RIGA TECHNICAL UNIVERSITY
Faculty of Electronics and Telecommunications
Institute of Telecommunications

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DEVELOPMENT AND EVALUATION OF HIGH-SPEED OPTICAL ACCESS SYSTEMS

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering Sciences (Telecommunications), the present Doctoral Thesis is to be defended publicly on June 30, 2015 at the Faculty of Electronics and Telecommunications, Riga Technical University, Azenes Str. 16/20.

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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 Engineering Sciences 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 any other scientific degree.

Sandis Spolītis ……………………………. (Signature)

Date: ………………………

This Doctoral Thesis has been written in Latvian and consists of an introduction, 4 chapters, conclusion, bibliography with 174 reference sources, 5 appendices. It has been illustrated by 88 figures. The volume of the Doctoral Thesis is 163 pages.

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No sirds pateicos savai ģimenei: tēvam Guntim, mātei Initai, māsai Elīnai un maniem mīļajiem vecvecākiem. Bez jūsu palīdzības, atbalsta un mīlestības man tas nebūtu izdevies. Paldies Zanei, ka esi bijusi manas dzīves nozīmīga daļa doktorantūras laikā.

Paldies visiem, ar kuriem kopā esmu strādājis vai kuri mani ir atbalstījuši, bet kuru vārds šeit nav pieminēts.

Topicality of the Research

Nowadays, information transmission technologies using the optical fiber as the medium of information transmission bear a major importance in the field of telecommunications. The rapidly increasing volume of data flows to be transmitted demand a faster introduction of technologies in the telecommunications sector. Services like high-speed Internet and 3D television, which are ensured using one and the same client connection, demand ever increasing data transmission speeds [26]. The analysis performed by the company *Cisco* [8] shows that the data amount transmitted in access and metro networks has experienced a rapid increase, and already in 2013 exceeded the data flow amount transmitted in long-haul networks (see Fig. 1). This rate of increase will also continue further on and it is expected that in 2018 the amount of data transmitted in access and metro networks will amount to 62 % of the total transmitted data amount [8].

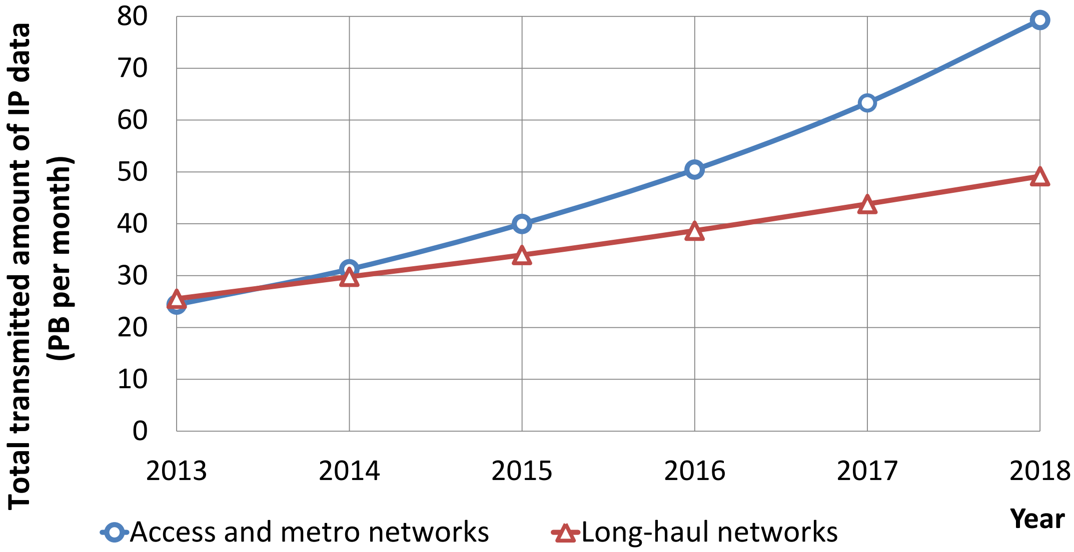

Fig. 1. Cisco global transmitted traffic forecast for the time period from 2013 to 2018 [8].

Bearing in mind the fact that the largest increase in the transmitted data amounts is observed at the access level, particular attention must be paid specifically to optical access networks. Most often, information transmission in these optical access lines right to the client's apartment or house is ensured using a single optical fiber (OF) [13, 14].

The subject-matter examined in the Doctoral Thesis is topical because currently Latvia is undergoing a rapid development of the communications sector [14, 49, 50]. As of now, the existing optical access communications systems are using time division multiplexed passive optical network (TDM-PON) technology, but within the upcoming five years, as the need for bigger data transmission speeds increases, it will be necessary to update the existing network infrastructure and to introduce a high-speed wavelength division multiplexed passive optical network (WDM-PON) technology, which can ensure higher data transmission speeds (over 2.5 and 10 Gbit/s) at a longer distance (at least 20 km) than the current TDM-PON technology can provide (with transmission speeds of up to 2.5 Gbit/s) [2, 37, 38, 46, 51].

The growing amount of Internet users and data flows (from such services as online video games, high resolution video streaming, telemedicine services, video conferencing, computerised high frequency trading systems and others) pose several challenges for the communications network operators, and they are forced to improve the infrastructure of the fiber optical network [6, 28]. Therefore, optical access networks must be capable of ensuring ever higher data transmission speeds (2.5 and 10 Gbit/s) with lower signal latency, by using the existing electrical and opto-electrical components inasmuch as possible. It must be mentioned that an ERDF project "Next Generation Electronic Communications Networks in Rural Areas" is being implemented in Latvia since 2012; its aim is to develop next generation networks (NGN) in the remote rural areas of Latvia and to promote the achievement of the Europe 2020 strategy targets (by 2020, to ensure that all households have an option to receive access to Internet at a minimum speed of 30 Mbit/s and 50 % of households in 2020 will have the Internet with the access speed of at least 100 Mbit/s) [52]. The project provides for developing a 7000 km long optical line which would ensure optical network access at 500 connection points. Thus, it will be necessary to ensure access technologies that perform "last mile" data transmission, which is the network from the service provider's access point to an individual telecommunications service user [52]. The technologies and solutions developed within the framework of the Doctoral Thesis can be fully used for successful implementation of the aforementioned project and for ensuring communications services from the service provider to the end-user.

The Aims and Tasks of the Thesis

Upon summing up the aforementioned facts, the following **aim of the Doctoral Thesis** is proposed: to assess methods of enhancing the performance of WDM optical access communications systems using theoretical and experimental research.

To achieve the aim set, it is necessary to perform the following **key tasks**:

1. To assess the technological solutions of time division multiplexed (TDM) and wavelength division multiplexed (WDM) optical access communications systems and their key elements;
2. To assess the application of chromatic dispersion compensation methods in improving data transmission quality and increasing the maximum transmission distance, by creating up to 16 channel WDM-PON and SS-WDM PON communications system simulation models with the transmission speed of up to 10 Gbit/s per channel;
3. To develop a powerful broadband ASE light source model with a flat curve of output optical signal frequencies, which can be used for implementing an up to 16 channel SS-WDM PON system in the C band (1530–1565 nm);
4. To create an experimental model of WDM-PON and SS-WDM PON communications systems with dispersion compensation and to perform the possible comparative analysis of practically obtained results with simulation data;
5. To develop a prototype of an electro-optical spectrum sliced transceiver for transmitting and receiving high-speed optical signals, as well as to assess its performance, by implementing 1 Gbit/s NRZ electrical signal slicing, transmission via 25 km standard single-mode optical fiber span, and reconstruction using a limited up to 500 MHz electrical component frequency throughput band;
6. To assess the causes of latency of the signal to be transmitted in high-speed optical access systems and to create a model for achieving a smaller time delays of these systems inasmuch as possible.

The Research Methods

To perform the tasks set forth in the Doctoral Thesis and to analyze the problems, mathematical calculations, numerical simulations, and experimental measurements are used. For implementing WDM-PON and SS-WDM PON systems, nonlinear Schroedinger equation was used in numerical simulations, along with the direct and inverse fast Fourier transform, as well as the Monte Carlo method for assessing the bit error ratio (BER).

In digital signal processing (DSP) of the spectrum sliced transceiver, direct and inverse fast Fourier transform is used to perform multiple signal processing in the frequency and time domain. To assess the optical signal quality in a simulated environment and in real experiments, measurements of power, spectrum, eye diagrams, and bit error ratio were used. Scientific experiments described in the Doctoral Thesis were performed at the laboratory of fiber optics transmission systems of RTU Institute of Telecommunications (Latvia) and at the laboratory of the DTU Fotonik Institute Metro-access and Short Range System Group (Denmark).

Research Results and Scientific Novelty

Novel achievements of the Doctoral Thesis are as follows:

1. A numeric model of a powerful broadband ASE light source has been developed, ensuring +23 dBm (200 mW) average output power with basically flat curve of frequency transmission ranging from 192.3 THz to 194.0 THz (from 1545.32 nm to 1558.98 nm).
2. Technological solutions of 8 and 16 channel SS-WDM PON systems with the transmission speed of up to 10 Gbit/s in a channel have been developed enabling them to be fully integrated in the existing optical access networks, based on ITU-T G.694.1 frequency plan.
3. The application of the semiconductor optical amplifier has been evaluated increasing the data transmission speed from 2.5 to 10 Gbit/s in 16-channel spectrum sliced WDM-PON systems.
4. A model of spectrum sliced transceiver has been developed, which, by using digital signal processing (DSP), enables the transmission of 1 Gbit/s NRZ sliced broadband electrical signal, using electrical and opto-electrical system components with 500 MHz bandwidth, thus enabling to achieve a higher-speed data transmission using the already existing transmission system infrastructure.
5. The main causes of latency in optical TDM and WDM access systems have been evaluated, and ways have been found of how to reduce the overall typical transmission line latency by more than 20 %.

The following **main conclusions** have been drawn during the development of the doctoral thesis:

1. By employing chromatic dispersion compensation methods (DCF and FBG), 16-channel WDM-PON access systems with the transmission speed of 10 Gbit/s per channel, it is possible to increase the maximum transmission distance by more than 25 % (up to 70 km).
2. In case of dispersion compensation, it is possible to achieve a lower received signal BER by using fiber Bragg grating (FBG) instead of dispersion compensating fiber (DCF). It can be explained with the fact that FBG can be used at higher optical transmission powers, as it generates fewer nonlinear optical effects, which can distort the transmitted optical signal, as well as the amount of its introduced losses (around 3.5 dB per one DCM module) is typically smaller than in the case of DCF fiber (around 0.6 dB/km).
3. To establish a broadband ASE light source with the output power of at least +23 dBm (200 mW) and a flat curve of output optical signal spectrum in the system operation range (C-band), which are necessary for creating a 16-channel SS-WDM PON system, two cascaded EDFA amplifiers can be used, by adapting their parameters (erbium doped fiber length, pump light source capacity and wavelength).
4. Sliced electrical 1 Gbit/s NRZ signal can be transmitted through up to 25 km long SMF, DSF and NZ-DSF fibers, received and fully restored its 1 GHz frequency baseband form, by transmitting and combining 500 MHz wide frequency bands in the spectral width of sliced electrical component baseband.
5. In optical access-metro communications systems, it is possible to reduce the latency parameter by at least 20 %, if using the solution proposed in the Thesis, suggesting replacing the existing optical and opto-electrical system elements with lower delay elements.

The Practical Value of the Research

1. The results of scientific research of the Doctoral Thesis have been applied in the implementation of 3 international and 5 Latvian scientific research projects.
2. The recommendations prepared during the development of the Doctoral Thesis are intended for improving already operating optical access networks and for introducing new ones. The research results have been used in the improvement of fiber optical transmission systems of Ltd "Telia Latvija" and in the development of the ERDF project implemented by the Latvian State Radio and Television Centre "Next Generation Electronic Communications Networks in Rural Areas", as well as in the State Research Program (SRP) "Cyber-physical Systems, Ontologies and Biophotonics for Safe & Smart City and Society" (SRP SOPHIS).
3. A wavelength division multiplexed optical access system with chromatic dispersion compensation, patented in Latvia, has been developed on chirped fiber Bragg grating (FBG) base.
4. An experimental SS-WDM PON communications system model has been developed, and it can be enhanced with new elements and expanded up to even 10 Gbit/s transmission speed per channel; it is intended for further experimental studies.
5. Experimental spectrum sliced transceiver model has been developed, which can transmit, receive and restore 1 Gbit/s NRZ electrical signal, by slicing it into two frequency slices, where each of them takes up to 500 MHZ frequency baseband.

Thesis Statements to Be Defended

1. In wavelength division multiplexed PON access systems with the number of channels of up to 16 and transmission speed of up to 10 Gbit/s per channel it is possible to achieve increased maximum transmission distance even over 25 %, by using dispersion compensation with FBG grating.
2. In optical access communication systems, using the spectrum slicing technology, it is possible to transmit, receive, and restore a signal that is spectrally at least two times broader than possible in the existing electrical element frequency throughput band.
3. It has been proven in the Thesis that the signal latency accumulated in fiber optical access communications systems can be reduced by up to over 20 %, by replacing the exiting optical network components with the author's proposed lower introduced latency components.

Approbation of Research Results

The main results of the Doctoral Thesis have been presented at **21** international scientific conferences, reported in **4** publications in scientific journals, **16** publications in the full-text conference proceedings, **1** scientific monograph, **7** publications in the conference books of abstracts**, 2** Latvian patents and **1** application of Latvian patent.

Reports at the **international scientific conferences**:

1. Wagner C., Madsen P., **Spolitis S**., Vegas Olmos J.J., Monroy I.T. Sliceable transponders for metro-access transmission links// SPIE Photonics West 2015 – Optical Metro Networks and Short-Haul Systems (OPTO). **United States of America**, San Francisco, February 10–12, 2015 **(Invited).**
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5. **Spolitis S.,** Ivanovs G. Realization of up to 10 Gbit/s Spectrum Sliced Optical Access System// 8th International Conference "Advanced Optical Materials and Devices" (AOMD-8), Riga, **Latvia,** August 25–27, 2014.
6. **Spolitis S.**, Olonkins S., Porins J. Realization of Dense Bidirectional Spectrum Sliced WDM-PON Access System// 9th International Symposium on Communications Systems, Networks and Digital Signal Processing (CSNDSP 2014), **England,** Manchester, July 23–25, 2014.
7. Bobrovs V., **Spolitis S.,** Trifonovs I., Ivanovs G. Spectrum Sliced WDM-PON System as Energy Efficient Solution for Optical Access Systems// 5th IEEE Latin America Conference on Communications (LATINCOM 2013), **Chile,** Santiago, November 24–26, 2013.
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12. **Spolitis S.**, Bobrovs V., Ivanovs G. New Generation Energy Efficient WDM-PON System Using Spectrum Slicing Technology// 4th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT 2012), **Russia**, Saint Petersburg, October 3–5, 2012.
13. **Spolitis S.**, Bobrovs V., Ivanovs G. Investigation of High-Speed AWG Filtered Spectrum-Sliced WDM PON System// 8th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2012), **Poland**, Poznan, July 18–20, 2012.
14. **Spolitis S.**, Bobrovs V., Berezins S., Ivanovs G. Optimal Design of Spectrally Sliced ASE Seeded WDM-PON System// 15th International Telecommunications Network Strategy and Planning Symposium (NETWORKS 2012), **Italy,** Rome, October 15–18, 2012.
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1. Wagner C., Madsen P., **Spolitis S.,** Vegas Olmos J.J., Monroy I.T. Sliceable transponders for metro-access transmission links// Proceedings of SPIE Photonics West 2015, Optical Metro Networks and Short-Haul Systems (OPTO). – San Francisco, USA, February 10-12. – 2015. – pp. 1–11, **(Invited).**
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Latvian patents:

1. Bobrovs V., **Spolitis S**., Udalcovs A., Parts R., Ivanovs G.WDM-PON fiber optical access communication system with dispersion compensation, No. LV-14628, 2012.
2. Bobrovs V., Ozolins O., **Spolitis S**., Udalcovs A., Ivanovs G. Measurement scheme for evaluation of efficient bandwidth of wavelength filter, No. LV-14557, 2012.
3. Udalcovs A., Ozolins O., **Spolitis S**., Parts R., Bobrovs V. Mixed line rate wavelength division multiplexing communication system, patent application No. P-12-15, 2014.

