RIGA TECHNICAL UNIVERSITY

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THE USE OF WDM TECHNOLOGY IN PASSIVE OPTICAL ACCESS INFRASTRUCTURE SOLUTIONS

Summary of the promotion work

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RIGA TECHNICAL UNIVERSITY

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PROMOTION WORK
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The promotion work for a doctor's degree of engineering sciences (telecommunications) is to be defended publicly on the 12th of January at 17:00, 2012 at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Azenes Str., in the lecture-room No 210.

OFFICIAL REVIEWERS

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CONFIRMATION

I confirm that I have developed this promotion work for a doctor's degree of engineering sciences which has been submitted for reviewing at Riga Technical University. The promotion work is not submitted in any other university for a scientific degree.

Ilja Lasuks ……………………………. (Signature)

Date: ………………………

This promotion work is written in Latvian language. It contains Introduction, 5 Chapters, Conclusion, and Bibliography, 1 appendix, 108 figures and illustrations, with the total number of 144 pages. The Bibliography has 139 titles.

GENERAL DESCRIPTION OF THE WORK

Topically of the subject matter

Communications services delivering between user and service provider access point - the so-called "Last mile" - have always been a limiting factor in broadband telecommunications development [58-59, 68.70]. This problem was successfully solved using FTTx (Fiber to the X) technology [14-17]. FTTx is a type of solution which provides optical fiber to user's home, apartment, or to the distribution box near these customer premises [20, 21, 23-25]. These solutions make it possible to provide access to broadband services, that is important with so-called "Triple-play" package - data transmission, telephony and television - widespread in recent years [28, 45-46, 50-51].

Scientific studies focus mainly on EPON (Ethernet Passive Optical Network - Ethernet Passive Optical Network) and GPON (Gigabit Passive Optical Network - Gigabit Passive Optical Network) technology improvements, saving the installed fiber cable plant, in compliance with recommendations, as well as new solutions studies [29, 30, 35-38]. EPON and GPON technologies (as well as the new 10G EPON and 10G GPON) have bitrate limitations and lack of possibilities of expansion (dispersion, splitter attenuation, possible complexity of burst mode receiver) [12, 44, 47-48]. One of the solutions that can satisfy the growing bandwidth demand is WDM-PON technology [7, 9-11, 13, 69]. Currently there are two options for WDM-PON technology development: compatibility with first-generation PON solutions (EPON, GPON) and the creation of completely new incompatible solutions [18-19, 22, 26, 41-42].

This thesis investigates the possibility of using WDM technology in access networks, as well as determining the maximum number of users, and carries out the research of physical layer prospective realizations. The standard bitrates were chosen (1.25, 2.4, 10 Gbit/s) for the possible use of higher level protocols (Ethernet, SDH and GPON) [34], GPON and EPON possible splitting ratios (1 × 8, 16, 32, 64, 128) [35-38], as well as standardized distances (10 and 20 km) [35-38].

The topics of the research:

1. Minimum source output power calculation for each WDM-PON implementation at $BER < 1 \cdot 10^{-12}$ (bitrate 10 Gbit/s) and $BER < 1 \cdot 10^{-10}$ (bitrate< 2.5 Gbit/s) [35-38].
2. The evaluation of maximal client number for each WDM-PON implementation.

The research for each WDM-PON solution for interoperability with standards and the already installed infrastructure was based on the adoption of the following conditions:

1. Most widely distributed G.652 standard single-mode fiber [32] is used
2. Fiber length for each solution is 20 km
3. Frequency chirp effect and SBS threshold must be calculated only for 20 km fiber line
4. All WDM-PON solutions consist of the elements, that are widely available on the market. The elements with average parameters were chosen (laser sources, AWG multiplexers, APD receivers, modulators, ASE-sources, LEDs, connectors, filters, splitters, circulators, etc.)

The aim and tasks of the work

In a view of the prediction of passive optical access networks rapid development, create new solutions for WDM-PON implementation.

Therefore, **the aim of the promotion work was to evaluate the limitations of maximum number of subscribers for the use of WDM in passive access solutions, partially maintaining or creating a whole new infrastructure. Find minimum source output level for different WDM solutions for reliable operation.**

To achieve the set goal it was necessary to solve the following **basic tasks:**

1. To carry out analysis of the relevant literature and evaluate the development trends of existing and perspective PON systems and choose the necessary WDM concepts for the use in passive optical access networks;
2. To investigate the possibility of using the four-wave mixing effect in PON system realization and evaluate the potential number of subscribers;
3. To determine the SBS threshold for modulated signal in WDM optical line and determine the limitation of the maximal number of subscribers;
4. To calculate the frequency chirp influence on the rise of power losses for WDM/TDM-PON system
5. To calculate the minimum channel interval and the bandwidth for the SS-WDM system (LED and ASE source with a spectrum-slicing), a minimum output power at $BER<1 \cdot 10^{-10}$ and the maximum number of subscribers

The methodology of investigation

To fulfill the set tasks, theoretical computations as well as experimental measurements have been done, with analyzing the results obtained. Experimental measurements of the WDM / TDM-PON and SS-WDM systems have been made for the most important components. The obtained results were used to create models in OptSim modeling software that allows you to create WDM-PON concepts and model all the components necessary for WDM / TDM-PON, the SS-WDM and WDM-PON FWM enforcement. As the result of mathematical modeling a minimum-emitting (laser and LED ASE) power has been calculated for BER level $<1 \cdot 10^{-12}$ above 10 Gbit/s and $<1 \cdot 10^{-10}$ - up to 2.5 Gbit/s).

The results and scientific novelty of the investigation

The scientific novelty is the set of recommendations for existing GPON and 10GPON modernization as well as the new WDM-PON concept application. For the first time the four-wave mixing use in PON solutions has been investigated. **The main results**:

- The use of four-wave mixing effect in passive optical networks with WDM allows to set 16-subscribers system with 10 Gbit/s bitrate for each client. Also it is possible to increase it, using only 2 pump lasers. The pump power must be precizely controlled within 0.5 dB to get the minimum harmonics output power nonuniformity;
- Upgrading the existing GPON infrastructure makes it possible to provide transmission speeds of up to 10 Gbit/s per each subscriber with $BER<1 \cdot 10^{-12}$ and the distance up to 20 km. The maximum number of subscribers is limited by SBS nonlinear effect to 32;
- The frequency chirp effect must be taken into account during setting up the system. The power loss increases up to 5 dB in case of WDM/TDM-PON for chirp parameter <10 and a bandwidth $\Delta\lambda$ = 35 nm for WDM optical line;
- Using the spectral slicing with one broadband source and 16 light-emitting diodes, it is possible to get bitrate in downlink up to 1.25 Gbit / s and uplink - up to 622 Mbit / s with $BER<1 \cdot 10^{-10}$ LED; the number of subscribers is 16. Optimal channel interval is 1.6 nm and bandwidth - 0.9 nm, the required minimum power ASE-source with the flattering filter is 11 dBm and the output power of LED is -5.8 dBm;

Practical value of the work

- Necessary recommendations were provided for WDM-PON system implementation, complementing the existing infrastructure and constructing a network from scratch;
- The developed concepts for WDM-PON (WDM/ DM-PON, the ASE/LED and FWM for WDM-PON) can be used for the next generation systems manufacturing;
- Based on the results of the created WDM-PON layout it is possible to use it for next research producing as also patenting and collaboration with manufacturers;
- Patent for spectrum slicing source "spectrally sliced broadband light source in WDM passive optical network," Int. Cl. H04B10/17;
- The results of the doctoral thesis have been presented at the «Latvian Railway» technical center, as well as the data have been used in PON and DWDM network modernization and development;

The theses to be defended

1. Using the existing lasers can implement 8 and 16-channel access system using four-wave mixing effect, and provide download speeds up to 10 Gbit/s per subscriber using only two lasers;
2. Modernizing GPON and 10GPON systems with partial preservation of existing infrastructure and 10 Gbit/s transmission rate per subscriber, you can implement up to 32 subscribers, but is necessary to have one laser per each subscriber;
3. For the new WDM-PON with the number of subscribers up to 16, the bitrate in downlink up to 1.25 Gbit/s, uplink - 622 Mbit / s, the cheap spectral slicing SS-WDM technology must be used with one broadband ASE-source in downlink and 16 LED in uplink;

Scientific novelty

- Recommendations were developed for existing GPON and 10GPON modernization, complementing the existing infrastructure, as well as for newly developed WDM-PON solutions;
- Combined ASE and LED concept with channel interval of 200 GHz and bandwidth of 0.9 nm with and without flattering filter has been investigated;

- For the first time was investigated the use of four-wave mixing for PON development;

Approbation of the results at international scientific conferences and the publications

The main results of the promotion work were discussed at six international scientific conferences; they are also reflected in six articles published by scientific journals.

List of conferences:

1. The 12th International Conference „ELECTRONICS 2008”, KTU, Kaunas, Lithuania, 20.-22.05.2008
2. The 13th International Conference “ELECTRONICS 2009”, KTU, Kaunas, Lithuania, 12.-14.05.2009
3. The 14th International Conference “ELECTRONICS 2010”, KTU, Kaunas, Lithuania, 18.-20.05.2010
4. The 15th International Conference “ELECTRONICS 2011”, KTU, Kaunas, Lithuania, 17.-19.05.2011
5. RTU 50th Scientific Conference, Section Telecommunications, LATVIA, Riga
6. IEEE Swedish Communication Technologies Workshop, "Investigation of DWDM System Based on Cascaded Four-Wave Mixing"

List of publications:

1. Ļašuks I., Ozoliņš O., Ščemeļevs A. Investigation of Spectrum-Sliced WDM System // Electroncs and Electrical Engineering, 2008. No. 5(85). pp. - 45-48.
2. Ļašuks I. Investigation of Colorless WDM-PON Using a Broadband ASE-Source // Electroncs and Electrical Engineering , 2009. - No.6(94). - pp.- 43-46.
3. Ļašuks I. The Effect of Stimulated Brillouin Scattering on WDM-PON // Electronics and Electrical Engineering, 2010. - No. 7(103). – pp. 105-108
4. Ivanovs Ģ. , Ļašuks I., Ščemeļevs A. A Hybrid TDM/WDM PON System with FWM-Generated Source of Multiwavelength Optical Signals // Latvian Journal of Physics and Technical Sciences, 2010. - Vol. 5. -pp. 3-14,
5. Ļašuks I. The evaluation of 16-channel Hybrid ASE and LED WDM-PON// Electronics and Electrical Engineering, 2011. – No. 6(112). – pp. 33-36

6. O. Ozoliņš, V. Bobrovs, Ģ. Ivanovs, I. Ļašuks, International Journal of Physical Sciences, approved. „New-Generation Optical Access Transmission System Based on the Thin Film Filter Technology”

The results of the promotion work were employed during its execution to accomplish the investigation part of several projects:

1. In the framework of the State project “New technologies of electronic communications”: Reliability and safety of electric communication systems, Nr. V7408.1, RTU (2008,2009)
2. Investigation of wavelength division multiplexed broadband passive optical network realization (2009), RTU
3. Traffic consolidation research (IP over WDM networks), Nr. ZP 2008/16, RTU.
4. Traffic management research (fiber to-the-home in the optical communication system), Nr. ZP 2007/13, RTU.
5. Investigation of implementation possibilities for the next-generation mixed optically multiplexed communication systems, Nr. 09AP-42/09, European grant.

The structure of the thesis

Doctoral thesis volume is 144 pages. The thesis consists of an introduction, five chapters, bibliography and appendices.

The introduction contains a brief overview of modern access technologies.

The first chapter deals with PON technology trends from TDM-PON to WDM-PON and also carried out a comparative analysis between the different technologies. The result is a selection of three basic concepts of PON development using WDM and formulated the aim and objectives of the thesis.

The second chapter deals with research methodology and describes two important phases of research: mathematical modeling and practical implementation. The layout has been proposed for practical measurements, as well as explanation of the modeling software OptSim operation and BER calculation methodology.

The third chapter examines the research of four-wave mixing use in PON systems. First objective is to find the optimal conditions for generating channels with minimal power nonuniformity in order to get the maximum number of subscribers. Secondly – to find the maximum possible loss margin of 8 and 16-channel systems.

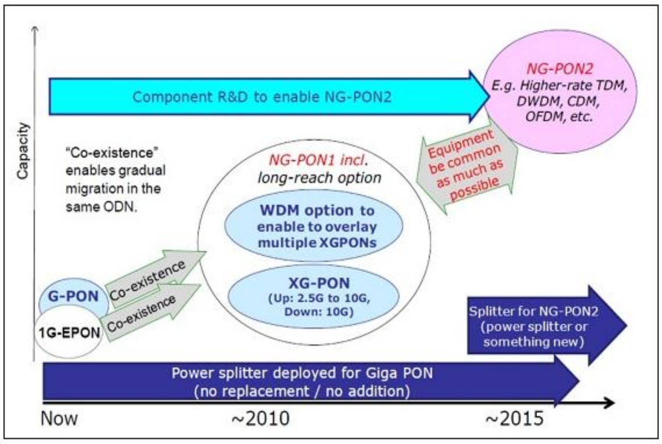
The fourth chapter consists of WDM/TDM-PON concept for the use in existing infrastructure. The layout of TDM-PON was created in a fiber optics laboratory and obtained the necessary data for mathematical modeling. The minimum required power levels for uplink and downlink, as well as the effects minimizing the maximum subscribers' quantity (frequency chirp and stimulated Brillouin scattering (SBS)), were investigated. The maximum possible number of subscribers has been calculated.

The fifth chapter deals with the explanation of SS-WDM concept with the use of broadband ASE-source in downlink and LED in uplink. The optimal channel interval and bandwidth were calculated. The ASE-source layout was established in the laboratory to obtain the necessary parameters for modeling; the minimum required source output power values for uplink and downlink have been obtained, and the maximum possible number of subscribers was found.

In summary, the main conclusions and future research directions are presented.

