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Comparison of Semiconductor Optical Amplifier and Discrete Raman Amplifier Performance in DWDM Systems

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Introduction

In the last decade the demand on high capacity transmission has increased rapidly. Thanks to this trend a growing amount of research has been done on Dense Wave Division Multiplexing (DWDM) transmission systems to achieve a higher transmission capacity over greater distances [1, 2]. To achieve longer transmission distances often in-line optical signal amplification is applied. Several types of optical amplifiers can be used in a DWDM transmission system, including Semiconductor Optical Amplifiers (SOA), Doped fiber optical amplifiers (DFA), discrete and distributed Raman amplifiers (RA and DRA).

The variety of optical amplifier types has led to necessity of choosing a particular optical amplifier type for a specified transmission system. One of the most popular solutions is the usage of Erbium Doped Fiber Amplifiers, but due to material characteristics small signal gain can be obtained only in a specific frequency band, which is relatively narrow, in the last couple of years SOAs and Raman amplifiers are increasingly applied [3].

Linear and non-linear effects, such as optical signal attenuation, dispersion, Four Wave Mixing (FWM), Cross Phase Modulation (XPM), Self-Phase Modulation (SPM) and so on, result in transmission quality degradation in DWDM systems. This has led to strict transmission quality requirements. Optical signal amplification may lead to severe amplified signal distortions, which may result in transmission quality degradation [2].

The main goal of this work is to compare a SOA and a discrete Raman amplifier injected signal distortions and ascertain whether of these two amplifier types is more likely to be used in a specific DWDM transmission system.

Simulation model

In order to obtain experimental results a strong mathematical tool is required. OptSim 5.2 has been chosen for this matter, hence this all-optical network simulator can handle complex simulations and introduce high accuracy results without acquiring high requirements to the hardware.

To investigate the performance of SOA and discrete Raman amplifier a simulation model of a 10 Gbit/s 16 channel DWDM transmission system with none-return-to-zero encoding technique, intensity on-off keying modulation format, and 50 GHz channel spacing has been introduced. The simulation scheme is shown in Fig. 1.

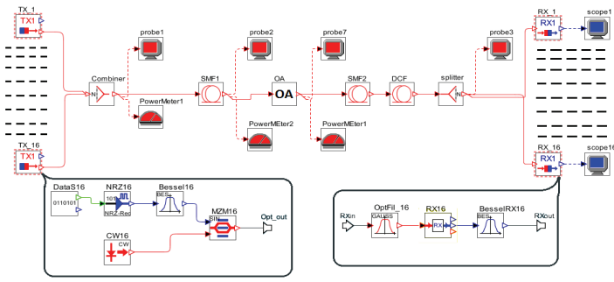

Fig. 1. Simulation model of the 16 channel DWDM transmission system

The transmitter block consists of 16 channel transmitters, each of them operating at its own frequency in range from 193.05 THz to 193.8 THz. Each transmitter includes a Data Source, NRZ coder, Electrical filter, Mach-Zender Modulator (MZM) and a 1 dBm Continuous Wave Laser. 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 72 kilometers of Single Mode Fiber (SMF) with 0,2 dB/km attenuation and 16 ps/nm/km chromatic dispersion. This SMF fiber length is determined by the required optical signal power at the input of the optical amplifier, which is very important due to amplifier saturation effect, especially when using a SOA. For a discrete Raman amplifier this parameter is not so relevant. This is why small signal power at the amplifier input has been optimized for the SOA. The small signal power at each channel at the amplifier input is around -22,4 dBm, and total signal power is -8,362 dBm (0,146 mW).

After processing through an amplifier, the amplified signal is transmitted through an SMF fiber of various length, which will be varied in order to obtain the maximum transmission distance, and then it enters a Dispersion Compensation Fiber (DCF). After propagating through the DCF fiber, the optical signal is divided among 16 receivers, where the optical signal is detected and converted into electrical current. Dispersion post compensation has been chosen in order to reduce the impact of FWM on the transmitted signal. DCF fiber attenuation at 1550 nm is 0,55 dB/km, and dispersion at the same wavelength is -80 ps/nm/km.

The amplifier parameters were previously optimized in order to reach the maximum possible extension in transmission distance using a single in-line amplifier. For SOA the only parameter that was optimized is the bias current, and is equal to 413 mA. The active layer and material parameters were obtained from [3], where a SOA has been optimized for a similar system.

