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EXPERIMENTAL SIMULATION OF COHERENT 40 GBPS 2-DPSK DWDM LONG-HAUL FIBER OPTICAL SYSTEM WITH COUNTER-DIRECTIONAL EDFA

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Abstract: **High speed and high capacity optical communication systems have become essential for todays high demand. High demand for broadband services and internet applications have been driving the development of optical networks rapidly. Transmission distance of fiber optical communication system can be further increased by incorporating fully optical amplification in the transmission route. The leading technology in optical amplification is based on erbium doped fiber amplifier (EDFA). In this paper we propose the 16 channel Dense Wavelength Division Multiplexed (DWDM) fiber optical communication system with transfer rate of 40 Gbps with counter-directional EDFA in program environment OptSim.**

Keywords: *Bit Error Rate, Dense Wavelenght Division Multiplexing, Erbium Doped Fiber Amplifier, Wavelength Division Multiplexing.*

I. INTRODUCTION

Introduction of amplification in optical domain was the major milestone in the evolution of multichannel optical transmission systems. Before fully optical amplifiers there were opto-electronic converters which converted optical signal to electrical form, then the signal was amplified and converted back to optical form. This process was very complex and required electrically powered opto-electronic converters. Fully optical amplifiers, such as erbium doped fiber amplifier (EDFA) spurred the development of a completely new generation of optical systems. The main advantage of EDFA is that it amplifies signals of multiple wavelengths simultaneously. That is definitely the reason of rapid development of WDM (Wavelength Division Multiplexing) systems. EDFA dramatically reduces the cost of long-haul fiber optical systems [1-3].

This paper presents the simulation model of coherent 16 channel 2-DPSK DWDM (Dense Wavelength Division Multiplexing) system with transmission rate of 40 Gbps and EDFA in counter-directional configuration. Performance of proposed DWDM system is evaluated using probability of error information. In the second chapter we present EDFA itself, third chapter is dedicated to the description of proposed simulation model and experimental results are presented in chapter four [3-6].

II. OVERVIEW OF EDFA TECHNOLOGY

Erbium doped fiber amplifier is a fundamental structure constructed of erbium doped fiber, wavelength coupler, pump light source and optical isolator [6].

Erbium doped optical fiber is a special kind of silica fiber, the core of which is doped with Er^{3+} erbium ions. Electrons of erbium doped optical fiber can be excited to higher energy levels by light with shorter wavelength. EDFA is very efficient in the C (1530 nm - 1560 nm) and L (1570 nm - 1610 nm) bands. The ideal EDFA gain characteristic is achievable in the 1530 nm - 1560 nm region. The gain eventually reaches 0 dB at a wavelength of 1616 nm [6-8].

The typical gain of the erbium doped optical fiber amplifier to a distance of approximately 10 meters is 20-30 dB. The maximum achievable power at the output of the amplifier is limited by the output of the light source [8].

Configuration of EDFA is following: the length of erbium doped fiber may be up to 40 m, as a pump light source (980 nm or 1480 nm) can be used continuous wave laser, wavelength coupler allows to combine the information signal and the optical source signal of the pump so that it is possible simultaneous transmission via EDF, the optical isolator is used to prevents feedback and also protects laser from damage caused by backscatter wave. The EDFA output is equipped with narrowband filter that prevents spontaneous emission of the amplifier. An important factor that significantly affects the effectiveness of EDFA is the selection of the light source. In practice, we use light sources with wavelengths of 980 nm and 1480 nm in co-directional, counter-directional and bi-directional mode. In the co-directional pumping mode, the pump wavelength propagates in the same direction as the transmitted signal. On the other hand, in the counter-directional pumping mode the pump signal propagates in opposite direction to the transmitted signal. Bi-directional pumping mode is the combination of the previous two modes so the input signal propagates in forward direction and two pumps are used in opposite direction to each other [6, 9, 10]. In practice, it is very common to use both types of pump wavelengths in bi-

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directional EDFA scheme. 980 nm pump in the first stage provides low noise and sufficient gain and 1480 nm pump in the second stage provides high output power. The structure of counter-directional EDFA that is used later in simulation of 16 channel DWDM is illustrated on Figure 1.

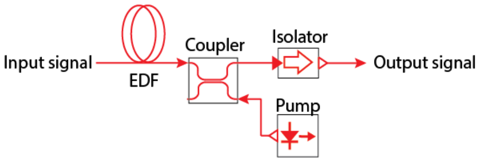


Figure 1. Counter-directional EDFA

The advantage of EDFA is a gain of 20 to 50 dB, work in the C and L band and independence from temperature and polarization. EDFA amplifiers enable amplification of signal level up to 50 dB in the C and L band. Other doped amplifiers containing other donor ions reach similar gain values but in the other working spectrum, mostly towards the O or E band [2, 11].