Chapter 1

The first chapter deals with the evolution of PON technology and the possible development trends. Existing GPON and EPON technology is widely used in various countries and regions of the world [17.28]. Any technology immediately after the introduction needs the further development [64-66]. 10G EPON and 10G GPON increased the speed of the common channel using TDM multiplexing; however, it has the limitations of possible upgrade. There are two development concepts. FSAN (Full Service Access Networks) concept is shown in Fig. 1.1. [59]. Here are two possible paths defined. NGPON1 (Next Generation PON) is the first path, which uses existing fiber infrastructure and splitter with a possible addition of client-side filters. This trend includes an increase in speed per channel of 10 Gbit / s (XGPON - here X is 10). This trend meets the conditions for compatibility with EPON and GPON. NG-PON2 path requires new splitting devices like WGR (waveguide Grating Router -) [1, 31, 43, 49]. Compatibility with existing infrastructure and standards in this case is not mandatory. These solutions are intended to speed up to 1 Gbit/s per subscriber. Another vision of the access network development was made by ITU. In this case, FTTH WDM-PON means the different XGPON flow joining in single fiber and ultra-dense WDM PON – NG-PON2 with complete replacement of the power splitter by AWG (Arrayed Waveguide Grating) and a wavelength distribution to each customer [45,46]. The common place for both conceptions is the use of WDM which is the only way for further development.



1.1. Fig. FSAN conception for PON development

Looking at all possible technologies, from concept, which provides the use of existing infrastructure (NGPON1), and the concept, which requires a completely new infrastructure (NGPON2), three technologies were selected:

- FWM WDM-PON

FWM effect application in WDM-PON is a completely new solution, which enables transmission speed in downlink and uplink up to 10 Gbit / s using only two lasers, and able to get up to 16 carriers for further modulation [54];

- WDM/TDM-PON

  Technological advantage of this concept is the possibility to use the existing infrastructure and broad-produced components. Transmission speed in downlink reaches up to 10 Gbit/s uplink - up to 10 Gbit/s. This solution requires a single laser to each subscriber [56];

- SS-WDM

  This technology allows you quickly and in cost-effective way ("colorless" LED in uplink and shared broadband ASE source-use in downlink) to create new networks, using safe components (LED life span up to 10^8 hours). Transmission speed in downlink reaches up to 1.25 Gbit/s, uplink - up to 622 Mbit/s [52, 53, 55]. All customers need only a broadband source for downlink and LED for each channel in uplink.

Chapter 2

This section examines the research stages.

1.) Mathematical modeling

The obtained results of the layout are used for mathematical modeling in OptSim software, which allows you to create WDM-PON system and simulate linear and nonlinear fiber effects and modeling of all components required for WDM / TDM-PON, SS-WDM and WDM-PON FWM. The BER parameter is used for quality assessment because it is the most widely used for evaluating the digital systems. As a result of mathematical modeling, minimum-emitting power (laser and LED ASE) at BER level ($<1 \cdot 10^{-12}$ at speeds up to 10 Gbit /s and $<1 \cdot 10^{-10}$-speeds up to 2.5 Gbit/s) was calculated.

2.) Layout creation for practical experiments.

WDM/TDM-PON and SS-WDM systems are partly created in a model (layout) to determine the most important parameters of components (e.g. ASE source implementation for spectral slicing loss calculation). Full realization of the system layout is not possible because of limited material resources.

Research stages:

1. FWM WDM-PON System

   1.1. Pump laser power calculation for 8 and 16-channel systems
   1.2. Loss budget calculation
   1.3. 8 and 16-channel WDM-PON system simulation with BER <1 • 10-12 level using OptSim.

2. WDM/TDM-PON system

   2.1. Loss budget calculation
   2.2. Single channel TDM-PON system development in the laboratory
   2.3. The minimum required laser output power calculation for downlink for 16, 32 and 64-channel systems with BER <1 • 10^{-12} level using OptSim mathematical modeling
   2.4. The minimum required laser output power calculation for downlink for 16, 32 and 64-channel systems with BER <1 • 10^{-12} level using OptSim mathematical modeling
   2.5. SBS threshold experimental determination for the maximum possible number of subscribers calculation based on data obtained
   2.6. Frequency chirp impact calculation on power loss increases for WDM/TDM-PON system uplink

3. SS-WDM system

   3.1. A minimum LED output power calculation for uplink (8,16 and 32-channel system) with BER <1 • 10^{-10} using OptSim mathematical modeling
   3.2. ASE-source and the spectral slicing implementation, using the Erbium fiber with pump lasers and Bragg grating filter
   3.3. A minimum ASE-source output power level calculation for downlink (8,16 and 32-channel system) with BER <1 • 10^{-10} using OptSim mathematical modeling

Mathematical modeling

The mathematical apparatus for WDM (including WDM-PON) system calculation uses of non-linear Schrodinger equations [2, 60-62]. If pulse width > 5 ps, and peak intensity < $1 GW/cm^2$, the equation is [2,60-62]:

$$i\frac{\partial A}{\partial z} + \frac{i\alpha}{2}A - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + \gamma|A|^2 A = 0 \quad (2.1)$$

Where: T – pulse width [s], A – amplitude [dBm], α - attenuation [dB/km], β_2 – dispersion parameter [ps^2/km], z – distance of the z-axis [km], γ – nonlinearity coefficient.

The analytical solution of the Schrodinger equation is based on variety of numerical pseudo spectral methods. Split-Step Fourier method belonging to this class is characterized by shorter calculation time [2,60-62] OptSim is based on a TDSS (Time Domain Split Step) algorithm to realize the signal distribution equation in fiber[2,60-62].

$$\frac{\partial A}{\partial z} = (\hat{D} + \hat{N})A \tag{2.2}$$

Differential operator D describes the dispersion and attenuation of a linear medium. N is the operator which describes the impact of nonlinear effects on pulse propagation [75].

$$\hat{D} = -\frac{i\beta_2}{2}\frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial T^3} - \frac{\alpha}{2} \tag{2.3}$$

The algorithm uses for calculation of a(t, z) separately D and N operators with step Δz (h). Split-step method is an approximate solution, which defines that the linear and nonlinear effects are calculated separately with step h. TDSS calculates N in time domain using calculated convolution results for each sample [2, 60-62]:

$$TDSS \rightarrow A_L[n] = A[n] * \boldsymbol{h}[n] = \sum_{k=-\infty}^{\infty} A[k]\boldsymbol{h}[n-k] \tag{2.4}$$

OptSim simulation software allows creating a fiber optic transmission system using the connected blocks; each block represents one of the system components (e.g., laser or external modulator). All the parameters of components can be modified optimizing them for the use in real conditions. Each block is simulated separately, based on the parameters and input signal. WDM scheme consists of a pulse generator which is connected to the encoder. In all cases is used NRZ code, because it is the most widely distributed. Encoder is connected to an external MZM (Mach-Zander Modulator - Mach-Zanders modulator). MZM is also connected to a CW laser. In all simulations, where the BER dependence on the laser output power is calculated, this value is measured after MZM, which corresponds to power, which is entered into the fiber. WDM multiplexer OptSim implementation consists of a filter with the defined amplitude-frequency characteristic (in this case Gaussian) and the loss value (Fig.2.1.).

Before and after the fiber an attenuator is placed, which describes the attenuation of connectors at operator and subscriber sides. In all simulations the standard single-mode fiber G.652D is used. The attenuation level was chosen with a reserve: 0.25 dB / km for C and L bands, and 0.4 dB / km for O band. Receiver in all cases is APD with sensitivity -24 dBm at BER 1 • 10^{-12}. Electrical filter in OptSim model is inside the receiver with 4-stage filtering and 7.5 GHz 3-dB band. Behind the filter the oscilloscope or eye-diagram analyzer were placed. All results are based on eye-diagram analyzer.

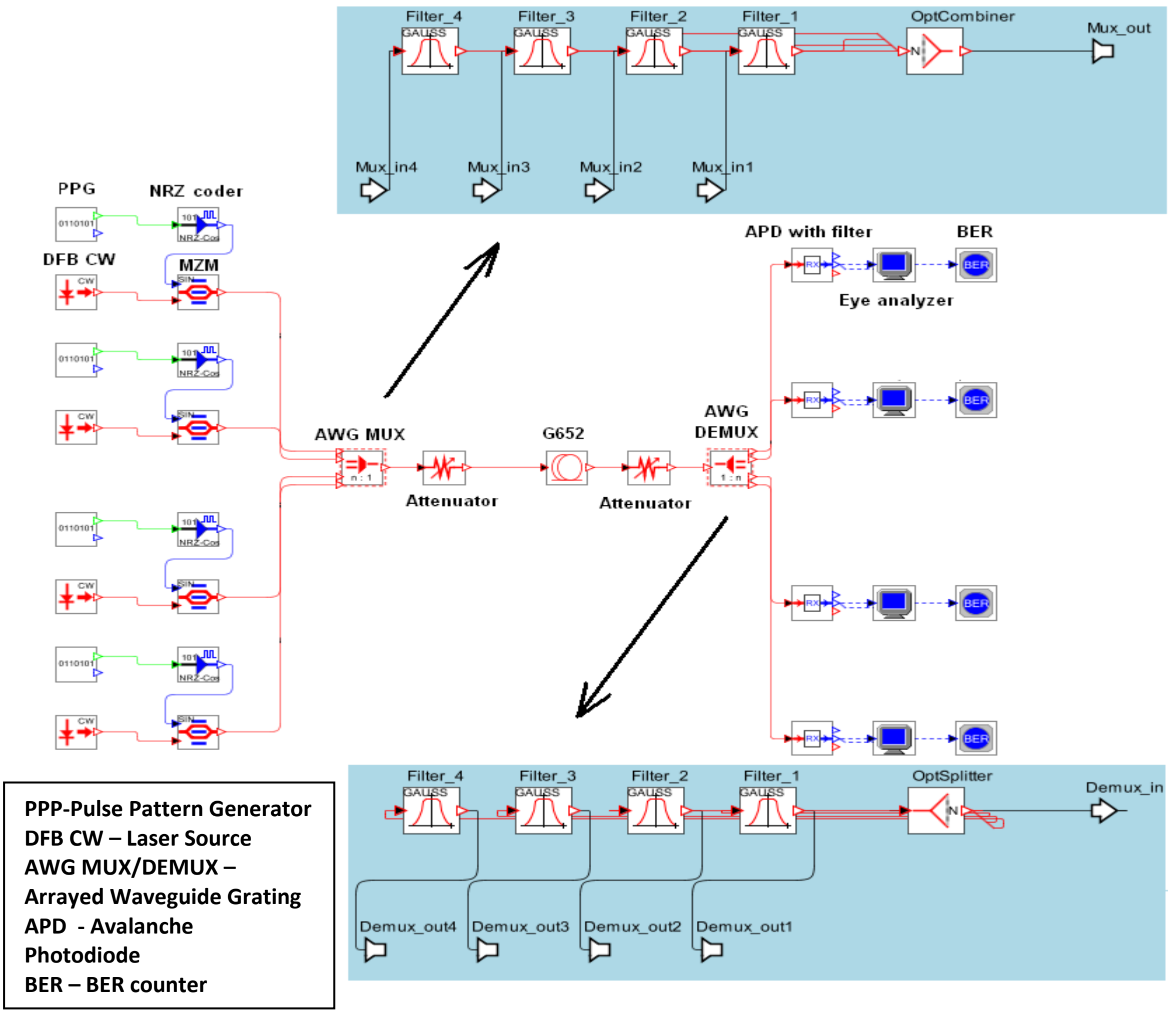


Fig. 2.1. OptSim WDM scheme

Experimental realization

Experimental measurements were made in the fiber optic transmission systems laboratory using highly precise measurement equipment: the spectrum analyzer, power and wavelength meter. Signal quality assessment was made with eye-diagram analyzer (with BER-masks) and PPG (Pulse Pattern Generator) to create a variety of standardized transmission bitrates.

WDM / TDM-PON system is made using DFB laser with variable wavelength and output power, Mach-Zander external modulator, G652D fiber, variable attenuator and eye-diagram analyzer. The system is implemented in single channel option (see Figure 2.2.) with the possibility to obtain the parameters that are independent on the number of channels (ER – extinction ratio, the pulse rise and fall time, pulse shape at the end of the line to choose the correct method for calculating BER).

EDFA amplifier is used for SBS threshold measurements with output power up to 23 dBm and the power meter with wavelength detection. SBS threshold has been measured for modulated signal and the CW mode.

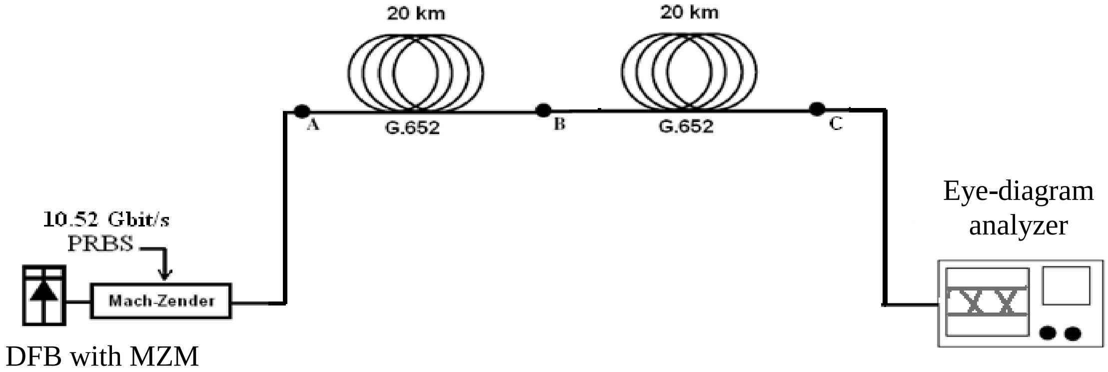


Fig. 2.2. WDM / TDM-PON measurement scheme

The laser output power was increased step by step to obtain the border, where Brillouin scattering begins to reflect the input power. (See Fig. 2.3.)