The discrete Raman amplifier is implemented on a 1,3 kilometer long High Non-Linearity Fiber (HNLF) basis which was designed for Raman amplification, the physical parameters of which were specified in [4]. A bidirectional pump, which consists of 550 mW 1446 nm co-propagating and 700 mW 1459 nm counter-propagating pumps, is used to amplify the signal. HNLF fiber attenuation at 1450 nm is 0,5 dB/km and at 1450 nm - 0,61 dB/km. The core effective area of HNLF fiber is 10 μm^2, which is 8 times smaller than in a SMF fiber, the non-linear coefficient also is higher. This may result in significant non-linear effects influence on the transmitted signal, and may cause severe signal distortion if the pump power is too high.

The most convenient way of assessing transmission quality is analyzing the Eye-diagrams and obtaining the bit-error-rate (BER) values of the received signal at each of the 16 channels. In order to assess SOA and RA optical amplifier performance and to estimate transmitted signal distortions, which occur during the amplification process, Eye-diagrams of a specific transmitted signal channel at the input and output of the optical amplifier are analyzed. For this matter the signal at the output of the amplifier will be attenuated in order to compensate the amplifier gain. For assessing the inter channel crosstalk, a transmitter of a specific channel will be eliminated, and optical spectrum will be observed at the end of the link.

Results and discussions

The aim of this section is to compare the results received simulating a transmission system with no signal amplification, with an in-line SOA, and with an in-line distributed Raman amplifier, which were described in the previous section. To obtain the maximum gain in transmission distance, which can be achieved using a SOA or a RA, at first it is necessary to find the maximum transmission distance for a system without optical amplification. To do so, the maximum length of the SMF fiber was found, for which BER values are still below the 10^{-12} mark. The simulation results are shown in table 1. The length of the DCF fiber was also varied to find the balance between compensated dispersion and DCF inserted loss.

Table 1. Simulation results

Amplifier type	None	SOA	RA
Trans. distance	69 km	112 km	119 km
DCF length	5 km	15 km	17 km
Amplifier Gain	None	17,4 dB	19,87-19,98 dB
Maximal BER	$9{,}35\cdot10^{-13}$	$7{,}85\cdot10^{-13}$	$9{,}73\cdot10^{-13}$
Signal power at the link output	-23,57 dBm	-21,07 dBm	-21,61 dBm

At first, it is helpful to note that the obtained Gain in not the maximum achievable for SOA and RA optical amplifiers, the amplifier gain coefficients that are shown in table 1 are optimal for the transmission system under test.

If a more powerful pump source is used in both cases a far greater small signal gain could be achieved. Unfortunately, in our transmission system, due to relatively high total input power at the input of the optical link (20,144 mW), and relatively small channel spacing, fiber non-linearity, especially FWM, is the dominating factor that causes transmission quality degradation in cases with optical amplification. Because channel spacing is even, some of the FWM generated spectral components frequencies match with transmitted signal channel frequencies, and this may result in huge amount of inter channel crosstalk [5]. As it is shown in table 1, the maximal achievable transmission distance for a system without optical amplification is 69 kilometers, for a system with an in-line SOA – 112 kilometers, and for a system with a discrete Raman amplifier – 119 km. The main reason for such 7 km transmission difference between systems with optical amplification is the difference in amplifier gain, but higher pump power in case of a SOA resulted in rapid growth BER values at the receiver end.

In order to understand such quality degradation it is necessary to take a look at Eye-diagrams at the input and output of the optical amplifiers that relate to channels where the highest BER value was found.

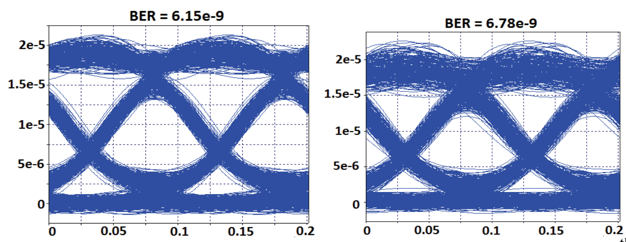

Fig. 2. Eye-diagrams with equalized signal intensities of the 9th channel before (to the left) and after amplification (to the right) using SOA

Fig. 2 shows Eye-diagrams that relate to the 9th channel in a system with an in-line SOA at the input and at the output of the optical amplifier. This channel has been chosen, because in it the highest BER value was observed. It's obvious, that the total noise level of the transmitted optical signal has risen significantly as shown by the widening of the line at the logical "1" level. The amplifier non-linear response is represented by the expressivity of

FWM generated products. This shows that the FWM produced spectral component intensity level at this channels frequency has increased more than the total signal and noise level. It is also observed, that transition lines between logical “0” and logical “1” became wider. This shows that the SOA phase response is not linear enough to provide signal amplification without causing distortion that produce pulse broadening in the time domain.

