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Design and Implementation of WDM-PON Solutions

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Additional information is available at the end of the chapter

1. Introduction

Internet traffic is growing very rapidly. Based on Cisco Visual Networking Index (VNI) forecast and methodology, global IP traffic has increased more than 4 times in the past 5 years, and will increase 3 times over the next 5 years. Moreover, it will reach 1 zettabyte (ZB) per year or 83.8 exabytes (EB) per month in year 2015 and exceed 1.4 ZB per year or 120.6 EB per month threshold by the end of year 2017. Video-on-demand traffic will triple by year 2016. For these reasons there will be need for optical access networks which are capable to handle with large data amounts, consume less energy and are cost effective [3].

PONs has been considered to be one of the most promising solutions for access networks due to its broad bandwidth and low-cost infrastructure [4]. Especially, spectrum sliced wavelength division multiplexed passive optical network can be an attractive and cost effective solution to satisfy the growing worldwide demand for transmission capacity in the next generation fiber optical access networks [1, 2]. In principle there are two major factors that will influence the telecommunication networks of the future. The first one is the need to support high bandwidths and low latency and the second one is to use an architecture that is both cost and energy efficient [5]. Recent studies have uncovered that a large amount of electricity is consumed by telecom equipment's in broadband enable countries. Therefore it is important to put research effort for minimizing energy consumption in fiber optical access networks [6].

Traditional WDM systems have multiple transmitter lasers operating at different wavelengths, which need to be wavelength selected for each individual channel operated at a specific wavelength [1, 2]. It increases complexity of network architecture, cost and wavelength management [7]. The strength of spectrum sliced WDM-PON technology is use of one common broadband seed light source and its ability to place electronics and optical elements in one central office (CO), in that way simplifying the architecture of fiber optical network [1]. By

using only one light source instead of one for every user we can make optical access system more energy efficient or in other words "green". It is reported that the total energy consumed by the infrastructures of communication networks including Internet take up more than 3% of the current worldwide electric energy consumption. In specific, the access networks contribute to a larger portion of the overall energy consumption when compared to the core and transport networks [8]. Spectrum sliced WDM PON systems benefit from the same advantages as traditional WDM, while employing low cost incoherent light sources like amplified spontaneous emission (ASE) source or light-emitting diode (LED) [7, 9].

The optical bandwidth per channel of SS-WDM PON system is large compared to the bit rate. Therefore, dispersion significantly degrades the performance of this system more than it is observed in conventional laser-based systems [10]. The influence of dispersion needs to be studied in order to understand the characteristics of a spectrum sliced WDM PON system employing standard single mode optical fiber (SMF).

It is very important to build a new type optical system based on widely used frequency grid, recommended by international standards because of such a system potentially is much more compatible with other already existing WDM-PON optical systems. The main benefit includes the reduction of network architecture complexity as well as cost per one user. It is possible by replacing the classic WDM-PON system (where one laser source is used for each user) with our proposed spectrum sliced dense WDM PON system with CD compensation (where one seed broadband ASE source is spectrally sliced and used for multiple users) [11, 12].

The more information we are transmitting the more we need to think about parameters like available bandwidth and latency. Bandwidth is usually understood by end-users as the important indicator and measure of network performance. It is surely a reliable figure of merit, but it mainly depends on the characteristics of the equipment. Unlike bandwidth, latency and jitter depend on the specific context of transmission network topology and traffic conditions. As network latency we understand delay from the time of packet transmission at the sender to the end of packet reception at the receiver [13]. If latency is too high it spreads data packets over the time and can create an impression that an optical network is not operating at data transmission speed which was expected. Data packets are still being transported at the same bit rate but due to latency they are delayed and affect the overall transmission system per-formance [14].

It should be pointed out, that there is need for low latency optical networks in almost all industries where any data transmission is realized. It is becoming a critical requirement for a wide set of applications like financial transactions, videoconferencing, gaming, telemedicine and cloud services which requires transmission line with almost no delay performance. These industries are summarized in references [15, 16] and shown below (see Table 1).

In fiber optical networks latency consists of three main components which adds extra time delay: the optical fiber itself, optical components, and opto-electrical components. Therefore, for the service provider it is extremely important to choose best network components and think on efficient low latency transport strategy [17, 18].

Industry	Applications and services
Education	• video conferencing • live-streaming • rich learning content • dynamic e-learning platforms • presentation applications • dynamic administration tools • cloud-based applications
Healthcare	• Picture Archiving Communications Systems (PACS) • telemedicine, telehealth applications • diagnostic imaging • Electronic Medical Records (EMR) • patient portals • mobile healthcare applications and equipment
Media and Entertainment	• live-streaming breaking news • television shows • videoconferencing • movies over Internet • transfer large files, images, and videos from the field to studios around the world • real-time gaming
Government	• interaction between communities and their governments • transportation management, • emergency response and general commerce • circulation of documents • self-service portals
Legal	• sharing large, bandwidth-intensive files quickly and securely • secure and high speed access to critical files "24 hours a day, 7 days a week"
Finance	• High-Frequency Trading (HFT) and high speed information exchange • financial transactions • connections to brokers, dealers, exchanges, hedge funds and information feeds

Table 1. Industries where low latency services are very important.

There are many researches about improvement of transmission speed in fiber optical networks while impact and sources of latency is not investigated sufficiently. As mentioned before, latency is a critical requirement for a wide set of applications. Even latency of 250 ns can make the difference between winning and losing a trade [19]. Surely "latency reduction" is among the hot key-words for vendors, end-users and telecommunication service providers. According to a recent market analysis, the request for ultra-low latency services is increasing dramatically and opening many opportunities especially in the field of end-to-end high-speed optical services [20]. Latency reduction is very important in financial sector, for example, in

the stock exchange market where 10 ms of latency could potentially result in a 10% drop in revenues for a company [21]. No matter how fast you can execute a trade command, if your market data is delayed relative to competing traders, you will not achieve the expected fill rates and your revenue will drop [22]. Low latency trading has moved from executing a transaction within several seconds to milliseconds, to microseconds, and even nanoseconds. Nowadays, a millisecond improvement in network speeds offers competitive advantage for financial institutions [23].

2. Latency issue in optical networks

It is important to look at latency as consisting of different components. Latency is a time delay experienced in transmission system and it describes how long it takes for data to get from transmission side to receiver side. In a fiber optical communication systems it is essentially the length of optical fiber divided by the speed of light in fiber core, supplemented with delay induced by optical and electro optical elements plus any extra processing time required by system also called overhead [24]. Signal processing delay can be reduced by using parallel processing based on large scale integration CMOS technologies [25].

Added to the latency due to propagation in the fiber, there are other path building blocks which affect the total data transport time [17, 24]. These elements include opto-electrical conversation, switching and routing, signal regeneration, amplification, chromatic dispersion compensation, compensation of polarization mode dispersion (PMD), data packing, digital signal processing (DSP), protocols and addition forward error correction (FEC) [24]. Data transmission speed over optical metro network must be carefully chosen. If we upgrade 2.5 Gbit/s link to 10 Gbit/s link then CD compensation or amplification may be necessary, but it also will increase overall system latency. For optical lines with transmission speed more than 10 Gbit/s (e.g. 40 Gbit/s) a need for coherent detection arises. In coherent detection systems CD can be electrically compensated using DSP which also adds latency. Therefore some companies avoid using coherent detection for their low-latency network solutions [26].

From the standpoint of personal communications, effective dialogue requires latency < 200 ms, an echo needs > 80 ms to be distinguished from its source, remote music lessons require latency < 20 ms, and remote performance < 5 ms. It has been reported that in virtual environments, human beings can detect latencies as low as 10 to 20 ms. In trading industry or in tele-health every microsecond matters. But in all cases, the lower latency we can get the better system performance we can achieve [25, 27].

2.1. Single mode optical fiber

In standard single-mode fiber (SMF) major part of the light signal travels in the core while a small amount of light travels in the cladding. Optical fiber with lower group index of refraction provides an advantage in low latency applications [27].
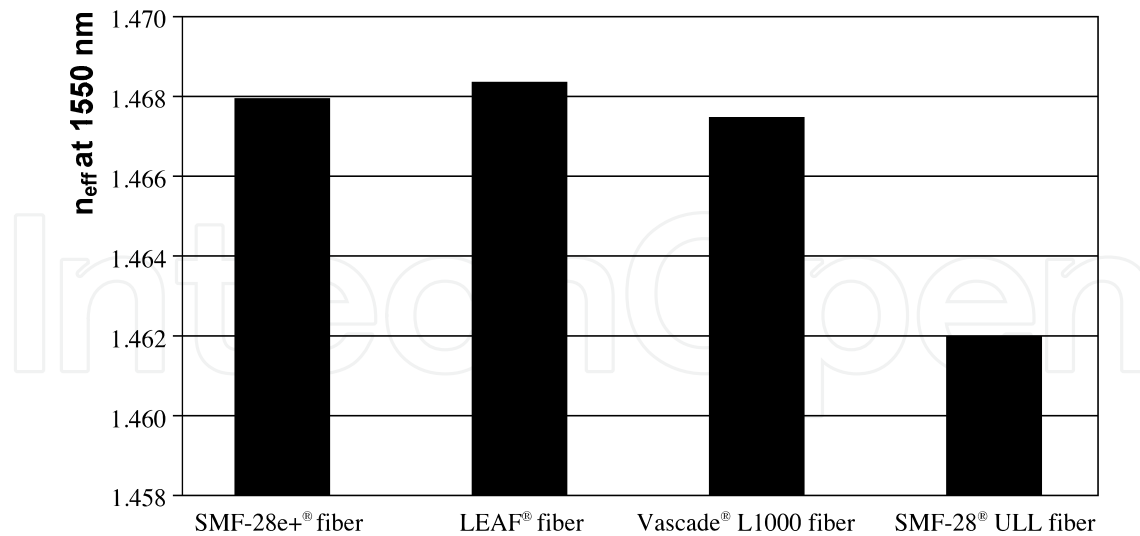
Figure 1. Effective group index of refraction impact of various commercially available Corning single mode fiber types [28].

Therefore it is useful to use a parameter "effective group index of refraction (n_{eff}) instead of "index of refraction (n)" which only defines the refractive index of core or cladding of single mode fiber. The n_{eff} parameter is a weighted average of all the indices of refraction encountered by light as it travels within the fiber, and therefore it represents the actual behavior of light within a given fiber [28]. Figure 1 illustrates the impact of profile shape on n_{eff} by comparing its values for several Corning single mode fiber products with different refractive index profiles.