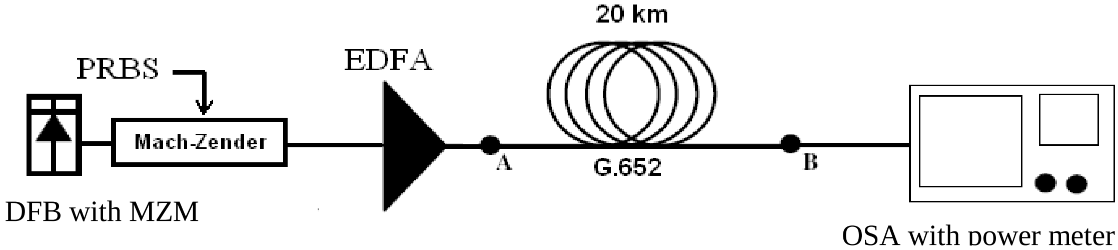
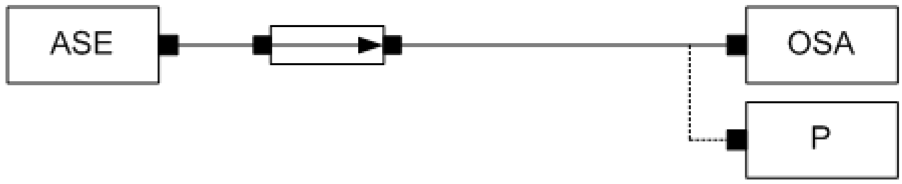


Fig. 2.3. SBS threshold measurement scheme

For the SS-WDM system realization the ASE-source was used with output power of 7.7 dBm and spectral width (FWHM) 32.28 nm (Fig. 2.4). GFF filter declines the output power to 2.2 dBm (Fig. 2.5). Based on the obtained ASE-source spectrum a mathematical model for subsequent calculations is created.



2.4. ASE source spectrum measurement scheme

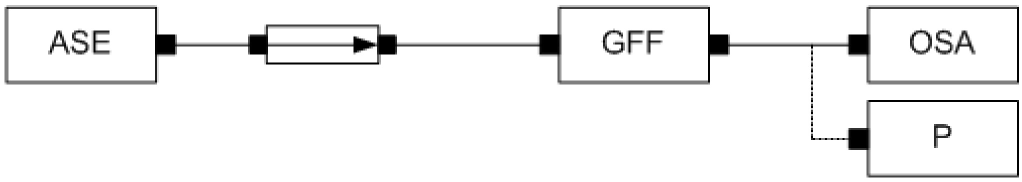


Fig.2.5. ASE source spectrum measurement scheme

Summarizing OptSim software description:

- Fiber optic transmission quality assessment must be done using BER parameter;

- All BER calculations were made using Gaussian statistics, except the case of using SOA with internal noises, where chi-square $\chi 2$ statistics should be used[60-62];

- BER deviation does not exceed 5% limit, when WDM / TDM-PON, the SS-WDM and WDM-PON FWM system simulations are made for at least 1024 bits [60-62];

With the help of layout parameters for OptSim components creation were obtained. For WDM/TDM-PON case:

- Extinction Ratio
- Pulse rise and fall time
- Pulse shape at the end of the line to choose the correct method for calculating BER

SBS threshold level for CW and modulated signal was measured with the help of WDM/TDM-PON layout.

ASE-source case:

- ASE-source spectrum

- Slicing loss value
- Sliced channel spectral shape

Chapter 3

FWM interaction belongs to the non-linear Kerr effects. This effect is mainly seen in WDM systems with multiple channels and this effect was considered as negative. The «useful» part of this effect began to implement in parametric amplifiers [3-6, 63].

In these studies it has been observed that, together with the amplifying, the carrier frequencies can be generated using one or two pump lasers. Based on this phenomenon, it is possible to use generated carrier frequencies for further modulation [6]. FWM interaction effect was not previously used in PON system implementation [54].

This concept is based on the fact that two pump lasers with a help of FWM interaction generate carrier frequencies (harmonics) in highly non-linear fiber. Then harmonics or carriers are demultiplexed, modulated (with an external modulator) and multiplexed, the power level of harmonics is up to 10 dBm as also a narrow spectral width (1 GHz) achieved, which allows you to transmit signals at speeds up to 10 Gbit/s. These speeds are chosen for the use of Ethernet protocol, which is mostly used in transmission networks. The tasks for the system mathematical modeling are defined (see Fig. 3.1.) below:

- Pump laser power calculation for 8 and 16-channel systems using OptSim for mathematical modeling ;
- 8 and 16-channel system simulation with target BER $<1 \cdot 10^{-12}$;

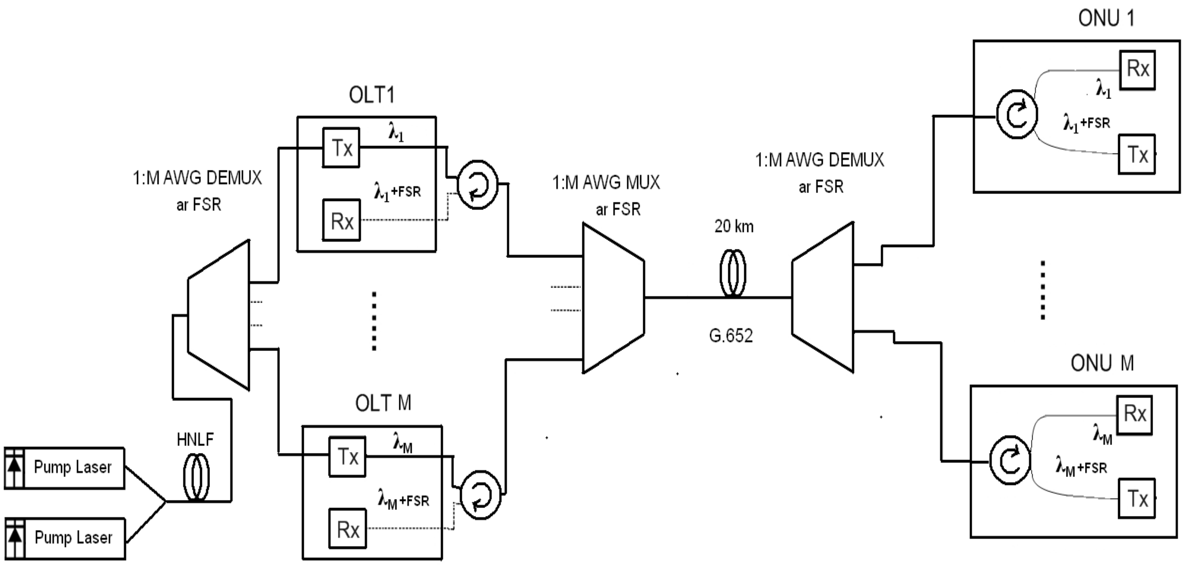


Fig.3.1. FWM for WDM-PON systems with WDM in uplink

The carriers generation technique is based on FWM interaction effect, which needs short length (≈ 1 km) of highly non-linear fiber with pump laser assistance. Carrier frequencies generation scheme is shown in figure 3.1. After carrier frequencies generation they are filtered for the individual channel modulation [54].

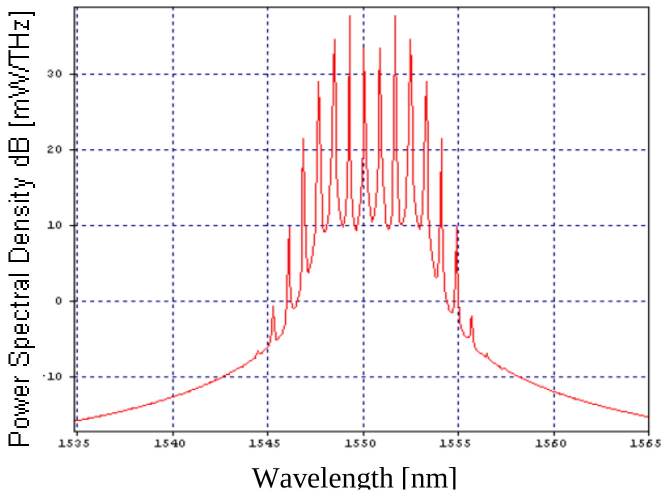


Fig.3.2. Generated harmonics

The resulting channels are multiplexed and inserted into the fiber. (See Fig. 3.1). Figure 3.2. shows the generated harmonics before demultiplexing. Gradually changing the pump laser power and HNLF length, has been found the optimal situation where the channel power difference is minimum and channel output power is maximum. Figures 3.3-3.4 show the channel output power distribution.

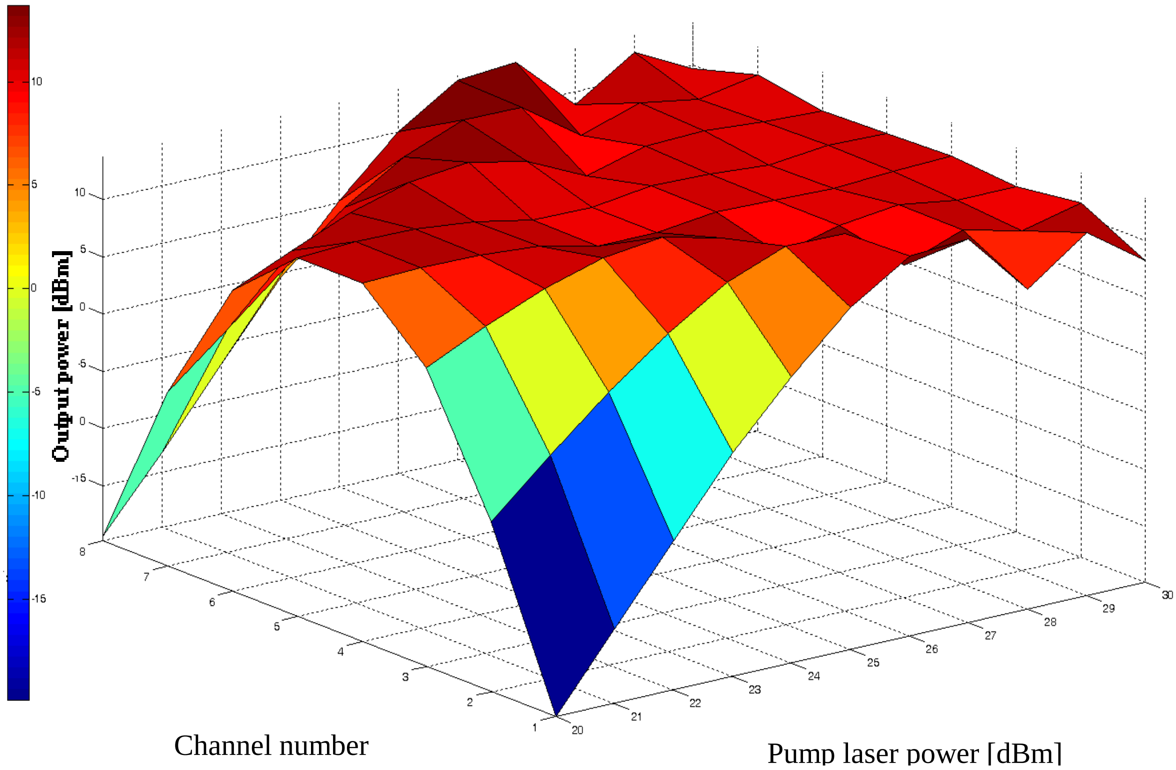


Fig.3.3. Harmonic power dependence on Pump laser power 8-channel system

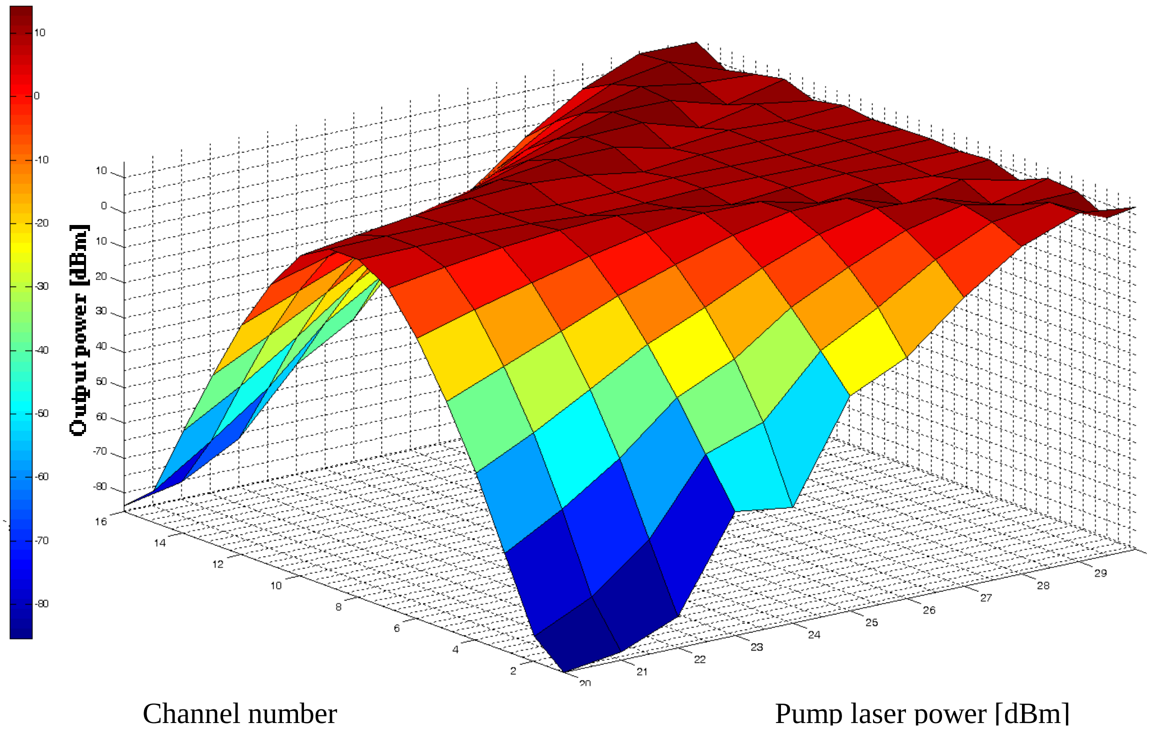


Fig.3.4. Harmonic power dependence on Pump laser power 16-channel system

Table 3.1.

