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Comparative performance of Raman-SOA and Raman-EDFA hybrid optical amplifiers in DWDM transmission systems

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To combine the benefits and compensate for the drawbacks of different optical amplifier types, a hybrid amplifier can be composed. The authors consider two most frequently used hybrid amplifiers that can provide better performance: a semiconductor optical amplifier (SOA), and an erbium doped fiber amplifier (EDFA), both in combination with a distributed Raman amplifier (DRA). To compare performance of the hybrid amplifiers, the eye diagrams of detected signals were analyzed and the maximum transmission distances were found. The results obtained show that even under the conditions advantageous for a SOA-DRA hybrid, the EDFA-DRA combination will produce less distortions of the amplified signal.

Key words: Dense wavelength division multiplexing, hybrid amplifier, semiconductor optical amplifier.

INTRODUCTION

During the last decade the evolution of available multimedia services and the rapid growth in the number of worldwide internet users has given rise to the demand for high capacity networks; this, in turn, causes a major shift in the evolution of optical transmission systems. Nowadays, one on the most typical solutions for raising transmission capacity is the use of wavelength division multiplexing (WDM), where different optical signal frequencies are used in order to achieve simultaneous transmission of a definite number of optical channels over a single fiber. It is also important to maintain the required level of system performance over a longer transmission distance. Such multichannel systems – in addition to linear effects such as optical attenuation and chromatic dispersion – are highly sensitive to the fiber non-linearity, the presence of which may result in serious signal distortion thus causing a dramatic degradation of a system's performance. Still, the effect that puts the greatest limitations on the transmission distance is the optical signal attenuation (Bobrovs et al., 2011a, b; Olonkins et al., 2012).

To compensate for optical signal attenuation, two ways are known: the use of signal repeaters and optical signal amplification. The former solution is not the best for WDM systems, because it requires demultiplexing, conversion, processing and regenerating of signals of all 16 channels; therefore, it is too complex and expensive (Agrawal, 2002). At the same time, by amplifying the optical signal we raise its power during transmission without conversion into any other form; the method is therefore simpler and much cheaper than those using repeaters. In some of the types of optical amplifiers optical signal gain is provided

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Abbreviation: Dense wavelength division multiplexing, **DWDM;** hybrid amplifier, **HA;** semiconductor optical amplifier, **SOA;** erbium-doped fiber amplifier, **EDFA;** distributed Raman amplifier **DRA;** nonlinear optical effects, **NOEs;** amplified spontaneous emission, **ASE.**

through stimulated emission, and in the others fiber nonlinearity is used.

In the amplifier medium also a spontaneous emission also occurs, which is amplified together with the transmitted signal. This results in the amplified spontaneous emission (ASE) noise, which in some cases can seriously limit the total transmission distance.

In WDM transmission systems the following types of optical amplifiers are used: semiconductor optical amplifiers (SOAs), doped fiber amplifiers (DFAs), discrete (lumped), and distributed Raman amplifiers (LRAs and DRAs). In the nearest future, parametrical amplifiers will also become available for multichannel systems. Each of these amplifier types has its own benefits and drawbacks. The main problem with SOAs is that they produce the largest amount of ASE and their gain dynamics can cause serious signal distortions. The DFAs can provide signal amplification with considerably less signal impairments than in the SOA case; however, their gain spectrum is highly frequency-dependent due to the characteristics of the doped material. Raman amplifiers can provide the most noiseless amplification; in this case the gain spectrum can easily be changed by varying the number of pumps and their frequencies, while to achieve a high enough gain a very powerful pump is needed, the use of which is not economically reasonable (Agrawal, 2002). To compensate for the drawbacks and combine the benefits of different amplifiers, these can be used together, forming a hybrid amplifier. In modern transmission systems a great variety of such combinations can be used; we, therefore, decided to carry out research on the hybrid amplifiers.

INVESTIGATION ON THE AMPLIFIER TYPES

As already mentioned, for amplification of optical signals the stimulated emission is used. In SOAs, the electrical energy is applied as a pump to achieve the population inversion, and amplification is achieved via the stimulated recombination luminescence. The spontaneous carrier lifetime in the active region of material is times smaller than in other amplifier types, so it is highly important for the SOA to work close to the saturated mode in order to keep the ASE level low. The amplifier gain dynamics, which is determined by the quick carrier recombination lifetime, for SOAs is faster than in other types of amplifiers. Consequently, the amplifier will respond relatively quickly to the changes in the input optical signal power. This may cause severe signal distortions, especially in multichannel systems (Connely, 2004). Because pulses from different channels are amplified simultaneously, the pulse belonging to one channel may drain the total higher energy level population, thus resulting in smaller optical gain for a pulse that corresponds to another channel; this process is called cross-gain modulation (Agrawal, 2002). The main advantages of using SOAs are their broad amplification bandwidth (that is, -3 dB up to 70 nm) and relatively low price (Agrawal, 2002).