It is known that speed of light in vacuum is 299792.458 km/s. Assuming ideal propagation at the speed of light in vacuum, an unavoidable latency value can be calculated as following in Equation (1):

$$\Delta_{light} = \frac{1 \text{ km}}{c} = \frac{1 \text{ km}}{299792.458 \text{ km / s}} = 3.336 \ \mu s \tag{1}$$

However, due to the fiber's refractive index light travels more slowly in optical fiber than in vacuum. In standard single mode fiber defined by ITU-T G.652 recommendation the effective group index of refraction (n_{eff}), for example, can be equal to 1.4676 for transmission on 1310 nm and 1.4682 for transmission on 1550 nm wavelength [29]. By knowing n_{eff} we can express the speed of light in selected optical fiber at 1310 and 1550 nm wavelengths, see Equations (2) and (3):

$$V_{1310nm} = \frac{c}{n_{eff}} = \frac{299792.458 \text{ km / s}}{1.4676} = 204273.956 \text{ km} \Big/ s \tag{2}$$

$$V_{1550nm} = \frac{c}{n_{eff}} = \frac{299792.458 \text{ km / s}}{1.4682} = 204190.477 \text{ km} \Big/ s \tag{3}$$

By knowing speed of light in optical fiber at different wavelengths (see Equation (2) and (3)) optical delay which is caused by 1 km long optical fiber can be calculated as following:

$$\Delta_{1310nm} = \frac{1 \text{ km}}{V_{1310nm}} = \frac{1 \text{ km}}{204273.956 \text{ km / s}} = 4.895 \; \mu s \tag{4}$$

$$\Delta_{1550nm} = \frac{1 \text{ km}}{V_{1550nm}} = \frac{1 \text{ km}}{204190.477 \text{ km / s}} = 4.897 \; \mu s \tag{5}$$

As one can see from Equations (4) and (5), propagation delay value of optical signal is affected not only by the fiber type with certain n_{eff}, but also with the wavelength which is used for data transmission over fiber optical network. It is seen that optical signal delay values in single mode optical fiber is about 4.9 μs. This value is the practical lower limit of latency achievable for 1 km of fiber in length if it were possible to remove all other sources of latency caused by other elements and data processing overhead [7].

Photonic crystal fibers (PCFs) can have very low effective refractive index, and can propagate light much faster than in SMFs [25]. For example, hollow core fiber (HCF) may provide up to 31% reduced latency relative to traditional fiber optics [30, 31]. But there is a problem that attenuation in HCF fibers is much higher compared to already implemented standard single mode fibers (for SMF α=0.2 dB/km but for HCF α=3.3 dB/km at 1550 nm) [32]. It is reported even 1.2 dB/km attenuation obtained in hollow-core photonic crystal fiber [33].

2.2. Chromatic dispersion compensation

Chromatic dispersion (CD) occurs because different wavelengths of light travel at different speeds in optical fiber. CD can be compensated by dispersion compensation module (DCM) where dispersion compensating fiber (DCF) or fiber Bragg grating (FBG) is employed [34].

A typical fiber access optical network will require DCF approximately 15 to 25% of the overall fiber length. It means that use of DCF fiber adds about 15 to 25% to the latency of the fiber [17, 18]. For example, 100 km long optical metro network where standard single mode fiber (SMF) is used, can accumulate chromatic dispersion in value about 1800 ps/nm at 1550 nm wavelength [29]. For full CD compensation is needed about 22.5 km long DCF fiber spool with large negative dispersion value (typical value is-80 ps/nm/km) [35]. If we assume that light propagation speed in DCF fiber is close to speed as in SMF then total 100 km long optical network's latency with CD compensation using DCF DCM is about 0.6 ms.

Solution how to avoid need for chromatic dispersion compensation or reduce the length of necessary DCF fiber is to use optical fiber with lower CD coefficient value. For example, non-zero dispersion shifted fibers (NZ-DSFs) were developed to simplify CD compensation while making a wide band of channels available. NZ-DSF fiber parameters are defined in ITU-T G. 655 recommendation [36]. Today NZ-DSF fibers are optimized for regional and metropolitan high speed optical networks operating in the C-and L-optical bands. For C band it is defined that wavelength range is from 1530 to 1565 nm, but for L band it is from 1565 to 1625 nm [37].

For commercially available NZ-DSF fiber chromatic dispersion coefficient can be from 2.6 to 6.0 ps/nm/km in C-band and from 4.0 to 8.9 ps/nm/km in L-band. At 1550 nm region typical CD coefficient is about 4 ps/nm/km for this type of fiber. It can be seen that for G.655 NZ-DSF fiber CD coefficient is about four times lower than for standard G.652 SMF fiber [27, 38]. Since these fibers have lower dispersion than conventional single mode, simpler modules are used that add only up to 5% to the transmission time for NZ-DSF [7]. This enables a lower latency than using SMF fiber for transmission. Another solution how to minimize need for extra CD compensation or reduce it to the necessary minimum is dispersion shifted fiber (DSF) which is specified in ITU-T G.653 recommendation. This fiber is optimized for use in the 1550 nm region and has no chromatic dispersion at 1550 nm wavelength. Although, it is limited to single-wavelength operation due to non-linear four wave mixing (FWM), which causes optical signal distortions [39].

If CD is unavoidable another technology for compensation of accumulated CD is a deployment of fiber Bragg gratings (FBG). DCM with FBG can compensate several hundred kilometers of CD without any significant latency penalty and effectively remove all the additional latency that DCF-based networks add [7]. In other words, a lot of valuable microseconds can be gained by migrating from DCF DCM to FBG DCM technology in optical metro network [40]. Typical fiber length in an FBG used for dispersion compensation is about 10 meters. Therefore, normally FBG based DCM can introduce from 5 to 50 ns delay in fiber optical transmission line [27].

One of solutions how to avoid implementation of DCF DCM which introduces addition delay is coherent detection where new transmission formats like quadrature phase-shift keying (QPSK) can be used. However, it must be mentioned that it can be a poor choice from a latency perspective due to the added digital signal processing (DSP) time they require. This additional introduced delay can be up to 1 μs [24, 31].

2.3. Optical amplifiers

Another key optical component which adds additional time delay in optical transmission line is optical amplifier. Erbium doped fiber amplifiers (EDFA) is widely used in fiber optical networks. EDFA can amplify signals over a band of almost 30 to 35 nm extending from 1530 to1565 nm, which is known as the C-band fiber amplifier, and from 1565 to 1605 nm, which is known as the L-band EDFA. The great advantage of EDFAs is that they are capable of simultaneously amplifying many WDM channels and there is no need to amplify each individual channel separately. EDFAs also remove the requirement for optical-electrical-optical (OEO) conversion, which is highly beneficial from a low-latency perspective. However it must be taken into account that EDFA contains few meters erbium-doped optical fiber (Er^{3+}) which adds extra latency, although this latency amount is small compared with other latency contributors. Typical EDFA amplifier contains up to 30 m long erbium doped fiber. These 30 m of additional fiber add 147 ns (about 0.15 μs) time delay [27].

Solution how to avoid extra latency if amplification is necessary is use of Raman amplifier instead of EDFA or together (in tandem) with EDFA. This combination provides maximal signal amplification with minimal latency. Raman amplifiers use a different optical charac-

teristic to amplify the optical signal [9, 27]. Raman amplification is realized by using stimulated Raman scattering. The Raman gain spectrum is rather broad, and the peak of the gain is centered about 13 THz (100 nm in wavelength) below the frequency of the pump signal used. Pumping a fiber using a high-power pump laser, we can provide gain to other signals, with a peak gain obtained 13 THz below the pump frequency. For example, using pumps around 1460–1480 nm wavelength provides Raman gain in the 1550–1600 nm window, which partly cover C and L bands. Accordingly, we can use the Raman's effect to provide gain at any wavelength we want to amplify. The main benefit regarding to latency is that Raman amplifier pump the optical signal without adding fiber to the signal path, therefore we can assume that Raman amplifier adds no latency [41].

2.4. Transponders and opto-electrical conversion

Any transmission line components which are performing opto-electrical conversation increase total latency. One of key elements used in opto-electrical conversation are transponders and muxponders. Transponders convert incoming signal from the client to a signal suitable for transmission over the WDM link and an incoming signal from the WDM link to a suitable signal toward the client. Muxponder basically do the same as transponder except that it has additional option to multiplex lower rate signals into a higher rate carrier (e.g. 10 Gbit/s services up to 40 Gbit/s transport) within the system in such a way saving valuable wavelengths in the optical metro network [41].

The latency of both transponders and muxponders varies depending on design, functionality, and other parameters. Muxponders typically operate in the 5 to 10 µs range per unit. The more complex transponders include additional functionality such as in-band management channels. This complexity forces the unit design and latency to be very similar to a muxponder, in the 5 to 10 µs range. If additional FEC is used in these elements then latency value can be higher [7]. Several telecommunications equipment vendors offer simpler, and lower-cost, transponders that do not have FEC or in-band management channels or these options are improved in a way to lower device delay. These modules can operate at much lower latencies from 4 ns to 30 ns. Some vendors also claim that their transponders operate with 2 ns latency which is equivalent to adding about a half meter of SMF to a fiber optical path [41].

2.5. Optical signal regeneration

For low latency optical metro networks it is very important to avoid any regeneration and focus on keeping the signal in the optical domain once it is entered the fiber. An optical-electronic-optical (OEO) conversion takes about 100 µs, depending on how much processing is required in the electrical domain [24]. Ideally a carrier would like to avoid use of FEC or full 3R (signal power, shape and length) regeneration. 3R regeneration needs OEO conversion which adds unnecessary time delay. Need for optical signal regeneration is determined by transmission data rate involved, whether dispersion compensation or amplification is required, and how many nodes the signal must pass through along the fiber optical path [26].

2.6. Forward error correction and digital signal processing

It is necessary to minimize the amount of electrical processing at both ends of fiber optical connection. FEC, if used (for example, in transponders) will increase the latency due to the extra processing time [7]. This approximate latency value can be from 15 to 150 μs based on the algorithm used, the amount of overhead, coding gain, processing time and other parameters [27].

Digital signal processing (DSP) can be used to deal with chromatic dispersion (CD), polarization mode dispersion (PMD) and remove critical optical impairments. But it must be taken into account that DSP adds extra latency to the path. It has been mentioned before that this additional introduced delay can be up to 1 μs [31].

2.7. Example of latency optimized optical network

In this section we present optimized model of 160 km long optical metro access network operating at 10 Gbit/s bitrate. The aim of this section to show how much optical network can be optimized in terms of latency by replacing conventional latency inducing optical and electrical components to low-latency components. In Figure below we propose two optical transmission networks – conventional and latency optimized, see Fig. 2(a) and Fig. 2(b).

First optical metro network (see Fig. 2(a)) consists of two transponders, DCF DCM for CD pre-compensation, two EDFA amplifiers to boost optical signal, and two 80 km long ITU-T G.652 SMF fiber spans.

