Research Article

Comparison of the Optical Amplifiers EDFA and SOA Based on the BER and Q-Factor in C-Band

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Currently it is not possible to create a fully optical communication system without a software tool which simulates an optical communication line in real conditions prior to its construction. The aim of this article is to establish a comparison between the EDFA (erbium doped fibre amplifier) and SOA (semiconductor optical amplifier) optical amplifiers in the WDM (wavelength division multiplexing) system. The system contains a four-channel WDM with speed of 10 Gbps and optical fibre with length of 80 km. Simulations are conducted in the programme environment “*OptSim*.” The quality of the optical communication system is evaluated by the BER (bit error rate) and Q-factor for individual wavelengths, namely, of 1558 nm and 1562 nm, which are within the C-band.

1. Introduction

With the increasing need for higher transfer speeds and greater quantity of transferred data, the optical cable lines are reaching their limits of transfer capacities. One of the options for more effective usage of optical lines is wavelength multiplexing. Using a transfer speed of 10 Gbps (STM-64) with the help of WDM, 128 spectral channels achieving a transfer speed of 1 Tbps could be created in one optical fibre [1, 2]. Because transferring of the optical signal over great distances leads to its attenuation, the transmission path contains optical amplifiers. In optical communication the EDFA fibre amplifiers, SOA semiconductor amplifiers, or amplifiers based on the Raman effect are the most widely used ones [2–4]. In the second chapter the WDM standard and its division are described. The third chapter is devoted to the error rate BER and related Q-factor. The fourth chapter describes EDFA and SOA optical amplifiers and their basic principles. In the last chapter a simulation is created for the comparison of BER and Q-factor while evaluating the properties of the optical amplifiers.

2. Wavelength Multiplex

WDM is based on the idea of combining several optical signals into one optical fibre with usage of different wavelengths for transmitting each of these signals. The transmitter modulates the information for each of the used frequencies. All the contributions from n -channels are combined into one optical fibre in the multiplex. A simplified principle is shown on Figure 1.

Techniques of WDM could be divided into three groups: WWDM (wide wavelength division multiplex), DWDM (dense wavelength division multiplex), and CWDM (coarse wavelength division multiplex).

WWDM belongs to the older types and it is frequently used mainly because of its cost-effectiveness. Four mostly utilized wavelengths have a spacing of information-bearing greater than or equal to 20 nm.

DWDM is the most widely used system for backbone lines [5]. The spacing between information-bearing wavelengths is only 0.8 nm and with increased frequency, a spacing of 0.4 nm can be encountered. Nowadays systems known as

FIGURE 1: Simplified principle of WDM.

UDWDM (ultradense wavelength division multiplex) also exist. These systems utilize spacing of only 0.2 nm or even 0.1 nm. However decreasing values of spacing place bigger demands on the components being used in transmission path, mostly on the DFB (Distributed Feedback) lasers. Thanks to DWDM systems it is possible to transfer tens or hundreds of parallel optical lines. Recommendation ITU-T G.694.1 specifies individual transfer channels within the wavelength range from 1490 nm (200.95 THz) to 1620 nm (186 THz), which are included in S, C, or L band [5–7]. DWDM is defined by its normalised frequency of 193.1 THz. For correct functioning it is necessary for the wavelength not to diverge from the normalised wavelength by more than ± 0.16 nm.

CWDM emerged as a cheaper variation of DWDM. The requirements placed on components used for CWDM are not as strict and technologically demanding as for DWDM components. Spacing between individual channels is according to the recommendation ITU-T G.694.2 stated as 20 nm so it is possible to use laser diodes without cooling requirements [8, 9]. The overall tolerated variance from the nominal wavelength is within ± 6 –7 nm. CWDM enables a transfer of 18 channels while using type G.652.D fibre.

3. BER and Q-Factor

Q-factor defines the analogue quality of the digital signal with regard to SNR (Signal to Noise Ratio). It contains all physical deterioration factors degrading the signal and causing BER [3, 10]. The higher the value of Q-factor is, the lower the value of BER is (Figure 2). Q-factor is defined by the following:

$$Q = \frac{I_1 - I_0}{\sigma_1 - \sigma_0}, \quad (1)$$

FIGURE 2: Ideal and simulated BER values and Q-factor.

where I_1 represents the logical level “1,” I_0 represents logical level “0,” σ_1 represents standard variance of logical level “1,” and σ_0 represents standard variance of logical level “0.”

