POWER OPTIMIZATION OF LINEAR SIGNAL IN DWDM SYSTEM

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Summary. *The power optimization problem of a linear signal in multichannel system with spectral division of optical channels is considered taking into account nonlinear interference of an optical fibre and noise of the optical amplifier, formulas for power calculation of channel signals are deduced at different channel offsets.*

Construction of next generation networks is accomplished by sealing of existing and creating of new fiber-optic communication lines with the help of DWDM (Dense Wavelength Division Multiplexing) technology. During the design of trunks using this technology it is necessary to take into account nonlinear interference four-wave mixing (FWM) [1], which can lead to the interchannel interference and decrease the quality of organized optical channels.

During the calculations it's also needed to take into account a number of other noises, such as the intrinsic noise of the optical amplifier (amplified spontaneous emission ASE). It's also known that the power of group signal of DWDM directly influences the value of power of noise FWM and doesn't influence the power of noise ASE. That's why during the designing of DWDM trunk the optimization of signal transmitter have to be done in order to minimize the probability of error in the optical channel. In the works [2-3] are presented the expressions for calculation of power of FWM noises, but the main attention in it is dedicated to the comparison of the theoretical calculation results and experimental measurements of the interference power. The choice of the optimal power values of channel signals in the transmitter in these works was not carried out. Since WDM systems typically operate according to a standard optical fiber (recommendation of ITU G. 652), this is what should be focused on.

Therefore, the aim of this article is to optimize the signal strength of the transmitter DWDM system with regard to the effect of four-wave mixing in standard optical fiber.

In the foreign literature[2-3] the next formula represents the power of noise of FWM:

$$P_{ijk}(f_i, f_j, f_k) = \frac{\eta}{9} D^2 \gamma^2 P_i P_j P_k e^{-\alpha L} \left\{ \frac{(1-e^{-\alpha L})^2}{\alpha^2} \right\}, \tag{1}$$

where P_i, P_j and P_k - are the values of power of input channel signals on the frequencies f_i, f_j and f_k; D – the coefficient of wobble hypothesis (D=3 at i=j and D=6 at i≠j); α - optical fiber attenuation coefficient; L – OF section length.

In this formula and the following text of the article is considered the peak power of the signal. For NRZ code used in DWDM systems, the average power of the signal is 3 dB below the peak.

The nonlinearity coefficient γ at a wavelength of λ is calculated by the formula

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}, \tag{2}$$

where n_2 - the nonlinearity coefficient of the refractive index ($n_2 = 2,68 \cdot 10^{-20}$ m^2/W); A_{eff} – effective area of optical fiber (A_{eff} =50 mkm^2).

Further, the effectiveness η FWM is described by the formula:

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left[1 + \frac{4e^{-\alpha L}\sin^2\left(\dfrac{\Delta\beta L}{2}\right)}{\left(1 - e^{-\alpha L}\right)^2}\right]. \qquad (3)$$

The ratio of phase matching $\Delta\beta$ depends on interchannel interval, of chromatic dispersion $Dc\ (\lambda)$ and its derivative $dDc\ (\lambda)\ /\ d\ \lambda$ at a wavelength of λk

$$\Delta\beta = \frac{2\pi\lambda_k^2}{c}\Delta f_{ik}\Delta f_{jk}\left[D_c(\lambda) + \frac{\lambda_k^2}{2c}\left(\Delta f_{ik} + \Delta f_{jk}\right)\frac{dD_c(\lambda)}{d\lambda}\right], \qquad (4)$$

Where the inter-channel interval equals $\Delta f\ i_k = |f_i\text{-}f_k|$ and $\Delta f_{jk} = |f_j\text{-}f_k|$;
c – speed of light ($c \approx 3 \cdot 10^8$ m/s).

The power of FWM noise on the frequency fm equals to the sum of all products:

$$P_{\mathrm{FWM1}}(f_m) = \sum_{i=1}^{N}\sum_{j=i}^{N} P_{ijk}(f_i, f_j, f_k), \qquad (5)$$

where N is the number of channels.
During the computation, in this equation for each combination of *fi* and *fj* it is necessary to calculate $f_k = f_i + f_j - f_m$. If the condition $f_1 \le f_k \le f_N$, power of FWM noise at the frequency f_m is calculated by the formula (1), otherwise the interference power is equal to zero.