Pre-compensation configuration of accumulated chromatic dispersion was chosen because our researches proved it more effective than post-compensation method [34]. Fiber optical line is chosen 160 km in length because typically fiber optical metro networks are up to 200 km long [2].
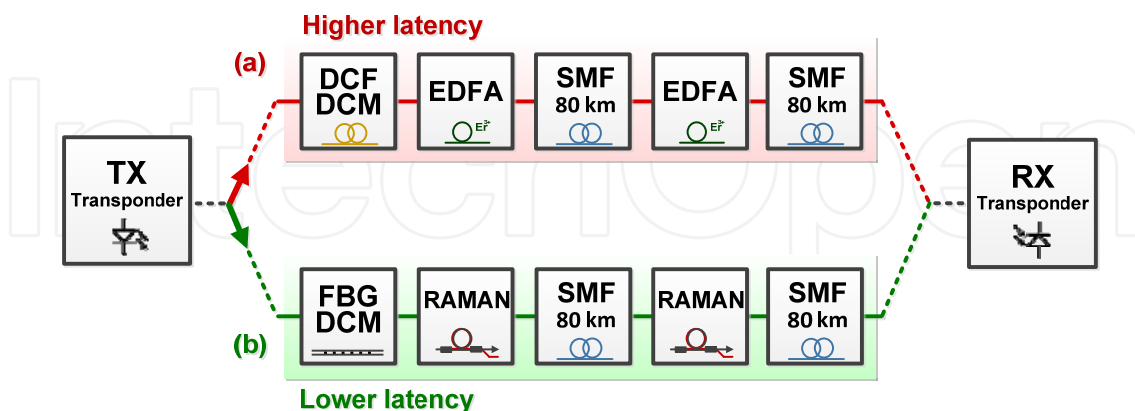

Figure 2. Optical metro network with (a) conventional elements and (b) latency optimized elements.

Second network scheme is latency optimized (see Fig. 2(b)), where we replaced conventional transponder by ultra-low latency transponders, DCF DCM replaced by FBG DCM and EDFA amplifiers are replaced by Raman amplifiers.

For total latency calculations of both optical systems we assume that 64 byte packet which adds 51.2 ns network interface delay is transmitted. Here we used typical latency parameters we described previously in this work and compared results; see from obtained data (see Table 2).

As one can see from obtained data (see Table 2), total latency amount is reduced by 21.6% or 216.24 μs. In this case the main benefit comes from optimization of chromatic dispersion compensation scheme from DCF DCM to FBG DCM and replacement of conventional transponders to low latency transponders.

Line component	Conventional network	Latency optimized network
2 x 80 km ITU-T G.652 SMF fiber spans	4.9 μs x 160 km = 784 μs	4.9 μs x 160 = 784 μs
1 CD compensation module (DCM)	DCF DCM: 25% of 784 μs = 196 μs	FBG DCM: 50 ns
2 Optical amplifiers	EDFA: 2 x 0.15 μs = 0.3 μs	RAMAN adds no delay
2 Transponders	2 x 10 μs = 20 μs	2 x 4 ns = 8 ns
2 Network interface delays	2 x 51.2 ns = 102.4 ns	2 x 51.2 ns = 102.4 ns
Total latency value	1 ms	0.784 ms

Table 2. Latency calculation for conventional and latency optimized network.

3. Measurement technique and accuracy

Our research is based on powerful and accepted mathematical simulation software OptSim. It solves complex differential nonlinear Schrödinger equation (NLSE) using split-step Fourier method (SSFM). This equation describes optical signal propagation over the fiber and can be written as Equation (6) [42]:

$$\frac{\partial}{\partial z} \cdot A + \frac{\alpha^1}{2} \cdot A + j \cdot \frac{\beta_2}{2} \cdot \frac{\partial^2}{\partial t^2} \cdot A - \frac{\beta_3}{6} \frac{\partial^3}{\partial t^3} \cdot A = j \cdot \gamma \cdot \left| A \right|^2 \cdot A \qquad (6)$$

where A(t, z) is complex optical field; z is fiber length, [km]; α^1 is linear attenuation coefficient of an optical fiber, [km^{-1}]; β_2 is the second order parameter of chromatic dispersion, [ps^2/nm]; β_3 is the third order parameter of chromatic dispersion, [ps^3/nm]; γ is nonlinear coefficient, [W^{-1}·km^{-1}]; t is time, [s]. NLSE takes into the account linear and nonlinear affects and they influence to optical signal distortions. The principle of split-step method is better illustrated by (6), which can be written as follows [42]:

$$\frac{\partial}{\partial z} \cdot A(t,\ z) = (\hat{D} + \hat{N}) \cdot A(t,\ z) \tag{7}$$

$\hat{D}$ is linear operator responsible for linear effects such as dispersion and attenuation [42]:

$$\hat{D} = -\frac{\alpha^l}{2} - j \cdot \frac{\beta_2}{2} \cdot \frac{\partial^2}{\partial t^2} + \frac{\beta_3}{6} \cdot \frac{\partial^3}{\partial t^3} \tag{8}$$

$\hat{N}$ is nonlinear operator, which takes into account Kerr and other nonlinear effects (NOEs) [42]:

$$\hat{N} = j \cdot \gamma \cdot |A|^2 \cdot A \tag{9}$$

In general split-step method is based on assumption that linear and nonlinear effects affect optical signals independently. This statement can be considered as true if we assume that all fiber length z is being divided into sufficiently small spans Δz, and only then these linear and nonlinear effects by turns are taken into account for each $\frac{\Delta z}{2}$ segment.

There are two basic algorithms for realization of SSFM: time domain split step (TDSS) and frequency domain split step (FDSS). These two algorithms differ only with an approach that is being used for calculation of linear operator $\hat{D}$. While in both cases nonlinear operator $\hat{N}$ is being calculated in time domain [42].

Operator $\hat{D}$ is being fully characterized by its impulse response h(t) and it is mathematically correct to calculate its influence to A(t, z) optical field using products of mathematical convolution. In TDSS case it can be written as follows [42]:

$$A_L[n] = A[n]*h[n] = \sum_{k=-\infty}^{\infty} A[k] \cdot h[n-k] \tag{10}$$

This algorithm calculates this convolution in time domain and precisely obtains time delay values between signals with different wavelength. In OptSim software this TDSS algorithm is realized using finite impulse reaction (FIR) filters. This sophisticated technique provides complete control of an overall mistake that may occur during all process of calculating. By contrast FDSS calculates $\hat{D}$ in frequency domain but firstly for this algorithm is necessary to calculate fast Fourier transformation (FFT) from A[n] signal samples and from h(t) impulse reaction. Then it is necessary to use invers FFT (FFT^{-1}) to convert obtained data array to time sample domain. FDSS algorithm can be mathematically described using following equation [42]:

$$A_L'[n] = A[n] \otimes h[n] = FFT^{-1}\{FFT(A[n]) \times FFT(h[n])\} \tag{11}$$

As one can see, then in this case circular convolution is used for obtaining signal sample array$A_L^{'}[n]$. This array may contain fewer samples than it is necessary to obtain actual convolution products—$A_L[n]$ sample array. Hence this algorithm is easier to implement than TDSS and it requires less computation time and resources but serious errors may occur during calculation [42].

Equation (7) can be solved assuming that $\hat{D}$ and $\hat{N}$ operators are independent and fiber span Δz length is small enough (5-100 meters, depending on the simulation accuracy requirements). Then optical signal after propagation over Δz span can be described in the following manner [42]:

$$A(t,\ z + \Delta z) \cong \exp\left[\frac{\Delta z}{2} \cdot \hat{D}\right] \cdot \exp\left\{\Delta z \cdot \hat{N}\left[A\left(t,\ z + \frac{\Delta z}{2}\right)\right]\right\} \cdot exp\left(\frac{\Delta z}{2} \cdot \hat{D}\right) \cdot A(t,\ z) \tag{12}$$

For the evaluation of system performance will be used such parameter as Q-factor and BER value. Q=7.03 (16.94 dB) corresponds to the commonly used reference for BER of 10^{-12}. Q factor and BER confidence interval magnitude depends on the total number of simulated bits N_{total} [42]:

$$dev[Q^{*}] \equiv \sigma_Q \cong \frac{Q}{\sqrt{2 \cdot N_{total}}} \tag{13}$$

where Q is Q-factor value that can be calculated using following Equation (9) [42]:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \tag{14}$$

where $\mu_{1,0}$ and $\sigma_{1,0}$ are the mean and the standard deviation of the received signal, when a logical "1" and "0" is transmitted, and $\pi \approx 3.14$ [42].

$$BER = \frac{1}{2} \cdot erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{15}$$

Using Equation (13) Q-factor uncertainty range can be expressed as [42]:

$$range = 20 \cdot \log_{10}\left(\frac{1 + \sqrt{\frac{2}{N_{total}}}}{1 - \sqrt{\frac{2}{N_{total}}}}\right) \tag{16}$$

Q-factor uncertainty range for 1024 simulated bits that is used in our schemes is equal to 0.77 dB. For 1024 of simulated bits these intervals are:

$$Q_{for16.94dB} \in \left[16.55; 17.31\right],\ \left[dB\right] \tag{17}$$

$$\log 10\{BER_{for\ 10^{-12}}\} \in [-12.97; -11.04] \tag{18}$$

Q-factor and BER value 95% ($\pm\ 2\sigma_Q$) confidence intervals for 16.94 dB nominal value can be obtained using Equation (13) and Equation (15) assuming that we are dealing with Gaussian distribution.

4. Background of spectrum slicing technique and WDM PON models

Spectrum slicing technique is one of basic techniques available in WDM PON systems in order to reduce the cost of components and simplify the passive network architecture. There incoherent broadband light source (BLS) is sliced and equally spaced multi-wavelength channels is generated [2]. The aim of spectrum slicing is to employ a single BLS for transmission on a large number of wavelength channels (see Fig. 3).

Figure 3. Operational principle of spectrum sliced multi-channel fiber optical transmission system.

At first, BLS is sliced with arrayed-waveguide grating (AWG). Afterwards, optical slices are modulated, multiplexed by second AWG and transmitted over standard single mode optical fiber line. Channels are demultiplexed by third AWG located after SMF and received by direct detection optical receiver. This receiver can be PIN photodiode or avalanche photodiode (APD). Broadband light sources like LED, SLED (superluminescent diode) or ASE can be used in spectrum sliced systems for data transmission. Transmission power available for each separate optical channel depends on the slice width. It should be considered that a larger slice will increase not only the total channel power but also increase the influence of dispersion and therefore the number of available WDM channels [2]. In our research we choose ASE as BLS for spectral slicing because it has the highest optical output power compared to other above mentioned broadband light sources.

4.1. Experimental models of WDM PON transmission system

Erbium doped fiber amplifier (EDFA) emits high power amplified spontaneous emission (ASE) noise in C band (wavelength from 1530 to 1565 nm) and L band (wavelength from 1565

to 1625 nm) if there is no signal to be amplified. This effect is used to design broadband ASE light source in this research. ASE noise generation and gain occurs along all EDFA fiber length and it depends on erbium ion (Er^{3+}) emission and absorption spectrum [14]. Broadband ASE light source realization can be done in different ways: by using one EDFA or connecting several amplifiers in cascade mode (one after another). The latter method allows achieving almost flat ASE output spectrum and higher output power because of better Er^{3+}ions usage along several amplifiers.

