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Abstract	Fiber optic transmission systems are used for high-speed traffic transmission in modern telecommunication NGN and IMS networks. Optical channels of optical transport hierarchy (OTH) communication systems

have a bandwidth of 2.5 to 100 Gbps, so the study of their characteristics is an urgent task. The problem of studying the quality parameters (Q-factor) of optical OTH signals of the OTU1 and OTU2 types is solved in the current section. A simulation model of an intensity modulated optical transmission system has been developed to solve this problem. This model contains a transmitter, an optical transmission path with optical amplifiers and an optical signal receiver. Optical fiber simulation model allows to introduce linear and nonlinear distortions of the propagation medium into the signal and it is based on the Split-Step Fourier Method. The noise of the optical amplifier was generated by using the inverse discrete Fourier transform to increase the performance of the model. Comparison of the results of modeling and analytical calculations was carried out to check the accuracy of the proposed simulation model. The influence of the signal power of the transmitter and the quantity of linear path optical sections on the Q-factor of the signal in the receiver is calculated. It is proposed to optimize the transmitter signal power by the criterion of maximizing the Q-factor to increase the length of the 3R regeneration section.

Keywords (separated by '-')	Fiber - OTH - Communication system - Quality - Modeling

Author Proof

Evaluation of Quality Parameters of an Intensity-Modulated Optical Transmission System

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Abstract. Fiber optic transmission systems are used for high-speed traffic transmission in modern telecommunication NGN and IMS networks. Optical channels of optical transport hierarchy (OTH) communication systems have a bandwidth AQ1 of 2.5 to 100 Gbps, so the study of their characteristics is an urgent task. The problem of studying the quality parameters (Q-factor) of optical OTH signals of the OTU1 and OTU2 types is solved in the current section. A simulation model of an intensity modulated optical transmission system has been developed to solve this problem. This model contains a transmitter, an optical transmission path with AQ2 optical amplifiers and an optical signal receiver. Optical fiber simulation model allows to introduce linear and nonlinear distortions of the propagation medium into the signal and it is based on the Split-Step Fourier Method. The noise of the optical amplifier was generated by using the inverse discrete Fourier transform to increase the performance of the model. Comparison of the results of modeling and analytical calculations was carried out to check the accuracy of the proposed simulation model. The influence of the signal power of the transmitter and the quantity of linear path optical sections on the Q-factor of the signal in the receiver is calculated. It is proposed to optimize the transmitter signal power by the criterion of maximizing the Q-factor to increase the length of the 3R regeneration section.

Keywords: Fiber · OTH · Communication system · Quality · Modeling

1 Introduction

Optical fiber transmission systems (OFTS) form the backbone of a modern telecommunications network. The transmission speed of digital transmission systems over optical fiber has increased from several megabits per second to several hundred gigabits per second.

The development of an Erbium Doped Fiber Optic Amplifier (EDFA) made it possible to amplify the signal (1R regeneration) without converting it into an electrical form. This reduced the cost of the transmission system and allowed the construction of

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a wavelength division multiplexing (WDM) transmission system. Today, on the backbone section of the network, dense wavelength multiplexing (DWDM) systems with a frequency grid of 100 GHz and below are used. An important parameter of the optical transmission system is the type of modulation of the optical signal. The transmission speed, signal immunity and the total cost of the system depend on it. Today, the most common is signal intensity modulation (IM), which is used when the digital stream has a speed of 10 Gbps or lower.

DWDM systems have evolved to optical transport hierarchy (OTH) transmission systems. In these systems, user information is multiplexed into optical channel transport blocks (OTUk) of four hierarchy levels (k = 1, 2, 3, 4). In OTH transponders of the OTU1 (2.7 Gbps) and OTU2 (10.7 Gbps) levels, the intensity modulation of the laser diode is used.

The optical fiber line path of OTH systems contains the propagation medium (optical fiber) and optical amplifiers. The propagation medium introduces linear and nonlinear distortions into the information signal [1]. The optical amplifier also introduces the additive noise of amplified spontaneous emission [2].

Calculation of signal immunity in the receiver of the transmission system is one of the urgent tasks. To solve the problem of studying the noise immunity of transmission system signals, it is possible to use two modeling methods: analytical (mathematical) and simulation modeling.

The first method involves obtaining analytical expressions that correspond to the signal processing processes in the functional blocks of the transmission system and their statistical parameters. Models built by this method are not flexible, since a small change in the system configuration requires the development of a new or significant revision of the existing model. Today, accurate simulation of linear and non-linear distortion of the propagation medium is performed only by numerical methods. On their basis, it is possible to build full-fledged simulation models of transmission systems. These models allow to obtain reliable data on the quality of the signal at various points in the transmission system.

This article describes the mathematical and simulation model of the intensity modulated optical transmission system in the MatLab program.

2 Analytical Model of Optical Transmission System

In this subsection, we analyze the noise immunity of the generalized model of the optical transmission system (Fig. 1). The block diagram contains a transceiver, an optical fiber transmission path (OFTP) and a signal receiver.

We begin our analysis of the optical transmission system using the analytical and simulation methods and without optical signal modulation. Further, this model can be expanded to a transmission system with any modulation.

The transmitter signal in complex form can be written as an expression

$$\dot{E}_{\text{tr}}(t) = \sqrt{P_{\text{tr}}(t)}\, e^{j\varphi_{\text{tr}}(t)} e^{j\omega_0 t}, \tag{1}$$

where $P_{\text{tr}}(t)$ and $\varphi_{\text{tr}}(t)$ - average power and phase of the transmitter signal,

ω_0 and φ_0 - frequency and initial phase of the laser signal.

The optical transmission path consists of N_{sect} identical sections (Fig. 1), each of which contains a length L_{of} of fiber and an optical erbium-doped fiber amplifier (EDFA).