The disadvantage is the lack of selectivity of what needs to be amplified, the noise and the impossibility to use EDFA as a preamplifier for very weak signals just before the detection circuits [1,2].

III. SIMULATION MODEL OF 40 GBPS DWDM

In order to simulate 16 channel DWDM system we used OptSim simulation software form the company RSoft. OptSim is the professional simulation software aimed for network and photonic designers. We can simulate fiber optical systems in optical time domain and optical frequency domain. It supports transmission with wavelength division multiplexing, optical amplification and advanced simulation of fiber linear and nonlinear effects including SRS (Stimulated Raman Scattering), SBS (Stimulated Brillouin Scattering), SPM (Self Phase Modulation), CPM (Cross Phase Modulation) and FWM (Four Wave Mixing). Each component or subsystem within OptSim is represented as one block and simulation runs independently of blocks. The downside of OptSim is the lack of optical time domain reflectometry [12-14].

The simulation model of 16x40 Gbps 2-DPSK DWDM system with counter-directional EDFA is illustrated on Figure 2. The simulation model consists of transmitting part, optical distribution part and receiving part. Transmitting part is formed of 16 2-DPSK wavelength channels. Logical data are generated by pseudorandom binary source (PRBS) with transmission rate of 40 Gbps. These logical data are formed to an electrical signal by electrical NRZ (Non-Return to Zero) modulator. Electrical signal is then bound to optical phase modulator (OPM) based on $LiNbO_3$. Optical carrier is generated by continuous wave laser with launch power of -10 dBm. The emission frequencies of 16 channels are in the range of 192.80 – 194.30 THz with 100 GHz channel spacing between adjacent channels (according to ITU-T 694.1).

Optical distribution part consists of total 100 km of optical fiber. This simulation model uses two sections of single mode optical fiber (SMF). Nonlinear refraction index of SMFs is 2.2e-020 m^2/W and attenuation is 0.22 dB/km. After every 25 km there is line counter-directional EDFA. The total length of optical fiber path is 100 km. In order to investigate influence of EDFA on proposed DWDM system we tested quality of transmission for four different lengths of EDF – 10, 20, 30 and 40 meters and two pump wavelengths – 980 nm and 1480 nm. Pump power was set to 5 dBm (3.166 mW). Input insertion loss was set to 1.2 dB and output insertion loss to 0.8 dB. New spectral components caused by nonlinear effects, most notably FWM, are partially limited by bandpass optical filter placed between the two sections of SMF. Attenuation component marked as “Connection” is simulating the insertion loss normally caused by connecting two optical components.

40 Gbps 2-DPSK receiver is formed of bandpass optical filter to filter the channel of certain frequency, 2-DPSK optical receiver which converts the phase difference into intensity signal that can be detected by simple photoconductor, electrical low pass filter and optical probe. Optical probe is used to analyze received electrical signal and calculate probably of error of transmission.

The performance of proposed simulation setup is analyzed only for channel 1 (194.30 THz), channel 7 (193.70 THz), channel 12 (193.20 THz) and channel 16 (192.80 THz) at four values of length of EDF – 10, 20, 30 and 40 meters and two values of pump wavelength – 980 nm and 1480 nm.