Harmonic generation parameter summary

Channel number	8	16
HNLF length (km)	1.1	1.25
Laser power (dBm)	25	28
Maximum power nonuniformity (dB)	3.25	6.76

Given the fact that the pump output power values here are fixed and its change brings to channels instability, in this case, the BER dependence is derived from the additional inserted attenuation. The additional attenuation was increased by the step (1 dB), while the BER is below $1 \cdot 10^{-12}$. The power reserve (2 dB) is included in the power budget. Uplink is realized using DWDM/TDM-PON principle (Fig. 3.1.), where each subscriber has its own wavelength in uplink.

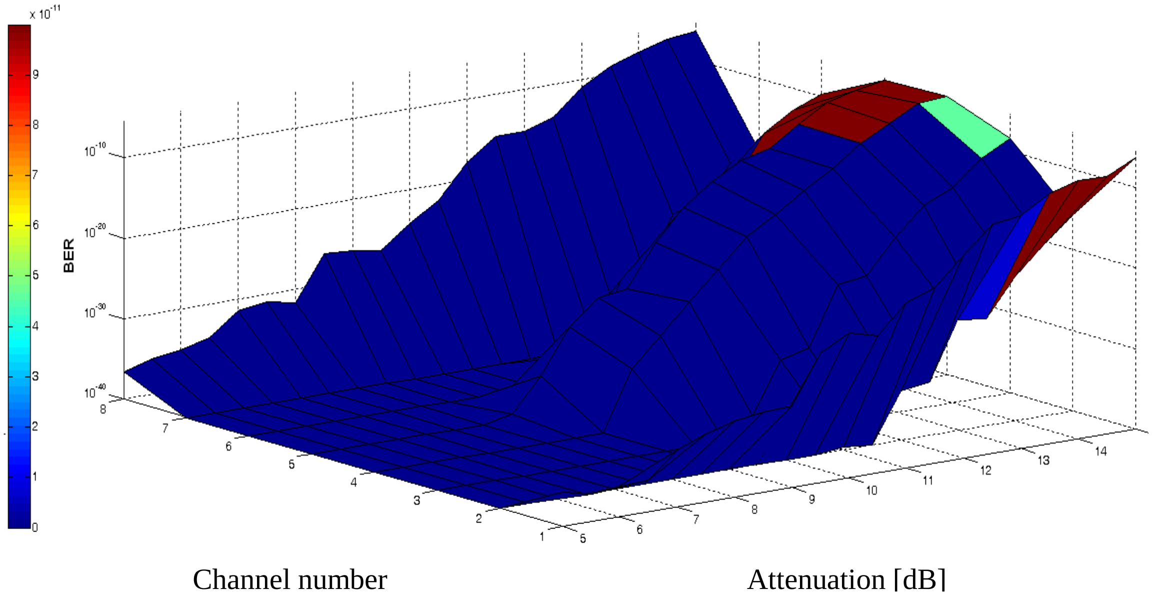


Fig.3.5. BER dependence on additional attenuation for 8-channel system.

Table 3.2.

8 and 16-channel system simulation results

Channel number	8	16
Maximum additional attenuation [dB]	13	11.5
BER maximum differnece (side channels)	$1 \cdot 10^{20}$	$1 \cdot 10^{25}$

Based on the results (see Fig. 3.5), we can conclude that the BER nonuniformity together with output power nonuniformity increased for 16-channel system to 6.76 dB. Power budget reserve (in conjunction with the included 2 dB margin) is sufficient for stable operation of the system. It should be noted, the pump laser output power should be carefully monitored (0.5 dB step) to maintain the output power stability of the resulting carrier frequencies. Subscriber number can be increased by using three pump lasers, however, generating conditions of carrier frequencies (pump laser output power and nonlinear fiber length) will change.

Chapter 4

This chapter deals with WDM/TDM-PON technology implementation options, which include the minimum laser output power calculation (for a standard solution with partial preservation of existing infrastructure), maintaining the BER level of less than $1 \cdot 10^{-12}$. This solution requires one laser for each subscriber in downlink (32 lasers) and one laser for all subscribers in uplink. Existing infrastructure includes G.652D fiber with a maximum distance of 20 km and with a maximum splitting ratio of 1 × 64 [35-38], which corresponds to the GPON standard. The effect of limiting factors on the maximum number of subscribers and loss budget was considered. TDM-PON or GPON (see Fig. 4.1.) modernization requires the use of existing infrastructure. Already installed system (usually GPON) includes cables, connectors, patch panels, various types of connections and splitters. OLT is located at the service provider and the ONU at the customer. This infrastructure (non-ONU and OLT) costs at least 70% (till 90%) of the system CAPEX [23]; that is why infrastructure should be left unchanged

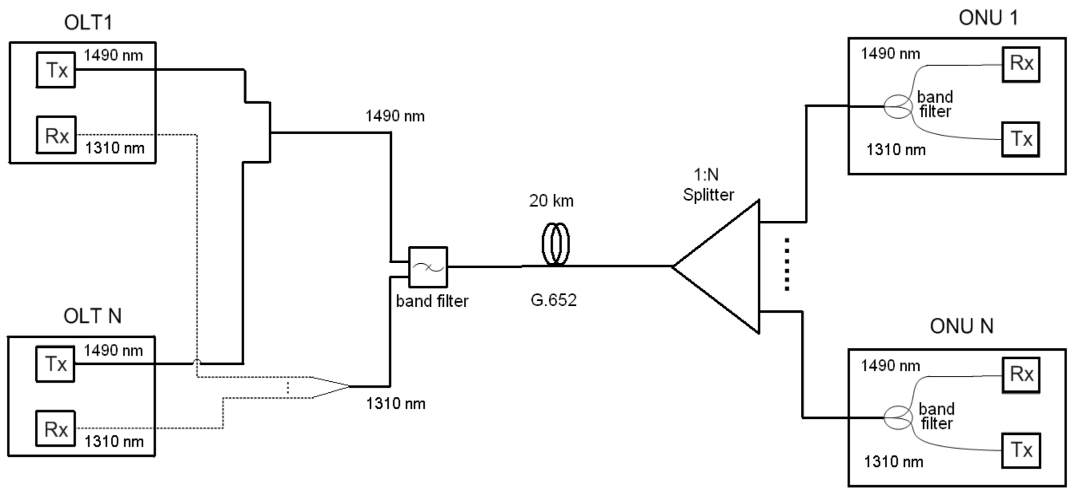


Fig. 4.1. TDM-PON logical scheme

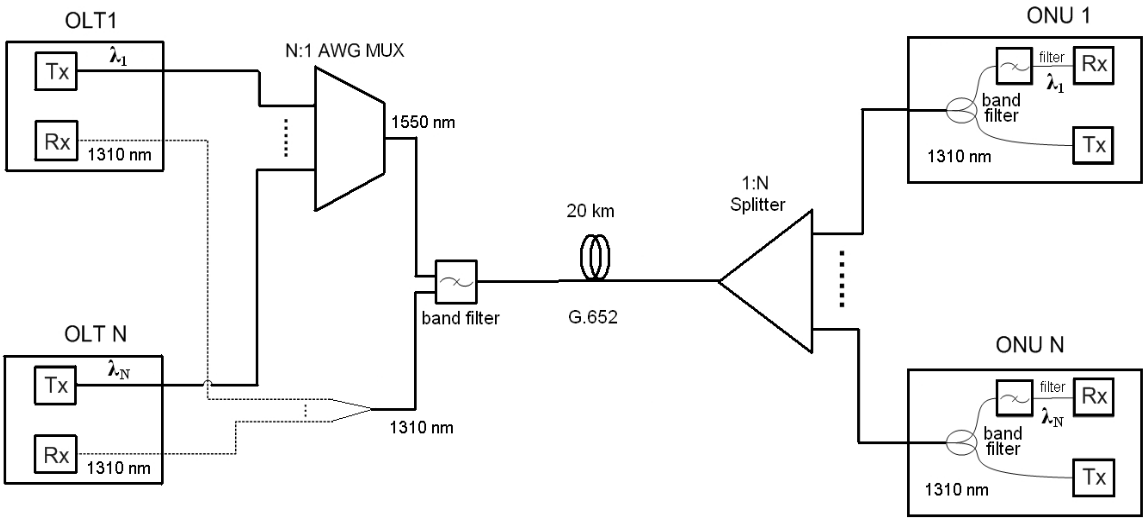


Fig. 4.2. WDM/TDM-PON logical scheme

Figure 4.2. shows WDM / TDM-PON concept for TDM-PON distribution. Unlike the ITU defined solution [35-38], WDM / TDM-PON downlink channels are implemented using WDM with standard step between channels (100 GHz) [33] using a laser array and AWG multiplexer. The power splitter is saved; however, each ONU is supplemented with TFF (Thin Film Filter). Uplink stream is realized with the help of TDM using the 1310 nm wavelength. The main difference from other studies [10, 11, 58] that WDM is used in downlink and TDM - in the uplink (with the use of splitter).

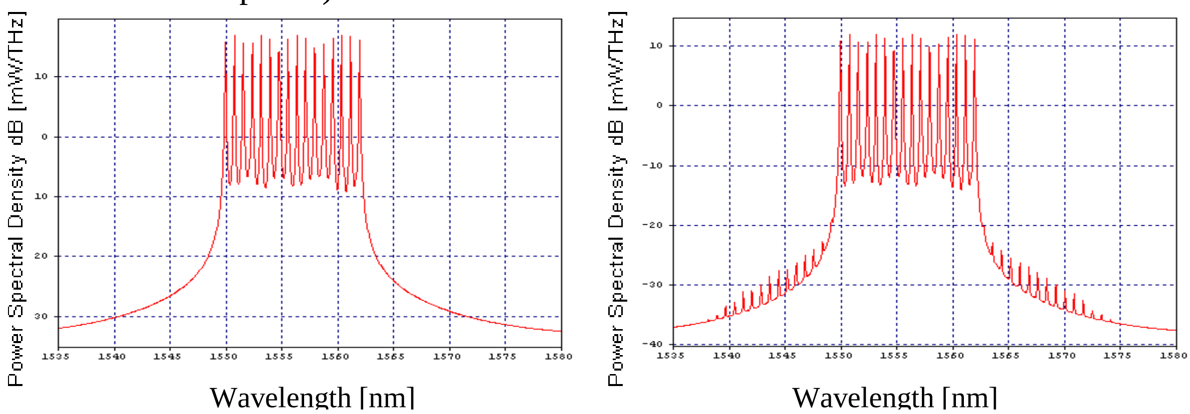


Fig.4.3. Power spectral density at the beginning and the end of the line at 5.4. dBm output power (worst channel BER = $1.27 \cdot 10^{-12}$) of 16-channel system

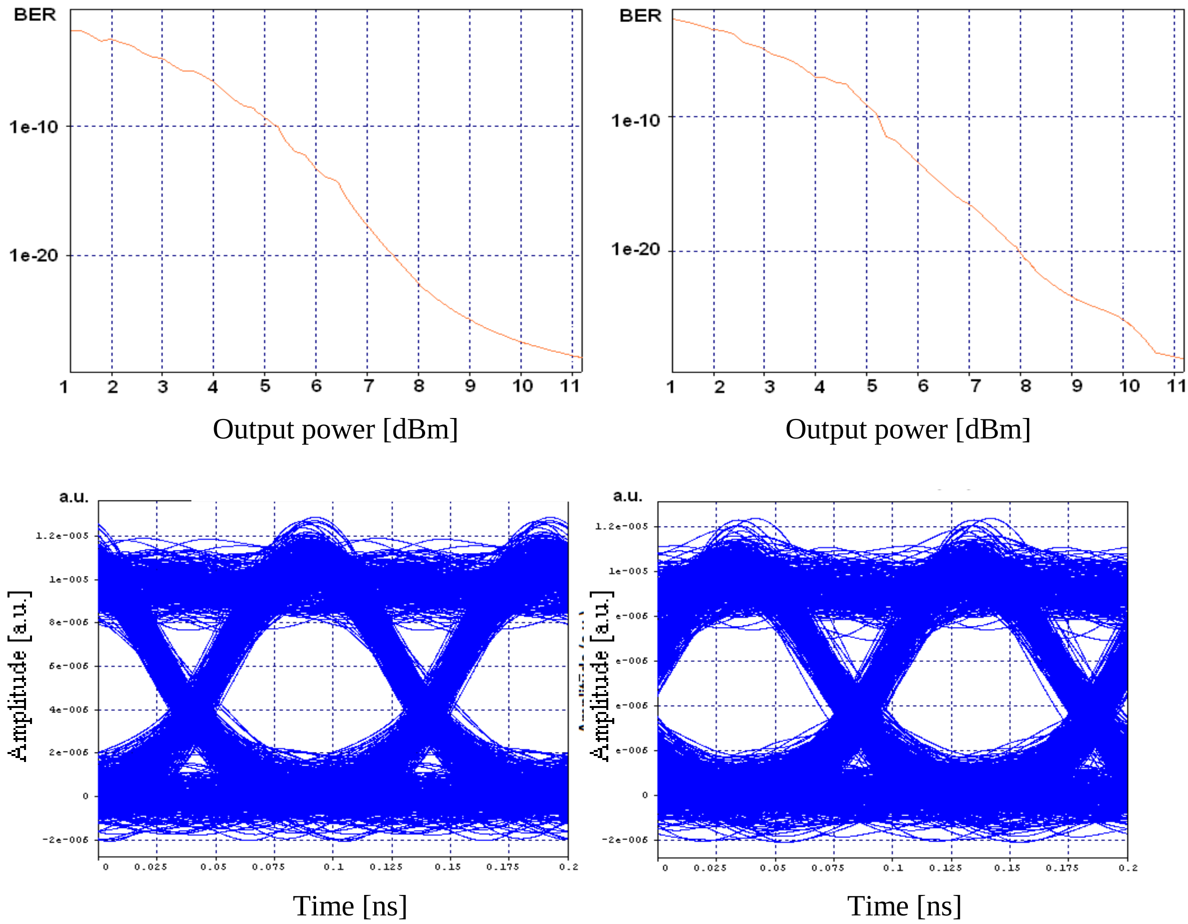


Fig. 4.4. 16 channel system: a.) BER dependence on the output power for the worst and the best channel b) Eye diagram of the worst and the best channel at BER ≈ $1 \cdot 10^{-12}$

16, 32 and 64-channel system mathematical modeling is designed to get the minimum required laser output power (for an external modulator output), where the system BER is less than $1 \cdot 10^{-12}$. All connectors attenuation and power reserve are simulated using variable attenuator. Additional loss of power budget due to ER (Extinction Ratio) and dispersion is included in BER calculation algorithm. ER has been obtained with the help of layout. All the IL (Insertion Loss) values are selected on the basis of analyses of optical components which are available on the market [51].

