RIGA TECHNICAL UNIVERSITY
Faculty of Electronics and Telecommunications
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Investigation of Parametric and Hybrid Amplifier Applications in WDM Transmission Systems

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Economics, is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Sergejs Olonkins ……………………………. (Signature)

Date:

The Doctoral Thesis has been written in the Latvian language. It contains an Introduction, 4 Chapters, Conclusion, Bibliography with 130 reference sources, and 2 appendices. It has been illustrated by 54 figures. The volume of the present Doctoral Thesis is 147 pages.

PATEICĪBA

Izsaku pateicību promocijas darba vadītājam profesoram Vjačeslavam Bobrovam, par vērtīgajiem padomiem, ieteikumiem un rādīto motivāciju promocijas darba izstrādes gaitā. Paldies arī profesoriem Ģirtam Ivanovam un Jurģim Poriņam par palīdzību promocijas darba izstrādes sākuma. Īpašo pateicību gribētos izteikt saviem kolēģiem un telpas telpas biedriem Andim Supem, Aleksejam Udaļcovam un Sandim Spolītim un Oskaram Ozoliņam, ar kuriem man bija gods strādāt kopā doktorantūras laikā. Paldies jums par draudzīgo atmosfēru, padomiem un atbalstu, kas viennozīmīgi sekmēja šī darba izstrādi.

No sirds pateicos savai ģimenei: tēvam Valerijam, mātei Irinai un māsai Ekaterinai. Bez jūsu palīdzības, atbalsta un mīlestības man tas nebūtu izdevies.

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LIST OF ABBREVIATIONS

A

ASE — Amplified Spontaneous Emission

AWG — Arrayed Waveguide Grating

B

BER — Bit Error Rate

C

CC-FWM — Channel-Channel Four-Wave Mixing

CW — Continuous Wave laser

CWDM — Coarse Wavelength Division Multiplexing

D

DCF — Dispersion Compensating Fibre

DFA — Doped Fibre Amplifier

DRA — Distributed Raman Amplifier

DWDM — Dense Wavelength Division Multiplexing

E

EDFA — Erbium Doped Fibre Amplifier

EYE — Eye Diagram Oscilloscope

F

FBG — Fibre Bragg Grating

FOPA — Fibre Optical Parametric Amplifier

FWHM — Full Width Half Maximum

FWM — Four-Wave Mixing

H

HDWDM — High Density Wavelength Division Multiplexing

HNLF — High Non-Linearity Fibre

L

LRA — Lumped Raman Amplifier

M

MZM — Mach-Zehnder Modulator

N

NF — Noise Figure

NRZ — Non-Return-to-Zero

O

OOK — On-Off Keying

OSNR — Optical Signal-Noise Ratio

P

PC-FWM — Pump-Channel Four-Wave Mixing

PMD — Polarization Mode Dispersion

PolSK — Polarization Shift Keying

PON — Passive Optical Network

R

RIN — Relative Intensity Noise

RX — Receiver

S

SBS — Stimulated Brillouin Scattering

SMF — Single Mode Fibre

SOA — Semiconductor Optical Amplifier

SOP — State of Polarization

SRS — Stimulated Raman Scattering

T

TDM — Time Division Multiplexing

TX — Transmitter

W

WDM — Wavelength Division Multiplexing

Z

ZDWL — Zero Dispersion Wavelength

Topicality of the Theme

Over the last two decades, a rapid expansion of the amount of information to be transferred has been observed. This tendency is explained by the rapid increase of Internet and other service users, as well as with the increasing availability of these services. This rapid growth in the amount of globally transmitted data is also associated with the expansion of the range of services offered, including such resource-consuming services as high resolution video transmission, video-conferencing and cloud computing, as well as with increasing popularity of such services [1]–[5].

According to the latest Cisco forecast, the total amount of global IP traffic in 2016 will reach 1.1 zettabytes, whereas in 2018 — 1.6 zettabytes. The forecasted increase in the monthly transferrable IP traffic over the period from 2013 until 2018 is shown in *Fig. 1.a*. Studies performed by Cisco show that in comparison with 2012 the amount of Internet traffic transferred in the peak hours in 2013 increased by 32 %, whereas the average daily volume of transferrable Internet traffic increased by 25 % [6]. If this tendency remains, then in 2018 the volume of transferrable Internet traffic during the peak hours will reach 1 petabit per second, whereas the daily average will reach 311 terabits per second [6], [7]. According to Bell Labs forecast, the results of which are shown in *Fig. 1.b*, during the period from 2012 until 2017, the increase of traffic in backbone networks will reach 320 %, whereas in metro networks — 560 % [8].

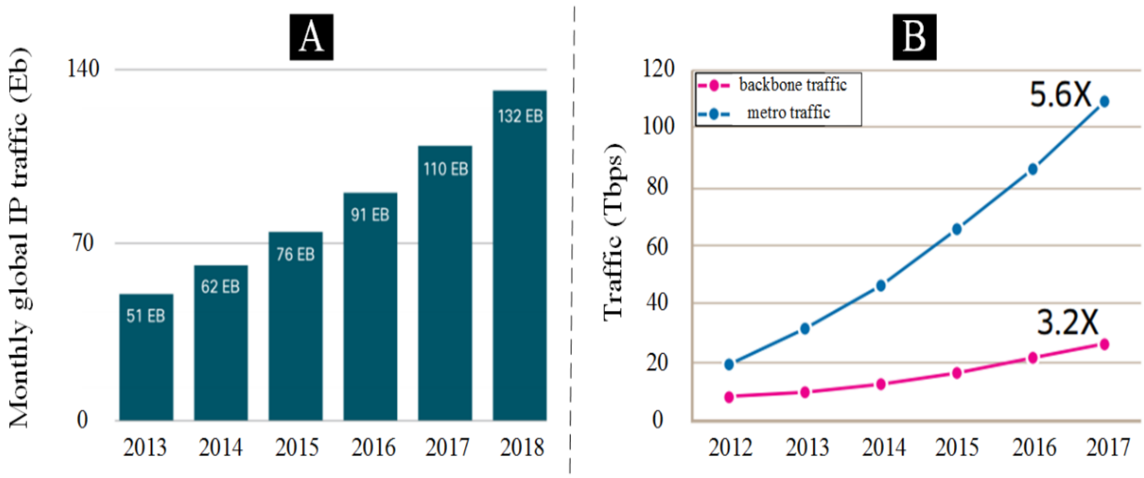

Fig. 1. Cisco forecast of the monthly transferrable IP traffic (a), and Bell Labs forecast of the transferrable data amount in backbone and metro networks (b) [6], [8].

To satisfy this constantly increasing demand for higher network capacity, fibre optical transmission systems have been studied and applied with a growing intensity [9], [10]. Currently optical transmission systems with wavelength division multiplexing (WDM) have attracted much attention, as this technology allows using the available optical fibre resources more effectively than alternative technologies [11]–[14].

It is possible to increase the WDM system throughput capacity either by increasing the data transmission speed in channels or the number of channels. The wavelength band that is used for transmission in WDM systems is limited due to the wavelength dependence of optical signal attenuation in optical fibres [15], [16]. In modern transmission systems, the minimum attenuation of single-mode optical fibres is 0.2 dB per kilometre, and it is observed in the “C” wavelength band, which corresponds to wavelengths from 1530 to 1565 nm. Regardless of the fact that the attenuation value is so low, its impact accumulates with every next kilometre. In long-haul transmission systems, where transmission lines are several hundred and even thousand kilometres long, the attenuation substantially degrades the quality of the received signal, as the photodetector sensitivity is limited [17]–[19]. As the number of channels increases, the attenuation caused by the optical signal division also increases, especially in cases where power splitters are used [20]. However, by increasing the speed of data transmission, it becomes necessary to reduce the optical noise produced by optical components (light sources, modulators, amplifiers, receivers etc.), as higher transmission speed signals have lower noise immunity.

Therefore, solutions are needed for compensating the ever-increasing accumulated signal attenuation in an ever-broader wavelength range. Currently, erbium doped fibre amplifiers (EDFAs) are most commonly used around the globe for compensation of optical signal attenuation. The amplification bandwidth of EDFAs is strictly limited (for conventional EDFA solutions, it is only 35 nm), which restricts the wavelength range used for the transmission in existing systems [21]–[23]. It is, thus, necessary to seek for new solutions to amplifying optical signals and for opportunities of expanding the range of amplified wavelengths and increasing the attainable amplification level for the already existing optical signal amplification solutions. This can be achieved by combining amplifiers of various types. In such a way, it is possible to combine the positive properties and partly compensate the drawbacks of different types of amplifiers.

During recent years, the need to increase transmission capacity of existing optical networks together with requirements for reducing the total cost of construction and maintenance of optical networks has induced increasing interest in all-optical signal processing [24]–[27]. In contrast to solutions with optical-electrical-optical (O/E/O) signal conversion, which induces the so-called “bottlenecks” in optical transmission systems, all-optical signal processing is performed in real time, while the signal is transmitted through a nonlinear medium [28]. Therefore, all-optical signal processing allows avoiding the part of transmission capacity limitation that is caused by O/E/O signal conversion.

The progress in nonlinear material research has resulted in commercial production of optical fibres and other components with high values of the nonlinear coefficient. Therefore, the optical power, required to initiate fibre nonlinearities, has become lower [26]. Fibre nonlinearity is the main mechanism that is used for all-optical signal processing. Optical amplifiers are the only optical devices capable of rising the power of optical signal high enough to induce manifestation of nonlinear effects during transmission. That is why the usage of optical amplifiers for all-optical signal processing purposes has been intensively studied all over the world during recent years, and various applications of optical amplifiers have been demonstrated [24]–[27], [29]–[31].

The Aim and Tasks of the Thesis

Upon summing up the aforementioned facts, **the aim of the Doctoral Thesis** is proposed: to assess the applications of hybrid optical amplifiers for improving the operations of SOA and EDFA optical amplifiers in WDM transmission systems, as well as to explore the possible applications of parametric amplifiers for all-optical signal processing.

To achieve the set aim, the following **main tasks** have to be performed:

1. To assess the possibilities of usage of hybrid amplifiers for compensating the deficiencies of EDFA and SOA optical amplifiers;
2. To perform equalisation of EDFA gain spectrum and to increase the optical signal-to-noise ratio at the amplifier output by implementing a hybrid Raman-EDFA solution;
3. To reduce the noise generated by SOA and to increase the attainable transmission distance by implementing a hybrid Raman-SOA solution;
4. To assess the potential of using the single-pump and dual-pump fibre optical parametric amplifier in the processing of optical signals;
5. To develop a multicarrier source with even distribution of optical power and channel spacing, using a fibre optical parametric amplifier;

6. To assess all-optical modulation format conversion from 2-POLSK to NRZ-OOK by using a parametric amplifier with one linearly polarised pumping radiation;
7. To emphasise an optical signal from a polarization multiplexed optical flow using a fibre optical parametric amplifier with one linearly polarised pumping radiation.

Research Methodology

In this Doctoral Thesis, the analysis of problems and the proposed tasks have been performed using mathematical calculations and numerical simulations, as well as doing experimental measurements. The results of numerical simulations have been obtained by using the non-linear Schrödinger equation, as well as with the direct and inverse discrete fast Fourier transform. In simulations, the non-linear Schrödinger equation calculations have been performed using the time domain split step method. For defining the bit-error ratio, the Monte Carlo method has been applied. For configuring the optical amplifiers and assessing their parameters, optical power values, power spectra and received signal eye diagrams, as well as bit-error ratio values have been obtained. For evaluating the performance of the proposed solutions in WDM transmission systems, the highest bit-error ratio among all channels or the worst channel of the system has been used. To verify the accuracy of numerical simulation results, the experimental model with two EDFA amplifiers has been created in laboratory conditions, which has been replicated in the used simulation environment. As result, a comparison has been performed among the obtained spectra, power, and eye diagrams.

The Results and Scientific Novelty of the Research

The scientific novelty of the Doctoral Thesis:

1. A dual-pump fibre optical parametric amplifier, insofar as known to the author, has been used for the first time for creating a multi-channel source in WDM transmission systems, to double the number of channels (in the proposed solution from 16 to 32) with an even inter-channel interval and the power level difference between the channels of less than 2 dB.
2. A single-pump fibre optical parametric amplifier with linearly polarised pumping radiation has been used for emphasising orthogonally polarised optical light for the first time, which can be used for 2PolSK signal conversion to NRZ-OOK modulation format, as well as for emphasising a signal with a certain state of polarisation from the overall polarisation multiplexed optical flow.