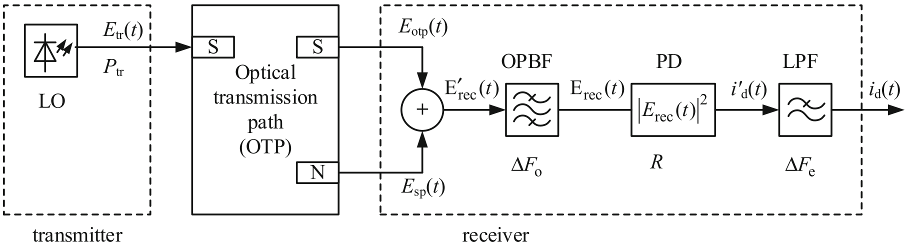


Fig. 1. Generalized model of a channel of a transmission system with wavelength multiplexing

The mathematical model of the optical transmission path is shown at the Fig. 2. It assumes linear amplification of the signal and the generation of additive noise in the optical amplifier. In further calculations, we will assume that the signal attenuation in the fiber is completely eliminated in the optical amplifier ($G = 10^{0,1\alpha L_{\text{of}}}$). At the amplifier output, there is also spontaneous emission noise $E_{\text{sp1}}(t)$ in addition to the useful signal.

The noise is formed in two polarization planes and the average noise power of one amplifier in one polarization plane is determined by the expression [2]

$$P_{\text{sp1}} = PSD_{\text{sp1}}\,\Delta F_o = n_{\text{sp}}(G-1)\,h\nu\,\Delta F_o, \tag{2}$$

where PSD_{sp1} - the spontaneous emission noise power spectral density;

n_{sp} - the spontaneous emission coefficient of an optical amplifier;

G - the amplifier gain;

h - the Planck's constant ($h = 6{,}626 \cdot 10^{-34}$ J * s);

ν - the optical signal frequency (for bandpass signal coincides with laser frequency $\nu = \omega_0/2\pi$);

ΔF_{o} - bandwidth of the optical bandpass filter (OBPF) in a receiver of a transmission system.

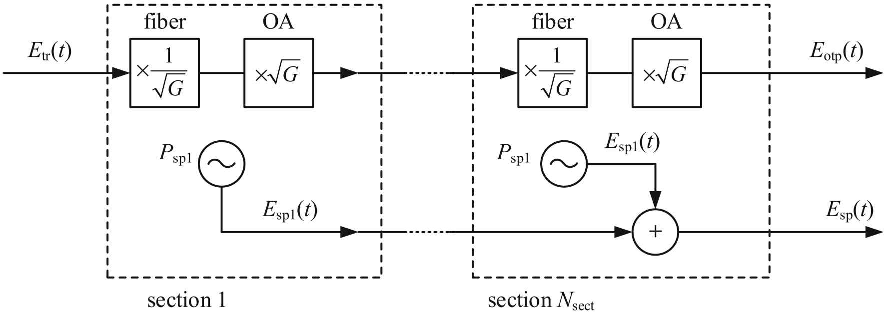


Fig. 2. Block diagram of a model for an optical transmission path

The spontaneous emission factor can be calculated using the noise factor NF of the optical amplifier

$$n_{\text{sp}} = \frac{NF}{2} = \frac{10^{0,1nf}}{2}. \tag{3}$$

In the case when the optical transmission path contains several amplifiers N_{oa} with the same parameters, the total spontaneous emission noise power increases proportionally:

$$P_{\text{sp}} = PSD_{\text{sp}}\,\Delta F_o = n_{\text{sp}}(G-1)\,h\nu\,\Delta F_o\,N_{\text{oa}}, \tag{4}$$

where PSD_{sp} - total noise spectral density of all amplifiers ($PSD_{\text{sp}} = N_{\text{oa}}\,PSD_{\text{sp1}}$).

The input signal of the receiver (Fig. 1) is the sum of the useful signal $E_{\text{otp}}(t)$ and the total spontaneous emission noise $E(t)$:

$$E'_{\text{rec}}(t) = E_{\text{otp}}(t) + E_{\text{sp}}(t) = E_{\text{tr}}(t) + E_{\text{sp}}(t). \tag{5}$$

In this expression, the equality of signals $E_{\text{otp}}(t) = E_{\text{tr}}(t)$ is accepted, since in this version of the transmission system model there are no signal distortions in the propagation medium and full compensation of the signal attenuation in the amplifier is assumed.

The band-pass optical filter does not introduce significant distortions into the signal spectrum, since in this version of the system model there is no signal modulation in the transmitter. Therefore, in the further text of the article, the equality of the input and output signal of the filter is also accepted $E_{\text{rec}}(t) = E'_{\text{rec}}(t)$.

The electric field of the spontaneous emission noise has a uniform spectral power density (Fig. 3) and it is described by the expression [3]

$$\dot{E}_{\text{sp}}(t) = \sum_{k=-M}^{M} \sqrt{PSD_{\text{sp}}\delta\nu}\,\exp\bigl[j((\omega_0 + 2\pi k\delta\nu)t + \Phi_k)\bigr], \tag{6}$$

where Φ_k - random phase of noise component k ($\Phi_k \in [0,\ 2\pi]$).

The photodiode (PD) is a square-law detector, so the current at its output has the form

$$i'_{\text{d}}(t) = R\,|E_{\text{rec}}(t)|^2, \tag{7}$$

there R - the photodiode responsivity.

The electric current consists of the sum of three separate components at the output of the photodiode:

$$\begin{aligned} i'_{\text{d}}(t) = R\,|E_{\text{rec}}(t)|^2 &= R\Bigl(|E_{\text{tr}}(t)|^2 + 2\,|E_{\text{tr}}(t)|\,\bigl|E_{\text{sp}}(t)\bigr| + \bigl|E_{\text{sp}}(t)\bigr|^2\Bigr) \\ &= i'_{\text{s-s}}(t) + i'_{\text{s-sp}}(t) + i'_{\text{sp-sp}}(t). \end{aligned} \tag{8}$$

These terms are beating between components:

1) signal $i'_{\text{s-s}}(t) = R\,P_{\text{tr}}$;