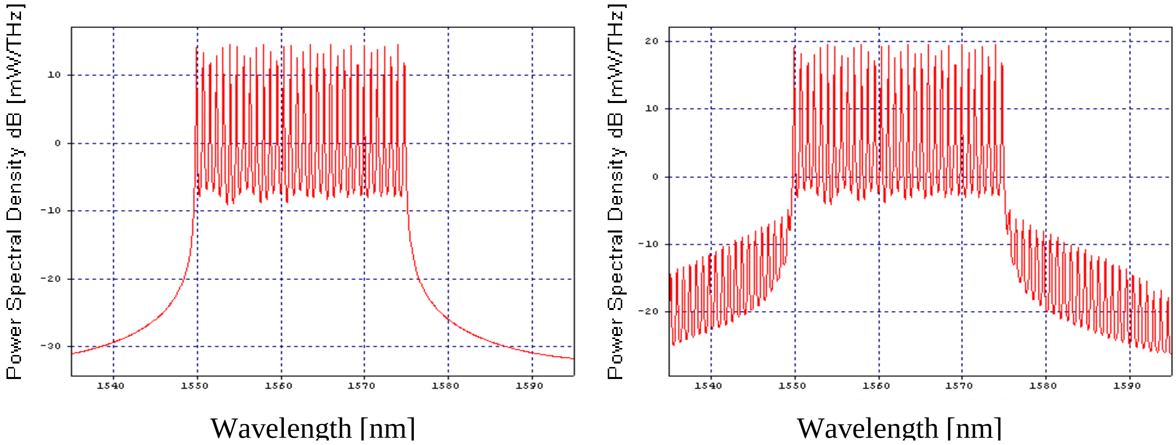


Fig.4.5. Power spectral density at the beginning and the end of the line at 13.4. dBm output power of 32-channel system

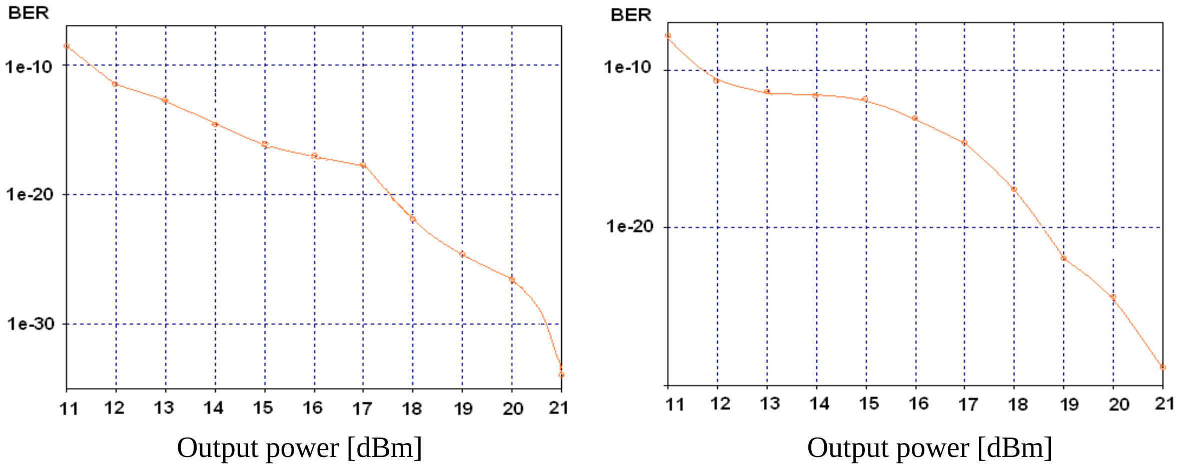


Fig.4.6. BER dependence on the output power for the worst and the best channel

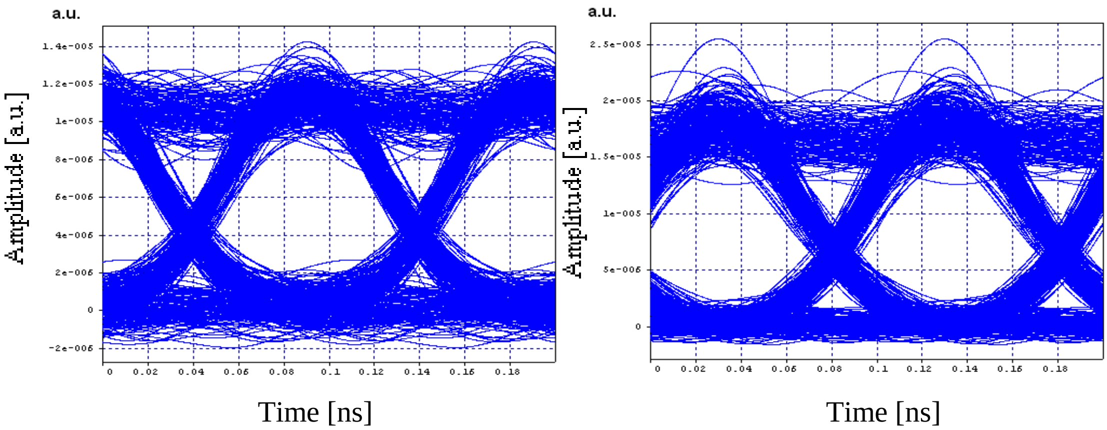


Fig.4.7. Eye diagrams for the worst and the best channel at BER ≈ 1 • 10^{-12} (32-channel system)

Table 4.1.

Loss budget difference (WDM/TDM-PON with splitter)

Channel number	Theoretical loss budget [dB]	Needed loss budget [dB]	Output power [dBm]
16	28.9	29.7	5.7
32	35.1	37.7	13.7
64	39.8	43.4	19.4

Uplink stream is realized in the second optical window - 1310 nm (WDM/TDM-PON) and the 3rd window - 1550 nm (DWDM/TDM-PON). Simulation is done using the same methodology as for the downlink stream.

The minimum laser power for BER level, equal to or less than $1 \bullet 10^{-12}$, was sought. In addition FEC coding (in downlink modeling was not possible to use FEC due to OptSim constraints) was applied, using the RS (25a, 23b, 16) code according to the ITU G.987.2 recommendation. 10 Gbit / s uplink speed was selected to be able to use the ready 10G GPON ITU-T recommendations.

Table 4.2

Loss budget for uplink (WDM/TDM-PON)

Channel number	Inserted attenuation [dB]	Output power [dBm]
16	26.7	2.7
16 (FEC)	26.7	0.1
32	31.4	7.4
32 (FEC)	31.4	4.8
64	34.7	10.7
64 (FEC)	34.7	8.1

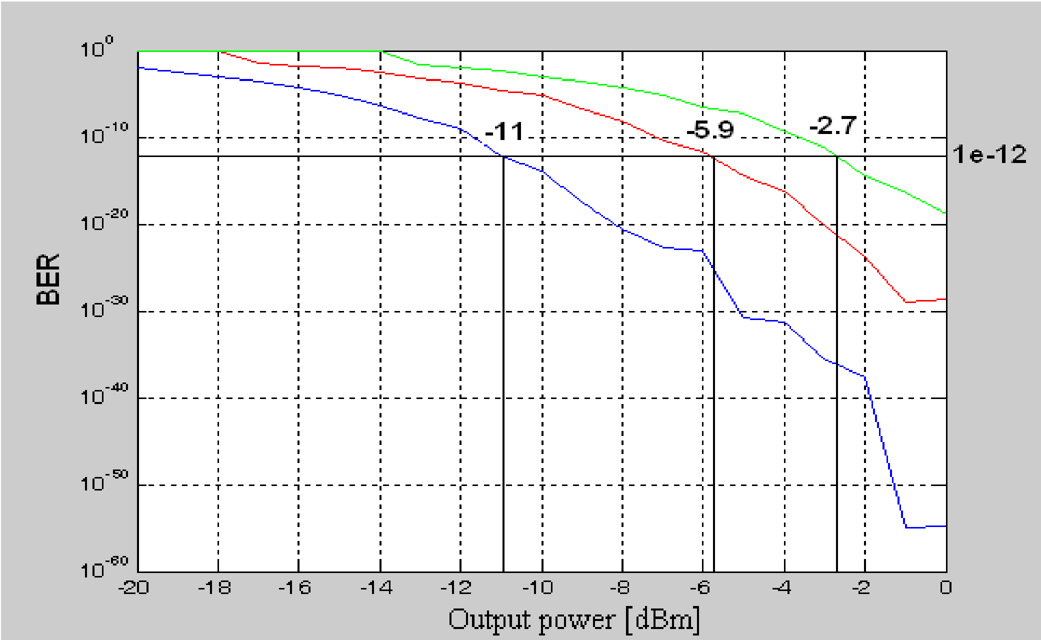


Fig.4.8. BER dependence on output power for 16,32,64 channel system without FEC°

Based on the results obtained, the minimum necessary laser output power for 32 channel system is 13.7 dBm in downlink, 4.8 dBm in uplink with BER <1 • 10^{-12}.

Frequency chirp

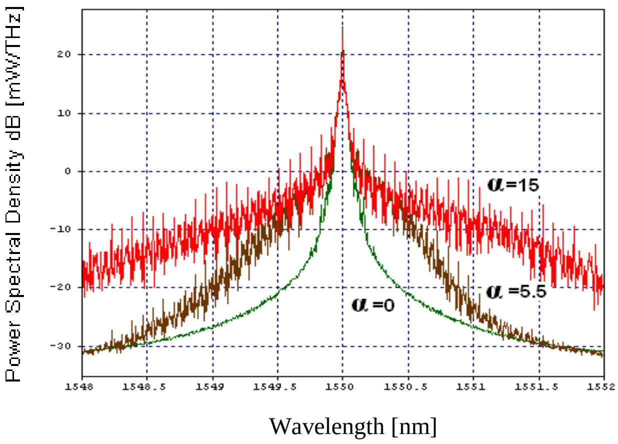


Fig. 4.9. Frequency chirp caused spectrum broadening

The laser with external modulator is used for downlink in WDM/TDM-PON concept. To reduce the costs of subscriber set, in uplink laser with internal modulation must be used, avoiding the expensive external modulator. Using the internal modulation will cause the frequency chirp effect [2]. Linear frequency modulation (or frequency chirp) is one of the effects that can significantly reduce the transmission rate and increase losses. This effect is observed in all lasers with internal modulation. Frequency chirp primarily impact the increase of losses, which limits the power budget and number of subscribers. Laser chirp parameters can be gotten in the passport data (they can vary from 1 to 10) [2]. Formulas 4.1 and 4.2 [2] allow analytically calculate the chirp effect on power losses. β3 parameter effect on the D parameter is calculated separately.

$$\delta_d = -5\log_{10}\left[1 - \left(4BLD\sigma_\lambda\right)^2\right] \quad (4.1)$$

B – bitrate [bit/s]
L – line length [km]
D – dispersion parameter [ps•nm/km]
σ_λ - spectrum broadening
C – chirp parameter

$$\delta_C = 5\log_{10}\left[(1 + 8C^2\beta_2 B^2 L)^2 + (8\beta_2 B^2 L)^2\right] \quad (4.2)$$

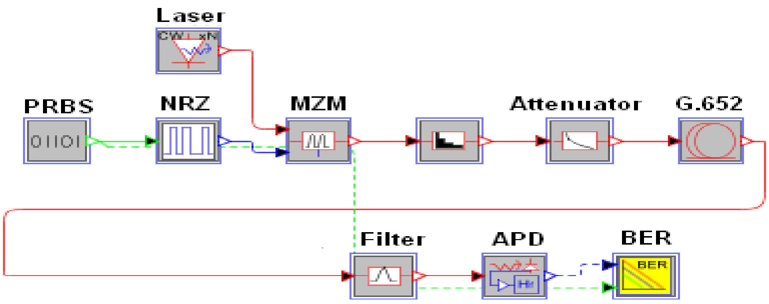


Fig. 4.10. OptSim scheme for determining the chirp

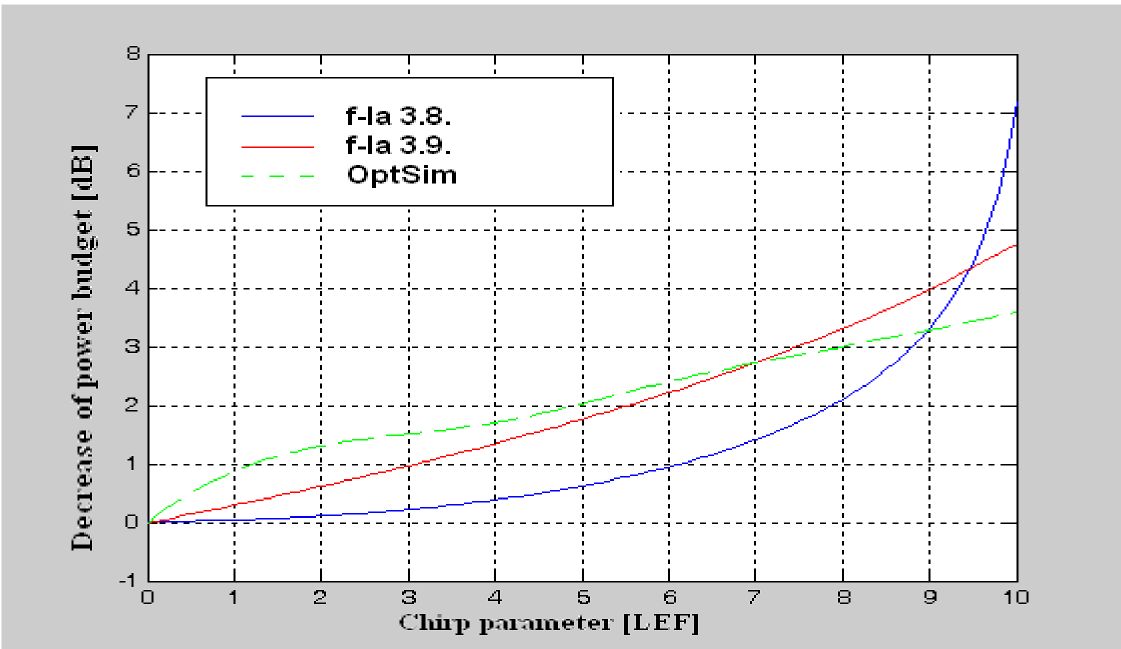


Fig.4.11. Power budger decrease due to chirp (1310 nm)

The scheme in Figure 4.10 corresponds to the minimum output power determination for WDM/TDM-PON system uplink (Fig.4.2). In this case, the chirp parameter was increased step by step in the external modulator (in this case, the internal modulator is imitated by external modulator for the possibility to change the chirp parameter value) and found the minimum output power (after modulator), which corresponds to BER = 1 • 10^{-12}. Minimum required power difference with the measurement, where C = 0, is considered to be an increase of power budget loss. The chirp effect on loss was calculated using OptSim, because the formulas 4.8 and 4.9 gives inaccurate results.

