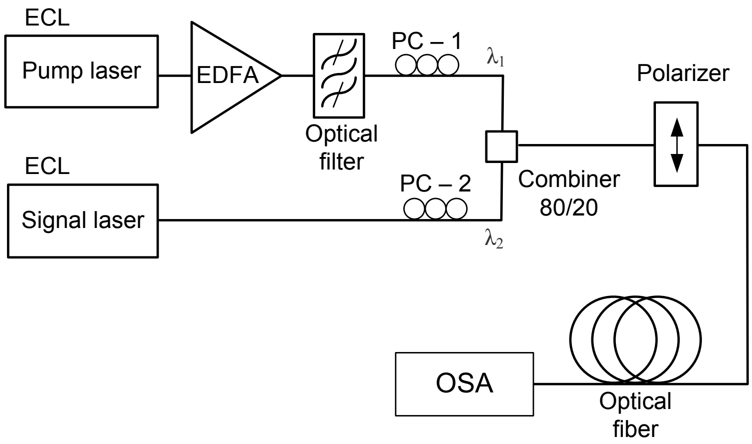

Fig. 8. Experimental *γ* measurement scheme, using FWM.

signals are combined using an asymmetric combiner, in the outlet of which 80 % of the pump wave power and 20 % of the signal power end up. It reduces the signal component power to prevent multiple FWM mixing in the optical fiber [41]. After the polariser, the optical signal is fed into the HNLF fiber, the output of which is connected to OSA to measure the FWM generated components power.

To assess how the maximum power of the FWM-generated component changes depending on the wavelength difference between the pump and signal component, all maximum powers determined from spectrums were displayed in a single graph, as shown in *Fig. 9*. Circles that are connected with the dotted black line represent the experimental measurement results, whereas the solid red and solid blue line represent calculation results using the equation (6). The red line represents the case when the pump and signal wave in the entire length of the fiber propagates without changing the state of polarisation, whereas the blue line shows the calculated results, when the pump and signal wave state of polarisation is completely random and the nonlinear coefficient in this case is reduced to 8γ/9. The coefficient 8/9 is an averaged calculation, i.e. assuming that the pump and signal wave state of polarisation changes randomly, as they propagate along the optical fiber, which does not maintain the state of polarisation [3]. As shown in *Fig. 9,* the results obtained with the equation (6) using *γ* (solid red line) and 8*γ*/9 (solid blue line) do not fully depict the actual FWM components power changes depending on Δ*λ*.

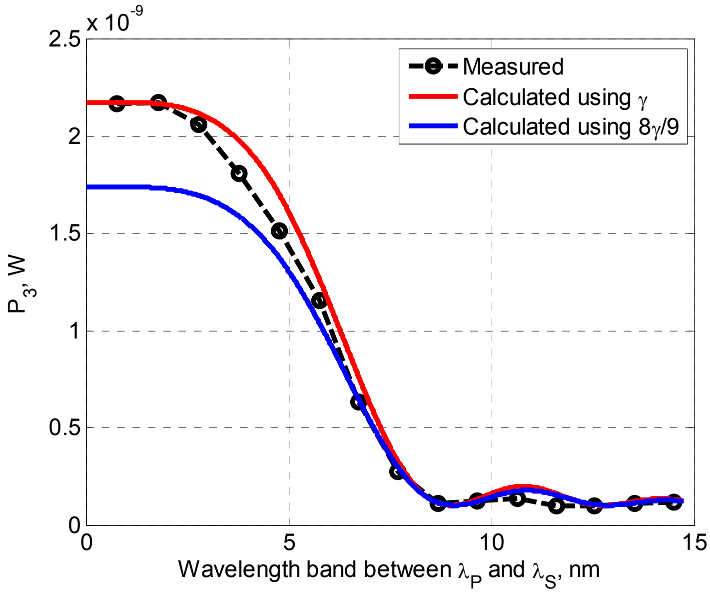

Fig. 9. Calculated and measured FWM component ($\lambda_{FWM} = 2\lambda_p - \lambda_s$) power depending on the pump (λ_p) and signal (λ_s) component wavelength difference.

Therefore, in order to incorporate the state of polarisation changes impact on the FWM components optical power into the mathematical model (6), a parameter such as effective nonlinear coefficient γ_{eff} is introduced. For a dispersion shifted fiber, changes of this parameter, by increasing the wavelength interval between the pump and signal component, is best described by a hyperbolic secant function

$$\gamma_{eff}(\Delta\lambda) = \frac{8\gamma}{9} + \frac{\gamma}{9}\operatorname{sech}\left(\frac{\Delta\lambda^{A_0}}{T_0}\right), \qquad (7)$$

where A_0 and T_0 are function argument adjustment parameters and $\Delta\lambda$ is the difference between the pump and signal component wavelengths [34].