Results of the Doctoral Thesis have been used for implementation of 3 international and 5 Latvian scientific research projects:

International scientific research projects:

1. ERDF project: “Next Generation Electronic Communications Networks in Rural Areas”. Project No. 3DP/3.2.2.3.0 /12/IPIA/SM/001
2. EU FP7 Research Project: “FENDOI” – Flexible Edge Nodes for Dynamic Optical Interconnection of Access and Core Networks. Project Ref. No. 322328.
3. EU FP7 Research Project: “IPHOBAC-NG” – Integrated Photonic Broadband Radio Access Units for Next Generation Optical Access Networks. Project Ref. No. 619870.

Latvian scientific research projects:

1. National Research Program: “Cyber-physical Systems, Ontologies and Biophotonics for Safe & Smart City and Society.” (SRP SOPHIS). Project No.10–4/VPP–4/11.
2. ESF project: “Establishment of ICT Group for Transmission, Processing and Management of Large Data Amounts”. Project No. 2013/0012/1DP/1.1.1.2.0/13/ APIA/VIAA/051.
3. ERDF project: “Design of High-speed Optical Access Networks and Elements”, No. 2010/0270/2DP/2.1.1.1.0/10/APIA/VIAA/002.

4. ESF project "Smart City Technologies to Improve the Quality of Life". Project No. 2013/0008/1DP/1.1.1.2.0/13/APIA/VIAA/016.
5. ESF project: "Support for the Implementation of Doctoral Studies at Riga Technical University", Project No. 2009/0144/1DP/1.1.2.1.2/09/IPIA/VIAA/005.

The Volume and Structure of the Doctoral Thesis

The volume of the Doctoral Thesis is 164 pages. It consists of an introduction, four chapters, bibliography and five appendices.

The first chapter of the Thesis proposes the aim of the research along with the tasks, scientific novelty, thesis statements as well as offers a summary of the main results and defines further research directions.

The second chapter of the Thesis deals with studying and evaluating WDM-PON and spectrum sliced WDM-PON or SS-WDM PON systems in simulated OptSim program environment and experimentally at the laboratory of fiber optical transmission systems (FOTS) of RTU Institute of Telecommunications. In this chapter, the implementation of WDM-PON and SS-WDM PON systems is evaluated along with the increase of signal quality, system performance and maximum transmission distance, using chromatic dispersion compensation methods — dispersion compensating fiber (DCF) and fiber Bragg grating (FBG). Unlike other previously conducted studies in the field of fiber optical access systems, a numeric comparison has been performed between DCF and FBG dispersion compensation methods. The WDM-PON system scheme with dispersion compensation as developed within the chapter is patented in Latvia (certificate No. LV-14628).

The third chapter considers the development of a new type of spectrum sliced transceiver, where the transmitted baseband signal slicing and combining are effectuated in an electrical environment of transceivers, by employing digital signal processing (DSP). These studies have been conducted during the doctoral internship at the Technical University of Denmark, the Laboratory of the Metro-Access & Short Range Systems Group, in collaboration with researchers representing DTU Fotonik (Denmark) and Heinrich Hertz Institute (Germany) under the supervision of Professor Idelfonso Tafur Monroy and Assoc. Prof. Juan José Vegas Olmos. Within the co-operation, an electro-optical spectrum sliced transceiver prototype was successfully developed for high-speed optical signal transmission and receiving, as well as its operations are assessed by 1 Gbit/s NRZ electrical signal slicing, transmission through a 25 km long standard single-mode optical fiber section, and reconstruction, using a limited up to 500 MHz frequency throughput band of electrical components.

The fourth chapter of the Thesis evaluates the main causes of latency in optical access systems. As a result of the analysis, it is found that the overall access system latency can be reduced by at least 20 %, by replacing typical optical and electrical components with other − low latency components, without changing the access network typology.

The Doctoral Thesis is concluded with summarized and justified main conclusions of the research. The appendices include lists of conferences, publications, projects, Latvian patent certificates and recommendations from the doctoral internship.

SUMMARIES OF CHAPTERS OF THE DOCTORAL THESIS

Chapter 1

The first chapter of the Doctoral Thesis evaluates the development of fiber optical transmission systems. Moreover, a comparative analysis is performed between time division multiplexed passive optical networks (TDM-PON) and wavelength division multiplexed passive optical networks (WDM-PON). In optical access and metro-networks, the transmitted data amount has experienced a rapid increase, and the increase rate will also be preserved further on; therefore, particular attention should be paid specifically to these networks [8].

Currently, Latvia is experiencing a rapid development of data transmission systems and Internet [14, 49, 50], using TDM-PON technology; however, over the upcoming five years, as the need for higher data transmission speeds increases, it will be necessary to update the existing network infrastructure and to introduce a high-speed WDM-PON technology, which can provide higher data transmissions speeds (2.5 and 10 Gbit/s per channel) at a bigger distance (over 20 km) than the existing TDM-PON technology can with the incoming data flow being divided to all optical network terminals (ONT) [37, 38, 46].

Next generation PON systems (NGPON) can be implemented using the existing infrastructure, for instance, on the GPON system base, by upgrading it (NGPON1 solution), or on the basis of a completely new fiber optical network infrastructure (or upon performing a partial network infrastructure replacement), where the optical power splitter is replaced with an optical signal splitter according to light wavelengths (NGPON2 solution) [47, 48]. Upon considering the available fiber optical transmission system technologies, it was concluded that WDM-PON and spectrum sliced WDM-PON systems, which have been studied in the Doctoral Thesis, are fully suitable for a higher speed NGPON2 technological solution, see Fig. 2 [5, 7, 12, 20, 32-35, 40]. Application of wavelength division multiplexing in optical access networks enables the option for each user to assign a separate optical wavelength.

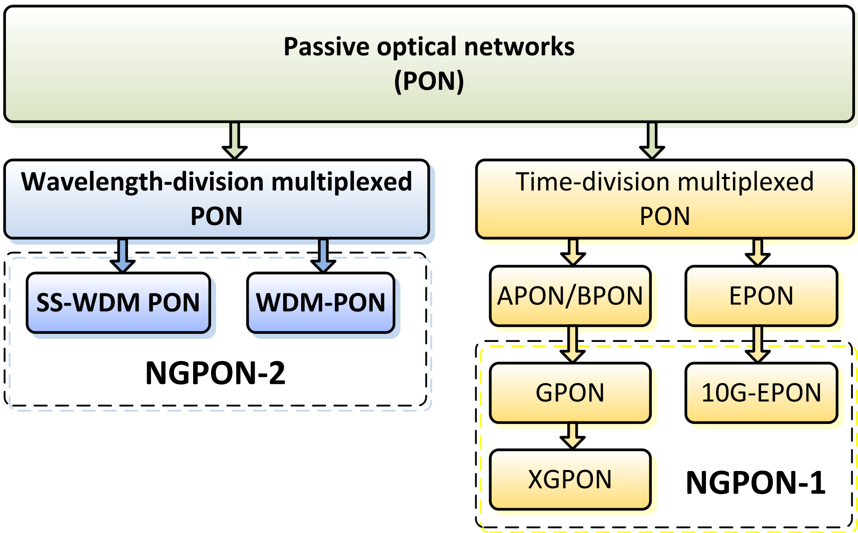
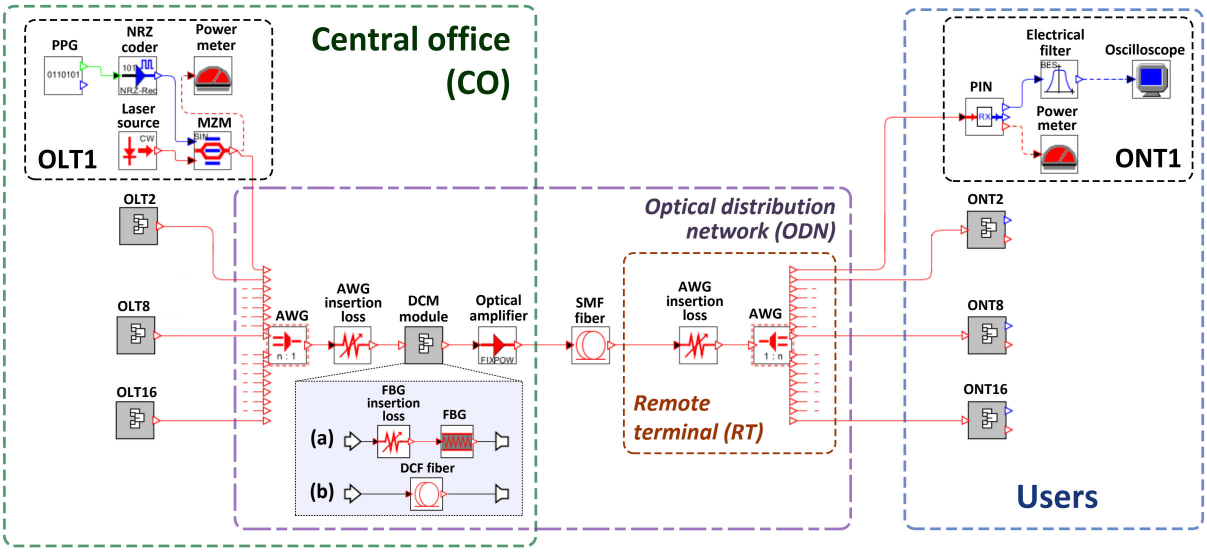


Fig. 2. Classification of passive optical access networks (PON).

In order to achieve a data transmission speed in NGPON systems of 2.5 and 10 Gbit/s for each user, a very significant aspect is the accumulated chromatic dispersion compensation [3, 4, 36]. Without using the chromatic dispersion compensation, the maximum achieved transmission distance (typically 20 km) and speed (2.5 Gbit/s) are significantly limited, as the impulse sequence, transmitted as a result of it, is distorted and loses its form. The next generation passive optical network (NGPON) infrastructure is affected by two main requirements: it must ensure a high frequency throughput band and data transmission speed, as well as a sufficiently low network delay or latency, all the while maintaining network architecture as simple as possible [27, 48]. Electrical and opto-electrical components, which are located in the transmitter and receiver block (transceiver) of the high-speed fiber optical transmission system, are considered to be its weak point, as they feature a limited frequency throughput band (in optical access networks, typically from 2.5 to 10 GHz), and accordingly also the transmission speed (2.5 or 10 Gbit/s) [28, 39]. Therefore, it is necessary to seek for solutions of how to increase this frequency throughput band in the existing transceivers [39, 41]. It must be borne in mind that by increasing the data transmission speed and distance, depending on the contents of the transmitted information, the latency parameter of the optical transmission system becomes ever more important. Latency is the time between sending and receiving a message. Latency increases as the optical signal propagates through fiber or other elements, affecting the overall data transmission speed [29, 31]. Contrary to the frequency throughput bandwidth, latency and jitter depend on the transmission system network topology (the number of elements used, line length etc.) and data flow parameters (transmission speed, data packet length etc.) [24]. It is particularly important in NGPON access networks, where a large part of the transmitted data amount is made of high resolution television, online videogames, high quality video streaming, computerized high frequency trading systems, video conferences and other online services [15].

Chapter 2

The second chapter of the Doctoral Thesis deals with WDM-PON and spectrum sliced WDM-PON or SS-WDM PON system development and research in a simulated OptSim program environment and experimentally at the Laboratory of Fiber Optical Transmission Systems (FOTS) of RTU Institute of Telecommunications. In creating up to 16-channel WDM-PON and SS-WDM PON communications system simulation models with the transmission speed of up to 10 Gbit/s per channel, the improvement of signal quality, system performance, and maximum transmission distance is evaluated by using chromatic dispersion (CD) compensation methods − dispersion compensating fiber (DCF) or fiber Bragg grating (FBG). To assess the performance of the developed systems, BER threshold of $BER < 1 \cdot 10^{-9}$ [1] is selected for WDM-PON transmission systems in the OptSim simulation program, whereas in the SS-WDM PON system it is selected at $BER < 1 \cdot 10^{-10}$ [19]. By applying the obtained simulation and experimental results, a WDM-PON fiber optical access communications system with dispersion compensation on chirped fiber Bragg grating basis is developed and patented with the Latvian patent No. LV-14628.



AWG – Arrayed waveguide grating
DCF – Dispersion compensating fiber
DCM – Dispersion compensation module
FBG – Fiber Bragg grating
MZM – Mach-Zehnder modulator
NRZ – Non-return-to-zero coding
OLT – Optical line terminal
ONT – Optical network terminal
PIN – PIN photodiode
PPG – Pulse pattern generator
SMF – Single-mode fiber

Fig. 3. Simulation scheme of dense 16-channel WDM-PON access system with NRZ coding, 10 Gbit/s transmission speed per channel and DCM module located in central office (CO).

Chromatic dispersion compensation in wavelength division multiplexed access systems with the transmission speed of 2.5 and 10 Gbit/s per channel is very important, because the optical impulse, as it propagates in a fiber, loses its shape and becomes distorted due to the dispersion. Along with the light impulse broadening it interferes in time with impulses, which propagate alongside, thus restricting the maximum data transmission speed and the maximum ensured transmission distance of the fiber optical access system [1, 25]. The impulse broadening is the cause of intersymbol interference (ISI), as a result, the received signal can contain errors, because on the receiver side it is impossible to accurately discern the sequence of the transmitted bits. Within the framework of the chapter, high-speed multichannel WDM-PON and SS-WDM PON access communications systems with dispersion compensation were created through simulation and experimentally corresponding to the NGPON2 technological solution with partial replacement of the existing network infrastructure. Therefore, initially, 16-channel WDM-PON system with data transmission speed of 10 Gbit/s per channel was realized in the OptSim simulation program (see Fig. 3).

Output spectrum of 16-channel WDM-PON system before the AWG demultiplexer separating the optical signal incoming from the OLT (transmitter side) to all ONT terminals is seen in Fig. 4.a.

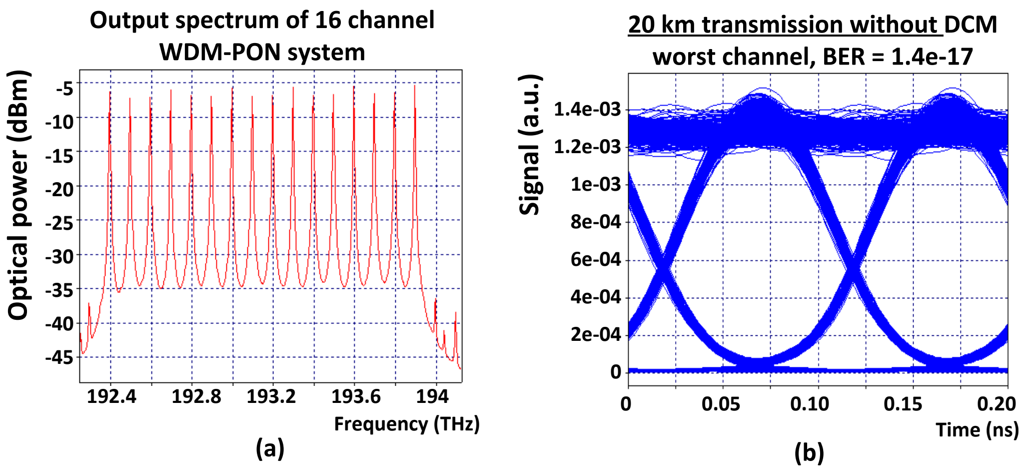


Fig. 4. Realized WDM-PON system's (a) 16-channel output spectrum after AWG demultiplexer and (b) eye diagram of the worst channel, without use of CD compensation.