BER is defined by the ratio of defectively received bits bE to the overall amount of received bits p in time t :

$$\text{BER} = \frac{bE}{p \cdot t}. \quad (2)$$

Error rate is among basic indicators of quality of the optical transfer. In real optical communication systems the nonzero likelihood of error decision or sample value is

FIGURE 3: (a) Energy levels of erbium and (b) absorption and emission spectrum of transition ${}^4I_{15/2} \leftrightarrow {}^4I_{13/2}$.

represented by the value of logical “0” or logical “1” [3, 11, 12]. In real optical communication the BER should be around 10^{-12} . The BER calculation taking into consideration the Q-factor is defined as

$$\text{BER} = \frac{1}{2} \operatorname{erfc} \left(\frac{Q}{\sqrt{2}} \right) \approx \frac{\exp(-Q^2/2)}{Q \cdot \sqrt{2\pi}}. \quad (3)$$

A script was created in “Matlab” for the BER calculation as a Q-factor function for the 16-channel DWDM system according to ITU-T G.694.1 (Figure 2).

4. Optical Amplifiers EDFA and SOA

Optical amplifiers are frequently used components for wavelength division multiplex systems. In contrast with repeaters, they enable restoration of the light flow in the fibre without the necessity of conversion into electrical form. They are universal components amplifying analogue and numeric signals at any arbitrary transfer speed [13]. Currently there are optical SOA semiconductor amplifiers, EDFA fibre amplifiers, and amplifiers in the bases of the Raman effect.

4.1. EDFA. EDFA consists of a fibre doped by erbium ions of the energy level Er^{3+} . Energy levels important for the amplification of the optical signal in 1.5 μm band are shown in Figure 3(a). In Figure 3(a) metastable level is ${}^4I_{13/2}$, which can be utilized either directly on 1480 nm or through the level of ${}^4I_{11/2}$ on 980 nm. The lifespan of an ion on level ${}^4I_{11/2}$ is very short (approximately 7 μs) in comparison with the lifespan on level ${}^4I_{13/2}$ (approximately 10 ms), so the ion excited to the level ${}^4I_{11/2}$ goes quickly through to the metastable level ${}^4I_{13/2}$. Individual levels are marked according to the Russell-Saunders convention based on the quantum atomic theory. Expansion of levels shown in Figure 3(b) illustrated the shape of the absorption and emission transition spectrum ${}^4I_{15/2} \leftrightarrow {}^4I_{13/2}$ in erbium doped optical fibre [13].

The inseparable part is a pair of optical isolators where the isolator prevents the radiation created by spontaneous emission which corrupts the amplification at input. The second isolator at the output prevents the transmission of laser rays and consequently any possible damage to the amplifier itself as the rays are reflected back into the amplifier (Figure 4). A combination of several key factors made the EDFA amplifier choice number one for today’s optical communication systems based on the WDM technology [14, 15]. Its most important factors are the following: compact and highly effective semiconductor laser pumps, polarizing independence, simplicity of the device, and the nonexistence of mutual cross-talk while amplifying the WDM signals.

4.2. SOA. The main difference between the SOA and EDFA amplifiers is the active area where the gain generation happens. In the EDFA case it is generated directly in the optical fibre but in the case of SOA it happens directly in the structure of the semiconductor. Another important difference is the principle of energy supply which is used for obtaining the amplification (in the EDFA case it is via laser pump). In SOA the energy is supplied by electrical excitation current. Figure 5 is a schematic portrayal of SOA. The input signal is amplified on whole active area due to a coherent semiconductor stimulated emission. The principle of light amplification through SOA is based on the recombining electrons and holes at the transition of p - n structure.

The semiconductor amplifiers are made as chip in an enclosed case able to keep a constant temperature. By regulating temperature it is possible to set appropriate wavelength to obtain maximum gain. SOA are similar to lasers in their construction and functioning principle but with one fundamental difference. SOA amplifiers contain antireflex layer against creation of resonance and the signal accumulation within the medium. During construction the most important thing is the choice of a semiconductor material with good quantum efficiency. Quantum efficiency is defined

FIGURE 4: Scheme of EDFA connection.

