Simulation influence of the thermal noise of PIN photodetector on performance DWDM optical network

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Abstract – **In this paper using simulation DWDM optical network with software OptiSystem is shown the influence of thermal noise PIN photodetector on the transmission quality. As a measure of quality used optical Q factor. On the basis of obtained results is discussed how to modify the transmission quality and behavior of the thermal noise with a variation of numbers amplifying section and the quantity of flow per channel. Graphically is shown change Q factor for different values of the thermal noise, the number amplifying section and length amplifying section.**

Keywords – **DWDM networks, thermal noise, Q factor, amplifying section.**

I. INTRODUCTION

WDM (Wavelength Division Multiplexing) is a technology which multiplexing multiple optical carrier signals on a single fiber using different wavelengths for the transmission of different information. At least attenuation in the optical fiber is achieved by applying the wavelength of 1550 nm, i.e. using the "third optical window" [1],[2]. WDM systems allow expansion of existing capacity without laying additional fiber optic cables. The capacity of the existing system is expanding using multiplexers and demultiplexers at each end of the system [3], [4].

DWDM (Dense Wavelength Division Mulitplexing) DWDM relates to optical signals multiplexed within the 1550 nm range in order to influence Erbium Doped Fiber Amplifier (EDFA), which are effective for wavelengths from 1525 to 1565 nm (C band).

Unlike a DWDM, CWDM (Coarse Wavelength Division Mulitplexing) uses a much larger spacing between channels. To enable 16 channels on one fiber, CWDM uses the entire frequency range between the second and third optical window (1300 nm and 1550 nm).

For successful transmission of optical signals over long distances is using the EDFA amplifiers. Weak signal enters in the erbium doped fiber in which light is injected using the laser to pump. This light excites erbium atoms to release stored energy as additional light of wavelengths around 1550 nm. How this process continues through the fiber signal becomes stronger. EDFA is available in C and L windows but quite narrow range (1530-1560 nm) [1], [2], [5].

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Thermal noise (also known as Johnson-Nyqvist noise) is electrical noise created thermal (Braun) the movement of electrons within the electrical conductors without any external influence. This noise occurs regardless of the applied external voltage, unlike other sources of noise.

The variance of thermal noise can be given as expression [1], [2]:

$$\sigma_T^2 = \frac{4k_B T}{R_L} F_n \Delta f \qquad (1)$$

where k_B is the Boltzmann constant, T is the absolute temperature, R_L is the load resistor, Δf is the effective noise bandwidth, and F_n represents the factor by which thermal noise is enhanced by various resistors used in pre- and main amplifiers.

The performance of an optical receiver depends on the SNR (signal-to-noise ratio). The SNR of any electrical signal is defined as

$$SNR = \frac{\text{average signal power}}{\text{noise power}} = \frac{I_p^2}{\sigma^2} \qquad (2)$$

where i_p is defined as $I_p = RP_{in}$ (R is the responsivity of the *PIN* photodiode defined as $R = \frac{\eta q}{h\nu}$). In most cases of practical interest, thermal noise dominates receiver performance ($\sigma_T^2 >> \sigma_S^2$). Neglecting the shot-noise (σ_S^2), Eq. (2) can be written as

$$SNR = \frac{R_L R^2 P_{in}^2}{4k_B T F_n \Delta f} \qquad (3)$$

Optical Q factor is given with expression [1],[2]:

$$Q = \frac{I_0 + I_1}{\sigma_0 + \sigma_1} \qquad (4)$$

Q factor is determined based on the average value of the signal I_1 and standard deviations σ_1 in the event of receipt" 1" i.e. based on the average value of signals I_0 and standard σ_0 deviation in case of receipt "0". In WDM networks, the transmission quality was achieved for the values of Q> 5.4.

II. SYSTEM MODEL

The appearance of WDM optical networks for the analysis in the OptiSystem [11] software is given in Fig. 1. It consists of an optical source, DWDM multiplexers, optical fibers, EDFA amplifiers, DWDM demultiplexers and optical receiver.