DFAs make use of rare-earth elements for doping some silica fibers during the manufacturing process. For this purpose, many different rare-earth elements can be used (erbium, thulium, neodymium, ytterbium, chromium etc.) (Cheng and Huang, 2013). The most usable element is erbium, because it allows optical amplifiers to operate in the C-band, (that is from 1530 to 1565 nm). In order to achieve efficient pumping in erbium- doped fiber amplifiers (EDFAs) the 980 and 1480 nm semiconductor lasers are applied, while population inversion is achievable using co-propagating, counter-propagating and bi-directional pumps. The gain spectrum of EDFAs is determined by the molecular structure of the doped fiber, and is strictly wavelength-dependent. The main disadvantage of EDFAs is that their wavelength-dependent gain spectrum bandwidth is only about 40 nm; besides, it is not flat. On the other hand, it determines amplification of individual channels when a WDM signal is amplified, so no cross-gain saturation occurs. Due to a relatively long spontaneous carrier lifetime in silica fibers, this allows achieving high gain for a weak signal with low noise figure, which represents the difference in signal-noise ratio at the input and output of the device under consideration (Agrawal, 2002). This is the main reason why the EDFAs are most frequently used for optical amplification.

Nowadays, Raman amplifiers are being deployed in most of the new long-haul and ultra-long haul fiber optic transmission systems, placing them among the first widely commercialized nonlinear optical devices in telecommunications (Islam, 2004a). In Raman amplifiers a small signal gain arises from stimulated Raman scattering (SRS) – the energy transfer from a powerful pumping optical beam to the amplified signal. In silica fibers, the peak amplifications correspond to the signal frequency that is ~ 13.2 THz lower than the pumping one; this frequency difference is called the Stokes shift. Such downshift is defined by the energy of optical phonons which represent the vibration mode of medium (Islam, 2004a). Despite the fact that the spontaneous Raman scattering spectrum is broad, the coherent nature of the process implies that the small signal radiation becomes coherently amplified by the SRS. The main advantage of Raman amplifiers is that the gain spectrum is very broad, and its shape can be changed by varying the number of pumps and their wavelengths (Mustafa et al., 2013). The relatively low noise figure of Raman amplifiers also is a significant benefit. It is these two aspects that make Raman amplifiers the main component of hybrid amplifiers, as they can be used to enhance the gain of a particular amplifier, and to broaden and equalize the gain spectrum, adding very little noise to the amplified signal. The main disadvantages of Raman amplifiers are the poor pumping efficiency at lower signal power (Tragarajan and Ghatak, 2007), and the use of expensive powerful lasers capable of delivering great powers into single-mode fibers.

In the systems with optical amplification the intensity of amplified signal can reach the level high enough to cause fiber nonlinearity, which may result in serious inter-channel crosstalk, thus also in a dramatic decrease in the transmission quality. For the systems that are highly sensitive to fiber nonlinearity (such as dense WDM (DWDM) systems with equal channel spacing) it is very important to keep track of the inter-channel crosstalk produced by the four-wave mixing (FWM). Indeed, such FWM induces spectral components with frequencies that may coincide with those of transmitted signal channels, thus limiting the amplifier gain for which the required quality of service is maintained. In such cases, the ASE and other amplifier-produced signal distortions may have a great impact on the maximum achievable transmission distance. This means that SOAs are not the preferable type of optical amplifier for such a system.

With the mentioned gain limitations the Raman amplifiers may cause too much inter-channel crosstalk, while the DFAs also can raise the signal intensity level significantly enough to cause inter-channel crosstalk, and, due to their gain- frequency dependence, they may not provide equivalent amplification for all of the system's channels so this needs to be equalized. The use of a SOA-DRA or, alternatively, of an EDFA-DRA hybrid may help to overcome these problems (Islam, 2004b).

In general, two types of hybrid amplifiers are known: the wideband hybrid amplifier (WB-HA) and the narrowband hybrid amplifier (NB-HA) (Islam, 2004b). In the former a wider band for the gain is obtained using combinations of different amplifier types, while in the NB-HA such combinations are meant for obtaining a compound with lower ASE-produced noise and higher gain of the amplified signal.

Raman amplifiers are an essential component of hybrid amplifiers. Obviously, hybrid SOA-EDFAs can be used in the cases where it is necessary to widen the gain spectrum of an EDFA, which could be done applying the most cost-effective solution (Zimmerman and Spiekman, 2004); however, such a combination generates a greater amount of ASE than in the cases of EDFA-DRAs or SOA-DRAs. This significantly affects the total system performance in the case of a nonlinearity-sensitive transmission system, where, due to the limitations on signal amplification caused by nonlinearity, the received optical power penalty plays a great role as it affects the receiver's sensitivity needed for achieving a definite bit error rate (BER). Therefore, normally it is not applied in long haul or DWDM systems. Our previous studies show that the noise figure of Raman amplifiers is much lower than that of EDFAs, and definitely lower than in the cases where SOAs are used. So the best way to achieve a higher gain with lower noise figure or a wider amplification band is to use a SOA or an EDFA in combination with a distributed Raman amplifier (DRA). For this purpose, we can also use another type Raman amplifiers – the discrete ones (Islam, 2004b); however, due to a small effective area and a high nonlinearity coefficient of the HNLFs and dispersion compensating fibers employed as the amplifier medium in LRAs, the discrete RAs generate a multitude of nonlinearity-related distortions in the cases when the intensity level of a weak signal to be amplified is relatively high.