FIGURE 5: Schematic organisation of SOA.

as a ratio between maximal amount of generated photons to the number of excited charges of the carrier [16]. Among applicable elements for the construction are the following: arsenic (As), gallium (Ga), aluminium (Al), indium (In), and phosphor (P). The used materials are the alloys of these elements: GaAs, AlGaAs, InGaAs, InGaAsP, InAlGaAs, and InP.

4.2.1. Principle of the Stimulated Emission in SOA. Stimulated emission precedes stimulated absorption which happens when the absorbed energy is passed on to the electron in a higher valence band of the semiconductor because of the subsequent excitation of that electron to a higher energy level in conductivity band. Excitation of the medium happens as a result of the current of electric energy in our case via electrode connected to the semiconductor. In case of a considerable electron population being on the higher energy level, a population inversion is made. It is a base for the stimulated emission of more photons [16–18]. Photons radiated at stimulated emission are highly coherent and have the same direction and phase as the stimulating ray. The

principle of the stimulated emission and population inversion can be seen in Figure 6.

4.2.2. Usage of SOA. Because of simple integration of the amplifier into the receiver, the SOA is often used as a preamplifier when the signal is amplified just before it reaches the receiver. In the same way APD (Avalanche Photodiode) adds additional noise to the signal; the preamplifiers degrade the SNR spacing thanks to the noise of the spontaneous emission. The SOA has a relatively high noise value ($F_n = 5\text{--}8\text{ dB}$) compared to the EDFA ($F_n = 4\text{ dB}$). However, it is difficult to obtain power levels higher than 10 mW due to relatively small values of the output saturation power which are around 5 mW. Although the SOA can be used to amplify several channels simultaneously, their greater usage in WDM is hampered by their basic problem of relatively quick response. In the ideal case the signal from individual channels is amplified with constant gain [13, 18]. Parameters like sensitivity, nonlinear effects, polarization, and high junction losses make these amplifiers harder to use than the in-line amplifiers. The advantage against the EDFA

FIGURE 6: The principle of the stimulated emission.

FIGURE 7: Four-channel WDM system.

is usable band of wavelengths from 1280 nm to 1650 nm. But the EDFA has proved to be more preferable to amplify the signal in the fully optical communication systems thanks to their better parameters. The SOA are utilized as a fast switch for routing in WDM. They are often used as a cheaper option of the optical amplifiers in metropolitan optical networks.

5. Design of the DWDM System for the Comparison of EDFA and SOA

Four-channel WDM system was created in the programme environment "OptSim" for purposes of comparing the BER and Q-factor (Figure 7).

5.1. Achieved Results. As DWDM standard is still being developed and there is compressing of individual channels, it is necessary to prevent FWM (Four-Wave Mixing) and select appropriate spacing between the channels. Ahmed et al., 2014, designed 8-channel DWDM system to observe FWM phenomena while changing various parameters (input power, channel spacing, number of channels, optical gain, core size, RZ and NRZ modulation, and bit rate). Based on the article, we have created DWDM system with spacing of 50 GHz between individual channels in C-band. When using 12.5 GHz and 25 GHz, FWM started to be significantly affected [19]. Ivaniga et al., 2015, created 8-channel and 16-channel WDM system to compare two codes, NRZ and Miller code, which affected SPM (self-phase modulation) phenomenon at a fibre length of 100 km. The results obtained in the article were used for setting of broadcast channels, and NRZ code was used for better error rate [20]. Pump current for SOA has been selected on the basis of achieved results [21]. BER ranged from $1 \cdot 10^{-4}$ to $1 \cdot 10^{-12}$. From the results published in this article SOA amplifier was designed in order to reach the best error rate for particular wavelengths [21]. The EDFA parameter settings and the length of erbium doped fibre have been designed on the basis of [22]. Obtained results helped to design individual components [22]. Olonkins et al., 2012, created DWDM system and compared SOA and DRA at distances of 112 km and 119 km with BER of about $1 \cdot 10^{-13}$ [23].