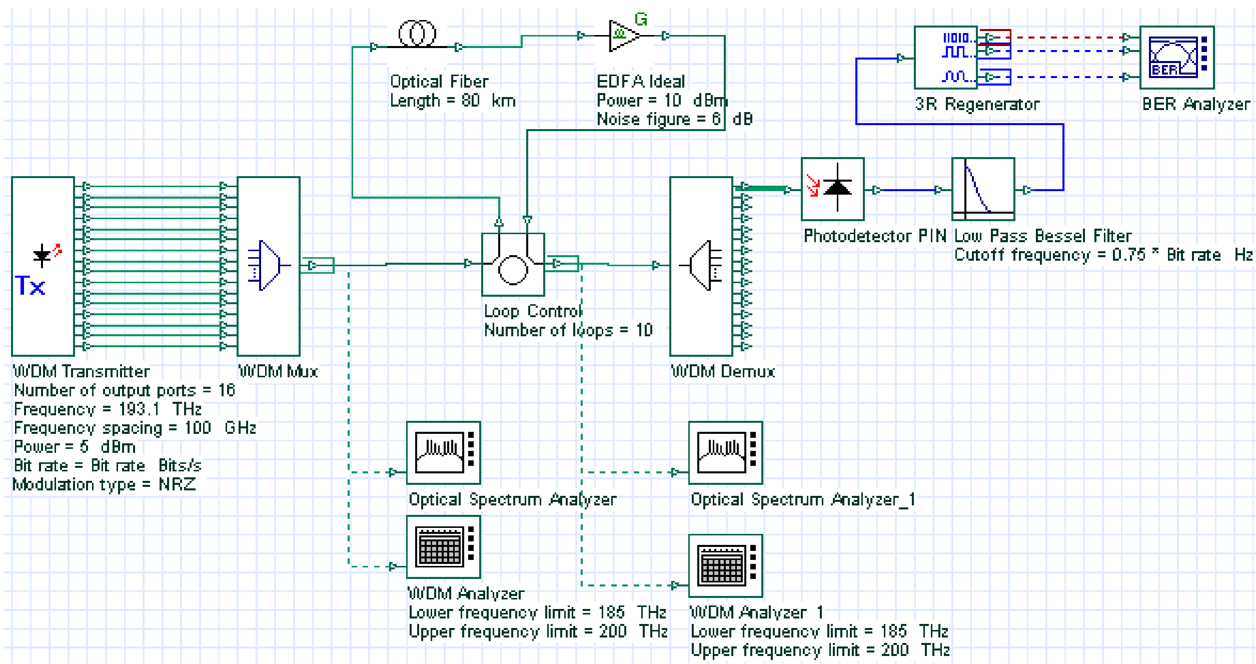

Fig. 1. The appearance of DWDM networks

Observe the optical WDM 16-channel network in the third optical window with the bit rate at channel 1 Gb/s and 5 Gb/s.

The power emitted by each source is 5 dBm. The system works in the third optical window and the frequency of each DWDM channel: first channel 193.1 THz, second channel 193.2 THz, third channel 193.3 THz, ... Channels operating at wavelengths: 1552,524 nm, 1551,721 nm, 1550,918 nm, ..., respectively. The frequency of each channel is separated by 100 GHz.

Signals are transmitted from the multiplexer through optical fiber amplified with EDFA amplifier. Gain EDFA is 10 dBm, noise that enters is the 6 dB. Amplifiers were set at 50 km, and the number of amplifying section changes from 1 to 10 in order to obtain the influence of the length of the section on the quality of signal transmission. System working in the third optical window so the weakening of the fiber is 0.2 dB/km.

On the receiver side, the signals coming to demultiplexers whose channels work on the same frequencies as the multiplexer. At the exit of the demultiplexers is optical receiver which consists of three elements: PIN photodetector, low-pass Bessel filter and 3R regenerator. Thermal noise is changing in the PIN photodetector in the range of 10^{-26} W/Hz up to 10^{-18} W/Hz. Optical receivers usually have a range of thermal noise in the bordered 10^{-24} W/Hz up to 10^{-20} W/Hz.

