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About Quality of Optical Channels in Wavelength Division Multiplexing Systems of Optic Fibers

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Abstract

Researches and the analysis of factors of the systems influencing quality with division according to radiation wavelength are given in article. Especially the communication quality in systems with wave division of channels is influenced by hindrances from Four Wave Mixing. In this regard the technique of definition of number of products of nonlinear effect of Four Wave Mixing getting to ranges of working channels, results of calculation of combinational products for the different number of channels in systems with division according to radiation wavelength is given. Power of a hindrance of Four Wave Mixing in systems with wave division of channels is calculated. Methods of reduction of influences of these nonlinear effects are considered. Conclusions and recommendations on ensuring quality of optical channels are provided in systems with wave division.

Keywords: *system, wavelength division multiplexing, optical fiber, channel, nonlinear effects, signal level, optical power, transmission quality, four wave mixing*

1. Introduction

In the conditions of fast development of technologies, production, economy, science and technology, the accelerated rates also the volume of the transmitted data increases. Increase in volume of the transmitted data imposes new requirements to quality of the provided services. Telecommunication operators have to provide quality of information transfer at acceptable capital and operational expenditure. At the same time it is necessary to increase the bandwidth of transmission media and to qualitatively serve the arriving traffic that obliges operators to provide compliance of all technical characteristics of elements, systems and network of telecommunication to standard requirements.

One of technologies of the transport network of telecommunications providing high capacity is the fiber-optical system of transfer with a wave division of wavelength division multiplexing channels (WDM). Essence of technology of wave division of channels are in what on fiber can be transferred at the same time a little bearing with different wavelength, this technology divides suitable for transfer on fiber of length of waves into several ranges. In each range the optical signal on the set wavelength is transmitted and these channels are independent. WDM uses for signal transmission with different speeds a wide strip of single-mode fiber in the area with small losses. The digital signal transmitted by different spectral channels can be as with identical speeds and protocols, and different. Each channel can provide about directed and opposing signaling on one fiber. The grid of frequencies for WDM is established in the range of frequencies from 184,5 TGts up to 195,9375 TGts, with a step of the frequencies of 12,5 GHz, 25 GHz, 50 GHz, 100 GHz and more than [1].

It is possible to change the capacity of network depending on inquiries of users by change of parameters of spectral channels. Use of modern technologies allows to multiplex channels with an interval at the level of nanometer. It is possible even to realize multiplexing on sub nanometer range, but at the same time more great demands are placed on components. Multiplexing 8, 16, 32 or more spectral channels with a small channel interval is called dense multiplexing on DWDM wavelength. The G.692 ITU-T standard suggests to take the frequency of 193,1 TGts (the corresponding wavelength 1552,52nm) as an absolute standard, other frequencies of spectral channels undertake with an interval of multiple 100 GHz (the corresponding difference of lengths of waves multiply of 0,8 nanometers) [2]. DWDM not only considerably increases the capacity of network and more fully uses the bandwidth of optical

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fiber, but also has a set of advantages, such as light expansibility and reliability of operation, especially to them should note a possibility of direct connection of various services and granting a wide strip.

At introduction of WDM the quality of signaling is influenced by specific factors which are demanded by researches. Research of influence of major factors as four wave mixing (FWM) and also hindrances from the neighboring canals and the restriction of total power of a light signal introduced in optical fiber will allow to solve problems of realization and introduction of the WDM systems and will promote ensuring the required quality of transfer of optical signals. The aforesaid shows relevance of a subject of this article. The purpose of article is the research of quality of signaling in the perspective fiber-optical systems of transfer with division according to wavelength.

2. Research Method

The following problems are for this purpose solved:

a. The analysis and a research of the major factors influencing quality of signaling in WDM;
b. The analysis of the WDM parameters providing high-quality signaling;
c. A research of methods of improvement of quality of signaling in WDM.

The factors influencing quality of transfer of WDM are given in Figure 1. Factors between axes the power and time belong to the fiber-optical systems of transfer (FOST) with temporary division and wave division of channels. On an axis of power such parameters as the power of the laser, loss in fiber and the losses brought by components are postponed.

