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Study of fibreoptic communication links with the optical regeneration of signals

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***Abstract*. Wavelength-division-multiplexing fibreoptic communication links with optical 2R regenerators based on a saturable absorber are mathematically simulated. The results of optimisation of specific configurations of symmetric lines are presented, and it is shown that the transmission distance in systems with the periodic optical regeneration of signals considerably exceeds that in systems without optical regenerators.**

Keywords: *fibreoptic communication links, dispersion management, saturable absorber, optical regeneration, error-bit rate.*

1. Introduction

The modern development of fibreoptic communication links is amazing. The world production of optical fibres at the verge of the XX and XXI centuries has achieved 60 million km per year, i.e., more than 100 km of fibreoptic communication links have been laid per minute [1]. All the continents are coupled with each other by underwater fibreoptic communication cables, whose total length is sufficient for wounding the earth six times. The development of broadband optical amplifiers resulted in the creation in the late 1990s of experimental fibreoptic communication links with the number of wavelength-division-multiplexing (WDM) channels exceeding 100, which provided the bit rate above 1 Tbit s^{-1}.

At present, the two methods for a further drastic increase in the information capacity of fibreoptic communication links are being discussed: the broadening of the spectral region and the increase in the number of WDM channels, and also the increase in the bit rate in each channel.

Among the most promising methods for increasing the transmission capacity in an individual WDM channel up to 40 Gbit s^{-1} and above are the dispersion management and optical regeneration of signals.

In systems with the dispersion management, periodically alternating fibres with chromatic dispersion of opposite signs are used, which allows one to control the dispersion broadening of a pulse, to increase the signal-to-noise ratio, and decrease the influence of nonlinear effects on the degradation of optical pulses (see, for example, [2]).

There exist several types of optical signal regeneration [3], which involve:

(i) The regeneration of the signal amplitude (1R regeneration);

(ii) the regeneration of the signal amplitude and shape (2R regeneration);

(iii) the regeneration of the signal amplitude, shape, and temporal position (3R regeneration).

In this paper, we simulated dispersion-management WDM communication links with incorporated optical 2R regenerators and the 40-Gbit s^{-1} rate in a WDM channel. The main element of such regenerators is a saturable absorber [4 – 7].

2. Principal scheme and a mathematical model of an optical regenerator

The operation of a saturable absorber (SA) is based on the absorption of the incident signal power if it proves to be lower than a threshold saturation power P_{sat}. For powers exceeding P_{sat}, the transmission coefficient of the saturable absorber rapidly increases and tends asymptotically to unity. Under such conditions, the low-power amplified spontaneous noise and background dispersion emission are suppressed. The use of a saturable absorber together with a narrowband optical filter (F) and a highly nonlinear fibre (HNF) provides the suppression of noise in single bits. The enhancement of nonlinearity in the fibre is achieved in fact due to a decrease in the effective area of the mode.

We selected the configuration of the optical regenerator (OR) after the preliminary simulation of several possible schemes. The scheme of the optical regenerator considered in this paper is shown in Fig. 1.

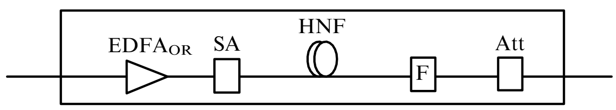

Figure 1. Scheme of the optical regenerator.

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The input signal coupled to the optical regenerator was first amplified in an erbium-doped fibre amplifier ($EDFA_{OR}$). Then, the pulse saturated in the SA. The loss function $\alpha(t)$ in the SA, which depends on the time and power of the input signal, is described by the equation

$$\frac{d\alpha(t)}{dt} = -\frac{\alpha(t) - \alpha_0}{\tau} - \frac{\alpha(t)P(z^*, t)}{\tau P_{sat}}, \qquad (1)$$

where $P(z^*, t) = |A(z^*, t)|^2$ is the signal power distribution; α_0 are the constant losses; $z^* \equiv \text{const}$ is the fixed distance; and τ is the characteristic response time of the saturable absorber. We used in the calculations the values $\alpha_0 = 0.53$, $P_{sat} = 7$ dB, and $\tau = 5$ ps.