During the implementation of the Doctoral Thesis the following **main conclusions** have been reached:

1. The implementation of the hybrid Raman-EDFA amplifier has allowed not only equalising the gain spectrum, but also increasing OSNR in all channels by 1.7–2.6 dB. The usage of the distributed Raman amplifier in cascade as a pre-amplifier has allowed the EDFA to operate closer to the saturation point and, therefore, the EDFA noise figure decreased by 0.3–0.4 dB. The OSNR increase is also related to the fact that due to the coherent nature of Raman scattering, DRA amplifies the signal more effectively than the noise, which allows obtaining negative noise figure values (from –0.4 to –0.6 dB);
2. The implementation of the hybrid Raman-SOA amplifier has enabled the use of such SOA configuration, at which SOA produced the lowest amount of amplified signal distortions. As a result, by using the Raman-SOA hybrid amplifier, it is possible to obtain approximately the same BER level as in the case when the SOA is used as a single in-line amplifier for a signal, which is weaker by 1.5 times. This has allowed increasing the attainable transmission distance by 12 km or by 11 %;
3. While changing the power of FOPA pumping radiation, the non-linear phase mismatch of the parametric process also changes. Therefore, while configuring the pump power, the wavelength must also be changed accordingly;

4. Modulating of the FOPA pumping radiation phase, which has been used for increasing the SBS threshold, has caused spectral expansion of idlers by 54 %. Therefore, the frequency tones used in systems with wavelength conversion for pumping radiation phase modulation must be selected in a way that ensures that the spectral expansion of idlers remains as low as possible;
5. By manipulating with the parameters of dual-pump FOPA, it is possible to achieve an increase in the number of carrier signals from 16 to 32, simultaneously ensuring equal channel spacing of 100 GHz and maximum difference in power levels of 1.9 dB among all channels. It has been found that, in case when each carrier signal power at the input of the FOPA is equal to 0 dBm, the CC-FWM interactions produce considerable inter-channel crosstalk. Due to this reason, when using the idlers to double the number of carriers, it is necessary to control the power of carrier signals in the amplifier input;
6. It has been found that even when using polarisation maintaining HNLF fibres, due to the influence of self-phase modulation and cross-phase modulation, a change in interposition of SOP of the signal and FOPA pumping radiation has been observed, as they are transmitted through HNLF. As result, the signal, the SOP of which is orthogonal in respect to the SOP of the pumping radiation at HNLF input, has been amplified by 1.5–1.6 dB;
7. In a single-channel system with 2PolSK signal conversion to NRZ-OOK modulation format, power penalty of 0.4 dB has been observed between the NRZ-OOK signal from the standard single-channel system and the converted signal. Whereas, in the case of the idler spectral component, the power penalty is lower by 0.2 dB. These results can be explained by the fact that the idler produced by the parametric FWM process does not contain the logical "0" component radiation from initial 2PolSK signal, which for the converted NRZ signal is interpreted as noise;
8. In the multi-channel system with modulation format conversion, a more explicit manifestation of CC-FWM processes has been observed among the idlers rather than among channels at initial frequencies. This can be explained by the fact that pump power exceeding 35 mW is required to obtain BER values below the 10^{-12} threshold in all 8 channels in the idler frequency band than for signals at their initial frequencies. As a result of such amplification difference, more explicit CC-FWM manifestation has been observed, which accordingly has led to additional inter-channel crosstalk. Additionally, crosstalk generated by CC-FWM has not only been transferred to the idlers from the signals at their initial frequencies, but also generated among the idlers;
9. Unlike the system with modulation format conversion, in the system with signal emphasising from the flow of two orthogonally polarised signals, a situation is observed, when at the same frequency it is possible that the logical "1" components are observed in both channels simultaneously. Therefore, the influence of orthogonally polarised radiation on the quality of the emphasised signal is larger by 0.4 dB (in the case of idlers, by 0.3 dB) than in a system with modulation format conversion.

Practical Value of the Doctoral Thesis:

1. The results of scientific research conducted within the present Doctoral Thesis have been used in implementation of two international (ESF and ERDF), one Latvian, and one RTU scientific research projects;
2. Within the framework of the Co-operation Agreement, the activity on increasing the efficiency of optical signal amplification in fibre optical transmission systems has been included in the project prepared for the SJSC "Latvijas Valsts Radio un Televīzijas Centrs" — "Assessment of Backbone Network Technologies and the Main Tendencies of Their Design" (ERDF project No. 3DP/3.2.2.3.0/12/IPIA/SM/001 "Development of Next Generation Broadband Electronic Communications Networks in Rural Areas");

3. One Latvian patent application has been filed for the development of a multi-channel light source in a fibre optic access transmission system with wavelength division multiplexing. The patent application number is P-15-45.

The Thesis Statements to be Defended

1. Implementation of hybrid amplification solutions can cause an increase in the optical signal to noise ratio in WDM transmission systems up to 3 dB for every channel, which allows increasing the attainable transmission distance and reducing the bit-error ratio.
2. By using the idler generating property of the parametric amplifier, the number of channels can be doubled in the transmitter block in WDM transmission systems.
3. Signal conversion from polarisation binary shift keying to NRZ-OOK modulation format can be achieved by using the parametric amplifier with linearly polarised pumping radiation.
4. By using a parametric amplifier with linearly polarised pumping radiation, it is possible to perform optical signal emphasising in systems with polarisation multiplexing.

Approbation of Results

The main results of the Doctoral Thesis have been presented in **10** international scientific conferences, as well as in **4** publications in scientific journals, **6** publications in full-text conference proceedings, **3** articles in conference books of abstracts, and **one** Latvian patent application.

Participation in International Scientific Conferences:

1. **Olonkins S.**, Bobrovs V., Ivanovs Ģ. *Comparison of Semiconductor Optical Amplifier and Discrete Raman Amplifier Performance in DWDM Systems* // Electronics and Electrical Engineering, Lithuania, Palanga, June 18–20, 2012.
2. **Olonkins S.**, Bobrovs V., Poriņš J. *Comparison of Co and Counter-propagating Raman Amplification in Nonlinearity Sensetive DWDM Transmission Systems* // Developments in Optics and Communications 2012, Latvia, Riga, April 12–14, 2012.
3. **Olonkins S.**, Bobrovs V., Ozoļiņš O., Poriņš J., Lauks G. *Hybrid Optical Amplifiers for Flexible Development in Long Reach Optical Access Systems* // IV International Congress on Ultra-Modern Telecommunications (ICUMT 2012), Russia, Saint Petersburg, October 3–5, 2012.
4. **Olonkins S.**, Bobrovs V. *Implementation of FOPA with Pimp Phase Modulation for an 8 Channel DWDM Transmission System* // Developments in Optics and Communications 2013, Latvia, Riga, 10 April 2013.
5. **Olonkins S.**, Bobrovs V., Ivanovs Ģ. *Investigation of Fiber Optical Parametric Amplifier Performance in DWDM Transmission Systems* // Electronics and Electrical Engineering, Lithuania, Palanga, 19 June 2013.
6. **Olonkins S.**, Ozoliņš O., Bobrovs V., Poriņš J., Ivanovs Ģ. *Binary PolSK to OOK Modulation Format conversion in Single-Pump FOPA for Optical Access Networks* // Fiber Optics in Access Networks 2013, Kazahstan, Almati, 11 September 2013.
7. **Olonkins S.**, Supe A., Ļašuks I, Poriņš J. *Demonstration of Binary PolSK to OOK Modulation Format Conversion Using a Single-Pump Fiber Optical Parametric Amplifier* // International Symposium on Communication Systems, Networks & Digital Signal Processing 2014, United Kingdom, Manchester, 25 June 2014.
8. **Olonkins S.**, Ļašuks I., Poriņš J. *Demonstration of Polarization Muiltiplexed Signals Division Using a Fiber Optical Parametric Amplifier* // Progress in Electromagnetics Research Symposium (PIERS 2014), China, Guangzhou, August 25–28, 2014.
9. **Olonkins S.**, Spolītis S., Ļašuks I., Bobrovs V. *Cost Effective WDM-AON with Multicarrier Source Based on Dual-Pump FOPA* // International Congress on Ultra- Modern Telecommunications (ICUMT 2014), Russia, Saint Petersburg, October 6–8, 2014.

10. **Olonkins S.**, Bobrovs V. *Implementation of Fiber Optical Parametric Amplifier for Distinguishing of Polarization Multiplexed Signals in Optical Transmission Systems* // Advanced Optical Materials and Devices (AOMD8), Latvia, Riga, August 25–27, 2014.

Publications in **scientific journals**:

1. **Olonkins S.**, Bobrovs. V., Ivanovs Ģ. **Comparison of Semiconductor Optical Amplifier and Discrete Raman Amplifier Performance in DWDM Systems** // Electronics and Electrical Engineering, 2012, Vol. 123, Iss.7, pp. 133–136, ISSN 1392-1215**.**
2. Ivanovs Ģ., Bobrovs V., **Olonkins S.**, et al. **Application of the Erbium-Doped Fiber Amplifier in Wavelength Division Multiplexing (WDM) Transmission Systems** // International Journal of Physical Sciences (IJPS), Vol. 9 Iss. 5, pp. 91–101, ISSN 1992–1950.
3. Bobrovs V., **Olonkins S.**, Ivanovs Ģ., Poriņš J. **Comparative Performance of Raman-SOA Hybrid Optical Amplifiers in DWDM Transmission Systems** // Latvian Journal of Physics and Technical Sciences, 2012, No.6, pp. 41–54, ISSN 0868–8257.
4. **Olonkins S.**, Bobrovs V., Ivanovs G. **Investigation of Fiber Optical Parametric Amplifier Performance in DWDM Transmission Systems** // Electronics and Electrical Engineering, 2014, Vol.20 Iss. 1, pp. 88–91, ISSN 1392-1215.

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

1. **Olonkins S.**, Bobrovs V., Ozoļiņš O., Poriņš J., Lauks G. **Hybrid Optical Amplifiers for Flexible Development in Long Reach Optical Access Systems** // IV International Congress on Ultra-Modern Telecommunications (ICUMT 2012), (ISBN: 978-1-4673-2017-7), October 2012, pp. 605–610.
2. **Olonkins S.**, Ozoliņš O., Bobrovs V., et al. **Binary PolSK to OOK Modulation Format Conversion in Single-Pump FOPA for Optical Access Networks** // 4th International Workshop on Fiber Optics in Access Networks (FOAN 2013), (ISBN: 978-1-4799-1502-6), September 2013, pp. 15–20.
3. **Olonkins S.**, Ļašuks I., Poriņš J. **Demonstration of Polarization Multiplexed Signals Division Using a Fiber Optical Parametric Amplifier** // Progress in Electromagnetics Research Symposium (PIERS 2014), August 2014, pp. 1669–1673, (ISBN 978-1-934142-28-8).
4. **Olonkins S.**, Spolitis S., Ļašuks I., Bobrovs V. **Cost Effective WDM-AON with Multicarrier Source Based on Dual-Pump FOPA** // 6th International Congress on Ultra-Modern Telecommunications and Control Systems and Workshops (ICUMT 2014), October 2014, pp. 23–28.
5. **Olonkins S.**, Supe A., Ļašuks I., Poriņš J. **Demonstration of Binary PolSK to OOK Modulation Format Conversion Using a Single-Pump Fiber Optical Parametric Amplifier** // 9th International Symposium on Communications, Systems, Networks and Digital Signal Processing (CSNDSP 2014), June 2014, pp. 955–959.
6. Spolitis S., **Olonkins S.**, Poriņš J. **Realization of Dense Bidirectional Spectrum Sliced WDM-PON Access System** // 9th International Symposium on Communications, Systems, Networks and Digital Signal Processing (CSNDSP 2014), July 2014, pp. 552–557.

Publications in **conference books of abstracts**:

1. **Olonkins S.**, Ivanovs Ģ. **Comparison of Co and Counter-propagating Raman Amplification in Nonlinearity Sensitive DWDM Transmission Systems** // Developments in Optical Communications 2012, (ISBN 978-9984-49-518-7), April 2012, pp. 82–83.

2. **Olonkins S.**, Bobrovs V. **Implementation of FOPA with Pump Phase modulation for an 8 Channel DWDM Transmission System** // Developments in Optics and Communications 2013, (ISBN: 978-9984-49-518-7), April 2013, pp. 34–35.
3. **Olonkins S.**, Bobrovs V. **Implementation of Fiber Optical Parametric Amplifier for Distinguishing of Polarization Multiplexed Signals in Optical Transmission Systems** // Advanced Optical Materials and Devices 2014, (ISBN 978-9934-51-758-7), August 2014, pp. 27–28.

Latvian **patent**:

Using the results that are described in the present Doctoral Thesis, one Latvian patent application has been prepared: "Wavelength Division Multiplexed Fibre Optical Access Transmission System with a Multicarrier Light Source".

The results of the present Doctoral Thesis have been used for implementation of 2 international (ESF and ERDF) and 2 Latvian scientific research projects:

International scientific research projects:
1. ERDF project "Development of High-Speed Optical Access Networks and Elements" (activity "Support to Science and Research"), Nr. 2010/0270/2DP/2.1.1.1.0/10/APIA/VIAA/002;
2. ESF project "Smart Urban Technologies for Improving the Life Quality", No. 2013/0008/1DP/1.1.1.2.0/13/APIA/VIAA/016.

Latvian scientific research projects:
1. "Active Combined Wavelength Division Multiplexed Fibre Optic Transmission System", RTU, No. ZP-2014/19;
2. "Technologies for a Secure and Reliable Smart City", NRP, No.10-4/VPP-4/11.

The Scope and Structure of the Doctoral Thesis

The volume of the Doctoral Thesis is 147 pages. The Thesis consists of the introduction, four chapters, bibliography, and two appendices. The introduction covers the topicality of the performed research and the study directions of the Doctoral Thesis are defined.

In the first chapter of the Thesis, operations of EDFA, SOA, Raman and Brillouin optical amplifiers are studied, characteristics of these types of amplifiers are compared. The chapter concludes with the formulation of aim and tasks of the Doctoral Thesis, and afterwards its novelty, thesis statements to be defended, and the key results are summarised.

In the second chapter of the Thesis, the potential of using EDFA, SOA and Raman amplifiers for implementation of hybrid optical amplifiers is analysed. Thereafter, simulation models of transmission systems with Raman-EDFA, and Raman-SOA hybrid amplifiers are introduced using OptSim simulation software. The Raman-EDFA hybrid amplifier is implemented for equalising the EDFA gain spectrum and increasing OSNR at the output of the amplifier, but in the case of the hybrid Raman-SOA solution — for reducing the amount of signal distortion caused by SOA and for increasing the attainable transmission distance.

The third chapter of the Thesis includes an analysis of operations of single-pump and double-pump parametric amplifiers and definition of the factors that affect their performance. A multi-channel WDM transmission system model is introduced, in which the signal is amplified using a single-pump FOPA and the performance of this amplifier is assessed. Afterwards, a multicarrier source model is introduced based on a dual-pump FOPA. A Latvian patent application has been submitted for this multicarrier source model. Idler spectral components produced by such use of the parametric amplifier has been introduced for the first time.

In chapter four, the polarisation dependence of the parametric gain and its applicability in optical signal processing are discussed. Simulation models of a single channel and multi-channel systems are introduced, where the single-pump FOPA linearly polarised pumping radiation is used for converting a signal with polarisation binary shift keying to NRZ-OOK modulation format, and an assessment of performance of the provided solutions is performed. Afterwards, the use of a single-pump FOPA with linearly polarised pumping radiation emphasising optical signal from a flow of two polarisation multiplexed signal is introduced and assessed. Insofar as known to the author, both potential applications of FOPA described in this chapter have been examined and described for the first time.

In the summary, the main conclusions are presented. The appendices include lists of conferences, publications, and projects.