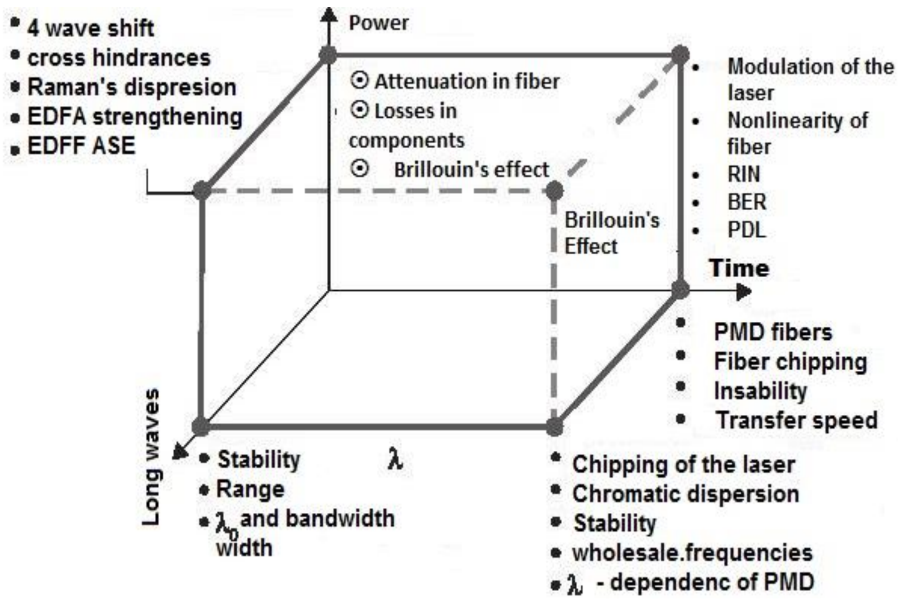

Figure 1. The factors influencing quality of WDM

Along other axis the parameters connected with time are postponed. It is polarizing mode dispersion of fiber, chromatic dispersion and also instability of a signal and speed of transfer. On crossing of axes there are new parameters demanding account: depth of modulation of the laser, nonlinearity of fiber, relative intensity of noise and coefficient of bit mistakes.

The axis wavelength belongs only to the WDM system and much more complicates representation of key parameters. Along an axis of lengths of waves the following parameters are postponed: stability of a range, spectral range of the EDFA amplifier, central wavelength and width of bandwidth. On crossing of parameters of time and wavelength settle down: deviation of frequency of the laser, chromatic dispersion, stability of optical frequency and phase noise. Joint influence of wavelength and power is shown in such phenomena as: the strengthened spontaneous radiation of ASE, strengthening of EDFA, cross hindrances, four wave mixture and the compelled combinational dispersion (Raman). And, at last, the compelled Brillouin-Mandelstam's dispersion is defined by all set of variables [3].

At WDM design all these factors have to be considered in a due measure. The wrong design often doesn't allow to realize potential opportunities of the used expensive equipment [4]. We will consider the above-mentioned major factors influencing quality of signaling in WDM. At WDM realization first of all it is necessary to provide the maximum coefficient of strengthening of EDFA at the maximum relation signal/noise. It takes place when using lasers with the wavelength on which the minimum absorption of optical radiation is provided. In this regard recently the increasing distribution is found by lasers with the wavelength of 980 nanometers which in comparison with lasers on 1480 nanometers provide smaller absorption at bigger coefficient of strengthening of EDFA.

Other factor defining the choice of the laser are its stability and a spectral characteristic of radiation which define degree of their negative impact on EDFA as the last add optical noise (ASE) to the strengthened signal in all strip of transmission frequencies, but not to an entrance of each certain canal. It, leads to redistribution of levels of signals in various channels and to their mutual influence that predetermines need of measurement of level of noise on all communication line supporting many EDFA as each amplifier increases not only the level of a signal, but also level of noise. As a result noise extends on all lengths of waves whereas the signal passes only across canals with certain lengths of waves. As the level of strengthening of each amplifier changes depending on wavelength, there is a danger that noise of extra band signals will be strengthened stronger, than a useful signal. Though the difference at one stage of strengthening can be insignificant, several stages of strengthening can already have significant effect on the relation signal/noise.

