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METHOD OF DETERMINING THE LENGTH OF THE AMPLIFYING SECTION BY FOUR-WAVE MIXING FOR THE LINE BASED ON THE STANDARD FIBER

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МЕТОДИКА ВИЗНАЧЕННЯ ДОВЖИНИ ПІДСИЛЮВАЛЬНОЇ ДІЛЯНКИ ЗА ЧОТИРИХВИЛЬОВИМ ЗМІШУВАННЯМ ДЛЯ ЛІНІЇ НА БАЗІ SF ВОЛОКНА

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МЕТОДИКА ОПРЕДЕЛЕНИЯ ДЛИНЫ УСИЛИТЕЛЬНОГО УЧАСТКА ПО ЧЕТЫРЕХВОЛНОВОМУ СМЕШИВАНИЮ ДЛЯ ЛИНИИ НА БАЗЕ SF ВОЛОКНА

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Abstract. The method for determining the length of the amplifying section limited by the four-wave mixing for the optical line based on the standard single-mode optical fiber, for the transmission system with the spectral sealing of the channels is developed. There obtained the equation for determining the length of the amplifying section of the fiber-optic transmission system, where the parameters of the transmitting optical module, parameters of the linear path of the transmission system and parameters of the quantum fiber optic amplifiers are related. The forms of this equation for different channels and for different intervals between channels are presented. The spectral characteristics of the difference between the levels of the gain of one quantum fiber optic amplifier and the noise power of one amplifier, which is counted on one optical channel, are determined. The dependence of the length of the amplifying section on the number of quantum fiber optic amplifiers for STM-16 and STM-64 transmission systems is established.

Key words: optical fiber, four-wave mixing, quantum fiber-optic amplifier, amplifying section.

Анотація. Розроблено методику визначення довжини підсилювальної ділянки, обмеженої чотирихвильовим змішуванням для оптичної лінії на базі стандартного одномодового оптичного волокна для системи передачі зі спектральним ущільненням каналів. Отримано рівняння для визначення довжини підсилювальної ділянки волоконно-оптичної системи передачі, в якому пов'язані параметри передавального оптичного модуля, параметри лінійного тракту системи передачі та параметри квантового волоконно-оптичного підсилювача. Наведено форми даного рівняння для різної кількості каналів та для різного інтервалу між каналами. Визначено спектральні характеристики різниці рівнів коефіцієнта підсилення одного квантового волоконно-оптичного підсилювача та потужності шуму одного підсилювача, що перерахована на один оптичний канал. Встановлено залежність довжини підсилювальної ділянки від кількості квантових волоконно-оптичних підсилювачів для систем передачі рівня СТМ-16 та СТМ-64.

Ключові слова: оптичне волокно, чотирихвильове змішування, квантовий волоконно-оптичний підсилювач, підсилювальна ділянка.

Аннотация. Разработана методика определения длины усилительного участка, ограниченного четырехволновым смешиванием для оптической линии на базе стандартного одномодового оптического волокна для системы передачи со спектральным уплотнением каналов. Получено уравнение для определения длины усилительного участка волоконно-оптической системы передачи, в котором связаны параметры передающего оптического модуля, параметры линейного тракта системы передачи и параметры квантового волоконно-оптического усилителя. Приведены формы данного уравнения для различного количества каналов и для разного интервала между каналами. Определены спектральные характеристики разности уровней коэффициента усиления одного квантового волоконно-оптического усилителя и мощности шума одного усилителя, пересчитанной на один оптический канал. Установлена зависимость длины усилительного участка от количества квантовых волоконно-оптических усилителей для систем передачи уровня СТМ-16 и СТМ-64.

Ключевые слова: оптическое волокно, четырехволновое смешивание, квантовый волоконно-оптический усилитель, усилительный участок.

Problem statement

At the present stage of development of the telecommunication services market, fiber-optic transmission systems (FOTS) are widely used in the construction of transport telecommunication lines, as well as in the construction of distribution, corporate and inter-object networks. In this case, there are also negative physical phenomena that limit the possibilities of using optical fibers (OFs), especially when transmitting information over long distances. Unlike one-wave FOTS, in systems with wavelength division multiplexing, in addition to attenuation of the optical signal, chromatic dispersion, nonlinear effects, in particular, four-wave mixing, should also be taken into account.