DETAILED DESCRIPTION OF THE THESIS CHAPTERS

Chapter I

Amplification of optical signals is based on the energy transfer from pumping optical radiation or another type of energy to the amplifiable optical signal. This process is implemented differently in various types of optical amplifiers. In general, the amplification process uses the stimulated emission phenomenon in the amplification environment, such as, for instance, semi-conductor optical amplifiers or doped fibre optical amplifiers. Furthermore, such non-linear optical effects as Raman, Brillouin and four-wave mixing are used to amplify optical signals in cases of Raman, Brillouin and parametric optical amplifiers, respectively [32].

The mechanism of amplifying optical signals is based on occurrence of stimulated light emission in the gain medium. The light emission phenomenon can be explained using the Rutherford-Bohr atomic model. Bohr has stated that atoms may jump from one energy state to another, by performing what is known as the quantum jump, corresponding to a change of orbit. This orbit change requires a change in the energy level; therefore, if the atom jumps from the higher energy state to the lower energy state, it will produce a photon. A photon contains energy, which corresponds to the difference between the initial higher energy level and lower occupied level energy, as the overall energy of the process must remain unchanged. This assumption derives from the law of conservation of energy [33]. Thus, photon energy can be determined according to the following equation [34]:

$$E_{photon} = E_2 - E_1 = hv_{photon}, \tag{1.1}$$

where E_{photon} — the generated photon energy,

E_1 and E_2 — the high and low energy level,

h — the Planck constant,

v_{photon} — the generated photon frequency.

Optical amplifiers can be classified according to the nature of the amplification process [34]:

1) amplifiers, in which amplification is obtained, using linear properties of the material (semi-conductor optical amplifiers (SOA) and amplifiers on rare-earth element doped fibre basis (xDFA)),
2) amplifiers, for which the principle of operations is based on non-linear properties of the material (Raman optical amplifiers, Brillouin optical amplifiers and parametric amplifiers (FOPA)).

A second way of classifying optical amplifiers is according to the medium, in which amplification takes place:

1) amplifiers, in which semi-conductor material is used (SOA),
2) amplifiers, which are produced on the basis of optical fibres.

The main parameters that are used to characterise optical amplifiers are the level of amplification, the gain bandwidth, the saturation power of the amplifier, polarisation sensitivity of the produced gain, and the amount of signal impairments produced by the amplifier.

The achievable level of amplification is determined as the relation of the output signal power to the power of the same signal in the input of the amplifier. Amplifiers are sometimes also described with amplification efficiency, which describes the amplification as a function of the pumping power. The unit of measurement of efficiency of amplification is dB/mW [35].

The bandwidth of the amplifier produced gain is applied to the wavelength or frequency range, in which the use of the amplifier is effective, namely, where it can ensure an increase in signal power. This value is especially important in WDM transmission systems, as it limits the number of channels in such systems [34].

The saturation point for an optical amplifier is the maximum attainable output power value, namely, when the optical signal power in the amplifier output no longer increases, while raising the signal power at the amplifier input. When the input power is increased above the saturation point, all carriers in the gain medium are already in a saturated status, and a higher level of energy transfer to the amplified signal is no longer possible. The saturation power is defined as the output power, at which 3 dB decrease in amplification is observed, in respect to the maximum possible level of amplification [34].

The dominating source of noise in optical signal amplifiers is the amplified spontaneous emission (ASE), which originates in the gain medium [36]. The amount of noise generated by amplifiers depends on various factors. The most important of these are the gain medium material parameters (for example, the spontaneous lifetime of the energy level), gain spectrum, noise bandwidth, amplifier saturation and population inversion parameters. The problem of noise generated by an amplifier is most explicit in systems, where it is required to use multiple amplification stages, therefore placing the amplifiers in a cascade, such as backbone optical networks. Each amplifier in such cascades not only amplifies the transmitted signal, but also the noise generated by the amplifier from the previous amplification stage and additionally adds ASE noise of its own [34]. To assess the amount of ASE noise generated by the amplifier, the noise figure (NF) parameter is normally used. This value describes the optical signal-to-noise ratio (OSNR) changes, as the signal passes through the amplifier [34], [37].

In the studies conducted by the author, by using simulation software OptSim 5.2, the performance of SOA, EDFA, lumped Raman amplifier (LRA) and the distributed Raman amplifiers under equal operating conditions has been compared. The simulation scheme introduced for this purpose is displayed in *Fig. 2*. Such a structure of the WDM transmission system simulation model will also be used further in the research, when the operations of an amplifier are analysed.

The performance of different types of amplifiers has been compared in a 16-channel DWDM transmission system with 10 Gbps transmission speed per channel, 50 GHz channel spacing and NRZ-OOK modulation format. In each case, also the length of the dispersion compensating fibre (DCF) has been determined. Optical amplifiers have been used as inline amplifiers. The comparison of SOA, EDFA, LRA and DRA performance is available in *Table 1*.

The largest transmission distance has been achieved in a system with the DRA. Here, just like in the case of LRA, the attainable amplification is limited by the impact of fibre nonlinearity on the quality of the amplified signal. A 1150 mW co-propagating pumping radiation is used for DRA pumping. The amplification process occurs in the transmission line section between the DRA pumping source and the receiver block. Thus, the SMF fibre attenuation reduces the signal amplification rate in the direction from the amplifier to the receiver block, which allows achieving much larger amplification than in the case of LRA, and accordingly increases the attainable transmission distance. Irrespective of the fact that the average amplification in the case of DRA is larger just only by 0.7 dB than in the case of the EDFA amplifier, the achieved transmission distance is larger by 11 km than in the system with EDFA. This can be explained by the low amplification efficiency of the Raman amplifiers at low powers of the amplified optical radiation. Thus, the signal, the power of which is much larger than the noise power, will be amplified more effectively than the noise generated by the amplifier. Nevertheless, such characteristic of the amplifier should also be interpreted as a serious drawback of the distributed Raman amplifiers, as the need arises to use powerful pumping lasers (1150 mW strong pumping radiation is necessary to achieve amplification of 25 dB). EDFA is able to ensure a high level of signal amplification; however, this could be achieved only in a 35 nm wavelength region in the "C" optical band. The typical noise figure of EDFAs is higher than in the case of LRA and DRA. The main deficiency of SOAs is a very high number of produced signal impairments; therefore, this type of amplifiers is rarely used in WDM systems, even though their gain spectrum is much broader in comparison with EDFAs.

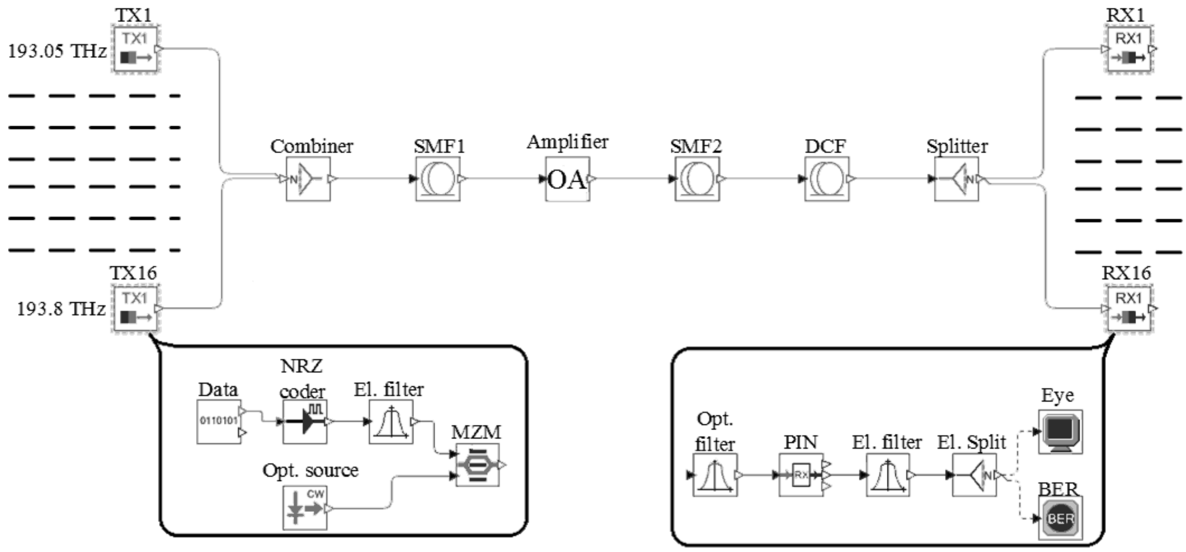

Fig.2. Simulation model of the 16-channel 10 Gbps DWDM transmission system used for comparison of optical amplifier performance.

Table 1

Summary of the Results Obtained in the 16 Channel 10 Gbps DWDM Transmission System Depending on the Type of Amplifier Used (column 2 — without using an amplifier)

Amplifier type	—	SOA	EDFA	LRA	DRA
Transmission distance, km	69	112	135	119	146
DCF length, km	5	15	20	17	20
Gain in wavelength range from 1546 to 1553 nm, dB	—	17.4	23.4–25.1	19.9–20	24.9–25
NF in wavelength range from 1546 to 1553 nm, dB	—	—	4.5–4.6	3–3.1	–8.6
Level of inter-channel crosstalk in the channel with the highest BER, dBm	–55.5	–50	–47.9	–48.3	–49.3

Taking into account the excessive number of SOA produced signal impairments, the strong wavelength and unevenness of the EDFA produced gain, and the low amplification effectivity of Raman amplifiers, it is clear that, if Cisco and Bell Labs forecasts are correct, then it will be necessary to find another optical signal amplification solution that could ensure a higher level of amplification over a broader wavelength band, and at the same time that would amplify signal impairments as little as possible.

The first possible solution is to combine the aforementioned optical amplifiers into a hybrid optical amplifier, which would allow compensating for the negative properties of various amplifier types, for instance, to expand and equalise the EDFA gain spectrum, or would reduce the SOA-generated noise proportion in the amplifier output.

Another possible solution is the use of fibre optical parametric amplifiers (FOPAs). This type of amplifiers can ensure a high level of amplification over a broad wavelength band, and, if compared to other lumped amplifier types, given an optimised configuration, they produce very small number of signal impairments. Moreover, parametric amplifiers can also be used for all-optical signal processing purposes, for example, for wavelength conversion [38], [39], dispersion compensation [40], time-division multiplexed signal demultiplexing [31] and 2R and 3R all-optical signal regeneration (2R — signal power and form regeneration; 3R — signal power, form and phase regeneration) [41], [42].

Chapter II

This chapter is dedicated to studies of hybrid optical amplifiers, which were obtained by applying the combinations of currently commercially used optical amplifiers (SOA, EDFA and Raman amplifiers). The possibilities of applying hybrid Raman-EDFA and Raman-SOA solutions in WDM transmission systems for improving the operations of existing lumped inline amplifiers have been studied and demonstrated. Due to the excessive number of SOA produced signal distortions and the strong wavelength dependency of EDFA produced gain, the implementation of EDFA-SOA hybrid solution has not been considered.

The unevenness of the EDFA gain spectrum and signal distortions caused by ASE noise significantly affect the performance of the whole transmission system, especially in systems with several amplification spans. To demonstrate the impact of the unevenness of EDFA gain spectrum and of the generated signal distortions, a 16-channel 10 Gbps DWDM transmission system simulation model has been introduced with 4 amplification spans. Equal power of the optical flow has been ensured at each amplifier input.

The obtained results are shown in *Fig. 3*. After each amplification span, BER value of the detected signal increases by 2–3 orders (given the same input signal power). Upon comparing the EDFA gain spectra after the 1st and 4th amplification span, it is found that amplification decreases on average by 11.6 dB, whereas the amplification difference between the channels increases from 1.3 to 4.3 dB. The following conclusions are drawn:

- every additional EDFA not only generates the amplified spontaneous emission noise, but also amplifies the noise produced by the previous amplification spans. This significantly degrades the quality of amplifiable signal;
- the ASE power level after each amplifier is gradually increasing. Accordingly, part of the erbium ion population inversion is used to amplify the noise generated in the previous amplification spans. As a result, the part of the obtained population inversion, which was used for signal amplification, has decreased.

The slope of the gain spectrum increases after each amplification span. Uneven amplification is undesirable in multi-channel WDM systems, especially in systems with several cascaded EDFA inline amplifiers, as it leads to difference between power levels of various channel, which, accordingly, will lead to a signal quality degradation in channels with a lower amplification level.

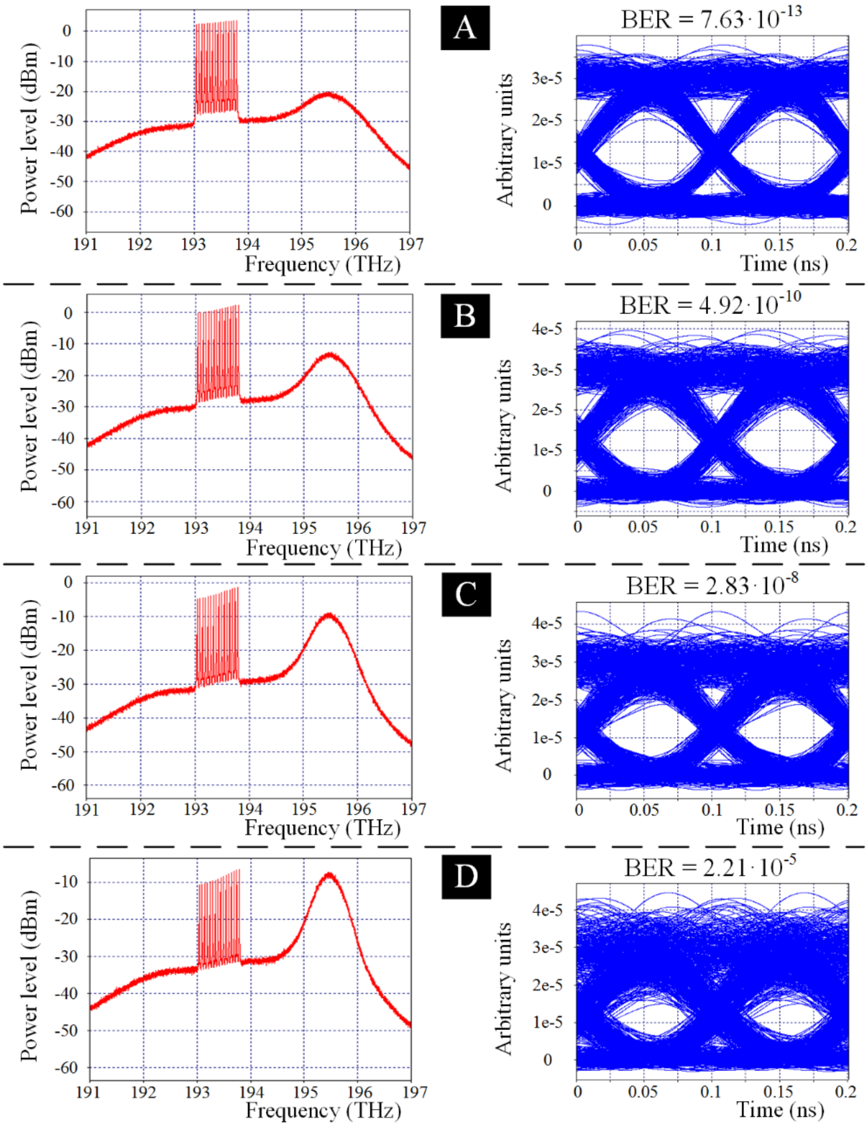

Fig. 3. Optical spectra at the output of the EDFAs (to the left) and Eye diagrams of the signal detected in the 9th channel (to the right) after 1st (a), 2nd (b), 3rd(c) and 4th(d) stages of amplification.

