

FIBRE-OPTIC COMMUNICATION LINES

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Mathematical simulation of an experimental prototype of a high-speed nonreturn-to-zero differential phase-shift-keying fibre-optic communication system

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Abstract. **The influence of chromatic dispersion, optical power, and nonlinear distortions in a fibre-optic communication system on the quality of data transmission based on nonreturn-to-zero differential phase-shift keying at a rate of 40 Gbit s^{-1} in one spectral channel have been numerically simulated and experimental studied. The results of direct numerical calculations and estimates based on the quality factor (*Q* factor) are in qualitative agreement with the experimental data. It is found experimentally that the dependence of the error rate on the accumulated dispersion has a plateau in the range from –50 to 50 ps nm^{-1}; a similar dependence is obtained in the numerical calculation based on the *Q* factor. The optimal calculated value of the power launched into each of 10 sections of a line with a total length of 1000 km is 2–4 dBm; it corresponds to the experimental value of 3 dBm.**

Keywords: *fibre-optic communication system, mathematical simulation, bit error rate, differential phase-shift keying.*

1. Introduction

When optical signals are transmitted through a fibre-optic communication system (FOCS), standard binary return-to-zero on–off keying (RZ OOK) is used in the overwhelming majority of cases to code information. In this keying the logical unity and zero are represented as the presence and absence of a pulse, respectively. During few recent years the researchers have been interested in the possibility of coding data using differential phase-shift keying (DPSK) [1]. In this case, data are coded by the optical-phase difference between neighboring pulses: the logical unity is coded as a shift of the phase of the optical pulse associated with the current bit by π with respect to the previous bit, while the logical zero corresponds to the case where two neighboring bits have the same phase. Several investigations have shown that this format improves significantly the data transmission quality in long FOCSs in comparison with the standard format: OOK [2, 3].

Currently, communication systems with data transmission rates of 10 Gbit s^{-1} per spectral channel or lower are most widespread. Further development of modern data transmission systems is aimed, somehow or other, at increasing the distance at which data and their amount are transmitted. One of the ways for increasing the amount of data transmitted is to increase the transmission rate in a spectral channel. When increasing this rate from 10 to 40 Gbit s^{-1}, a number of factors, previously insignificant, begin to affect the transmission process. These factors include the polarisation mode dispersion and nonlinear effects. The latter have different nature and may cause the pattern effect [4]. Currently, active studies are performed, which are aimed at compensating the dispersion and decreasing the influence of nonlinear effects for data transmission rates of 40 Gbit s^{-1} or higher [5].

In this paper, we report the results of mathematical simulation and laboratory analysis of the transmission of optical signals through a FOCS at a rate of 40 Gbit s^{-1} in one spectral channel using differential phase-shift keying. A mathematical simulation of an experimental communication system was performed and the simulation results were compared with the data of laboratory studies of the dependence of the error rate on the accumulated dispersion and average signal power. The experimental communication system that is considered here has recently been successfully tested by the Russian company T8 Ltd. The communication-line parameters were chosen so as to cover the most complex lines of Russian telecoms operators, both with respect to the length of signal amplification lines and the total line length.

2. Results of laboratory experiments

Preliminary physical experiments and numerical calculations must be performed before direct installation of the FOCS. Laboratory experiments are used to investigate a number of characteristics of the system, such as the sensitivity and level of photodetector overload, dependence of the bit error rate (BER) on the optical signal-to-noise ratio (OSNR), etc. Mathematical simulation and numerical calculations often make it possible to determine the optimal (i.e., reducing the number of errors to minimum) parameters of the optical system.

2.1. Back-to-back line

A back-to-back line is a very simple FOCS configuration, the main elements of which are an optical transmitter, optical amplifier (noise source), and optical detector. The corresponding experimental setup is schematically shown in Fig. 1.

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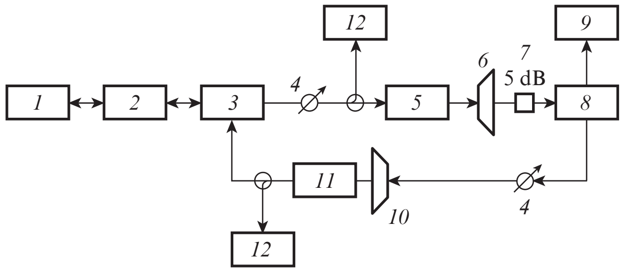

Figure 1. Schematic of the experimental setup modelling a back-to-back line: (*1*) BER meter, (*2*) TP-10-FEC unit, (*3*) TP-40G transponder, (*4*, *7*) tunable and fixed attenuators, (*5*, *8*) erbium-doped fibre amplifiers EDFA-1 and EDFA-2, (*6*, *10*) spectral multiplexers, (*9*) optical spectrum analyser, (*11*) variable Teraxion dispersion compensator, and (*12*) optical power meter.