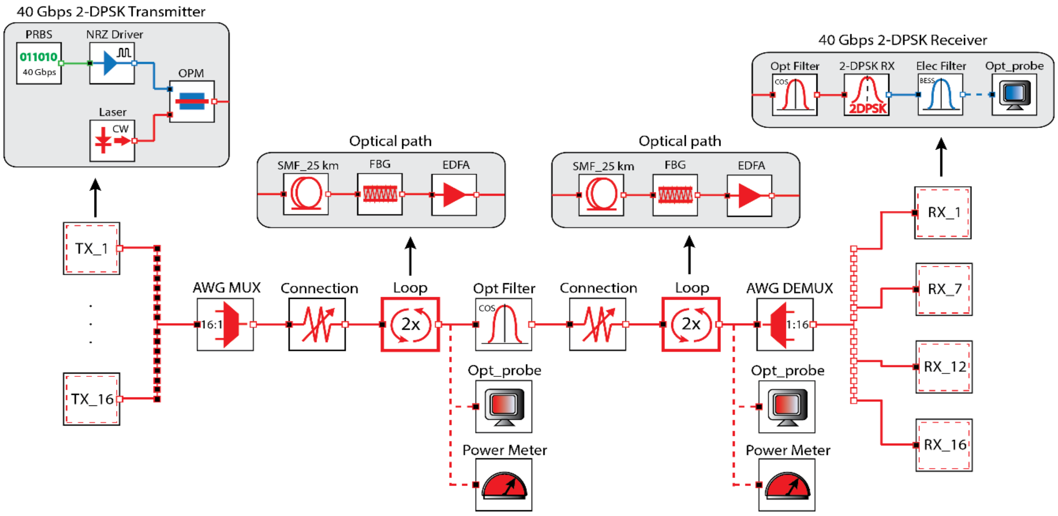
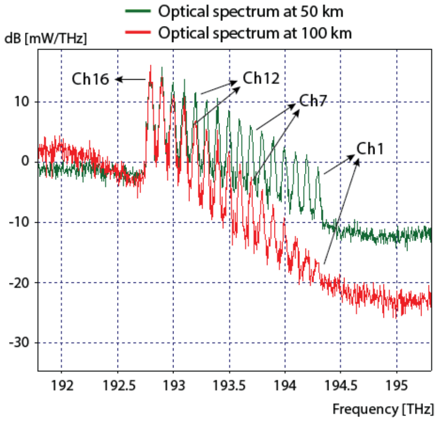


Figure 2. Simulation model of 16x40 Gbps 2-DPSK DWDM system

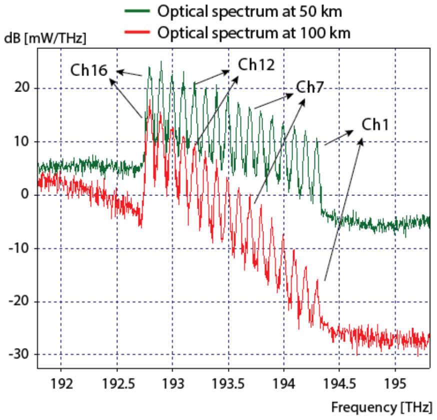
IV. RESULTS AND DISCUSSION

Optical spectra of 16 wavelength channels with counter-directional EDFA after 50 km is on Figure 3 and after 100 km is on Figure 4. From the experimental results we can see that optical power of individual wavelength channels gradually decreases as the length of erbium doped fiber increase. This interesting phenomenon is caused by the length of erbium doped fiber inside EDFA. The exact levels of power after 50 km and 100 km of optical distribution path are recorded in Table 1. Based on this table, assumption is, that probability of error of analyzed channels will increase with increasing length of EDF.



980 nm pump, 30 m of EDF

Figure 3. Optical spectra after 50 km



1480 nm pump, 30m of EDF

Figure 4. Optical spectra after 100 km

Table 1. Power levels after 50 km and 100 km of optical distribution path

Pump	980 nm	1480 nm	980 nm	1480 nm
EDF length [m]	Power level at 50 km [dBm]		Power level at 100 km [dBm]	
10	13.386	11.748	6.872	7.182
20	14.958	17.341	7.137	8.560
30	7.935	17.269	7.484	8.921
40	6.743	11.305	6.835	12.645

From the Table 1 we can see that the use of 1480 nm pump wavelength results in higher gain values compared to a 980 nm pump wavelength. However, 1480 nm pump shows lower efficiency and higher noise.

To calculate probability of error in transmission process we used eye diagrams of received channels. Eye diagram is a very useful indicator of transmission quality. From this display we can extract few parameters that tell us the performance of tested channel or whole system. The most important parameter is bit error rate (BER). The other parameter is Q-factor [2]. Q-factor is a function of OSNR and it represent the system tolerance in dB. BER and Q-factor are in very close relation:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{\sqrt{2\pi}Q} exp\left(-\frac{Q^2}{2}\right), \tag{1}$$

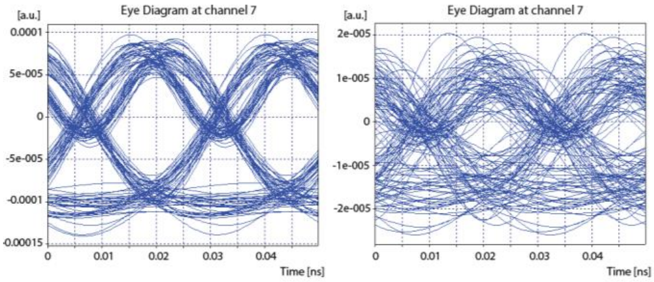
The general equation for calculating Q-factor is [4]:

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_o}, \tag{2}$$

where I_1 and σ_1 are mean values and variance output by Gaussian pulse “1” and I_0 and σ_0 are mean values and variance output by Gaussian pulse “0” [2].

