Abstract—The present paper discusses and compares the performance of energy and cost efficient 8-channel and 16-channel spectrum-sliced wavelength-division-multiplexed passive optical networks (SS-WDM PONs) operating at 2.5 Gbit/s transmission speed and realized by slicing of spectrally-uniform amplified spontaneous emission (ASE) source. It is demonstrated that SS-WDM PON access systems are able to provide data transmission for downstream traffic in a 20 km reach with BER<10^{−10} by using additional chromatic dispersion compensation techniques, namely dispersion compensation fiber and fiber Bragg grating.

Keywords—Spectrum slicing, wavelength division multiplexing passive optical network (WDM-PON); amplified spontaneous emission (ASE); arrayed-waveguide gratings (AWGs); dispersion compensation fiber (DCF); fiber Bragg grating (FBG)

I. 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 [1].

Passive optical networks (PONs) have been considered to be one of the most promising solutions for access networks due to its broad bandwidth and low-cost infrastructure [2]. Especially, spectrum sliced wavelength-division-multiplexed passive optical network (SS-WDM PON) 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 [3, 4]. 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 the second one is to use an architecture that is both cost and energy efficient [5]. Recent studies have revealed that a large amount of electricity is consumed by telecom equipment 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 [3, 4]. 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 [3]. 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).

In this paper we build multi-channel SS-WDM PON systems and compare its performance as well as overall performance improvement using two different chromatic dispersion (CD) compensation techniques - dispersion compensating fiber (DCF) and fiber Bragg grating (FBG). It is demonstrated 8-channel and 16-channel SS-DWDM PON systems with CD compensation and broadband ASE seed light source with flat spectrum in wavelength range from 1545.32 nm to 1558.98 nm (C-band). In contrast to other studies made in this field before [4, 10], our main goal of this research is to evaluate up to 16 channel SS-WDM PON system by implementing dispersion compensating fiber (DCF) and fiber Bragg grating (FBG) for CD compensation in dispersion compensation module (DCM) as well as investigate the overall performance of this system by building it on the ITU-T DWDM frequency grid, defined in recommendation G.694.1.
Based on this recommendation channel spacing is chosen equal to 100 GHz (0.8 nm in wavelength) [11]. It must be remarked that our research differs from other researches [4, 10], with data transmission speed which is chosen 2.5 Gbit/s per channel, and is relatively high for this type of optical access networks. We are confident that 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) is potentially capable to replace existing classical WDM-PON access system (where one laser source is used for each user) [12]. The main benefit of our proposed system includes reduction of optical network architecture complexity, improvement of energy efficiency and cost reduction per one user.

II. BACKGROUND SPECTRUM SLICING TECHNIQUE

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 [4, 13]. The aim of spectrum slicing is to employ a single BLS for transmission on a large number of wavelength channels, see Fig. 1.

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 [4]. 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.

III. EXPERIMENTAL SIMULATION MODEL OF UP TO 16-CHANNEL SS-WDM PON SYSTEM

This paper section contains description of multi-channel spectrum sliced WDM PON access system and broadband spectrally uniform ASE source realization in newest Synopsys RSoft 5.3 simulation software which is widely used for design of high-performance optical communication systems.

A. Realization of spectrally uniform ASE light source with high output power

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 EDFA 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. 2.

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 Fig. 3.

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 around 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 in Fig. 3, fluctuations of optical power level are minimal and spectrum in this employed region is almost flat.

B. Simulation setup and basic parameters

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 $10^{-10}$ [15].

As one can see in Fig. 4, SS-WDM PON simulation scheme we built consists of up to 16 channels. The 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 [11].

Broadband ASE light source, which realization and output spectrum is shown in Fig. 2 and Fig. 3 respectively, 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 athermal 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 $V_{\pi}$ of 5 Volts and maximum transmissivity offset voltage 2.5 Volts. Next, 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 (AWG2) and sent into standard optical single mode fiber (SMF) defined in ITU-T recommendation G.652 [16, 17].

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 $A_{eff} = 80 \mu m^2$, typical attenuation $\alpha =0.2$ dB/km, dispersion coefficient $D = 16$.
ps/(nm·km) and dispersion slope $D_{sl} = 0.07$ ps/(nm²·km) at the reference wavelength $\lambda = 1550$ nm [18].

As one can see in Fig. 4 (middle), two simulated CD compensation methods implemented in DCM module are FBG and DCF. In our research we use DCF fiber with $A_{eff} = 20 \, \mu m^2$, attenuation $\alpha = 0.55 \, \text{dB/km}$, dispersion coefficient $D = -80$ ps/(nm·km) and dispersion slope $D_{sl} = 0.19$ ps/(nm²·km) at the reference wavelength $\lambda = 1550$. 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 noise reduction [14].

IV. RESULTS AND DISCUSSION

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 Fig. 5 and Fig. 6 it is shown optical spectrum on the output of ASE source and spectra after each flat-top type 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 [16]. 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.

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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.

As one can see in Fig. 7(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. In Fig. 9 is displayed 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.

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. 7(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. 7(c). The comparison between DCF and FBG in terms of performance improvement shows that FBG provides higher performance improvement.

When FBG is used for CD compensation 8-channel SS-WDM PON system reaches BER of 10^{-10} at -17.5 dBm received power after 10 km span. After 20 km span it reaches above mentioned BER value at -16.4 dBm received optical power. If DCF is used for CD compensation in 8-channel system then received optical power after 10 km span must be at least -17.2 dBm and after 20 km span it must be at least -15.9 dBm to provide data transmission with BER<10^{-10}.

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 Fig. 8(a) power penalty to receive optical signal after 10 km with defined BER is about 2.8 dB. Performance of transmission system is too low to provide data transmission over 20 km SMF fiber span with BER<10^{-10}, please see Fig. 10.
It is shown in Fig. 8(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 fiber 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 (Fig. 8(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.

V. CONCLUSION

In this work we have realized and investigated the performance of high speed 8-channel and 16-channel spectrum sliced WDM-PON systems where dispersion compensation fiber and fiber Bragg grating was used for accumulated chromatic dispersion compensation to provide high system performance with BER<10^{-10}. Design of broadband spectrally-uniform ASE source with +23 dBm output power in system’s operating wavelength range using two EDFA amplifiers connected in cascade mode is shown and briefly described as well. It was found that using chromatic dispersion compensation the maximum reach of up to 16-channel SS-WDM PON systems can be extended at least twice – from 10 km to 20 km. By using FBG we achieved better results than using DCF for accumulated CD compensation in terms of system performance improvement. We believe that spectrumsliced WDM-PON system can completely replace WDM-PON system in such a way making optical access systems more energy efficient and green.

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REFERENCES