Note that instead of differential equation (1), the integral equation corresponding to the generalised model of losses in the saturable absorber can be used:

$$\alpha(t) = \alpha_0 \exp\left[-\int_0^1 \frac{ds}{\tau}\left(1 + \frac{P(z^*, s)}{P_{sat}}\right)\right]$$

$$\times\left\{1 + \int_0^1 \frac{d\xi}{\tau} \exp\left[\int_0^{\xi} \frac{dx}{\tau}\left(1 + \frac{P(z^*, x)}{P_{sat}}\right)\right]\right\}. \qquad (2)$$

Then, the transfer function is $T(t) = 1 - \alpha(t, P(z^*, t))$, and the action of the saturable absorber on the signal is described as

$$P_{out}(z^*, t) = [1 - \alpha(t, P_{in}(z^*, t))]P_{in}(z^*, t) = T(t)P_{in}(z^*, t). \qquad (3)$$

Here, $P_{in}(z^*, t)$ and $P_{out}(z^*, t)$ are the signal powers at the input and output of the saturable absorber, respectively.

Then, the signal propagates along the HNF with the anomalous group-velocity dispersion. A decrease in the effective interaction area in the HNF results in the enhancement of nonlinear effects: in particular, self-phase modulation in a medium with anomalous dispersion leads to the formation of a soliton-like pulse. This provides the effective feedback when the signal propagates through the optical filter F, which produces the losses increasing with the input pulse energy. As a result, the self-adjustment and self-control of the signal energy take place. The width of the Gaussian transmission band of the optical filter F is 100–120 GHz. The typical length of the HNF is 3–6 km. The average output power of the OR is regenerated to its initial value with the help of a linear attenuator (Att).

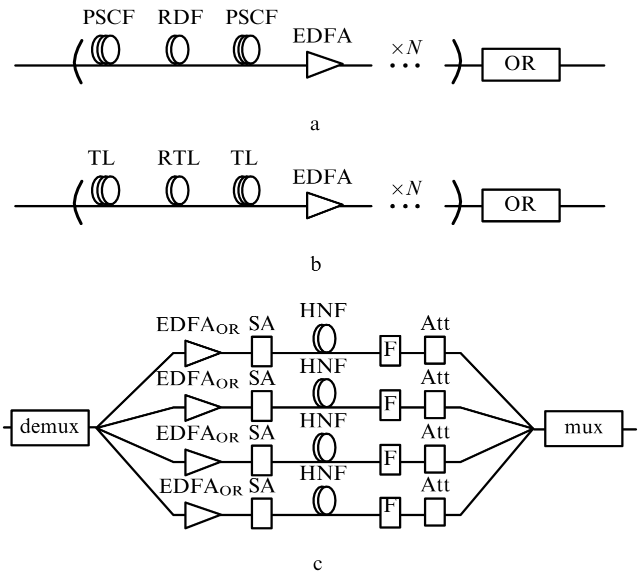

Figure 2. Schemes of the periodic sections of different communication links (a, b) and the optical regenerator for the system with four individual transmission channels (c); (mux) multiplexer, (demux) demultiplexer.

3. Formation of autosoliton regimes

First we studied the autosoliton regimes of propagation of single optical pulses. The problem of construction of autosoliton regimes involved the search for stable solutions, which were determined by fixed points in the energy-pulse width-phase modulation parameter space (chirp). The phase modulation parameter (chirp) of the pulse is described by the expression $C = \frac{1}{2}\partial^2\varphi/\partial t^2$, where φ is the pulse phase. Because the existence of such regimes was determined by the parameters of the system, they were called autosolitons.