When multiplexing and DE multiplexing signals of bandwidth of channels have to correspond precisely to the chosen lengths of waves not to create cross hindrances, and extra band suppression on each channel has to be rather high for an exception of influence of the neighboring canals and side petals. Besides, they have to provide only the admissible shift of the central wavelength of the leading laser of any channel without essential weakening of a signal.

Optical amplifiers, as a rule, of EDFA, provide economic operation of WDM due to essential strengthening of all channels irrespective of schemes of modulation and the used protocols. It means that the modulated optical signal can be transmitted to very long distances without the need for intermediate recovery and repeated formation of the transmitted data. However during creation of network, especially when certain canals support several amplifiers, it is necessary to consider dependence of strengthening of EDFA on wavelength, moreover, as indicators of noise of separate EDFA exert a great influence on integrity of an optical signal, they will define the necessary number of amplifiers and as a result the maximum extent of connection. The linear optical amplifiers used in the WDM systems according to the characteristics have to correspond to the recommendations of ITU-T G.661, G.662, G.663 [5-7].

For WDM functioning, characteristics of the most optical fiber (OF) are more important. When studying WDM considerably bigger attention has to be paid to chromatic dispersion. WDM usually use small, carefully controlled part of optical range for reduction of influence of Four Wave Mixing (FWM). Also in WDM working with use of high speeds, the special complexity is represented by a question of polarizing mode of dispersion (PMD) at which the speed of distribution of a light wave depends on her condition of polarization. Now there are no known ways of elimination of influence of this type of dispersion. PMD has to be measured and reduced, by means of the choice of components.

With the advent of WDM, levels of signals have increased is hundredfold. At association of an exit of the laser transmitter with the optical amplifier it was necessary to generate levels of signals about +20 dBm to offset the losses caused by use of the passive WDM elements. These high levels of signals have aggravated many reasons leading to deterioration, anyway leading to degradation of a signal and characteristics in general [8].

Therefore it is necessary to reduce total power, entered into fiber. Maximum power of each optical channel P_{max} (in dBm) depends on the full optical capacity given from a transponder exit to an input of fiber P_{full} (optical power (in dBm) and numbers of the multiplexed lengths of waves of n

$$P_{max.} = P_{full.} \cdot 10 \lg n. \quad (1)$$

Considering that P_{full}. it is limited to either a class of safe level of radiation of the laser, or admissible level of total nonlinear distortions in a core of fiber and makes size from 17 to 30 dBm for different producers of the equipment of WDM, it is possible approximately to estimate as this power counting on the channel for different number of channels as shown in Table 1 changes.

From this table it is visible that at a large number of channels falling of power can make (against initial level -2 channels) 21 dB, and it can lead to problems with ensuring the necessary level of coefficient of mistakes in the optical channel. The only way of fight against it is increase in effective cross-sectional area of fiber [9].

Table 1. Level of the maximum power in each WDM channel at her uniform distribution

Number of channels, n	2	4	8	16	32	64	128	256
P_{full} = 17 dBm	14	11	8	5	2	-1	-4	-7
P_{full} = 30 dBm	27	24	21	18	15	12	9	6

In WDM owing to dependence of index of refraction of OF on electric field there are nonlinear effects. The main destabilizing factor is the nonlinear effect as FWM. In a result of parametrical strengthening when the intensity of a laser signal reaches critical level and when OF plays a passive role of the environment of distribution, there are four wave mixture, generation of harmonicas in which several optical waves interact thanks to a nonlinear response of the electrons of external covers excited by them.

FWM leads to emergence of the new disturbing harmonicas, part of them gets to working canals of system. From compliance of the disturbing harmonicas with frequencies of the working channel cross hindrances appear. These disturbing factors worsen quality of signaling and can put out of action the WDM system completely. FWM essence (from positions of quantum mechanics) is that if there is an interaction of four linearly polarized along an axis x optical waves $f_{1,}, f_2, f_3, f_{4,}$ to frequencies that destruction of photons of one frequency and the birth of photons of other frequencies at conservation of energy can be observed and an impulse. It can occur according to two schemes:

a. transmission of energy of three photons to the fourth, generated at a frequency

$$f_4 = f_1 + f_2 + f_3;$$

b. transmission of energy of two photons two new, generated at frequencies

$$f_3 + f_4 = f_1 + f_2.$$

Formally these schemes can be consolidated in one: $f_4 = f_1 + f_2 \pm f_3$, having generalized it for a case of interaction of three linearly polarized any waves f_i, f_j, f_k presented in the form [9]

$$f_{ijk} = f_i + f_j \pm f_k. \quad (2)$$

FWM can arise even in single-channel systems between signals of the working channel and components of the strengthened spontaneous issue of optical amplifiers and also between the main and side mode.