Figure 4.b shows that after the transmission through a 20 km long optical line section, the system performance is still very high (BER = $1.4 \cdot 10^{-17}$), therefore, by increasing the line length, it was estimated that the maximum ensured data transmission distance between the transmitter (OLT) and the receiver (ONT) is 57 km, without using CD compensation, at BER < 10^{-9}.

To improve the performance of a WDM-PON system, CD compensation with DCF fiber and FBG grating was used. The dispersion compensation module (DCM), consisting of dispersion-compensating optical fiber, typically features a rather high attenuation (up to 0.6 dB/km at $\lambda = 1550$ nm) and negative dispersion (normally $D \approx -80$ ps/nm/km), which compensates for the positive chromatic dispersion accumulated in the fiber optical transmission line (its amount normally is $D \approx 16$ ps/nm/km), or it performs chromatic dispersion pre-compensation [1, 4]. This negative dispersion for DCF fiber is achieved in the manufacturing process, by creating a complex fiber light refractive index profile [1, 11].

The fiber refractive index in the Bragg grating used in the DCM module, suitable for multichannel WDM systems, features a periodic structure with periods that are not constant but change lineally along with the fiber length. The grating period Λ, nm is the distance between two contiguous light refractive index maximums [1, 25]. Due to its changing structure, a chirped Bragg grating reflects certain wavelengths λ_B from specific optical fiber points, but does not affect the propagation of other wavelengths in the grating. The wavelength which will be reflected in the Bragg grating is expressed with the following equation:

$$\lambda_B = 2\Lambda n_g, \quad (1)$$

where λ_B — reflected wavelength, nm;
Λ — grating period, nm;
n_g — effective group refractive index of fiber.

Such grating of variable structure is obtained on the basis of germanium doped silicon optical fiber, in a small optical fiber core segment treated with ultraviolet light. At the beginning of Bragg grating the grating period is smaller, but as the length of the grating increases, the period width is increasing lineally. Therefore, shorter signal wavelengths are reflected sooner and have less propagation delay through the fiber Bragg grating, but longer signal wavelengths travel further into the grating before they are reflected back and accordingly have more propagation delay, resulting in reconstruction of the dispersion-affected light impulse form [11].

Initially, CD compensation was performed in WDM-PON system using 7 km long DCF fiber in the dispersion compensation (DCM) module, which allowed increasing the transmission distance from 57 km to 68 km, while preserving BER < 10^{-9}, see Fig. 5a. Whereas, when using the variable FBG DCM module (see Fig. 5b), the necessary compensated CD amount at $\lambda = 1550$ nm was found −1100 ps/nm, which allowed increasing the transmission distance of WDM-PON system from 57 km to 72 km, at BER < 10^{-9}.

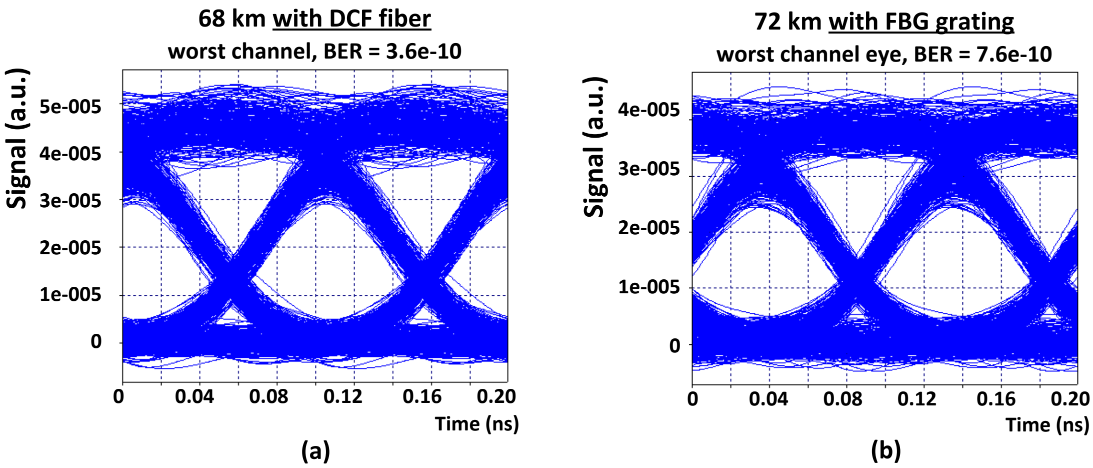


Fig. 5. Eye diagrams of received signal at maximum achieved distance in WDM-PON system by realizing CD compensation with (a) DCF DCM and (b) FBG DCM.

As seen from the results, the use of DCF for CD compensation allowed improving the transmission distance of system by 19 %, whereas the use of FBG by 26 %. In this case, FBG DCM shows better results than DCF DCM, as FBG features comparatively lower introduced losses (up to 4 dB per device, regardless of the necessary compensated dispersion amount) if compared to DCF (up to 0.6 dB/km at $\lambda = 1550$ nm), and it can be used with higher optical transmission power (for instance, FBG DCM by *Teraxion* can be used with power of up to +27 dBm [42]), as it has less nonlinear properties.

For the approbation of the simulation scheme of the WDM-PON access communication system and for the verification of mathematically obtained results, using the optical, electro-optical and electrical equipment available at the FOTS Laboratory of RTU TI, an experimental up to 16-channel WDM-PON transmission system model was created featuring transmission speed of 10 Gbit/s per channel, central frequency of 193.1 THz and transmission distance of 20 km, see Fig. 6.

The created WDM-PON system consists of 3 main parts: OLT or the transmitter part, ODN or the optical line part with a remote terminal (RT) and several ONT or a receiver part. In line with the previously created simulation model, OLT contains an electrical signal generator with NRZ coder, optical signal external MZM modulator and a continuous wave laser. In the created WDM-PON system (see Fig. 6), the optical signal from several transmitters is combined with an AWG multiplexer. After the AWG multiplexer, the tunable FBG DCM module is located for implementing chromatic dispersion pre-compensation and EDFA optical amplifier to compensate for AWG and DCM introduced losses. The optical signal is amplified in the EDFA amplifier and then fed into a 20 km long ITU G.652 standard single–mode optical fiber.

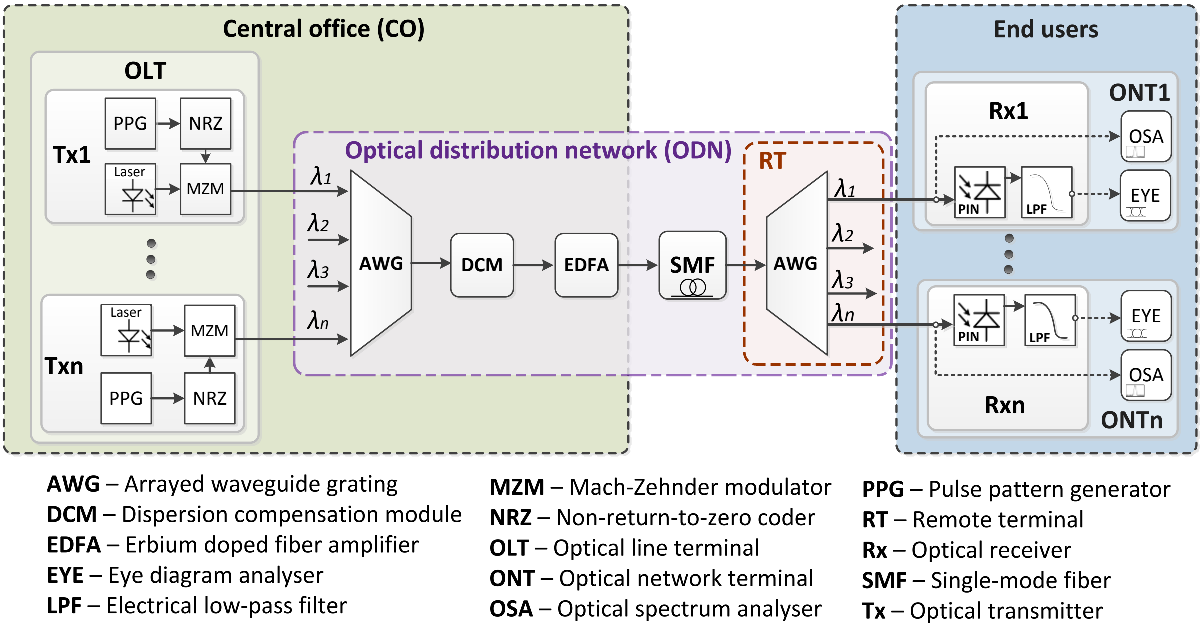


Fig. 6. Experimental model of WDM-PON optical access system with data transmission speed 10 Gbit/s per channel.

The signal arriving at the remote terminal (RT) is demultiplexed and each channel is then directed at the specific ONT, where, using the PIN photodiode, it is then detected and transformed in an electrical signal [4, 36]. The receiver part contains the eye diagram analyzer (EYE), which enables assessing its quality using eye diagrams, as well as an optical spectrum analyzer (OSA), which shows the spectrum of the received optical signal.

For investigation of chromatic dispersion influence and its compensation, FBG DCM module by *TeraXion* was used in the created WDM-PON system, ensuring a variable CD compensation amount ranging between -1200 and +1200 ps/nm at λ = 1550 nm. Therefore, by changing the introduced CD amount ranging from −1000 to +1000 ps/nm, the impact of CD overcompensation, compensation, and additionally introduced dispersion on the transmitted signal was assessed, see Figures 7 and 8. This dispersion compensation range between −1000 ps/nm and +1000 ps/nm was selected to fully assess insufficient CD compensation, as well as overcompensation, which clearly experimentally simulates the CD impact on the transmitted optical impulse. The level of dispersion "+1000 ps/nm" (see Fig. 7f) simulates additionally 62 km of optical line length, provided that the optical signal is not affected by losses in the optical fiber and nonlinear optical effects.

As shown in Fig. 7d, without applying dispersion compensation (Dc = 0 ps/nm), the quality of transmitted and received signal has been affected by the dispersion only slightly — minor signal distortions are observed in the logical "1" level. By implementing full dispersion compensation (Dc = −320 ps/nm), based on the previously measured chromatic dispersion amount (see Fig. 7c), improvement of the received signal quality is observed. When performing CD overcompensation or implementing an exceedingly extensive CD amount compensation (shown in Fig. 7a and 7b), as well as by introducing additional dispersion amount in the optical line (shown in Fig. 7e and 7f), significant optical signal quality distortions are observed at the logical "1" and "0" level.

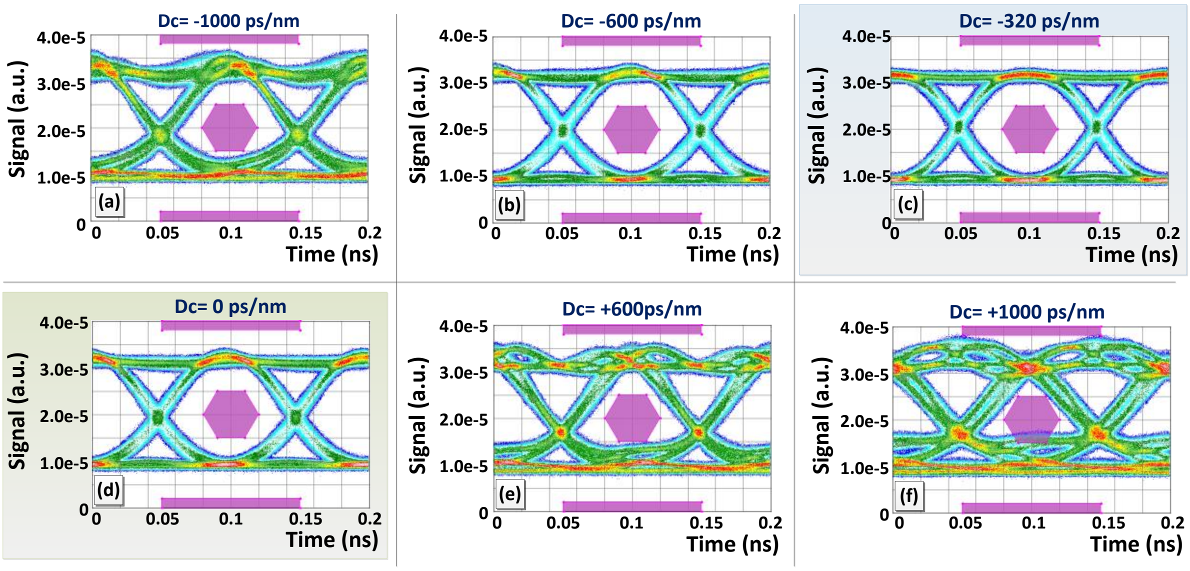


Fig. 7. Eye diagrams obtained from the worst channel of 10 Gbit/s WDM-PON access system under different FBG DCM chromatic dispersion compensation levels (Dc): (a-b) dispersion over-compensation, (c) full dispersion compensation, (d) dispersion is not compensated and (e-f) additional amount of dispersion is added to the optical line.

Figures 7e and 7f show that by introducing additional dispersion of at least 600 ps/nm in a 20 km long optical line, signal and mask overlapping are observed, and consequently the defined BER value is exceeded and the signal received in the receiver contains bit errors.

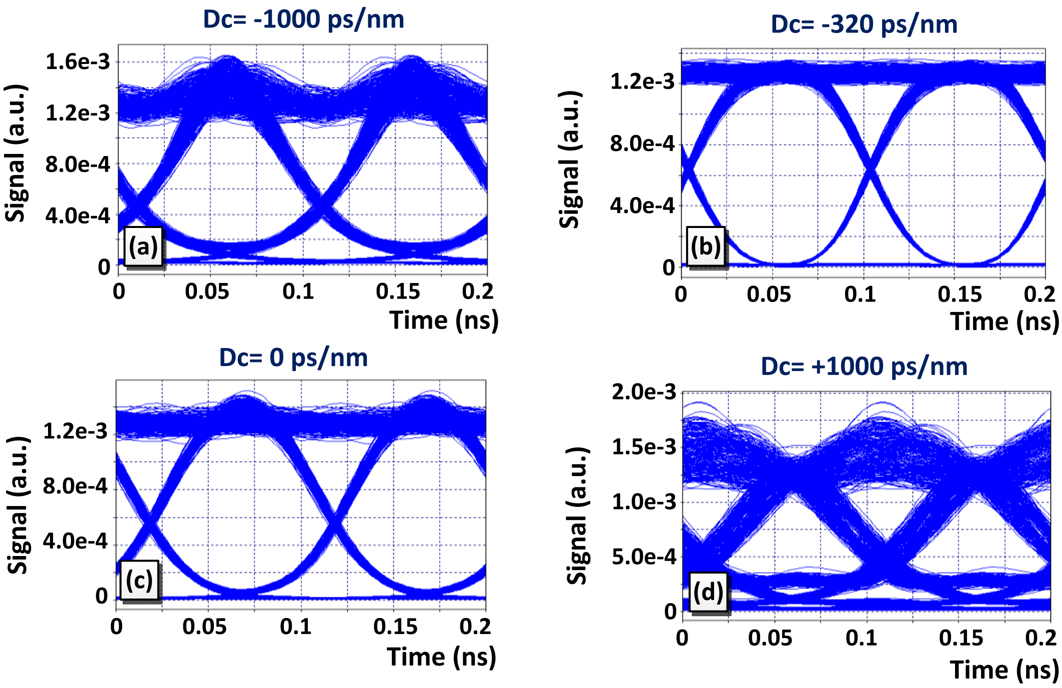


Fig. 8. Eye diagrams of received signal after 20 km transmission obtained via simulation of 10 Gbit/s WDM-PON system with different chromatic dispersion compensation values of FBG DCM module.

From the obtained results (Figures 7 and 8), it can be concluded that for ensuring maximum system performance, it is very important to first calculate and measure the CD amount introduced in the optical transmission line, before effectuating its compensation. If comparing the obtained experimental results with simulated results (obtained from the simulation scheme of the WDM-PON transmission system shown in Fig. 3), as well as using eye masks, it was concluded that they were practically matching.