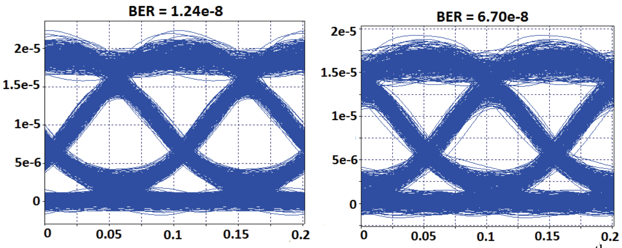

Fig. 3. Eye-diagrams with equalized signal intensities of the 6th channel before (to the left) and after amplification (to the right) using RA

Fig. 3 shows Eye-diagrams that relate to the 6th channel in a system with an in-line distributed Raman amplifier. As in the case with SOA, this channel is chosen in order to observe the worst scenario among all transmitted 16 channel signals. It is necessary to note that HNLF caused 0.793 dB attenuation, which hasn’t been taken into account during intensity equalization of signal before and after amplification, because it also represents the impact of the amplifier on the transmitted signal.

If we compare Fig. 2 and Fig. 3 it can be seen, that in the case of SOA the amplifier produced noise is much higher than in the case of discrete Raman amplification. The ASE produced noise can be seen, but the amount of it is not as large, so it is not the factor that has limited the effective pump power value and hence also the transmission distance in the case with an in-line RA. To find the cause of this transmission distance limitation it is necessary to observe the inter channel crosstalk.

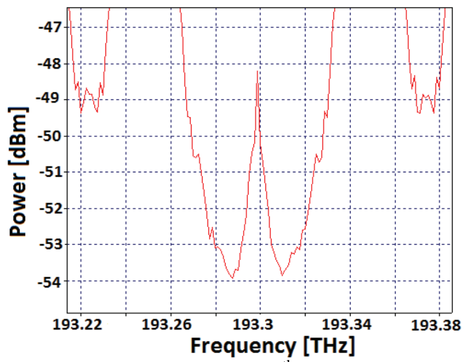

Fig. 4. Inter channel crosstalk in the 6th channel at the end of the link in a system with a RA

Fig. 4 represents the inter channel crosstalk, observed in the 6th channel of a transmission system with an in-line discrete Raman amplifier. It can be seen that the peak of this spectral component is at 193.3 THz, which corresponds directly to the 6th channel. This leads to a conclusion, that the observed inter channel crosstalk mostly is produced by FWM. If the power of the discrete amplifier pumps would be greater, it would result in higher small signal gain, which would cause greater FWM influence on the transmitted signal, thus resulting in higher inter channel crosstalk power and transmission quality degradation. This spectral component power peak has reached -48,3 dB power at its peak.

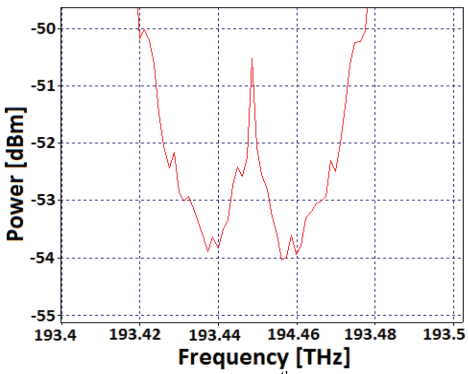

Fig. 5. Inter channel crosstalk in the 9th channel at the end of the link in a system with a SOA

Fig. 5 shows the accumulated inter channel crosstalk, that occurs in the 9th channel at the output of the link of the transmission system with optical amplification using SOA. Here the peak power of the observed crosstalk is found to be -50,55 dBm. If we compare the amount of the accumulated crosstalk in the worst channels of both systems, we will see that in the system with a RA the amount of inter channel crosstalk is by 2,25 greater than in the system, where SOA is used. The main reason for this is that the smaller amount of generated noise allowed to use greater pump power, thus rezulting in a higher small signal gain. This has raised the overal intensity level and rezulted in greated FWM influence on the transmitted signal.

As shown in table 1, the minimal signal peak power level at the output of the optical link, for which the BER level was below 10^{-12} mark is -23,57 dBm, and it is observed in the transmission system without optical amplification. In the case where a SOA has been used to amplify the propagaiting signal this value reaches -21,07dBm, and in the case where RA has been used this value is -21,61 dBm. To get a clear view of the situation Eye-diagrams of the channels, where the highest BER values were observed, are demonstrated below.