The line consists of a BER meter operating at a rate of 10 Gbit s^{-1}; a TP-10-FEC unit, which performs signal encoding/decoding at a rate of 10 Gbit s^{-1} and corrects errors; aggregation transponder TP-40G, which forms an optical signal at a rate of 43.7 Gbit s^{-1} from four flows with a rate of 10 Gbit s^{-1} and operates inversely in the reception mode; erbium-doped fibre amplifiers (EDFAs); tunable and fixed attenuators; spectral multiplexers DWDM, which play the role of optical filters; and a Teraxion tunable dispersion compensator.

This line was used to perform laboratory experiments on transmitting a bit flow with a rate of 40 Gbit s^{-1} in one spectral channel using the NRZ DPSK format. The dispersion accumulated at the end of the line was varied with the aid of a tunable dispersion compensator. As a result, a dependence of BER on the accumulated dispersion was obtained for a fixed OSNR value: 8.08 dB (Fig. 2).

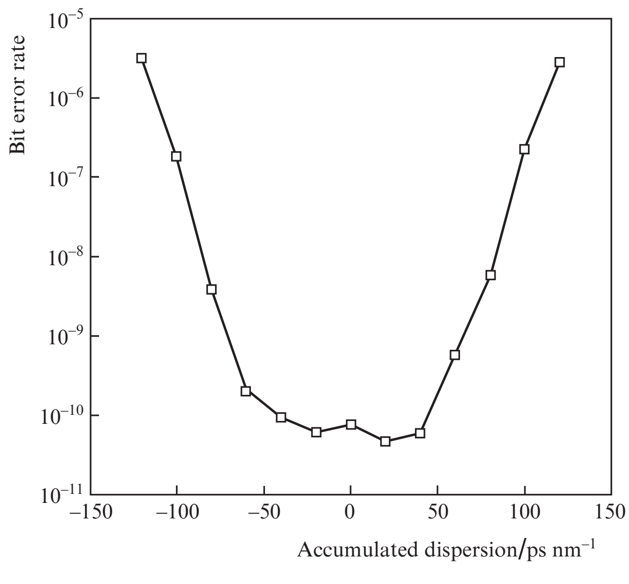

Figure 2. Experimental dependence of BER on the accumulated dispersion for a back-to-back line at OSNR = 8.08 dB and signal power on the receiver 2.2 dBm.

Note that this curve has a plateau: BER changes only slightly in the range of accumulated dispersion from –50 to 50 ps nm^{-1}. This fact can be explained as follows: during signal detection in the receiver the time averaging was performed over an interval that is shorter than the bit interval. Therefore, small broadening and intersection of neighboring optical pulses, which occur at a small nonzero dispersion, do not affect the bit detection quality.

2.2. Main line

Our experimental studies were primarily aimed at developing and implementing a FOCS with a total length of 1000 km based on a single-mode fibre (SMF) to transmit data at a rate of 40 Gbit s^{-1} in one spectral channel using the NRZ DPSK format. The block diagram of the FOCS under study is shown in Fig. 3.

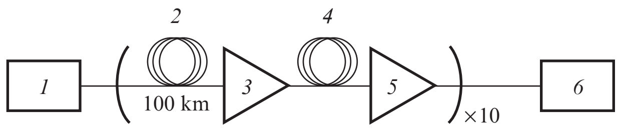

Figure 3. Schematic FOCS configuration: (*1*) emitter unit, (*2*) SMF, (*3*, *5*) EDFA-1 and EDFA-2 amplifiers, (*4*) fibre dispersion compensator, and (*6*) optical signal receiver.

A periodic section of the line includes a 100-km-long SMF segment, two erbium-doped fibre amplifiers (EDFA-1 and EDFA-2), a fibre segment compensating for dispersion, and blocks for emitting and receiving optical signals. This scheme is the simplest version of a controlled-dispersion system. Dispersion-controlled solitons can be used as data carriers in these lines [6, 7]. The line consists of 10 sections. EDFA-1 and EDFA-2 compensate for the signal optical loss in a section. Forward error correction (FEC) is used to reduce the error rate.

To date, the results of the experiment performed with the main FOCS give grounds to state the following: a loop test on the output receiver of the 1000-km optical line did not reveal any errors during continuous 36-h bit flow transmission; this result corresponds to BER < 5×10^{-15}. The radiation power introduced into the SMF was 3 dBm.