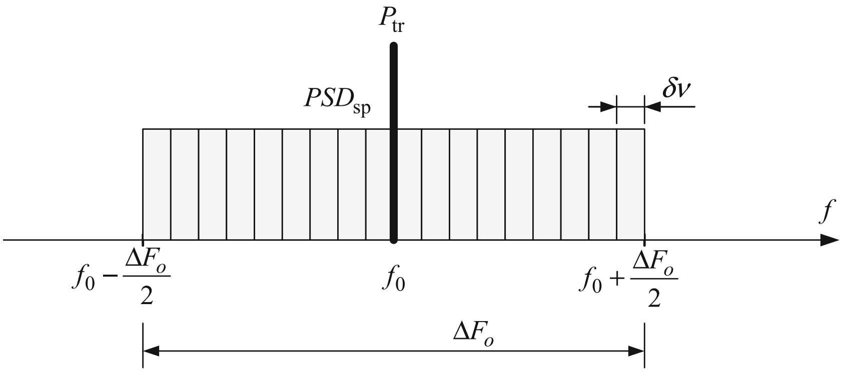


Fig. 3. Model of the signal spectrum and noise at the output of the optical filter

2) signal and spontaneous emission $i'_{\text{s-sp}}(t)$;
3) spontaneous emission $i'_{\text{sp-sp}}(t)$.

The presentation of signal and noise in a complex form allows us to apply elements of the theory of vector analysis. The signal vector at the receiver input $\overline{E}_{\text{rec}}$ is the sum of the vectors of the useful signal $\overline{E}_{\text{tr}}$ of the transmitter and the spontaneous emission noise $\overline{E}_{\text{sp}}$ (Fig. 4).

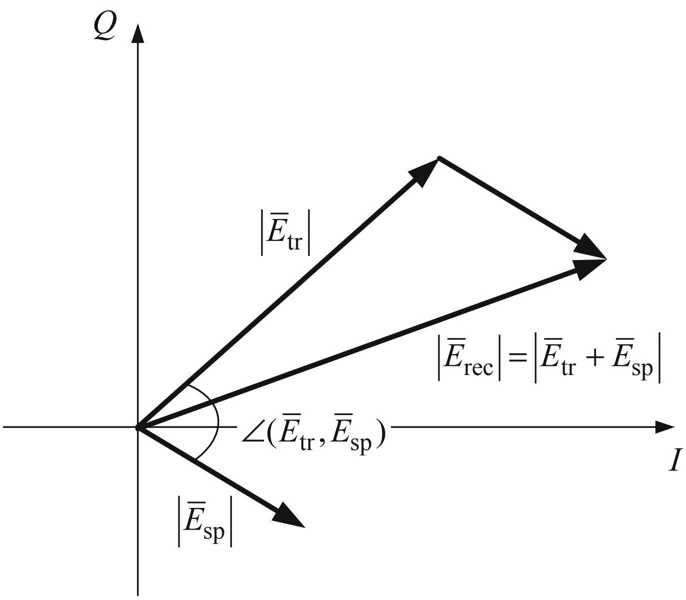


Fig. 4. The vector sum of the signal at the input of the optical receiver

In scalar form, the current at the output of the photodiode has the expression:

$$\begin{aligned} i'_{\mathrm{d}} &= R\left|\overline{E}_{\mathrm{rec}}^{2}\right| = R\left|\overline{E}_{\mathrm{tr}}^{2} + 2\overline{E}_{\mathrm{tr}}\cdot\overline{E}_{\mathrm{sp}} + \overline{E}_{\mathrm{sp}}^{2}\right| \\ &= R\left[\left|\overline{E}_{\mathrm{tr}}\right|^{2} + 2\left|\overline{E}_{\mathrm{tr}}\right|\left|\overline{E}_{\mathrm{sp}}\right|\cos\angle(\overline{E}_{\mathrm{tr}},\overline{E}_{\mathrm{sp}}) + \left|\overline{E}_{\mathrm{sp}}\right|^{2}\right]. \end{aligned} \quad (9)$$

3 Development of a Simulation Model of an Intensity Modulated Optical Transmission System

In this subsection, the problem of evaluating the quality of OTU1/OTU2 OTH signals transmission using intensity modulation of the optical signal in the transmitter is solved. It also includes the task of optimizing the main parameters of the system (functional blocks and signal). To solve this problem, it is necessary to develop a simulation model of the transmission system, which will take into account the signal formation algorithm in the transmitter, its distortion in the propagation medium and detection in the receiver.

In the simulation model, the continuous signal is replaced by its samples, which are generated with a sampling interval $T_{\mathrm{s}} = 1/F_{\mathrm{s}}$, where F_{s} is the sampling frequency. In this case, the continuous time t in the previous expressions is replaced by a discrete value $t_k = k\,T_{\mathrm{s}}$. It is necessary to use the function of the inverse fast Fourier transform to accelerate the generation of samples of the spontaneous emission interference according to expression (6) in the passband $(f_{\min}; f_{\max})$ of the optical bandpass filter.

It is implemented according to the following expression in the MatLab system [4]

$$\dot{x}(k) = ifft(\dot{A}(n)) = \frac{1}{N_{FFT}}\sum_{n=0}^{N_{FFT}} \dot{A}(n)\exp\left(j\frac{2\pi nk}{N_{FFT}}\right), \quad (10)$$

where N_{FFT} - the dimension of Fast Fourier Transform;

k - the signal sample number in the time domain;

n - the complex amplitude number in the signal spectrum ($k,\ n \in [0; N_{FFT} - 1]$).

The spectrum of the discrete Fourier transform contains N_{FFT} complex amplitudes $\dot{A}(n)$ with frequencies

$$f_n = F_{\mathrm{s}}\frac{n}{N_{FFT}}. \quad (11)$$

They are uniformly distributed in the frequency range from 0 to $F_{\mathrm{s}}(N_{FFT} - 1)/N_{FFT}$ with an interval $\Delta f_{FFT} = F_{\mathrm{s}}/N_{FFT}$.

It is necessary to find the sum of the complex amplitudes with positive frequencies $(f_{\min}; f_{\max})$ to synthesize the narrowband complex noise with a uniform power spectral density. These terms correspond to the range of numbers $n \in [n_{\min}; n_{\max}]$ in the expression (10):

$$n_{\min} = \frac{f_{\max}N_{FFT}}{F_{\mathrm{s}}}, \quad (12)$$

$$n_{\max} = \frac{f_{\max}N_{FFT}}{F_{\mathrm{s}}}. \quad (13)$$

The modulus of the complex amplitudes should be multiplied by a factor Δf_{FFT} since the discrete Fourier transform is applied:

$$\dot{A}(n) = \sqrt{PSD_{\text{sp}} \Delta f_{FFT}} \exp(j\,\Phi_n), \tag{14}$$

where Φ_n is the random phase of the spectrum component n, which has a uniform probability distribution density ($\Phi_n \in [0; 2\pi]$).