3. Results and Analysis

The analysis has shown that, in WDM influence of FWM is especially destructive since the FWM level is sensitive to system characteristics: to increase in power in the channel; to increase in number of channels; to reduction of a step between channels that causes need of a research of their influence on the level of hindrances and a ratio signal/noise.

However in works the accurate technique of determination of power of hindrances isn't given in spectral channel WDM that doesn't allow to calculate precisely the optical signal/noise ratio (OSNR) in the channel and to compare this size to existing rules. The analysis has shown that, in WDM influence of FWM is especially destructive since the FWM level is sensitive to system characteristics: to increase in power in the channel; to increase in number of channels; to reduction of a step between channels that causes need of a research of their influence on the level of hindrances and a ratio signal/noise.

In this regard the technique of definition of number of the products getting to the canal is of interest. In Figure 2 the arrangement of the optical bearing channels in WDM range at the restrictions stated above is shown, let the influencing channels are i, j, to. Signals in channels i, j, k create the nonlinear hindrance of the third order of the first sort getting to channel x at the expense of FWM. Frequency of this hindrance can be or a three-frequency product of a type of $f_x=f_i+f_j-f_k$, or two-frequency a type of $f_x=2\ f_j-f_k$. Here i, j, k can accept any values within the total number of channels N

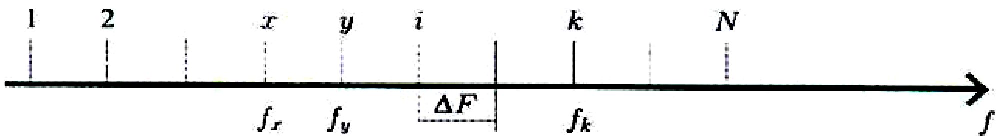

Figure 2. An arrangement of the optical bearing channels in WDM range

The canal in N-channel system to which three-frequency products get has number:

$$x = i + j - k \tag{3}$$

when performing conditions

$$\left.\begin{aligned} &1 \le i, j.k \le N; \\ &i \ne j \ne k \\ &i, j, k, x > 0; \\ &j > i; k > j \end{aligned}\right\} \tag{4}$$

For a two-frequency product the channel y to which these products get has number

$$y = 2j - k \tag{5}$$

on condition of

$$\left.\begin{aligned} &i = j \ne k; \\ &k > j; \\ &i, j, k, y > 0 \end{aligned}\right\} \tag{6}$$

If optical signals get to channels i, j, k at the same time, then the frequency of channel x which gets a three-frequency product is equal:

$$f_x = f_i + \Delta F(j - k) \tag{7}$$

Follows that fx can is both on a working range of WDM, and out of it, i.e. as a result of FWM the range in OF considerably extends. Total number of products of nonlinearity is defined from a ratio [8]:

$$N_{\sum} = N^2(N-1)/2 \tag{8}$$

For example, for eight-channel system *(N=8)* N_{Σ}=224, а при *N*=16 number of products N_{Σ}=1920. In Figure 3 results of calculation of number of products are given in channels at N=8 (a, b) and N=16 (c, d). Three-frequency products are presented in Figures 3a and 3c, and two-frequency-in Figure 3b and 3d. From the Figure 3 it is possible to draw the following conclusions:

a. the maximum quantity of three-frequency products takes place in the central channels;
b. at increase in number of channels in system, the quantity of the influencing products sharply increases in the channel. For example, at N=the 8th maximum number of three-frequency products in the central channel N=24, and at N=the 16th Nc3 value=140. i.e. increase in capacity of system twice leads to sharp increase in number of the influencing products;
c. the quantity of two-frequency products in each channel are much less than number three-frequency (for example, at N=1610 eighth channel number of three-frequency products-140, and two-frequency-7).