3. Description of mathematical models

The signal propagation along an optical fibre is described by the generalised nonlinear Schrödinger equation for the complex envelope $A(z,t)$ of the electromagnetic field amplitude:

$$\mathrm{i}\frac{\partial A}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\mathrm{i}\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}+\gamma|A|^2A=-\mathrm{i}\frac{\alpha}{2}A. \qquad (1)$$

Here, z is the distance along the fibre; t is time; β_2 is the parameter of group velocity dispersion; β_3 is the third-order dispersion term; α is the damping coefficient; $\gamma = 2\pi n_2/(\lambda_0 A_{\rm eff})$ is the nonlinearity coefficient; n_2 is the nonlinear refractive index of the fibre; $\lambda_0 = 1550$ nm is the carrier wavelength; and $A_{\rm eff}$ is the fibre mode effective area. The parameters of optical fibres that were used in numerical calculations are given below.

	SMF	DCF
Loss at a wavelength of 1550 nm/dB km^{-1}	0.2	0.65
Dispersion/ps nm^{-1} km^{-1}	17	–100
Dispersion slope/ps nm^{-2} km^{-1}	0.07	–0.41
Nonlinearity coefficient/km W^{-1}	1.2	5.76

Equation (1) was solved numerically using the method of splitting into physical processes [8].

An erbium-doped fibre amplifier is modelled as a point device, which multiplies the optical signal amplitude by $\sqrt{G}$ (G is the amplifier gain) and adds spontaneous emission noise to the signal. Noise is described using the model of additive white noise. The white noise spectral density is calculated by the formula $S = (G - 1)n_{sp}h\nu_0$, where h is Planck's constant; ν_0 is the signal carrier frequency; and n_{sp} is the spontaneous emission coefficient, which is related to the amplifier noise factor NF by the expression $\mathrm{NF} = 2n_{sp}(G - 1)/G$. The EDFA noise factor was assumed to be NF = 4.5 dB in the calculations.

An optical filter is used to filter off the spontaneous emission noise introduced by the optical amplifier from the signal. The principle of the filter operation is based on multiplying the distribution of the pulse amplitude $A(\omega)$ by the filter transmission function in the Fourier space. This function has a Gaussian shape and a unit amplitude at the carrier frequency $\omega_0 = 2\pi c/\lambda_0$ and an FWHM = B_{opt}.

The tunable dispersion compensator is modelled as a linear point device, which either increases or decreases the accumulated chromatic dispersion.

In the mathematical simulation the optical receiver is considered to be an 'ideal' device, which receives an optical signal of any necessary power and transforms it into a current according to the rule $\Delta = I_0 - I_1$, where $I_0 = \frac{1}{2}|A_n + A_{n-1}|^2$ is the current of zeros; $I_1 = \frac{1}{2}|A_n - A_{n-1}|^2$ is the current of units; and n is the number of the bit interval. Then, the electric signal passes through a third-order Butterworth filter with a transmission band B_{el} and arrives at a device that detects bits directly (0 and 1 are detected when $\Delta > 0$ and $\Delta < 0$, respectively). The mathematical simulation was performed without applying FEC.

4. *Q* factor

The operation of any communication system is estimated by the error rate, which is defined as the ratio of the number of erroneously received bits to the total number of transmitted ones [9]. Currently, the minimum allowable error rate is considered to be BER = 10^{-9}, which corresponds to one erroneously received bit per 10^9 bits transmitted. Sequences of several thousands of bits are used in typical numerical calculations because of the scarce resources. However, such sequences are insufficient for direct simulation of small BER values. Thus, BER is estimated using different indirect methods, which are based on the statistical analysis of fluctuations of the shape of signal received.

When data are transmitted in the DPSK format, and the statistics of zero and unit bit currents at the receiver is described by the normal Gaussian distribution, BER is estimated using the model of 'current' Q factor, which is determined as follows [2, 10–12]:

$$Q_{el} = \frac{|\mu_0 - \mu_1|}{\sigma_0 + \sigma_1},$$

where μ_i, σ_i ($i = 0, 1$) are, respectively, the mathematical expectations and rms deviations of the current difference $\Delta = I_0 - I_1$ for zero and unit bits. The factor Q_{el} is related to the error rate as follows:

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{Q_{el}}{\sqrt{2}}\right). \quad (2)$$

Note that the Q_{el} factor does not yield an exact estimate of the communication system quality; however, its maximum value allows one to determine a set of optimal (i.e., reducing the number of errors to minimum) parameters of the optical system and the signal.

