Assessment of quality of signal transmission process in focs with DWDM

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Abstract. The power of a group DWDM signal increases nonlinear interference in the optical path, especially the value of the interference of the FWM. These interfering factors degrade signal transmission quality and can completely disable the WDM system. Therefore, when designing a DWDM system, it is necessary to optimize the power of the transmitted signal to minimize the probability of error in the optical channel. The article presents the research results and analysis of factors affecting the quality of fiber-optic communication systems with wave separation of channels. Selecting the optimal power level of the group signal and evaluating the transmission quality of optical communication channels in WDM allows us to solve the problem of science-based design, implementation, and effective operation of advanced optical communication systems with wave division of channels.

1 Introduction

The transition from systems with one wavelength to a system with several wavelengths leads to several problems, which arise due to the nonlinear properties of the fiber, insufficient suppression of adjacent channel signals by the demultiplexer, and the dependence of the loss of optical components on the wavelength, monitoring the wavelength, channel power and signal-to-noise ratio for network management, since WDM (wavelength division multiplexing) systems, unlike single-wave systems, in which only power measurements at various points of the network are required to detect a malfunction, a simple power measurement is not enough, spectral measurements of each channel are necessary. In single-channel FOCS (fiber optic communication systems), the transmission signal level is from -2 to +3 dBp, but in technology with wave separation of channels, to increase the communication range and to compensate for the loss of passive devices, it is necessary to generate signal levels of the order of + 20 dBp [1].

High power will lead to a change in the refractive index of OF (optical fiber), resulting in additional combination products.

With an increase in the input signal power, the quartz fiber's refractive index increases, leading to nonlinear phenomena and distortions. The main nonlinear effect is four-wave mixing (FWM). It is also necessary to consider several other interferences, such as the optical amplifier's noise (enhanced spontaneous ASE radiation). It is known that the power

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of a group DWDM (dense wavelength division multiplexing) signal directly affects the value of the interference power of the FWM and does not affect the noise power of the ASE. These interfering factors degrade signal transmission quality and can completely disable the WDM system. Therefore, when designing a DWDM system, it is necessary to optimize the power of the transmitted signal to minimize the probability of error in the optical channel [2-3].

The study of nonlinear effects was considered in the works of scientists such as Govind P.Agrawal, Shiva Kumar, M. Deen, R.K. Singh (USA), Ereminsky D.E. (Influence of the optical environment on transmission quality indicators in telecommunication systems with dense wave multiplexing, DWDM in telecommunication systems of railway transport), Bulgakova S.A. (Nonlinear phenomena in fiber-optic interferometers at low radiation powers in the fiber).

In our Republic of Uzbekistan, when using DWDM technology, we have not yet encountered the problems of nonlinear effects, but with an increase in the need for bandwidth, the number of optical channels and the power of the group signal increases, which will lead to nonlinear effects.

The effects of nonlinear effects were first discovered in the transatlantic FOCS link connecting Europe to America.

One of the main indicators of WDM systems is the quality of the transmitted information. The quality of information transmission determines the ability of the system to restore the transmitted signals with a given reliability. Therefore, when designing WDM systems, it is necessary to optimize the group signal power.

And also, the non-fulfillment of the conditions of a single-mode OF regime in practice also leads to the appearance of combination products and the manifestation of the nonlinearity of the OF. These nonlinear products exert mutual influence between parallel optical channels, which degrades the quality of the optical channels.

To justify the influence of a group signal's power on nonlinear interference and communication quality, the power of four-wave mixing, amplified spontaneous emission, and the Q-factor were calculated.

To meet the requirements for the quality of signal transmission through optical communication channels with WDM, optimization of the level of transmitted optical power through the communication channels of systems with WDM and justification of optical amplifiers, alignment of the gain of the optical amplifier, rational selection of the number of optical channels and stabilization of their level by power are proposed.

Choosing the optimal level of group signal power and assessing the transmission quality of optical channels in WDM allows us to solve the problem of scientifically sound design, implementation, and effective operation of promising optical communication systems with wave division of channels. The above shows the relevance of the topic of this work.

2 Objects and methods of research

This article discusses the choice of the optimal group signal power level in WDM systems and calculation examples.

For this, the following tasks are solved:

1. Analysis and study of the main factors affecting signal transmission quality in WDM systems.
2. WDM tizimlarida optik aloqa kanallari sifatini baholash usullarini tahlil qilish va guruhning signal quvvatining maqbul darajasini tanlash usuli.
3. Examples of calculating the optimal power level of the group signal and the power of the PBC and their impact on signal transmission quality in WDM systems.