Summing up all the aforementioned results, it has been concluded that it is necessary to configure the EDFA amplifier in a way to obtain the overall amplification spectrum that is as even as possible in the frequency range used for transmission, as well as to reduce the number of EDFA produced signal distortions.

Raman-EDFA Hybrid Amplifier

In the Raman-EDFA optical amplifier combination, most noise is generated by the EDFA amplifier. Therefore, in most cases, the Raman amplifier is used as a pre-amplifier in such cascades. EDFA amplifiers provide lower noise figures when functioning closer to the saturation point. Therefore, in hybrid amplifiers, EDFA with a relatively short doped fibre should be used (the longer the doped fibre, the higher level of amplification is obtained by the photons generated by spontaneous emissions). For the further analysis of the hybrid Raman-EDFA solution, a simulation model is used, which is shown in *Fig. 4*.

In the simulation model, the optical flows that are produced by the 16 transmitters are combined and transferred through a 150 km long standard single mode fibre (SMF1). The signal power level at the SMF1 fibre output in all 16 cannels has reached –37.1 ± 0.1 dBm. The overall optical flow has been amplified by the EDFA inline amplifier or by the hybrid Raman-EDFA amplifier (arrows in Fig. 4 show the layout of the hybrid amplifier), and afterwards transferred through a 50 km long SMF fibre (SMF2). Dispersion compensation has been performed using a fibre Bragg grating (FBG) and then the optical flow has been divided among 16 receivers, using an optical power splitter.

After comparing the gain spectra produced by the EDFA inline amplifier and the hybrid Raman-EDFA amplifier (see *Fig. 5*), it has been found that implementation of the hybrid solution allows reducing the gain difference among all 16 channels from 1.5 dB (in the case of the EDFA) to 0.1 dB (in the case of the hybrid amplifier).

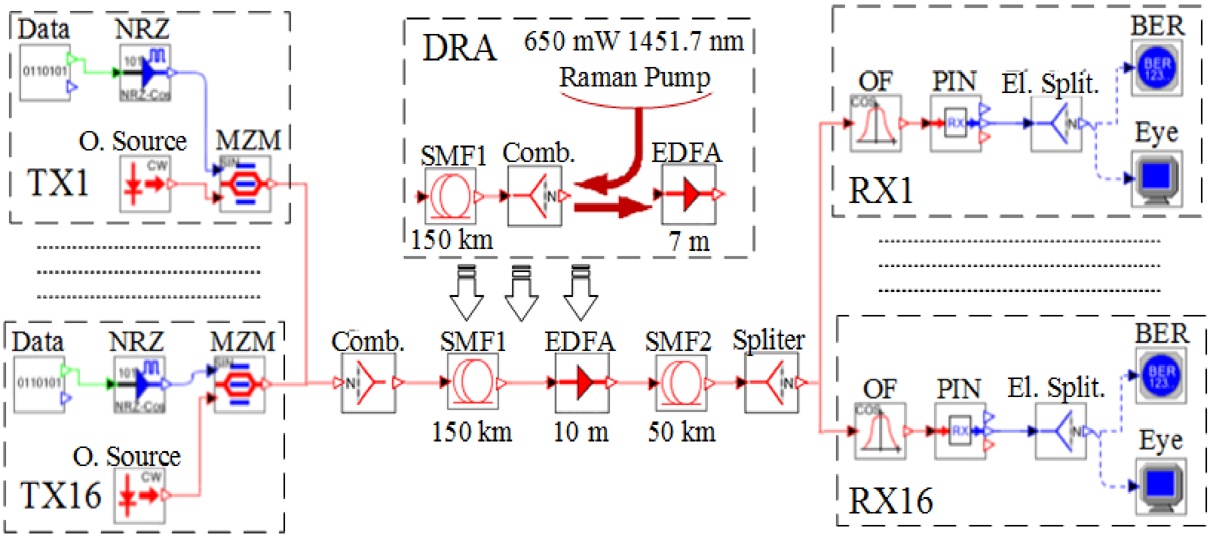

Fig. 4. Simulation model of the 16-channel 10 Gbps DWDM transmission system with an EDFA inline amplifier or with a hybrid Raman-EDFA amplifier.

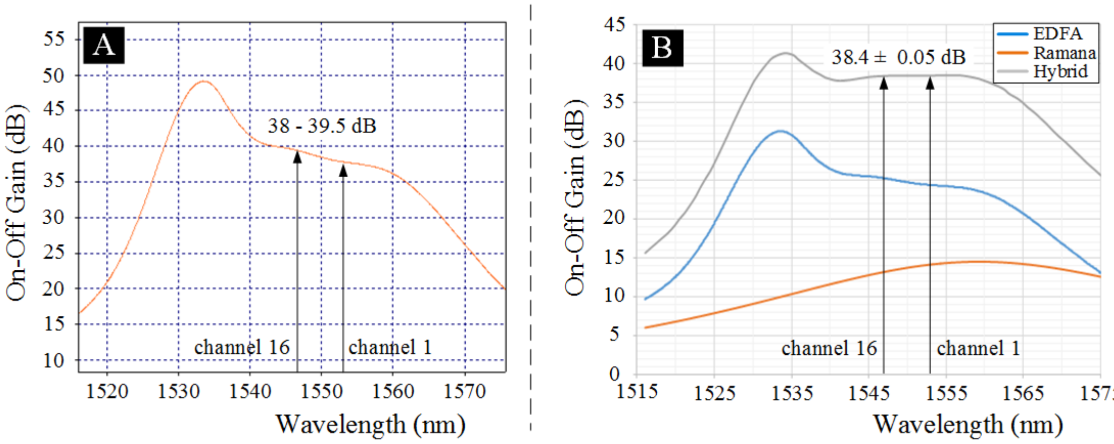

Fig. 5. Gain spectra of the EDFA inline amplifier (A) and of the hybrid Raman-EDFA amplifier (B).

As can be seen in *Fig. 6*, implementation of the hybrid solution has ensured OSNR improvement in all 16 channels from 1.7 up to 2.6 dB, that is, an average increase of ~ 2 dB. Such OSNR improvement can be explained by the following facts:

- the usage of the distributed Raman amplifier has raised signal power at the input of the EDFA by 13.1–14.1 dB, therefore, the EDFA functions closer to the saturation point;
- the EDF fibre length has decreased by 3 meters, which allows reducing the required input signal power for saturation of the EDFA;
- the coherent nature of stimulated Raman scattering (SRS) ensures that in SMF1 optical fibre, the signal is amplified more effectively than the low power optical noise, which allows obtaining negative noise figure values (from –0.4 to –0.6 dB in the wavelength region used for transmission), and accordingly improved OSNR.

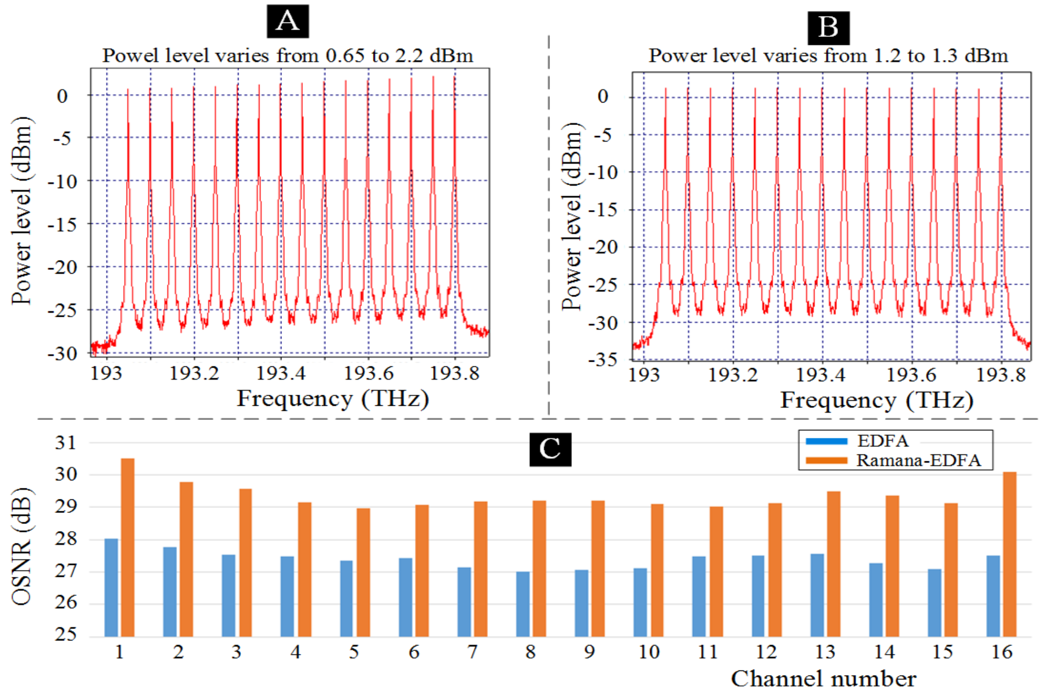

Fig. 6. Signal spectra at the output of the EDFA (a) and at the output of the hybrid Raman-EDFA amplifier (b), and OSNR comparison among all 16 channels in the system with the EDFA inline amplifier and the hybrid Raman-EDFA amplifier (c).

In the case of the hybrid amplifier, it has been found that raising the signal power at the input of the EDFA and reducing the length of the erbium doped fibre allow obtaining lower noise figure values by 0.3–0.4 dB for the EDFA.

Upon performing a comparison of operations of the aforementioned EDFA and Raman-EDFA solutions, it can be concluded that the hybrid amplifier can ensure more even amplification over a broader wavelength region and higher OSNR values. However, more powerful lasers are necessary for implementing such solutions, which increases the costs of developing this solution. For the EDFA inline amplifier 316 mW of pumping power is required to amplify the –37.1 dBm input signal by more than 38 dB. In the case of the hybrid solution, the Raman amplifier required 650 mW of pumping power to ensure that gain is high enough and that its slope can compensate the slope of the EDFA with 200 mW pump gain spectrum, but the total pumping power of the hybrid amplifier has reached 850 mW. However, the hybrid solution ensured gain difference below 1 dB over a 23 nm wavelength range (from 1538 to 1561 nm, by 17 nm more than that used for transmission of all 16 channels), which allows significantly increasing the number of channels in WDM transmission systems.

Raman-SOA Hybrid Amplifier

The Raman-SOA hybrid solution is configured in a way to reduce the number of signal distortions produced by the semiconductor optical amplifier and also to increase the attainable transmission distance. The introduced simulation model of the transmission system used for studying this amplifier combination is similar to the one used previously (see *Fig. 7.*).

The transmission line span length between the transmitter block and SOA is specifically selected to ensure optimum signal power at the input of the semi-conductor amplifier. Inserting the distributed Raman amplifier in a cascade before the semi-conductor amplifier would increase the signal power in SOA input, which would lead to a more explicit manifestation of nonlinear optical effects in the semi-conductor material and would, accordingly, deteriorate the quality of the amplifiable signal. Therefore, it is the semi-conductor amplifier that is used as the first in the cascade.

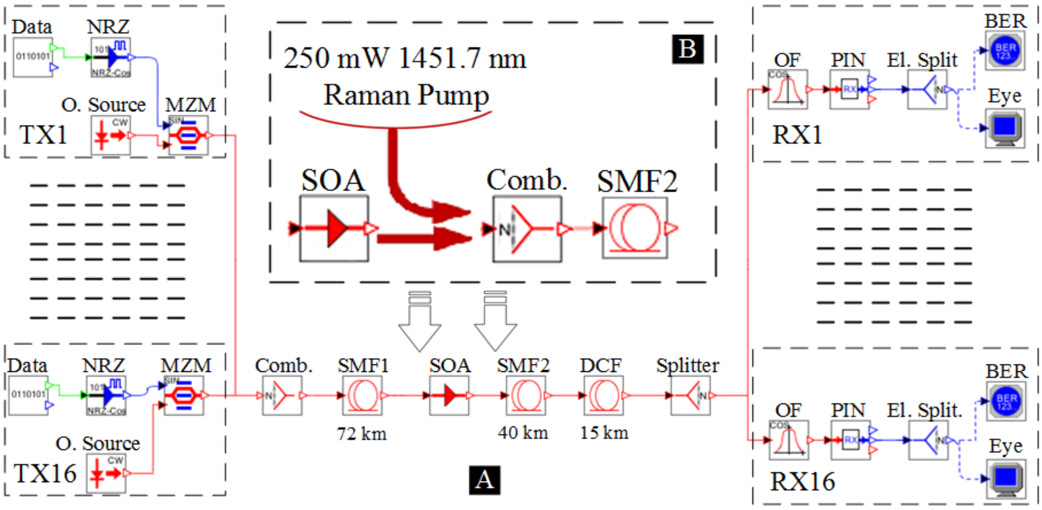

Fig. 7. Simulation model of the 16-channel 10 Gbps DWDM transmission system with the SOA inline amplifier (a) or with a hybrid Raman-SOA amplifier (b).