The next research stage after the development and examination of the WDM-PON system is the creation of a simpler architecture SS-WDM PON system of up to 16 channels with the transmission speed of up to 10 Gbit/s per channel, in which only one incoherent noise-like broadband light source, sliced in spectral "slices", using the AWG demultiplexer, which in its structure is an optical filter, is used for all subscribers [5, 12, 20, 32-35, 40]. It must be noted that the WDM-PON system can be substituted with an SS-WDM PON system, without replacing all network elements, but merely improving the transmitter (OLT), while the rest of network architecture with the receiver terminals (ONT) remain unchanged. Limited data transmission distance and data transmission speed (typically up to 2.5 Gbit/s per channel) due to chromatic dispersion, crosstalk between channels, as well as the intensity fluctuations of ASE light source, which significantly reduces the opening of the eye diagram eye, can be considered flaws of the spectrum slicing technology of incoherent broadband light sources.

The transmission distance and the number of available channels in the SS-WDM PON system is affected by the ASE source optical output power and the output spectrum non-uniformity. Therefore, within this chapter, a numerical model of a powerful broadband ASE light source was developed in the OptSim simulation program, ensuring +23 dBm (200 mW) average output power with a practically flat curve of output optical signal spectrum ranging from 192.3 THz to 194.0 THz (from 1545.32 nm to 1558.98 nm). In the mentioned frequency range, up to 16 SS-WDM PON system channels will be arranged, which according to ITU-T G.694.1 frequency plan are centered around 193.1 THz frequency [16]. The ASE source model is created using two cascaded optical EDFA amplifiers, by selecting the relevant parameters (erbium doped fiber length used in amplification (L_{EDF}), pump source power (P_{pump}) and wavelength (λ_p)), see Fig. 9.

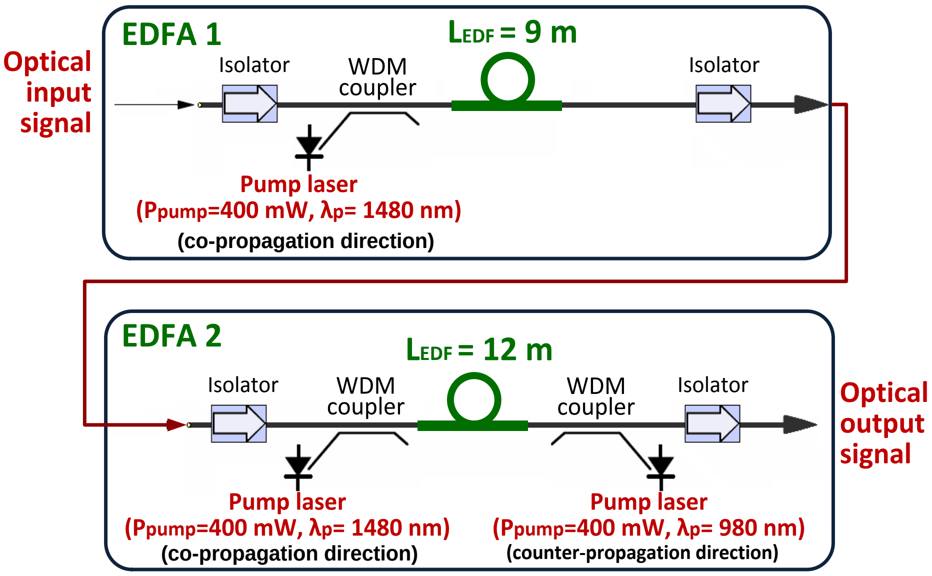


Fig. 9. Setup of two cascaded EDFA amplifiers and their basic parameters used for development of broadband ASE light source for 16-channel SS-WDM PON system.

The output spectrum with the most uniform power distribution for the implementation of an SS-WDM PON system with up to 16 channels was obtained on the condition that the output power of all pump lasers was 400 mW. In this case, the ASE light source with +23 dBm (200 mW) average output power was realized. Power level fluctuations of this light source do not exceed 0.42 dBm, see Fig. 10. The ASE light source model created in the OptSim program was used for further implementation and studying of 8 and 16 channel SS-WDM PON systems with the transmission speed of up to 10 Gbit/s per channel.

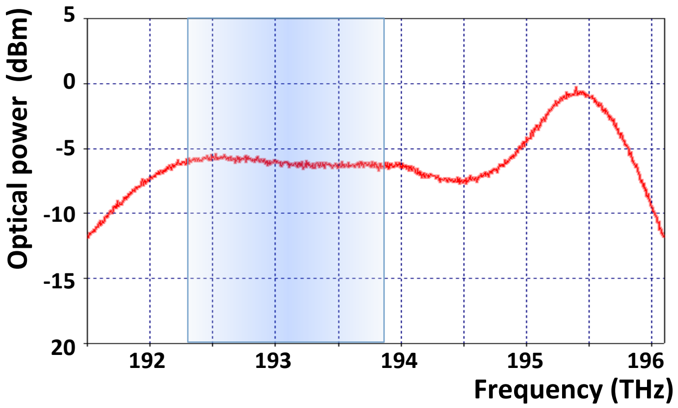


Fig. 10. The optical spectrum on the output of two cascaded EDFA system at the pump laser output power equal to P_{pump} = 400 mW.

The simulation scheme of an SS-WDM PON system with up to 16 channels with the created uniform output spectrum ASE broadband light source is shown in Fig. 11.

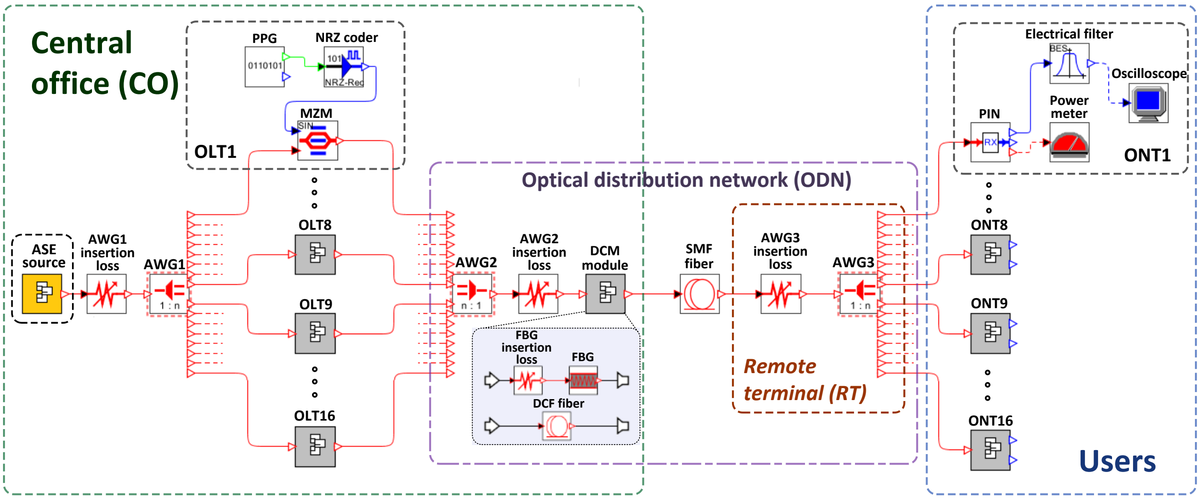


Fig. 11. Simulation scheme of up to 16-channel SS-WDM PON system with spectrally sliced broadband ASE light source and dispersion compensation module (DCM).

Figure 12 shows the optical signal spectrum in the output of ASE source, as well as after each AWG demultiplexer for both 8-channel and 16-channel SS-WDM PON systems.

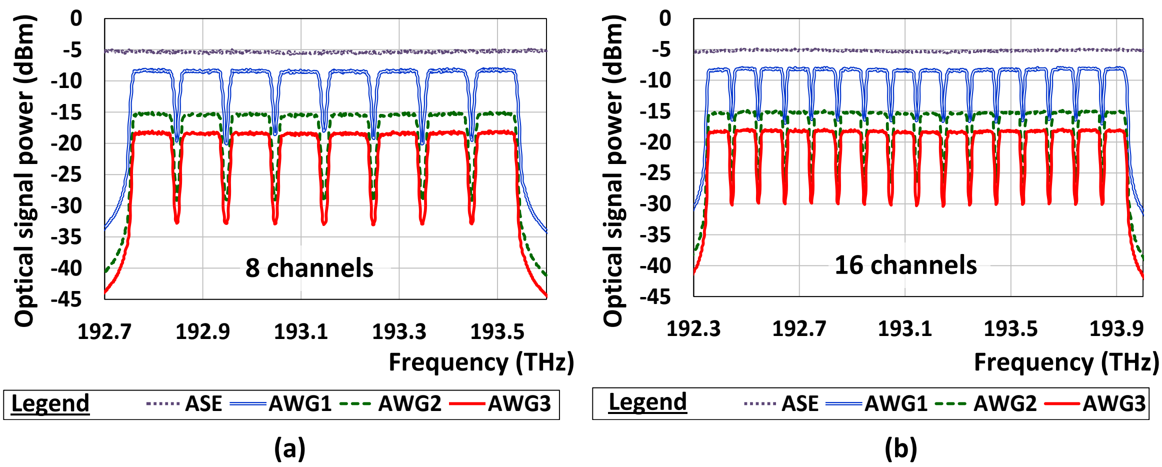


Fig. 12. Optical output spectrum of broadband ASE light source and each AWG unit in (a) 8-channel and (b) 16-channel SS-WDM PON system with line length equal to 10 km.

By consecutively implementing 8-channel and 16-channel SS-WDM PON access transmission systems with the transmission speed of 2.5 Gbit/s per channel, it was concluded that 20 km transmission without CD compensation with BER < 10^{-10} could not be ensured, and the maximum achieved data transmission distance was 10 km.

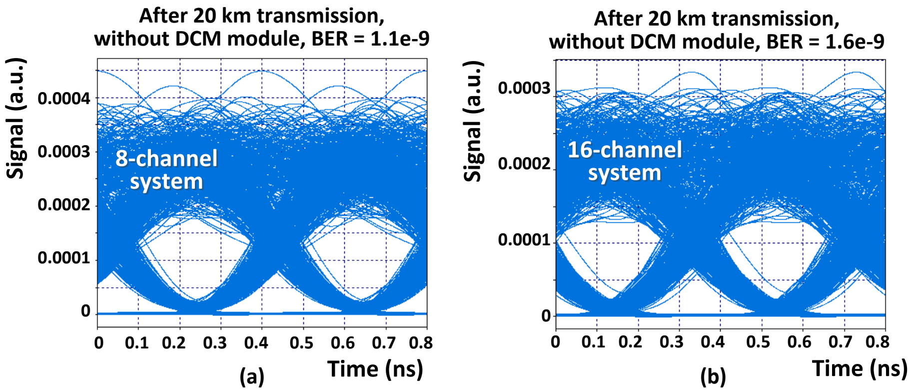


Fig. 13. Eye diagrams and BER values of received signals after 20 km transmission without use of DCM module in (a) 8-channel and (b) 16-channel 2.5 Gbit/s SS-WDM PON systems.

Figures 13a and 13b show that after the transmission through a 20 km long optical fiber line, due to the dispersion effects and spontaneous emission noise of the light source, the opening of the received signal eye diagram has significantly decreased, resulting in BER exceeding the necessary threshold value, defined as BER < 10^{-10}. As shown in Figs. 13, 14a and 15a, it is impossible to ensure a 20 km transmission without CD compensation with BER < 10^{-10} for both (8- and 16-channel) SS-WDM PON systems. It is explained with the noise-like nature of the ASE light source, because, as the FWHM (full width at half maximum) bandwidth of the light “slice” is relatively large (Bw = 90 GHz), the impact of chromatic dispersion increases more rapidly along with the increased transmission distance than is the case in wavelength division multiplexed access systems based on laser light sources (such as WDM-PON systems with DFB lasers in OLT units, in the transmitter part, where the laser FWHM Bw = 50 MHz).

Therefore, CD compensation with DCF DCM and FBG DCM modules was effectuated for both 8- and 16-channel SS-WDM PON systems, as a result the received signal BER, after a transmission of 20 km, by ensuring the required incoming optical signal level in the receiver, corresponded to the threshold (BER < 10^{-10}), as seen in Figs. 14b, 14c and 15b, 15c. The amount of compensated dispersion in the case of each system is shown in Table I.

Table I

Amount of Chromatic Dispersion to Be Compensated in 8-channel and 16-channel 2.5 Gbit/s SS-WDM PON Systems with Data Transmission Distance up to 20 km

Number of channels in SS-WDM PON transmission system			8 channels		16 channels	
Length of transmission line			10 km	20 km	10 km	20 km
Amount of accumulated dispersion			160 ps/nm	320 ps/nm	160 ps/nm	320 ps/nm
Method of compensation and amount of compensated dispersion	DCF fiber	*L*	2.5 km	4.7 km	2 km	4.5 km
		Dc	−200 ps/nm	−376 ps/nm	−160 ps/nm	−360 ps/nm
	FBG grating	*Dc*	−125 ps/nm	−290 ps/nm	−125 ps/nm	−280 ps/nm

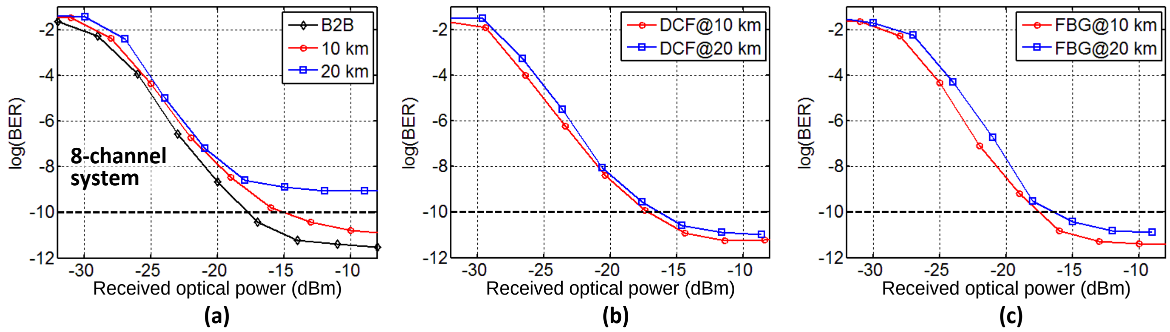


Fig. 14. BER as a function of received power in 8-channel SS-WDM PON system with various transmission distances and (a) without use of CD compensation and with implementation of CD compensation by (a) DCF fiber or (c) FBG grating.

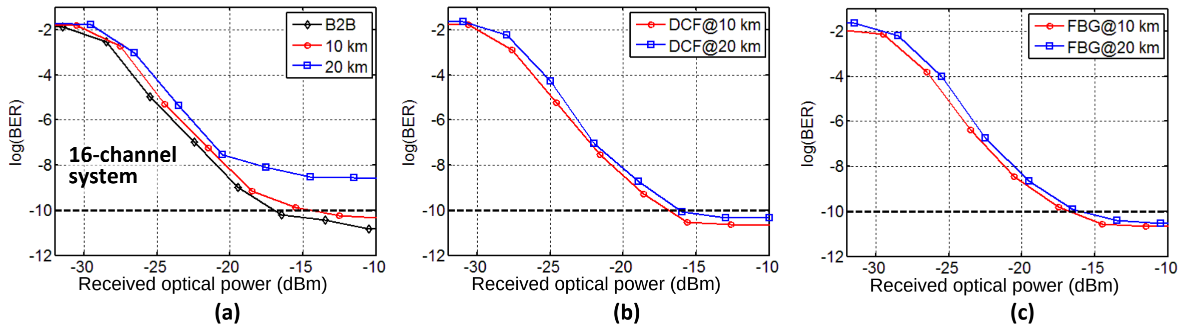


Fig. 15. BER as a function of received power in 16-channel SS-WDM PON system with various transmission distances and (a) without use of CD compensation and with implementation of CD compensation by (a) DCF fiber or (c) FBG grating.