In the linear path of optical communication systems with wave separation of channels, there are several elements, the parameters of which depend on the acting power of the optical signal and, therefore, are nonlinear four-port networks. These elements of the optical linear path include optical fiber (Fig. 1) [4-7], an optical amplifier, and others. The presence of nonlinearity leads to additional components appearing at the output of the corresponding four-port network, which was absent in the original group optical signal. In an optical linear path, nonlinearity distorts the transmitted information at individual wavelengths and causes additional interference due to mutual parasitic modulation. This interference, called interference from nonlinear transitions, can turn out to be both the same as the useful group optical signal, or mismatched.

Especially the quality of optical signal transmission in WDM systems is affected by nonlinear effects in the optical fiber. They are due to the nonlinear response of the optically transparent substance to an increase in the intensity of the light flux per unit cross-sectional area of the fiber core.

Under certain conditions and levels of transmitted signals, an optical fiber will have all the effects of nonlinearity when exposed to the input of two or more frequencies. This phenomenon can be more easily explained by the example of the effect of several frequencies on a nonlinear four-terminal network (this refers to an optical fiber, an optical amplifier operating in overload mode). At the output of the four-terminal network, the main signal and additional components are formed that were absent in the original signal; that is, in addition to the 2nd, 3rd, and other harmonics, several combination products of transformations are formed. These nonlinear products are dangerous because they exert mutual influence between parallel optical channels [8-10].

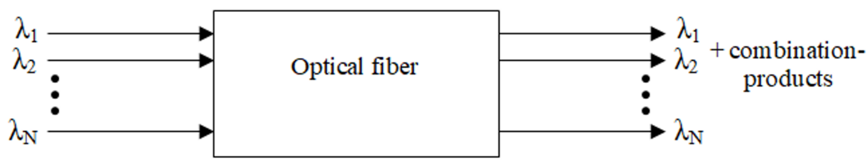

Fig. 1. Nonlinear behavior of the optical fiber as a nonlinear four-terminal network in a strong electromagnetic field.

3 Results and Discussion

In the case of transmission of a group signal of three waves, transformation products of the following form are formed.

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k, \text{ where } i \neq k, j \neq k .$$

In this case, twelve harmonics are formally generated from a mixture of total-difference frequencies of larger amplitude, namely: ω_{112}, ω_{113}, ω_{123}, ω_{132}, ω_{213}, ω_{221}, ω_{223}, ω_{231}, ω_{312}, ω_{321}, ω_{331}, ω_{332}, but actually, seven harmonics, since some harmonics frequencies coincide with the working frequencies of adjacent channels; if the step between the channels in the system is the same: $\omega_{213}=\omega_{123}=\omega_{112}$, $\omega_{132}=\omega_{312}$, $\omega_{231}=\omega_{321}=\omega_{332}$ (fig. 2).

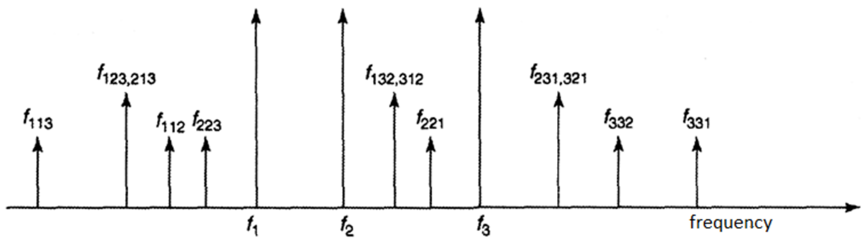

Fig. 2. Mixture of products generated thanks to the FWM for 3 optical signals [1].

Cross-nonlinear interference appears from the correspondence of the frequencies of the combination harmonics with the working channel. In this case, the total power of nonlinear interference $P_{\sum}$ in FOCS-WS can be determined by the following expression

$$P_{\sum} = \sum_{i=1}^{m} P_i$$

Where P_i *is* interference of the $i-$nd optical channel with wave separation; *m* is the number of optical channels.

To assess the interference from nonlinear transitions that arise in the optical linear path of optical communication systems, we represent the dependence of the power at the output of a nonlinear four-port network on the power at its input in the form of a polynomial of the first degree:

$$P_{\text{outlet}} = f(P_{inlet}) = \sum_{i=1}^{n} B_i \, P_{inlet}^{i} \qquad (1)$$

where B_i is a coefficient of approximation, characterizing the degree of nonlinearity of the four-port network.