In our research the broadband ASE light source is constructed from two EDFAs combined in cascaded mode. The smoothest ASE output spectrum can be achieved if 400 mW output power for all pump lasers is used, where first EDFA amplifier is pumped in co-propagating direction on 1480 nm wavelength, and second EDFA is pumped in co-propagating direction on 1480 nm as well as in counter-propagating direction on 980 nm (see Fig. 4).

Figure 4. Detailed scheme of cascaded EDFA system with optimized parameters.

Erbium doped fiber span with length of 9 m is used for first EDFA and 12 m long erbium doped span is used for second EDFA. In this manner a broadband ASE source with almost flat spectrum and total output power on the output of cascaded EDFA system about+23 dBm (200 mW) is being constructed. The output spectrum of realized broadband ASE noise-like light source which will be spectrally sliced using AWG unit is shown in Figure below (see Fig. 5).

The highlighted area in figure shows the 1545.322 nm to 1558.983 nm wavelength range (192.3 THz to 194.0 THz frequency, centered on 1552.524 nm wavelength or 193.1 THz in frequency) which will be used for our 8-channel and 16-channel spectrally sliced WDM-PON systems.

As one can see (see Fig. 5), fluctuations of optical power level are minimal and spectrum in this employed region is almost flat.

This section describes simulation scheme of SS-WDM PON system with up to 16 channels, 2.5 Gbit/s transmission speed per channel (total system's capacity is up to 40 Gbit/s) and chromatic dispersion compensation module (DCM).

The performance of simulated scheme was evaluated by the obtained bit error ratio (BER) value of each channel in the end of the fiber optical link. Basis on ITU recommendation G.984.2 it is taken into account that BER value for fiber optical transmission systems with data rate 2.5 Gbit/s per channel must be below 10^{-10}.
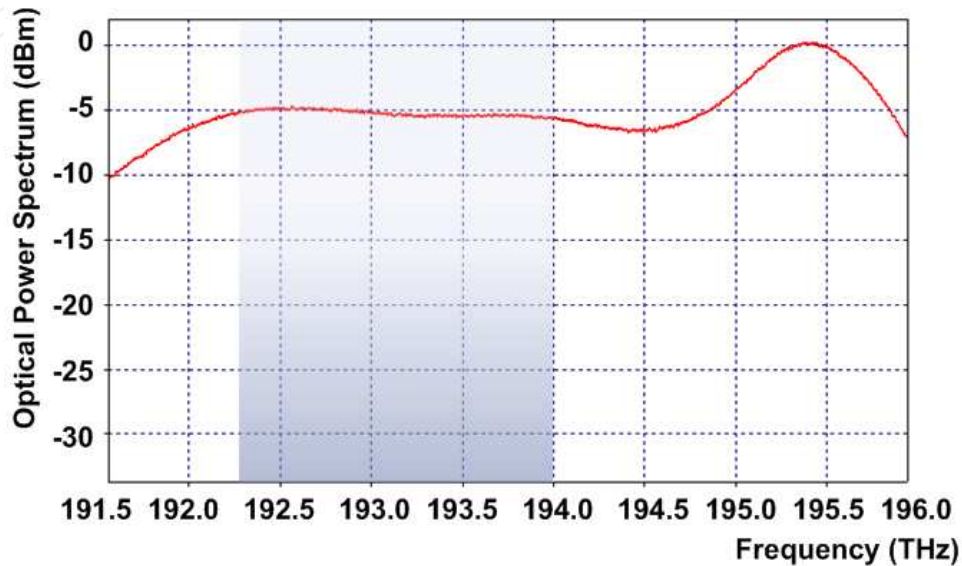

Figure 5. Output spectrum of noise-like ASE broadband light source.

As one can see in Figure 6, SS-WDM PON simulation scheme we built consists of up to 16 channels. Frequency grid is anchored to 193.1 THz and channel spacing is chosen equal to 100 GHz frequency interval. This frequency grid and interval is defined in ITU-T recommendation G.694.1. Broadband ASE light source is spectrally sliced using 8-channel or 16-channel flattop AWG filter (AWG1) with channel spacing equal to 100 GHz (0.8 nm in wavelength). Using this AWG unit we can obtain equally arranged optical channels (slices) with dense channel interval 100 GHz. Insertion losses of AWG units are simulated using additional attenuation blocks (attenuators). It is taken into account that simulated high-performance AWG multiplexers and demultiplexers are absolutely passive optical components with insertion loss up to 3 dB each. After spectrum slicing operation implemented by AWG1, optical slices are transmitted to optical line terminals (OLTs). OLTs are located at central office (CO). Each OLT consists of data source, non-return-to-zero (NRZ) driver, and external Mach-Zehnder modulator (MZM). Each MZM has 5 dB insertion losses, 20 dB extinction ratio, modulation voltage V_π of 5 Volts and maximum transmissivity offset voltage 2.5 Volts.

Generated bit sequence from data source is sent to NRZ driver where electrical NRZ pulses are formed. Afterwards formed electrical NRZ pulses are sent to MZM modulator. MZM modulates optical slices received from AWG1 and forms optical signal according to electrical drive signal. These formed optical pulses from all OLTs are coupled by AWG multiplexer
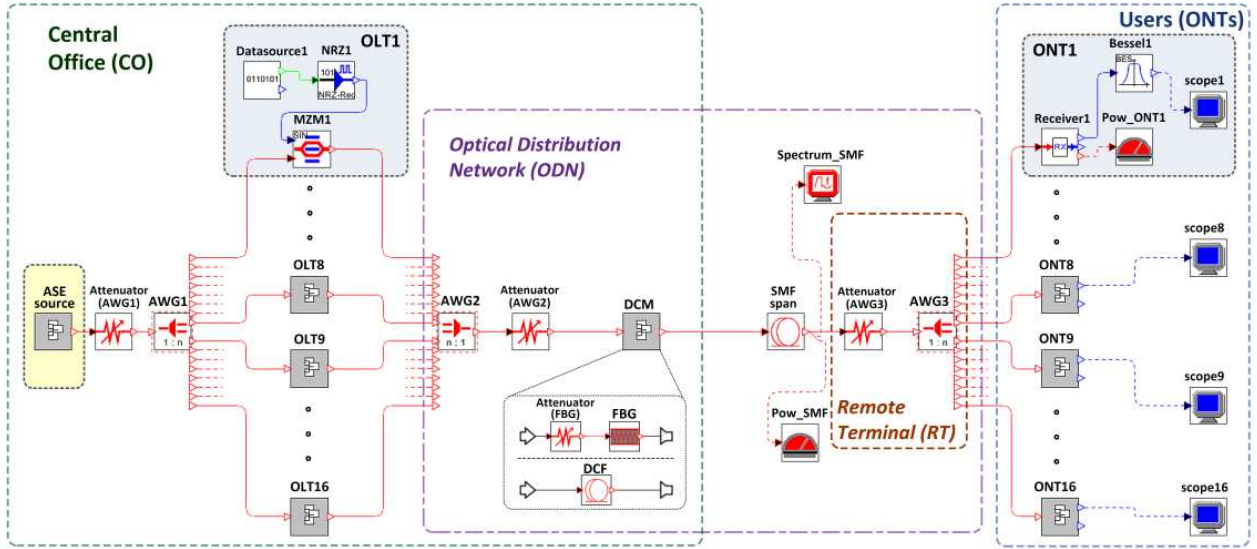
Figure 6. Simulation model of proposed high-speed up to 16-channel AWG filtered and ASE seeded SS-WDM PON system with DCM module.

(AWG2) and sent into standard optical single mode fiber (SMF) defined in ITU-T recommendation G.652 [12].

Information from OLT is transmitted to an optical network terminal (ONT) or user over the fiber optical transmission link called optical distribution network (ODN). ODN consists of AWG multiplexer, two optical attenuators, dispersion compensation module (DCM), SMF with length up to 20 km and two AWG demultiplexers. SMF fiber used in simulation setup has large effective core area A_{eff}=80 µm², typical attenuation α=0.2 dB/km, dispersion coefficient D=16 ps/(nm km) and dispersion slope D_{sl}=0.07 ps/(nm² km) at the reference wavelength λ=1550 nm.

As one can see in middle of Figure 6, two simulated CD compensation methods implemented in DCM module are FBG and DCF. In our research we use DCF fiber with A_{eff}=20 µm², attenuation coefficient α=0.55 dB/km, dispersion coefficient D=-80 ps/(nm km) and dispersion slope D_{sl}=0.19 ps/(nm² km) at the reference wavelength λ=1550 nm. For full compensation of chromatic dispersion accumulated by 10 km of SMF fiber we need about 2 km of DCF fiber. Simulated FBG is tunable in terms of both reference frequency and total dispersion value which can be compensated. Additional attenuator is used for simulation of FBG's 3 dB insertion loss. For the most accurate results we used real parameters of standard DCF fiber and tunable FBG in our simulation setup. In the end of fiber optical link 8 or 16 optical channels are separated using AWG demultiplexer (AWG3) which is located in remote terminal (RT). Receiver section includes ONT units. Each ONT consists of sensitivity receiver with PIN photodiode (sensitivity S=-25 dBm at sensitivity reference error probability BER=10⁻¹⁰), Bessel electrical lowpass filter (3-dB electrical bandwidth B_E=1.6 GHz), optical power meter and electrical probe to evaluate the quality of received optical data signal (capture eye diagram or spectrum). Optical signal is converted to electrical signal using PIN photodiode and filtered with Bessel electrical filter for noise reduction.

4.2. Advanced model of SS-WDM PON system

This section describes simulation scheme of more advanced, bidirectional 8-channel SS-WDM PON system with symmetrical 10 Gbit/s transmission speed per channel, gain saturated SOAs before optical modulators and chromatic dispersion compensation module (DCM) in downstream direction. For cost saving purposes DCM is not implemented in upstream direction because the influence of CD on 20 km long optical transmission line, where conventional laser based system (e.g. distributed feedback laser) is used may be considered as negligible [7]. Total system's capacity in downstream as well as in upstream direction is up to 80 Gbit/s.

