Research Article

Assessment Of The Quality Of Signal Transmission In Fiber-Optic Communication Systems With Wave Division Of Channels

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Abstract: High power a group DWDM signal will lead to a change in the refractive index of OF (optical fiber), as a result of which additional combination products are formed. And also the non-fulfillment of the conditions of a single-mode OF regime in practice leads to the appearance of combination products and the manifestation of non-linearity 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 the power of a group signal on the power of nonlinear interference and on the quality of communication, 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 quality of transmission 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 article presents the results of research and analysis of factors affecting the quality of fiber-optic communication systems with wave separation of channels.
Keywords: fiber-optic communication systems, wave division of channels, optical channel, nonlinear effects, transmission quality.

1. Introduction

Fiber-optic communication systems with wave division of channels (FOCS-WD) are a promising technology that offers an efficient and inexpensive way to expand the operating frequency range of a communication network. This technology allows telecom operators to meet the ever-growing needs of customers for new types of services and provides greater flexibility in the process of providing these services. By enabling fiber-optic communication lines to transfer information through several channels simultaneously, WDM (wavelength division multiplexing) systems make the most of available opportunities, easily increasing the transmission volume by more than 10 times compared to traditional time-multiplexing systems and have large potential opportunities. However, the design, installation and maintenance of WDM systems require more serious attention to limiting the number of monitored parameters. The transition from systems with one wavelength to a system with several wavelengths leads to a number of 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 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, the transmission signal level is from -2 to +3 dBp, but in a 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 [1-3]. With an increase in the input signal power, the refractive index of the quartz fiber increases, which leads to nonlinear phenomena and distortions. The main non-linear effect is four-wave mixing (FWM). It is also necessary to take into account a number of other interferences, such as the optical amplifier's own noise (enhanced spontaneous ASE radiation). It is known that the power of a group DWDM (dense wavelength division multiplexing) signal has a direct effect on 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.

The study of nonlinear effects (NE) was considered in the works of scientists as: noise due to FWM of pumping sources was considered in the works of Fludger Ch. R. S., Headley C., amplification and NE in semiconductor lasers in the work of G.S. Sokolovski [4], nonlinear effects of forced Mandelstam-Brillouin scattering in the works of S. A. Bulgakova [5]. The research of the influence of nonlinear effects on the optical signal in optical fiber is devoted to the works of scientists: Agrawal G.P., Chraply A.R., Marcuse D., Tkach R.W., Matera F., Andreev V.A., Burdin V.A. [6] and others. Problems of modeling FOCL with Raman amplifiers were considered in the works of scientists Fedoruk M.P., Turitsyn S.K., Shapiro E.G., Dashkova M.V. [7, 8].

However, these works do not take into account the contribution of noise, which becomes important with an increase in the gain over 20 dB, and the change in the OF refractive index from an increase in the power of the baseband signal has not been studied.

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.

The above shows the relevance of the topic of this work.

2. Statement of the problem

This article discusses the assessment of the quality of signal transmission in fiber-optic communication systems with wave separation of channels and their calculation.

For this, the following tasks are solved:

1. Analysis and study of the main factors affecting the quality of signal transmission in WDM systems.
2. Analysis of methods for assessing the quality of optical communication channels in WDM systems and a method for choosing the optimal power level of the group signal.
3. Examples of calculating the optimal power level of the group signal and the power of the PBC and their impact on the quality of signal transmission in WDM systems.

In the linear path of optical communication systems with wave separation of channels, there are a number of 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) [9], an optical amplifier and others. The presence of nonlinearity leads to the fact that additional components appear at the output of the corresponding four-port network, which were absent in the original group optical signal. In an optical linear path, nonlinearity not only distorts the transmitted information at individual wavelengths, but also causes additional interference due to mutual parasitic modulation, and 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.

An optical fiber under certain conditions and levels of transmitted signals will have all the effects of non-linearity 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, a number of combination products of transformations are formed. These non-linear products are dangerous in that they exert mutual influence between parallel optical channels.

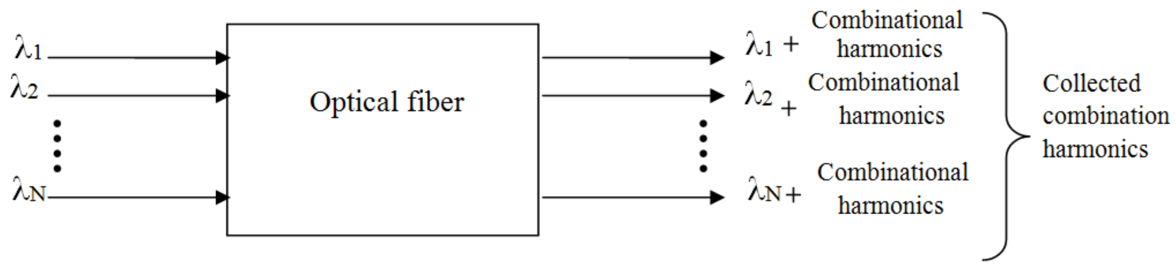

Fig.1. Nonlinear behavior of the optical fiber as a nonlinear four-terminal network in a strong electromagnetic field

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

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k,$$

where $i \neq k, j \neq k$.