To assess the degree of nonlinearity of a four-port network, we represent the input power as functions $P_{in} = P_{max} \cos wt$, then the output power is determined by the formula:

$$P_{outlet} = \sum_{i=1}^{n} B_i \, P_{max}^{i} \, cos^{i} \, wt \qquad (2)$$

Usually, the elements of the optical linear path have a weakly expressed nonlinearity, that is, B_i "B_{i-t} .

Under real conditions, the transmitted baseband signal is a more complex structure. Therefore, assessing the degree of nonlinearity of a four-port network only by harmonics turns out to be insufficient since, in addition to harmonics, the products of the interaction of individual components of a complex output signal are formed in the output signal.

The output signal is the sum of harmonic oscillations of the form

$$P_{inlet} = \sum_{i=1}^{n} P_k \cos(w_k t + \varphi_k) \qquad (3)$$

Then the expression at the output of the nonlinear four-port network following equation (2) will be equal to

$$P_{outlet} = \sum_{i=1}^{n} B_i \, [\sum_{k=1}^{m} P_k \cos(w_k t + \varphi_k)]^i \qquad (4)$$

It can be seen from this expression that the output power, in addition to harmonics, also contains combination components of the form $c_1w_1 \pm c_2w_2 \pm ... \pm c_mw_m$, where $c_1, c_2, ... , c_m$ are positive integers or zeros, and $c_1 + c_2 + … + c_m = N \leq n$, a N - determines the order of the nonlinearity product (combination components or harmonics). If $c_1 \pm c_2 \pm … \pm c_m = 1$, then the corresponding nonlinear products are called nonlinearity products of the first kind, and all the others are called products of the second kind. The first kind includes only products from odd degrees, that is, an odd product.

In practice, approximating the characteristics $P_{out} = \varphi$ (P_{in}) (amplitude characteristic) of a weakly nonlinear four-port network is sufficient to limit the full third degree. In this case, the variety of nonlinearity products can be comprehensively represented as:

1. Products of the second order: 2 w_x is second harmonics; $w_x \pm w_y$ is total and difference combination products.
2. Products of the third order: 3 w_x is third harmonics; $2w_x \pm w_y$, $w_x \pm w_y \pm w_z$ are the total and difference combination products, among which ($2w_x$ - w_y) and ($w_x + w_y$ - w_z) are products of the first kind.

The baseband signal at the output of the optical multiplexer can be regarded as a stationary random process. Following the central limit theorem of the probability theory, the probability distribution of instantaneous values of the power of a group signal as a stationary random process asymptotically tends to normal. Therefore, in what follows, we will assume that with a sufficiently large number of optical channels at different wavelengths at the input of the optical linear path P_{in} (t) is a normal stationary random process.

There are several types of nonlinear effects, each of them, to varying degrees, affecting the propagation of signals along the fiber. The most significant nonlinear effect is four-wave mixing.

Four Wave Mixing (FWM) leads to the appearance of interfering harmonics; some of them fall into the working channels of the system and interfere with the transmission of the main signal.

FWM is sensitive to system characteristics: increasing the signal power in a channel, increasing the number of channels, decreasing the step between channels, and affecting the level of interference and the signal-to-noise ratio [11].

An increase in the step between optical carriers and the presence of chromatic dispersion reduces the FWM process due to the destruction of the phase relations between the interacting waves. To reduce the influence of nonlinear effects, you can also use an uneven step or an increased step between the optical channels.

For the normal functioning of WDM systems, the characteristics of the optical fiber itself are more important. When studying WDM systems, much more attention should be paid to chromatic dispersion. The characteristics of the optical fiber must be taken into account when designing fiber-optic communication systems and then must be checked after installation since WDM systems are very sensitive to chromatic dispersion, a small but carefully controlled part of which is necessary to eliminate such a phenomenon as the mixing of four waves.

Quality indicators of digital channels and network paths and their requirements included in the relevant Recommendations ITU-T G.821, G.826 и M.2100 [12, 13] are more complete, allowing for comprehensive quality control of the Central Committee and T.

Error indicators of digital channels and paths are statistical parameters, and the corresponding probability determines the norms on them.