The implementation of the hybrid Raman-SOA solution allows using such mode of the semi-conductor amplifier, in which it produces minimum distortions of the amplified signal, whereas the amplification deficit, which occurs after reducing the pumping current value by 43 mA, is compensated by the DRA with a 250 mW 1451.7 nm co-propagating pump. The implementation of the Raman-SOA hybrid solution allows increasing the attainable transmission distance by 12 km. The gain spectrum of the DRA is shown in *Fig. 8.a*. Eye diagrams for channels with the highest BER value in a system with the SOA amplifier (9th channel) and in a system with the Raman-SOA hybrid amplifier (10th channel) are shown accordingly in *Fig. 8.b* and *Fig. 8.c*. From *Fig. 8.a* it can be seen that the DRA produced amplification is large enough to compensate the amplification deficit of 5.3 dB that occurs after reducing the SOA pumping current by 43 mA.

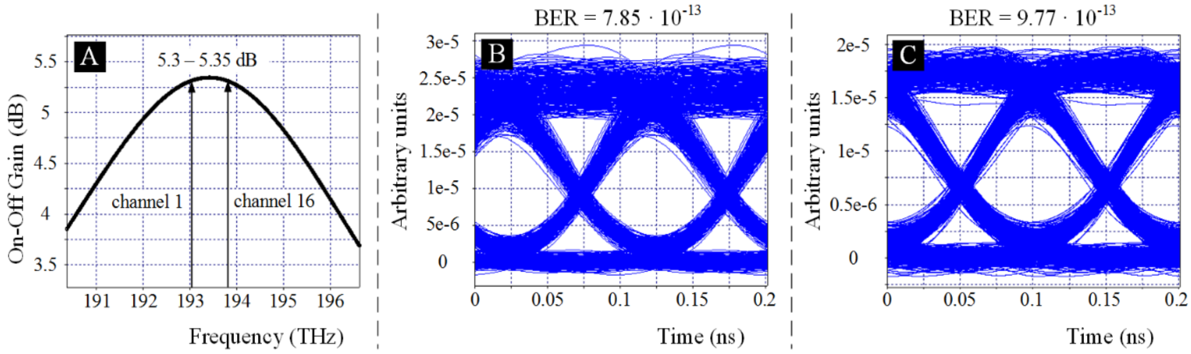

Fig. 8. DRA produced gain spectrum (a) and eye diagrams of the 9th channel in the system with the SOA inline amplifier (b) and the 10th channel in the system with the Raman-SOA hybrid amplifier (c).

After comparing *Fig. 8.b* and *Fig. 8.c*, it has been found that implementation of the Raman-SOA hybrid solution allows obtaining approximately the same BER level as in the case of SOA inline amplifier, but at signal power lower by1.5 times . This shows that, by using SOA together with the distributed Raman amplifier, and introducing relevant SOA pumping current adjustments, it is possible to substantially lower the amount of SOA produced noise and, therefore, to improve the quality of the amplified signal.

Parametric amplifiers can be based on degenerate FWM (in the single-pump case) and on non-degenerate FWM (in the dual-pump case). FOPA produced gain will reach its maximum, if the phase matching condition is met or if the phase mismatch parameter *k* is equal to zero. In the case of a single-pump FOPA, irrespective of the broad amplification range, the amplification spectrum is not even. In the experimental transmission system described in the Thesis, the gain -3dB bandwidth has reached 2.2 THz (see *Fig. 9*). It has been found that for ensuring an optimum operation mode of a single-pump FOPA it is necessary to maintain a small negative linear phase deviation in respect to the zero dispersion frequency, which would compensate the nonlinear phase mismatch. That is why the pumping radiation wavelength must be slightly larger than the fibre zero dispersion wavelength (ZDWL).

The gain spectrum bandwidth is very dependent on the non-linearity parameter of the medium and on the pumping radiation power and the length of the gain medium (HNLF fibre). Thus, by increasing the fibre length, it is possible to achieve a higher level of amplification, but in this case, the gain spectrum width will be reduced accordingly (the longer the fibre, the larger the accumulated phase mismatch is). Due to this reason, when constructing FOPA amplifiers, it is not recommended to use HNLF fibres that are longer than 1 km. If they are configured in a way to achieve as wide gain spectrum as possible, it is required to use as short HNLF fibre as possible, but to maintain the achievable amplification level, the pump power must be increased or a fibre with a higher non-linearity coefficient must be used. When selecting the pumping radiation parameters, one must keep in mind that, by changing the pumping radiation power, also the nonlinear phase mismatch is changed. Therefore, along with adjusting the pump power, its wavelength also needs to be reconfigured.

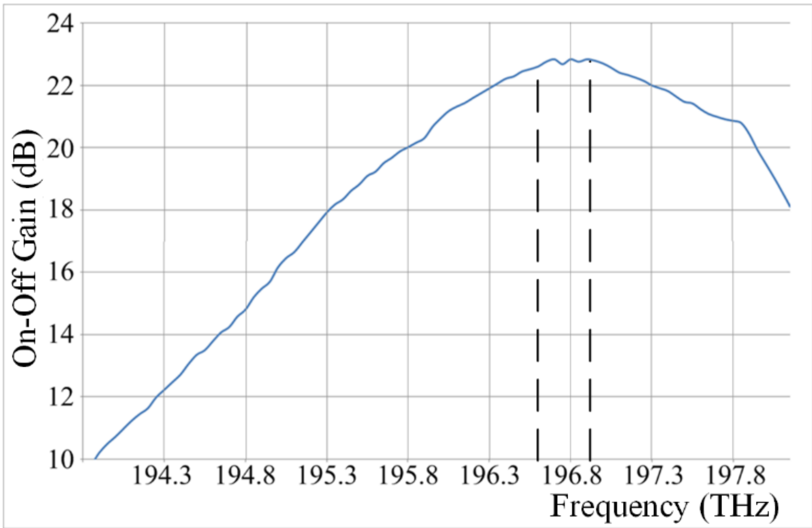

Fig. 9. Gain spectrum of the single-pump FOPA with 660 mW 1553.9 nm pumping radiation.

The performance of single-pump parametric amplifiers is affected by various factors, which must be taken into account when designing a specific FOPA. It is necessary to selectively choose the pumping radiation parameters to ensure as high amplification efficiency as possible and to avoid occurrence of excessive channel-channel four-wave mixing (CC-FWM) and pump-channel four-wave mixing (PC-FWM) produced inter-channel crosstalk, which in its turn is produced due to excessive pumping. The SBS threshold increase is also very important, otherwise the amplification effectiveness will decrease and the amplified signal will be distorted.

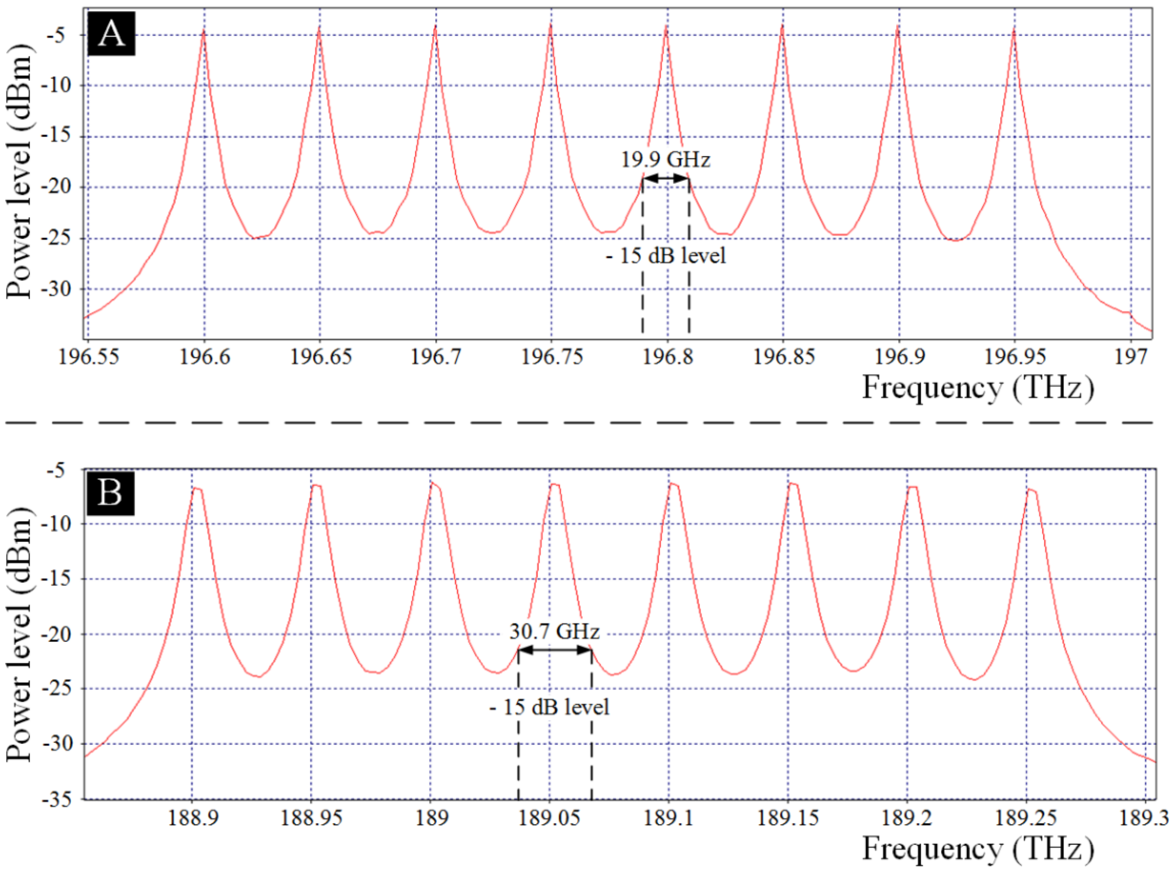

Fig. 10. Spectra of the amplified signal (A) and the generated idlers (B) at the output of the single-pump FOPA.

One of the most effective solutions of increasing the SBS threshold is phase modulation of the pumping radiation. However, as can be seen from the results shown in *Fig. 10*, if the choice of frequencies modulating the pumping radiation phase is not thoroughly considered, a substantial expansion of spectrum of the idler spectral components will occur. Therefore, in systems, in which idlers are used for all-optical signal processing, it must be ensured that the chosen pumping radiation phase modulation does not produce excessive spectral broadening of idlers (in the results shown in *Fig. 10* idler spectral broadening has reached 54 % at the level of –15 dB from the maximum power spectrum). For initiating the FWM process, it is also necessary to preserve the angular momentum among the four photons involved in the parametric interactions, as the parametric gain has explicit polarisation dependence.

Unlike single-pump FOPAs, dual-pump FOPAs can ensure even amplification over a very broad wavelength band. To achieve even amplification in a broad wavelength band, it is necessary to ensure that the wavelengths of the pumps are placed symmetrically in respect to the gain medium ZDWL, whereas the frequency distance between ZDWL and pumping radiations must be large enough (depending on the specific FOPA configuration), to avoid the impact of PC-FWM generated components on the quality of the amplified signal.

Since dual-pump FOPAs both degenerate and non-degenerate FWM, for 1 input signal it is possible to obtain at least 5 idlers (see *Fig. 11*, where ω_1 and ω_2 are the pumping source frequencies, but ω_3 is the signal), which are directly related to the amplifiable signal frequency. This leads to amplification spectrum depressions at frequencies near the frequencies of the pumps. It has been concluded from the results obtained in this study that at 0.5 mW pump power it is recommended that the amplified signal frequency is at a distance of at least 1.2 THz from pump frequencies.

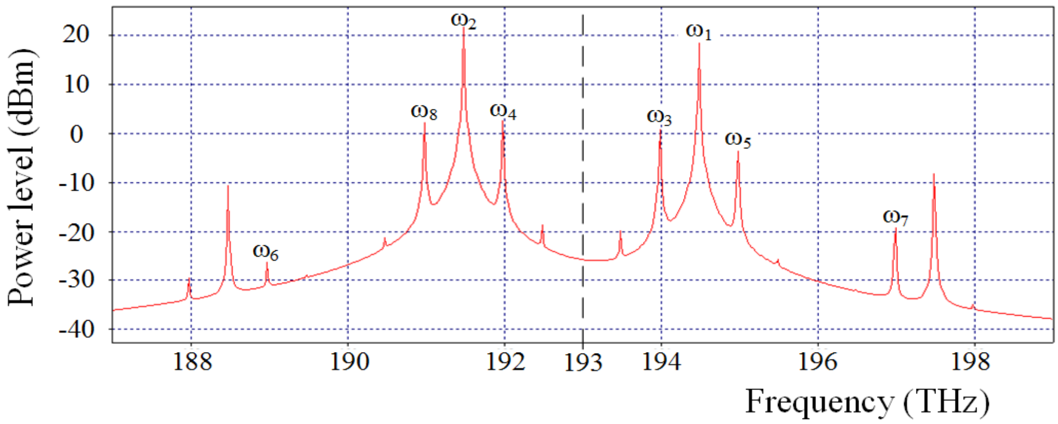

Fig. 11. Optical spectrum at the output of a dual pump FOPA with 200 mW 191.5 THz pumps and 500 meter long HNLF.

Just like in the case of single-pump FOPAs, dual-pump FOPAs also require the usage of one of the methods for mitigation of the negative impact of SBS. However, in the dual-pump case it is important to note that by manipulating with the phase of both pumping radiations it can be achieved that the relevant idler will not experience spectral broadening. The amplification efficiency in the case of dual-pump FOPAs is highly dependent on the SRS triggered energy transfer between the pumps. It is not possible to fully avoid this effect. To reduce its impact, normally higher power is used for the pump with the higher frequency than for the other pumping radiation, thus achieving that the average power difference between the pumps is minimum over the entire gain medium.

Multicarrier Source

In traditional WDM transmission system architecture, one optical source is required to produce a single channel carrier. It is not the most cost-effective solution, as, by increasing the number of transmission channels, the number of required light sources increases accordingly. Due to this reason, an increasing number of studies are conducted to find such transmission system architecture, which would be able to ensure a higher number of signal carriers using fewer optical sources [43]–[45]. FOPAs during the process of parametric amplification generate idler spectral components, which, in essence, are phase conjugated copies of the amplified signal. These idlers could be used not only for wavelength conversion or 2R and 3R signal regeneration, but also for increasing the number of carriers on the transmitter side of a WDM transmission system.