Further calculations are carried out for WDM system consisting of optical amplifiers N_{amp} and sections of equal length L (Fig. 1). In order to increase the signal level on the input of receiving optical module (ROM) there is also equipped an optical amplifier with a number (N_{amp}+1).

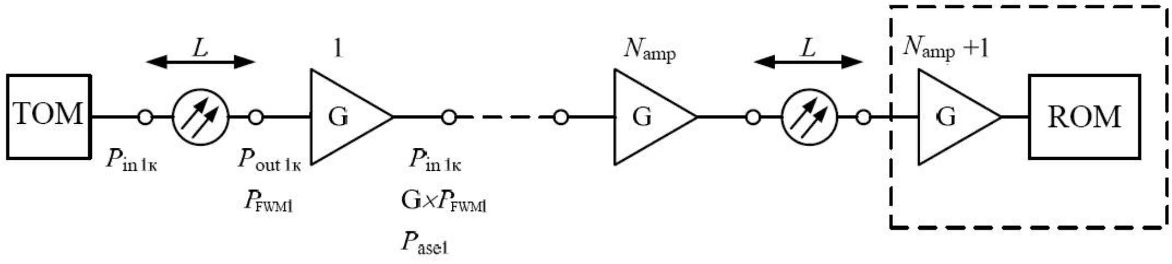


Figure 1 - Block diagram of a WDM system

We assume that the power of signal of 1 optical channel on the output of amplifier equals to the power of transmitting optical module (TOM) P_{in1k}. In this case, the signal of the power P_{out1k} on the output of OM section needs to be strengthened in G =P_{in1k} / P_{out1k} = 1 / $e^{-\alpha L}$ times.

It is known [5] that the power of the amplified spontaneous emission (ASE) is calculated by the formula

$$P_{ase1} = 2n_{sp}(G-1)hf_m\Delta f_o\,, \tag{6}$$

where n_{sp} - the coefficient of spontaneous emission of amplifier (n_{sp} =1,4);
h - Planck constant (h = 6,626*10^{-34}J/s);
Δfo – bandwidth of optical filter of WDM demultiplexer ($\Delta f_o \cong 1,25V$);
B - speed of transmission of a digital signal over an optical channel.

Since in this example all the parts are of the same length, the power of the amplified spontaneous emission at the input of the receiving optical module (ROM) is equal to the sum of the respective output powers of all the amplifiers:

$$P_{ase\Sigma} = P_{ase1}(N_{\text{amp}}+1)\,. \tag{7}$$

The FWM power at the input of ROM is calculated in the same way :

$$P_{\text{FWM}\Sigma} = P_{\text{FWM}}\,G(N_{\text{amp}}+1)\,. \tag{8}$$

On the output of the photodetector the optical noises FWM and ASE respectively form an electrical signal of the power

$$P_{\text{eFWM}\Sigma} = 2b^2 P_{\text{in1k}}\ \frac{P_{\text{FWM}\Sigma}}{8} \tag{9}$$

And

$$P_{ease\Sigma} = 4b^2 P_{in1k}\, P_{ase\Sigma} \frac{\Delta f_e}{\Delta f_o}, \qquad (10)$$

where Δf_e is the ROM electrical amplifier bandwidth (Δf_e ~ 0,7V)
The sensitivity of photodetector b equals:

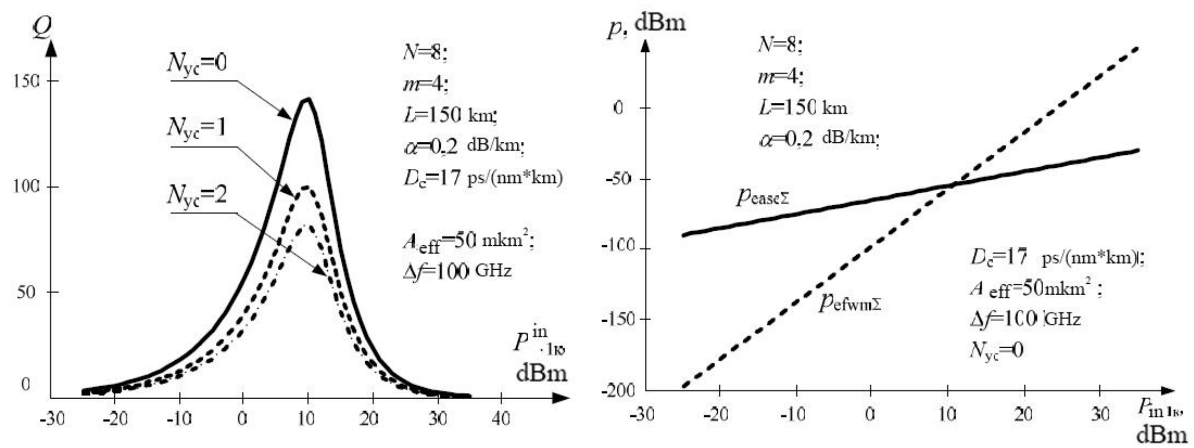
$$b = \frac{\eta e}{h f_m}, \qquad (11)$$