The power of the FWM of the generated harmonics f_{ijk} can be estimated by the following formula [14].

$$P_{ijk} = \eta(2\pi f_{ijk} a_{ij} / 3)^2 (\gamma / S_{eff})^2 (L / c)^2 P_i P_j P_k \exp(-\alpha L) \quad (5)$$

where η is FWM efficiency coefficient, a_{ij} is a coefficient equal to 3 if i=j, or 6 if i j, sometimes called the degeneracy coefficient; γ is coefficient of nonlinearity of the refractive index; S_{eff} is effective area S; c is speed of light; P_i, P_j, P_k are power of the original carriers; α is attenuation coefficient; L is length of the interaction propagation section.

Nonlinearity coefficient γ at wavelength λ calculated by the formula [15]:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (6)$$

n_2 - refractive index nonlinearity coefficient (n_2= 2, 68·10^{-20} m²/W); A_{eff} is effective area of optical fiber (A_{eff}=50 μm²).

The power of the FWM interference on the f_m frequency is equal to the sum of the power of all combination products:

$$P_{\text{FWM1}}(f_m) = \sum_{i=1}^{N} \sum_{j=i}^{N} P_{ijk}\left(f_i, f_j, f_k\right) \quad (7)$$

where N - is the number of channels.

When performing calculations using this formula for each combination f_i and f_j you need to calculate $f_k=f_i+f_j-f_m$. When the condition is met $f_1 \le f_k \le f_N$ the interference power of the FWM on the f_m frequency is calculated using the formula (2), otherwise, the interference power is assumed to be zero.

Further calculations will be performed for a WDM system consisting of N_a optical amplifiers and sections of the same length L (Fig. 3). To increase the signal level at the input of the receiving optical module (ROM), an optical amplifier with a number (N_a +1) is also installed.

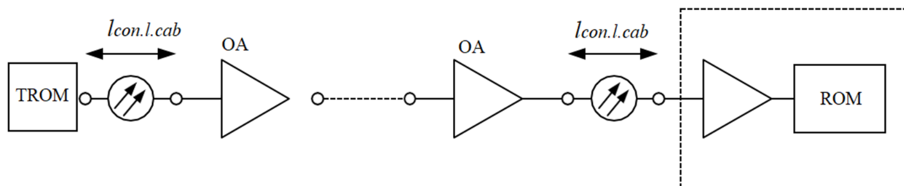

Fig. 3. Block diagram of the WDM system

Take the signal power of one optical channel at the output of an amplifier equal to the power of the transmitting optical module (TROM) P_{in1ch}. In this case, the signal with power P_{in1ch} at the exit of the section OF it is necessary to strengthen the $G = P_{in1ch} / P_{out1ch} = 1/e^{-\alpha L}$ once.

It is known that the power of amplified spontaneous radiation (ASE) is calculated by the formula

$$P_{ase1} = 2n_{sp}(G-1)hf_m\Delta f_0 \quad (8)$$

where n_{sp} is coefficient of spontaneous emission of the amplifier ($n_{sp} \approx 1,4$); h is Planck's constant (h=6,626·10^{-34} J·s); Δf_0 is the transmission bandwidth of the optical filter demultiplexer WDM ($\Delta f_0 \cong 1,25$ B); B is the speed of digital signal transmission over the optical channel.

Since, in this example, all the sections have the same length, the power of the amplified spontaneous radiation at the input of the receiving optical module (ROM) is equal to the sum of the corresponding power at the output of all the amplifiers:

$$P_{FWM\Sigma} = P_{ase1}(N_a{+}1) \tag{9}$$

At the output of the photodetector, the optical noise PMF and ASE, respectively, form an electrical signal with power:

$$P_{ease\Sigma} = 4b^2 P_{in1ch} \frac{P_{\text{чвс}\Sigma}}{8} \tag{10}$$

and

$$P_{ease\Sigma} = 4b^2 P_{in1ch} P_{ase\Sigma} \frac{\Delta f_e}{\Delta f_0} \tag{11}$$

where Δf_e is the bandwidth of the electrical amplifier ROM ($\Delta f_e \cong 0.7B$)

The sensitivity of the photodetector b is equal to [16]:

$$b = \frac{\eta e}{h f_m} \tag{12}$$

where η is quantum efficiency of a photodetector (η=0.8 for pin photodiode); *e* is electron charge (e=1.6·10^{-19} Kl).

The Q-factor and the associated error probability are calculated using the formulas [17]:

$$Q \approx \frac{bP_{\text{вх1к}}}{\sqrt{P_{ease\Sigma} + P_{\text{ечвс}\Sigma}}} \tag{13}$$

and

$$P_{error} = \frac{1}{\sqrt{2\pi}} \int_Q^{\infty} e^{\frac{x^2}{2}} \text{dx}. \tag{14}$$

We choose the input signal power because the group signal's power in DWDM technology should not exceed +23 dB.at higher values of the group signal power, the influence of nonlinear effects increases. With this in mind, the $P_{gr.s}$ is power of the group signal is selected as +20 dB, and the power of each optical channel is determined as follows:

The number of channels is converted to a logographic form [18, 19]:

10 lgN, dB,

$P_{in.ch}$= $P_{gr.s}$ - 10 lg N, dB.