The principal schemes of fibreoptic communication links are shown in Fig. 2. The periodic section of such links consists of two identical transmission fibres (PSCF in Fig. 2a and TL in Fig. 2b) with the positive dispersion and a dispersion-compensation fibre located between them (RDF and RTL, respectively) with the negative dispersion. The length of the periodic section of each of the links was 60 km, and the distance between optical regenerators was 300 km. The types of optical fibres and their parameters used in calculations are presented in Table 1. Here, PSCF is a pure silica core fibre, RDF is a reverse (negative) dispersion fibre. TL is a Teralight fibre, and RTL is a Reverse Teralight fibre.

The propagation of optical pulses along the communication link is described by the generalised nonlinear Schrödinger equation (NSE) [8]

$$i\frac{\partial A}{\partial z} + i\gamma A - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - i\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} +$$

Table 1. Types of optical fibres and their parameters.

Parameters	Fibre type				
	PSCF	RDF	TL	RTL	HNF
Attenuation at a wavelength of 1550 nm/dB km^{-1}	0.18	0.3	0.21	0.28	0.5
Effective fibre area/μm^2	110	20	60	28	6.5
Dispersion/ps nm^{-1} km^{-1}	20	−42	8	−16	2
Dispersion slope/ps nm^{-2} km^{-1}	0.06	−0.13	0.08	−0.16	0.03
Nonlinear refractive index/m^2 W^{-1}	2.7×10^{-20}	2.7×10^{-20}	2.7×10^{-20}	2.7×10^{-20}	2.7×10^{-20}

$$+\sigma\left[|A|^2A+\frac{\mathrm{i}}{\omega_0}\frac{\partial}{\partial t}(|A|^2A)-T_{\mathrm{R}}A\frac{\partial|A|^2}{\partial t}\right]=0. \quad (4)$$

Here, z is the distance along the link; t is the time; $|A|^2$ is the power; β_2 is the group-velocity dispersion parameter; β_3 is the third-order dispersion term; γ is the attenuation coefficient; σ is the Kerr nonlinearity coefficient; and T_{R} is the Raman response time. The quantities β_2, β_3, γ, and σ are represented by the functions of z, which allows us to take into account variations in these parameters on passing from one type of the fibre to another. The nonlinearity coefficient is $\sigma=2\pi n_2/(\lambda_0 A_{\mathrm{eff}})$, where n_2 is the nonlinear refractive index; λ_0 is the carrier wavelength; $\omega_0/2\pi=\nu_0=c/\lambda_0$ is the carrier signal frequency; c is the speed of light; and A_{eff} is the effective area of the fibre eigenmode.

Equation (4) was solved numerically by the method of splitting over physical processes. Let us represent this equation in the operator form

$$\frac{\partial A}{\partial z}=\left(\tilde{D}+\tilde{N}\right)A, \quad (5)$$

where

$$\tilde{D}=-\gamma-\mathrm{i}\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}+\frac{\beta_3}{6}\frac{\partial^3}{\partial t^3} \quad (6)$$

is the operator of the linear part, which takes into account dispersion effects and attenuation, and

$$\tilde{N}=\mathrm{i}\sigma\left[|A|^2+\frac{\mathrm{i}}{\omega_0}\frac{1}{A}\frac{\partial}{\partial t}(|A|^2A)-T_{\mathrm{R}}\frac{\partial|A|^2}{\partial t}\right] \quad (7)$$

is the nonlinear operator.

The NSE solution can be formally written as

$$A(z+h,t)=\exp\left[\int_z^{z+h/2}\tilde{N}(s)\mathrm{d}s\right]\exp\left[h\tilde{D}\right]$$
$$\times\exp\left[\int_{z+h/2}^{z+h}\tilde{N}(s)\mathrm{d}s\right]A(z,t). \quad (8)$$

The operator $\exp[h\tilde{D}]$ is calculated in the Fourier space:

$$\exp\left[h\tilde{D}\right]B(z,t)=\left\{F^{-1}\exp\left[h\tilde{D}(\mathrm{i}\omega)\right]F\right\}B(z,t), \quad (9)$$

where F is the Fourier transform operator. This scheme has the second-order accuracy in the step h [8].