From the obtained results, it was concluded that the highest performance of 8- and 16-channel SS-WDM PON systems was ensured by FBG application in the dispersion compensation module. By using FBG DCM, 20 km transmission can be ensured with a lower received optical power level (P = −16.4 dBm for 8-channel system and P = −16.0 dBm for 16-channel system) than in the case of DCF (P = −15.9 dBm for an 8-channel system and P = −15.2 dBm for a 16-channel system), see Figs. 14 and 15. Therefore, less powerful ASE light source can be used to achieve the same system performance results— transmission speed, distance, and the received signal BER.

Since the ASE generated intensity noise limits the maximum data transmission speed (2.5 Gbit/s per channel), solutions have been sought for reducing this noise.

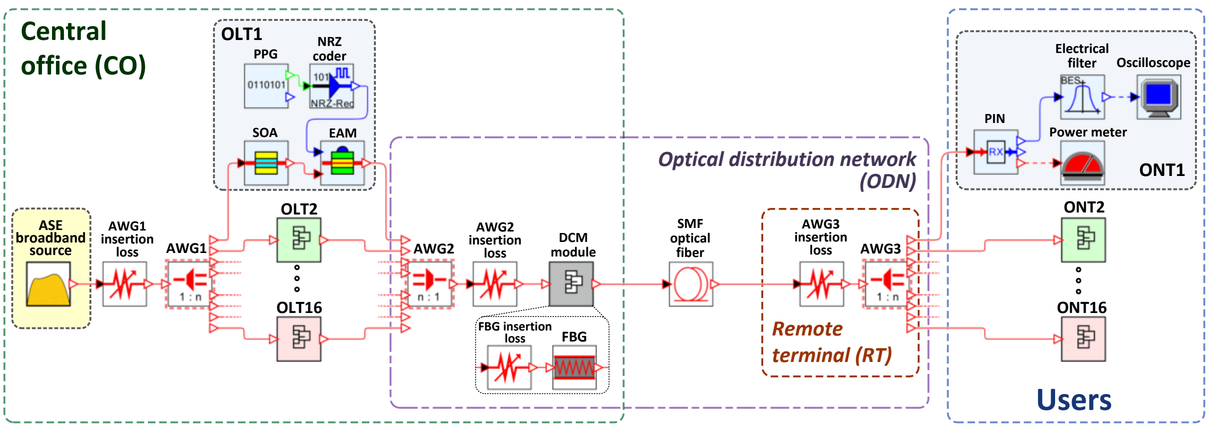


Fig. 16. Simulation scheme of 16-channel SS-WDM PON system with EAM modulator, intensity noise suppression with SOA and dispersion compensation module (DCM).

It was examined that by using a semiconductor optical amplifier (SOA) in a gain saturated mode before the optical modulator, it was possible to "suppress" the intensity noise or intensity fluctuations and to increase the data transmission speed from 2.5 Gbit/s to 10 Gbit/s per channel. To assess this solution, a 16-channel SS-WDM PON system was created in the OptSim simulation program with an electro-absorption modulator (EAM), intensity noise suppression with SOA and dispersion compensation module with fiber Bragg grating, see Fig. 16. As seen in Fig. 17, after the amplification of the optical signal and processing through SOA, the intensity fluctuations are much lower compared to the calculated average signal power level. The average SOA input noise-like signal value is 4.2 mW (+6.2 dBm), whereas SOA output average signal value is 140.2 mW (+21.5 dBm), see Fig. 17.

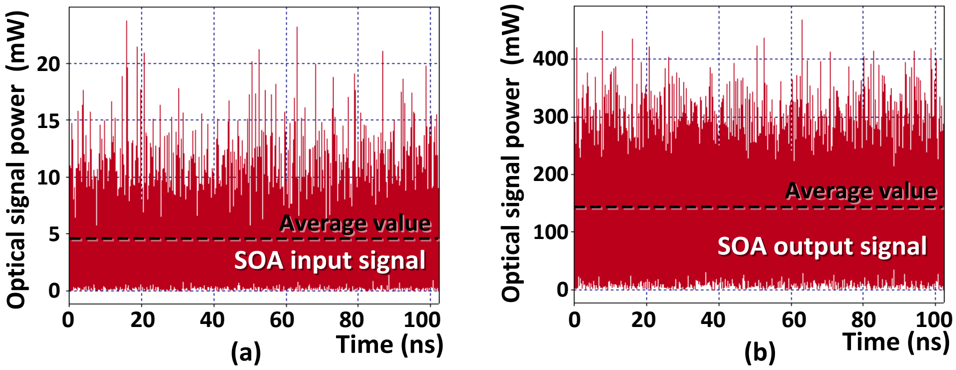


Fig. 17. Signal in time domain (a) on the input of SOA and (b) on the output of SOA after amplification and noise suppression.

As a result, it was found that by using SOA for suppressing intensity noise, operating in gain saturated mode, as well as by implementing dispersion compensation with FBG DCM, the transmitted and received signal quality improved significantly, resulting in BER = $1.9 \cdot 10^{-13}$ per channel with the lowest performance after transmission through a 20 km long standard single-mode optical fiber span. It must be added that in case when SOA and FBG DCM are not simultaneously employed, after a 20 km long transmission, the received signal BER in the channel is above the threshold which is 10^{-10}, see Fig. 18.

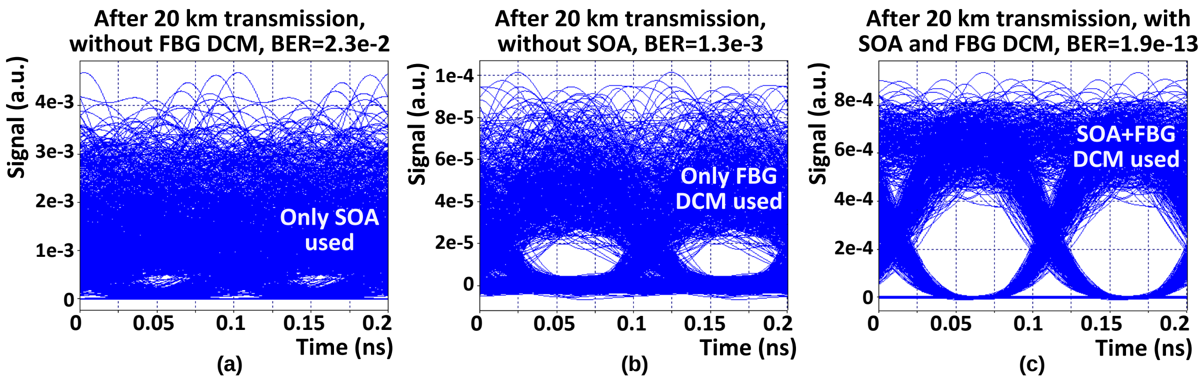


Fig. 18. Eye diagrams of received optical signals after 20 km transmission in 16-channel SS-WDM PON system: (a) without implementation of CD compensation, (b) without the use of SOA in OLT, and (c) with simultaneous use of SOA and FBG DCM at the transmitter side.

To assess the performance of the created 16-channel SS-WDM PON optical access system with the transmission speed of 10 Gbit/s per channel, BER curves were recorded as a function of the received power in B2B configuration (without an optical transmission line) and after up to 20 km transmission distances, by using FBG for dispersion compensation and SOA optical amplifier for suppression of ASE generated intensity noise (see Fig. 19).

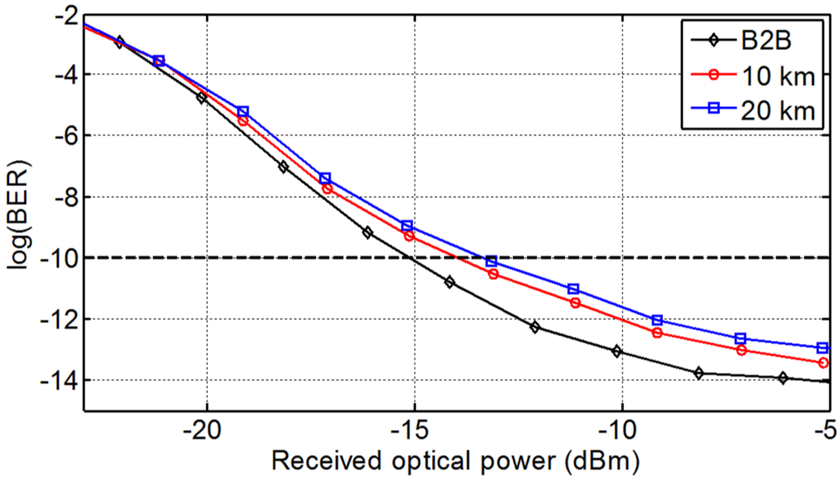


Fig. 19. BER as a function of received power in 16-channel SS-WDM PON system in B2B configuration and after transmission through 10 and 20 km long optical fiber lines.

Figure 19 shows that by ensuring the necessary received signal quality in a 16-channel SS-WDM PON system (BER < 10^{-10}), in B2B configuration, the minimum average received power level must be at least P = −14.7 dBm, after a 10 km transmission it must be P = −14.0 dBm, and after a 20 km transmission P = −13.4 dBm.

For the approbation of the SS-WDM PON access communication system simulation scheme and for the verification of the mathematically obtained results, within the technical potential afforded by the Laboratory of (FOTS) of RTU Institute of Telecommunications (TI), an experimental up to 16-channel SS-WDM PON transmission system model was created, with the transmission speed of 2.5 Gbit/s per channel, central frequency 193.1 THz and the transmission distance of 10 km, see Fig. 20.

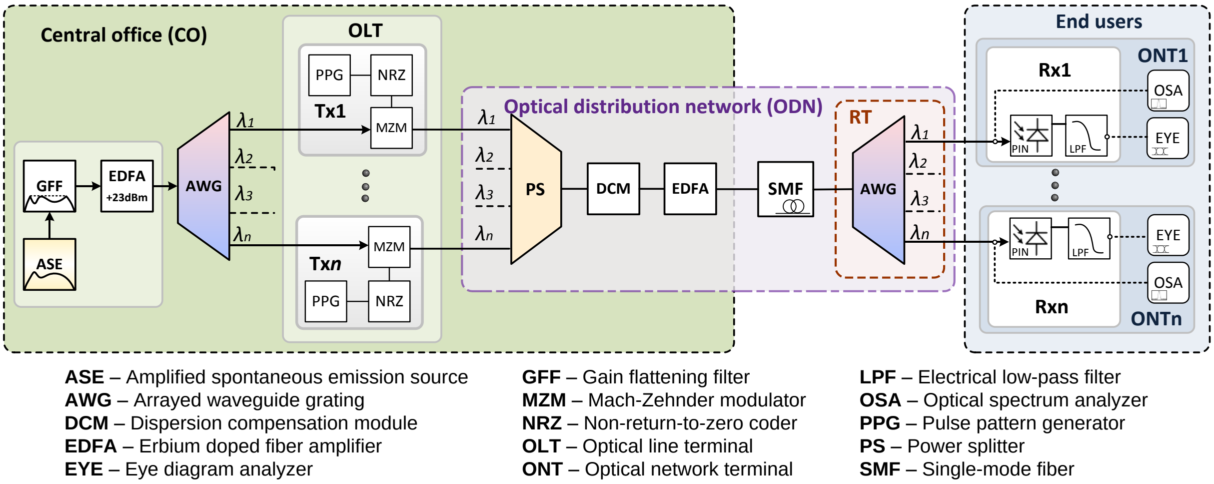


Fig. 20. Scheme of experimental up to 16-channel SS-WDM PON transmission system with data rate 2.5 Gbit/s per channel.

Experimental observations showed the received bit sequence level fluctuations or the patterning effect (from Eng. pattern — bit sequence), originating in the output of MZM modulator due to the optical signal intensity fluctuations. As shown in Fig. 21a and 21b, the output signal intensity of noise-like light source in time is not stable as it is, for instance, in the case of DFB laser output signal (see Figs. 21c and 21d).

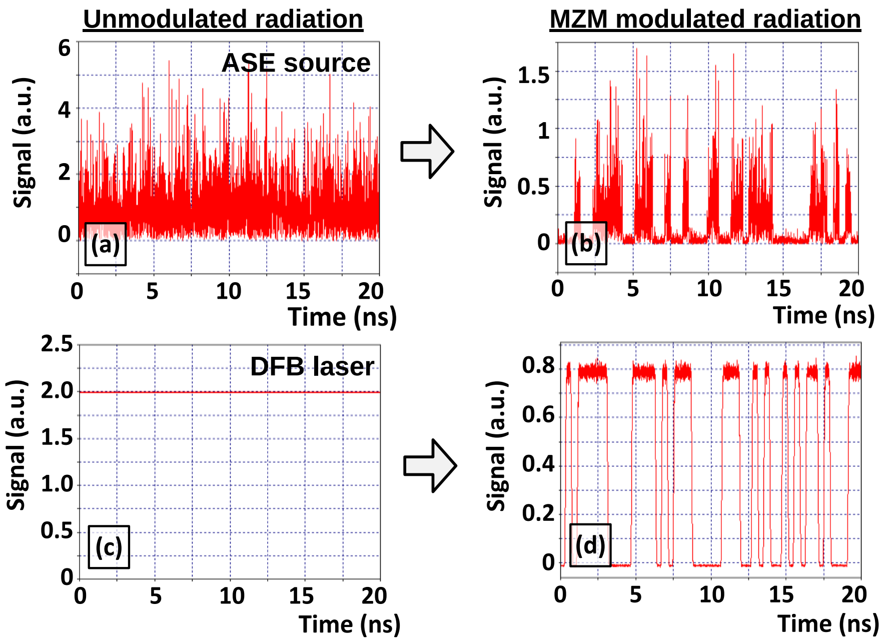


Fig. 21. Optical signal in time domain: (a) optical signal of sliced ASE light source (optical slice) in the input of MZM modulator and (b) on the output of MZM modulator after modulation; (c) radiation of DFB laser and (d) laser radiation after modulation with MZM.

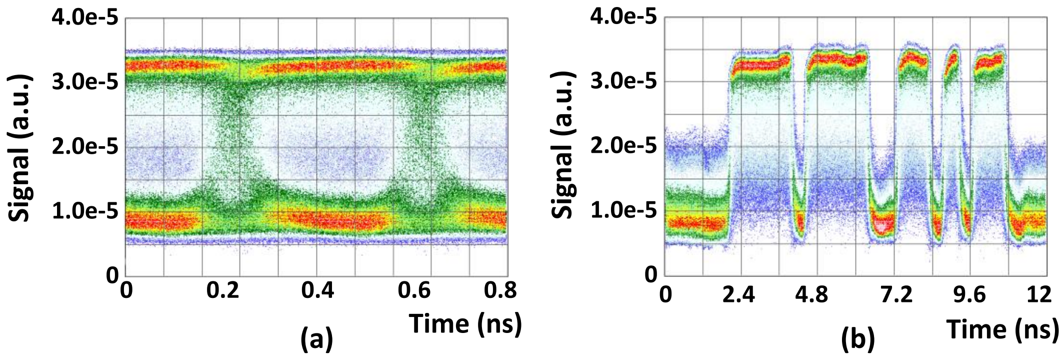


Fig. 22. Experimentally received signal's (a) eye diagram and (b) representation of signal in time domain after transmission through 10 km long optical fiber line.