The IFFT expression in MatLab contains an additional factor $1/N_{FFT}$, so the *ifft*() function should be multiplied by the inverse coefficient N_{FFT}:

$$\dot{E}_{\text{sp}}(k) = N_{FFT}\; ifft(\dot{A}(n)). \tag{15}$$

In the MatLab program according to Fig. 1, a model of a transmission system without modulation of the transmitter signal was created to check the validity of the proposed expressions.

Optical bandpass filters OPBF-1 and OPBF -2 are identical in implementation, have a bandwidth ΔF_{o} centered on the frequency $\omega_0/2\pi$. The signal samples at the output of the OPBF models is a discrete convolution of the input signal samples and the impulse response $h(k)$ of the filter [4]:

$$y(k) = \sum_{m=-\infty}^{k} x(m)h(k-m) = x(k) * h(k). \tag{16}$$

The impulse response samples $h(k)$ were calculated using the standard MatLab function fir1(). The transmission coefficient of the designed digital filter in the passband $(\omega_0/2\pi - \Delta F_{\text{o}}/2; \omega_0/2\pi + \Delta F_{\text{o}}/2)$ is close to 1.

Since the transmitter signal is unmodulated in this version of the transmission system model, the following approximations can be used

$$\dot{E}_{\text{tr}}(k) = \dot{E}_{\text{tr}}(k) * h_{\text{pbf}}(k) \approx \dot{E}'_{\text{tr}}(k), \tag{17}$$

$$\dot{E}_{\text{sp}}(k) = \dot{E}_{\text{sp}}(k) * h_{\text{pbf}}(k) \approx \dot{E}'_{\text{sp}}(k). \tag{18}$$

The impulse response of the low-pass filter model with a cutoff frequency ΔF_{e} was also calculated using the fir1() function. The verification of the reliability of the described models of the transmission system was carried out using the example of the initial data in Table 1.

The results obtained by analytical calculation according to the expressions [3] were taken as the actual power values:

$$P_{\text{s-sp}} = PSD_{\text{s-sp}}\, \Delta F_{\text{e}} = 4R^2 P_{\text{tr}} PSD_{\text{sp}} \Delta F_{\text{e}}, \tag{19}$$

$$P_{\text{sp-sp}} = R^2\, PSD_{\text{sp}}^2 \Delta F_o (\Delta F_o + 2\Delta F_{\text{e}}). \tag{20}$$

The calculation result was compared with the results of simulation models with real and complex signal representation. Simulation was also carried out in the Optiwave

Table 1. Transmission system model parameters

Functional block	Parameter	Value
Transmitter	Carrier frequency ω_0	100 GHz
	P_{tr}	$1 \cdot 10^{-3}$ W
	Sampling frequency F_s	640 GHz
	Samples quantity	$64 \cdot 10^5$
Optical transmission path	Optical section length L_{of}	100 km
	Attenuation coefficient α	0,2 dB/km
	N_{sect}	10
	Noise figure nf	6 dB
	PSD_{sp}	$2,521 \cdot 10^{-16}$ W/Hz
Receiver	ΔF_o	100 GHz
	Phodiode responsivity R	1 A/W
	ΔF_e	7,5 GHz

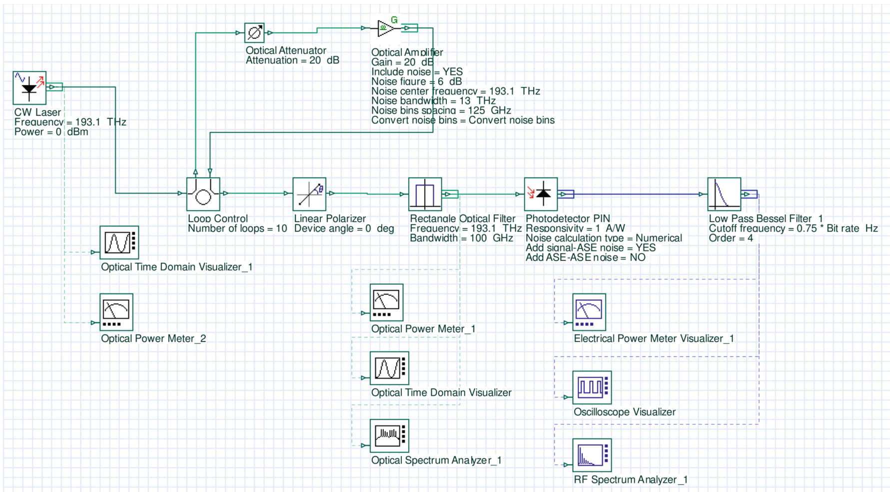


Fig. 5. Functional diagram of the simulation model in the Optiwave Optisystem

Optisystem 7 program according to the functional diagram of the virtual layout of the system (Fig. 5). All calculation and simulation results are summarized in Table 2.

The reliability of the results obtained was carried out by calculating the relative error δ of the signal power for each component of the output current [5]:

$$\delta = \frac{\Delta P}{P_{eT}} \cdot 100\% = \frac{P_{sim} - P_{ref}}{P_{ref}} \cdot 100\%, \tag{21}$$

where P_{ref} and P_{sim} - the reference and simulated power values, respectively.