The Four-Wave Mixing (FWM) phenomenon is a parasitic effect in FOTS, which greatly affects the quality of communication when using WDM systems. In wavelength division multiplexing systems FWM can cause interference (the phenomenon of the effect of a signal transmitted from one channel to another) between two channels with different wavelengths, as well as lead to an imbalance of channel capacities. At present, there is a need to develop a unified approach to determining the impact of FWM on the length of the amplifying section of FOTS.

Analysis of research and publications

For today, a technique has been developed for calculating the length of a regeneration section for attenuation and dispersion. The method of calculating the length of an amplifying section length limited with FWM (l_{FWM}) is cumbersome. General methods of the current l_{FWM} calculation method are outlined in [1, 2]. But the existing techniques require a large amount of input data and a large number of intermediate calculations.

Purpose of the work

The purpose of the work is to obtain the method for calculating the l_{FWM} parameter for WDM systems based on a standard single-mode optical fiber (SMF).

Development of the method for determining l_{FWM}

The allowable attenuation value at the length of one of the amplifying sections for the k-th channel belonging to the regeneration section with N fiber-optic amplifiers (FOAs) is equal to [1]:

$$\left[\alpha l_{FWM}\right] = p_{FWM} - 2\alpha_{con} - \alpha_s S - p_r - 10\lg\frac{hf_k}{10^{-3}} - 10\lg\Delta f_k - K_n - \left[s/n\right] - 10\lg N, \qquad (1)$$

where α – attenuation coefficient; p_{FWM} – the maximum allowable four-wave mixing power level of the signal on the transmission for an optical channel, dBm, calculated at the end of the amplifying section, km; α_{con} – losses in connectors of FOTS, dB; α_s – losses in splices of OFs, dB; S – number of splices on the regeneration section; p_r – reserve factor, dB; h – Planck's constant, equals $2{,}1\pi\cdot 10^{-34}$ J/Hz; f_k – central frequency of channel k, Hz; Δf_k – signal spectrum + noise in the same channel, Hz; K_n – noise ratio of a quantum fiber optic amplifier, dB; $\left[s/n\right]$ – the minimum permissible noise protection value for the length of the regeneration section with N fiber optic amplifiers, dB.

The maximum value of the attenuation factor for the optical cable (OC) with single-mode optical fibers according to recommendations of ITU [3]:

1) Recommendation ITU-T G.652.B:
α = 0,4 dB/km – for the wavelength of λ = 1310 nm;
α = 0,35 dB/km – for the wavelength of λ = 1550 nm; (2)
α = 0,4 dB/km – for the wavelength of λ = 1625 nm.

2) Recommendation ITU-T G.652.D:
α = 0,4 dB/km – for the wavelength of λ = 1310 nm;
α = 0,3 dB/km – for the wavelength of λ = 1550 nm; (3)
α = 0,4 dB/km – for the wavelength of λ = 1625 nm.

Optical fibers according to recommendations ITU-T G.652.A and G.652.C in accordance with [3] need to be used for short lines, since such OFs have relatively high values of the polarization mode dispersion. In the framework of this work, we will confine ourselves to the consideration of recommendations G.652.B and G.652.D.

The power of the four-wave mixing increases when the length of the line increasing. This sets limits on the transmission of power for each channel, depending on its length, with providing the necessary power reserve due to this phenomenon.

This limitation is shown on Fig. 1 [1] with reserve of 1 dB as for standard single-mode optical fibers as for non-zero dispersion-shifted fibers and zero dispersion-shifted fibers (continuous line – 8 channels at intervals of 100 GHz; dashed line – 32 channels, 100 GHz; dash-dotted line – 32 channels, 50 GHz). As can be seen from Fig. 1, the dependence of the parameter p_{FWM} on the length of the optical line is linear, which allows to determine p_{FWM} using a simple model in the form of a first-order polynomial. In Table 1 shows calculation formulas of p_{FWM} for different lengths of fiber-optic transmission lines (FOTL).