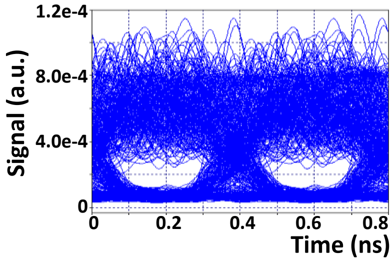
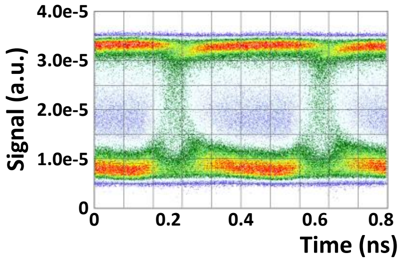
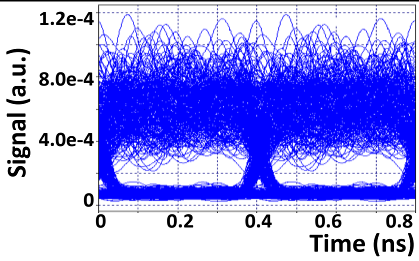
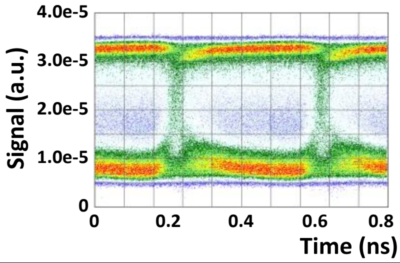
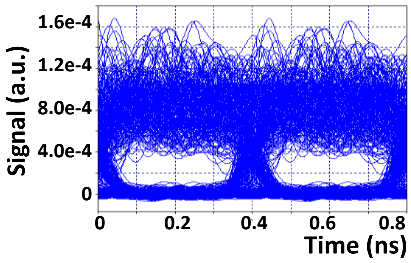
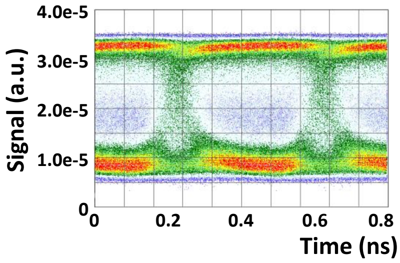
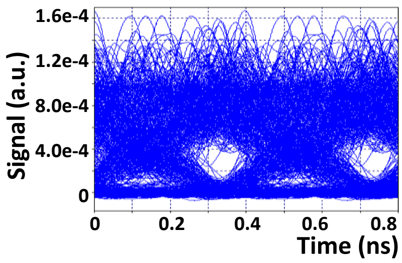
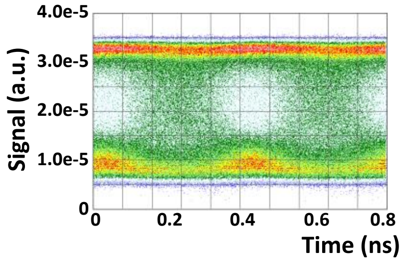
Due to the low extinction ratio of the experimentally used MZM modulator (ER≤13 dB) as well as due to the patterning effect, it is apparent that the eye diagram opening is covered by noise (see Fig. 22 and Table II). Transmitted bit sequence is apparent, however, since the intensity of incoming sliced ASE signal fluctuates in time, then output optical signal also experiences certain intensity fluctuations, which result in the fact that the eye opening is to a certain extent covered by noise.

In the experimentally used MZM modulator by *Avanex*, the logical "1" is formed according to the optical signal intensity arriving at the specific moment, which leads to the fact that the intensity level of logical "1" of the optical signal in the output of the modulator fluctuates in time (see Fig. 21b and 22b). These intensity noise fluctuations can be suppressed using SOA operating in gain saturation mode.

Just as WDM-PON, in the experimentally created SS-WDM PON system, CD compensation was implemented using FBG DCM, where the dispersion compensation amount was changed between −600 ps/nm and +600 ps/nm, in order to fully investigate the CD impact on the received signal.

Table II.

Eye Diagrams of Received Signal after 10 km Transmission Obtained via Simulations and Experimental Realization of 2.5 Gbit/s SS-WDM PON System with Different Chromatic Dispersion Compensation Values of FBG DCM Module

Dc (ps/nm)	**Simulation**	**Experiment**
-600		
-160		
0		
+600		

It has been observed that, as the dispersion amount increases, the received impulse form is distorted and broadens much faster than it is observed in the case of WDM-PON system. It can be explained with the fact that in an SS-WDM PON system, the light slice bandwidth before modulation (Bw = 90 GHz) is much bigger than the baseband of frequencies occupied by the signal (Bw = 2.5 GHz), whereas in a WDM-PON system, the laser bandwidth (linewidth) is 50 MHz. Accordingly, the impact of dispersion in SS-WDM PON systems is considerably stronger than in WDM-PON.

As seen from Table II, the received bit sequence transition from logical “0” level to logical “1” level visually matches and there are clearly visible similarities between the experimentally obtained measurement results and the simulation results. At Dc = 600 ps/nm introduced dispersion amount, marked received signal jitter is observed, it is apparent that the optical impulse is distorted and interferes with the transmitted adjacent impulses. Therefore, the simulation results can be considered reliable. It must be added that the representation of eye diagrams obtained in simulation and experimentally differ visually because the eye diagrams of the received signal obtained in the OptSim simulation tool are represented with lines, by connecting sample points, whereas experimentally obtained eye diagrams using the

Anritsu make eye diagram analyzer are represented as a set of sample points. The SS-WDM PON optical access system model developed experimentally at the FOTS Laboratory of RTU TI can be improved with new elements (EAM modulator, SOA, etc.) and increased to 10 Gbit/s transmission speed per channel.

Chapter 3

The third chapter of the Doctoral Thesis suggests a solution on how, by using the electrical and opto-electrical components existing in the optical access networks, having a restricted frequency throughput bandwidth, to transmit higher-bitrate signals, which comparatively require at least a two times wider frequency band.

The electrical and opto-electrical components, which are found in the transmitter and receiver block (transceiver) of the high-speed fiber optical access transmission system, are considered to be its weak point or bottleneck due to the limited frequency bandwidth and the transmission speed [28, 39]. The transmission speed of electrical components and accordingly the throughput band is restricted by the switching speed of transistors contained therein, as well as the heat originating as a result of it, which must be released [22]. The solution for the limited throughput bandwidth problem that does not require a complete transceiver replacement is an electro-optical spectrum sliced transceiver for high bitrate optical signal transmission and receiving in optical access networks, where, by using digital signal processing (DSP), the electrical baseband signal containing the transmitted information is sliced. Certain parts of the sliced signal are transmitted through the fiber optical access network and the initial signal is restored in the receiver. Such spectrum sliced transceiver can ensure faster transmission speeds by using the already existing transceivers with a limited frequency throughput bandwidth [39, 41, 44, 45]. This way, the telecommunications service provider can increase the frequency bandwidth of optical access network components multiple times and accordingly also the transmission speed.

Next generation optical access networks must be adaptive with regard to the ensured data transmission frequency bandwidth, which can dynamically change depending on the user demand. Thus, spectrum sliced transceiver technology, using DSP, in the nearest future will be a potential solution for overcoming the restrictions imposed by the limited frequency bandwidth of electrical components.

The given studies were conducted during the doctoral internship at the Technical University of Denmark (DTU), at the Metro-access & Short Range Systems Group Laboratory, in collaboration with researchers from DTU Fotonik (Denmark) and Heinrich Hertz Institute (Germany) under the supervision of Professor Idelfonso Tafur Monroy and the Assoc. Prof. Juan José Vegas Olmos.

By employing the baseband electrical signal spectrum slicing method examined within the scope of the Thesis, it is possible, using the electro-optical transceivers already existing in optical access networks, to transmit a signal that is spectrally at least two times or four times broader than it is possible by high frequency electronics used therein, without replacing the existing electrical and electro-optical components with others [44]. Spectrum slicing method is scalable, which means that the electrical signal with N GHz frequency bandwidth can be sliced not only in two signal slices, each taking up $\Delta f_{slice} = N/2$ GHz frequency baseband, or in four slices (each taking up $\Delta f_{slice} = N/4$ GHz frequency baseband), but even in 10 slices ($\Delta f_{slice} = N/10$ GHz) [44, 45]. Signal processing in frequency or time domain is performed in a DSP block, which in essence is a Matlab computing environment, where the fast Fourier transform or the inverse fast Fourier transform of the transmitted signal is realized, see Fig. 23.

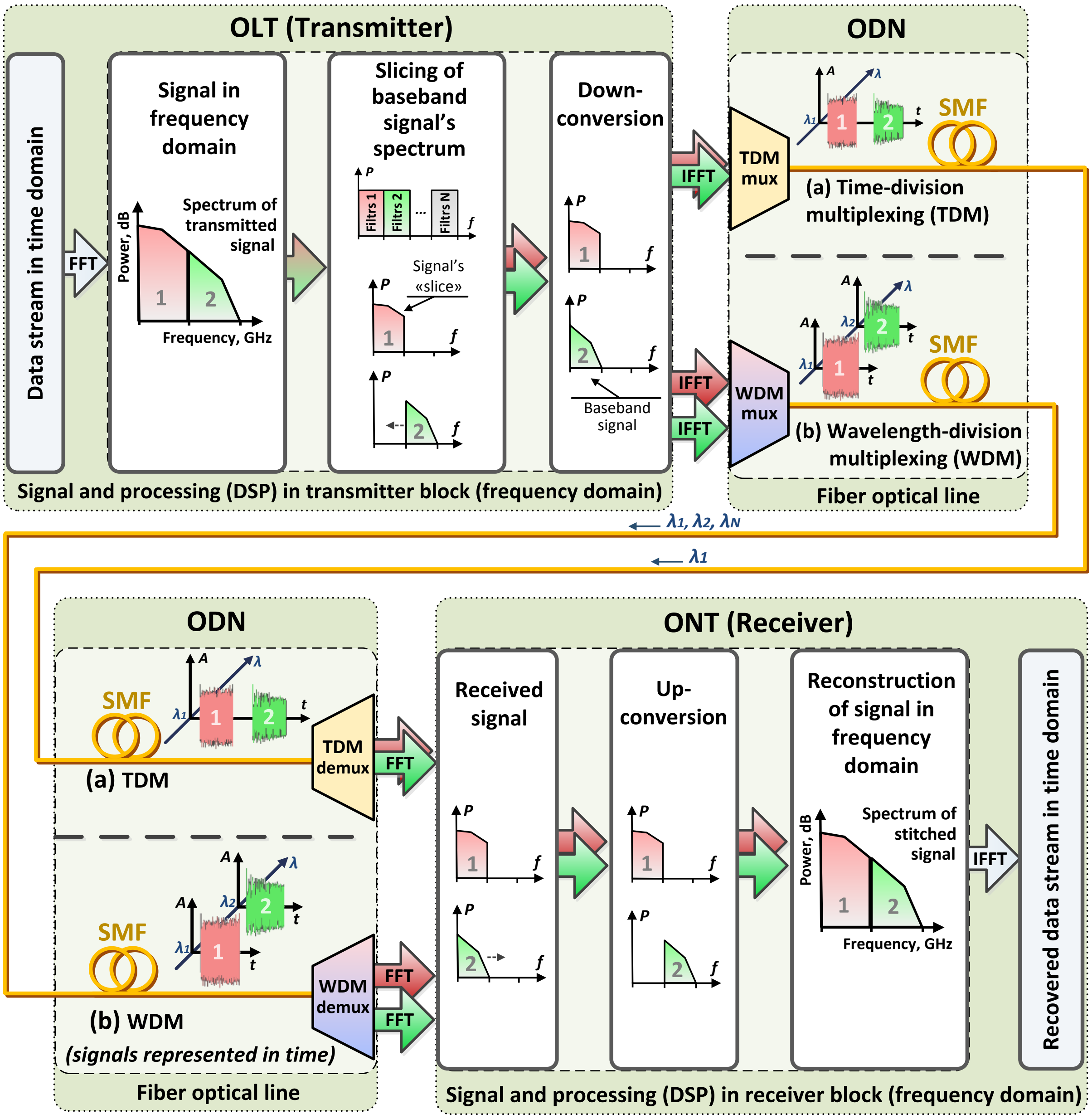


Fig. 23. Principle of slicing an input electrical baseband signal into two equal bandwidth slices at the OLT, transmission, reception and a reconstruction of the origin signal waveform at the ONT by using: (a) TDM or (b) WDM multiplexing technique.

Spectrum sliced signal slices can be transmitted one after another using time division multiplexing (TDM) (see Fig. 23a) or parallel by employing wavelength division multiplexing (WDM) (see Fig. 23b). In both cases, the bandwidth of electro-optical and electrical components of the transceiver is scalable and the necessary electrical bandwidth of the high-frequency network hardware is at least two times smaller than in the case of the initial electrical signal before slicing.

To prove the spectrum slicing technology principle and to assess its performance, an experimental prototype of a spectrum sliced transceiver was developed and its operation was assessed. The created prototype performs 1 Gbit/s NRZ electrical data signal slicing in two limited bandwidth slices, modulates them in optical domain one after another over time, transmits along up to 25 km long single-mode optical fiber (SMF) span, receives and restores the initial waveform of the signal, using a bandwidth of electrical equipment that is two times smaller, namely 500 MHz. The experimental scheme of spectrum sliced transceiver is shown in Fig. 24. It must be noted that before processing in DSP block, the electrical NRZ signal with the transmission speed of 1 Gbit/s takes up 1 GHz frequency baseband, whereas after processing with DSP, not more than 500 MHz.

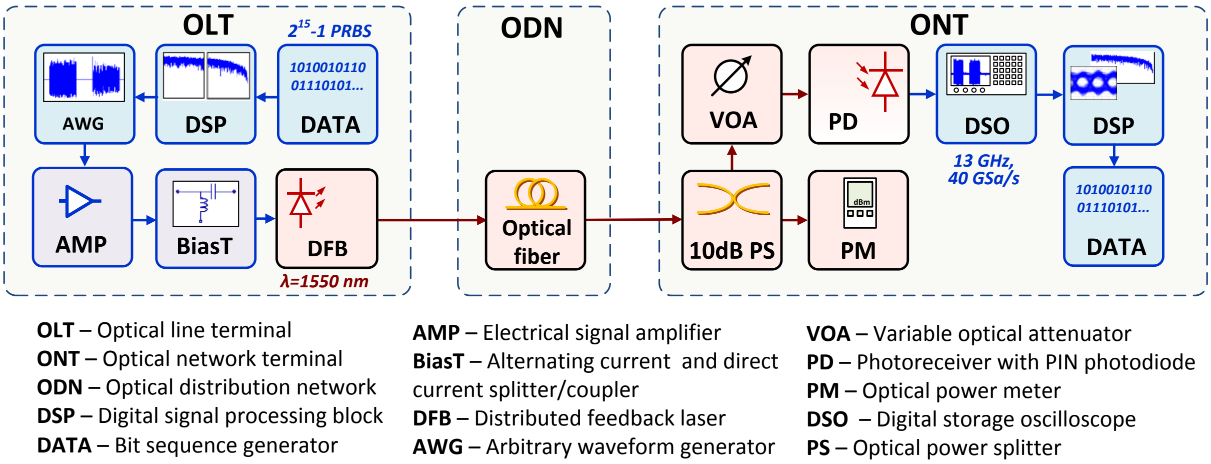


Fig. 24. Experimental setup of sliceable transceiver for slicing electrical baseband signal into two slices, transmission and reconstruction of initial signal in the receiver.

Initially, the electrical signal generator is creating a pseudo-random 2^{15}–1 bit sequence with the bandwidth of 1 GHz, which is fed to the coder and a NRZ coded electrical signal is created with the transmission speed of 1 Gbit/s (see Fig. 25a). This electrical signal contains information, which is transmitted in the created optical communications system. The spectrum of transmitted electrical signal with 1 GHz occupied electrical frequency baseband is shown in Fig. 25b.