Simulation scheme consists of 8 channels in downstream direction (see Fig. 7(a)) and 8 channels in upstream direction (see Fig. 7(b)). Channel spacing for both directions is chosen equal to 100 GHz frequency or 0.8 nm wavelength intervals. As one can see in Figure 7(a), broadband ASE light source, is spectrally sliced using 8-channel flattop AWG filter (AWG1) with channel spacing equal to 100 GHz. Using this AWG unit we can obtain equally arranged optical slices with dense channel interval. Insertion losses of AWG units are simulated using additional attenuation blocks. It is taken into account that simulated AWG multiplexers and demultiplexers are absolutely passive optical components with insertion loss up to 3 dB per unit. After spectrum slicing operation realized by first AWG1, optical slices are transmitted to optical line terminals (OLTs). OLTs are located at central office (CO).
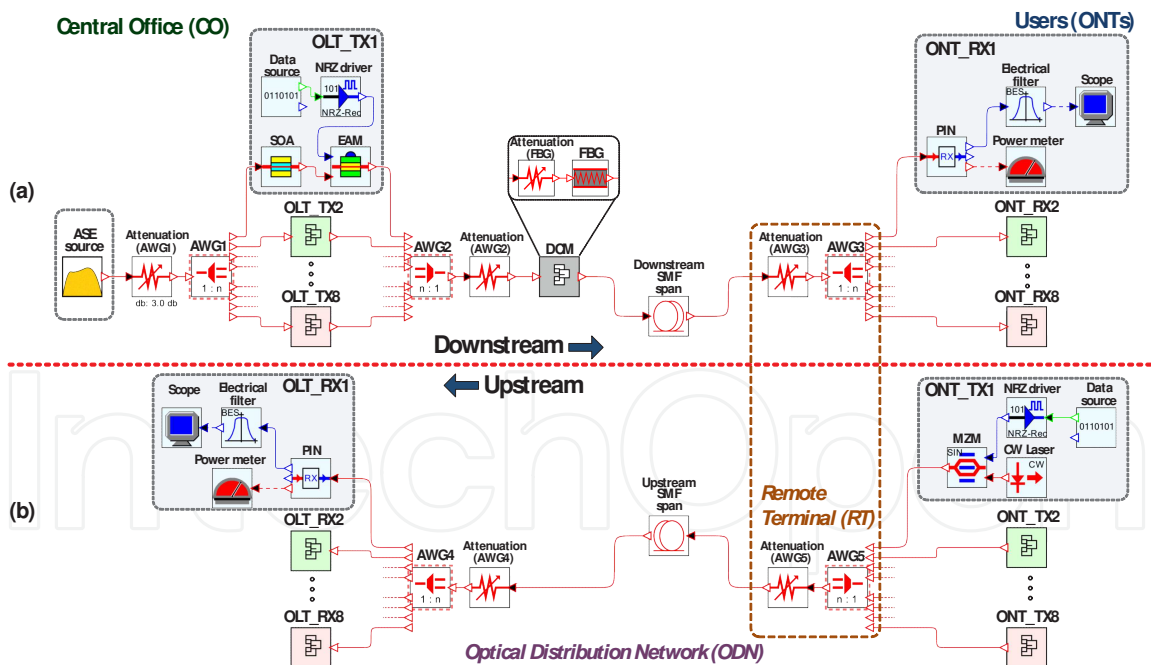

Figure 7. Setup of proposed bidirectional 8-channel SS-WDM PON system with data transmission speed 10 Gbit/s per channel. In (a) is shown downstream direction which is realized by using spectrum-slicing technique, and in (b) upstream direction where conventional laser based solution is used.

Each transmitter (Tx) of OLT consists of data source, non-return-to-zero (NRZ) driver, semiconductor optical amplifier (SOA) and polarization-insensitive electro-absorption

modulator (EAM). Compared with polarization-sensitive Mach–Zehnder modulator (MZM), the use of EAM gives a 3-dB gain in optical power and signal to noise ratio (SNR) [43]. Each EAM has 3 dB insertion loss and maximum applied voltage is 5 Volts. SOA is gain saturated and amplifying incoming carrier spectral slice and used for suppression of excess intensity noise (EIN) which comes from the spontaneous–spontaneous beating between different wavelength components of the spectrally sliced incoherent broadband ASE light source [43].

Generated bit sequence from data source is sent to NRZ driver where electrical NRZ pulses are formed and sent to EAM to drive it. Each EAM modulate amplified incoming spectral slices according to electrical drive signal and forms optical pulses. These formed optical pulses from all OLT transmitters (OLT_TX1 to OLT_TX8) are coupled by AWG multiplexer (AWG2) and sent into standard 20 km long SMF fiber.

We also used additional gain saturated semiconductor optical amplifier (SOA) before modulator to suppress excess intensity noise (EIN) which originates from the ASE source [43].

In general SOAs, due to their structure can be characterized as a semiconductor lasers without feedback, as the same mechanism is used in order to amplify incident light as in laser diodes. Semiconductor optical amplifiers are the type of amplifiers in which electrical energy is applied as a pump to achieve population inversion in the active region, and amplification is achieved via the process of stimulated recombination luminescence. When the intensity of the input optical signal increases, at a certain point the whole carrier population of the upper energy level is occupied by the process of amplification. Therefore, for a specific SOA at the certain intensity level of input optical signal the amplifier gain starts to decrease. Such behavior of semiconductor amplifiers is known as gain saturation. When gain saturation occurs, characteristics of the gain become nonlinear (device gain becomes inversely proportional to the input intensity). Therefore, intensity noise suppression of input optical signal takes place when operating in such a nonlinear mode.

The main idea of intensity noise suppression is following: when intensity of input optical signal is lower, saturated SOA will provide higher optical gain coefficient than during the moment when input optical signal reaches its maximal value. Therefore, on the output of SOA amplitude difference between intensity drops and peaks will not be so large when signal is observed in time domain, and obtained optical radiation will be more similar to the output of continuous wavelength lasers, which are normally used as carriers in cases when external optical signal intensity modulation is used.

Information from OLT transmitter part is sent to receiver part of optical network terminals (ONT_RX1 to ONT_RX8) over the fiber optical transmission link referred as optical distribution network (ODN). In our case for both transmission directions ODN consists of AWG multiplexers/demultiplexers, optical attenuators, and 20 km long SMF spans. In downstream direction FBG DCM is used for chromatic dispersion compensation. It is tunable in terms of both reference frequency and total dispersion value which can be compensated. Additional attenuator is used for simulation of FBG's insertion loss which is set 3 dB. In the end of downstream fiber optical link 8 optical channels are separated by using AWG demultiplexer (AWG3) which is located in remote terminal (RT).

Each ONT receiver (ONT_RX1 to ONT_RX8) consists of sensitivity receiver with PIN photo-diode (sensitivity is-19 dBm at BER=10^{-12}), Bessel electrical lowpass filter (3-dB bandwidth is 7.5 GHz), optical power meter and electrical scope to evaluate the quality of received signal (e.g. show eye pattern). Optical signal is converted to electrical signal using PIN photodiode and filtered with Bessel electrical filter for noise reduction.

As one can see in Fig. 7(b), which represents upstream optical transmission, conventional laser based system (where each user has its own individual light source) is realized. Each user's transmitter (ONT_TX1 to ONT_TX8) has its own continuous wavelength light source modu-lated by Mach-Zehnder modulator. Upstream transmission from user side to OLT receiver block (OLT_RX1 to OLT_RX2) is realized over separate 20 km long optical fiber span. OLT receiver structure is the same as for ONT receiver. As it mentioned before, dispersion com-pensation is not used in upstream transmission for cost reduction and network architecture's complexity reduction purposes.

In the simulation model it was decided to set all geometrical and material parameters of the active layer of the SOA as it was used previously in [43]. There these parameters were set as in a standard InGaAlAs travelling wave SOA with negligible residual facet reflectivity.

The only parameters which values were changed were the length of active layer and input bias current. In the proposed solution it was required to obtain gain saturation of the amplifier for input optical power of at least 5.5 dBm. Therefore, it was required to reduce the maximal optical gain that can be provided by the SOA. This was achieved by shortening the length of active layer of the SOA from 750 μm to 100 μm, in such a way significantly reducing the population of available carriers in the active layer, hence also lowering the value of amplifier's maximal gain. It was required to set appropriate value of input bias current to obtain such level of population inversion in active layer, which would provide BER values below the 10^{-12} threshold for detected signals in all ONTs.

Best results were obtained if pumping current of 370 mA was used for our SOAs located in OLTs transmitters. As mentioned in introduction part, when intensity of input optical signal is lower, saturated SOA will provide higher optical gain coefficient than during the moment when input optical signal reaches its maximal value. Instantaneous optical power at input and output of the SOA is represented in Figures 8(a) and 8(b) respectively.

It can be clearly seen that after processing through the SOA intensity fluctuations of the spectrally sliced optical flow have been reduced significantly. Unfortunately not all of the intensity noise was suppressed. The provided solution of intensity noise suppression applies only to the intensity noise which frequency is low in respect to the spontaneous carrier lifetime. The SOA carrier changes are rate limited by their lifetimes, and carrier changes cannot keep up with the high frequency intensity changes. Suppression of intensity noise, which frequency is high in respect to the carrier lifetime, requires more detailed investigation and a different approach for the SOA configuration [20].

Spectrum at the input and output of the SOA amplifier can be observed in Figure 9. By comparing both curves, it can be seen that spectrum of spectral slice (i.e. spectrum of spectral sliced carriers) at the output of the SOA is clearly broadened. Also, upper part (peak) of the
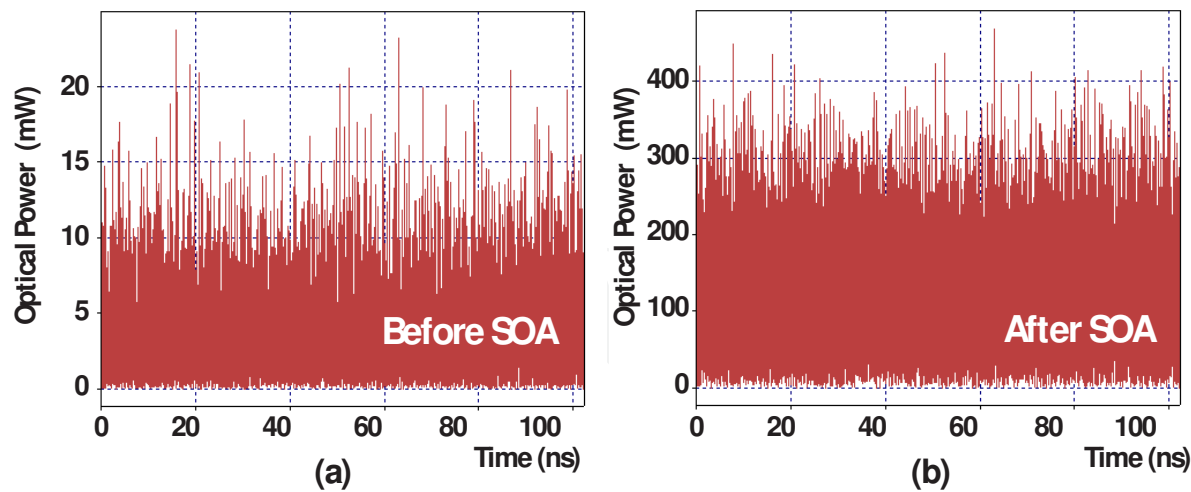
Figure 8. Time diagram of optical signal: (a) before SOA and (b) on the output of SOA.

spectral slice obtained a visible slope with the intensity peak shifted towards to lower frequency.

The spectral broadening of spectral slices, each containing multiple carriers, is caused by occurrence of two non-linear effects which became well seen as the SOA began to operate in the gain saturated mode: intra-channel four wave mixing (FWM) and self-phase modulation (SPM) of the carriers. Appearance of slope at the peak of spectral-sliced carriers is related to SPM, as phase modulation also has the effect of shifting the peak power toward longer wavelengths (lower frequencies) as the light travels through the SOA [43].