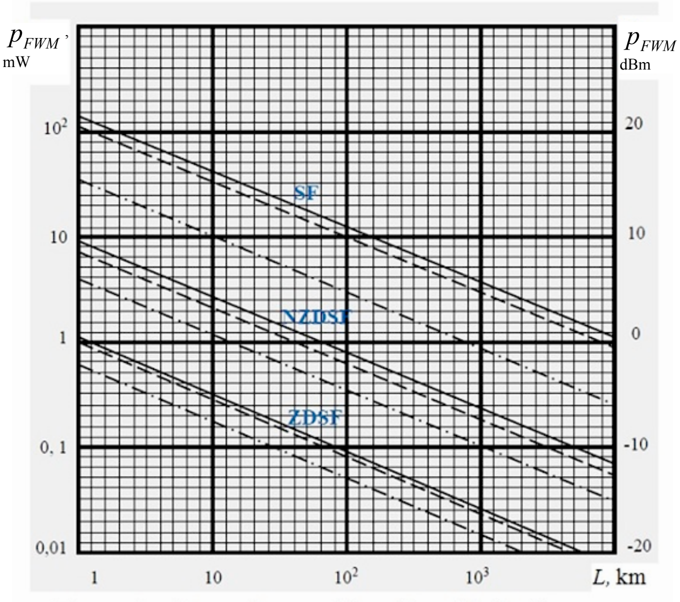

Figure 1 – Dependence of the allowable by four-wave mixing signal strength per channel on the length of the line with different number of channels in FOTS with WDM

Modern optical connectors, applied in single-mode OFs (FC, SC, LC, MU and others), have direct losses in the range of 0,1 to 0,2 dB. Therefore, to calculate the expression (1) it is acceptable to take α_{con} = 0,2 dB.

Losses at the point of OFs splicing should be [4]:

– 0,1 dB – nominally (for 70% splicing methods in FOTL);

– 0,15 dB – maximally (not more than 30% of the total number of splicing joints on FOTL).

As follows, for calculations by expression (1) we take α_s = 0,12 dB.

The reserve of energy potential on the length of the i-th amplifying section p_r (takes into account the deterioration with time of the technical characteristics of station equipment and cable) is within 2 … 6 dB. To calculate by expression (1) we take p_r = 6 dB.

Table 1 – Formulas for calculating the allowable by four-wave mixing signal strength per channel (p_{FWM}) for different lengths of the optical line (L_{FOTL}) with SMF

Number of channels and channel spacing	Line length is up to 10 км	Line length is 10 … 100 km	Line length is 100 … 1000 km	Line length is 1000 … 10000 km
8 channels, 100 GHz	$p_{FWM} = 21{,}5 - 0{,}55 L_{FOTL}$	$p_{FWM} = 16 - 0{,}055 L_{FOTL}$	$p_{FWM} = 11 - 5{,}5 \cdot 10^{-3} L_{FOTL}$	$p_{FWM} = 5{,}5 - 5 \cdot 10^{-4} L_{FOTL}$
32 channels, 100 GHz	$p_{FWM} = 20{,}5 - 0{,}55 L_{FOTL}$	$p_{FWM} = 15 - 0{,}055 L_{FOTL}$	$p_{FWM} = 10 - 5{,}5 \cdot 10^{-3} L_{FOTL}$	$p_{FWM} = 4{,}5 - 5 \cdot 10^{-4} L_{FOTL}$
32 channels, 50 GHz	$p_{FWM} = 15{,}5 - 0{,}55 L_{FOTL}$	$p_{FWM} = 10 - 0{,}055 L_{FOTL}$	$p_{FWM} = 4{,}5 - 5 \cdot 10^{-3} L_{FOTL}$	$p_{FWM} = -0{,}5 - 5{,}5 \cdot 10^{-4} L_{FOTL}$

The noise ratio (noise factor) is defined as $K_n = 10\lg \frac{(signal / noise)_{in}}{(signal / noise)_{out}}$, the default value of this parameter is within the range 5,5 … 6 dB [1]. To calculate by expression (1) we take K_n = 6 dB.

If there are N identical quantum fiber-optic amplifiers (QFOA) on the length of the regeneration section of FOTS, then noise protection (difference in signal and noise levels) will be written in the form [1]:

$$[s/n]_N = p_{FWM} - n_{an} - 10\lg N, \tag{4}$$

where p_{FWM} – the maximum allowable four-wave mixing power level of the signal on the transmission for an optical channel, dBm.