In this case, twelve harmonics are formally generated from a mixture of total-difference frequencies of a 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).

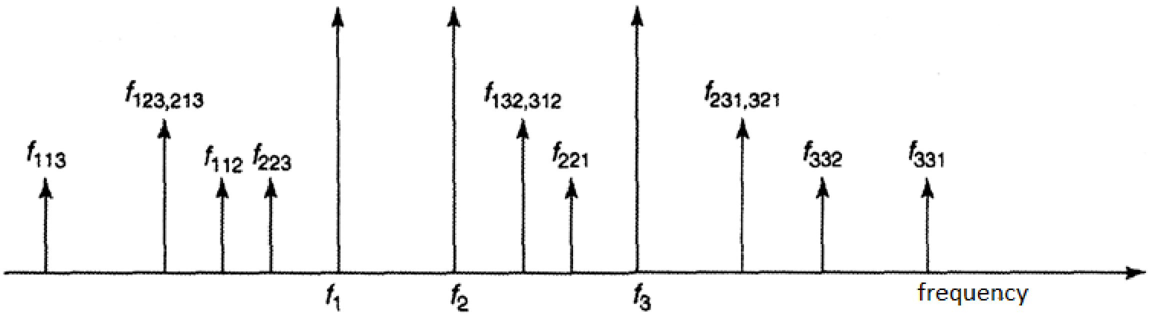

Fig.2. Mixture of products generated thanks to the FWM for 3 optical signals

3. Problem decision

From the correspondence of the frequencies of the combination harmonics with the frequencies of the working channel, cross-nonlinear interference appears. In this case, the total power of nonlinear interference P_Σ in FOCS-WS can be determined by the following expression

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

where $P_i -$ interference of the $i -$ nd optical channel with wave separation;
m - 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:

$$\mathrm{P}_{out} = f(\mathrm{P}_{in}) = \sum_{i=1}^{n} B_i P_{in}^i \tag{1}$$

where B_i- 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 $\mathrm{P}_{in} = \mathrm{P}_{max} \cos wt$, then the output power is determined by the formula:

$$\mathrm{P}_{out} = \sum_{i=1}^{n} B_i P_{max}^i \cos^i wt. \tag{2}$$

Usually, the elements of the optical linear path have a weakly expressed nonlinearity, that is, $\mathrm{B}_i \ll \mathrm{B}_{i-t}$.

In this case (1) and (2) can be written:

$P_{1h} \approx в_1 P_{max}$,

$P_{2h} \approx \frac{1}{2} в_2 P_{max}^2$,

$\vdots$

$P_{nh} \approx \frac{1}{2^{n-1}} в_n P_{max}^n$,

where P_{1h} – is the power amplitude of the useful signal component at the output; P_{2h}, P_{3h}, ..., P_{nh} – the amplitude of the powers of the harmonic components of the signal arising from the nonlinearity of the four-port network; P_{max} – is the input power amplitude.

To quantify harmonic distortion, harmonic coefficients are used:

$$к_{2h} = \frac{P_{2h}}{P_{1h}} = \frac{1}{2}\frac{в_2}{в_1} P_{max},$$

$$к_{3h} = \frac{P_{3h}}{P_{2h}} = \frac{1}{2}\frac{в_3}{в_2} P_{max},$$

$\vdots$

$$к_{nh} = \frac{P_{ng}}{P_{n-1h}} = \frac{1}{2}\frac{в_n}{в_{n-1}} P_{max}.$$

Under real conditions, the transmitted baseband signal is a more complex structure. Therefore, the assessment of 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

$$P_{in} = \sum_{i=1}^{n} P_к \cos(w_к t + \varphi_к).$$

Then the expression at the output of the nonlinear four-port network in accordance with equation (1) will be equal to

$$P_{out} = \sum_{i=1}^{n} B_i [\sum_{K=1}^{m} P_к \ \cos(w_к t + \varphi_к)]^i. \quad (3)$$

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 $c_1 + c_2 + \ldots + c_m = N \leq n$, a N - determines the order of the nonlinearity product (combination components or harmonics). If $c_1 \pm c_2 \pm \ldots \pm c_m = 1$, 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, the approximation of 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: $2w_x$ - second harmonics; $w_x \pm w_y$ - total and difference combination products.
2. Products of the third order: $3w_x$ - 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. In accordance with the central limit theorem of the theory of probability, 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.