Therefore, it is unclear whether SOA-DRA or EDFA-SOA combinations would provide better system performance in the case where the impact of fiber nonlinearity is strong. Our main goal was therefore to find out which of these combinations can ensure good enough signal amplification with less distortions (that is, with longer transmission distance) and without loss in the operational quality of a nonlinearity-sensitive transmission system.

SIMULATION SCHEME AND MEASUREMENT TECHNIQUE

Here, we will describe the simulation and measuring schemes used for performance estimation of hybrid optical amplifiers. To compare the performance of SOA-DRA and EDFA-SOA combinations a quality-characterizing parameter is to be evaluated. In our case, the most efficient way to assess the quality of transmission is to analyze the eye diagrams, which show patterns of the electrical signal after detection, and to evaluate BER values of the transmitted signal as a parameter featuring best the signal distortions arising during transmission. To estimate the transmitted signal distortions caused by fiber nonlinearity, we will observe its optical spectrum, while the level of ASE-generated noise will be assessed by noise figures.

To obtain the experimental results we needed a strong mathematical tool. For this purpose, the OptSim 5.2 simulation software was chosen, so that this all-optical network simulator can handle complex simulations and introduce high-accuracy results without imposing high requirements on the relevant hardware. This simulation tool uses the split-step method to perform integration of the fiber propagation equation (OptSim 5.2 User Guide, 2010):

$$\frac{\partial A(t,z)}{\partial z} = \{L + N\}A(t,z) \tag{1}$$

where A(t,z) is the optical field, L is the linear operator (for calculation of such linear effects as attenuation and dispersion), and N is the nonlinear operator (accounting for fiber nonlinearity).

The calculation is done dividing the whole optical link (fiber) into Δz-long spans, and deriving the L and N operators separately (Zimmerman and Spiekman, 2004). Two variants of the split-step method are applied: time domain split step (TDSS) and frequency domain split step (FDSS). These two differ only in the way the L operator is calculated: in the TDSS method – in the time domain, while in the FDSS – in the frequency domain. The nonlinear operator in both cases is obtained in the time domain. The former method gives highly precise results, however it is difficult to implement. The FDSS is easier to implement, but intrinsic errors (that decrease dramatically the precision of the results (OptSim 5.2 User Guide, 2010) can arise during the calculation process. Therefore, for our simulation the TDSS method was chosen.

For studying the signal distortions caused by hybrid amplifier a 10 Gbps 16- channel DWDM transmission system was designed,

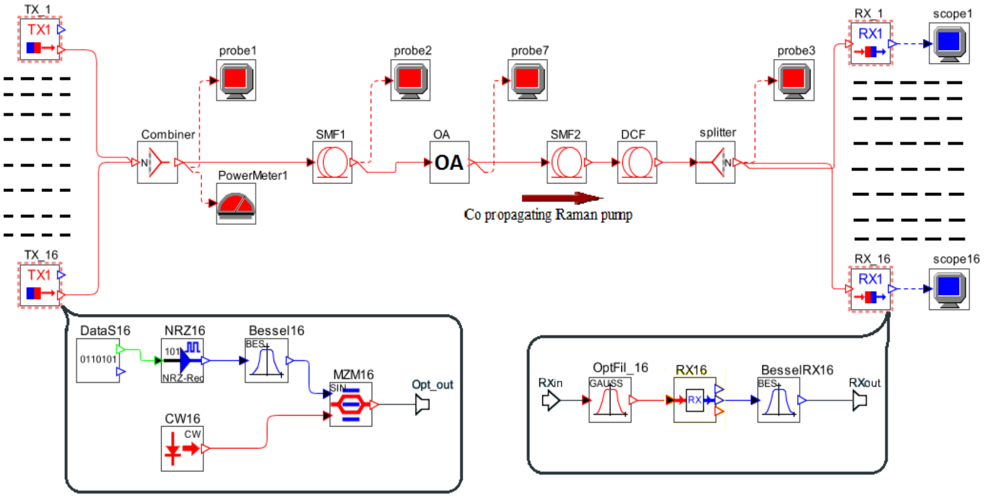

Figure 1. Simulation scheme of a 10 Gbit/s 16 channel DWDM system.