Allowable by ITU-T protection levels for each channel on the length of the regeneration section with N amplifiers must be [1]:

$$[s/n] = 18…21 \text{ dB} \ – \ \text{for STM-16}, \ [s/n] = 28…31 \text{ dB} \ – \ \text{for STM-64}. \tag{5}$$

To calculate the expression (1) we accept $[s/n]$ = 21 dB – for STM-16 and $[s/n]$ = 31 dB – for STM-64.

The width of the optical signal spectrum Δf_k can be determined by the formula [1]:

$$\Delta f_k = \Delta f_c + 2\Delta F = \frac{c \cdot \Delta\lambda}{\lambda^2} + 2{,}4B, \tag{6}$$

where Δf_c – carrier frequency spectrum of the optical signal, Hz; c – speed of light in vacuum ($3 \cdot 10^8$ km/s); λ – operating wavelength of the optical signal, μm; $\Delta\lambda$ – width of the radiation spectrum of the transmitting optical module, μm; B – transmission speed, for STM-16 B = 2,5 Gbit/s, for STM-64 B = 10 Gbit/s.

We introduce the parameter G:

$$G = -10\lg \frac{hf_k}{10^{-3}} - 10\lg \Delta f_k - K_n = g - n_0, \tag{7}$$

which is the difference between the gain factor of one QFOA (g) and the noise power of one QFOA, converted to one optical channel (n_0).

Using the expression (6) and the numerical values of some components of the expression (7), presented above, we obtain the expression (7) in the form:

$$G = g - n_0 = -10\lg \frac{59346\Delta\lambda + 4{,}7476 \cdot 10^{-4} \cdot B \cdot \lambda^2}{\lambda^3} - K_n, \tag{8}$$

where $\Delta\lambda$ – width of the radiation spectrum of the optical signal source, nm; λ – operating wavelength of the optical signal, nm; B – transmission speed, Gbit/s;

Considering (1) … (8), we have an equation to determine the parameter l_{FWM}:

$$l_{FWM} = \frac{1}{\alpha}\left(p_{FWM} - 27{,}4 - 0{,}12 \cdot S + G - 10\lg N\right) \ – \ \text{for STM-16}, \tag{9}$$

$$l_{FWM} = \frac{1}{\alpha}\left(p_{FWM} - 37{,}4 - 0{,}12 \cdot S + G - 10\lg N\right) \text{ – for CTM-64.} \qquad (10)$$

Parameter G mainly depends on the STM level, wavelength and on the spectrum radiation width. The graphs from Fig. 2 and 3 present the dependence of parameter G on signal wavelength for equipment STM-16 and STM-64 respectively. In calculations the values of radiation spectrum width $\Delta\lambda$ = 0,1, 0,2 and 0,3 nm are used.