We determine the energy spectrum of the group optical signal formed by the optical multiplexer at the output of the nonlinear four-port network (single-mode optical fiber, optical amplifier, etc.). Let us denote for convenience the instantaneous value of the power of the group optical signal at the input of the optical linear path P_{in} (t) through x, and the fixed values at t = t and t = t_2, respectively, through x_1 and x_2, so that is x = P_{in} (t); x1 = P_{in} (t_1); x2 = P_{in} (t_2). Similarly, the power at the output of a nonlinear four-port network is denoted by y, y_1, and y_2; moreover, $t_2 = t_1 + \tau$. Then equation (1) in this case takes the form

$$y(x) = \sum_{i=1}^{n} \text{в}_i x^i.$$

As is known, the spiral density G(w) and the correlation function к(τ) of a stationary random process are related to each other by the relation:

$$G(\mathrm{w}) = 4\int_0^\infty \kappa\ (\tau)\cos w\tau\, d\tau \qquad (4)$$

$$\kappa(\tau) = \frac{1}{2\pi}\int_0^\infty G\ (w)\cos w\tau\, dw$$

Thus, in order to find the energy spectrum of a group optical signal (including the spectrum of nonlinear interference) at the output of a nonlinear four-port network, it is necessary to determine the correlation function of the input signal. We will assume that a nonlinear four-port network does not contain reactive elements. This assumption is practically the case in single-mode optical fiber, optical amplifiers, and other optical components. The group optical signal at the output of a nonlinear four-port network (single-mode optical fiber and others) is also a random process, and its correlation function $\kappa_y(\tau)$ is determined by the expression:

$$\kappa_y(\tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{y}(\mathrm{x}_1)\,\mathrm{y}(\mathrm{x}_2)\ w_2(\mathrm{x}_1, \mathrm{x}_2, \tau)\, d\mathrm{x}_1 d\mathrm{x}_2,$$

where w_2 (x_1, x_2, τ) is a two-dimensional distribution function of a random stationary process at the output of a nonlinear four-port network. Since the output group optical signal x = P_{in} (t) obeys the normal law of probability distribution, then the distribution law of the signal at the output y = P_{out} (t) will be normal, and the two-dimensional distribution function will be equal to:

$$w_2(x_1, x_2, \tau) = \frac{1}{2\pi\kappa_x(0)\sqrt{1-R_x^2(\tau)}} \cdot \exp\left[\frac{x_1^2 + x_2^2 + 2R_x(\tau)x_1x_2}{2\kappa_x(0)\left[1-R_x^2(\tau)\right]}\right],$$

where κ_x (0) – is the correlation function of the input signal at $\tau = t_2 - t_1 = 0$;

$R_x(\tau) = \dfrac{\kappa_x(\tau)}{\kappa_x(0)} -$ is the correlation coefficient of the input optical signal.

Let us determine the correlation function of the input signal for the case when its energy spectrum, enclosed between the boundary frequencies w_H and w_B, is uniform and therefore approximately we can assume that

$$\left.\begin{array}{ll} G_x(w) = G_0 & \text{for } w_{\mathrm{H}} \le w \le w_{\mathrm{B}} \\ G_x(w) = 0 & \text{for } w_{\mathrm{H}} > w > w_{\mathrm{B}} \end{array}\right\}$$

Then, in accordance with (2.4), we find

$$\kappa_x(\tau) = \frac{1}{2\pi}\int_0^\infty G_x(w)\cos w\tau dw = \frac{1}{2\pi}\int_{w_{\mathrm{H}}}^{w_{\mathrm{B}}} G_0 \cos w\tau dw = \frac{G_0}{2\pi}\,\frac{\sin w_B\tau - \sin w_H\tau}{\tau}. \qquad (5)$$

At τ = 0, the correlation function of the group signal is equal to its variance; therefore, from expression (5) we find

$$\kappa_x(0) = \sigma^2 = \frac{G_0}{2\pi}\cdot\Delta w = G_0\cdot\Delta f = U_{in\ \mathrm{eff}}^2; \qquad (6)$$

where $\Delta f = \frac{w_H - w_B}{2\pi} = \frac{\Delta w}{2\pi}$;

$U_{in\ \mathrm{eff}}$ − effective voltage value of the input group signal.