Anderson compared optical amplifiers in terms of location in the transmission path. Three ways of using SOA and EDFA were used, and these are the preamplifier, booster, and in-line amplifier. Results of simulations for EDFA were better than the ones for SOA [24]. BER for in-line amplifier in EDFA ranged about $1 \cdot 10^{-10}$; the fibre length was 20 km and DCF was 5 km [24]. The measurement on a real CWDM device with EDFA-SOA was published [25]. Total distance of optical fibre is 65 km with attenuation of 0.2 dB and BER of about $1 \cdot 10^{-9}$. This configuration is suitable for MAN (Metro Access Network) [25]. The comparison of optical amplifiers was based on the location of optical communication systems, in which EDFA and SOA were used as booster in our simulation.

5.2. Design DWDM with EDFA and SOA. In the topology there are three junction lines. The red junction represents the optical signal, the blue one represents electrical signal, and the green junction illustrates the logical signal [26–28]. The whole optical communication system contains 4 transmission lines. Every optical transmitter contains 4 basic blocks. The data source generates a bit rate of “10 Gbps” in every optical transmitter. The logic signal enters the electrical generator. There is the drive type set to “on-off ramp,” using the modulation of type “NRZ” (Nonreturn to Zero) and the “RingFilter” is used with the value of f_0 set to “20 MHz.” The CW (Continuous Wave) laser is placed in the transmitter. Every CW has a Peak Power set to “1.07 mW” and the frequency of the first transmitter is “191.39 THz” while the spacing between the channels is “4 nm.” The last block in every transmitter is the external modulator. Every modulator is set to the modulation of type “Mach Zehnder” while the

insertion loss has the value of “5 dB” and the chirp factor is “0.5.” As it is shown in Figure 1, all optical lines enter the optical multiplex where the individual optical wavelengths are combined.

Optical multiplex has a representation set to “MultiBand” with loss of “3 dB” while the type of the filter is “Trapezoidal.” Other blocks represent the comparison of EDFA and SOA which were variable during the simulation. In Figure 7 it is shown as Channel 1 and Channel 2, respectively. The laser pump setting for EDFA was the Peak Power equal to “0.03 W” and it worked on wavelength of “980 nm.” The length of the erbium doped fibre was 15 m and fibre saturation parameter was equal to $1 \cdot 10^{15} \text{ m}^{-1} \text{ s}^{-1}$. In our simulation, fibre background loss was neglected, so the parameter background loss was set to “0.” The numerical integration of the power evolution rate equations was handled using Runge-Kutta fourth-order method [29]. Integration step along EDFA length was set to “0.1 m”; spacing between wavelengths in discretized power spectra was equal to “1 nm.” Iterative damping factor for numerical solution was “0.7” and convergence tolerance for numerical solution was set to “ $1 \cdot 10^{-4}$.” Figures 8(a), 8(b), and 8(c) show average atomic-manifold population for atomic levels N_1 and N_2 alongside the EDFA fibre. Based on the simulation (in Figure 8(b)) the Peak Power was chosen as 30 mW. It is noteworthy that its inversion has a tendency to reach the peak in the middle of EDFA where the pump is the least distressed. Apart from that, the combined effect of signal and the front ASE (Amplified Spontaneous Emission) has the tendency to use up the inversion at the EDFA output. Figures 8(d) and 8(e) are the forward- and backward-band power solutions for the respective four-channel WDM system.

The second amplifier of the SOA type had the pump current set to “0.17 A.” During simulations the spectral gain shape was set to “parabolic” and the wavelength peak gain was “1520 nm.” The following SOA parameters were used: η (current injection efficiency) was in the simulation set to 1.5, L (cavity length) is 0.5 mm, w (cavity width) is $3 \mu\text{m}$, and d (cavity thickness) is $800 \mu\text{m}$. SOA model provides many options for modelling of semiconductor amplifier. Flat, parabolic, and cubic gain models are based on the following equations for the material gain and gain peak wavelength:

$$g(N\lambda) = \alpha \cdot (N - N_0) - \alpha_1 \cdot (\lambda - \lambda_p(N))^2 + \alpha_3 \cdot (\lambda - \lambda_p(N))^3, \quad (4)$$