where η - quantum efficiency of the photodetector (η=0.8 for pin photodiode);
e – the electron charge (e=1,6·10^{-19} Cl).
Q-factor and the associated probability of error can be calculated by the formulas [6]:

$$Q \approx \frac{bP_{in1k}}{\sqrt{P_{ease\Sigma} + P_{eFWM\Sigma}}} \qquad (12)$$

$$P_{err} = \frac{1}{\sqrt{2\pi}} \int_Q^\infty e^{-\frac{x^2}{2}} dx \,. \qquad (13)$$

From the above formulas (1) to (11) we see that Q and P_{err} depend on the signal power of the transmitter P_{in1k} for standard OF (A_{eff}=50mkm^2) (Fig.2)



a) b)

Figure2. Influence of transmitting level on:

a) Q-factor;
b) the FWM noise and amplified spontaneous emission level.

To simplify further calculations we substitute formula (4) in (3), and then the result in formula(1). After that, perform the following approximation:

1) In the denominator of expression (3) $\alpha^2 \ll \Delta\beta^2$, so $(\alpha^2 + \Delta\beta^2) \approx \Delta\beta^2$;
2) For standard optical fiber in the formula (4) the value of the first addend Dc (λ) is much more of the second term, so the last one can be neglected;

3) as in formula (3), the sine is a periodic function, then for a sufficiently large number of channels N his argument will be of a uniform law of distribution in the range [0;2π], so the function can be replaced by its RMS value $\sin^2(\Delta\beta L/2) \approx 0{,}7^2 \approx 0{,}5$;

4)In the formula (4) we assume $\lambda_k \approx 1550$nm for all the channels *(1≤k≤N),* as interchannel interval is much greater than the wavelength of the first channel.

$$P_{\mathrm{FWM1}}(f_m) \approx const \cdot sum_{ij}, \tag{14}$$

where

$$const = \frac{1}{36}\frac{e^{-\alpha L}\left(1+e^{-2\alpha L}\right)c^2\gamma^2 P_{\mathrm{in1k}}^3}{\left[\pi\lambda_k^2 D_c(\lambda_k)\right]^2 \Delta f^4} \tag{15}$$

and

$$sum_{ij} = \sum_{i=1}^{N}\sum_{j=i}^{N}\frac{D^2}{\left|i-k\right|^2\left|j-k\right|^2}. \tag{16}$$

With this in mind, at the same power P_{in1k} and the interchannel interval Δf , the formula (5) takes the following form:

In the formula (16) the value of $k = i + j - \mathrm{m}$ must satisfy condition$1 \le k \le N$

The calculations has shown that the most part of the power of FMW noise happens in the central channels ($m = N/2$), that's why further calculations are held for these channels. Assuming the average calculations the formula (16) can be approximated as:

$$sum_{ijk} \approx 212{,}8\frac{\lg(N)}{N^{0{,}2}}. \tag{17}$$

From Fig. 2 we can conclude that at the point of extremum of the function Q (P_{in1k}) the equation $P_{ease\Sigma} \approx P_{e\mathrm{FWM}\Sigma}$.

Equating expressions (9), (10) and after the necessary transformations, we obtain the condition for an extremum of Q (P_{in1k}) :