From expression (6) it can be seen that the dispersion of the group signal is equal to its average power, which is allocated at a resistance of 1 Om. The correlation coefficient of the input signal, taking into account expressions (5) and (6), can be written

$$R_x(\tau) = \frac{G_0}{2\pi\tau\sigma^2} \cdot (\sin w_B\tau - \sin w_H\tau). \quad (7)$$

Knowing the parameters of the input signal, we can determine the correlation function of the signal at the output of the optical fiber, represented by the input of the nonlinear four-port network, by substituting the values $\kappa_x(0)$, $w_2(x_1\, x_2\, \tau)$ and $y(x)$ from (6), (4) and (3) into expression (1)

$$\kappa_y(\tau) = \frac{1}{2\pi\sigma^2\sqrt{1-R_x^2(\tau)}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sum_{i=1}^{n}\sum_{j=1}^{n} B_i B_j x_1^i x_2^j \cdot \exp\left[-\frac{1}{2\sigma^2[1-R_x^2(\tau)]}(x_1^2 + x_2^2 + +2R_x(\tau)x_1x_2)\right] dx_1 dx_2. \quad (8)$$

It is seen from expression (8) that the calculations of $\kappa_y(\tau)$ are reduced to determining the sum of the mean values of the product of two power functions of the normal process. Each term of this sum has the form

$$\kappa_{yij}(\tau) = x_1^i x_2^j B_i B_j = \frac{B_i B_j}{2\pi\sigma^2\sqrt{1-R_x^2(\tau)}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x_1^i x_2^j \cdot \exp\left[-\frac{1}{2\sigma^2[1-R_x^2(\tau)]}(x_1^2 + x_2^2 + +2R_x(\tau)x_1x_2)\right] dx_1 dx_2. \quad (9)$$

To calculate $\overline{x_1^i x_2^j}$, we use the Cramer expansion of the two-dimensional probability density of the normal process, with which expression (9) can be reduced to the form:

$$\overline{x_1^i x_2^j} = \sigma^{i+j} \sum_{K=0}^{\infty} N_{ik} N_{jk} \frac{R_x(\tau)}{K!}, \quad (10)$$

where

$$N_{\mu\kappa} = x^{\mu} F^{\kappa+1}(x) dx, \quad (11)$$

$$F^{\kappa+1}(x) = \frac{(-1)^{\kappa}}{2\pi} \int_{-\infty}^{\infty} \lambda^{\kappa} \exp\left[i\,\lambda\,x - \frac{\lambda^2}{2}\right] d\lambda. \quad (12)$$

The set of coefficients $N_{\mu\kappa}$, calculated in accordance with expression (11), forms a matrix of numbers, the elements of which are easy to find according to the following rule (as an example, in Table 1, the values of the coefficients $N_{\mu\kappa}$ are determined for μ from 0 to 7 and k - from 0 to 6) :

1. Elements above the main diagonal are zero, i.e. all coefficients $N_{\mu\kappa}$, for which $\kappa > \mu$, are equal to zero (in Table 1, we fill all cells to the right of the diagonal with zeros).
2. Below the main diagonal and on the diagonal itself (when $\mu = \kappa$), only elements with indices μ and κ of the same parity are nonzero (in Table 1 we fill in all other cells with zeros for which the parity μ and κ do not coincide, for example, for $\mu = 3$; $\kappa = 2$; $\mu = 6$; $\kappa = 3$, etc.).

Table 1: The values of the coefficients $N_{\mu\kappa}$ for from 0 to 7 and κ - from 0 to 6

μ	$N_{\mu\kappa}$ values at κ equal to						
	0	1	2	3	4	5	6
0	1	0	0	0	0	0	0
1	0	-1	0	0	0	0	0
2	1	0	2·1	0	0	0	0
3	0	-3·1	0	-3·2·1	0	0	0

4	3·1	0	4·3·1	0	4·3·2·1	0	0
5	0	-5·3·1	0	-5·4·3·1	0	-5·4·3·2·1	0
6	5·3·1	0	6·5·3·1	0	6·5·4·3·1	0	6·5·4·3·2·1
7	0	-7·5·3·1	0	-7·6·5·3·1	0	-7·6·5·4·3·1	0

3. The remaining elements of the matrix are defined as follows: to a given number μ, the numbers (μ-1), (μ-2), (μ-3), etc. are added as factors, so that everything is to the factors. So for example, for μ = 6 and κ = 2 we write two factors: 6 (6-1) = 6 · 5; for μ = 6 and κ = 4 we write four factors: 6 (6-1) (6-2) (6-3) = 6·5·4·3 and for μ = 6 and κ = 6 - six factors: 6 (6-1) (6-2) (6-3) (6-4) (6-5) = 6·5·4·3·2·1. Then we add as factors all odd numbers from (μ – κ – 1) to 1. For μ = 6 and κ = 2 to the factors 6 · 5 add all odd factors from (6–2–1) = 3 to 1, i.e. .e. 3 1. Finally, we get 6·5·3·1. Similarly, for μ = 6 and κ = 6 we have 6·5·4·3·2·1.