Figure 9. Optical spectra of spectral slices filtered by AWG1 demultiplexer: (a) before SOA and (b) on the output of SOA after amplification.

In Figure 10 it is shown spectrum of downstream optical signals on the output of all OLT transmitters (before multiplexing by AWG2 unit) and spectrum in the input of ONTs (after demultiplexing by AWG3).
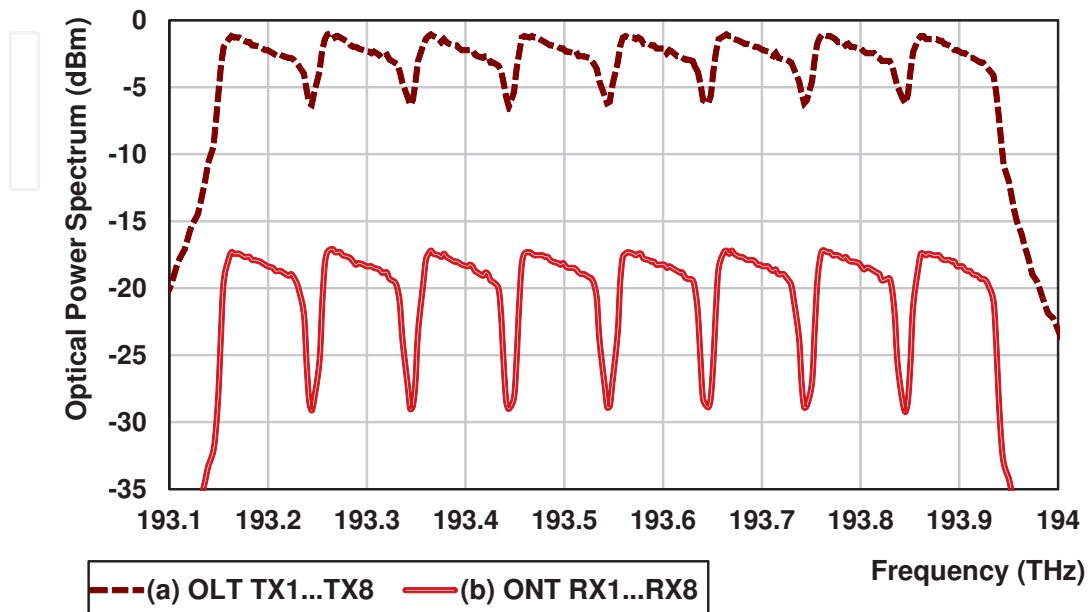

Figure 10. Optical power spectra of transmitted signals for spectrum-sliced WDM-PON downstream direction: (a) on the output of OLT transmitters and (b) on the input of ONT receivers (users) after 20 km transmission.

We found that optimal 3-dB bandwidth value of flat-top type AWG units for maximal quality of received signal and acceptably low crosstalk between channels must be about 90 GHz for spectrum sliced downstream and 50 GHz for laser based upstream system [7]. In case of ASE spectral slicing flat-top type AWG units shows good filtering performance because of its amplitude transfer function which provides good WDM channel separation at the same time passing sufficiently high optical power. The larger is width of spectral slice the better performance we can obtain. However, arising crosstalk between channels must be taken into account in this case [7]. It means that there is a tradeoff between optical filter bandwidth and crosstalk between spectrum sliced channels which can result in system's performance limitations.

In Figure 11 is shown spectrum of optical signals on the output of laser based ONT transmitters and in the input of OLT receivers after demultiplexing by AWG4 unit. As one can see all 8 upstream channel are well separated and any major spectral distortions is not observed. It must be mentioned, that for CD compensation and performance as well as network reach improvement of proposed 8-channel bidirectional SS-WDM PON system fiber Bragg grating dispersion compensation module (FBG DCM) was used. It is seen in Figure below (see Fig. 12(a)) that without CD compensation system performance is poor and successful data transmission is not possible.
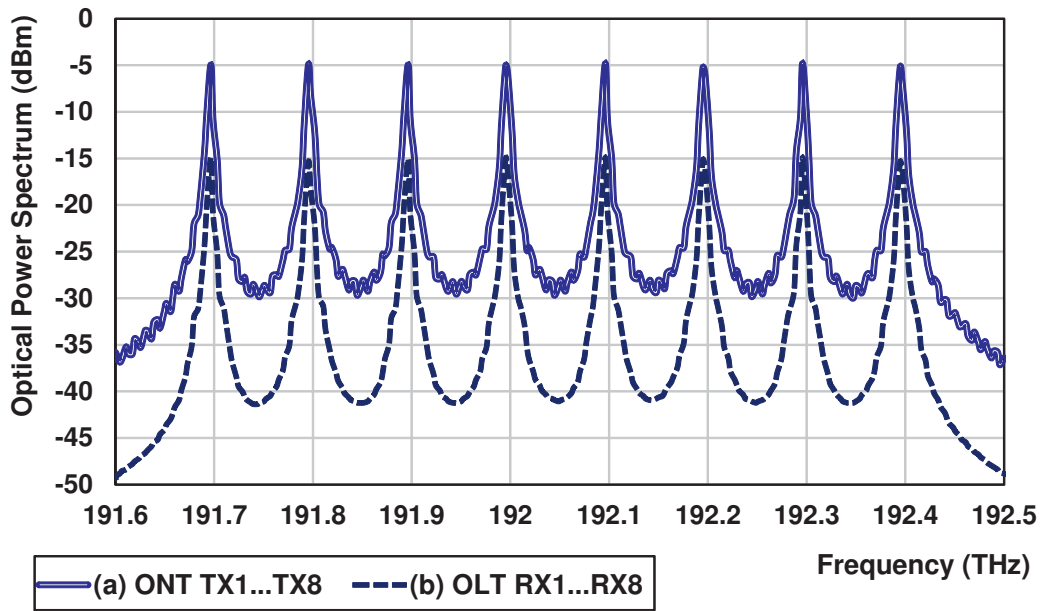
Figure 11. Optical power spectra of transmitted signals for laser based WDM-PON upstream direction: (a) on the output of ONT transmitters and (b) on the input of OLT receivers after 20 km transmission.

Theoretical value of accumulated CD for 20 km SMF fiber span is about 320 ps/nm. We found that optimal CD amount which must be compensated by FBG DCM for downstream 20 km SMF span is 310 ps/nm. Usage of gain saturated SOA for noise suppression was another key element to build spectrum sliced WDM-PON system operating below desired BER threshold. As it is shown in Figure 12(b), without gain saturated SOA downstream signal performance already after transmitter (back-to-back (B2B) measurement) is seriously affected by noise and BER is well above defined threshold (BER<10^{-12}).
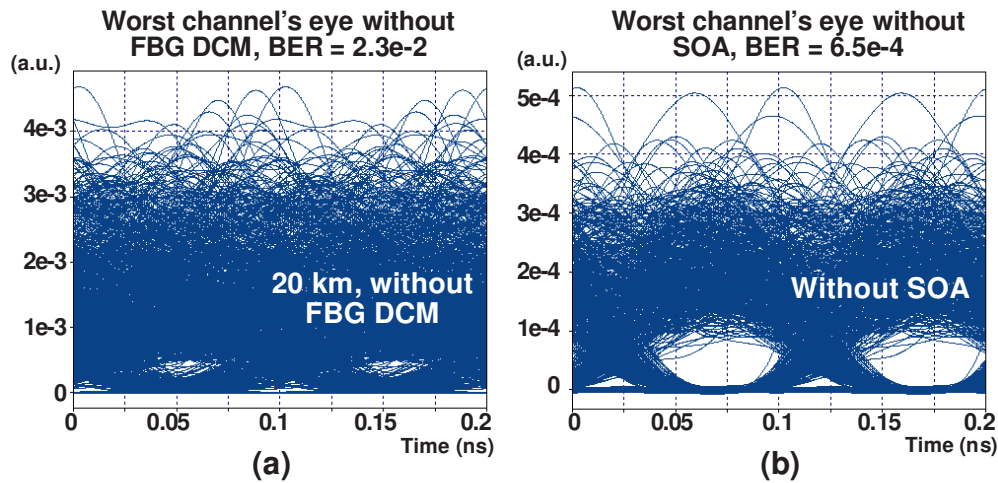

Figure 12. Received eye diagrams of downstream signals for bidirectional 8-channel spectrum sliced WDM-PON system: (a) after 20 km without FBG DCM for CD compensation and (b) without use of SOA for noise suppression (B2B measurement).
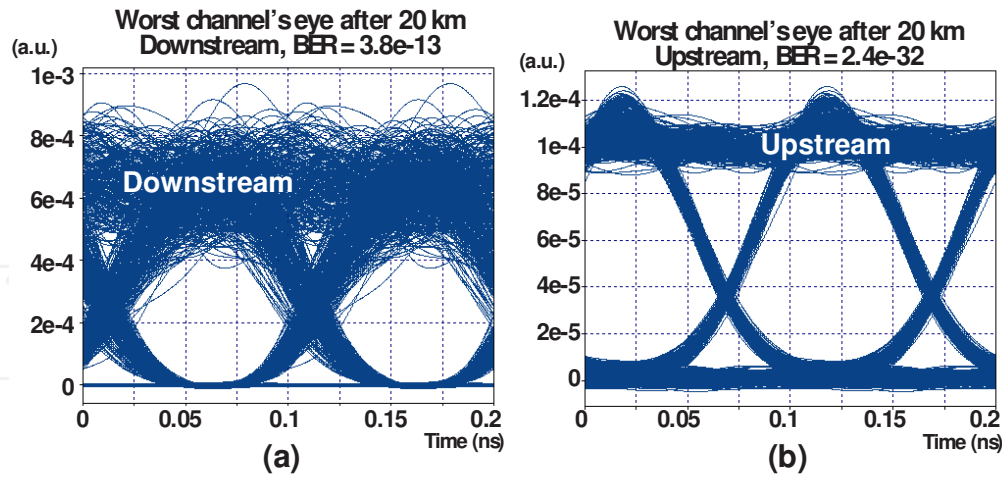
Figure 13. Received eye diagrams for bidirectional 8-channel WDM-PON system after 20 km transmission: (a) spectrum sliced downstream using SOA before modulator as well as FBG DCM for CD compensation, and (b) upstream signal eye pattern without additional DCM.