with the non-return-to-zero (NRZ) encoding, the on-off keying (OOK) intensity modulation format (less tolerant to the influence of fiber nonlinearity than advanced modulation formats (Bobrovs et al., 2011c), and a 50 GHz channel spacing. Such system configuration was chosen to purposefully to cause the Kerr effect in order to impact the amplified signal. This nonlinear effect (arising in systems with equal and relatively small channel spacing) produces strong inter-channel crosstalk, thus limiting the maximum intensity level of the transmitted signal and, therefore, the total amplification. In such a system the amplifier-produced signal impairments will directly influence the achievable transmission distance. Therefore it is easier to assess the performance of the amplifiers by comparing the achieved transmission distances. The simulation scheme comprising three main blocks: the transmitter block, the optical link and the receiver block, are shown in Figure 1.

The transmitter block consists of 16 NRZ-OOK externally modulated channel transmitters, each of them operating at its own frequency in the range from 193.05 to 193.8 THz. Each transmitter contains a pulse pattern generator (PPG), an NRZ driver, an electrical filter, a continuous wave (CW) laser, and a Mach-Zender's modulator. The continuous optical signal is externally modulated by NRZ-coded electrical pulses via an electro-optical MZM. Then all of the 16 generated optical signals are combined and transmitted through the optical link.

The signal first overcomes 72 km of a single mode fiber (SMF) with 0.2 dB/km attenuation and 16 ps/nm/km chromatic dispersion. The SMF length is dictated by the required optical signal power at the input of the optical amplifier, which is very important due to its saturation effect – especially when SOA is used. For an EDFA this parameter is also relevant, but it has been optimized for the semiconductor amplifier (due to the high level of noise produced by SOA and its gain dynamics). The weak signal power level for each channel at the amplifier input is around -22.4 dBm. Then the signal is amplified by an in-line SOA or an EDFA.

The two hybrid amplifiers (SOA-DRA and EDFA-DRA) will be compared as in-line amplifiers, because such amplifiers not only cause signal impairments and raise the intensity level significantly enough to cause fiber nonlinearities, but also amplify the nonlinearity-caused signal distortions accumulated during transmission. This makes the requirements for the total acceptable amount of amplifier noise stricter.

The SOA pumping current is optimized in order to minimize the amplifier-produced signal impairments. The EDFA parameters are chosen in such a manner that its gain spectrum irregularities would be easy to compensate with a single Raman amplifier pump, keeping in mind the total gain limitation caused by FWM. Then the amplified signal enters another SMF where it is amplified by a low-power DRA, the power of which allows for achievement of the maximum signal gain without causing too much nonlinearity-produced distortions. The length of this second SMF is variable in order to obtain the maximum transmission distance. At the end of optical link the signal enters a dispersion compensation fiber (DCF), the length of which will also be varied so as to find a balance between the dispersion compensation and the DCF insertion loss. After propagating through the DCF, the optical signal enters the receiver block. It is divided among 16 receivers, where the optical signal is filtered, detected and converted into electrical current. The DCF attenuation at 1550 nm is 0.55 dB/km, and the dispersion at this wavelength is -80 ps/nm/km.

RESULTS AND DISCUSSION

We will focus our attention on the results obtained with the simulation scheme described above. Besides, the amplifier optimization results will be presented, which may provide a good basis for estimating the cause of amplifier performance limitations. As already mentioned, in order to estimate the system performance the eye diagrams should be analyzed. The eye diagram is a powerful time domain tool for assessing the quality of the received signal and for analyzing the signal distortions. It can give much information on the timing jitter, the system rise time, and the signal amplitude distortions (Bobrovs and Ivanovs, 2008). First, we will discuss the configurations of SOA-DRA and EDFA-DRA allowing the maximum transmission distance to be achieved. The active layer parameters of the SOA and its other geometrical and material parameters were found in Singh and Kaler (2007), where a semiconductor optical amplifier was optimized for a similar system. They are specified in Table 1.

Table 1. The SOA parameters.

Parameter	Value	Unit
Amplifier length	750	µm
The active layer width	2	µm
The active layer thickness	0.2	µm
Confinement factor	0.41	µm
Transparency carrier density	$1.5 \cdot 10^{18}$	cm^{-3}
Differential gain constant	$2.1 \cdot 10^{-16}$	cm^{2}
Carrier recombination time	0.3	Ns
Input and output coupling losses	3	dB