$$\lambda_p(N) = \lambda_{p0} - \alpha_2 (N - N_{\text{ref}}),$$

where α (gain slope) is $2.78 \cdot 10^{-20} \text{ m}^2$, N_0 (carrier density) is $1.4 \cdot 10^{24} \text{ m}^{-3}$, and α_1 and α_3 (quadratic and cubic coefficients) have the value of 0. λ_{p0} (wavelength peak gain density) of 1552 nm and α_2 (wavelength peak gain slope) is 0. In our case, we have used the parabolic model where α_3 has the value of 0. The gain includes the carrier-density dependence of the peak gain wavelength and the quadratic dependence on the wavelength. This approach is very common one for dealing with an SOA spectral gain dependence. For solving the carrier

FIGURE 8: (a), (b), and (c) are average atomic level densities, (d) forward solution, and (e) backward solution.

rate equation, our model uses Runge-Kutta fourth-order and Adaptive Runge-Kutta fifth-order method [29].

For all simulations an optical fibre of the length “80 km” was used. The overall loss was “0.33 dB/km.” In all simulations the PMD (Polarization Mode Dispersion) and SBS (Stimulated Brillouin Scattering) were ignored. The Raman effect was considered at simulations with the Raman strength model being set to “fractional” and the Raman response fraction was “0.18.” The amplification of the optical signal is followed by the optical demultiplexing. Here is the overall loss of “3 dB” and the filter is of type “Trapezoidal.” Output of the WDM system is the optical receiver. Representation of simulated values is based on the type “Monte Carlo.” In the receiver the filter is of type “Bessel” with the bandwidth of “10 GHz.” The photodetector APD has quantum efficiency of “0.8.” Figure 9 is the comparison of BER for EDFA and SOA for the wavelength 1562 nm.

Value of BER for EDFA was measured as $4.395 \cdot 10^{-6}$ which had a corresponding Q-factor of 4.8765. For the SOA the BER was $1.042 \cdot 10^{-5}$ with the corresponding Q-factor of 4.6808. Figure 10 shows EDFA and SOA with wavelength of 1558 nm.

For the EDFA the BER measurement was $1.0203 \cdot 10^{-10}$ with corresponding Q-factor of 6.5461. For the SOA the BER was $1.6665 \cdot 10^{-4}$ with the corresponding Q-factor of 4.0647. The final values of BER and Q-factor for all four channels are in Table 1.

TABLE 1: Final values of BER and Q-factor for all four channels of WDM.

Optical amplifier	Wavelength [nm]	BER	Q-factor
EDFA	1566	$4.0129 \cdot 10^{-3}$	2.5966
SOA		$6.3464 \cdot 10^{-5}$	3.8744
EDFA	1562	$4.3905 \cdot 10^{-6}$	4.8765
SOA		$1.0412 \cdot 10^{-5}$	4.6808
EDFA	1558	$1.0203 \cdot 10^{-10}$	6.5461
SOA		$1.6665 \cdot 10^{-4}$	4.0647
EDFA	1554	$5.8535 \cdot 10^{-15}$	7.6987
SOA		$2.1023 \cdot 10^{-6}$	4.7197

6. Conclusion

The main aim of this article is the comparison of two optical amplifiers, the EDFA and the SOA in the DWDM system. The mentioned amplifiers were evaluated based on values of BER and the related Q-factor. For fully optical communication systems it is good for BER to be under 10^{-12} . In the article it is shown that the EDFA has a better error rate than the SOA. Currently the EDFA is among the most frequently used fibre amplifiers; the SOA are used mostly for their cost-effectiveness. With given simulations the wavelength of 1554 nm has been proven to be the best for EDFA with an

FIGURE 9: Comparison of BER for EDFA and SOA for wavelength of 1562 nm.

FIGURE 10: Comparison of BER for EDFA and SOA for wavelength of 1558 nm.

error rate of around 10^{-15} and the wavelength of 1558 nm being sufficient (Figure 10) with BER of around 10^{-10} . An insufficient error rate for EDFA was at a wavelength of 1566 nm and of around 10^{-3} . For SOA, an error rate better than 10^{-6} was not attained, which is visible in Figure 9, and because of that it is not applicable for the given WDM system. A programme was created in Matlab (Figure 2) where it is possible to observe BER and the related Q-factor.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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