Therefore, a model of a dual-pump FOPA has been introduced for doubling the number of existing carriers in a WDM transmission system. For this reason, a simulation model of a 32-channel DWDM transmission system has been created with 10 Gbps transmission speed per channel, 100 GHz channel spacing and NRZ-OOK modulation format. This system simulation model is displayed in *Fig. 12*.

The main feature in the simulation model, which is presented in *Fig. 12*, is that the FOPA is placed before the transmitter block, or at the 32-channel modulator inputs. The optical multicarrier source consists of continuous radiation lasers (CW1–CW16), an optical attenuator, two powerful pumping sources, two optical splitters and a 500-metre long HNLF fibre. One of the main goals of this experiment is to obtain 32 carriers with even frequency distribution (equal channel spacing), which can be achieved by using idlersω_4. Taking into account that the distribution of idlers ω_4 and the initial light source frequencies is symmetrical in respect to the gain medium ZDWL, it has been decided to place the carrier with the lowest frequency higher by 50 GHz than the HNLF fibre ZDWL (193 THz). Therefore, the frequencies of the 16 initial carriers are distributed in a range from 193.05 THz to 194.55 THz with 100 GHz channel spacing (see *Fig. 13.a*). The optical flow sent through the parametric amplifier is not modulated and basically represents a continuous radiation set. At the output of the HNLF, a combination is obtained consisting of 16 initial carriers, 16 idlers ω_4 (generated as a result of parametric processes), 2 pumps and other third-order spectral components (see *Fig. 13.b* and *13.c*). The pump power for both pumps is set to 400 mW each (26 dBm) and 190 THz and 196 THz frequencies are temporary chosen.

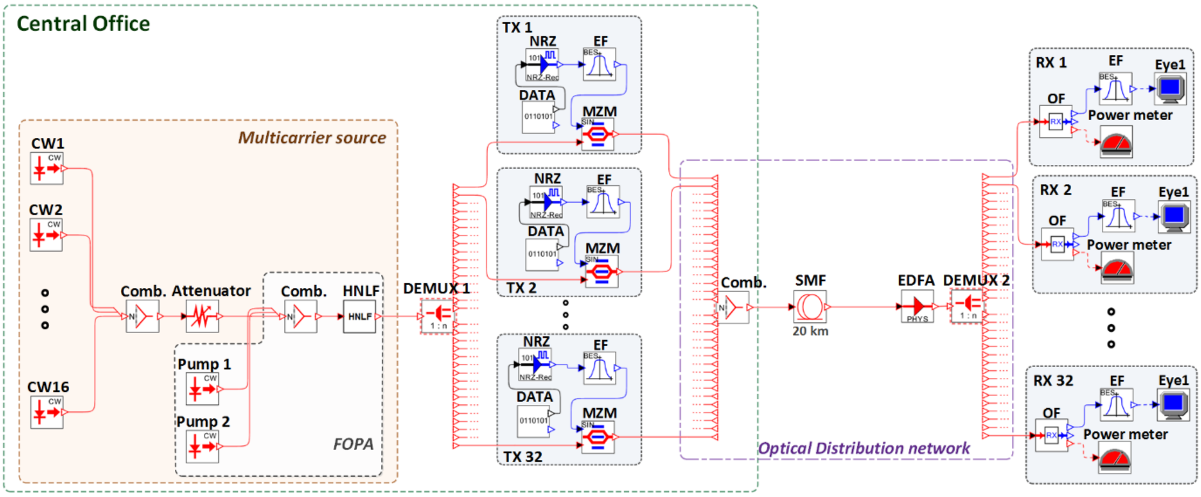

Fig. 12. Simulation model of the 32 channel 10 Gbps WDM transmission system with the provided multicarrier source solution, which is based on wavelength conversion using a dual-pump FOPA.

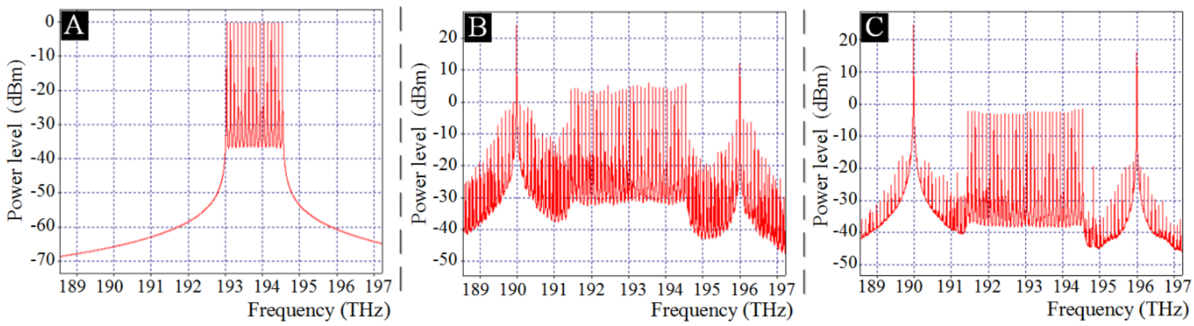

Fig.13. Optical spectrum at the input of the FOPA when initial carrier power is set to 0 dBm (a), and optical spectra at the output of the HNLF when the power of the initial carriers is set to 0 dBm (b) and to –10 dBm (c).

It has been found that when given an excessively high level of input signal power, CC-FWM processes will trigger explicit inter-channel crosstalk (see *Fig. 13b*). Due to this reason, when the idlers obtained as a result of parametric processes are used for increasing the number of carriers, it is necessary to limit the power of the carriers at the amplifier input. Based on the obtained results, the power level of the initial carriers at the input of the amplifier is reduced to –10 dBm. The alignment of idlers in respect to the central frequencies of the throughput band of demultiplexer filters is achieved by changing the frequency of the first pumping radiation (frequency obtained in simulations — 196.01 THz). With the aforementioned amplifier configuration, the maximum power level difference among all the 32 channels has been reduced to 1.9 dB.

To assess the performance of the proposed system architecture solution, BER value dependence on the received signal power in the channel with the poorest signal quality (the highest BER) is obtained. These results are compared to the corresponding results obtained in a system with traditional architecture (with 32 laser sources, which function in a continuous radiation mode). The obtained results are shown in *Fig 14*. It has been found that power penalty of 1.8 dB exists between the system with the proposed multicarrier source and the conventional 32-channel solution. It is important to note that part of the obtained power penalty is directly related to the large amount of ASE produced by the EDFA used as a pre-amplifier for ensuring the necessary signal power at the input of the received block.

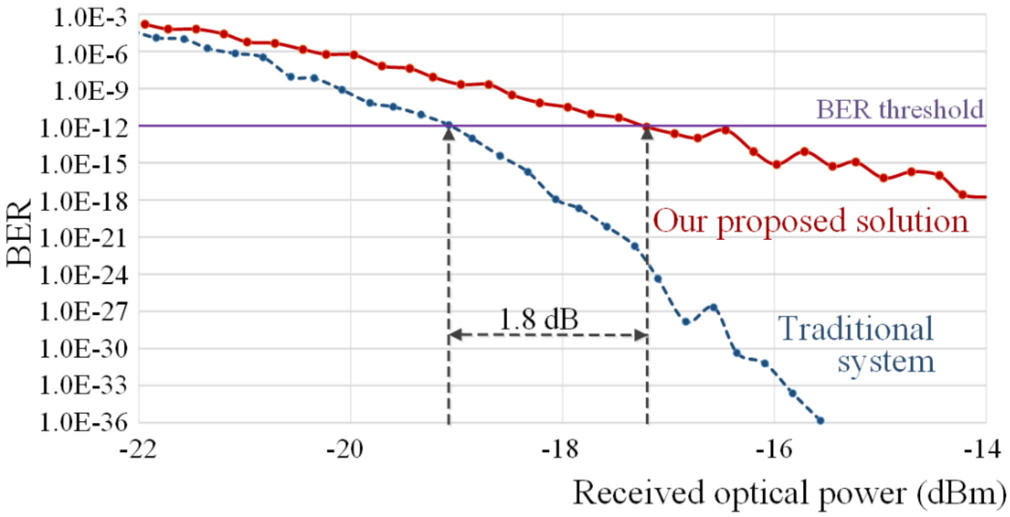

Fig. 14. BER value dependence on the power of the detected signal for the 12th channel in the system with the proposed multicarrier source solution (red line) and in the system with traditional architecture (blue line).

There are at least two alternatives to the proposed system architecture, which can produce more than one carrier per optical source: spectrum sliced systems [44], [46] and systems, which are based on FWM use for producing 3rd order spectral components (without the initial carriers) [45], [47]. Nevertheless, the use of idlers ω_4 produced by FOPA for doubling the number of carriers in WDM systems ensures the best carrier signal stability and, therefore, the highest quality of the transmittable signal.

Chapter IV

The chapter covers a study of polarisation dependence of parametric amplification and its possible applications in all-optical signal processing. It has been found that for dual-pump FOPAs the maximum amplification efficiency is achieved when both pumps are linearly polarised with the same state of polarisation (SOP), and their SOP corresponds to the SOP of the amplified signal. However, when the SOP of both linearly polarised pumps is orthogonal to the SOP of the amplified signal, amplification decreases to its minimum value, and in a broad frequency region it is equal to zero. The results obtained in this Thesis have shown that the same situation is observed also in the case of single-pump FOPAs.

This property of parametric amplifiers can be used for emphasising one state of polarisation from a combination of two orthogonally polarised optical components. The key problem, which is observed when the FOPA is used for emphasising a specific state of polarisation, is ensuring the conservation of the relative positioning of signal and pump SOP throughout the entire length of HNLF fibre. This problem occurs due to the following reasons:

- Due to the effect of fibre birefringence, SOP of optical radiation changes along the fibre, and, as result, random SOP rotation is observed. It is very difficult to compensate such a random SOP change, as the rotation rate is affected by various factors, such as temperature, the frequency of the transmitted radiation, internal and external mechanical loads etc. It is possible to avoid rotation of SOP of the pumps and the amplified signal by using polarisation maintaining HNLF as the gain medium.

- When the amplified signal and the pumps are propagating in the gain medium, additionally to fibre birefringence, their states of polarisation are also affected by self-phase modulation (SPM) and cross-phase modulation (XPM) nonlinear effects. Therefore, when configuring the parametric amplifier, it is first necessary to avoid excessing pumping, otherwise, it can lead to a more explicit occurrence of SPM and XPM, which decreases the efficiency of the FWM process in the gain medium.

It is not possible to completely avoid changes in relative positioning of the SOP of the signal and the SOP of the pump. To demonstrate this, a simulation model is introduced, where a single-pump FOPA (500 mW, 1533.9 nm) amplifies a signal with –31 dBm total optical power at the input of the HNLF. At first, both the signal and the pump are linearly co-polarised. During the simulation, the SOP of the pump is rotated in respect to the SOP of the amplified signal, and the power of the signal is observed at the output of the FOPA. It has been found that by using polarisation maintaining fibres, under the influence of SPM and XPM, a change in the relative positioning of the signal SOP and the pump SOP is observed. As a result of this change, even when the signal is orthogonally polarised in respect to the SOP of the pump at the input of the HNLF, the signal obtains 1.5–1.6 dB gain. When the SOP of the amplified signal is co-polarised with the SOP of the pump, the obtained amplification reaches 18.3 dB, which is by 16.7 dB higher than in case of orthogonal relative positioning of the SOP at the input of the HNLF.

As it has already been previously mentioned, the polarisation dependence of the parametric gain can be used for emphasising radiation with a specific SOP from the flow of orthogonally polarised optical components, which in its turn can be used for emphasising polarisation multiplexed signals and 2PolSK to NRZ-OOK modulation format conversion.

Modulation Format Conversion

For conversion of 2PolSK signal to NRZ-OOK modulation format, cases of single channel and multi-channel systems are considered. To avoid changes in relative positioning of the states of polarisation between pumping radiations, single-pump parametric amplifiers are used in both cases. In both cases, the FOPA is placed at the receiver (or receiver block) input.

At first, a single channel transmission system simulation model is introduced with 2PolSK modulation format, 150 km long optical fibre, and a FOPA pre-amplifier (which simultaneously performs modulation format and wavelength conversion functionality) and two receivers for detecting the converted NRZ-OOK signal at signal and idler frequencies. The introduced simulation model is displayed in *Fig. 15*.

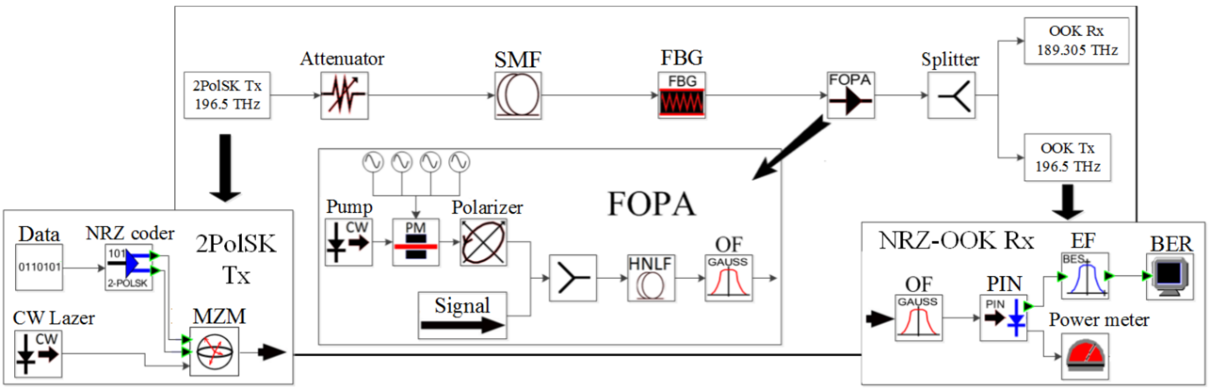

Fig. 15. Simulation model of the single-channel transmission system, where a single-pump FOPA with linearly polarised pumping radiation is used for 2PolSK to NRZ-OOK modulation format conversion.