Summarizing the results, the frequency chirp effect must be taken into account during setting up the system. The power loss increases till 5 dB in case of WDM/TDM-PON for chirp parameter <10 and a bandwidth $\Delta\lambda$ = 35 nm for WDM optical line. This means that the uplink output power must be 9.8 dBm (in comparison to the obtained value of 4.8 dBm) and the number of subscribers is limited by 32.

Brillouin scattering

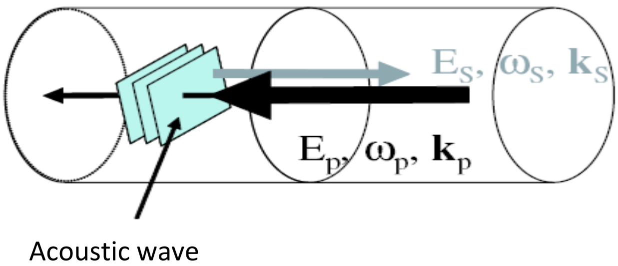


Fig.4.12. SBS in optical fiber

SBS is one of the main problems in modern networks (especially FTTH) because this effect limits the maximum input power and hence the maximum possible number of subscribers [2, 70]. Optical access networks have very limited power budget. Due to this effect (as SBS limits the maximum input power) it is impossible to use more powerful lasers.

To describe the nature of SBS see Fig. 4.12. It can be seen that the light-wave creates the acoustic wave, which changes the material refractive index with a fixed frequency. The refractive index changes due to the acoustic wave, the reflection of light wave occurs. SBS causes the energy pump from one wave to another wave of larger wavelength, but lost energy "absorbed" by molecular fluctuations or environmental fonons. In SBS the acoustic fonons are generated. The second wave is called the Stokes wave [2,71].

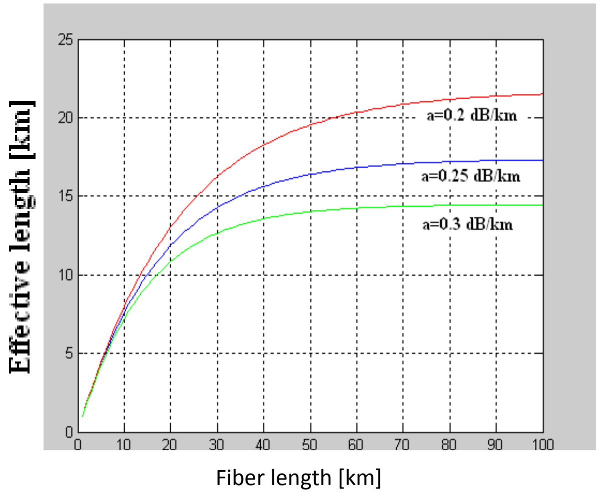


Fig.4.13. Effective length dependence on attenuation and fiber length

To calculate SBS threshold, the formula below must be used [2,71]:

$$P_{th} = 21\frac{KA_{eff}}{gL_{eff}} \cdot \frac{\Delta\upsilon_p - \Delta\upsilon_B}{\Delta\upsilon_B} \qquad (4.3.)$$

g – Brillouin amplification coefficient [W/m]

K – Polarisation state degree of freedom (according to ITU G.652, K = 2)

A_{eff} - Core effective area [μm^2]

$\Delta\upsilon_B$ – Brillouin spectral width [GHz]

$\Delta\upsilon_P$ – Emitter spectral width [GHz]

In data transmission networks the modulation is used. In our case it is ASK manipulation (Amplitude Shift Keying) or NRZ coding. Amplitude manipulation increasing the spectrum width and increases the SBS threshold. To find the SBS threshold for modulated signal (bitrate up to 10 Gbit/s) the scheme was established (see Fig. 4.14).

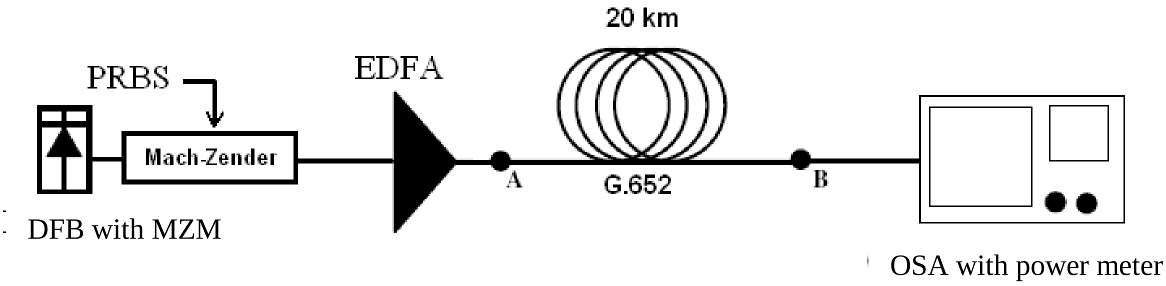


Fig. 4.14. SBS threshold measurment

Table 4.3

SBS threshold

Bitrate [Gbit/s]	**CW**	**1.25**	**2.5**	**10**
Theoretical results[dBm]	15.1	18.1	18.1	18.1
Practical results[dBm]	15.5	16.9	17.2	18

The following table summarizes the obtained experimental results and theoretical calculations. These results are valid for 20 km optical line and a laser with a bandwidth of 80 MHz, and modulation rate of 10 Gbit/s.

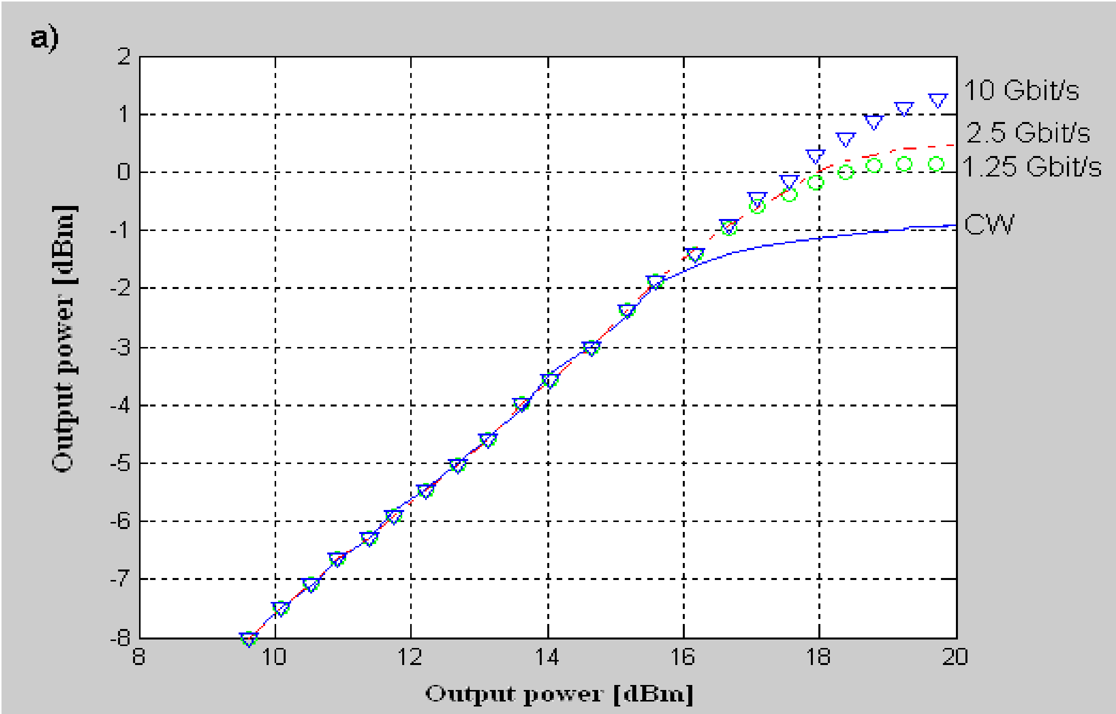


Fig. 4.15. SBS threshold decrease due to ASK

WDM/TDM-PON system mathematical modeling is based on the selected lasers with spectral width below 20 MHz (they are widely distributed in the market). Consequently, the data obtained in laboratory laser (80 MHz width) are suitable for mathematical modeling with modification according to the formula 4.3. SBS threshold increase due to ASK (calculated data) may also be applicable for lasers with the lowest band. At the line length = 20 km, the band <20 MHz, taking into account the measurement results, the SBS threshold for CW mode is equal to 8.9 dBm, and the ASK mode with a bit rate of 10 Gbit/s - 11.4 dBm. This means that SBS nonlinear effect limits the number of subscribers to 32 as the minimum required output power for 64 subscribers system is 15.4 dBm.

Chapter 5

WDM/TDM-PON main concept uses partial preservation of existing infrastructure. If the access network has been built from scratch, then the choice of options is not limited to existing infrastructure constraints. The concept, which will reduce the cost of access networks, can become "spectrally sliced" WDM (SS-WDM). SS-WDM systems do not use expensive laser diode, relying on broadband spectrum light sources such as LEDs, which are considerably cheaper and with a longer lifetime [41, 57, 52, 53, 55].

In the proposed configuration (fig.5.1) LED is used for uplink, which is "cut" in 8 or 16 channels (LED number is equal to the number of subscribers). In downlink one ASE-source is used, which is also "cut" in the same number of channels. ASE source is selected because it has higher power, and hence can be used for higher transmission rates (the higher the rate is, the lower is the power budget). LED maximum modulation rate is <1000 Mbit/s and the output power is limited to -5 dBm [62]. In customer sets LED is used with internal modulation, but in the downlink external modulation is used (in case of this solution the internal modulation of the ASE-cut channels cannot be used).

Spectrum slicing principle is as follows: first, using a filter (in this case AWG) is cut one channel, which is separately modulated in the downlink case. In uplink firstly light emitting diode is modulated, and then is cut its part of the spectrum. Using this operation, the slicing losses occur. Based on the calculations of the LED and the ASE-source channel bandwidth and channel interval is chosen 0.9 and 1.6 nm. It is a compromise between the dispersion effect (increasing even more bandwidth, the BER does not decrease), and slicing losses (18.8 dB at a bandwidth of 0.9 nm). Channel interval cannot be increased due to lack of the broadband source spectrum band.

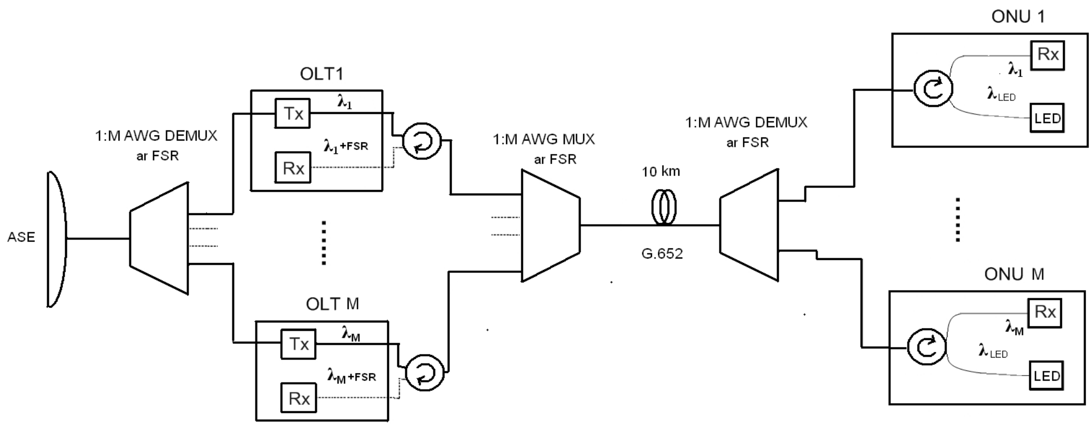


Fig.5.1. Duplex SS-WDM system

Uplink

Transmitter (LED) power was gradually increased until the BER is below $1 \cdot 10^{-10}$ with and without FEC (to get the minimum possible power output of the system for safe operation). All losses due to connections, components attenuation and power reserve were included in the calculations. Bitrate of 622 Mbit/s has been taken on the basis of the STM-4 interface. 311 Mbit/s speed is not standardized and is half of the STM-4. 1 Gbit/s bitrate (Ethernet) in uplink cannot be used because the LED modulation bandwidth is limited.

Table 5.1.