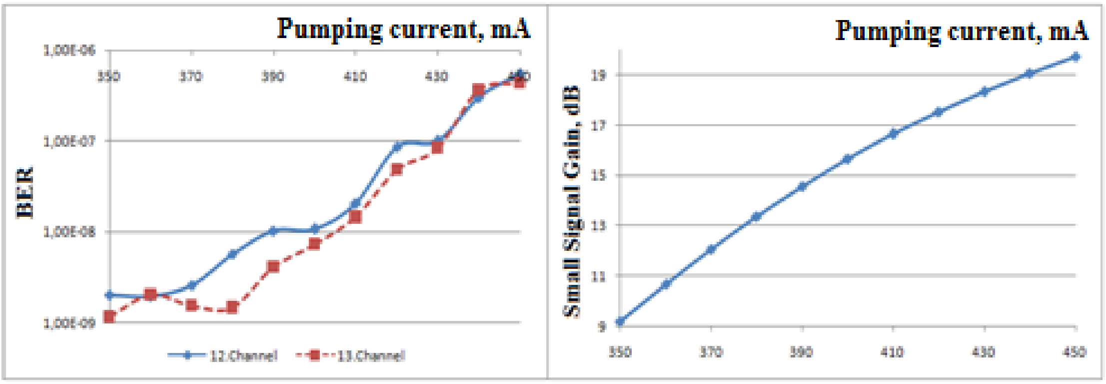

Figure 2. BER values at the output of SOA for channels 12 and 13 of the transmitted signal with gain compensation vs. pumping current (left); the optical gain vs. the pumping current (right).

The current to be used for pumping in the semiconductor amplifier should be chosen from the considerations of achieving the maximum amplification with the minimum noise. With this purpose in mind, we found the BER level in two channels for the signal before and after amplification at different current values (from 350 to 450 mA). The channels were purposely chosen with the highest and the lowest optical power level at the SOA output – the 12th and the 13th channel, respectively. It is important to note that in order to avoid the impact of the amplifier gain on the BER values of the two channels, the optical signal was intentionally attenuated, so that a weak signal's gain would be completely compensated. We also obtained the dependence of the amplified signal gain on the pumping current and its increase with every additional 10 mA. The results are shown in Figure 2.

The BER value of the 12th channel at the amplifier input was 2.04•10-9, and of the 13th channel – 9.96•10-10, that is, lower, despite the fact that the optical power of the 12th channel is slightly higher. This can be explained by the closeness of the 12th channel to the center of the transmitted signal spectrum, which increases (also slightly) its inter-channel crosstalk. For the pump current starting from 380 mA, the BER values of the two channels under consideration experience a significant increase. This evidences that for the pump current values over 370 mA the amount of amplifier-produced signal distortions starts to grow. Therefore, we took the 370 mA pumping current as optimal for this system.

In Figure 2 it could be seen that with increase in the pumping current the amplifier gain increment is becoming smaller. This evidences that the amplifier slowly reaches the maximum level of population inversion; thus, due to the short spontaneous carrier lifetime, the generated ASE also experiences an increment with the increase in pumping current. For its value of 370 mA the SOA provides a small signal gain of 12.1 dB. The fact that SOAs provide a very broad gain bandwidth is confirmed by another fact – that the difference in the optical gain values for all 16 channels is only 0.02 dB. The rest of the amplifier gain will be provided by a noiseless distributed Raman amplifier.

For the hybrid EDFA-DRA we have chosen a bi-directionally pumped EDFA, with 980 nm co-propagating and 1480 nm counter-propagating pumps. In our earlier research such combination of pump wavelengths showed the best result from those for many single and multiple pump combinations. The pump powers were chosen with the purpose to make the gain spectrum irregularity of the

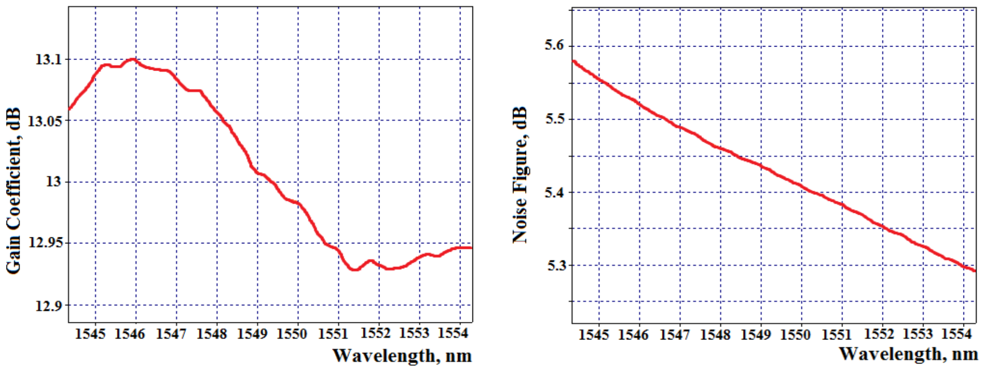

Figure 3. Gain spectrum (left) and noise figure (right) of the EDFA with 5 m long doped fiber and 10 dBm 980nm co-propagating and 16 dBm 1480 nm counter-propagating pumps.