To determine the HNLF fiber γ_{eff} change depending on $\Delta\lambda$, with the equation (6) the parameter γ was calculated given different pump and signal laser wavelength differences (see *Fig. 10.a*). On the ordinate axis, the parameter γ is represented in normalized form. The value of nonlinear coefficient in the case when the pumped and signal component wavelength difference is 0.5 nm is 10.6 $W^{-1}km^{-1}$ and it reduces to 9.4 $W^{-1}km^{-1}$ ($8\gamma/9$) at wavelength difference of $\geq$ 8 nm.

When performing the obtained parameter $\gamma(\Delta\lambda)$ approximation, it was found that also in the case of HNLF, the equation (7) most precisely describes the γ_{eff} changes depending on $\Delta\lambda$. With the iteration method, it was found that the best match is achieved in the case when the approximating function (7) coefficients: $A_0 = 2.0$ and $T_0 = 1.56\cdot10^{-17}$ [41]. Compared to the dispersion-shifted fiber (DSF), it was found that these parameters for the HNLF fiber differ (see Table 3).

Table 3.

Experimentally obtained parameters A_0 and T_0 for DSF and HNLF fibers

Fiber	A_0	T_0
DSF[34]	2.15	$5.48*10^{-19}$
HNLF	2.00	$1.56*10^{-17}$

By using the equation (6) and instead of γ insert the obtained HNLF γ_{eff} curve (see. *Fig. 10.a*), the FWM-generated harmonics power was calculated depending on the pump and signal component wavelength difference $\Delta\lambda$ (see *Fig. 10.b*).

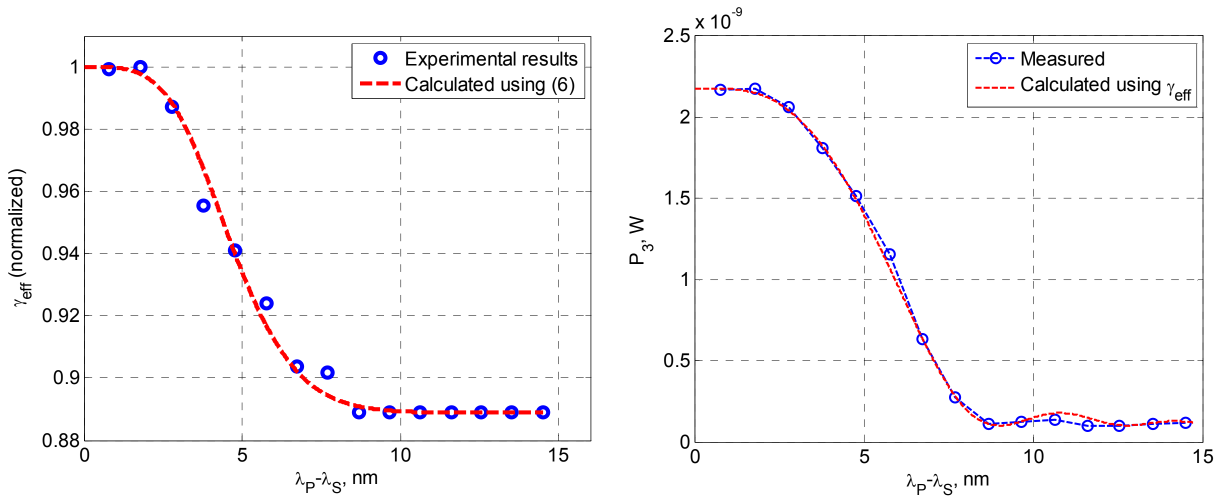

Fig. 10. a) Normalized γ_{eff} depending on $\Delta\lambda$ between the pumped and signal component.
Fig. 10. b) Measured and calculated (using γ_{eff}) FWM components power depending on $\Delta\lambda$ between the pumped and signal component.

As can be seen, using the parameter γ_{eff}, a very good match between the experimental data and the calculation data is achieved. Discrepancy can be observed only with larger wavelength differences between the pump and signal wave. It could be explained with the fact that in this region the FWM component power rapidly decreases and nears the sensitivity threshold of the OSA optical receiver. Since the studied signal power is very low (nearing -70 dBm), then it is masked with noises, which are caused by lasers and the optical amplifier, as well as by the light diode dark current.