Minimum required power for uplink

Bitrate	Minimum required power (dBm)			
	311 Mbit/s		622 Mbit/s	
	With FEC	Without FEC	With FEC	Without FEC
8 channels	-7.2	-10.6	-4	-7.8
16 channels	-5.6	-8.8	-1	-5.8
32 channels	1.4	-2	3.5	-0.1

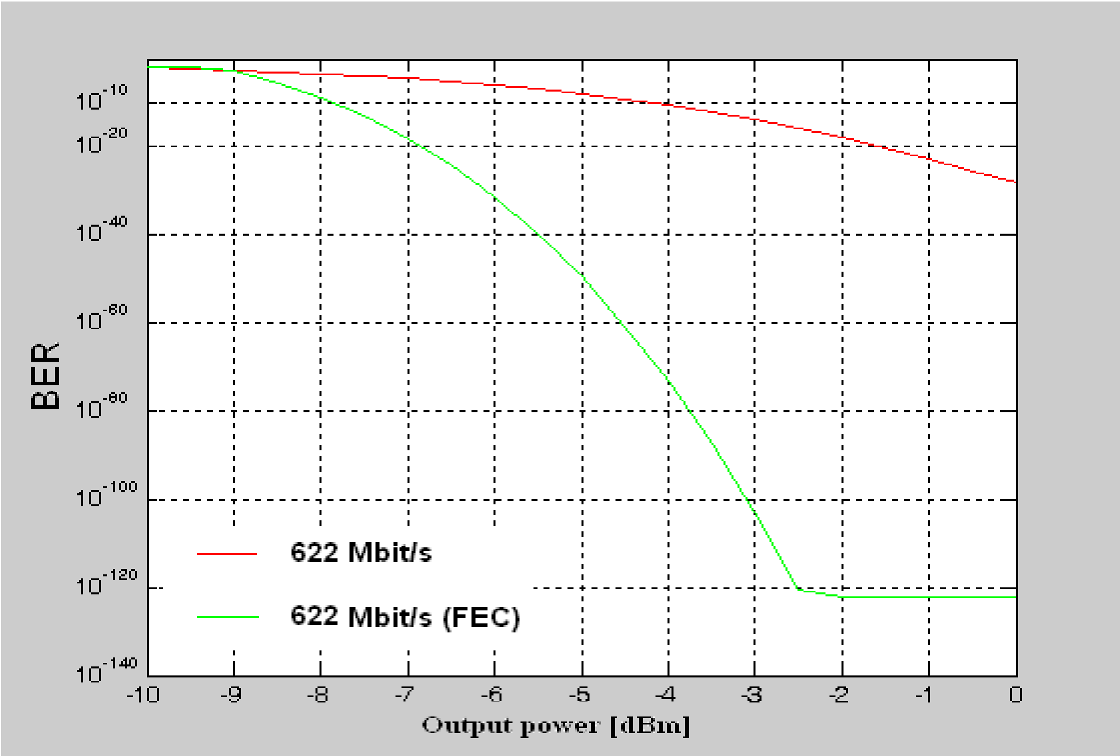


Fig.5. 2. BER dependence on the input power 8-channel system

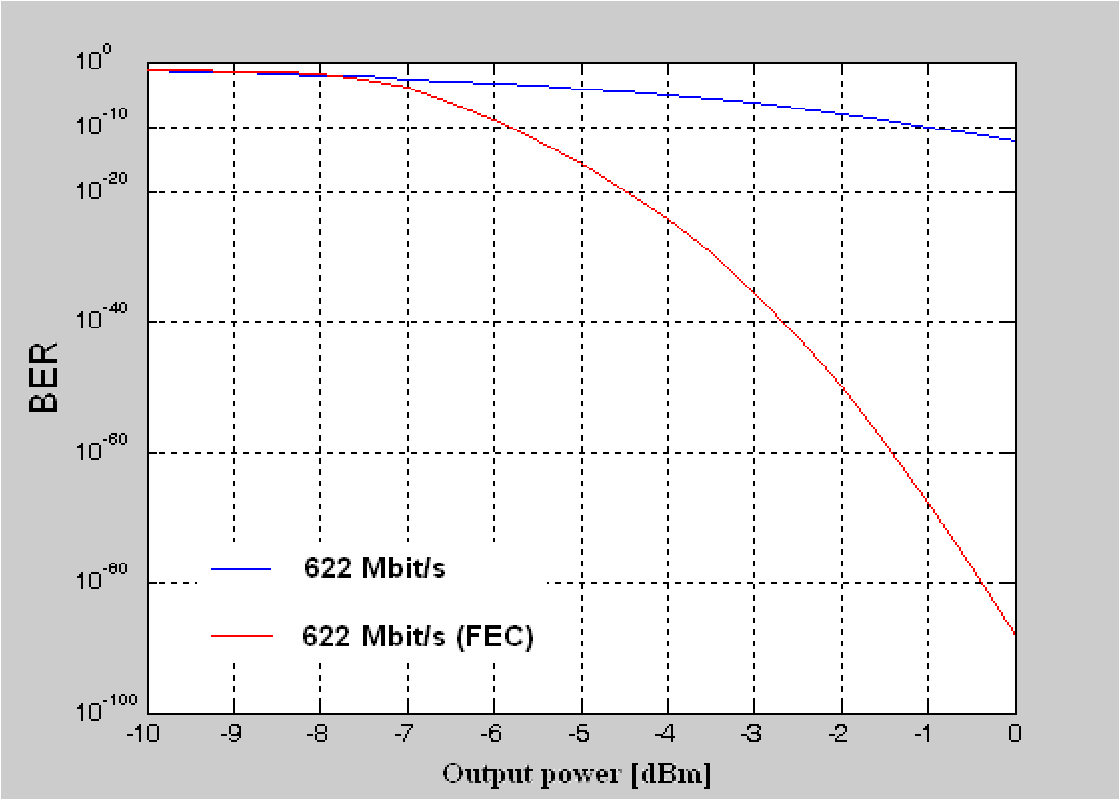


Fig.5.3. BER dependence on the input power 16-channel system

Summarizing the data, LED can be used safely in uplink in 8 and 16-channel configuration. 32-channel system cannot be achieved in uplink due to lack of ASE-source bandwidth (1532-1581 nm).

322 Mbit/s solution can be applied without FEC (output power lower than -5 dBm) for 8, and 16-channel systems. 622 Mbit / s bitrate rate for each subscriber is not possible without the use of FEC. 32 subscribers system is not possible due to LED output power limitation (-5 dBm).

Downlink

ASE broadband source is used in downlink of SS-WDM system (Fig. 5.4.) [8, 27]. Also, as LED, the ASE-source is "cut" in channels (Fig. 5.6) with the help of the AWG. In this case, the external modulation is used, the ASE source is common to all channels (as opposed to the LED, all of which were modulated separately). Unlike the LED, the ASE source has a wider spectral width and higher output power (up to 25 dBm). To create the ASE source in OptSim simulator for 8 and 16-channel system mathematical modeling, an experiment has been made in the fiber optics laboratory. The experiment consisted of: ASE source based on EDF fiber, optical spectrum analyzer (OSA), power meter (P) and passive elements.

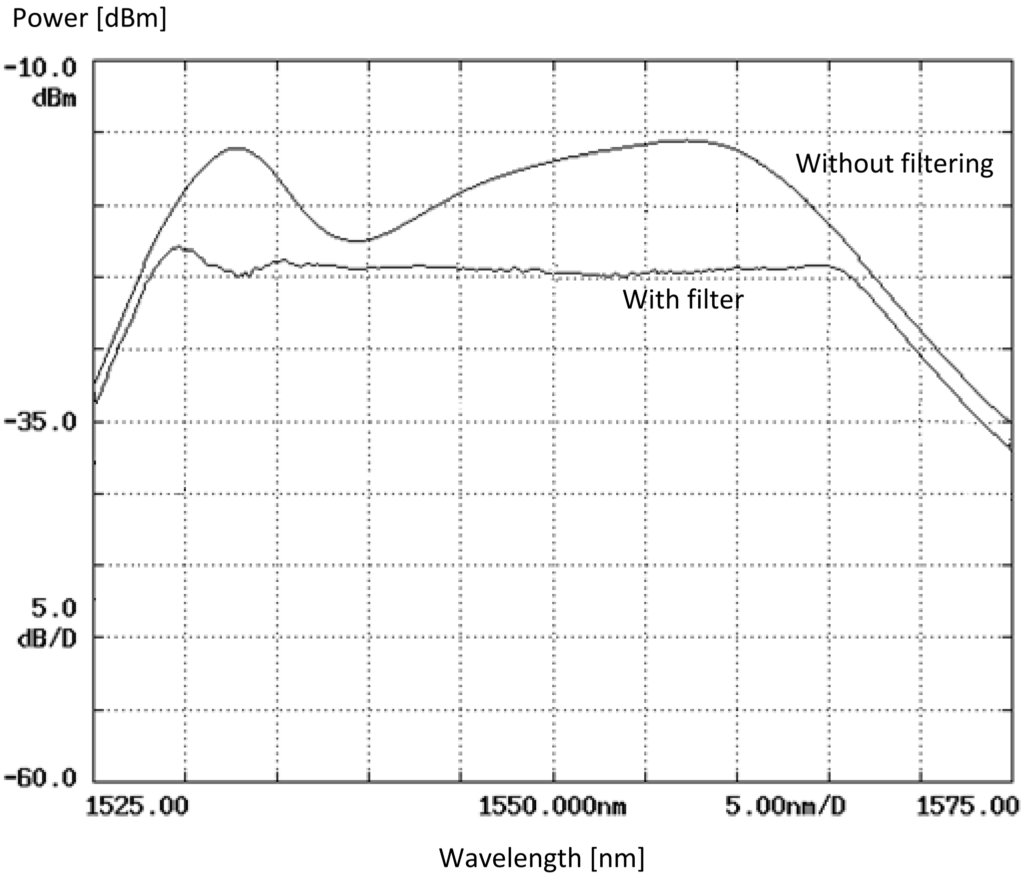


Fig.5.4. ASE-soyrce filtered and unfiltred spectrum

Based on the obtained ASE-source spectrum with and without gain flattering filter (Fig. 5.4.), OptSim model has been established (Fig. 5.5.), that is used in all calculations. 1 and 2.4 Gbit / s bitrates are selected with the possibility to use of standardized Ethernet and GPON interfaces.

Simulation methodology was as follows: ASE-source power was increased by the step (1 dB), while the BER level was less than $1 \cdot 10^{-10}$. Mathematical modeling was done for two bitrates. As a result, the use of gain flattering filter increased the required minimum output power by 2 dB. Despite the potential to increase the power budget, avoiding the flattering filter, the bitrate of 2.4 Gbit / s is not achievable due to spontaneous emission noise. Number of subscribers is also limited because the ASE-source has limited spectral range (1532-1581 nm).