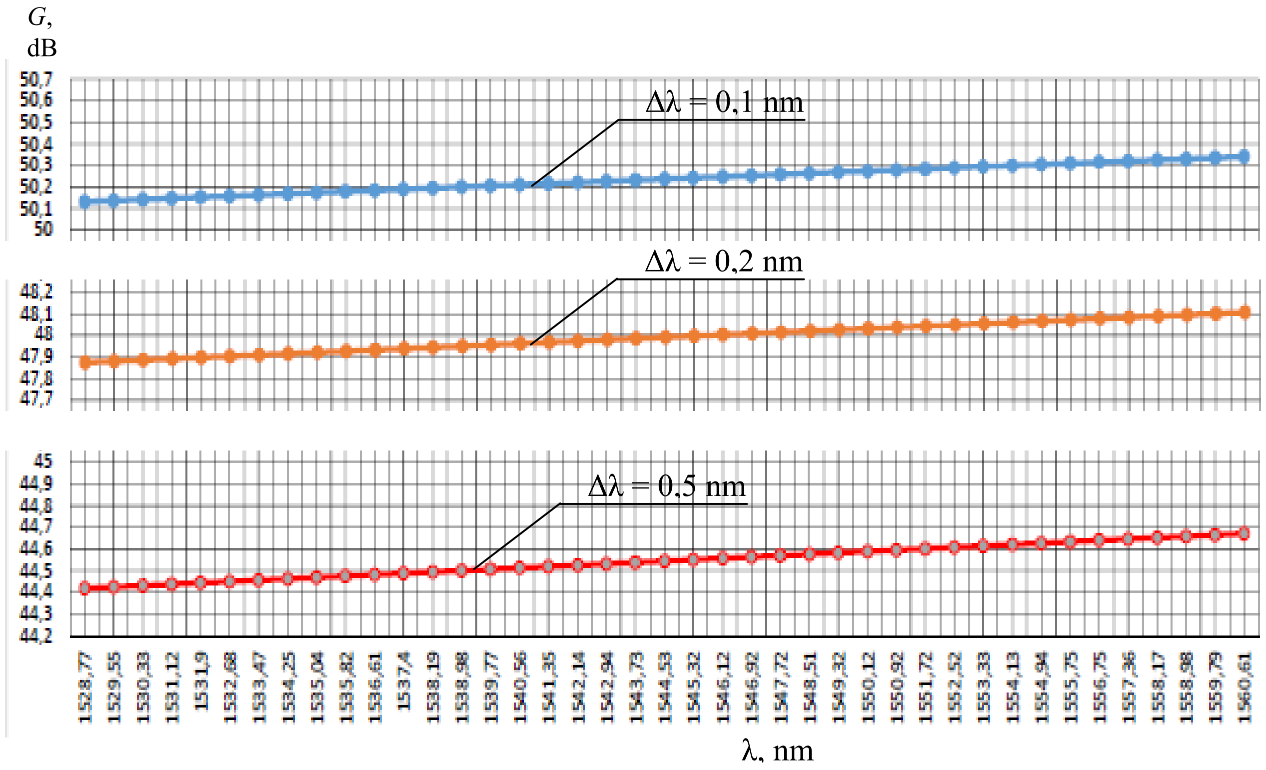

Figure 2 – Dependence of parameter G on the signal wavelength for equipment STM-16