Consider the process of formation of the autosoliton solution from the initial Gaussian pulse with the peak power $P_0=3$ mW and the FWHM $T_{0.5}=6$ ps. By varying the $\mathrm{EDFA_{OR}}$ gain in the optical regenerator and the attenuation coefficient of the attenuator, we can obtain the regimes of stable propagation of the carrier signal (Figs 3, 4). Any input pulse (within some region of parameter values) transforms to a stable asymptotic solution (optical autosoliton). Figure 3 shows the phase portrait of the signal in the C, $T_{0.5}$ plane, where C is the phase modulation parameter and $T_{0.5}$ is the signal FWHM. The distribution of the pulse power at the output of optical regenerators, i.e., at distances multiple of 300 km is shown in Fig. 4.

To demonstrate the SA efficiency upon noise suppression, we compare the power distributions of signals propagated over large distances in the system with an optical regenerator and analogous system without it. Figure 5 shows the power distributions for a Gaussian pulse with $T_{0.5}=6$ ps and $P_0=3$ mW propagated over a distance of 30 000 km for systems with the SA and without

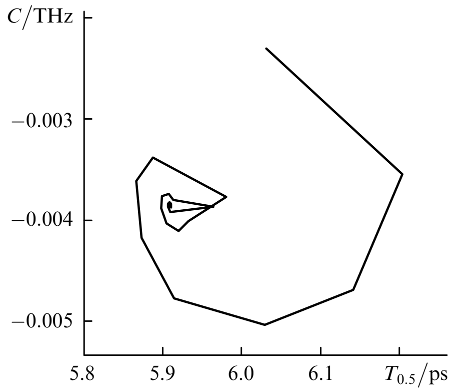

Figure 3. Phase portrait of the pulse parameters in the plane of the phase modulation parameter and pulse width.

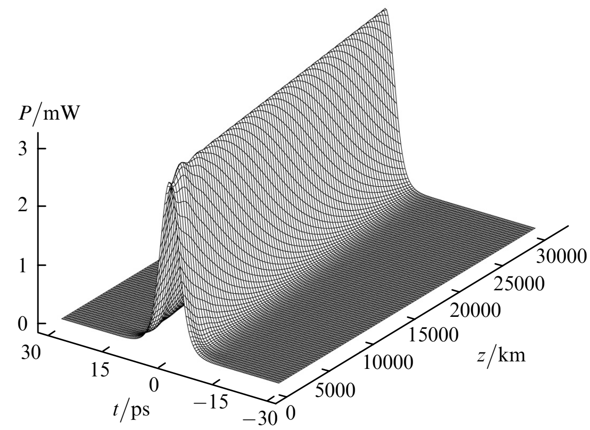

Figure 4. Dynamics of the Gaussian pulse with the initial FWHM $T_{0.5}=6$ ps and the initial peak power $P_0=3$ mW at the output of the optical regenerator.

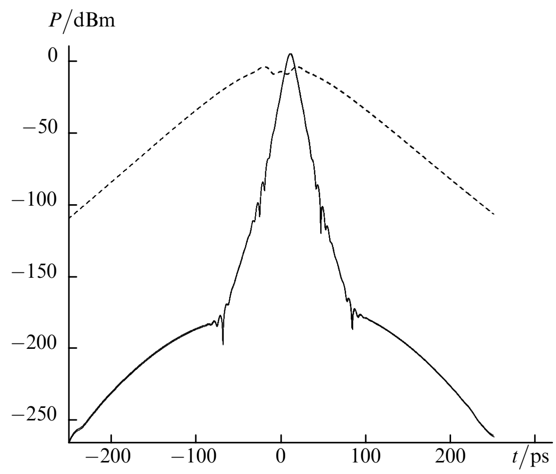

Figure 5. Power distribution of the Gaussian pulse with $T_{0.5}=6$ ps and $P_0=3$ mW propagated over the distance $z=30\,000$ km for the systems with a saturable absorber (solid curve) and without it (dashed curve).

it. One can easily see that saturable absorbers provide considerable noise suppression.