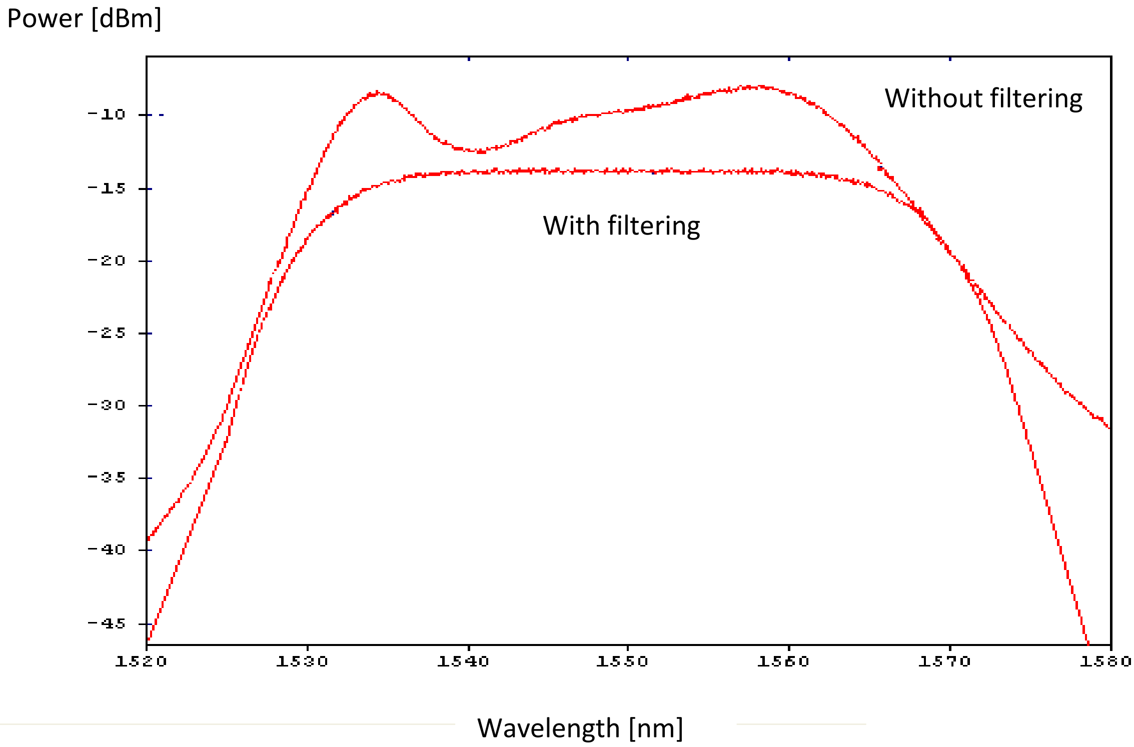


Fig.5.5. ASE-source model with and without filtering

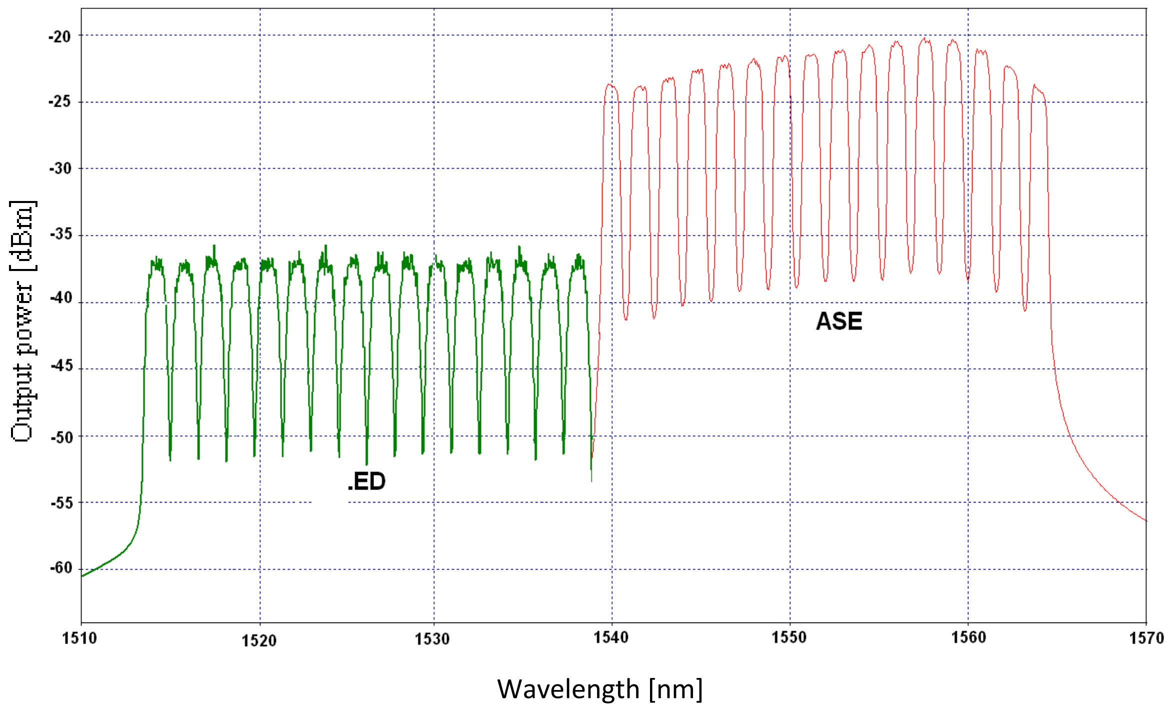
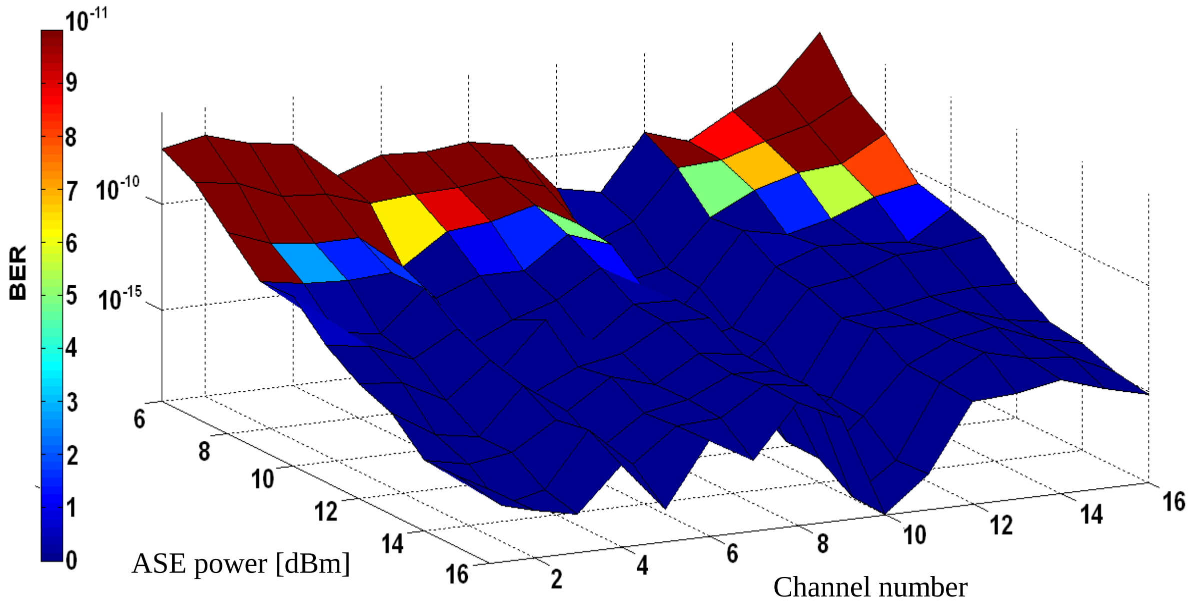


Fig.5.6. 16-channel system spectrum



Fi.5.7. BER dependence on the ASE power for 16-channel system at a rate of 1 Gbit / s

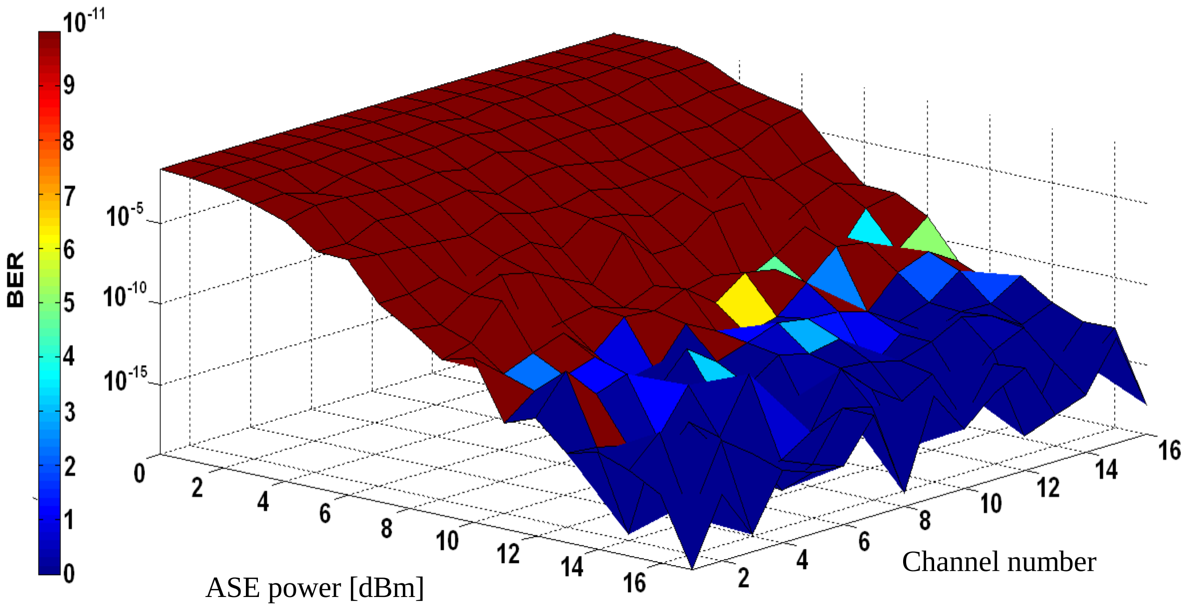


Fig.5.8. BER dependence on the ASE power for 16-channel system at a rate of 1 Gbit / s with GFF

Table 5.2.

Minimum ASE output power

	Minimum required power			
Bitrate	1 Gbit/s		2.4 Gbit/s	
ASE configuration	Without GFF	With GFF	Without GFF	With GFF
8-channels	7	9	-	-
16-channels	9	11	-	-

Based on the results obtained:

The optimal channel bandwidth and channel interval for SS-WDM system with spectral slicing is 0.9 and 1.6 nm.

622 Mbit/s uplink bitrate is only possible using FEC, and 311 Mbit/s bitrate doesn't need FEC. The minimum required power is -5.8 dBm.

In downlink 2.4 Gbit/s bitrate is not achievable. Output power increasing did not give any results. The flattering filter increases an average loss by 2 dB, but the channel power nonuniformity is the minimum. Analyzing the eye-diagram, we can conclude the existence of spontaneous emission noise, which degrades the system and does not allow to reach $1 \cdot 10^{-10}$ BER level by simply increasing the output power (which is particularly visible in the 2.4 Gbit/s system). 1 Gbit/s realization needs the minimum required power of 11 dBm with the gain flattering filter. The maximum possible number of subscribers is 16 due to ASE-source spectral and LED output power limitations.

SUMMARY

The Doctoral thesis aim was set, based on theoretical analysis, mathematical modeling and practical experiments **to evaluate the limitations of maximum number of subscribers for the use of WDM in passive access solutions, partially maintaining or creating a whole new infrastructure, and find minimum source output level for different WDM solutions for reliable operation.**

Analyzing the literature and looking at the WDM-PON solution trends, it is found that there are two concepts for next generation access networks: NGPON1, which includes the partial preservation of existing infrastructure, and NGPON2, which includes the setting up of new infrastructure. Examining and comparing the potential solutions three concepts of WDM-PON development were chosen.

The first of the concepts is the use of four-wave mixing effect (FWM WDM-PON). FWM effect use in PON is a completely new solution, which enables transmission bitrates in downlink and uplink up to 10 Gbit/s per each subscriber. Compared to conventional WDM here 16 wavelengths generation needs only 2 lasers. Highly non-linear fiber accelerates nonlinear interactions, and as the result 16 carrier frequencies (wavelengths) appear, which are modulated after generation. This system should take into account the fact that the laser output power must be accurately controlled, since the change over the 0.5 dB can lead to the output carrier frequencies power nonuniformity.

Firstly, the optimum pump laser output power with minimum possible FWM harmonic (valid channel in this case) power nonuniforimty was found, changing gradually pump laser power and a highly nonlinear fiber length. Given the fact that the output values here are fixed and the change brings to different channel output power instability in this case, the BER dependence is derived from the additional attenuation. Uplink is realized by the principle of DWDM-PON (Fig. 3.3.), where each subscriber has its own wavelength for uplink. Given the initial conditions:

- Band width – 1 GHz;
- Channel interval - 100 GHz;
- Pump frequencies 193.3 and 193.4 THz ;

Following conclusions were made according to mathematcal modeling data

- 8-channel generation with minimum output power nonuniformity of 3.25 dB and the maximum output power of 13.25 dBm requires pump laser power equal to 25 dBm and the HNLF length - 1.1 km;
- 16- channel generation with minimum output power nonuniformity of 6.76 dB and maximum output power of 13.94 dBm requires pump laser power equal to 28 dBm and the HNLF length - 1.25 km;
- 32-channel systems implementation at this moment is problematical with the currently existing laser output power and stability limitations;

The main result for FWM WDM-concept:

- **The use of four-wave mixing affect in passive optical networks with WDM allows to set 16-subscribers system with 10 Gbit/s bitrate for each client as also the possibility to increase it, using only 2 pump lasers. The pump power must be precizely controlled within 0.5 dB to get the minimum harmonics output power nonuniformity.**

The second of the concepts is meant to supplement the existing infrastructure, with the name of WDM/TDM-PON. This concept is planned for GPON/10GPON modernization within the next 5-year period. In this case, each subscriber in downlink needs its own laser. Unlike other concepts of NGPON1, time division in uplink, as well as splitter, is saved to reduce costs. Downlink speed - up to 10 Gbit/s per subscriber, uplink - up to 1.25 Gbit/s. The distance was chosen according to the ITU recommendation - 20 km. Simulation strategy for downlink and uplink was the following: 16, 32 and 64-channel system mathematical modeling was designed to get the minimum required laser output power (after the external modulator), where the system BER is less than $1 \cdot 10^{-12}$. To find the maximum possible number of subscribers, the SBS threshold was obtained experimentally (in order to find the maximum power that can enter the fiber). The second negative effect is frequency chirp. This effect appears using the internal modulation and increases losses. The loss increase due to chirp effect was calculated for the uplink.

The main results obtained in WDM / TDM-PON concept:

- **Upgrading the existing GPON infrastructure, it is possible to provide transmission speeds of up to 10 Gbit/s per each subscriber with BER<1•10^{-12} and the distance up to 20 km. The maximum number of subscribers is limited by SBS nonlinear effect to 32;**
- **The frequency chirp effect must be taken into account during setting up the system. The power loss increases to 5 dB in case of WDM/TDM-PON for chirp parameter <10 and a bandwidth Δλ = 35 nm for WDM optical line;**

The third of the concepts is ASE/LED system with spectrum slicing. In this case, using a single broadband noise-like ASE-source, you can get up to 16 channels. Uplink is realized using safe and cost-effective light-emitting diodes. This concept is intended to be a part of NGPON2 framework using simplified components to increase reliability ("colorless" LED and ASE). This concept can be implemented in the near future.

Unlike the other SS-WDM solutions, downlink bitrate reaches 1.25 Gbit/s and uplink - 622 Mbit/s.

It has been found the optimum channel bandwidth and channel interval for 16 subscribers system. Based on an analysis of publications, has been selected distance of 10 km due to dispersion effects and slicing loss.

For the first time it was investigated the ASE-source without the use of the gain flattering filter for spectral slicing. ASE-source wide spectral band is "cut" using AWG multiplexer. The resulting channels are then modulated by an external modulator. To create a system first of all the necessary channel interval and bandwidth must be calculated.

Simulation process was as follows: balancing between the dispersion effect and slicing losses the channel width and channel interval for the whole system were calculated.

After this ASE-source and LED power was increased by the step (1 dB), while the BER level is less than 1 • 10^{-10}. The simulation was made for 8 and 16-channel systems, changing bitrates from 1 to 2.4 Gbit/s with or without gain flattering of ASE spectrum for downlink. In case of uplink the bitrates of 322 and 622 Mbit/s without and with FEC were chosen.

For uplink part using LEDs with spectral width of 0.9 nm, channel interval of 1.6 nm and a distance of 10 km are obtained conclusions:

- 622 Mbit/s uplink bitrate is only possible using FEC (the minimum LED power is -5 dBm), and 311 Mbit / s bitrate doesn't need FEC;
- 32-channel system is not possible due to lack of output power. The potential number of subscribers is up to 16;

For downlink part using ASE-source with spectral width of 0.9 nm, channel interval of 1.6 nm and a distance of 10 km were obtained conclusions (specifying the shape of ASE–source spectrum and filter characteristics in the fiber optic transmission systems laboratory)

- 32-channel system implementation is not possible due to lack of spectral width of ASE-source (1532-1581 nm);
- Spontaneous emission noise, which reduces the power reserve of at least 10 dB, makes it impossible to implement 2.4 Gb/s system;
- Gain flattering filter increases the required minimum output power by 2 dB, but reduces the channel power nonuniformity to 0.5 dB, compared with 3.2 dB without the filter;

The main result for ASE/LED SS-WDM concept:

- **Using the spectral slicing with one broadband source and 16 light-emitting diodes, it is possible to get bitrate in downlink up to 1.25 Gbit /s and uplink - up to 622 Mbit / s with BER<$1 \cdot 10^{-10}$ LED; the number of subscribers is 16. Optimal channel interval is 1.6 nm and bandwidth - 0.9 nm, the required minimum power ASE-source with the flattering filter is 11 dBm and the output power of LED is -5.8 dBm;**

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