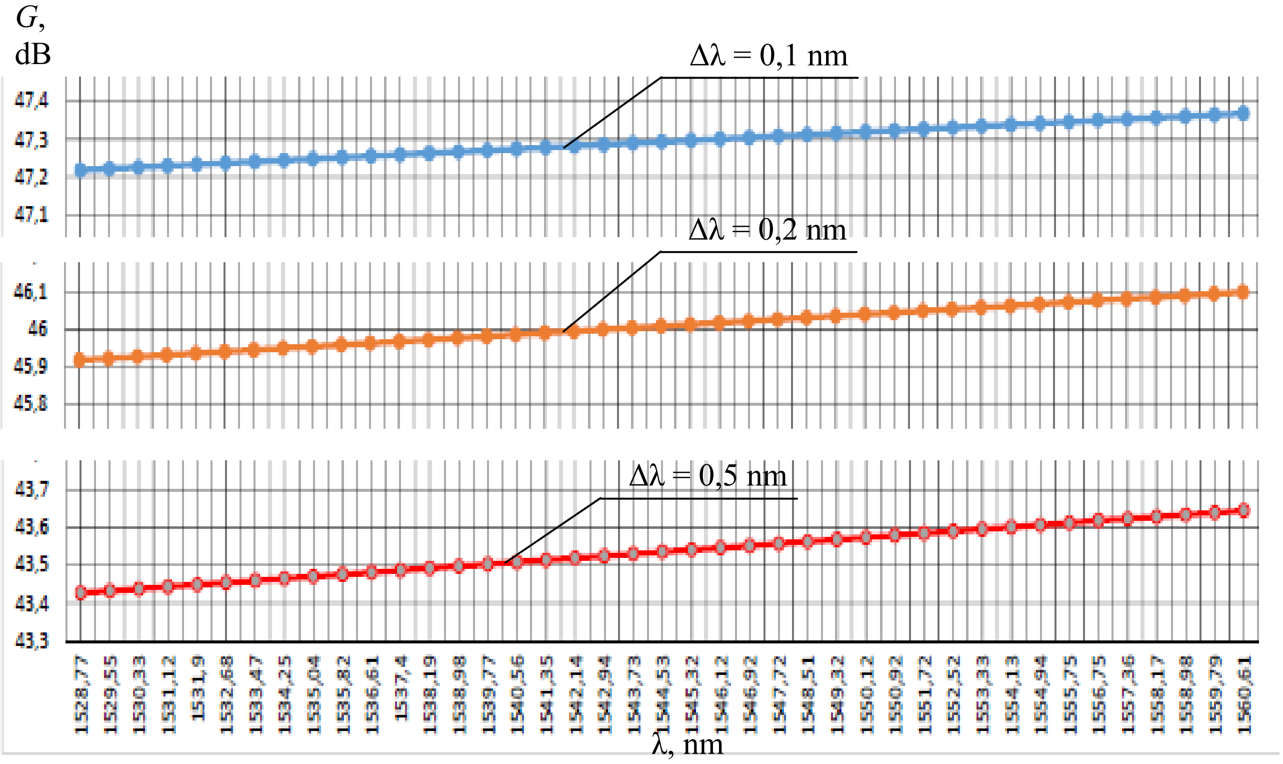

Figure 3 – Dependence of parameter G on the signal wavelength for equipment STM-64

The research has shown that within the frequency grid of WDM systems the parameter G varies in relatively small limits (0,2 … 0,3 dB). The dependence is linear.

Considering the attenuation coefficient of the SMF for the wavelength λ = 1550 nm, located within the WDM frequency grid, expressions for calculating the allowable by four-wave mixing signal power for a channel (Table 1) and equations (9), (10) defined the final equation for determining parameter l_{FWM}, presented in Table 2 … 5.

Table 2 – Equations to determine parameter l_{FWM} for WDM systems with optical fibers according to ITU G.652.B and equipment STM-16

Number of channels and channel spacing	Equations for determination l_{FWM}
Line length is up to 10 km	
8 channels, 100 GHz	$l_{FWM} = G/0{,}35 - 1{,}571 \cdot L_{FOTL} - 16{,}857 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0{,}35 - 1{,}571 \cdot L_{FOTL} - 19{,}714 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0{,}35 - 1{,}571 \cdot L_{FOTL} - 34 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
Line length is 10 … 100 km	
8 channels, 100 GHz	$l_{FWM} = G/0{,}35 - 0{,}157 \cdot L_{FOTL} - 32{,}571 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0{,}35 - 0{,}157 \cdot L_{FOTL} - 35{,}429 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0{,}35 - 0{,}157 \cdot L_{FOTL} - 49{,}714 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
Line length is 100 … 1000 km	
8 channels, 100 GHz	$l_{FWM} = G/0{,}35 - 1{,}571 \cdot 10^{-2} \cdot L_{FOTL} - 46{,}857 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0{,}35 - 1{,}571 \cdot 10^{-2} \cdot L_{FOTL} - 49{,}714 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0{,}35 - 1{,}429 \cdot 10^{-2} \cdot L_{FOTL} - 65{,}429 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
Line length is 1000 … 10000 km	
8 channels, 100 GHz	$l_{FWM} = G/0{,}35 - 1{,}429 \cdot 10^{-3} \cdot L_{FOTL} - 62{,}571 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0{,}35 - 1{,}429 \cdot 10^{-3} \cdot L_{FOTL} - 65{,}429 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0{,}35 - 1{,}571 \cdot 10^{-3} \cdot L_{FOTL} - 79{,}714 - 0{,}343 \cdot S - 28{,}571 \cdot \lg N$

Table 3 – Equations to determine parameter l_{FWM} for WDM systems with optical fibers according to ITU G.652.D and equipment STM-16

Number of channels and channel spacing	Equations for determination l_{FWM}
Line length is up to 10 km	
8 channels, 100 GHz	$l_{FWM} = G/0{,}3 - 1{,}833 \cdot L_{FOTL} - 19{,}667 - 0{,}4 \cdot S - 33{,}33 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0{,}3 - 1{,}833 \cdot L_{FOTL} - 23 - 0{,}4 \cdot S - 33{,}33 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0{,}3 - 1{,}833 \cdot L_{FOTL} - 39{,}667 - 0{,}4 \cdot S - 33{,}33 \cdot \lg N$
Line length is 10 … 100 km	
8 channels, 100 GHz	$l_{FWM} = G/0{,}3 - 0{,}183 \cdot L_{FOTL} - 38 - 0{,}4 \cdot S - 33{,}33 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0{,}3 - 0{,}183 \cdot L_{FOTL} - 41{,}33 - 0{,}4 \cdot S - 33{,}33 \cdot \lg N$