When SOA amplifier and FBG DCM were used for performance improvement of downstream direction, quality of obtained signal in receiver was sufficient and BER was below minimal threshold (see Fig. 13(a)). It is clearly seen that noise at logical "1" level is suppressed and eye opening became noticeably larger. It is due to the fact that gain saturated SOA is amplifying low intensity signal more than comparatively high signal and compress intensity fluctuations existing in input light signal, which in our case is spectrally sliced ASE. In Figure 13(b) we see, that eye diagram of upstream signal is quite good and eye is wide open. Some signal distortion due to CD is also seen, but for transmission distance of 20 km it can be considered as negligible.
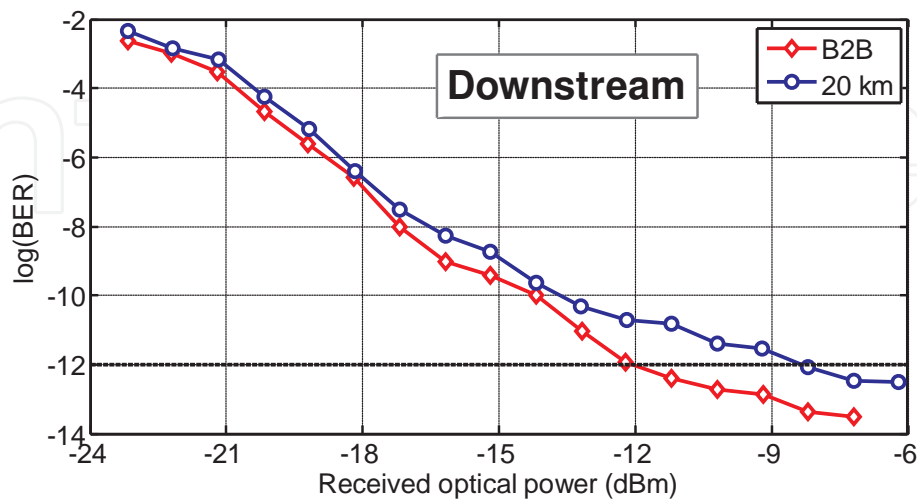

Figure 14. Measured BER performance of spectrum sliced downstream light signals in B2B configuration and after transmission through 20 km SMF fiber span.

For evaluation of downstream spectrum sliced system performance BER curve was measured (see Fig. 14). It can be observed, that power penalty to receive optical signal for 8-channel spectrum sliced downstream with desired BER<10^{-12} after 20 km transmission is 3.7 dB. This penalty is introduced by the cross talk effects, dispersion and due to the noise-like nature of broadband ASE light source.

In upstream transmission direction (see Fig. 15) minimal received power to obtain BER<10^{-12} must be more than-18.9 dBm for B2B configuration and-17.6 dBm for 20 km SMF transmission line.
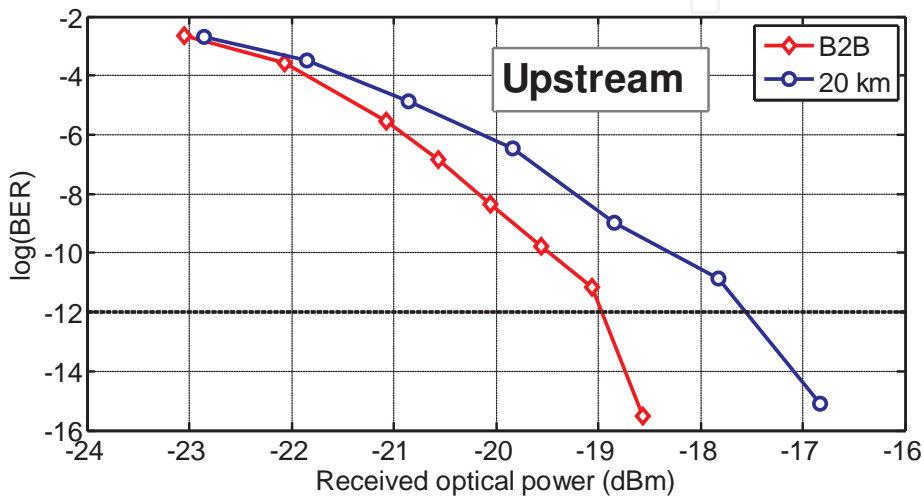

Figure 15. Measured BER performance of separate laser based upstream light signals in B2B configuration and after transmission through 20 km SMF fiber span.

As one can see in Figure 15, power penalty is about 1.3 dB, which can be explained by the influence of CD which broadens optical pulses as they travel along the optical fiber span.

5. Comparison and evaluation of DCF and FBG chromatic dispersion compensation methods for usage in up to 16 channel spectrum sliced WDM-PON access networks

There are compared two different CD compensation methods for improvement of maximal reach and performance of 8-channel and 16-channel AWG filtered SS-WDM PON system with flattened ASE broadband light source. In Figures 16 and 17 it is shown optical spectra on the output of ASE source and spectra after each flat-top AWG unit. We found that optimal 3-dB bandwidth value of flat-top type AWG unit for maximal system performance must be about 90 GHz for both SS-WDM PON systems. In case of ASE spectral slicing flat-top type AWG unit shows good filtering performance and high OSNR because of its amplitude transfer function that provides good WDM channel separation at the same time passing sufficient high optical power [12].
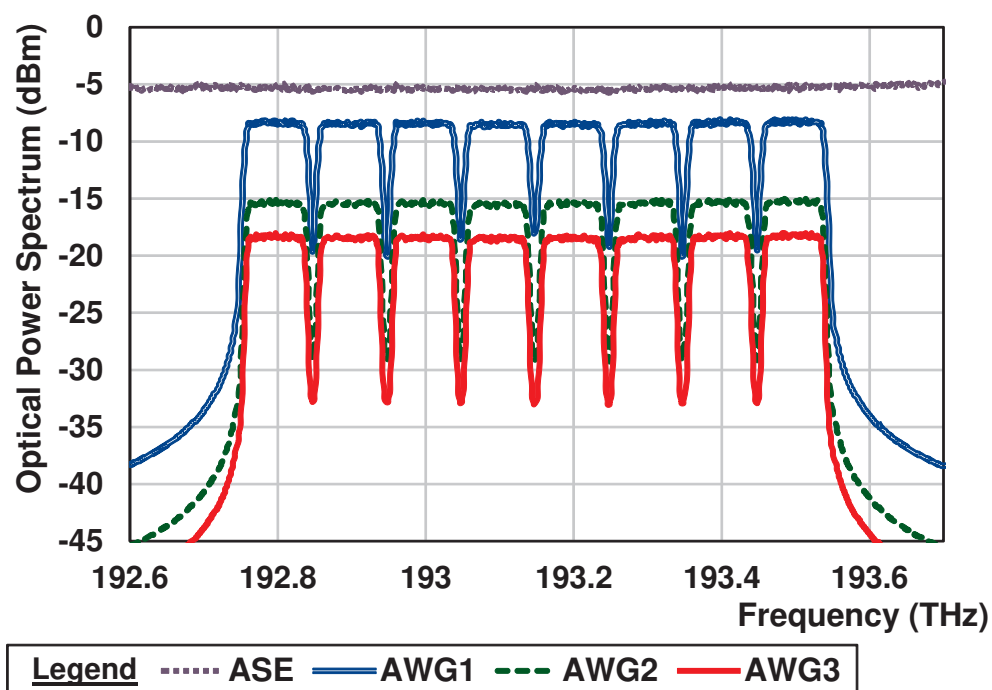
Figure 16. Optical output power spectrum of ASE source and 8-channel SS-WDM PON system after each stage of flat-top type AWG unit.
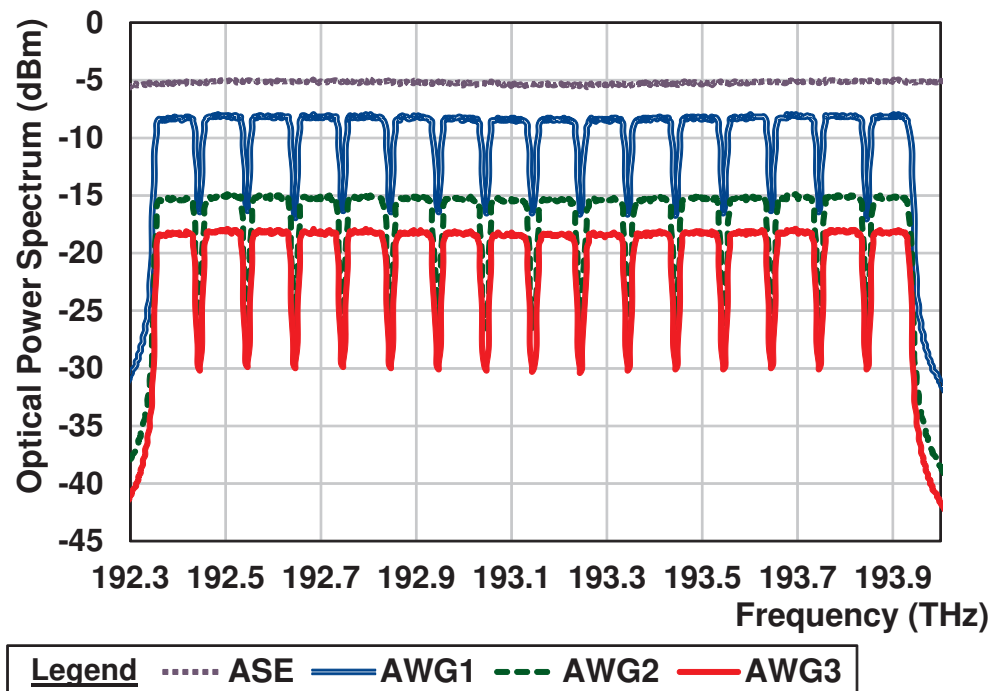

Figure 17. Optical output power spectrum of ASE source and 16-channel SS-WDM PON system after each stage of flat-top type AWG unit.

First, we studied both SS-WDM PON systems in back to back (B2B) configuration (without DCM and SMF fiber span in ODN) which was the reference to which we compared all other measurements.

In Figures 18(a) and 19(a) we show the BER versus optical received power for 2.5 Gbit/s 8-channel and 16-channel SS-WDM PON downlink transmission in B2B configuration as well as after 10 km 20 km transmission without chromatic dispersion compensation. In Figures 18(b) and 18(c), as well as 19(b) and 19(c) we show the BER versus optical received power for 2.5 Gbit/s 8-channel and 16-channel SS-WDM PON downlink transmission after 10 km and 20 km transmission realizing CD compensation by implementing DCF and FBG respectively.
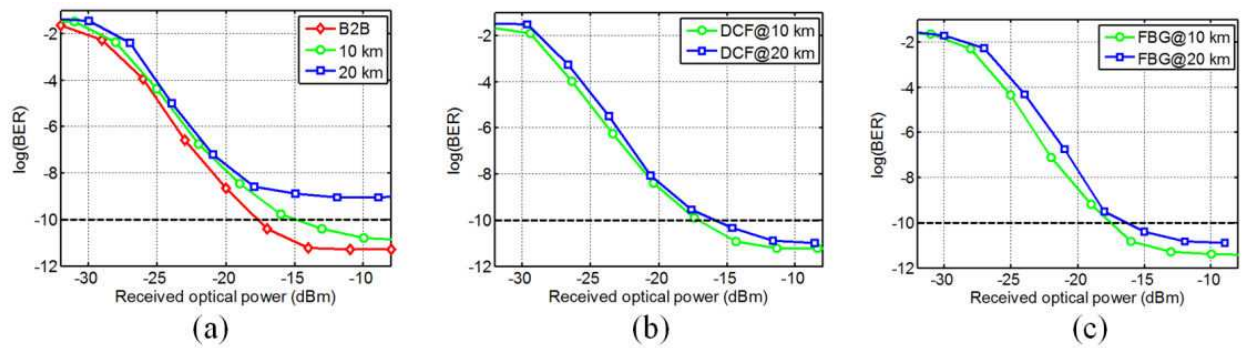

Figure 18. BER versus received optical power at the receiver for 8-channel SS-WDM PON system (a) without CD compensation, (b) using DCF for CD compensation, (c) using FBG for CD compensation.