4. The sign of the element $N_{\mu\kappa}$ depends on the parity of *κ*; for odd *κ*, the element is taken with a negative sign, for even *κ* - with a positive sign.

Thus, having determined the coefficients $N_{\mu\kappa}$ and substituting (10) into (1), and, accordingly, into (5), we obtain

$$\kappa_y(\tau) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{\kappa=0}^{\infty} B_i\, B_j\, \sigma^{i+j}\, N_{i\kappa} N_{j\kappa}\, \frac{R_x^{\kappa}(\tau)}{\kappa!}. \quad (13)$$

Substituting (13) into formula (4), we find the full energy spectrum of the group signal – DWDM or HDWDM system at the output of a nonlinear four-port network – an optical fiber, multiplexed in frequency (wavelengths) of each optical channel:

$$G_{\text{full}}(w) = \frac{4B_1^2 G_0}{2\pi}\int_0^{\infty}\frac{\sin w_B\tau - \sin w_{\text{н}}\tau}{\tau}\cos w\tau\, d\tau. \quad (14)$$

After simple transformations, expression (14) can be rewritten as follows:

$$G_{\text{full}}(w) = \frac{4B_1^2 G_0}{2\pi}\frac{1}{2}\left[\int_0^{\infty}\frac{\sin(w_B + w)\tau}{\tau}d\tau + \int_0^{\infty}\frac{\sin(w_B - w)\tau}{\tau}d\tau - \right.$$

$$\left. - \int_0^{\infty}\frac{\sin(w_H + w)\tau}{\tau}d\tau - \int_0^{\infty}\frac{\sin(w_H - w)\tau}{\tau}d\tau\right]. \quad (15)$$

Considering that

$$\int_0^{\infty}\frac{\sin px}{x}dx = \begin{cases} \frac{\pi}{2} \text{ for p} > 0, \\ 0 \text{ for p} = 0, \\ -\frac{\pi}{2} \text{ for p} < 0, \end{cases}$$

get $G_{\text{full}}(w) = B_1^2 G_0$.

The energy spectrum of the second and third order is determined from the expressions:

$$G_{H_2}(w) = 2B_2^2\sigma^4 4\int_0^{\infty} K_x^2(\tau)\cos w\tau\, d\tau = 8B_2^2\int_0^{\infty} K_x^2(\tau)\cos w\tau\, d\tau. \quad (16)$$

(16) – energy spectrum of second-order nonlinearity products.

$$G_{H_3}(w) = 6B_3^2\sigma^6 4\int_0^{\infty} K_x^3(\tau)\cos w\tau\, d\tau = 24B_3^2\sigma^6\int_0^{\infty} K_x^3(\tau)\cos w\tau\, d\tau. \quad (17)$$

(17) – energy spectrum of third-order nonlinearity products.

In expressions (16) and (17), the integrand is a power-law function (second and third, respectively), which can be represented as the product of the correlation functions of the input signal with wave compression of the optical fiber $K_x(\tau)$ and use the Fourier transform for the product of functions: if the spectral density $G_1(w)$ and $G_2(w)$ of functions f_1 and f_2, then the spectral density of their product is equal to:

$$G_{\text{pr}}(w) = \frac{1}{2\pi}\frac{1}{2}\int_0^{\infty} G_1(x)\, G(w-x)\, dx. \qquad (18)$$

Passing from the angular frequencies w to the frequency f and using relation (18), one can find the energy spectrum of the second-order nonlinearity products:

$$G_{\text{H}_2}(w) = 2B_2^2\sigma^4 4\int_0^{\infty} \text{K}_x(\tau)\cos 2\pi f\tau\, d\tau = B_2^2\int_0^{\infty} G_x(\xi)\, G_x(f-\xi)\, d\xi, \qquad (19)$$

where $G_x(\xi)$ is the energy spectrum of the input signal x (τ), limited by the following values:

$$\left.\begin{array}{l} G_x(\xi) = G_0 \quad \text{for } f_H \le f \le f_B, \\ G_x(\xi) = 0 \quad \text{for } f_H > f > f_B. \end{array}\right\} \qquad (20)$$

The limits of integration of expression (19) will be determined by the values of f for which the spectra, G_x (ξ) and G_x (f-ξ) overlap. Integrating on each interval of existence of the integral (19) taking into account (20), we obtain:

$$\left.\begin{array}{ll} G_{H_2}(f) = 2B_2^2G_0^2(\Delta f - f), & 0 < f \le \Delta f \\ G_{H_2}(f) = B_2^2G_0^2(f - 2f_H), & 2f_H \le f < f_H + f_B \\ G_{H_2}(f) = B_2^2G_0^2(2f_B - f), & f_H + f_B \le f \le 2f_B \end{array}\right\}, \qquad (21)$$

where $\Delta f = f_B - f_H$.