In addition to these network elements, include elements from which it is possible to read values that indicate the performance of the transmission of optical signals: WDM Analyzer, Optical Spectrum Analyzer and BER Analyzer [11].

III. Results Of Simulation And Discussion

In Tables I and II are given values of Q factor obtained by simulation, dependent on the different values of the thermal noise in the PIN photodetector for amplifying section of 50 km with a bit rate of 1 Gb/s and 5 Gb/s per channel, respectively. The obtained results shows that the increase in the number of amplifying section Q factor decreases for values of the thermal noise of 10^{-20} to 10^{-26} W / Hz. However, the thermal noise higher of 10^{-20} W/Hz leads to smaller fluctuations of Q factor, i.e. after his fall, to come up its growth in some amplifying sections.

If we consider the change of Q factors of the same sections, and for different values of the thermal noise we see that it increases with decreasing thermal noise to 10^{-24} W/Hz, when Q factor obtained approximately constant value.

Table I
Changing the Q factor for different values of thermal noise of PIN photodetector for amplifying section of 50 km on DWDM network bit rate 1 Gb/s per channel

thermal noise W/Hz	10^{-18}	10^{-20}	10^{-22}	10^{-24}	10^{-26}
50 km	14.8916	27.026	28.0084	27.9900	27.9859
100 km	13.0851	23.9029	24.8721	24.8619	24.8592
150 km	11.8144	18.9094	19.5492	19.5555	19.555
200 km	10.2939	17.5041	18.1705	18.1860	18.1868
250 km	10.5957	16.6127	17.0582	17.0686	17.0691
300 km	9.46335	15.9481	16.4939	16.5027	16.5031
350 km	9.66262	14.8035	15.2027	15.2135	15.2142
400 km	9.97910	13.8202	14.0451	14.0504	14.0507
450 km	9.12860	12.9756	13.1663	13.1700	13.1702
500 km	8.54721	11.5364	11.7276	11.7351	11.7357

Dependence of Q factor on the fiber length for bit rates 1 Gb/s and 5 Gb/s is given in Fig. 2. Dashed red line shows the limits of transmission quality on basis Q factor. From Fig. 2 we can see that the transmission quality can be achieved with a bit rate of 1 Gb/s per channel for all 10 amplifying sections if the value of the thermal noise PIN photodetector is 10^{-18} W/Hz and 10^{-22} W/Hz. In the case of transfer of 5 Gb/s per channel transmission quality can not be achieved in all 10 amplifying section (500 km). For value of the thermal noise 10^{-18} W/Hz distortion of quality transmission occurs after 250 km. For value of the thermal noise 10^{-22} W/Hz distortion of quality transmission occurs after 300 km.

Also, from Fig. 2 we can see that the drop Q factor is significantly more pronounced at lower values of the thermal noise than the higher values.

TABLE II
CHANGING THE Q FACTOR FOR DIFFERENT VALUES OF THERMAL NOISE OF PIN PHOTODETECTOR FOR AMPLIFYING SECTION OF 50 KM ON DWDM NETWORK BIT RATE 5 GB/S PER CHANNEL

thermal noise W/Hz	10^{-18}	10^{-20}	10^{-22}	10^{-24}	10^{-26}
50 km	8.02543	19.7139	20.3453	20.3177	20.3138
100 km	6.66421	17.0361	17.4225	17.3993	17.3963
150 km	7.05799	13.3352	13.3484	13.3309	13.329
200 km	5.95862	10.4932	10.517	10.5088	10.5079
250 km	5.41034	7.74074	7.75219	7.74878	7.7484
300 km	2.81884	4.42233	3.46192	3.46553	3.46588
350 km	3.06294	3.35063	3.3484	3.34782	3.34775
400 km	3.20253	3.40236	3.39184	3.39045	3.39031
450 km	3.1032	3.17188	3.15319	3.15109	3.15088
500 km	2.60183	2.95521	2.99387	2.99759	2.99796