Quality of transmission can be evaluated visually form eye diagram. In general, more open eye means lower BER and higher Q-factor. Eye diagram can reveal a lot of information about analyzed signal – amount of distortion in the channel, sampling rate, jitter or sensitivity to time error. Modern communication systems require BER value of $1x10^{-12}$ and Q-factor of 16.94 dB [2, 13].

Eye diagrams of received channel 7 (193.70 THz) and channel 12 (193.20 THz) can be seen on Figure 5 and Figure 6. Notice that for shorter length of EDF the eye is more open and lines are less distorted. Channel 7 shows low BER for 10 and 20 meters of EDF for both 980 nm and 1480 nm pumps. Channel 7 shows BER of $1.800x10^{-16}$ for 20 meters of EDF and $2.416x10^{-3}$ for 30 meters of EDF. Eye diagram of channel 12 is more open for 30 meters of EDF compared to 40 meters of EDF. BER is sufficient only for 30 meters of EDF - $3.015x10^{-12}$. Channel 12 does not reach sufficient BER for 40 meters of EDF and 1480 nm pump wavelength - $1.199x10^{-6}$.



980nm pump, 20 meters of EDF

980nm pump, 30 meters of EDF

Figure 5. Eye diagrams of channel 7

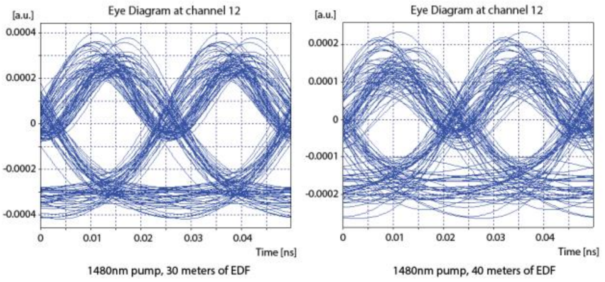


Figure 6. Eye diagrams of channel 12

All values of BER for all four analyzed channels (no. 1, no. 7, no. 12 and no. 16) are recorded in Table 2. As we can see, BER is proportional to the EDF length. The performance of 16x40 Gbps 2-DPSK DWDM system with counter-directional EDFA is dependent on pump wavelength. When using 980 nm pump wavelength, the output power is lower compared to 1480 nm pump wavelength. Considering obtained values of BER the performance of 16x40 Gbps 2-DPSK DWDM system with 1480 nm pump is exceptionally higher which makes system more robust and reliable.

Table 2. BER values of 16x40 Gbps 2-DPSK DWDM with counter-directional EDFA

EDF length [m]	10	20	30	40
Channel	980 nm pump wavelenght			
	Bit Error Rate			
1	3.874×10^{-13}	2.830×10^{-6}	2.275×10^{-2}	2.275×10^{-2}
7	2.122×10^{-24}	1.800×10^{-16}	2.416×10^{-3}	1.689×10^{-3}
12	1.132×10^{-26}	6.051×10^{-20}	2.195×10^{-7}	2.738×10^{-3}
16	6.848×10^{-33}	1.350×10^{-21}	8.564×10^{-13}	5.611×10^{-9}
Channel	1480 nm pump wavelenght			
	Bit Error Rate			
1	7.014×10^{-15}	4.017×10^{-10}	2.180×10^{-2}	2.275×10^{-2}
7	2.673×10^{-27}	1.865×10^{-22}	5.175×10^{-9}	8.755×10^{-3}
12	1.081×10^{-31}	1.575×10^{-19}	3.015×10^{-12}	1.199×10^{-6}
16	9.148×10^{-30}	1.300×10^{-13}	6.327×10^{-8}	1.002×10^{-10}

IV. CONCLUSSION

This paper is focused on modeling 16x40 Gbps 2-DPSK DWDM system with counter-directional EDFA. Proposed simulation DWDM system can be used in the long-haul applications such as undersee optical networks. Simulation results validate that the length of erbium doped fiber affects the transmission performance. As expected, transmission of optical signal is less distorted when using 1480 nm wavelength pump. This pump wavelength also offers higher output level compared to 980 nm wavelength pump. Requisite power levels and noise figure can be seriously affected by choosing the right length of EDF and pump wavelength. Important in multichannel fiber optical systems are nonlinear effects – the main degradational mechanism in fully optical networks. These effects are power sensitive, which means that refractive index of optical fiber may change when transmitting higher power signals.

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