This chapter studies the methods of measuring the nonlinear coefficient of optical fiber, by applying nonlinear effects: SPM and FWM. A description is given about the developed P-SPM measurement method, which is patented in Latvia and a comparison of results with the CW-SPM method is performed in the case of two different optical fibers. Another of the studied γ measurement methods is based on the FWM nonlinear effect. This method was used to determine the HNLF fiber parameter γ, as well as its dependence on the optical radiation polarisation was found, described with the parameter γ_{eff}. Just like for the DSF fiber, also the HNLF fiber γ_{eff} is described with a hyperbolic secant function, but the coefficients A_0 and T_0 differ at function argument $\Delta\lambda$.

Chapter 4

Chapter 4 of the thesis describes a very relevant NOE application – optical signal regeneration. Experimental 40 Gbit/s RZ OOK optical signal regeneration was performed using the Mamyshev type regenerator (MTR). In developing the regenerator, the nonlinear medium used was the HNLF fiber studied in Chapter 3 of the work. Also two different optical filters were used in the MTR block scheme to assess their impact on the regenerator functionality and to find the best possible optical signal regeneration, based on actual components parameters. The signal quality improvement is analysed comparing the regenerator input and output signal extinction ratio (ER) and the BER parameter. The study employed simulations with the computer software Synopsis OptSim 5.3, as well as actual measurements with a developed regenerator mock-up. The experimental part of the study was performed in cooperation with the Optical Communications and Photonics scientists group of the University of Aveiro at the “Optical transmission system components” laboratory led by the professor Mario F.S. Ferreira and the assoc. prof. Armando N. Pinto.

Traditionally, optical signal regeneration is performed in the electrical domain, by doing an optical/electrical transition. However, this method has a relevant shortcoming – the operation speed of electronic devices is restricted. Therefore, for high data transmission rates (≥10 Gbit/s), also other signal regeneration methods are studied. One of such methods is the use of fiber NOE in optical signal regeneration. Since fiber nonlinearity is nearly instantaneous, it occurs practically without any delay which could affect short (<0.1 ns) optical impulses [32].

The MTR regenerator functioning is based on the SPM-triggered signal spectral broadening. The regenerator’s input signal spectrum consists of the valid signal spectrum and the undesirable noise spectrum components. If the signal to be regenerated is not fully masked with noise, then the signal spectrum components power is higher than the noise components. Thus, SPM will cause a more marked signal spectrum broadening compared to the noise spectrum in the HNLF output. Therefore, to reduce the amount of noise in the signal to be regenerated, filtering is performed with a narrowband filter (filter pass bandwidth depends on the signal to be regenerated) which central wavelength do not coincide with the central wavelength of the initial signal, but it is shifted to one side by a certain wavelength band $\Delta\lambda$ (see *Fig. 11.*).

Filtering at shifted wavelength $\Delta\lambda$ ensures that the regenerator transmission function differs between the signal and the noise. If the noise power in the regenerator input signal is comparable to the signal spectral harmonic power, then signal regeneration is not possible,