5. Results of numerical simulation

5.1. Back-to-back line

Figure 4 shows schematically the model that was used for numerical calculations of the propagation of optical pulses along a back-to-back line. The calculations were performed using pseudorandom sequences containing $2^{16} - 1$ bits. The bit interval was 25 ps, a value corresponding to a transmission rate of 40 Gbit s^{-1}. The initial average signal power was 6 dBm. The noise power was chosen such as to ensure a relatively small OSNR value at the receiver and to make it possible to count errors directly. The optical filter width B_{opt} = 100 GHz was taken from the experimental data.

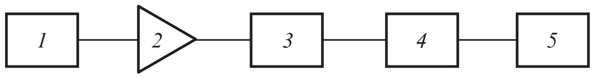

Figure 4. Model of back-to-back line for numerical count: (*1*) emitter unit, (*2*) EDFA, (*3*) tunable dispersion compensator Teraxion, (*4*) band filter, and (*5*) optical signal receiver.

Figure 5 shows the dependences of BER on the accumulated dispersion, which were obtained either by counting errors directly ($\mathrm{BER_{dir}}$) or based on the Q_{el} factor ($\mathrm{BER_{el}}$). It can be seen that at B_{el} = 100 GHz the curves, in accordance with the experimental results, have a plateau. At a given bandwidth of the electric filter, the averaging is performed over an interval of 10 ps, and the insignificant overlap of neighbouring pulses does not increase the number of erroneously received bits. It can also be seen that the numerical estimate of BER, obtained using the current Q factor, does not coincide quantitatively with the result of direct count. The reason for this discrepancy is the inaccuracy of the model of white Gaussian noise.

It is known that the electric filter of the receiver affects the signal detection quality and that a filter bandwidth of 40 GHz is optimal at a data transmission rate of 40 Gbit s^{-1} [13]. One can in Fig. 5 that at B_{el} = 40 GHz the $\mathrm{BER_{dir}}$ and $\mathrm{BER_{el}}$ curves have only one minimum, which corresponds to zero accumulated dispersion (pulses are not broaden).

5.2. Main line

Let us consider the results of the numerical calculations for the main FOCS developed. The length of the DCF segment was set by the average dispersion of the section and determined from the relation

$$\langle D \rangle = \frac{D_{SMF}L_{SMF} + D_{DCF}L_{DCF}}{L_{SMF} + L_{DCF}},$$

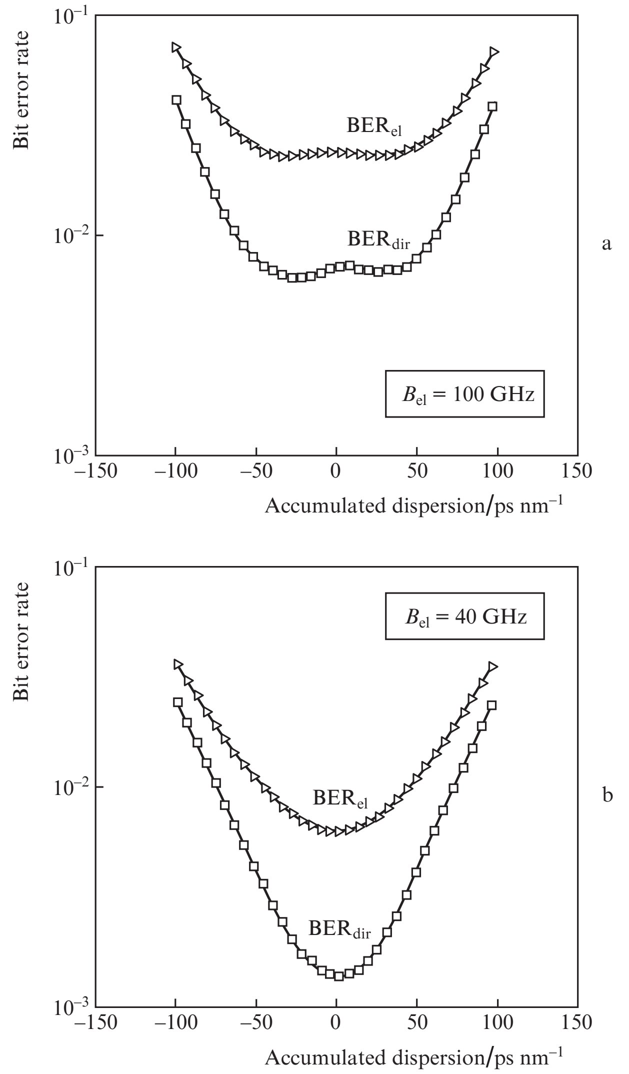

Figure 5. Dependences of BER on the accumulated dispersion at different B_{el} values.

where D_{SMF} and D_{DCF} are, respectively, the chromatic dispersions of SMF and DCF and L_{SMF} and L_{DCF} are their lengths. The filter bandwidth is B_{el} = 40 GHz.