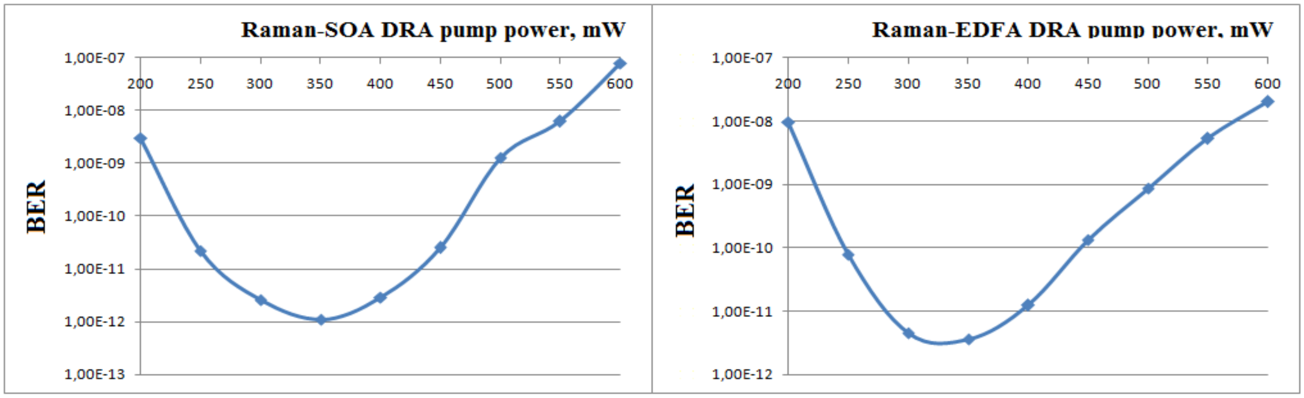

Figure 4. System's BER dependence on the power of a 1451.8 nm SOA-DRA (left) and EDFA- DRA (right) co-propagating pump.

EDFA easier to compensate with a single-pump Raman amplifier. In our case, the 16 channels occupy a ~ 6 nm bandwidth, in the limits of which a low-power single-pump DRA gain difference is < 0.5 dB. Taking this fact into account, we decided that a 5 m long doped fiber should be used for our EDFA, with the population inversion achieved using a combination of 10 dBm 980 nm co-propagating and 16 dBm 1480 nm counter-propagating pumps. The obtained gain spectrum and noise figure are shown in Figure 3, where the gain spectrum obtained for wavelengths from 1547 to 1553 nm varies from 12.93 dB to 13.1 dB. This but minor gain unevenness and the specific shape of the gain spectrum allowed us to conveniently equalize the obtained gain-wavelength dependence by applying a single-pump Raman amplifier. The noise figure obtained for the wavelengths under attention varies from 5.33 to 5.49 dB, which is rather a large increment for the EDFAs operating at high levels of population inversion. For the optimal amplifier configuration the noise figure close to 3 dB mark is achievable (Agrawal, 2002). So the EDFA configuration was not optimal, still the obtained noise figure is lower than the theoretical for a SOA.

After configuration of EDFA and SOA this procedure was carried out for the co-propagating Raman pump wavelengths and power in both cases. For the SOA-DRA hybrid the main requirement to the Raman pump was to ensure the minimum difference in the signal gain for all 16 channels. To achieve this, the center of the amplifier gain should coincide with the central wavelength of the transmitted signal. We found out that a 1451.8 nm pump is most suitable for this purpose. In the case of hybrid EDFA-DRA a pump is needed to ensure that the Raman amplification maximum coincides with the EDFA amplification minimum, which, in turn, corresponds to the wavelength of 1551.5 nm (or 193.23 THz frequency). It was found that to satisfy this criterion a 1453.1 nm pump is to be used.

To find the optimal pump power, we considered the BER values of all 16 channels and obtained the maximum one (further in the text the system's BER) and its dependence on the co-propagating pump power in both cases (Figure 4). From the results obtained it can be seen that in both cases for the pump power over 350 mW the amount of FWM-generated crosstalk exceeds the permissible value and seriously deteriorates the total