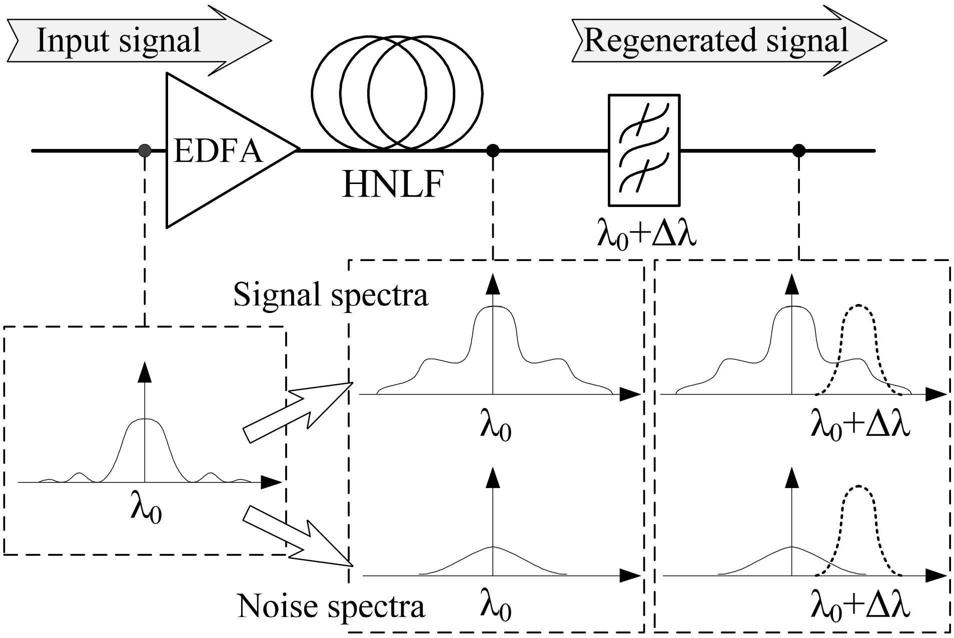

Fig. 11. The operating principle of the Mamyshev type regenerator

because the regenerator transmission function for the signal and the noise becomes identical. However, the maximum noise level is not strictly defined as it depends on the signal parameters (SPM-caused signal spectral broadening in the fiber is proportional to pulse shape describing function derivation by time) and on the regenerator block scheme and the used components parameters (amplifier power, HNLF nonlinear coefficient and dispersion, optical filter parameters).

The developed experimental regenerator scheme is presented in *Fig. 12*. It consists of three main blocks: the transmitter, regenerator, and receiver. At the transmitter output, optical signal is obtained which will then be regenerated. The bit pattern generator creates a pseudo-random binary pulse sequence. The bit transmission rate is 40 Gbit/s and the impulse code is return to zero (RZ). The pseudo-random electrical signal is fed to the Mach–Zehnder modulator (MZM), to perform continuous laser radiation amplitude modulation. The external cavity laser (ECL) was used in experiments. To achieve that the regenerator input signal had noise, the electric voltage which was fed to $LiNbO_3$ crystal was changed, thus achieving that MZM was running in a non-optimum operation mode. Thus, a distorted output signal with noise harmonics in the spectrum was obtained [42].

The transmitter part output was connected to the developed regenerator. It consists of erbium doped fiber amplifier (EDFA), which can amplify the input optical signal even up to 25 dBm, to achieve the necessary SPM-caused spectral broadening in HNLF fiber. The HNLF fiber length is 863.9 meters, the attenuation coefficient is 2.8 dB/km at 1550 nm, the zero dispersion wavelength λ_{ZD} is 1525 nm and dispersion at 1550 nm is 0.45 ps/nm/km, whereas the nonlinear coefficient 10.6 $W^{-1}km^{-1}$ [41]. An optical filter is connected to the HNLF output. Two different optical filters will be used in the developed regenerator mock-up: a fixed and a tunable filter (see the transmission functions in *Fig. 13.*). It is possible to adjust the tunable filter pass band central wavelength in a range from 1450 – 1650 nm and the pass bandwidth at -3 dB level from 0.1 – 0.7 nm. The central wavelength of the fixed filter is 1549.32 nm. Accordingly to achieve different wavelength offsets $\Delta\lambda$ a tunable laser was used in the receiver part.

Before the receiver part, a non-symmetric (20/80) optical splitter is connected to control the incoming signal power level. If the level is too high, then using a variable optical attenuator (VOA) it is reduced to the permissible optical oscilloscope input level to perform eye pattern measurements.