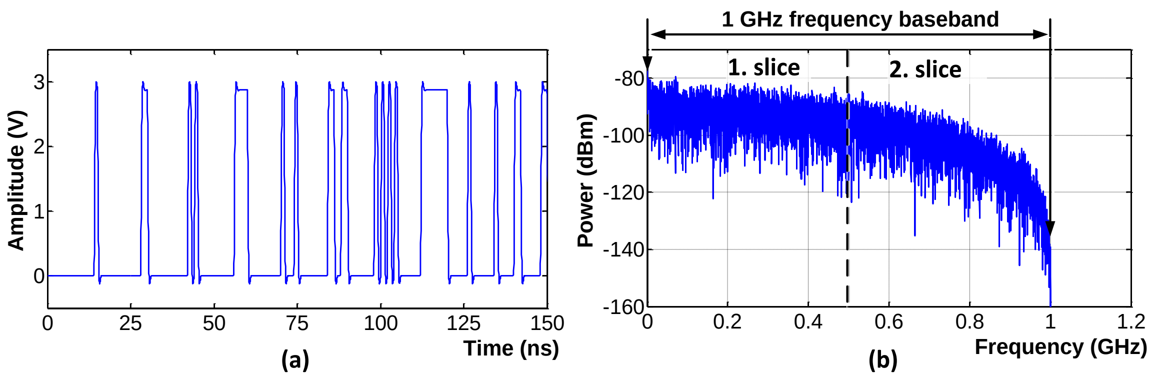


Fig. 25. (a) Time diagram and (b) spectrum of generated 1 Gbit/s electrical signal.

In the DSP block, using digital signal processing in the Matlab environment, the electrical data signal, which takes up 1 GHz frequency bandwidth (see Fig. 25b), will be sliced into two identical bandwidth ($\Delta f_{slice} = 500$ MHz) frequency slices (see Fig. 26). After the slicing operation, the signal slice with the higher frequency band (2nd slice) was shifted to the baseband (see Fig. 26b) using DSP. Afterwards, once both frequency slices are in the baseband from 0 to 500 MHz, they are prepared for transmission through the fiber optical transmission line.

To perform both frequency slice transmission, they together with a 2.45 μs time guard-band were combined in a single signal, which, as a result, took up no more than 500 MHz frequency baseband. This bandwidth is two times smaller than the bandwidth taken up by the signal before the slicing operation. The length of a signal containing each slice waveform is 4.1 μs. Figure 27a shows both slices separately in a time domain (for better representation, only time-frame from 0 ns to 150 ns is shown) as well as both slices combined in a time domain (see Fig. 27b).

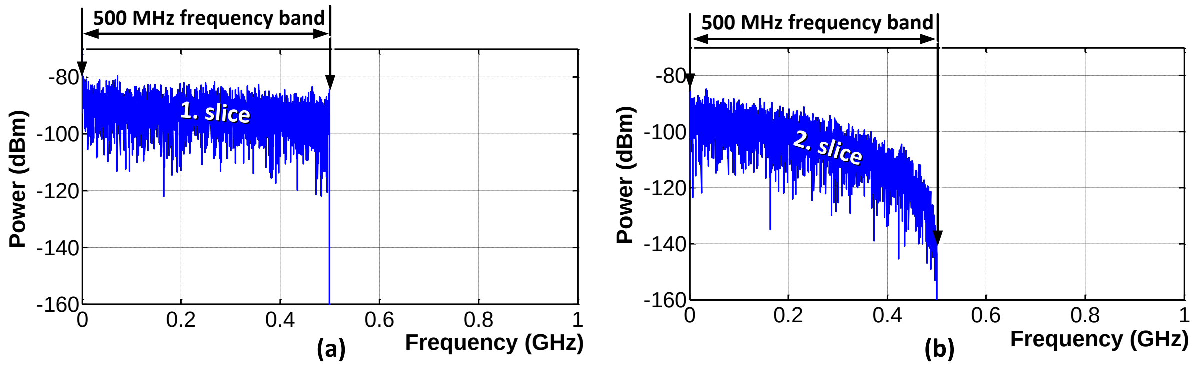


Fig. 26. Spectrum of sliced signal with 1 GHz bandwidth into two 500 MHz bandwidth slices.

The signal with the waveform shown in Fig. 27b containing both slices is sent to 1.25 GS/s *Agilent* arbitrary waveform signal generator (AWG) with the bandwidth of 500 MHz. In the output of AWG, an electrical signal of a certain waveform is generated depending on the digital control signal as shown in Fig. 27b.

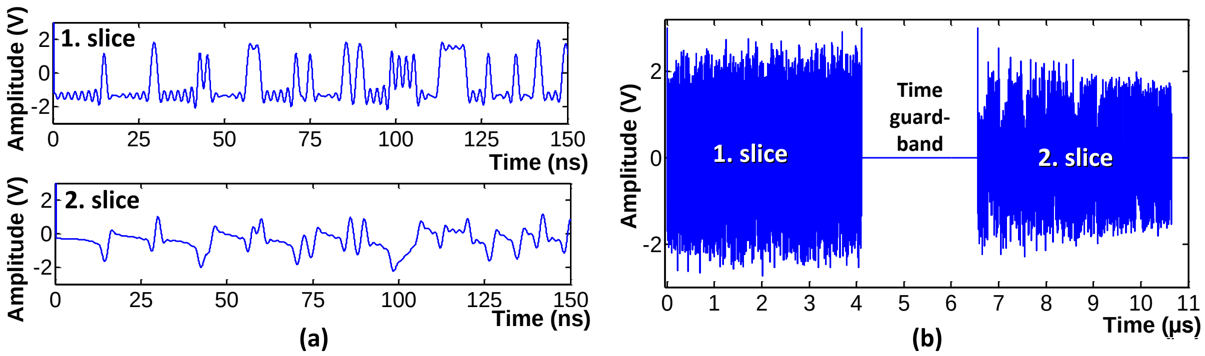


Fig. 27. (a) Separately shown time diagrams of both 500 MHz slices and (b) time diagram of formed electrical signal obtained by combining both slices in time, which is used for direct modulation of DFB laser.

The electrical signal generated in the output of AWG was amplified and used through BiasT (separator of direct current from alternating current) for direct DFB laser modulation. In the experiment, a DFB laser with the central wavelength of $\lambda = 1550$ nm was used. It was measured that the average optical signal power on the output of directly modulated laser was 2.9 dBm. The further modulated optical signal was fed into the optical distribution network (ODN) depicted by the optical single-mode fiber. The received signal quality and the performance of spectrum sliced transceiver was assessed using 3 different single-mode optical fiber types up to 25 km long: standard single-mode optical fiber (SMF), dispersion shifted fiber (DSF) and non-zero dispersion shifted optical fiber (NZ-DSF). The received optical signal was initially split in the power splitter (PS), where one output with 10 dB attenuation was used for system monitoring purposes, whereas the other was fed further on to a variable linear attenuator (VOA).

The optical signal from the output of VOA was fed to the photoreceiver block with PIN photodiode, where it was transformed into an electrical signal. In a B2B configuration (without an optical transmission line) the average received signal power was −6.4 dBm. The electrical signal in the output of the photoreceiver (see Fig. 28a) was received and stored in the *Agilent* digital storage oscilloscope (DSO) memory. Experimentally used DSO featured a 13 GHz frequency bandwidth, and for recording the received electrical signal, 1.25 GSa/s sampling rate was used. The signal stored in the DSO memory was then processed in the DSP block, as a result, from two signal slices, which both together took up a 500 MHz frequency baseband, the initial 1 GHz signal was reconstructed, and the BER was evaluated depending on the average power of the received optical signal. In order to restore the initial signal waveform from the received signal (see Fig. 28a) containing both sliced signal slices, each individual signal slice was extracted (see Fig. 28b).

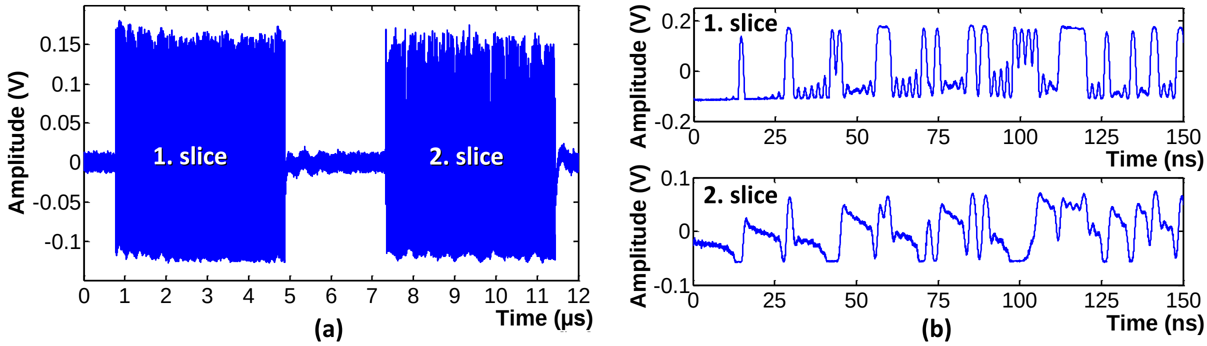


Fig. 28. (a) DSO captured electrical waveform which is used for further processing in DSP block and (b) both electrical slices of received signal, separated in time by using DSP.

In order to successfully restore the transmitted signal, it is necessary that the second slice is located in its initial frequency band (from 0.5 to 1 GHz). Therefore, by using DSP, the second slice was shifted to its initial position, which meant that all pre-requisites were met for restoring the sliced, transmitted and received signal (see Fig. 29a and 29b).

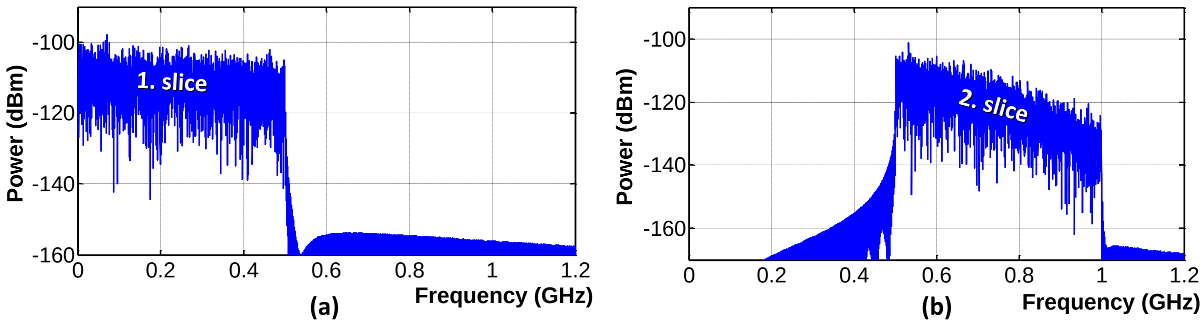


Fig. 29. (a) Spectrum of first slice and (b) second slice extracted from received signal, before realization of signal stitching operation in DSP block.

As the second slice is located in its initial frequency position, it is possible to combine both frequency slices in a single baseband signal, as seen in Fig. 30a.

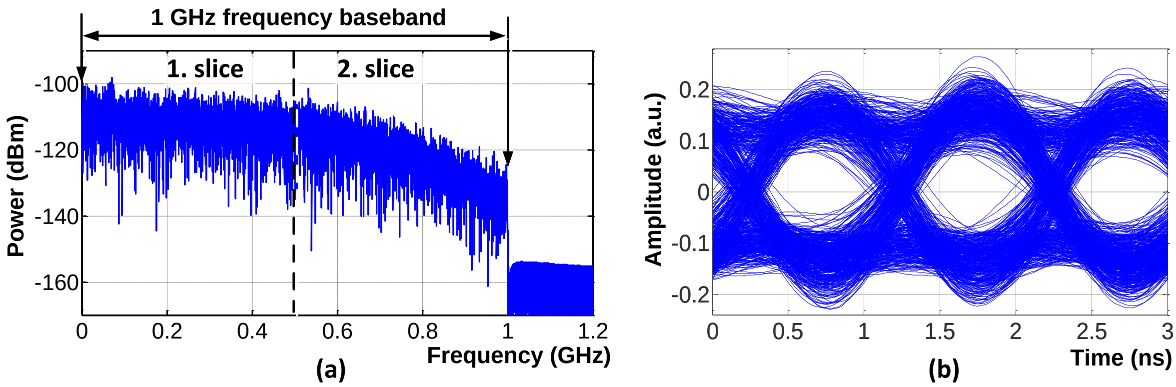


Fig. 30. (a) Spectrum of restored 1 Gbit/s electrical baseband signal and (b) its eye diagram after signal detection in B2B configuration (without using transmission line).

Figure 30b shows that the eye diagram opening of the restored signal after receiving in B2B configuration (the transmitter output is connected directly to the receiver input with an optical patch cord) is big enough; however, minor signal distortions are observed, as well as jitter. The cause of these distortions is the use of an electrical amplifier, as well as multiple digital signal processing (FFT, IFFT) in the time and frequency domain. Figure 31 shows a comparison between the initial 1 Gbit/s NRZ signal and the restored 1 Gbit/s NRZ signal, which was transmitted, received and restored, using the 500 MHz electrical frequency bandwidth.

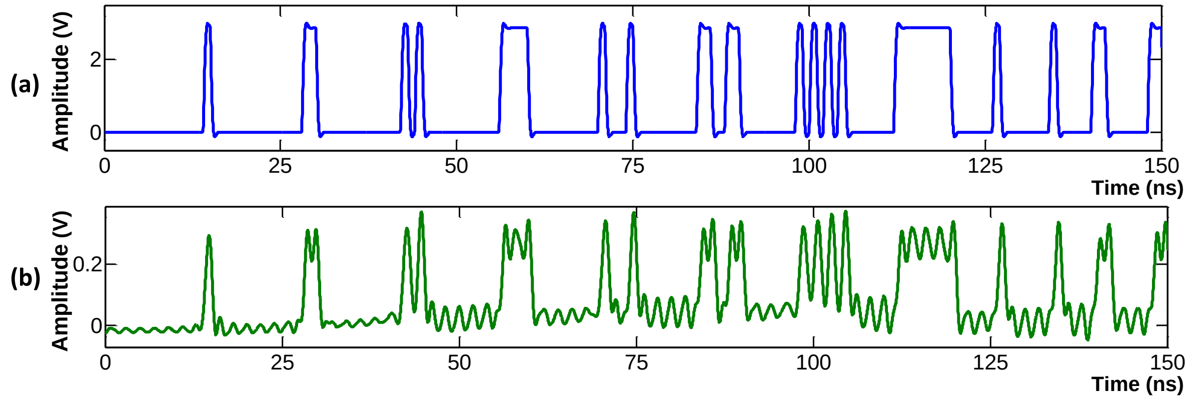


Fig. 31. (a) Time diagram of initial input electrical signal before realization of slicing operation and (b) time diagram of transmitted and restored sliced signal.

As shown in Fig. 31b, using the restored signal it is possible to fully reconstruct the initial sequence of bits, which was transmitted and received using the spectrum sliced transceiver solution. Figure 32a shows the eye diagram of received signal after a 25 km transmission through a standard single-mode optical fiber (SMF) section. As can be seen, the eye is open enough, which means that successful information transmission can be achieved in the distance of up to 25 km. BER, depending on the average received optical power of the signal, by employing SMF, DSF and NZDSF optical fibers in the transmission can be seen in Fig. 32b. This diagram shows the performance of a spectrum sliced transceiver with the data transmission speed of 1 Gbit/s, by realizing the electrical baseband signal slicing, transmission and stitching in the receiver, using DSP.

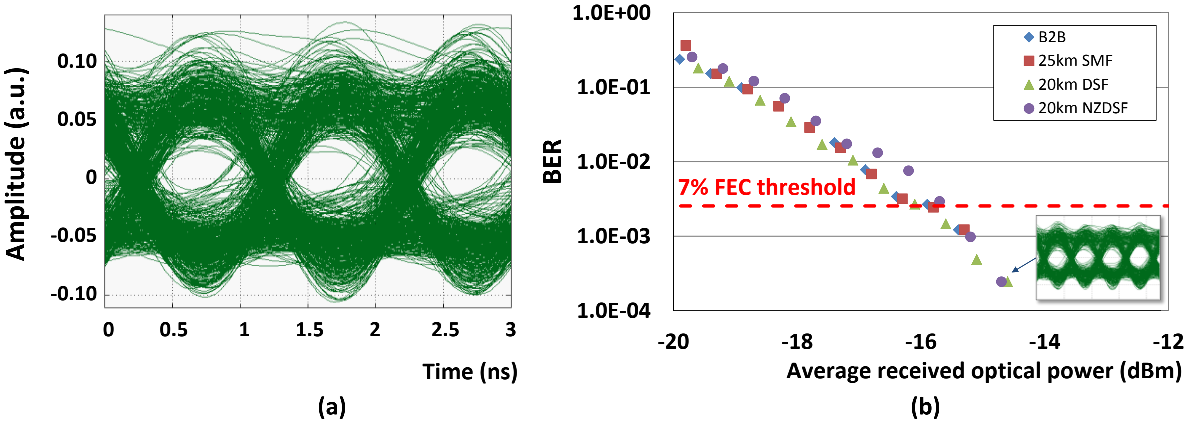


Fig. 32. (a) Eye diagram of detected and restored signal after transmission through 25 km long standard single-mode fiber, and (b) BER as a function of received power by using various optical fiber types in transmission.