III. JUSTIFICATION OF THE INFLUENCE OF THE POWER OF THE GROUP SIGNAL ON THE POWER OF NONLINEAR INTERFERENCE AND ON THE QUALITY OF COMMUNICATION. CALCULATION OF THE FOUR-WAVE MIXING POWER, AMPLIFIED SPONTANEOUS EMISSION, Q-FACTOR

There are several types of nonlinear effects, each of them to varying degrees affect 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 affects the level of interference and the signal-to-noise ratio. An increase in the step between optical carriers and the presence of chromatic dispersion reduce 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, small, but a 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 [10, 11], are more complete, allowing for a comprehensive quality control of the Central Committee and T.

Error indicators of digital channels and paths are statistical parameters, and the norms on them are determined by the corresponding probability. The power of the FWM of the generated harmonics f_{ijk} can be estimated by the following formula [12]:

$$P_{ijk} = \eta(2\pi f_{ijk}a_{ij}/3)^2(\gamma/S_{eff})^2(L/c)^2 P_iP_jP_k\exp(-\alpha L),$$

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

Nonlinearity coefficient γ at wavelength λ calculated by the formula [13]:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \qquad (22)$$

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

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

$$P_{\text{FWM1}}(f_m) = \sum_{i=1}^{N} \sum_{j=i}^{N} P_{ijk}\left(f_i, f_j, f_k\right), \qquad (23)$$

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 (1), 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). In order 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.

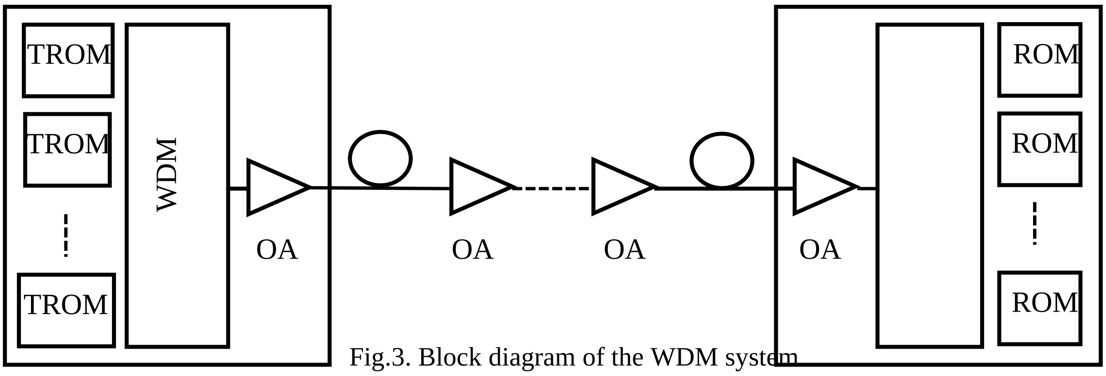

Fig.3. Block diagram of the WDM system

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 (ASR) is calculated by the formula

$$P_{ase1} = 2n_{sp}(G-1)hf_m\Delta f_0, \qquad (24)$$

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

$$P_{FWM\Sigma} = P_{ase1}(N_a+1). \qquad (25)$$

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

$$P_{ease\Sigma} = 4b^2 P_{in1ch} \frac{P_{\text{чвс}\Sigma}}{8} \qquad (26)$$

and

$$P_{ease\Sigma} = 4b^2 P_{in1ch} P_{ase\Sigma} \frac{\Delta f_e}{\Delta f_0}, \quad (27)$$

where Δf_e- the bandwidth of the electrical amplifier ROM ($\Delta f_e \cong 0{,}7B$)

The sensitivity of the photodetector b is equal to [14]:

$$b = \frac{\eta e}{h f_m}, \quad (28)$$

where η- quantum efficiency of a photodetector (η=0,8 for pin photodiode); e – electron charge (e=1,6·10^{-19} Kl).

The Q-factor and the associated error probability are calculated using the formulas [15]:

$$Q \approx \frac{b P_{\text{вх1к}}}{\sqrt{P_{ease\Sigma} + P_{\text{ечвс}\Sigma}}}, \quad (29)$$

and

$$P_{error} = \frac{1}{\sqrt{2\pi}} \int_Q^{\infty} e^{\frac{x^2}{2}} \text{dx}. \quad (30)$$

We choose the input signal power based on the fact that the power of the group signal 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 $P_{gr.s}$-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 [16]: 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:

1. Number of channels, N=16, 64, 160 pcs.
2. Number of amplifiers, N_a=8 pcs.
3. The transmission speed of the line, B= 10 Gbit/s
4. Planck constant, h= 6,626·10^{-34}j·s
5. Length of the amplifying section, L= 100 km
6. Coefficient of spontaneous emission of the amplifier, n_{sp}=1,4
7. The efficiency of FWM, η =0,8
8. Attenuation coefficient of OF, α=0,2 dB/km
9. Signal frequency, f_m= 1,93·10^{14} Hz
10. Amplifier gain, G=40
11. The charge of the electron, e= 1,6·10^{-19} Kl
12. The bandwidth of the electrical amplifier ROM, Δf_e=0,7B
13. 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	16	64	160
P_{in1ch}	6,25	1,5625	0,625
Q	684,8914	175,1296	70,3774
$P_{FWM\Sigma}$	2,2 ·10^{-5}	7,6 ·10^{-5}	0,000118
$P_{ase\Sigma}$	2,5·10^{-6}	8,5·10^{-6}	1,3·10^{-5}

From the above formulas (22) - (30), it can be seen that the $P_{\text{FWM}\Sigma}$ and Q-factor depend on the power of the transmitter signal (Fig. 4, 5).

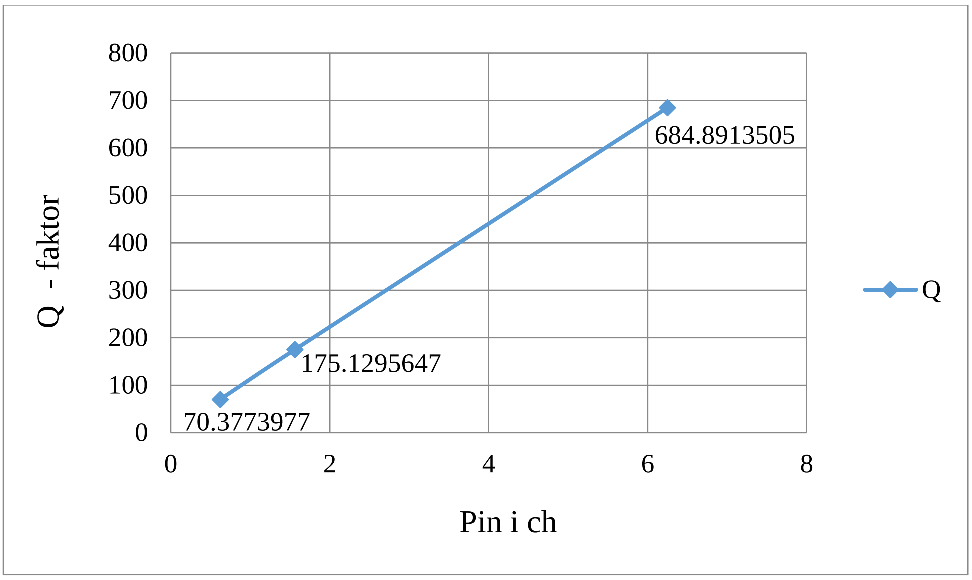

Fig. 4: The dependence of the Q-factor of the power signal

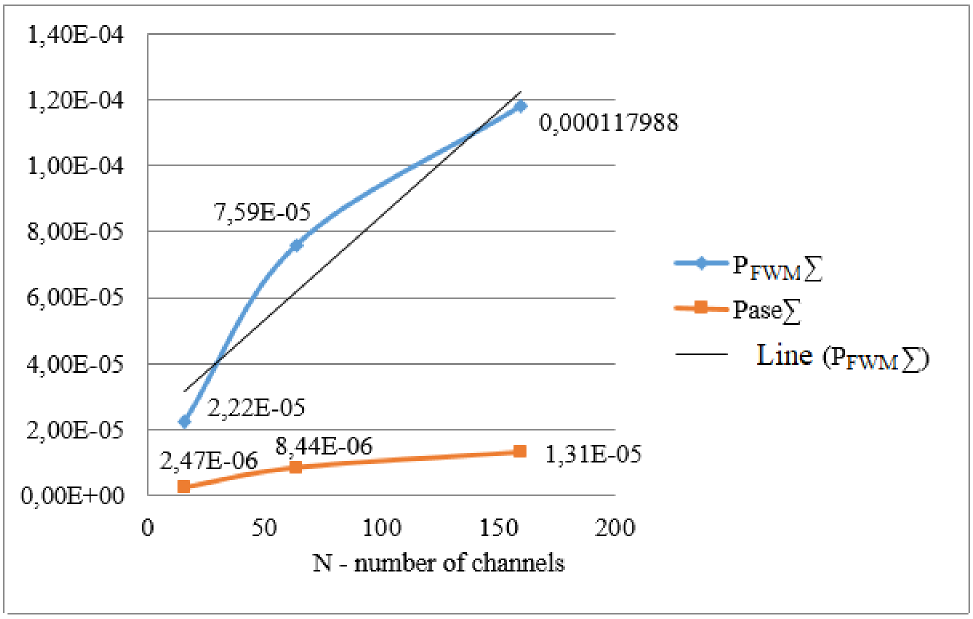

Fig. 5: Dependence of $P_{FWM\sum}$ and $P_{ASE\sum}$ on the number of channels

4. Conclusions

Based on the results of the study, the following conclusions were obtained: - In WDM systems, the influence of FWM is especially damaging because the FWM level is sensitive to system performance. - The level of FWM decreases sharply in systems with a step of 200 GHz, in comparison with systems with a step of 100 GHz, as well as with a decrease in the absolute value of chromatic dispersion; - 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 non-linear 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; - optical amplifier gain equalization and the number of optical amplifiers [17-19]; -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 [20] 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 quality of transmission 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.

References

1. Generic characteristics of optical fiber amplifier devices and sub-systems, ITU-T Recommendation G.662, (10.98).
2. Mirazimova, G.X. About quality of optical channels in wavelength division multiplexing systems of optic fibers. TELKOMNIKA, Vol.16, No.5, pp.2005-2013, 2018.
3. Friman, R. Volokonno-opticheskie sistemy svyazi: Perevod s angliyskogo pod red. N.N. Slepova. M.: Texnosfera, 2003 (in Russian).
4. Sokolovskiy, G.S. Usileniya i nelineynye effekty v poluprovodnikovyh lazerah s periodicheskimi optikeskimi neodnorodnostyami. Avtoreferat. Sankt-Peterburg, 2010 (in Russian).