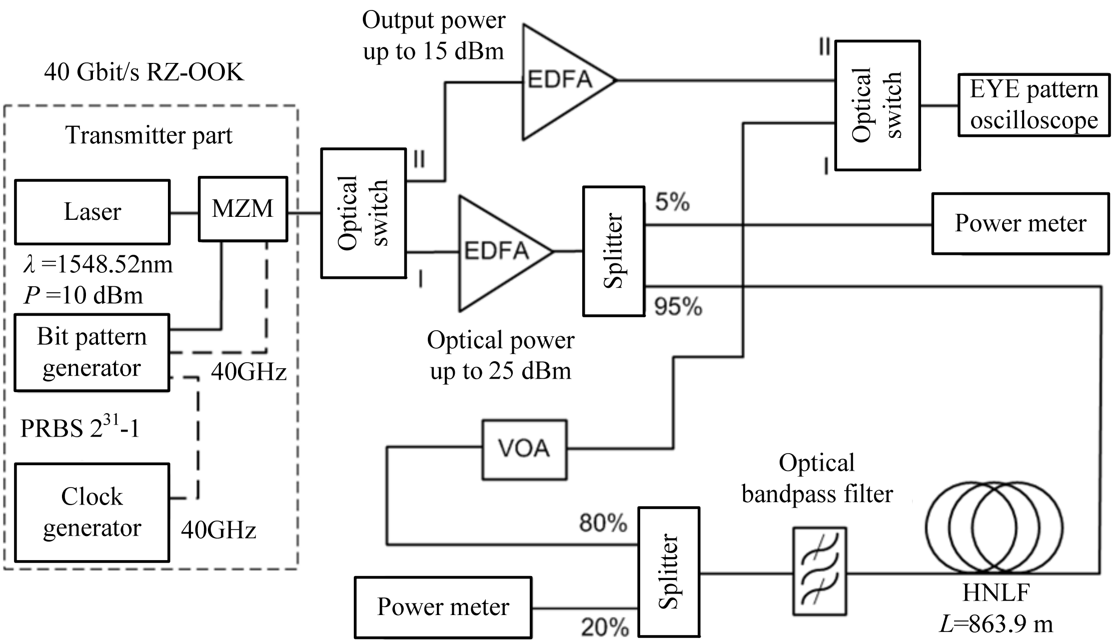

Fig. 12. Scheme of the developed experimental regenerator.

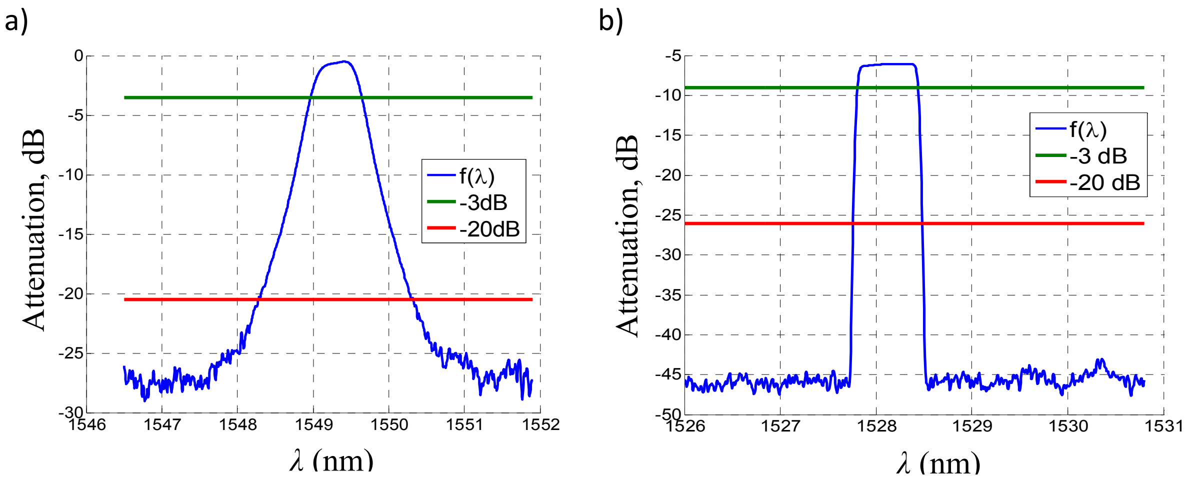

Fig. 13. Fixed (a) and tunable filter (b) transmission functions.

To find the MTR filter parameters at which the output signal quality improves, first, computer simulations were performed using the software Synopsys OptSim 5.3. Calculations are based on solving the nonlinear Schrödinger equation by employing the split-step method. Simulations were performed with a model that fully corresponds to the experimentally developed regenerator (see *Fig. 12*). Thus, the parameters of all components were set exactly as was the case for components used in experiments.

Firstly, the width of the tunable filter pass bandwidth was determined, in which the lowest BER level is obtained by filtering 40Gbit/s RZ OOK signal. The lowest filter output signal BER was obtained at the filter pass bandwidth of 0.625 nm at -3dB level. The following step was to determine the filter pass band shift from the central wavelength of the signal, at which the best optical signal regeneration is obtained. By performing computer simulations, it was found that the lowest BER for the regenerator output signal is in the case when the filter pass band is shifted from the central wavelength of the signal by 0.7 nm.

When performing experimental optical signal regeneration, the improvement of SNR and ER parameters of the regenerator output signal were evaluated in comparison with noisy input signal parameters. It was concluded from the results that the best outcome in the case of a fixed filter is when the filter shift is $\Delta\lambda$ = 0.7 nm and the EDFA output power is 100 mW, which give ER improvement by 3.1 dB and SNR improvement by 1.3 dB (see *Fig. 14*).