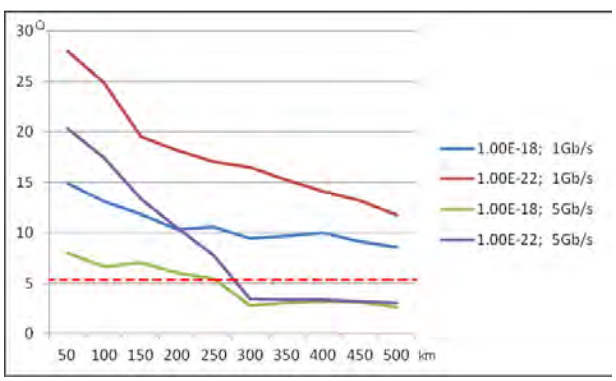

Fig. 2. Changing the Q factor at a bit rate of 1 Gb/s and 5 Gb/s per channel for the values of the thermal noise of 10^{-18} W/Hz and 10^{-22} W/Hz at amplifying sections of 50 km

The values of Q factor for the reduced value of the amplifying section of 25 km, for characteristic value of thermal noise of PIN photodetectors are given in Table III, for a bit rate of 5 Gb/s per channel.

In Figs 3, 4 and 5 shows the change Q factor when using amplifying sections 25 and 50 km and bit rate of 5 Gb/s per channel for the values of the thermal noise 10^{-18} W/Hz, 10^{-22} W/H and 10^{-26} W/Hz, respectively. Dashed red line shows the limits of transmission quality on basis Q factor.

In Figure 3 we see that whether we use the amplifying section 25 or 50 km distorsion of quality transmission occurs at the same length of 250 km. The behavior of Q factor for using amplifying sections 25 km and 50 km is approximately the same while there is a high quality transmission. When the Q factor drops below 5.4 occurs to abrupt change of its value in applying these amplifying sections. For the amplifying section of 50 km fall of Q factor is much more pronounced than in the case of a amplifying section of 25 km.

TABLE III
CHANGING THE Q FACTOR FOR DIFFERENT VALUES OF THERMAL NOISE OF PIN PHOTODETECTOR FOR AMPLIFYING SECTION OF 25 KM ON DWDM NETWORK BIT RATE 5 GB/S PER CHANNEL

thermal noise W/Hz	10^{-18}	10^{-22}	10^{-26}
25 km	6.98781	24.1337	24.2221
50 km	8.21292	21.9389	21.906
75 km	6.63424	18.9021	18.8769
100 km	6.47925	16.8889	16.8883
125 km	6.16904	13.2485	13.2831
150 km	6.9117	12.5919	12.5805
175 km	5.87067	10.7422	10.7382
200 km	5.97327	9.7244	9.71713
225 km	5.20897	8.40222	8.41579
250 km	5.39137	7.23923	7.23421
275 km	4.27537	6.62766	6.63298
300 km	4.45094	5.84338	5.83978
325 km	2.95336	3.21382	3.21286
350 km	2.87996	3.1264	3.12646
375 km	3.03281	2.9827	2.98049
400 km	2.87397	2.95531	2.95414
425 km	2.60157	2.94393	2.94562
450 km	2.85298	2.84018	2.83829
475 km	2.68203	2.73249	2.73183
500 km	2.33638	2.612	2.61413

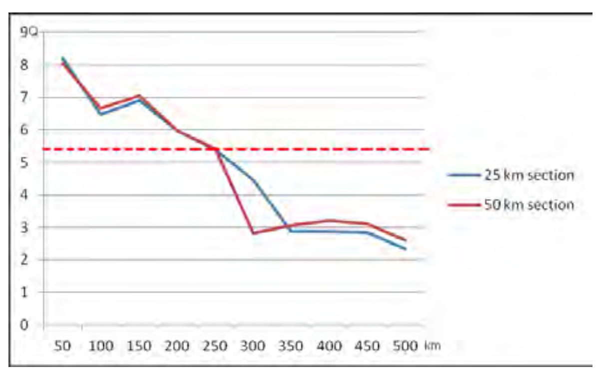

Fig. 3. Changing the Q factor at the thermal noise of 10^{-18} W/Hz for amplifying sections 25 and 50 km

In the case of the thermal noise of 10^{-22} W/Hz and 10^{-26} W/Hz curve behavior of Q factor is identical (Figs. 4 and 5 are similar. When the value thermal noise falls below 10^{-22} W/Hz, Q factor tends constant value.