In case of a single-channel system, the primary task is to assess the new modulation format conversion solution created within the scope of the Thesis, by obtaining a power penalty introduced specifically by the process conversion of the modulation format. Based on the obtained results, 535 mW 1554.1 nm pumping radiation is chosen, the phase of which is modulated with the following frequency tones: 180 MHz, 420 MHz, 1.087 GHz and 2.133 GHz. Such configuration ensures 14.8 dB gain for the logical "1" component of 2PolSK signal, which is sufficient for ensuring BER value below the 10^{-12} mark for the obtained NRZ-OOK signal.

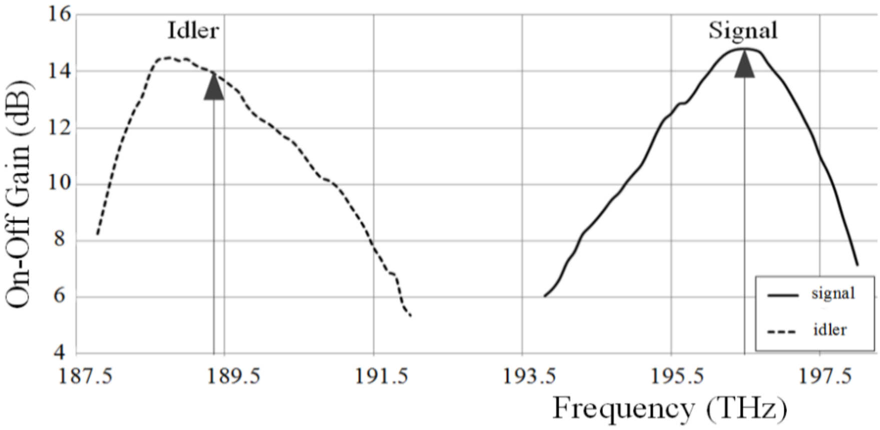

Fig. 16. Gain spectrum produced by the single-pump FOPA with linearly polarised pumping radiation at signal frequencies (solid line) and at idler frequencies (dotted line).

Based on the obtained results, it has been concluded that the idler requires lower pump power to ensure BER values below the 10^{-12} mark, even though the gain for idler is lower by 0.8 dB than the signal (see *Fig. 16*). Therefore, in the case of a single-channel system, it is recommended to process the idler spectral component as the informative signal. These results can be explained by the fact that the signal at its initial frequency contains the orthogonally polarised logical "0" component, which for the obtained NRZ-OOK signal is interpreted as noise.

It has been found that the power of the obtained NRZ-OOK signal that is necessary to ensure BER value below 10^{-12} is –23.65 dBm, whereas the necessary idler power is –23.8 dBm (see *Fig. 17*). In a standard single-channel system with NRZ-OOK modulation format, the signal power required to ensure BER value below the 10^{-12} threshold has reached –24 dBm. Thus, there is power penalty of 0.4 dB between the NRZ-OOK signal from the standard single-channel system and the converted signal. It is important to note that the power penalty between the NRZ-OOK signal from the standard single-channel system and the generated idler is lower by 0.1 dB(only 0.2 dB). These results are explained by the fact that the idler produced during the FWM process does not contain the logical "0" component of the initial 2PolSK signal, which in this case is interpreted as noise for the converted NRZ signal. The obtained power penalty values are also attributable to the relative intensity noise, which is transferred from the pumping radiation to the amplifiable signal, as well as to the phase SOP mismatch between the pump and the amplified signal that occurs due to SPM and XPM.

In the case of the multi-channel system, the goal is to assess the performance of the developed modulation format conversion solution in the presence of inter-channel crosstalk. When converting 2PolSK signal to NRZ-OOK modulation format, using FOPA with linearly polarised pumping radiation, one must pay special attention to the control of the level of inter-channel crosstalk produced by the CC-FWM interactions because if the SOP pumping radiation and SOP signal coincide, the FWM process takes place with its maximum efficiency, including also production of the CC-FWM inter-channel crosstalk.

To assess the performance of the proposed solution in the presence of inter-channel crosstalk, a 16-channel 10 Gbps DWDM transmission system is introduced with 2PolSK initial modulation format and 100 GHz channel spacing (see *Fig. 18*). In this system, the access network is divided into two branches, 8 channels in each. Only those results are included in the Thesis, which are obtained in the 2nd access network branch, where the signal is divided among 8 receivers using an optical splitter with 10.5 dB attenuation.

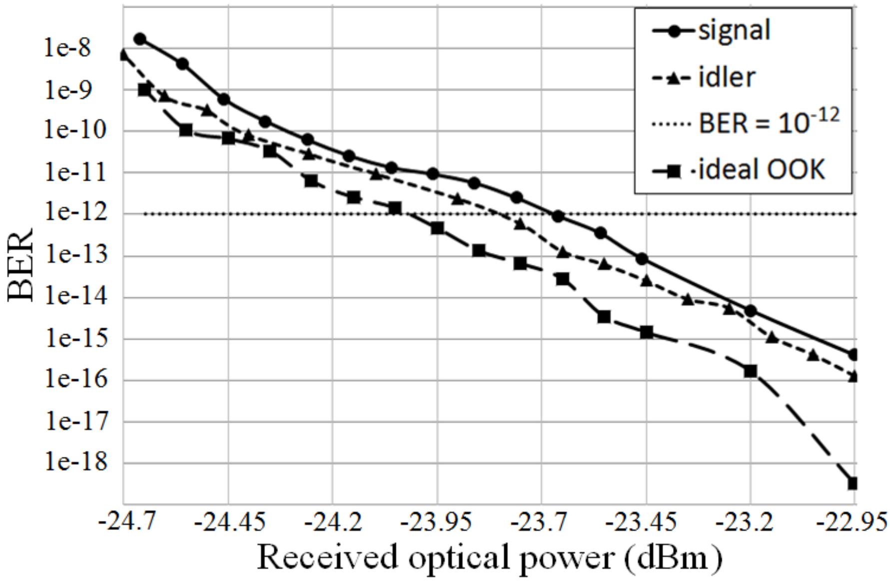

Fig. 17. BER value dependence on the detected signal power in the standard single-channel transmission system (dashed line), and in the system with modulation format conversion at the initial signal frequency (solid line) and at idler frequency (dotted line).

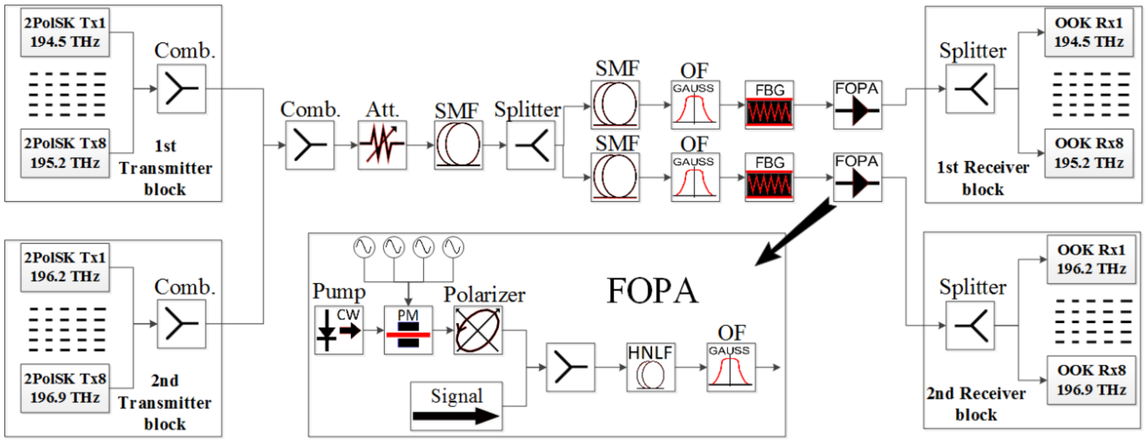

Fig. 18. Simulation model of the 16-channel WDM transmission system with two access network branches, where in each branch the FOPA pre-amplifier is used for 2PolSK to NRZ-OOK modulation format conversion.

Based on the obtained results, in the 2nd access network branch, 790 mW 1554.15 nm pumping radiation is used, the phase of which is modulated with the same frequency tones as in the case of a single-channel system: 180 MHz, 420 MHz, 1.087 GHz and 2.133 GHz. It has been found that to ensure BER values below the 10^{-12} threshold, all 8 idlers require pump power that is by 35 mW higher than in the case of the signals at their initial frequency. The obtained gain for the idler spectral components is lower by at least 2.2 dB, whereas the gain spectrum slope near its maximum is higher than in the initial signal frequency band (see *Fig. 19*). The obtained level of amplification in the initial signal frequency band changes in the range from 30.3 to 30.9 dB among all 8 channels; thus, the amplification difference between the channels reaches 0.6 dB. Between the idler spectral components, such difference has reached 2.6 dB (from 26.1 to 28.7 dB), but the biggest amplification difference between the signal at its initial frequency and the corresponding idler has reached 4.2 dB. This explains the need for pump power exceeding 35 mW to ensure BER values below the 10^{-12} mark in the idler frequency band.

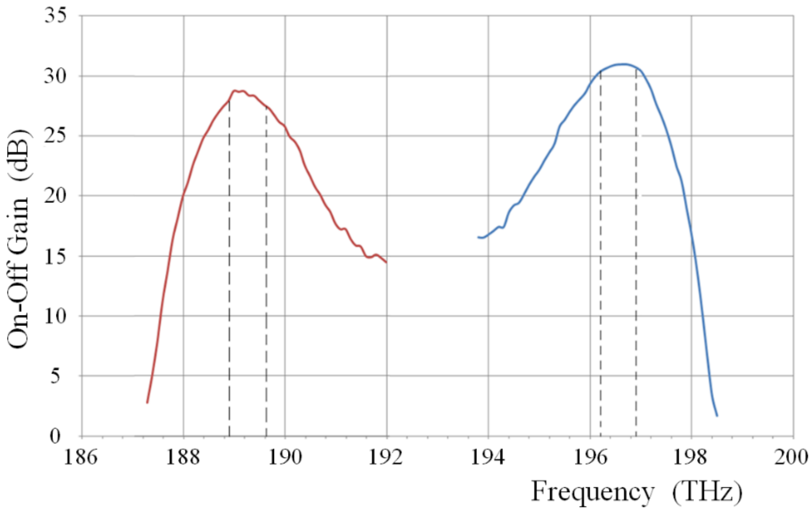

Fig. 19. Gain spectrum ensured by the FOPA with 790 mW 1554.15 nm linearly polarised pumping radiation at initial signal frequencies (blue line) and idler frequencies (red line).

To assess the performance of the proposed solution, the results obtained in the 2nd branch of the access network are compared to the standard 8-channel DWDM system without signal amplification. The detected signal power required to ensure a certain BER value in the 5th channel of the 2nd access network branch both at the initial signal and idler frequenciesis compared with the same results obtained in the standard 8-channel DWDM system. As seen in *Fig. 20*, in a system with modulation format conversion, to ensure BER values below the 10^{-12} mark, the required signal power is at least –23.5 dBm. In the standard 8-channel system, the corresponding required power level is –23.9 dBm; therefore, in this case, the power penalty between the signal with the converted modulation format and the signal from the standard 8-channel solution is 0.4 dB. It must be particularly emphasised that, contrary to the single-channel system, in the multi-channel system, the idler BER values are higher than those of signals at their initial frequencies — when receiving the idler corresponding to the 5th channel, at least –23.15 dBm is required to ensure a BER value below the 10^{-12} threshold, which is more by 0.3 dB than receiving the signal of the 5th channel at its initial frequency.

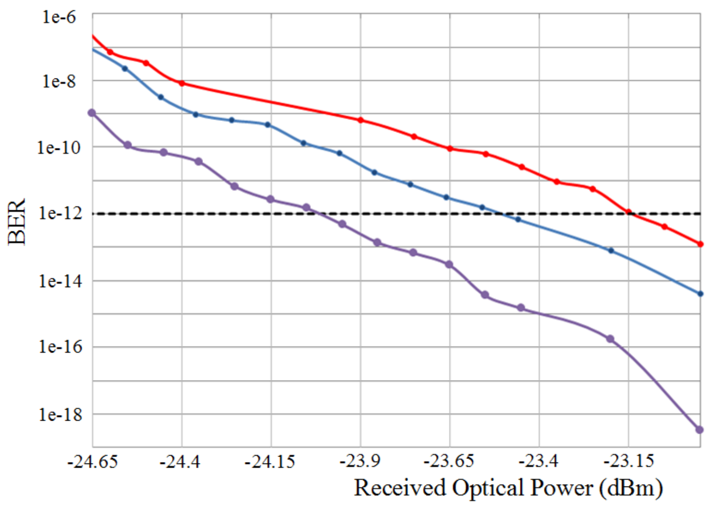

Fig. 20. BER value dependence on the detected signal power in the standard 8-channel transmission system (violet), and in the 5th channel on the 2nd branch of the multi-channel system with modulation format conversion at the initial signal frequency (blue) and idler frequency (red).

It has been found that in case of the idler, larger amplitude fluctuations are observed, which densify the logical “0” and logical “1” component levels of the eye diagrams. The cause behind generating noise of such range is CC-FWM produced inter-channel crosstalk, which is produced as a result of parametric amplification and creates third-order spectral components, the frequencies of which correspond to the frequencies of the amplified signals. As mentioned previously, the gain difference between the idlers is much larger (by 2 dB) than between the signals at their initial frequencies. Therefore, more explicit manifestation of CC-FWM processes is observed, which also produces additional inter-channel crosstalk. Moreover, the crosstalk caused by CC-FWM is not only transferred from signals at their initial frequencies to the idlers, but is also generated between the idlers.

It has also been found that the pumping radiation phase modulation leads to spectral expansion of the idlers by approximately 40 %, which, accordingly, results in additional inter-channel crosstalk. Inter-channel crosstalk caused by the CC-FWM interactions and idler spectral broadening is the main reason why, in the case of idlers, the power penalty in relation to the standard system is larger by 0.4 dB than for signals at their initial frequencies.

Division of Polarisation Multiplexed Signals

The second studied application of parametric gain polarisation dependence is the emphasizing of a signal with a specific SOP from a combination of two polarisation multiplexed NRZ-OOK signals. For this purpose, a 2-channel 10 Gbps transmission system with NRZ-OOK modulation format and polarisation multiplexing is introduced (see *Fig. 21*). Both signals, the SOP of which are mutually orthogonally allocated, are transmitted using the same frequency — 196.5 THz.