Continuation of Table 3

32 channels, 50 GHz	$l_{FWM} = G/0,3 - 0,183 \cdot L_{FOTL} - 58 - 0,4 \cdot S - 33,33 \cdot \lg N$
Line length is 100 … 1000 km	
8 channels, 100 GHz	$l_{FWM} = G/0,3 - 1,833 \cdot 10^{-2} \cdot L_{FOTL} - 54,67 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0,3 - 1,833 \cdot 10^{-2} \cdot L_{FOTL} - 58 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0,3 - 1,67 \cdot 10^{-2} \cdot L_{FOTL} - 76,33 - 0,4 \cdot S - 33,33 \cdot \lg N$
Line length is 1000 … 10000 km	
8 channels, 100 GHz	$l_{FWM} = G/0,3 - 1,67 \cdot 10^{-3} \cdot L_{FOTL} - 73 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0,3 - 1,67 \cdot 10^{-3} \cdot L_{FOTL} - 76,33 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0,3 - 1,833 \cdot 10^{-3} \cdot L_{FOTL} - 93 - 0,4 \cdot S - 33,33 \cdot \lg N$

Table 4 – Equations to determine parameter l_{FWM} for WDM systems with optical fibers according to ITU G.652.B and equipment STM-64

Number of channels and channel spacing	Equations for determination l_{FWM}
Line length is up to 10 km	
8 channels, 100 GHz	$l_{FWM} = G/0,35 - 1,571 \cdot L_{FOTL} - 45,429 - 0,343 \cdot S - 28,571 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0,35 - 1,571 \cdot L_{FOTL} - 48,286 - 0,343 \cdot S - 28,571 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0,35 - 1,571 \cdot L_{FOTL} - 62,571 - 0,343 \cdot S - 28,571 \cdot \lg N$
Line length is 10 … 100 km	
8 channels, 100 GHz	$l_{FWM} = G/0,35 - 0,157 \cdot L_{FOTL} - 61,143 - 0,343 \cdot S - 28,571 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0,35 - 0,157 \cdot L_{FOTL} - 64 - 0,343 \cdot S - 28,571 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0,35 - 0,157 \cdot L_{FOTL} - 78,286 - 0,343 \cdot S - 28,571 \cdot \lg N$
Line length is 100 … 1000 km	
8 channels, 100 GHz	$l_{FWM} = G/0,35 - 1,571 \cdot 10^{-2} \cdot L_{FOTL} - 75,429 - 0,343 \cdot S - 28,571 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0,35 - 1,571 \cdot 10^{-2} \cdot L_{FOTL} - 78,286 - 0,343 \cdot S - 28,571 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0,35 - 1,429 \cdot 10^{-2} \cdot L_{FOTL} - 94 - 0,343 \cdot S - 28,571 \cdot \lg N$
Line length is 1000 … 10000 km	
8 channels, 100 GHz	$l_{FWM} = G/0,35 - 1,429 \cdot 10^{-3} \cdot L_{FOTL} - 91,143 - 0,343 \cdot S - 28,571 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = G/0,35 - 1,429 \cdot 10^{-3} \cdot L_{FOTL} - 94 - 0,343 \cdot S - 28,571 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = G/0,35 - 1,571 \cdot 10^{-3} \cdot L_{FOTL} - 108,29 - 0,343 \cdot S - 28,571 \cdot \lg N$

Table 5 – Equations to determine parameter l_{FWM} for WDM systems with optical fibers according to ITU G.652.D and equipment STM-64

Number of channels and channel spacing	Equations for determination l_{FWM}
Line length is up to 10 km	
8 channels, 100 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,833 \cdot L_{FOTL} - 53 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,833 \cdot L_{FOTL} - 56,33 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,833 \cdot L_{FOTL} - 73 - 0,4 \cdot S - 33,33 \cdot \lg N$
Line length is 10 … 100 km	
8 channels, 100 GHz	$l_{FWM} = {}^{G}/_{0,3} - 0,183 \cdot L_{FOTL} - 71,34 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = {}^{G}/_{0,3} - 0,183 \cdot L_{FOTL} - 74,64 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = {}^{G}/_{0,3} - 0,183 \cdot L_{FOTL} - 91,33 - 0,4 \cdot S - 33,33 \cdot \lg N$
Line length is 100 … 1000 km	
8 channels, 100 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,83 \cdot 10^{-2} \cdot L_{FOTL} - 88 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,83 \cdot 10^{-2} \cdot L_{FOTL} - 91,33 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,67 \cdot 10^{-2} \cdot L_{FOTL} - 109,67 - 0,4 \cdot S - 33,33 \cdot \lg N$
Line length is 1000 … 10000 km	
8 channels, 100 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,67 \cdot 10^{-3} \cdot L_{FOTL} - 106,33 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 100 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,67 \cdot 10^{-3} \cdot L_{FOTL} - 109,67 - 0,4 \cdot S - 33,33 \cdot \lg N$
32 channels, 50 GHz	$l_{FWM} = {}^{G}/_{0,3} - 1,83 \cdot 10^{-3} \cdot L_{FOTL} - 126,39 - 0,4 \cdot S - 33,33 \cdot \lg N$