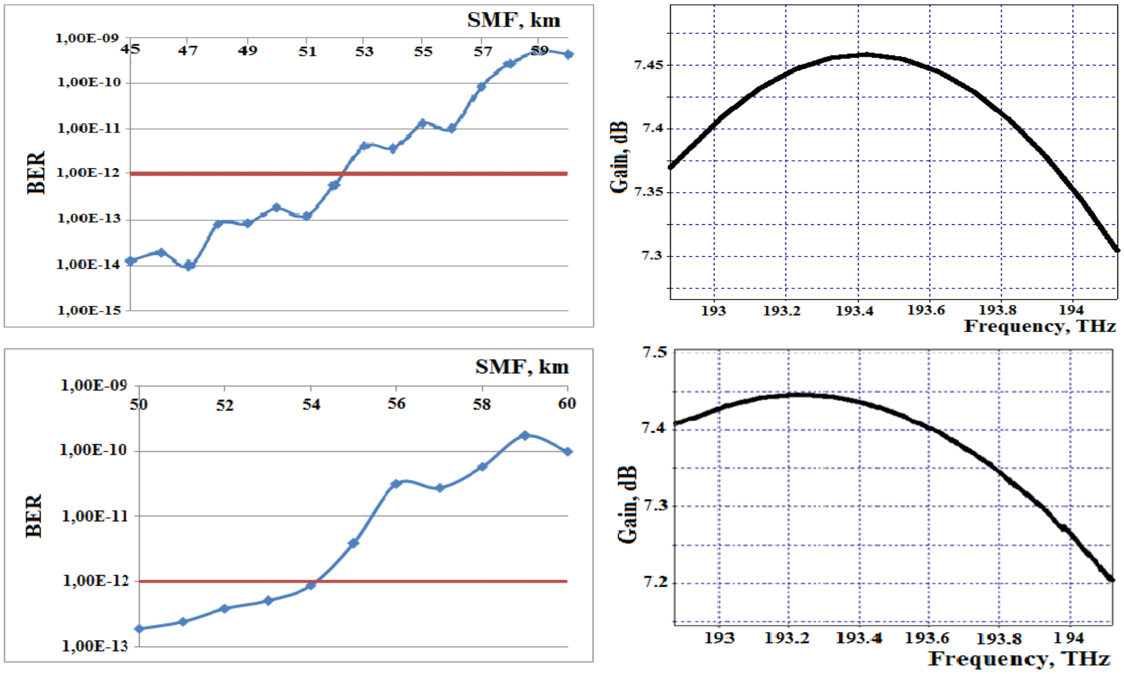

Figure 5. Dependences of the system's BER on the SMF length between the amplifier and the receiver block (left), and the DRA produced gain spectra (right) in the cases of SOA-DRA (above) and EDFA-DRA (below).

system performance. Therefore, 350 mW was found to be the most suitable value in the existing conditions. Since the SMF for DRA plays the role of amplifier medium, to obtain the total DRA gain we should first define the SMF length between the amplifier and the receiver block, thus also deriving the maximum transmission distance. For this, it is required to obtain the optimal DCF length, which, on the one hand, is determined by the total accumulated chromatic dispersion, while, on the other, is limited by the signal attenuation caused by DCF insertion. In both cases, the optimal DCF length was found to be 17 km. To find the maximum transmission distance we obtained the dependence of the system's BER on the sought-for SMF section length shown in Figure 5 along with the DRA gain spectra. The dependences shown in Figure 5 evidence that in the case of SOA-DRA the maximum SMF length between the amplifier and the receiver block providing the system's BER < 10-12 is 52 km, thus the overall transmission distance will be 124 km. For the EDFA-DRA based system this fiber length is 54 km, and the transmission distance – 126 km. It is important to add that we have obtained also the maximum transmission distance for the system in which no amplification was applied, and it was equal to 69 km. This means that the SOA-DRA combination was able to extend this distance by 55 km and the EDFA-DRA – by 57 km. The optical signal values at the receiver block input for the system with no amplification varied from -23.32 to -23.57 dBm, for the SOA-DRA based system from -21.78 to -21.44dBm, and for that with EDFA-DRA – from -21.31 to -21.05 dBm. To identify the factors that limit transmission in each of the three cases the eye diagrams of the channels with the worst BER were analyzed. These, together with the relevant inter-channel crosstalk, are shown in Figure 6.

As was expected, in the case with no amplification the main limitation factor is the optical signal attenuation. It also can be seen that even without amplification the optical signal intensity is high enough to initiate FWM, and the produced minor inter-channel crosstalk also affects the BER value. From the eye diagram of the 7th channel of the EDFA-DRA based system it can be seen that the FWM produced inter-channel crosstalk is the main limiting factor for transmission, since the FWM harmonics are clearly seen on the level of logical ”1”, and the critical BER value was reached with a higher level of the detected signal power than in the other two cases. For the SOA-DRA based system this inter-channel crosstalk is also quite high, though lower than in the case with EDFA-DRA, due to ~ 0.8 dB difference in the amplification in both cases. Still, the BER limit was reached at a shorter transmission distance, and not due to the mentioned difference, because the level of the detected signal was high enough to ensure the required quality of transmission. If we compare the optical signal power levels at the input of the receiver block, it can be seen that the average difference is ~ 0.4 dB, while the difference in the amplification is ~ 0.8 dB. Therefore it is clear that the SOA produces more ASE noise than the