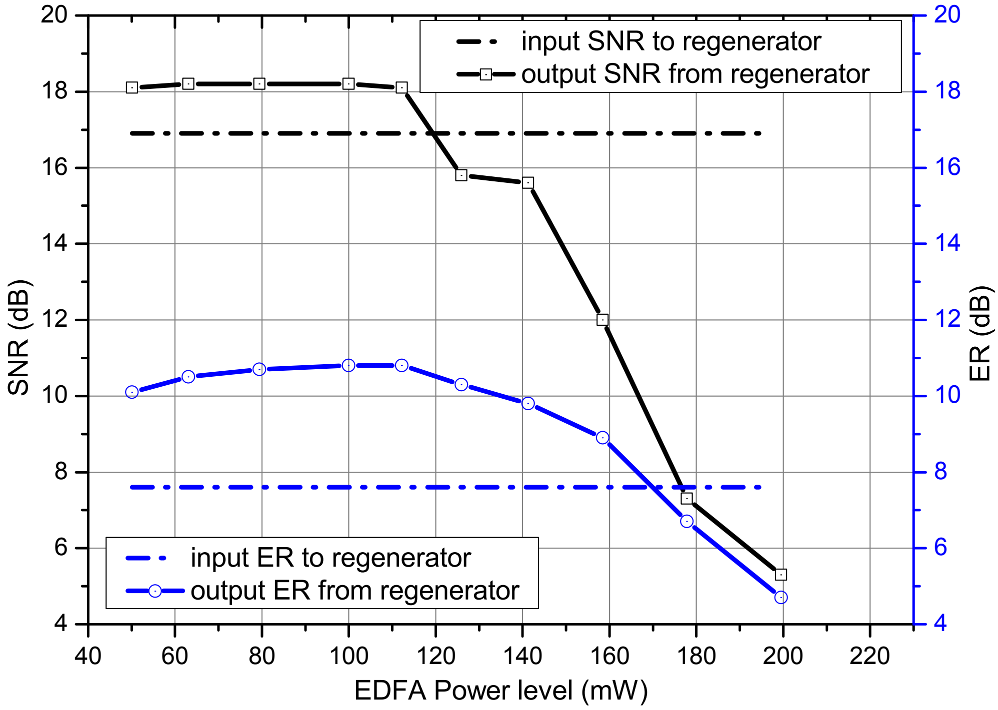

Fig. 14. Input and output optical signal ER and SNR in fixed filter case at filter shift $\Delta\lambda$=0.7 nm.

After the best MTR parameters were determined (EDFA output power and filter shift $\Delta\lambda$) with the fixed filter, the tunable filter was inserted in the regenerator block scheme. Also in this case, the best optical signal quality improvement was obtained at filter shift of $\Delta\lambda$=0.7 nm corresponding to the results obtained in computer simulations. In this case, ER improvement by 5.2 dB and SNR improvement by 2.3 dB was obtained at EDFA pump power of 100 mW (see *Fig. 15.*).