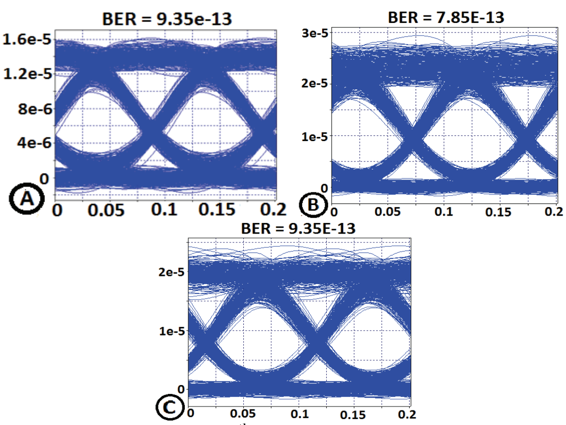

Fig. 6. Eye-diagram of the 5th channel of a system without signal amplification(A), Eye-diagram of the 9th channel of a system with SOA(B), and Eye-diagram of the 6th channel of a system with RA(C)

Fig. 6 represents the Eye-diagrams of channels in which the highest BER value was found for all three observed transmission systems. As can be seen, it has be confirmed that a SOA produces a lot more ASE noise than a RA, and mainly this has caused the rise of the signal power level needed at the detection process to enshure a BER value below the 10^{-12} mark.

Ii is also clear from Fig. 6C, that in case where a discrete Raman amplifier is used the generated noise value is much smaller, and the main limitation factor in this perticular transmission system is the FWM produced inter channel crosstalk.

Conclusions

The main aim of this article was to obtain the maximal transmission distances for a system with a single in-line semiconductor optical amplifier and a system with a single in-line distributed Raman amplifier, and to identify the degradation factors that influenced transmission distance the most.

The results show that the semiconductor amplifier was able to enlarge the maximal transmission distance from 69 to 112 kilometers. The main factor that has limited transmission was amplifier produced noise, the amount of which was far greater than in the case of the discrete Raman amplifier, which in turn has managed to extend transmission distance to 119 kilometers.

The main factor that held down transmission in the system with a discrete Raman amplifier was inter channel crosstalk, which was a product of the Four Wave Mixing non-linear effect. The amount of such accumulated crosstalk at the end of the optical link for a discrete Raman amplifier was by 2,25 dB greater than in the case with a semiconductor optical amplifier. It is also necessary to note that this difference in accumulated inter channel crosstalk in our case is mostly explained by the signal intensity difference at the amplifier output. On the other hand the non-linear response of the semiconductor optical amplifier and the small effective area together with the high non-linear coefficient of the discrete Raman amplifier also made serious impact on the quality of transmission and limited the total achievable length of the link.

Acknowledgements

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In the last decade due to the growing demand on high capacity transmission, DWDM transmission systems have evolved rapidly. The growth of transmission speed and the decrease in channel spacing has resulted in stricter requirements to the elements used in optical signal transmission process, including optical amplifiers. In this article we take one of the most popular DWDM solutions – a 10 Gbit/s 16 channel NRZ-OOK 50 GHz DWDM transmission system, and implement a SOA and a RA as a single in-line amplifier, in order to estimate and compare their performance, and to identify and estimate the main factors that limit the total transmission quality in both cases. Ill. 6, bibl. 6, tabl. 1 (in English; abstracts in English and Lithuanian).

S. Olonkins, V. Bobrovs, G. Ivanovs. Puslaidininkinio optinio stiprintuvo ir diskretinio Raman stiprintuvo, naudojamų DWDM sistemose, tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 7(123). – P. 133–136.

Pastarąjį dešimtmetį augant didelės talpos perdavimo poreikiui, DWDM perdavimo sistemos sparčiai tobulėjo. Dėl perdavimo greičio didėjimo ir kanalo vietos mažėjimo griežtėjo reikalavimai optinio signalo perdavimo procese dalyvaujantiems elementams, įskaitant ir optinius stiprintuvus. Pasirinktas populiariausias DWDM sprendimas – 10 Gbit/s 16-os kanalų NRZ-OOK 50 GHz DWDM perdavimo sistema ir puslaidininkinis optinis stiprintuvas bei Ramano stiprintuvas, implementuoti kaip vienas stiprintuvas, siekiant įvertinti ir palyginti jų našumą, ir identifikuoti bei įvertinti pagrindinius veiksnius, kurie riboja bendrą perdavimo kokybę abiem atvejais. Il. 6, bibl. 6, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).