Table 2. Results of calculation and simulation of a transmission system without modulation of an optical signal

Noise term	Noise power for model type, W (relative error δ)			
	Analytical model	Simulation model (real signal)	Simulation model (complex signal)	Simulation model (Optiwave Optisystem)
P_{s-s}	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$
P_{s-sp}	$7{,}564 \cdot 10^{-9}$	$7{,}341 \cdot 10^{-9}$ (−2,95%)	$7{,}322 \cdot 10^{-9}$ (−3,20%)	$8{,}37 \cdot 10^{-9}$ (10,66%)
P_{s-sp}	$7{,}311 \cdot 10^{-10}$	$7{,}177 \cdot 10^{-10}$ (−1,83%)	$7{,}17 \cdot 10^{-10}$ (−1,93%)	$7{,}34 \cdot 10^{-10}$ (0,4%)

Comparing the results from Table 2, we can conclude that the error in the power values $P_{\text{s-sp}}$ and $P_{\text{s-sp}}$ from the MatLab model does not exceed 2–3%. The noise power calculated using the Optiwave Optisystem virtual layout has an error of 10.66%.

Now let us consider the operation of the model of the transmission system with intensity modulation according to the block diagram in Fig. 6. This model is developed using the theory of complex numbers, since only this format allows for modeling the fiber using the Split Step Fourier Method.

A pseudo-random sequence generator (PRBS) generates a sequence of information symbols $a_n = \{0, 1\}$ that control an optical modulator (OM). Binary symbols 0 and 1 are transmitted by pulses of an optical signal with a power of P_0 and P_1, respectively. Taking into account the same probability of the formation of binary symbols in the information source ($P(0) = P(1) = 0{,}5$), the average power of the transmitter signal can be calculated by the expression:

$$P_{\text{tr}} = P_0 \cdot P(0) + P_1 \cdot P(1) = 0{,}5(P_0 + P_1). \tag{22}$$

In this work, to reduce the quantity of variable parameters that affect the quality indicators of the system, a zero value of the power of the zero symbol is used ($P_0 = 0$). In this case, the average power of the transmitter signal, according to formula (22), will be half the peak power of a binary unit pulse ($P_{\text{tr}} = 0{,}5P_1$).

Given the above statistical parameters, the transmitter output signal can be written as

$$\dot{E}_{\text{tr}}(t) = \sqrt{P_{\text{tr}}}\,\sqrt{2}\sum_{n=1}^{N_{\text{symb}}} a_n \exp\left[j\omega_0(t - nT_{\text{T}})\right], \tag{23}$$

where N_{symb} - the number of information symbols in the test sequence of the mathematical model of the system;

n - the number of the current binary symbol.

To compensate for chromatic dispersion, two main methods are used in optical transmission systems in practice:

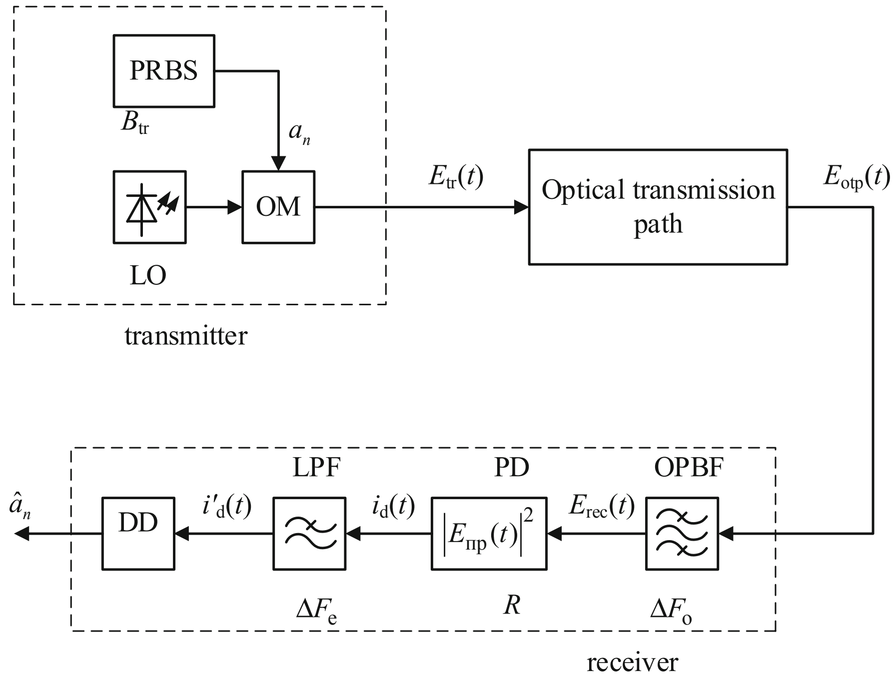


Fig. 6. Functional diagram of the model of the transmission system with intensity modulation

1) separate dispersion compensation units (DCU) as part of each section or at the output of the transmission path;
2) algorithms for electronic compensation of dispersion in the transponder receiver.

In this section, a study of the qualitative parameters of the transmission system with separate dispersion compensation devices as part of each section is carried out.

The next block of the functional diagram of the model (Fig. 2) is an optical bandpass filter (OPBF). In the previous section, a model based on an FIR filter was used to verify the accuracy of the spontaneous emission noise generation and the optical signal detection process. Its order affects the width of the frequency response transition regions and the quality characteristics of the system. Therefore, in this section of the work, an ideal optical bandpass filter was used to reduce the number of variable parameters that affect the quality characteristics of the system. It is easy to implement by filtering the signal based on IFFT and FFT operations in the frequency domain:

$$E_{rec}(t) = F_{-1}\left\{K_{opbf}(\omega)F\left\{E_{otp}(t)\right\}\right\}. \tag{24}$$

The filter transmission coefficient $K_{opbf}(\omega)$ has a unit value in the operating frequency band $(\omega_{min}; \omega_{max})$ of the optical channel:

$$K_{opbf}(\omega) = \begin{cases} 1, & \omega_{min} \le |\omega| \le \omega_{max} \\ 0, & |\omega| < \omega_{min},\ |\omega| > \omega_{max}. \end{cases} \tag{25}$$

The photodiode model is implemented according to expressions (7) and (8). A low-pass filter at the output of the photodiode has a significant effect on the appearance of the eye diagram of the received signal. In the model without modulation of the optical signal, which was used in the previous subsection, a high-order FIR filter was applied.

In real optical transmission systems with signal intensity modulation, a Bessel-Thompson filter of the 4th order is used as a low-pass filter.