The main result of the calculations is that the FOCS parameters were optimised in order to determine the ranges of values corresponding to minimum BER. The calculations were performed by varying the initial average pulse power, the average dispersion of one periodic section, and the dispersion accumulated in the line.

Figure 6 shows the level lines of the Q_{el} factor in the plane of the following parameters: the initial signal power and the average dispersion of one section, at a fixed dispersion accumulated in the line.

Note that the larger the Q_{el} factor, the smaller the error rate; therefore, it is the areas with maximum Q_{el} in the diagrams that are most important. It can be seen that the maximum values of the Q_{el} factor correspond to the initial powers in the range of 2.5–4 dBm and negative average dispersion of the section.

Figure 7 shows the Q_{el} level lines in the (initial signal power–accumulated dispersion) plane, at $\langle D \rangle = -1.1$ ps nm^{-1} km^{-1}. It can be seen that Q_{el} reaches maximum values at an accumulated dispersion in the range from 0 to 30 ps nm^{-1}. The maximum

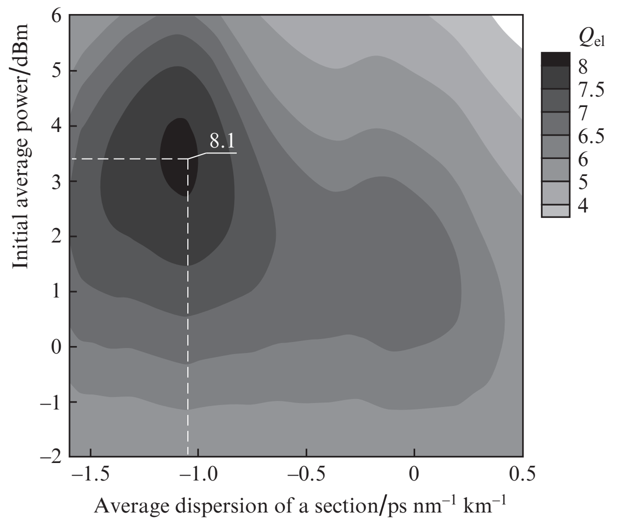

Figure 6. Q_{el} level lines in the plane of the initial average signal power and the average dispersion of a section at zero accumulated dispersion.

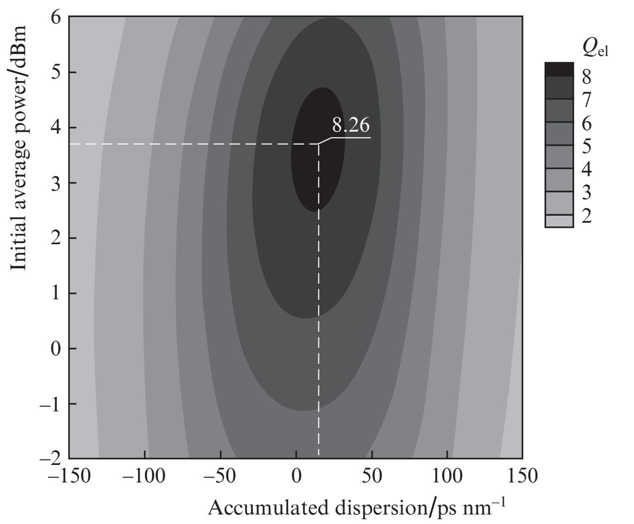

Figure 7. Q_{el} level lines in the (initial average signal power–accumulated dispersion) plane at $\langle D \rangle = -1.1$ ps nm^{-1} km^{-1}.

Q_{el} value is 8.26, which, according to estimate (2), corresponds to BER = 7×10^{-17}.

6. Conclusions

We performed mathematical simulation of data transmission in the NRZ DPSK format at a rate of 40 Gbit s^{-1} in one spectral channel. The simulation results were compared with the experimental data.

It was experimentally found that the dependence of the error rate on the accumulated dispersion has a plateau in the range from −50 to 50 ps nm^{-1}. The results of direct numerical calculations and estimates based on the quality parameter (Q factor) confirm this result for a filter with a bandwidth exceeding 80 GHz.

A 1000-km FOCS composed of 10 sections was optimised. The data of the numerical calculations show that the optimal power introduced into each of the ten sections is 2–4 dBm. The optimal average dispersion of a section is in the range from –1.4 to –0.9 ps nm^{-1} km^{-1}, which is also in agreement with the experimental results.

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