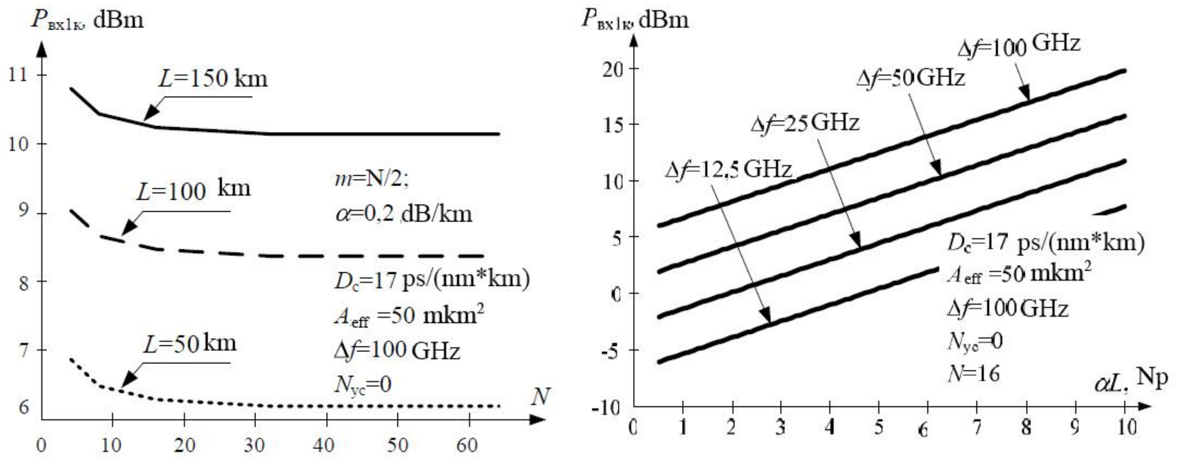
$$P_{\text{FWM}\Sigma} \approx 9P_{\text{ase}\Sigma} \,. \tag{18}$$

Obtaining the maximum value of the Q-factor at the input of the photodetector is possible in case of fulfillment of conditions (18) on each section line. In the diagram (Fig. 1) all sections of the same length, so it is enough that the condition $\times P_{FWM1} = 9P_{ase1}$.
In this case, from the expressions (14) and (15) we determine the optimal value of P_{in1k}

$$P_{\text{вх1к}} = \sqrt[3]{\frac{9P_{ase1}}{\frac{1}{36}\frac{e^{-\alpha L}\left(1+e^{-2\alpha L}\right)c^2\gamma^2 G}{\left[\pi\lambda_k^2 D_c(\lambda_k)\right]^2 \Delta f^4} sum_{ijk}}} \,. \tag{19}$$

This formula allows you to find the optimal value of signal power for sections with known parameters of the transmitter, receiver and transmission media. A graph of the optimal level of transmission from the number of channels of the WDM system is shown in Fig. 3a. This graph shows that the optimum power of the optical signal at the input of the optical fiber should slightly increase with increasing of its length. This is because with increasing of length of the optical fiber the attenuation is increased and the power of FWM noises is reduced. Therefore, t is necessary to increase the input power to perform the conditions of maximization of the Q-factor (18). Also the graph shows that the input power P_{in1k} should decrease with increasing number of channels N. This is because the increase in the number of channels leads to an increase in the number of summands in the formula (16) and to the increase the power of FWM noises. Therefore, to satisfy the condition (18), at a constant value of $P_{ase\Sigma}$ input power P_{in1k} should decrease.

The value of expression (19) depends on the following parameters of the transmission medium: dispersion D_c , attenuation coefficient α and the length of fiber L. DWDM systems, mostly,operate using the standard optical fiber with the value of dispersion D_c =17 ps/(nm*km), that's why depend mostly on the fiber attenuation αL . Numerical calculations show that the dependence $P_{\text{in1k}}(\alpha L)$ is linear (Fig. 3,b). Approximation formulas for the calculation of this relation for different inter-channel spacing Δf are given in table. 1. It should be noted that the damping factor has to be substituted in Neppers.



a) b)

Figure 3. The dependence of optimal transmitting level on the:
a)number of channels of WDM system;
b)OF attenuation.

Table 1 – The computing power of the individual channel signals at the input S

Δf, GHz	P_{in1k}, dBm
100	$1,45\alpha L + 5,22$
50	$1,45\alpha L + 1,2$
25	$1,45\alpha L - 2,82$
12,5	$1,45\alpha L - 6,83$

Summarizing, we can conclude that to maximize the Q-factor is necessary to optimize the signal power of the transmitter according to expression (19). With the increase in the number of channels N, the optimal value of the power signal of one channel of the transmitter decreases as the number of summands of interchannel interference increases in the expression (14). The greatest number of summands corresponds to the average channels, the least – to the side ones. Also the approximate expressions for calculating of the optimum values of the signal power of the transmitter depending on the attenuation of optical fiber are got.

In further studies in this direction it is necessary to investigate the behavior of power of FWM noise with uneven frequency interval between channels distribution.

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