Its advantage is the maximally flat phase response in the passband of the filter [4]. The transfer characteristic of this filter is written by the following expression:

$$H_4(\omega) = \frac{B_0}{\sum\limits_{k=0}^{4} B_k y^k} = \frac{B_0}{B_0 + B_1 y + B_2 y^2 + B_3 y^3 + B_4 y^4}, \tag{26}$$

where B_k - are the coefficients of the Bessel-Thompson filter ($B_0 = B_1 = 105$, $B_2 = 45$, $B_3 = 10$, $B_4 = 1$ [6]);

$y = 2{,}114 j\omega/\omega_{\text{cut}}$ - the imaginary frequency variable;

$\omega_{\text{cut}} = 2\pi \cdot 0{,}75 \cdot f_{\text{clk}} = 1{,}5\pi f_{\text{clk}}$ - the LPF cutoff frequency ($|H(\omega_{\text{cut}})| = 1/\sqrt{2}$);

f_{clk} - the clock frequency of an information signal ($f_{\text{clk}} = B_{\text{tr}}$).

The frequency response of this filter normalized to the cutoff frequency is shown in Fig. 7.

One of the main parameters of digital channels and paths of optical transmission systems is the bit error rate (BER). This factor depends on the signal-to-noise ratio at the receiver input. During the operation of the system, the parameters of the eye diagram of the signal at the input of the receiver's decision device (DD) are studied. The bit error probability depends on the intermediate quality parameter Q-factor, which is calculated according to the expression:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}, \tag{27}$$

where μ_1 and μ_0 - average values (mathematical expectation) of the samples of symbols 1 and 0, respectively;

σ_1 and σ_0 - average deviation of samples of symbols 1 and 0.

The optimal value of the signal sampling offset time ΔT in the decision device should be determined in the process of calculating the Q-factor. The offset time ΔT is within the range ($0 \le \Delta T < T_{\text{clk}}$) and the maximum value of the variable Q corresponds to its optimal value. Taking this limitation into account, the determination of signal parameters μ and σ in expression (27) should be performed according to the following expressions:

$$\begin{aligned}
\mu_1 &= M\Big[i'_{\text{d}}(nT_{\text{T}} + \Delta T)\big|_{a_n=1} \Big], \\
\mu_0 &= M\Big[i'_{d}(nT_{\text{T}} + \Delta T)\big|_{a_n=0} \Big], \\
\sigma_1 &= \sqrt{D\Big[i'_{\text{d}}(nT_{\text{T}} + \Delta T)\big|_{a_n=1} \Big]}, \\
\sigma_0 &= \sqrt{D\Big[i'_{\text{d}}(nT_{\text{T}} + \Delta T)\big|_{a_n=0} \Big]},
\end{aligned} \tag{28}$$

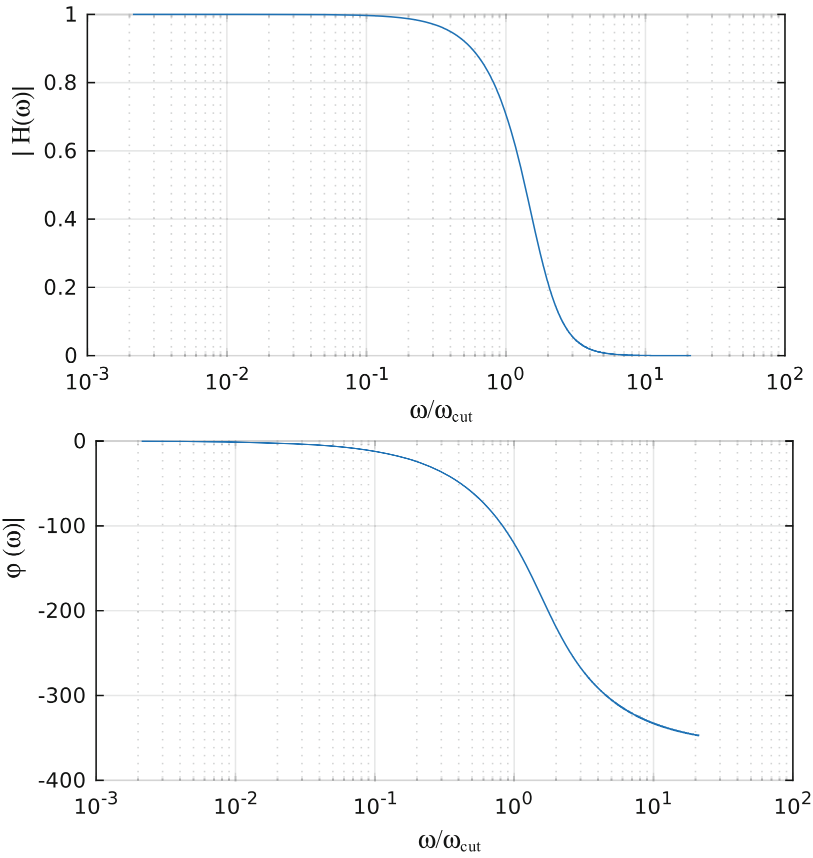


Fig. 7. Normalized frequency response of the 4th order Bessel LPF

where M [] and D[] - are operations for calculating the mathematical expectation and variance of a discrete random variable, respectively;

a_n - are binary symbols at the PRBS output ($1 \leq n \leq N_{\text{symb}}$).

4 Validation of the Simulation Model and Optimization of the Optical Signal Parameters

According to the above functional diagram (Fig. 6), a simulation model of one OFTS channel with IM was built in the MatLab environment. Its quality characteristics depend on the parameters of the transmitter, OTP and receiver. In the further text of the work, the effect of the transmitter power and the quantity of OTP sections on the total noise power $P_{\text{n}\sum} = P_{\text{s-sp}} + P_{\text{sp-sp}}$ and Q-factor of the OFTS channel is considered. Other parameters remained unchanged, and their numerical values corresponded to those given in table. 1. The simulation was carried out for standard digital OTH channels of the OTU1 ($B_{\text{tr}} = 2.666$ Gbps) and OTU2 ($B_{\text{tr}} = 10.709$ Gbps) types, in which it is advisable to use the intensity modulation of the optical signal.