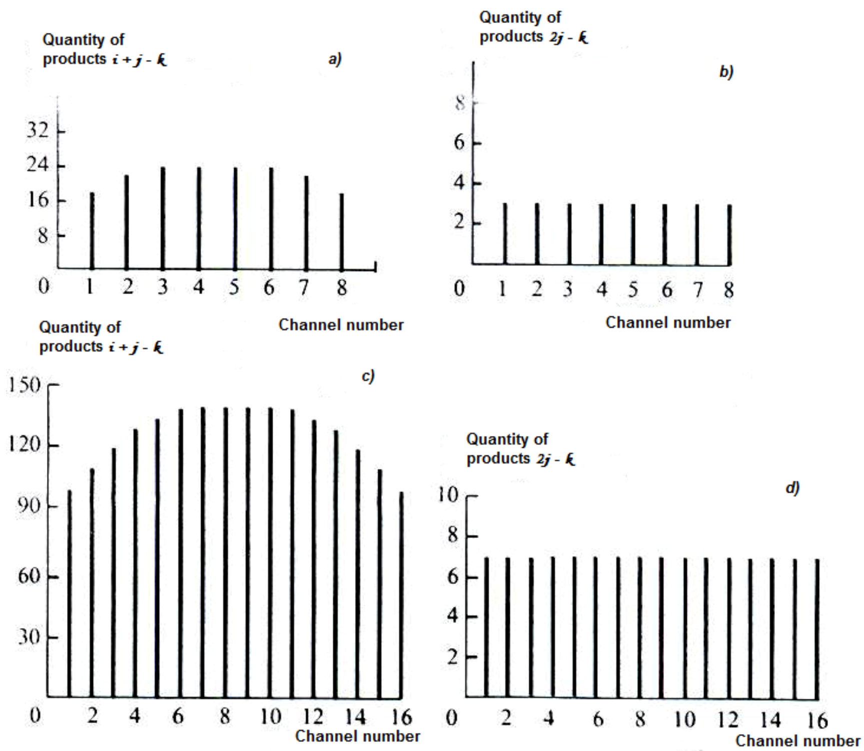

Figure 3. Results of calculation of number of products in channels at N=8 (a,b) and N = 16 (c,d)

We will consider calculation of power of hindrances because of FWM on an entrance of the linear amplifier of flight of WDM. According to the recommendation of ITU-T G.692, width of a range of the channel is accepted equal 0,1 nanometers (12,5 GHz). We will determine hindrance power because of FWM on an entrance of the amplifier with a length of flight of L. Calculation of power of each product of nonlinearity is executed in [8-9]. The general power of products of nonlinearity in the channel x is defined from expression:

$$P_x = (P_{i,j,k} N_{3c} + P_{2,j,k} N_{2c})\omega, \quad (9)$$

where N_{3c}, N_{3c} -quantity of three-frequency and two-frequency products of nonlinearity, respectively; $P_{i,j,k}$ and $P_{2,j,k}$ -capacities of each type of a product;

$$\omega = 2B(ГГц)/12{,}5, \quad (10)$$

a coefficient of channel spectrum spreading under the high-speed transmission. $P_{i,j,k}$ We will write down power in a look:

$$P_{i,j,k} = \eta_{i,j,k} \xi P_{in}^3 \exp(-\alpha L), \quad (11)$$

where P_{in} -power in one channel at the WDM transmitter booster exit; $\eta_{i,j,k}$ -the efficiency of FWM which is function of a mismatch of phases between signals of the interacting waves.

When determining power of nonlinear hindrances in the channel for section it is necessary to consider that this power collects from the amplifier to the amplifier. We will assume that all flights in section of identical length and amplifiers don't create nonlinear hindrances, then on an entrance of each amplifier there will be products of FWM which amplify the amplifier. Besides, the output power of a signal will create FWM in each flight. Therefore hindrance power because of FWM on an entrance of the WDM receiver can be determined on a formula:

$$P_{xc} = \sum_{i=1}^{N} P_{xnnp} = NP_{xnn}. \quad (12)$$

If lengths of flights aren't identical, then generally

$$P_x = \sqrt{\sum_{i=1}^{N} P_{xnnp}^2}. \quad (13)$$

We will define security of a signal from a hindrance because of FWM from a ratio:

$$OSNR = 10 \lg \frac{P_{ch}}{P_{xc}}, dB \quad (14)$$

Results of calculation. We will calculate capacities of the products arising because of FWM for the section WDM at a transfer speed 10gbit/s for different types of the fibers, proceeding from data given in Table 2.