4. Examples of optimisation of WDM fibreoptic communication links

Below, we present the main results of calculations of the optimisation of fibreoptic communication links with a total bit rate of $K \times 40$ Gbit s^{-1}, where K is the number of WDM channels. The distance between the adjacent WDM channels for the carrier wavelength $\lambda_0 =$ 1550 nm was 1.6 nm (200 GHz), and we considered typically from four to eight channels in the calculations.

The 'quality' of the communication system is estimated by the bit error rate (BER), which is the ratio of the number of error bits to the total number of transmitted bits [9]. It is assumed that the data transmission quality is acceptable when BER $\leqslant 10^{-9}$ (which corresponds to one error bit per 10^9 transmitted bits). We will define P_1 and P_0 as the error probabilities for the detection of signals '1' and '0', respectively [9]:

$$P_1 = \int_{-\infty}^{I_d} p_1(x)\mathrm{d}x, \quad P_0 = \int_{I_d}^{\infty} p_0(x)\mathrm{d}x,$$

where I_d is the resolution level, which is determined from the condition of the minimum BER $= (P_1 + P_0)/2$. We assume also that the density probabilities of the appearance of '0' and '1' have the normal distribution

$$p_i(x) = \frac{1}{\sqrt{2\pi}\sigma_i}\exp\left[-\frac{(x-\mu_i)^2}{2\sigma_i^2}\right],$$

where μ_i are the average values; σ_i are dispersions, $i = 0, 1$. Then, we introduce the Q factor, which is related to the BER as

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp(-Q^2/4)}{\sqrt{2\pi}Q}, \quad (10)$$

where $Q = (\mu_1 - \mu_0)/(\sigma_1 + \sigma_0)$. Note that BER $\leqslant 10^{-9}$ corresponds to $Q \geqslant 6$.

The optical amplifier not only amplifies the input optical signal but also adds the amplified spontaneous emission (ASE) noise to it. The latter reduces the signal-to-noise ratio of the system and increases the BER, thereby deteriorating the transmission characteristics of the fibreoptic communication link.

The optical signal power has an optimal value because at low powers the ASE noise of EDFAs increases the BER. The signal-to-noise ratio increases when higher power pulses are used, however, the role of nonlinear effects also increases in this case, resulting in the deterioration of the signal quality. Therefore, there exists a certain peak power of input pulses with a fixed width that provides the best balance between noise and nonlinear effects from the point of view of the Q factor value.

The initial mathematical model describing the spontaneous emission noise is the 'white' noise model. In the case of an EDFA, the spectral density of the white noise is calculated from the expression

$$S_{sp} = (G-1)n_{sp}h\nu_0, \quad (11)$$

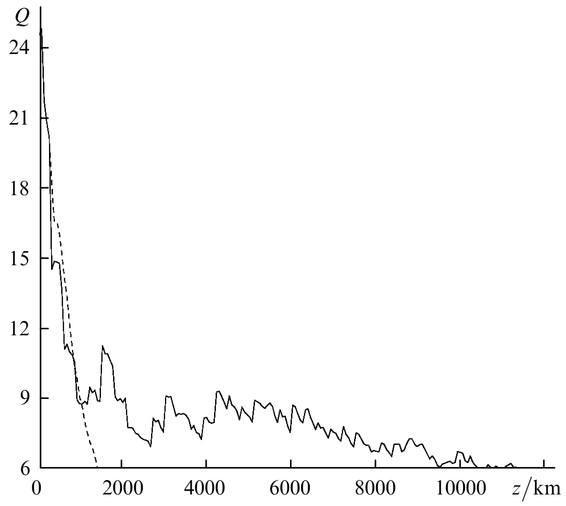

Figure 6. Typical dependence of the Q factor of the transmission distance in one of the WDM channels in the system with the optical regenerator (solid curve) and without it (dashed curve) for the dispersion-management optical communication link.