As one can see in Figure 18(a), power penalty to receive optical signal for 8-channel system with BER<10^{-10} after 10 km transmission is 2.7 dB. The minimal BER value of received signal after 20 km transmission is above defined BER threshold and it means that qualitative data transmission is not possible in this case.
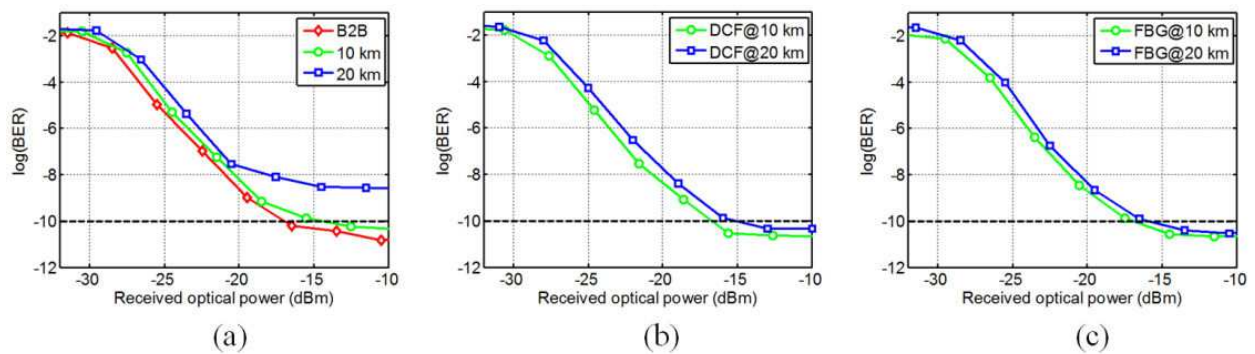

Figure 19. BER versus received optical power at the receiver for 16-channel SS-WDM PON system (a) without CD compensation, (b) using DCF for CD compensation, (c) using FBG for CD compensation.

In Figure 20 are shown eye diagrams of received signal in B2B configuration (BER<10^{-10}) and after 20 km long SMF span (here BER>10^{-10}) without CD compensation.

Theoretical value of accumulated CD for 10 km SMF fiber span is about 160 ps/nm and 320 ps/nm for 20 km span. We found that optimal CD compensation amount that must be compensated by FBG for 10 km span is 125 ps/nm for both 8-channel and 16-channel systems. For 20 km SMF span we must compensate 290 ps/nm in 8-channel system and 280 ps/nm in 16-channel system. In order to make optimal CD compensation in 8-channel system we used 2.5 km DCF fiber before 10 km long SMF fiber span, and 4.7 km DCF fiber before 20 km span. For 16-channel system it was used 2 km long DCF before 10 km span and 4.5 km DCF before 20 km SMF span. In case of FBG it was used incomplete CD compensation, but in case of DCF the optical line was overcompensated.
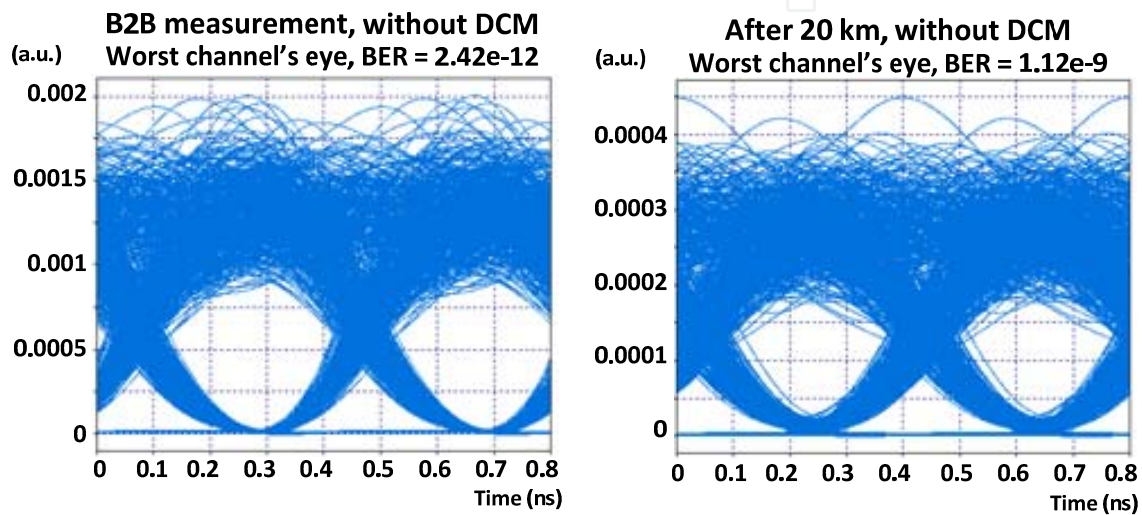

Figure 20. Eye diagrams and BER values of received signals from worst channels of 8-channel SS-WDM-PON scheme without DCM module for measured B2B signal and signal after 20 km transmission.

Usage of DCF for accumulated CD compensation provides extension of network reach from 10 km to 20 km as well as improvement of network performance for both line lengths, (see Fig. 18(b)). In this figure it is seen that, for a BER of 10^{-10} using DCF for CD compensation, the power penalty to pass from 10 km transmission to 20 km transmission is 1.3 dB. This penalty is introduced by the cross talk effects, dispersion and due to the noise-like nature of broadband ASE light source. The power penalty for BER of 10^{-10} to pass from 10 km to 20 km is 1.1 dB in case when FBG is used for compensation of accumulated CD for reach extension and performance improvement of proposed 8-channel SS-WDM PON system, (see Fig. 18(c)). The comparison between DCF and FBG in terms of performance improvement shows that FBG provides higher performance improvement.

After investigation of 8-channel SS-WDM PON system the simulation model of 16-channel system was realized. Results show that the overall performance of this system is slightly lower than 8-channel system using the same ASE source. As one can see in Figure 19(a), power penalty to receive optical signal after 10 km with defined BER is 2.8 dB. Performance of transmission system is too low to provide data transmission over 20 km SMF fiber span with BER<10^{-10} (see Fig. 21).
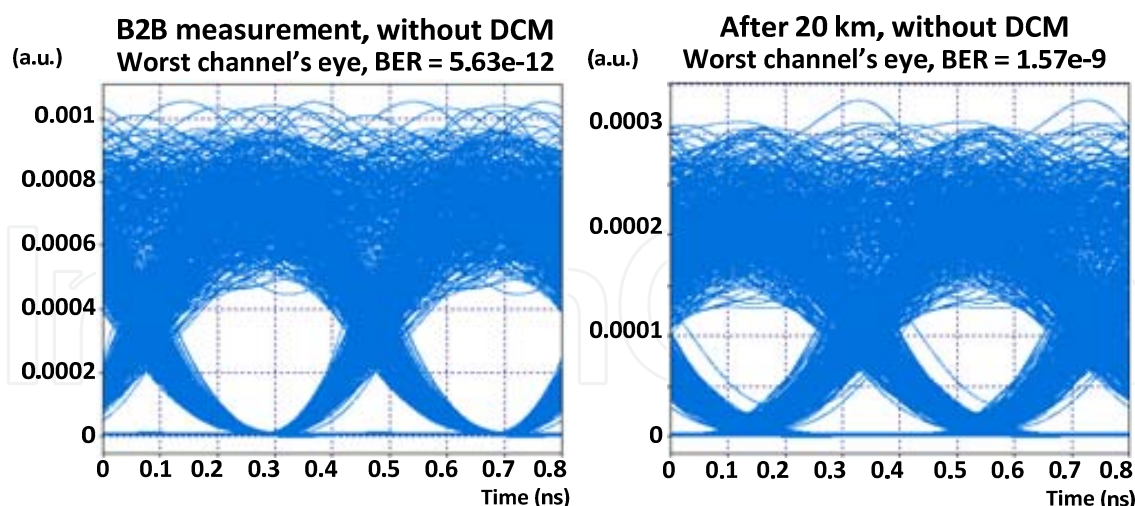
Figure 21. Eye diagrams and BER values of received signals from worst channels of 16-channel SS-WDM-PON scheme without DCM module for measured B2B signal and signal after 20 km transmission.

It is shown (see Fig. 19(b)) that usage of DCF fiber for CD compensation improve access system's performance and it is capable to operate over 20 km SMF span with BER<10⁻¹⁰. In case when DCF is used for CD compensation the power penalty for BER of 10⁻¹⁰ to pass from 10 km to 20 km is 1.5 dB. If FBG is used (see Fig. 19(c)) power penalty is 1 dB. When FBG is used for CD compensation in 16-channel system BER of 10⁻¹⁰ is reached at-17 dBm received optical power after 10 km fiber span and at-16 dBm power after 20 km long span.

When DCF fiber is used for CD compensation minimal received power must be-16.7 dBm for 10 km SMF fiber span and-15.2 dBm for 20 km fiber span or transmission line. As it is seen from obtained results performance between FBG and DCF for CD compensation and system efficiency improvement of 8-channel and 16-channel SS-WDM PON systems are close. However, FBG provides better CD compensation performance. Instead of DCF fiber it can be used at higher optical powers without inducing nonlinear optical effects and additional signal distortion which can occur due to small effective core area of a DCF fiber.

6. Conclusion

We report on causes of latency in fiber optical networks and solutions how to minimize it. Latency is a critical parameter in a wide set of applications like financial transactions, teleme-dicine, cloud services and other real-time applications which requires optical transmission line with the smallest available time delay. It was shown that latency can be greatly reduced by replacing conventional network components with low-latency components and by optimizing optical network path trying to keep it short as possible. Future telecommunication networks must be cost and energy efficient, in the same time supporting high bandwidths and low latency. We showed the realization of cost effective up to 16-channel dense WDM-PON system where spectrum sliced spectrally uniform ASE source is used as a light source. It is shown the

design of this broadband spectrally-uniform ASE source with+23 dBm output power in system's operating wavelength range by using two EDFA amplifiers connected in cascade mode. We also demonstrated excess intensity noise (EIN) suppression by using additional SOA in transmitter section as well as experimentally compared two different chromatic compensation methods, namely dispersion compensation fiber (DCF) and fiber Bragg grating (FBG) for implementation of signal performance improvement in high-speed spectrum sliced optical access systems.

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