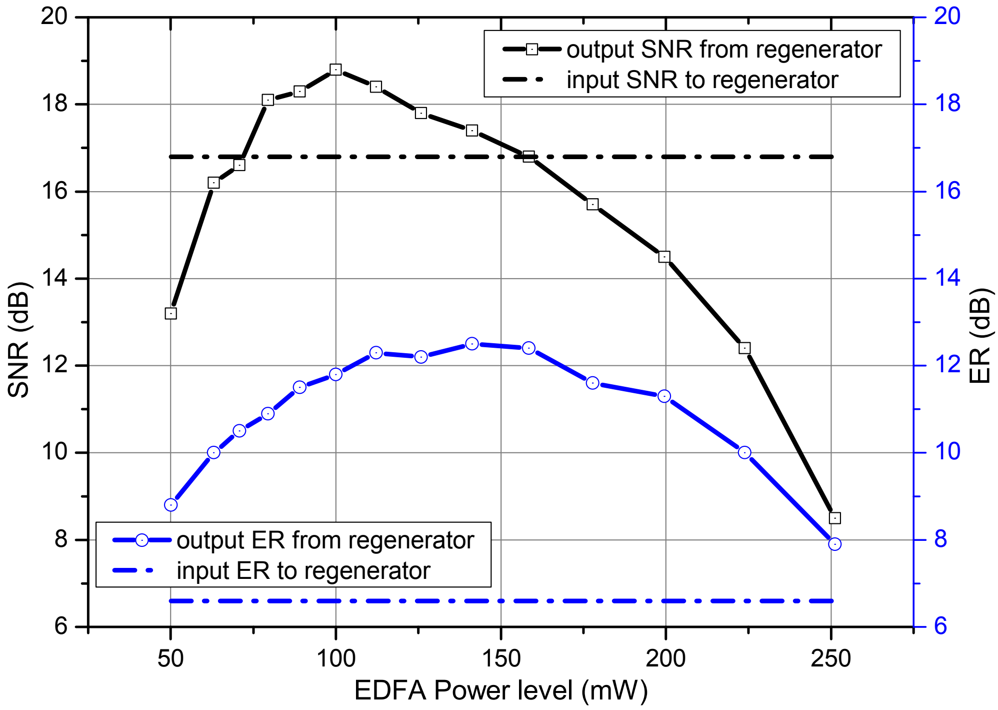

Fig. 15. Input and output optical signal ER and SNR in tunable filter case at filter shift $\Delta\lambda$=0.7 nm.

The distorted input signal eye pattern and the regenerated output signal eye pattern in the case of the tunable filter is shown in *Fig. 16*. It is evident that a SPM-based regenerator very effectively reduces noise at "zeroes", whereas the level of "ones" is lifted higher due to signal amplification, which is done before the HNLF fiber. As can be seen, the level of "ones" is still relatively noisy. It is because the regenerator is operating within wavelength range, where the used HNLF fiber features positive dispersion ($\lambda > \lambda_{ZD}$). The preferable wavelength range is where the dispersion is below zero ($\lambda < \lambda_{ZD}$), because there is no occurrence of undesirable modulation instability or nonlinear mixing between the signal and ASE noise which can bring in additional noise [19]. However, in the area, where dispersion is higher than zero ($\lambda > \lambda_{ZD}$), signal regeneration is possible, as higher pulse amplitude ensures higher ER and accordingly – also SNR.

Better regenerator results, taking into account the input and output signal ER and SNR, were obtained with the tunable filter. Compared to the fixed filter, in the case of the tunable filter, the regenerated signal ER improvement of more than 2.1 dB and SNR improvement of more than 1.0 dB was achieved. It can be explained taking into account the transmission characteristic curves of both filters used (see *Fig. 13.*). The tunable filter bandwidth at -3dB level is practically identical with the fixed filter bandwidth, but the most

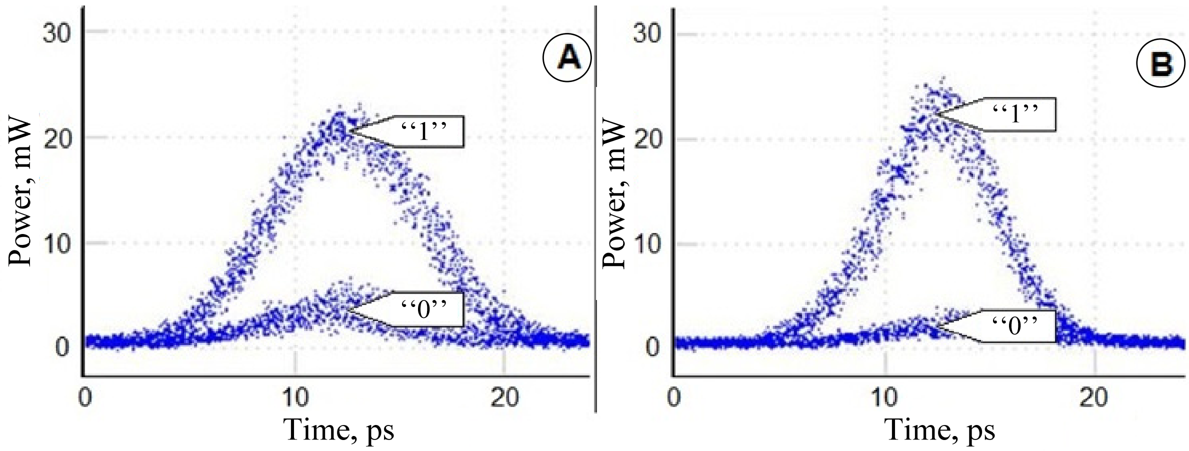

Fig. 16. Distorted optical signal in regenerator input (A) and regenerated signal in the output (B) using the tunable filter.

notable difference is observed at -20dB level, where the bandwidth is by 1.325 nm narrower than that of the fixed filter. It means that at this level, the tunable filter is more than two times narrower and the obtained regenerator transmission function is more suitable for regenerating optical signals. It proves that not only the filter shift from signal central wavelength $\Delta\lambda$, but also the filter transmission characteristic curve has a significant impact on the regenerator functioning [42].