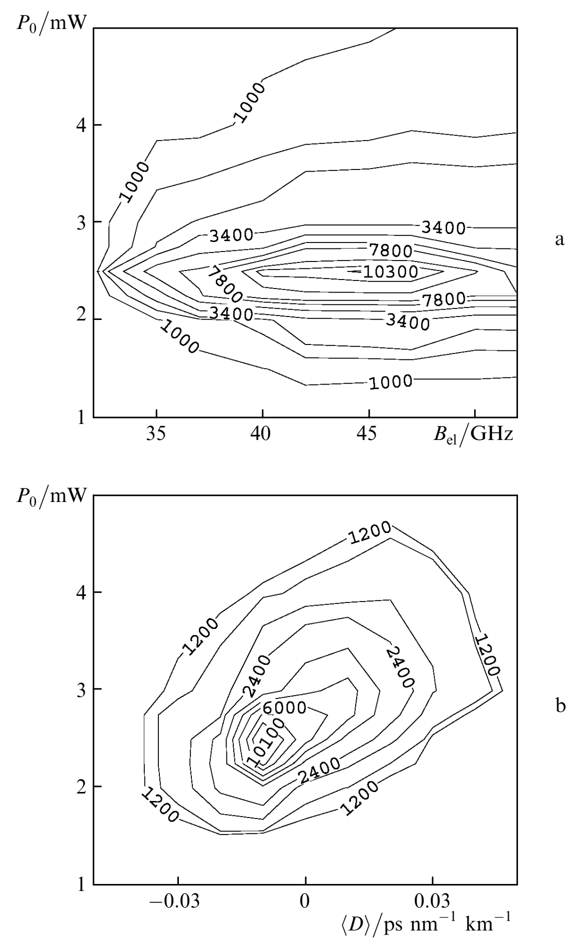

Figure 7. Lines of the transmission distance level (in km) as functions of the input peak power $P_0\langle D\rangle$ and the electric filter bandwidth B_{el} (a), as well as of the mean dispersion $\langle D\rangle$ (b) for the PSCF + RDF+ PSCF + EDFA configuration.

where h is Planck's constant; G is the signal gain; n_{sp} is the spontaneous emission coefficient, which is related to the amplifier noise figure (NF) by the expression [9]

$$\mathrm{NF} = \frac{2n_{\mathrm{sp}}(G-1)}{G}. \qquad (12)$$

For WDM systems, an individual optical regenerator was used in each WDM channel after demultiplexing, as shown in Fig. 2. The optimisation was performed for the two configurations of symmetric fibreoptic communication links (Fig. 2) consisting of the periodic sections PSCF+ FDF + PSCF + EDFA and TL + RTL + TL + EDFA of length 60 km and optical regenerators separated by 300 km.

Let us specify the transmission distance as the distance for which the condition $Q \geqslant 6$ is fulfilled. The transmission distance was calculated by using from 5 to 11 pseudorandom sequences, each of them containing 128 bits, and the transmission distance in each of the channels was determined by the median average over the distances, which was calculated for each of the sequences [10]. Then, the transmission distance was selected as the least distance for all possible channels.

The typical dependence of the Q factor of the fibreoptic link on the distance is shown in Fig. 6. One can see that the presence of optical regenerators in the system allows one to increase considerably the distance for which $Q \geqslant 6$.

The results of massive numerical calculations are presented in Figs 7 and 8. Figure 7 shows the results of optimisation of the PSCF + RDF+ PSCF + EDFA link. One can see that for the optimal parameters of the optical regenerator, the input pulse peak power, and the average dispersion of the link, the data transmission distance can exceed 10 000 km. The corresponding system without optical regenerators has the transmission distance of about 2 000 km.

Figure 8 shows the results of optimisation of the TL + RTL + TL + EDFA communication link. In this case, the transmission distance can exceed 8 000 km when the parameters of the system are optimal. Finally, Fig. 9 presents the dependences of the transmission distance for the PSCF + RDF + PSCF + EDFA link on the parameters P_{sat} and α_0 of the saturable absorber.