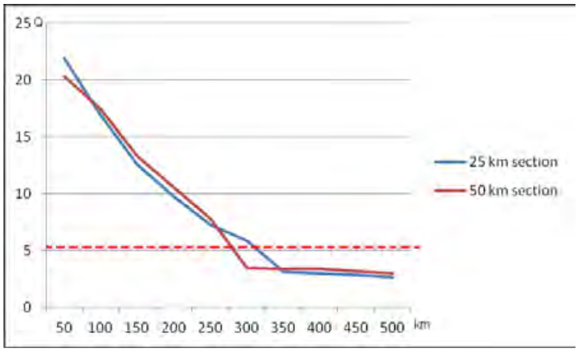

Fig. 4. Changing the Q factor at the thermal noise of 10^{-22} W/Hz for amplifying sections 25 and 50 km

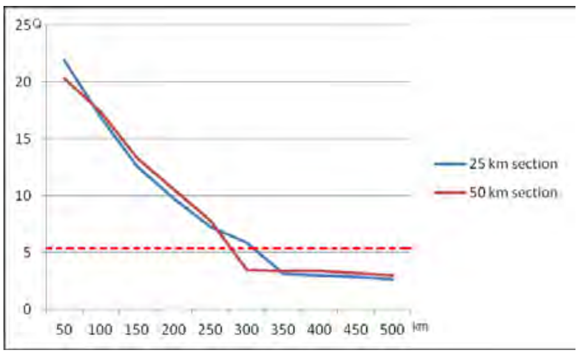

Fig. 5. Changing the Q factor at the thermal noise of 10^{-26} W/Hz for amplifying sections 25 and 50 km

From Figs. 4 and 5 we see that the behavior of the curve Q factor for amplifying section of 25 km and 50 km is not similar as the case for higher values of thermal noise. A faster decline in Q factor is achieved with amplifying sections of 50 km compared to the 25 km amplifying section. Better quality of transmission can be achieved by applying the amplifying section of 25 km with respect to section of 50 km.

IV. Conclusion

With simulation of the DWDM network is obtained the values of Q factors for different values of the thermal noise PIN photodetector and different number of amplifying sections. Based on these results we conclude that the increase in the number of amplifying section Q factor decreases for values of the thermal noise of 10^{-20} to 10^{-26} W/Hz. For higher thermal noise of 10^{-20} W/Hz Q factor also decreases but on the some amplifying sections there is a slight of his growth.

Quality transmission can be achieved with a bit rate of 1 Gb/s per channel for all 10 amplifying sections if the value of the thermal noise PIN photodetector is 10^{-18} W/Hz and 10^{-22} W/Hz. In the case of transfer of 5 Gb/s and value of the thermal noise 10^{-18} W/Hz distortion of quality transmission occurs after 250 km. For value of the thermal noise 10^{-22} W/Hz distortion of quality transmission occurs after 300 km.

Executed a comparison of Q factor and quality of transmission if the length amplifying sections cut from 50 km to 25 km, i.e. if you use twice many amplifiers. In the case of the thermal noise 10^{-18} W/Hz, regardless of whether use of the amplifying section 25 or 50 km distorsion of quality transmission occurs at the same length of 250 km. The behavior of Q factor for using amplifying sections 25 km and 50 km is approximately the same while there is a high quality transmission. When the Q factor drops below 5.4 occurs to abrupt change of its value in applying these amplifying sections.

In the case of the thermal noise of 10^{-22} W/Hz and 10^{-26} W/Hz the behavior of the curve Q factor for amplifying section of 25 km and 50 km is not similar as the case for higher values of thermal noise. Better quality of transmission can be achieved by applying the amplifying section of 25 km with respect to section of 50 km.

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