For example, the number of channels N=18. Then 10 lg18=12.6 dB,

$P_{in.ch}$= 20 – 12.6=7 dB=5.5 mW.

From the above formulas, we calculate the Q-factor and evaluate the impact of FWM on the quality of communication in WDM systems. To do this, enter the following source data (table 1).

Table 1. Source data

Number of channels, PCs.	N	18, 64, 100
Number of amplifiers, PCs.	N_a	1
The transmission speed of the line, Gbit/s	B	10
Planck constant, j·s	h	$6.626 \cdot 10^{-34}$
Length of the amplifying section, km	L	120
Coefficient of spontaneous emission of the amplifier	n_{sp}	1.4
The efficiency of FWM	ŋ	0.8
Attenuation coefficient of S, dB / km	α	0.2
Signal frequency, Hz	f_m	$1.93 \cdot 10^{14}$
Amplifier gain	G	30
The charge of the electron, KL	e	$1.6 \cdot 10^{-19}$
The bandwidth of the electrical amplifier ROM	Δf_e	0.7B
Bandwidth of the optical filter of the WDM demultiplexer	Δf_o	1.25B

The results of calculating the power of four-wave mixing amplified spontaneous radiation and Q-factor are shown in Table 2.

Table 2. Results of four-wave mixing power amplified spontaneous emission and Q factor

N	18	64	100
P_{in1ch}	5.555556	1.5625	1
Q	708.3149	203.092	130.3403
$P_{FWM\Sigma}$	$2.22 \cdot 10^{-5}$	$7.59 \cdot 10^{-5}$	$11.8 \cdot 10^{-5}$
$P_{ase\Sigma}$	$2.47 \cdot 10^{-6}$	$8.44 \cdot 10^{-6}$	$1.31 \cdot 10^{-5}$

From the above formulas (2) - (13), it can be seen that the $P_{FWM\Sigma}$ and Q-factor depend on the power of the transmitter signal (Fig. 4, 5).

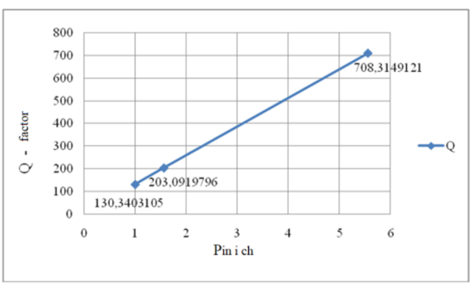

Fig. 4. The dependence of the Q-factor of the power signal

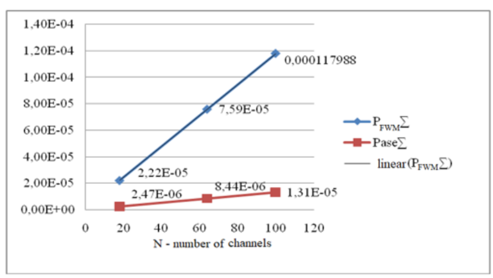

Fig. 5. Dependence of $P_{FWM\Sigma}$and $P_{ASE\Sigma}$ on the number of channels

4 Conclusion

The FWM is sensitive to the power of each optical channel. As the number of channels increases, the power of each channel must be reduced. High power and nonlinear interference affect the level of interference and the quality of communication.

To meet the quality requirements for transmitting signals over optical channels with WDM, the following recommendations are offered:

- optimization of the level of transmitted optical power over the communication channels of systems with WDM. The level of the group optical signal should not exceed +23 dB of the set value recommended in ITU-T G. 662 [20];

-optical amplifier gain equalization and the number of optical amplifiers;

-rational distribution of inter-channel intervals, the number of wavelengths, and stabilization of their power level;

-the impact of FWM increases dramatically when the frequency range decreases to 50 GHz and when the optical power input to the optical fiber increases. To neutralize the FWM effect, you can use uneven intervals between channels in WDM.

Selecting the optimal power level of the group signal and evaluating the transmission quality of optical communication channels in WDM allows us to solve the problem of science-based design, implementation, and effective operation of advanced optical communication systems with wave division of channels.

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