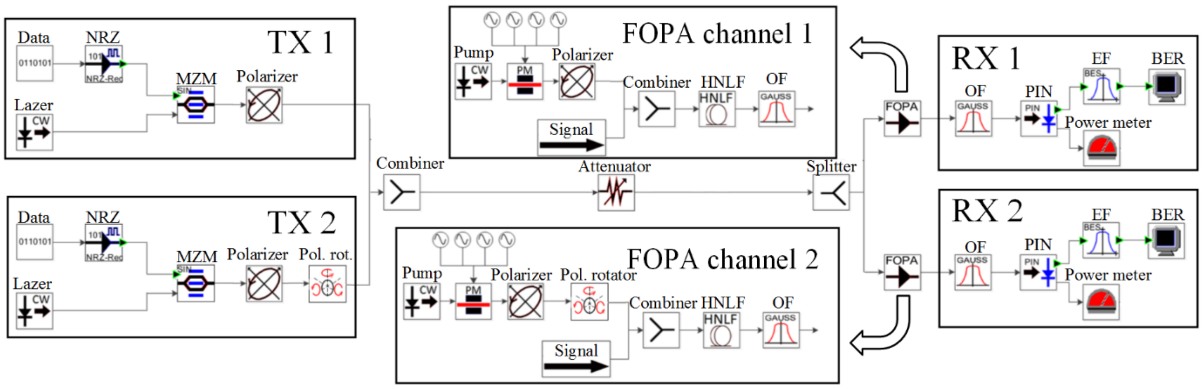

Fig. 21. Simulation model of the two-channel optical transmission system with FOPA for division and amplification of polarisation multiplexed signals.

Based on the obtained results, a decision has been made to use 530 mW 1553.9 nm pumping radiation in the case of both FOPA, because this is the lowest pump power that can ensure BER values below the 10^{-12} threshold in both the 1st and the 2nd channel. Previously described results have shown that phase modulation of the pump can cause spectral broadening of idlers. In a situation, when the probability that both orthogonally polarised optical radiations are observed simultaneously in the logical “1” level is high, the mutual deviations of the SOP of optical components have a bigger impact on the quality of the amplified signal than in the case when such simultaneous transmission of logical “1” is not performed (for example, in the case of 2PolSK signal). Therefore, it is important to minimise the phase mismatch between the pumping radiation and the amplified signals, which can also cause a change of the relative positioning of SOP between the signal and the pump. Bearing in mind this fact and having observed the FOPA produced gain spectrum and in the OSNR at the output of the amplifier, the following frequency tones have been selected for pumping radiation phase modulation: 0.13 GHz, 0.42 GHz, 1.087 GHz and 1.94 GHz. The obtained signal gain in the 1st channel has reached 20 dB, whereas in the 2nd channel — 20.1 dB. Idler component gain maximum is lower by 0.7 dB (see *Fig. 22*).

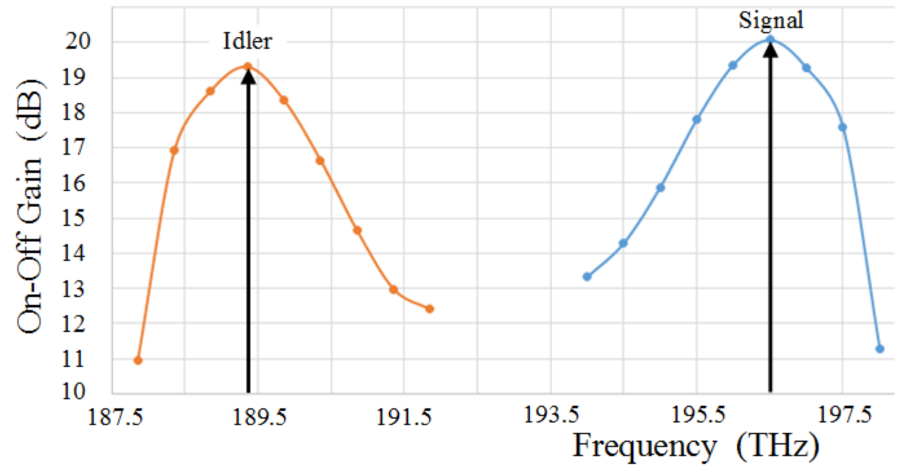

Fig. 22. FOPA produced on-off gain for the 1st channel at idler frequencies (orange line) and at the initial signal frequencies (blue line).

To assess the performance of the proposed solution BER value dependence on the received signal power is obtained, and these results are compared with the same results obtained in a standard single-channel transmission system with NRZ-OOK modulation format without optical signal amplification. It can be concluded from the results shown in *Fig. 23* that there is a power penalty of 0.8 dB between the signal detected in the 1st channel and the signal from the standard single-channel NRZ-OOK system. The power penalty for the idler spectral component has reached 0.5 dB.

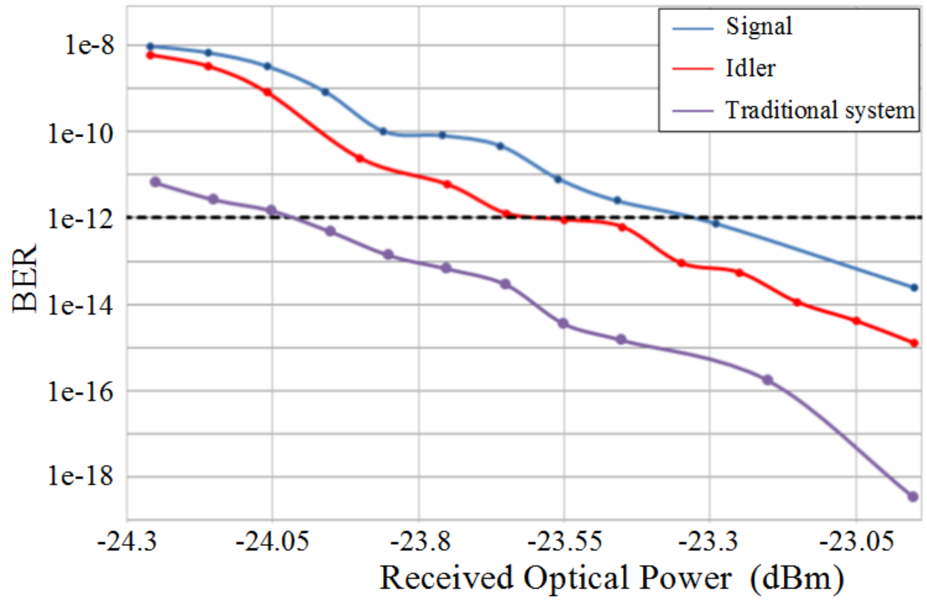

Fig.23. BER value dependence on the power of the detected signal in the standard single-channel system (violet) and in the 1st channel of the system with the chosen FOPA configuration of the signal at its initial frequency (blue) and of the idler (red).

Unlike the system with modulation format conversion, in this case, a situation has been observed, when, given the same frequency, it is possible that the logical "1" of orthogonally polarised components is observed simultaneously in both channels. Thus, the effect of orthogonally polarised radiation on the divided signal quality is higher than in a system with modulation format conversion. This is the fact, which mainly explains a larger power penalty value than in a single-channel system with modulation format conversion. A lower power penalty value in the case of idler component is explained by the fact that the orthogonally polarised radiation of the 2nd channel is not included in the parametric amplification and idler generation process, and, therefore, it is not reflected in the idler itself. Irrespective of the fact that the amplification of orthogonally polarised (2nd channel) radiation is much lower (1–2 dB), its power level is still sufficiently high to affect the BER value of the divided signal, which in our case produces an additional power penalty of 0.3 dB. The idler use has allowed achieving a lower power penalty in respect to the standard single-channel system with the NRZ-OOK modulation format, whereas to achieve a BER value below the 10^{-12} threshold it is necessary to use pump power that is larger by 10 mW than that when receiving the initial signal with 196.5 THz frequency.

Upon comparing the amplification spectra in a single-channel system with modulation format conversion and in a system with polarisation multiplexed signal division, it has been concluded that the amplification obtained in the latter case is larger by 5.2 dB (14.8 and 20 dB, respectively), irrespective of the fact that the pumping radiation power differs only by 5 mW. This is explained by the following two factors:

- In a system with signal division from orthogonally polarised signal combination, the signal power level at the input of the HNLF fibre is lower by 3.4 dB (–44.1 dBm). Therefore, the amplifier requires a lower pumping radiation power for ensuring a specific amplification level.
- Secondly, to minimise the idler spectral broadening in a system with polarisation multiplexed signal division, the frequency tones used for pumping radiation phase modulation are reconfigured, and the achieved amplification difference clearly shows that with the given configuration SBS mitigation is more effective than in a system with modulation format conversion.

Upon summing up all the information presented in this chapter, it can be concluded that polarisation dependence of the parametric amplification can be used for emphasising optical radiation with a specific state of polarisation from a flow of two orthogonally polarised optical radiations. FOPA with linearly polarised pumping radiation can be used both for 2PolSK signal conversion into NRZ-OOK modulation format and for signal emphasising from a flow of two polarisation multiplexed optical signals. In both cases, such FOPA configurations have been found, which ensure that the BER values of the processed signal are below the 10^{-12} mark, at the same time, none of the proposed solutions cause power penalty that exceeds 1.8 dB in comparison with the relevant standard solutions.

MAIN RESULTS OF THE DOCTORAL THESIS

Upon performance of the tasks defined in the first chapter of the present Thesis, the following **main results and conclusions of the Doctoral Thesis** have been reached:

1. The implementation of the hybrid Raman-EDFA amplifier has allowed not only equalising the gain spectrum, but also increasing OSNR in all channels by 1.7–2.6 dB. The usage of the distributed Raman amplifier in cascade as a pre-amplifier has allowed the EDFA to operate closer to the saturation point and, therefore, the EDFA noise figure decreased by 0.3–0.4 dB. The OSNR increase is also related to the fact that due to the coherent nature of Raman scattering, DRA amplifies the signal more effectively than the noise, which allows obtaining negative noise figure values (from –0.4 to – 0.6 dB);
2. The implementation of the hybrid Raman-SOA amplifier has enabled the use of such SOA configuration, at which SOA produced the lowest amount of amplified signal distortions. As a result, by using the Raman-SOA hybrid amplifier, it is possible to obtain approximately the same BER level as in the case when the SOA is used as a single in-line amplifier for a signal, which is weaker by 1.5 times. This has allowed increasing the attainable transmission distance by 12 km or by 11 %;

3. While changing the power of FOPA pumping radiation, the non-linear phase mismatch of the parametric process also changes. Therefore, while configuring the pump power, the wavelength must also be changed accordingly;
4. Modulating of the FOPA pumping radiation phase, which has been used for increasing the SBS threshold, has caused spectral expansion of idlers by 54 %. Therefore, the frequency tones used in systems with wavelength conversion for pumping radiation phase modulation must be selected in a way that ensures that the spectral expansion of idlers remains as low as possible;
5. By manipulating with the parameters of dual-pump FOPA, it is possible to achieve an increase in the number of carrier signals from 16 to 32, simultaneously ensuring equal channel spacing of 100 GHz and maximum difference in power levels of 1.9 dB among all channels. It has been found that, in case when each carrier signal power at the input of the FOPA is equal to 0 dBm, the CC-FWM interactions produce considerable inter-channel crosstalk. Due to this reason, when using the idlers to double the number of carriers, it is necessary to control the power of carrier signals in the amplifier input;
6. It has been found that even when using polarisation maintaining HNLF fibres, due to the influence of self-phase modulation and cross-phase modulation, a change in interposition of SOP of the signal and FOPA pumping radiation has been observed, as they are transmitted through HNLF. As result, the signal, the SOP of which is orthogonal in respect to the SOP of the pumping radiation at HNLF input, has been amplified by 1.5–1.6 dB;
7. In a single-channel system with 2PolSK signal conversion to NRZ-OOK modulation format, power penalty of 0.4 dB has been observed between the NRZ-OOK signal from the standard single-channel system and the converted signal. Whereas, in the case of the idler spectral component, the power penalty is lower by 0.2 dB. These results can be explained by the fact that the idler produced by the parametric FWM process does not contain the logical "0" component radiation from initial 2PolSK signal, which for the converted NRZ signal is interpreted as noise;
8. In the multi-channel system with modulation format conversion, a more explicit manifestation of CC-FWM processes has been observed among the idlers rather than among channels at initial frequencies. This can be explained by the fact that pump power exceeding 35 mW is required to obtain BER values below the 10^{-12} threshold in all 8 channels in the idler frequency band than for signals at their initial frequencies. As a result of such amplification difference, more explicit CC-FWM manifestation has been observed, which accordingly has led to additional inter-channel crosstalk. Additionally, crosstalk generated by CC-FWM has not only been transferred to the idlers from the signals at their initial frequencies, but also generated among the idlers;
9. Unlike the system with modulation format conversion, in the system with signal emphasising from the flow of two orthogonally polarised signals, a situation is observed, when at the same frequency it is possible that the logical "1" components are observed in both channels simultaneously. Therefore, the influence of orthogonally polarised radiation on the quality of the emphasised signal is larger by 0.4 dB (in the case of idlers, by 0.3 dB) than in a system with modulation format conversion.

The results of the scientific research conducted within the Doctoral Thesis have been used in the implementation of international scientific research projects "Smart Urban Technologies for Improving the Quality of Life" (ESF) and "Development of High-Speed Optical Access Networks and Elements" (ERDF), as well as "Technologies for a Secure and Reliable Smart City" (state research programme) and "Active Wavelength Division Multiplexed Hybrid Fibre Optic Transmission System" (RTU). Within the framework of the co-operation agreement, the topicality of increasing the amplification efficiency of optical signals in fibre optic transmission systems has been included in the project prepared for the SJSC "Latvijas Valsts Radio un

Televīzijas Centrs" — "Assessment of Backbone Network Technologies and the Main Tendencies of Their Design" (ERDF project No. 3DP/3.2.2.3.0/12/IPIA/SM/001 "Development of Next Generation Broadband Electronic Communications Networks in Rural Areas").

Based on the results presented in the present Doctoral Thesis, a Latvian patent application has been prepared about the development of a multicarrier light source in a wavelength division multiplexed fibre optic access network. The patent application number is P-15-45.

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