To check the reliability of the simulation results, the Q-factor was also calculated according to the modified version of the expression (27).

Simulation showed (Fig. 8) that for a fixed number of OTP sections, the dependence of the Q-factor on the transmitter signal power has an extremum in the form of a maximum.

Its origin can be explained by the fact that the signal-to-noise ratio of the receiver is influenced by two factors: interference noise of spontaneous emission $P_{n\sum}$ and nonlinear signal distortions in the propagation medium. At low values of the transmitter signal power, nonlinear distortions practically do not appear and the OFTS channel operates in a linear mode. In such a case, an increase in the transmitter signal power P_{tr} results in a proportional increase in the signal-to-noise ratio and Q-factor. Further increase in transmitter power requires to the manifestation of nonlinear distortion. They lead to a change in the temporal waveform and increasing of its spectrum, which, in combination with spectrum limitation in the OBPF, leads to intersymbol interference of the digital signal. Therefore, for each value N_{sec} dependence $Q(N_{sec}, P_{tr})$ has an extremum corresponding to the optimal power value $P_{tr\ opt}$. Dependence $P_{tr\ opt}\ (N_{sec})$ at the bottom of Fig. 8 shows that increasing the OTP length leads to a decreasing in the required transmitter signal power. This is due to the accumulation of signal distortions with an increasing in the length of the propagation medium. For a digital path of the OTU1 type, the optimal power value is higher (14 mW for one OTP section versus 2 mW for OTU2), since self-modulation distortions are stronger for a shorter clock interval (higher transmission rate).

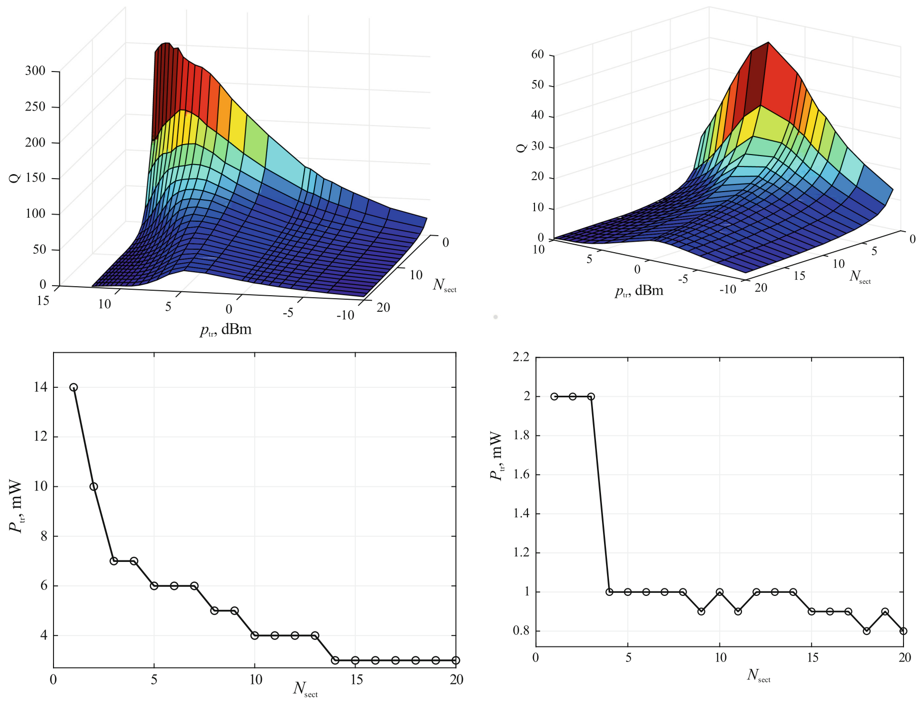
To check the reliability of the proposed model of the FOTS channel with MI, a simulation model with a similar diagram and parameters of functional blocks was developed in the Optiwave Optisystem environment (Fig. 9). It was later used as a source of valid data to check the accuracy of the MatLab model. For the optimal power value $P_{tr\ opt}(N_{sec})$ calculated in MatLab, modeling was carried out in the Optiwave Optisystem.

After that, the relative simulation error was calculated by comparing the power of the total noise $P_{n\sum}$ and the Q-factor of the signal:

$$\delta Q = \frac{\Delta Q}{Q_o} = \frac{Q_M - Q_o}{Q_o} \cdot 100\%, \tag{29}$$

where Q_M and Q_o are the numerical values of the Q-factor obtained by modeling in MatLab and Optiwave Optisystem at the same values P_{tr} and N_{sec}.

Comparison of power graphs $P_{n\sum}(N_{sec})$ in Fig. 10 shows an almost complete coincidence of the results obtained for both considered variants of the OFTS channel of the OTU1 and OTU2 type. The relative Q-factor error for one section of the optical transmission path is equal to 22.67% for OTU1 and 17.23% for OTU2. When the number of sections is more than 5, the relative modeling error does not exceed 4–5% for both types of optical channel that were studied. The discrepancy in the results for short-length OTP is explained by some differences in the implementation of certain functional blocks by the models, for example, Butterworth LPF. The indicated error is not critical, since the main task of modeling is to check the reliability of expressions and optimize the parameters of the OFTS signal.



a) b)

Fig. 8. Influence of the power and the number of OTP sections on the output parameters of the OFTS OTH channel of the OTU1 (a) and OTU2 (b) types

As stated earlier, the Q-factor is an intermediate parameter for determining the bit error probability (BER). For intensity modulation, the relationship between them is determined by the following expression [2, 7]:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right). \tag{30}$$

The considered dependence $BER(Q)$ is exponential (Fig. 11), therefore the value $Q \approx 6$ corresponds to the optical channel with standard quality ($BER = 10^{-10}$), and for the channel with improved performance ($BER = 10^{-12}$) the parameter Q increases to 7.

For such values of the Q-factor, according to the Fig. 10, a relatively small simulation error of up to 5% is already achieved. It should also be noted that the use of numerical modeling data obtained by commercial software such as Optiwave Optisystem is conditional.