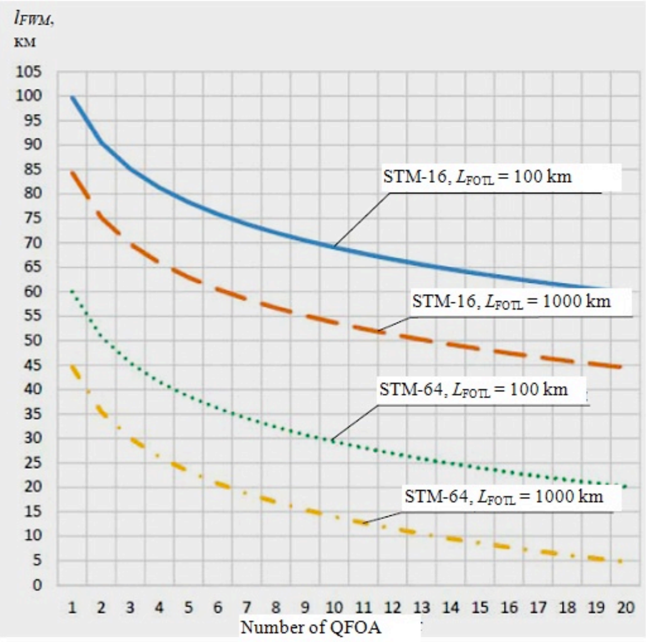

Figure 4 – Dependence of the length of the amplifying section, limited by FWM (l_{fwm}), on the number of QFOA on a regeneration section

During the research the depending of the length of the amplifier section, limited by FWM (l_{FWM}) on the number of QFOA on a regeneration section are obtained. Some of the obtained dependencies are illustrated in Fig. 4.

For calculations, the results of which are shown in Fig. 4, the following data were used: operating wavelength of the optical signal λ = 1550,92 nm, width of the transmitter spectrum Δλ = 0,1 nm, number of optical channels – 32, channel spacing – 100 GHz, type of optical fiber – SMF rec. ITU-T G.652.D, constructional length of an optical cable – 5 km. The graphs for transmission systems STM-16 and STM-64 are presented for line length 100 km and 1000 km.

The proposed method of determining the length of the amplifying section, limited by FWM (l_{FWM}) involves using the following parameters:

1. Length of the fiber-optic line.

2. Type of optical fiber.
3. Constructional length of the OC.
4. Wavelength of the optical signal (λ).
5. Width of the radiation spectrum (Δλ).
6. Number of optical channels and channel spacing.
7. Transmission speed.

The method for determining the l_{FWM} parameter includes three steps:

1. By expression (8) or by graphs on Fig. 2 and 3 determine the difference between the gain of one QFOA and the noise level of one QFOA, converted to one optical channel (parameter *G*).
2. Taking into account the data on Table 2 ... 5 choose the equation to determine l_{FWM}, solve it for different values of the number of QFOA on the regeneration section of FOTS.
3. Building a dependency of l_{FWM} on the number of QFOA (on the example of Fig. 4) make a decision on choosing the optimal value of l_{FWM} for the regeneration section of FOTS.

Conclusions:

1. The scientific novelty of the performed work is that it has received further development of a method for determining the length of the reinforcing section, limited by FWM. The developed method allows at the design stage to make decisions on the number of QFOA which can be successively included into the regeneration section.
2. The practical significance of the work is that its material can be used by design engineers in the design projects of FOTL.

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