As shown in the BER diagram, by employing forward error correction (FEC) with 7 % of data overhead and ensuring at least the average optical signal power −15.8 dBm received at the photoreceiver, the two slice spectrum sliced transceiver can ensure error-free data transmission with BER < 10^{-10}, by using up to 25 km long optical line with the SMF, DSF, or NZDSF optical fiber for data transmission. An additional 7 % overhead means that the transmitted bit sequence is supplemented with additional 7 % of bits, which allows performing error correction of the received signal bit sequence, if any errors have occurred. By employing the forward error correction, it is possible to perform the signal BER correction from the level BER < $2.55 \cdot 10^{-3}$ to the level BER < $1 \cdot 10^{-10}$ [18].

Chapter 4

Chapter 4 of the Doctoral Thesis considers the key causes of optical signal latency in fiber optical metro-access communication systems, as well as gives recommendations for reducing the latency introduced by optical and electro-optical elements [6, 15, 23, 24, 29].

With the progress of such services as high resolution video streaming, telemedicine services and health care systems, online videogames, virtual and augmented reality, video surveillance, cloud computing services, video conferences, financial transactions and computerized high frequency trading systems, it is also necessary to improve the optical access network architecture and technological solutions, by ensuring data transmission speeds of 2.5 and 10 Gbit/s for each client with a signal delay or latency as small as possible [6]. The latency parameter describes the time period from the first data bit transmission to the sender's communication interface until the receipt of the final bit at the receiver's communication interface. The overall latency in fiber optical networks is formed of three key components: transmission media or the optical fiber itself, optical components and electro-optical components. Thus, it is important for the telecommunications service provider to carefully choose the optical network components and consider a low latency network topology [15, 31]. There have been previous studies on how to improve the transmission speed in fiber optical transmission systems, whereas the impact and causes of latency, as well as the ways of reducing them have not been sufficiently examined or summarized yet [15, 24, 31]. The demand for ultra-low latency services is increasing rapidly, and this opens up several opportunities, especially in fiber optical access and metro transmission systems [30]. In fiber optical transmission systems, the cause of latency is the optical signal delay in the optical fiber, supplemented with signal delay occurring due to optical and electro-optical elements, along with additional signal processing time required for successful system functioning. These optical and electro-optical elements are transceivers, optical signal regenerators, optical erbium doped fiber amplifiers (EDFAs) and Raman amplifiers, chromatic dispersion compensating optical fibers (DCFs) and fiber Bragg grating (FBG) dispersion compensation modules (DCMs), digital signal processing (DSP) blocks with or without forward error correction (FEC) of the signal [29, 31].

In optical access and also metro networks, it is necessary to carefully choose the data transmission speed, as it can have a significant impact on the overall system latency. By increasing the system data transmission speed from 2.5 to 10 Gbit/s, CD compensation might be required, along with optical signal amplification, which will introduce additional latency in the network [6].

In a standard single-mode optical fiber, at least 80 % of light is travelling along the core, whereas no more than 20 % of light is travelling along the cladding [11]. In low latency optical access networks, optical fibers with a lower group index of light refraction are more favorable [6]. In order to assess the time delay in single-mode optical fibers, it is useful to employ the effective group index of refraction (n_{eff}) instead of core (n_1) or cladding (n_2) index of refraction. The effective group index of refraction (n_{eff}) is the average index of refraction, which takes into account both the n_1 and the n_2 value; therefore, it is more objective to use n_{eff} rather than n_1 or n_2 [10]. Today's optical fiber manufacturers, such as *Corning*, show only the n_{eff} value (for example, at $\lambda = 1550$ nm, a single-mode *Corning SMF28e* optical fiber $n_{eff} = 1.4682$, but at $\lambda = 1310$ nm $n_{eff} = 1.4676$) [9, 21]. Since the speed of light in vacuum is $c = 299792.458$ km/s and the index of refraction $n_0 = 1$ [43], unavoidable optical signal latency in vacuum can be calculated as follows:

$$\Delta_{vacuum} = \frac{1\,km}{c} = \frac{1\,km}{299792.458\ km/s} = 3.336\,\mu s \tag{2}$$

Nevertheless, in the optical fiber, the index of refraction ranges between 1.45 and 1.50; therefore, the optical signal in a fiber propagates slower than in vacuum, which leads to a higher signal latency.

If the n_{eff} value is known, the speed of light in the selected optical fiber at 1310 nm and 1550 nm wavelengths can be calculated as follows:

$$V_{1310nm} = \frac{c}{n_{eff\_1310nm}} = \frac{299792.458\ km/s}{1.4676} = 204273.956\ km/s \tag{3}$$

$$V_{1550nm} = \frac{c}{n_{eff\_1550nm}} = \frac{299792.458\ km/s}{1.4682} = 204190.477\ km/s \tag{4}$$

Using the previously calculated speed of light in a single-mode optical fiber given at different wavelengths, signal latency, introduced by 1 km long optical fiber section, can be calculated as follows:

$$\Delta_{1310nm} = \frac{1\,km}{V_{1310nm}} = \frac{1\,km}{204273.956\,km/s} = 4.895\,\mu s \tag{5}$$

$$\Delta_{1550nm} = \frac{1\,km}{V_{1550nm}} = \frac{1\,km}{204190.477\,km/s} = 4.897\,\mu s \tag{6}$$

As seen from Equations (5) and (6), the optical signal delay in the optical fiber depends on n_{eff} and on the wavelength used in the transmission. Based on the obtained calculation results, it can be assumed that a 1 km long single-mode optical fiber section introduces 4.9 µs signal latency [31]. In a fiber optical transmission system, chromatic dispersion is compensated using a dispersion compensating module (DCM), which contains a dispersion compensating optical fiber (DCF) section or fiber Bragg grating (FBG) [3, 36]. Typical long-reach fiber optical access and metro networks require DCF fiber length of 15 to 25 % of the total optical transmission line length. As a result, using the DCF fiber, also the signal latency is increasing by about 15 to 25 % [15, 31].

It must be borne in mind that latency does not originate only in the transmission line, but also in the transceivers themselves. Particular attention should be paid to the network interface delay or the serialization delay. It describes the time interval needed to convert the data intended for transformation into a serial bit stream, which can be transmitted through the fiber optical transmission network (see Equation 7).

$$\text{Network interface delay} = \frac{\text{data packet size (bits)}}{\text{transmission bitrate (bits/second)}} \tag{7}$$

Table III provides network interface delay values, when serializing 64 and 512 byte data packets at transmission bitrates of 622 Mbit/s, 1 Gbit/s, 1.25 Gbit/s, 2.5 Gbit/s and 10 Gbit/s, which correspond to the data transmission speeds used in the existing and next generation optical access networks [6].

Table III

Values of Network Interface Delay Depending on the Data Packet Size and Bitrate

	Size of data packet (bytes)	Bitrate (Gbit/s)				
		0.622	1	1.25	2.5	10
Network interface delay (ns)	64	823.2	512	409.6	204.8	51.2
	512	6585.2	4096	3276.8	1638.4	409.6

Network interface delay, when processing relatively small-sized packets (e.g., 64 bytes) is lower than when processing large data packets (e.g., 512 byte) at a constant transmission bitrate. If a bitrate of 10 Gbit/s is used, then the time delay caused by the network interface for a 64 byte packet will be 51.2 ns, whereas for a 512 byte packet it will be 409.6 ns. Thus, the larger data packet must be transmitted, the higher signal latency will be introduced due to its processing at a constant transmission bitrate.

The sources of latency and typical time delay values introduced by them are summarized in Table IV. As shown, optical fiber is one of the key causes for latency or time delays in access and metro optical networks. The second most important element that can introduce a significant amount of latency is the chromatic dispersion compensation module (DCM).

Table IV

Latency Sources in Optical Access and Metro Networks and Their Typical Induced Time Delay Values

Name of line component	**Typical induced latency value**
Single-mode fiber (SMF)	4.9 μs per 1 km fiber length
Dispersion compensating optical fiber module (DCF DCM)	up to 25% from ITU-T G.652 single-mode fiber latency or up to 5% of ITU-T G.655 NZ-DSP fiber latency
Dispersion compensating fiber Bragg grating module (FBG DCM)	5 to 50 ns
Digital signal processing (DSP)	up to 1 μs
Forward error correction (FEC)	no 15 to 150 μs
Optical EDFA amplifier	about 0.15 μs per unit
Optical RAMAN amplifier	adds no additional latency
Optical transceivers	commonly used optical transceivers in optical fiber networks: 5 to 10 μs
	ultra-low latency transceivers: 4 to 30 ns
Optical signal regeneration (OEO conversion)	about 100 μs

In order to numerically evaluate the latency reduction methods in fiber optical access networks, a point-to-point optical metro-access transmission system model was created with an 80 km long total standard single-mode optical fiber section, chromatic dispersion compensation, optical signal amplification and the transmission speed of 10 Gbit/s (see Fig. 33). This was done with the purpose of showing numerically how the existing optical metro-access network can be improved, by replacing the typical optical and electrical components with other — lower latency components recommended by the author, without changing the network topology.

The first optical metro-access network (see Fig. 33a) consists of two transceivers, DCF DCM dispersion compensation module, EDFA amplifier to amplify the optical signal, and two 40 km long ITU-T G.652 single-mode optical fiber sections. The length of each optical fiber section is 40 km, as it is the ITU recommended single-mode optical fiber length, when not using optical signal amplification [17].

The second optical metro-access network (see Fig. 33b) is a reduced latency network consisting of two ultra-low latency transceivers, DCF DCM is replaced with FBG DCM, and the EDFA amplifier in this solution is replaced with the Raman optical amplifier, which does not introduce time delay because, unlike EDFA, it amplifies the passing optical signal without using an additional optical fiber section.

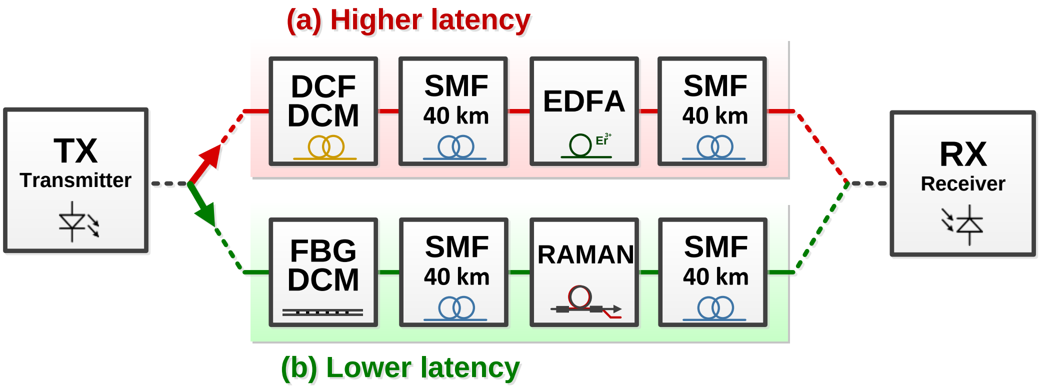


Fig. 33. Point-to-point optical metro-access network with (a) high latency conventional elements and (b) low latency optical and electro-optical elements.

To calculate the total latency reduction obtained by replacing the existing optical network components with lower latency components, at first, latency introduced by each component can be summarized in a table (see Table 5).

Table V

Calculation of Total Latency for Typical and Reduced Latency Point-to-point Metro-access Systems with Data Transmission Distance of 80 km

Line component	**Conventional transmission system**	**Reduced latency transmission system**
2 x 40 km ITU-T G.652 single-mode fiber spans	4.9 µs x 80 km = 392 µs	4.9 µs x 80 = 392 µs
1 CD compensation module (DCM)	DCF DCM: 25% of 392 µs = 98 µs	FBG DCM: 50 ns
1 optical amplifier	EDFA: 0.15 µs	RAMAN amplifier adds no delay
2 transceivers	2 x 10 µs = 20 µs	2 x 4 ns = 8 ns
2 network interface delay	2 x 51.2 ns = 102.4 ns	2 x 51.2 ns = 102.4 ns
Value of total accumulated latency:	**510.25 µs**	**392.16 µs**

When calculating the total introduced latency of each system, it was assumed that a 64 byte data packet was being transmitted (64 byte is a typical data packet size in market data messaging systems), causing 51.2 ns network interface delay in the electrical part of each transceiver. As seen from Table V, the obtained results prove that by using the existing standard single-mode fiber optical transmission line and replacing the DCF dispersion compensation module with an FBG module, the EDFA optical amplifier with a Raman amplifier, which does not use an additional optical fiber section for amplification, as well as the transceivers used in the transmission with low-latency transceivers, the overall latency of the aforementioned transmission system is reduced from 510.25 μs to 392.16 μs, which is decreased by 118.09 μs or by 23.1 %.

MAIN RESULTS OF THE DOCTORAL THESIS

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

1. If compared to TDM-PON systems, WDM-PON and SS-WDM PON systems are more suitable for next generation PON (NGPON) networks, as they can ensure at least 10 Gbit/s downflow data transmission speed for each subscriber;
2. By employing chromatic dispersion compensation methods (DCF and FBG), the maximum transmission distance of a 16-channel WDM-PON access system, with the transmission speed of 10 Gbit/s per channel, can be increased by more than 25 % (within limits of up to 70 km);
3. By carrying out dispersion compensation, a lower received signal BER can be achieved, using the fiber Bragg grating (FBG) instead of a dispersion compensating fiber (DCF). This is explained with the fact that FBG can be used at a higher optical transmission power, since it generates fewer non-linear optical effects, which can distort the transmitted optical signal, and additionally, the losses introduced by it (around 3.5 dB per one DCM module) are typically lower than in the case of the DCF fiber (around 0.6 dB/km);
4. The broadband ASE light source with the output power of at least +23 dBm (200 mW) and a flat curve of the output optical signal spectrum in the system operation range (C-band) necessary for the implementation of a 16-channel SS-WDM PON system can be created using two cascaded EDFA amplifiers, by adjusting their parameters (erbium doped fiber length, pump light source power and the wavelength);
5. The sliced electrical 1 Gbit/s NRZ signal can be transmitted through up to 25 km long SMF, DSF and NZ-DSF fibers and received, and its 1 GHz frequency baseband form can be fully restored, by transmitting and combining 500 MHz wide frequency band slices in the spectral width of the electrical component baseband;
6. In optical access-metro communications systems, it is possible to reduce the latency parameter by at least 20 %, when using the solution proposed in the Thesis, providing for a replacement of the existing optical and opto-electrical system elements with lower delay elements.

In conclusion, it must be emphasized that the obtained results can be employed to improve the currently operated optical access transmission systems and to introduce new ones. Within the framework of a cooperation agreement, recommendations were applied in practice for the improvement of Ltd "Telia Latvija" fiber optical transmission systems and in the development of the ERDF project implemented by the Latvian Radio and Television Centre "Next Generation Electronic Communications Networks in Rural Areas", as well as in the State Research Program (VPP) "Cyber-physical Systems, Ontology, and Biophotonics for Safe & Smart City and Society". By employing the obtained results, a WDM-PON fiber optical access communications system with dispersion compensation implemented on the basis of chirped fiber Bragg grating was developed and patented (Latvian patent No. LV-14628).

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