Table 2. Different Types of the Fibers

Type of fiber	SMF	DSF
α, dB/km	0,22	0,22
A_{eff}, sm^2	$5 \cdot 10^7$	$5 \cdot 10^7$
X_{1111}, sm^3/erg	$8{,}9 \cdot 10^{15}$	$8{,}93 \cdot 10^{15}$
$D_s, ps/nm \cdot km$	18	3,5
$dD_s/d\lambda, ps/nm \cdot km$	0,093	0,080
n	1,467	1,469

Table 2. Different Types of the Fibers

Type of fiber	SMF	DSF
L, km	80	
λ, km	1550	
Full optical strip, GHz	2000	

It has turned out that at the exit of the section consisting of eight identical flights, the power of nonlinear hindrances in the noisiest 8th channel was 408,24 pW for SMF and 129,9 nW-for DSF fiber. Calculation of OSNR was made from the assumption that signal power in one channel at the exit of the amplifier of 1 MW and the line turns on eight amplifiers. At the same time the relation the signal/hindrance makes 48 dBm for SMF fiber, 15,8 dBm-DSF.

On the basis of dependence between the relations a signal/hindrance and probability of a mistake in the channel for WDM, we conclude that probability mistakes less than 10-12 that satisfies to the recommendations of ITU-T only for SMF fiber. Increase in a step between optical bearing and chromatic dispersion reduce FWM process, due to destruction of phase ratios between the interacting waves. For reduction influence of nonlinear effects it is also possible to use an uneven step or the increased step between channels.

4. Conclusion

By results of the conducted researches it is possible to draw the following conclusions:

a. WDM-the developing, branched technology difficult and multiple parameter system which the set of the internal and external destabilizing factors influencing quality of signaling influence;
b. The main destabilizing factors influencing quality of signaling in WDM are: influence of FWM, a hindrance in the neighboring canals and restrictions of the total power of a light signal entered into optical fiber, a relation deviation signal/noise;
c. Identification of the reasons worsening quality of the transmitted signals and finding of ways of their compensation decide by means of use of mathematical methods. In work methods of a research of characteristics of system from her parameters are used generally;
d. In WDM influence of FWM is especially destructive since the FWM level is sensitive to system characteristics.
e. in 200 GHz decreasing step systems, the FWM level sharply decreases to compare with 100 GHz decreasing step systems, absolute value of chromatic dispersion is redacted also

Recommendations about ensuring the required quality of transfer of optical signals to WDM:

a. It is necessary to optimize the transferred power of an optical signal taking into account the correct arrangement of amplifiers.
b. To turn on attention, on rational distribution of inter channel intervals, the number of lengths of waves and their stabilization;
c. The systems using G.653 fiber have the biggest nonlinear effect of FWM, but the arrangement of frequency of the working channel near zero dispersion can lead to significantly short length of the line (tens of kilometers). Therefore use of G.653 fiber in the DWDM systems isn't recommended [10].
d. In standard G.652 FWM fibers very much it is less. However use of G.652 [11] fibers in the DWDM systems isn't expedient because big dispersion reduces length of the regeneration site.
e. Influence of FWM is less in G.655 fibers, especially in fibers with a big effective area.
f. Dispersion, on the one hand, has to be rather small, so that it didn't cause broadening of impulses. On the other hand, for suppression of the cross hindrances arising because of nonlinear effects, dispersion has to be rather big therefore as dispersion, optimum for WDM, it is necessary to recognize fibers with the nonzero displaced dispersion of G.655 [12];
g. For neutralization of effect of FWM it is possible to use uneven intervals between WDM channels;

h. The considered method of calculation of nonlinear hindrances because of FWM can be used both for design of the main WDM, and for the analysis of results of their testing.

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