Higher ER and SNR values could be obtained by using multiple signal regeneration or creating a regenerator cascade connection. With such a connection, it can also be achieved that the output optical signal wavelength is the same as the input signal, by performing filtering to initial wavelength in the second phase. It is possible because the SPM spectral broadening is symmetrical.

THE MAIN RESULTS OF THE PROMOTION WORK

The **main results and conclusions of the promotion work** obtained during fulfilment of the tasks defined in Chapter 1 are as follows.

1. Upon comparing the obtained A_{eff} results between calculations with the plane wave superposition method, infrared CCD camera, and transverse shift method for a single mode fiber corresponding to the ITU-T recommendation G.652 D, it was found that the results of the experimental transverse shift measurements are reliable as all results fell within the boundaries of the error margin (+/- 1μm^2);
2. If the optical fiber refractive index profile is not given, then A_{eff} calculations with the plane wave superposition method are not feasible. In this case, measurements must be used to determine A_{eff};
3. With the experimental transverse shift method, it was found that the EDF fiber A_{eff} in the wavelength range from 1470 to 1575 nm increases by 1.1 μm^2. However, in the case of the single mode fiber, it was determined that A_{eff} increases by 4.4 μm^2 in the wavelength range from 1520 to 1580 nm which is due to the refractive index dependence on the wavelength. Thus, it can be concluded that the nonlinear coefficient of the optical fiber decreases as the optical signal wavelength increases, because optical radiation intensity decreases;
4. With the developed P-SPM method, a much broader spectral expansion was achieved than with the CW-SPM method for both G.652 D and G.655 C type fiber. Thus, the calculated coefficient γ for both fibers was higher ($\Delta\gamma$=0.07 or by 8%) in the case of P-SPM. It indicates to the fact that a pulsed optical signal better triggers the emergence of SPM in a fiber. Moreover, in the case of CW-SPM method, the impact of the stimulated Brillouin scattering on the measurement process must be accounted for;
5. With the experimental γ measurement method based on FWM, it is possible to determine the fiber γ and γ_{eff}, which points to the impact of fiber polarisation mode dispersion on FWM. In the case of HNLF fiber, just like that of DSF fiber, the γ_{eff} change depending on the pump and signal laser wavelength difference, is best described with the hyperbolic secant function. However, coefficients A_0 and T_0 differ at function argument Δλ, which in the case of HNLF is: A_0 =2.0 and T_0 =1.56·10^{-17};
6. With the computer programme Synopsis RSoft OptSim 5.3 achieved optical filter pass band shift from the central wavelength of signal ($\Delta\lambda$=0.7 nm) fully matched the experimentally obtained results in the case of fixed and tunable filter alike;
7. The best optical signal regeneration result was obtained with the tunable optical filter at EDFA output power of 100mW and the optical filter pass bandwidth of 0.625 nm, shifted from the central wavelength of the signal by 0.7 nm. The signal ER improvement by 5.2 dB and SNR – by 2.3 dB. Upon comparison of results between the signal regeneration with the fixed and tunable filter, it was found that the regenerator with a tunable filter the regenerated signal ER is higher by 2.1 dB and SNR – by 1.0 dB.

In conclusion, it must be emphasised that the studied effective area and nonlinear coefficient measurement methods may be used for evaluating SiO_2-based optical fibers – both new and currently used. Within the framework of the cooperation agreement, the topicality of measuring the nonlinear coefficient of optical fibers is included also in the assessment for VAS “Latvijas Valsts Radio un Televīzijas Centrs”: “Assessment of backbone network technologies and main design trends”. New functionality is also developed: 40 Gbit/s RZ OOK signal shape regeneration completely in the optical domain using on HNLF-fiber based Mamyshev type regenerator. It enables improving the rate of operation of optical communication systems and increasing the maximum transmission distance.

During the studies, several patents have been prepared as well. The developed γ parameter measurement scheme, in which SPM is triggered with NRZ-OOK optical signal with the bit transmission rate of 10 Gbit/s, which corresponds to the hierarchy level STM-64 (9953.28 Mbit/s) of synchronous digital hierarchy data transmission rate has received the Latvian patent No. LV-14296. Approvals have been received also in the case of two European patent applications regarding a new structure optical fiber connector and a scheme for measurements of stimulated Brillouin scattering threshold power.

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