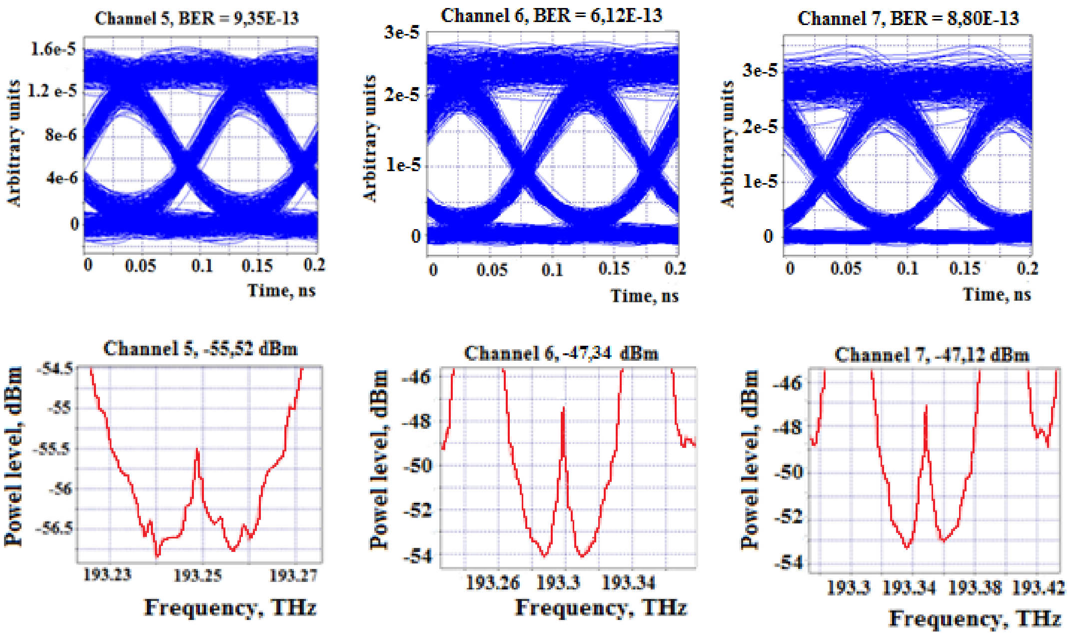

Figure 6. Eye diagrams for the channels with the worst BER (above) in the system with no amplification (left), with SOA-DRA (center), and with EDFA-DRA (right); the inter-channel crosstalk in the corresponding channels (below).

EDFA, which, in addition to the inter-channel crosstalk, increases the detected signal power penalty at the receiver.

Conclusions

Based on the results obtained in this work, the following conclusions can be drawn:

1. The fiber nonlinearity in the implemented 16-channel DWDM transmission system has been found to exert a strong influence on the quality of transmission, which allowed the performance of narrowband SOA-DRA and EDFA-DRA hybrid amplifiers to be compared.
2. Testing the amplifiers under severe conditions has given a clear view on the amplified signal distortions. The parameters of SOA were adjusted so that it would produce higher amplification with less signal distortions. It was observed that increasing the SOA pumping current (from 370 mA on) leads to a signal's BER growing after amplification, which points to greater signal distortions generated by SOA.
3. Implementation of hybrid amplification can provide more equal gain for all channels of the system under attention. In the case of the EDFA-DRA solution the parameters of the EDFA were adjusted to obtain the gain spectrum which could easily be equalized by a single-pump Raman amplifier. The introduced EDFA configuration ensured 0.17 dB gain difference among all 16 channels, but after supplementing the EDFA with a DRA we obtained the gain spectrum with only 0.05 dB maximal difference in amplification.
4. Even a non-optimally configured EDFA produces less signal distortions than the SOA. The input signal power was adjusted specially for the SOA, thus the EDFA was not optimally configured; still the EDFA-DRA hybrid amplifier showed better results and provided transmission over a longer optical link than the SOA-DRA (126 and 124 km, respectively). The SOA-DRA provided an average gain of 19.6 dB, and the EDFA-DRA – of 20.4 dB.
5. Since the EDFA generated less signal distortions, the EDFA-DRA solution ensured better quality of amplification than the SOA-DRA. In both cases, the main factor that limited transmission was the FWM-produced inter-channel crosstalk, with the DRA pumping power being the same. So the difference in the total transmission quality can be explained only by the performance of the SOA and the EDFA. In the case of SOA-DRA the total amplification was slightly lower, thus also lower inter-channel crosstalk could be expected. Still, the non-optimally configured EDFA-DRA showed better results. This can be explained by heavier signal distortions that those produced by SOA, even though it was configured in a manner to obtain more gain with less noise.

So it is clear that even though the gain spectrum of the EDFA can be quite uneven, the EDFA-DRA hybrid can ensure better quality of transmission than the SOA-DRA one, even in the conditions favorable for the latter. Of course, if the signal power level at the input of amplifier was lower, also its fiber nonlinearity produced distortions would have been smaller, with much greater gain and longer transmission distance provided by both hybrid amplifiers. Still the results obtained give quite clear view on their performance. The main conclusion therefore is: despite greater signal distortions produced by SOA-DRA, due to the spectral limitations of EDFAs it still is the preference solution for broad coarse WDM (CWDM) transmission systems.

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