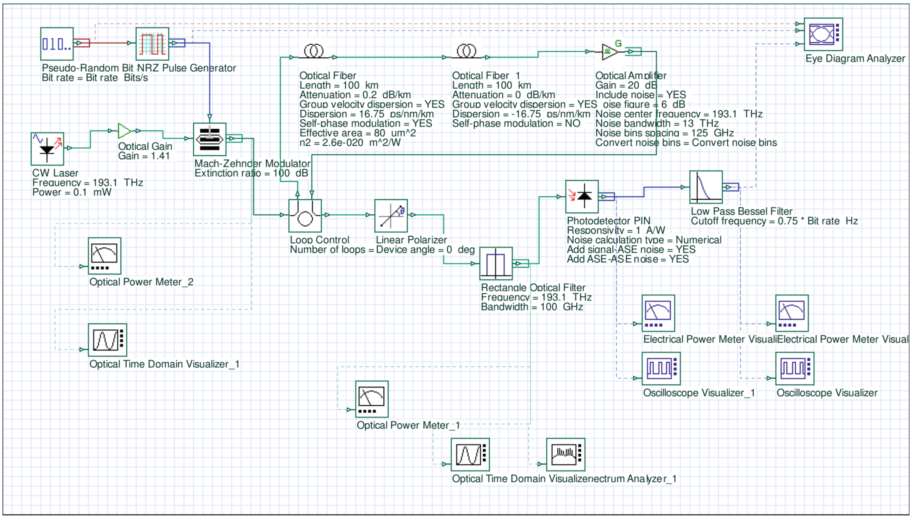
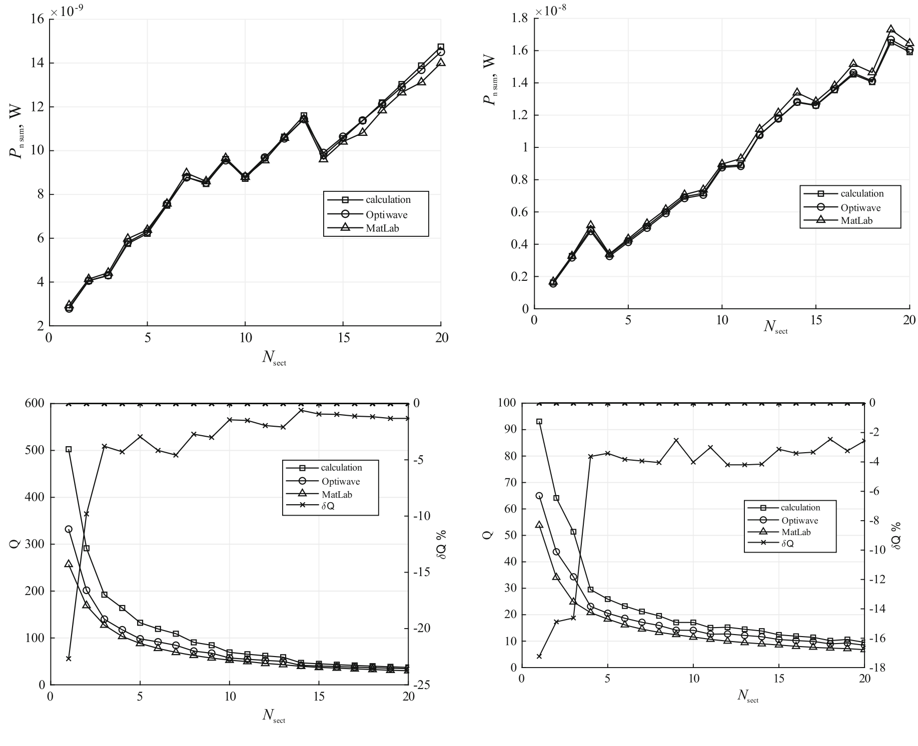


Fig. 9. Functional diagram of the OFTS with IM channel simulation model in Optiwave Optisystem



a) b)

Fig. 10. Quality parameters of optical channel of OTU1 (a) and OTU2 (b) type

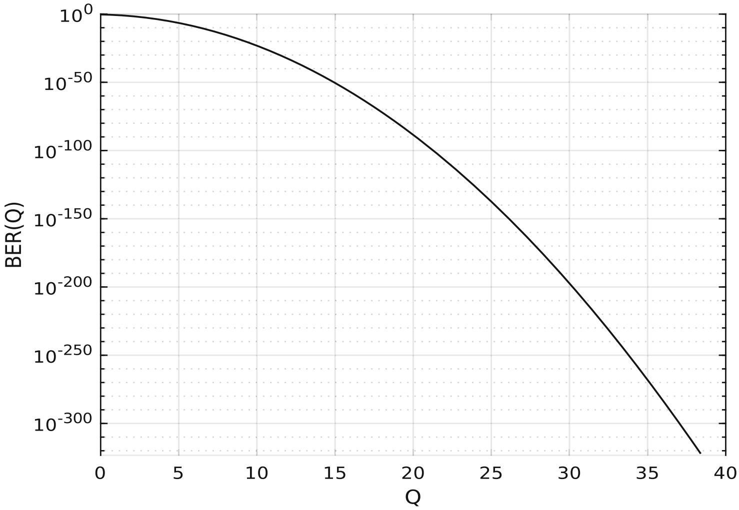


Fig. 11. Influence of Q-factor signal at a bit error probability

5 Conclusion

In this work, the qualitative parameters of the optical transmission system with intensity modulation was performed. An analytical model of signal transformations in the transmitter and receiver was proposed. A simulation model of the transmission system has been developed in the MatLab program, which allows introducing distortions of the propagation medium and amplifier noise.

A variant of the formation of the additive noise of an optical amplifier based on the discrete Fourier transform was proposed. The verification of the reliability of the results obtained was carried out by a control calculation using analytical expressions and modeling in the Optiwave Optisystem program. Comparison of the results of the model without signal modulation in MatLab showed that the simulation error is 2–3% compared to the calculation using analytical expressions.

Comparison of the system simulation with intensity modulation showed that in the case of an optical path from one optical section, an error of the Q-factor of the order of 20% is observed. This is caused by a difference in the internal construction of some elements of the transmission system block diagram. When the number of optical sections is more than 4, the simulation error does not exceed 4–5%.

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Chapter 2

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