5. Bulgakova, S.A. Nelineynye явleniya v optovolokonnyx interferometrax pri malyx moshchnostyax izlucheniya v svetovode. Sankt-Peterburgskiy gosudarstvennyy universitet informatsionnyh texnologiy, mexaniki i optiki. Avtoreferat. Sankt-Peterburg, 2010 (in Russian).
6. Andreev, V.A., Voronkov, A.V., Bourdin, A.V. and Dashkov, M.V. Simulation Modeling of Fiber Optic Communication Links // Proceedings of SPIE, vol. 4579, pp. 46-53. 2001.
7. Fedoruk, M.P., Shapiro, A.D. and Shapiro, E.G. Modelirovanie volokonno-opticheskix liniy svyazi s ramanovskimi usilitelyami // Avtometriya. t. 39.-№4. pp. 109-116. 2003.
8. Dashkov, M.V. Modelirovanie i isledovanie volokonno-optickoy linii peredachi so spektralnym uplotneniem i ramanovskimi usilitelyami. Avtoreferat. Samara 2006 (in Russian).
9. Sharvarko, V.G. Volokonno-opticheskie linii svyazi: Uchebnoe posobie. - Taganrog. Izd-vo TRTU, p.170, 2006 (in Russian).
10. Error performance of an international digital connection operating at a bit rate below the primary rate and forming part of an Integrated Services Digital Network, ITU-T Recommendation G.821.
11. End-to-end error performance parameters and objectives for international, constant bit-rate digital paths and connections, ITU-T Recommendation G.826.
12. Dmitriev, S.A. and Slepov, N.N. Volokonno-opticheskaya texnika: Sovremennoe sostoyanie i perspektyvy. 2-e izd., Perab. i dop.: OOO "Volokonno-opticheskaya texnika", p.576, 2005 (in Russian).
13. Shiva, K. and Deen, M.J. Fiber Optic Communications: Fundamentals and Applications. USA publisher. p. 572, 2014.
14. Pedyash, V.V. and Reshetnikova, O.S. Power optimization of linear signal in DWDM system. Odessa national academy of telecommunications named after A.S. Popov. № 5, p. 7, 2009.
15. Yoshihisa Yamamoto and Kyo Inoue. Noise in Amplifiers // Journal of Lightwave Technology. Vol. 21, Issue 11, p. 2895, 2003.
16. Mirazimova, G.X., Sobirov, O.B. and Aminov, M.I. Control of group signal strength transmitted in dense wavelength density systems. International conference on importance of information-communication technologies in innovative development of sectors of economy, p.620-623, 2018.
17. Definition and test methods for the relevant generic parameters of optical fiber amplifiers, ITU-T Recommendation G.661, (10.98).
18. Generic characteristics of optical fiber amplifier devices and sub-systems, ITU-T Recommendation G.662, (10.98).
19. Application related aspects of optical fiber amplifier devices and sub-systems, ITU-T Recommendation G.663, (4.00).
20. Spectral grids for WDM applications: DWDM frequency grid, ITU-T Recommendation G.694.1, (6.02).