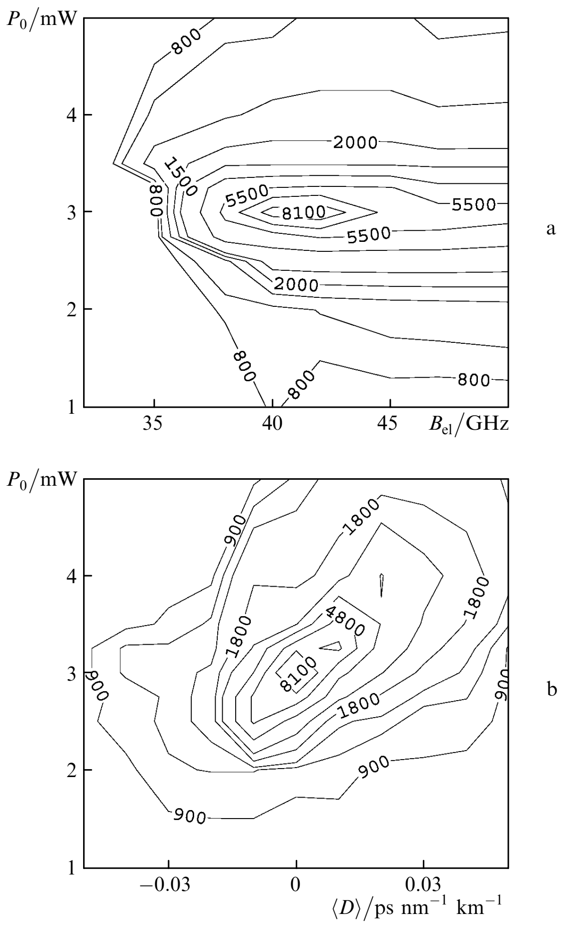

Figure 8. Same as in Fig. 7 for the TL + RTL + TL + EDFA configuration.

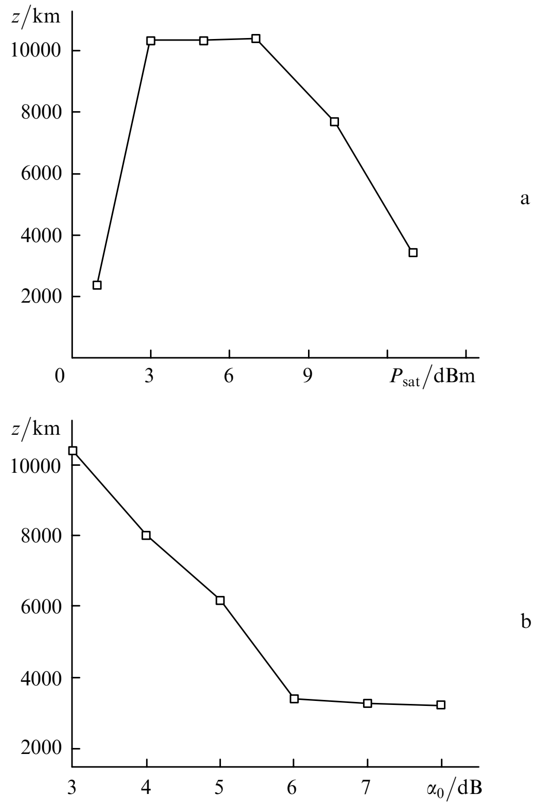

Figure 9. Dependences of the data transmission distance z on the saturation power P_{sat} (a) and constant losses α_0 (b) for the PSCF + RDF + PSCF + EDFA configuration.

5. Conclusions

We have presented the results of numerical simulations of fibreoptic communication links with optical regenerators based on a saturable absorber with a bit rate of 40 Gbit s^{-1} in a WDM channel. The autosoliton propagation regimes for a single optical pulse have been found. The symmetric WDM communication links have been optimised. The transmission distance above 10 000 km has been achieved for the PSCF + RDF + PSCF + EDFA communication link. The transmission distance for the TL + RTL + TL + EDFA link exceeds 8 000 km.

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