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New data format for fibreoptic dense wavelength-division-multiplexing communication links

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***Abstract*. A flat-top format is proposed for the transmission of digital signals with the sinc-shaped profile of a single pulse resonantly located along several bit intervals. Due to a rapid decrease of the spectral power, such a format reduces the interaction between two adjacent frequency channels. Numerical simulation showed the possibility of error-free transmission at a rate of 40 Gbit s^{-1} over 1200 km in the link with the 0.8-bit s^{-1} Hz^{-1} spectral efficiency without using polarisation wavelength-division multiplexing.**

Keywords: *fibreoptic communication links, digital signal transfer format, wavelength-division multiplexing, frequency channels, fibres for data transfer.*

1. Introduction

A further increase in the total capacity of fibreoptic communication links became possible due to an increase in the spectral efficiency of data transmission. In the last decade, high-bit-rate (40 Gbt s^{-1} and above) dense wavelength-division multiplexing (DWDM) data-transfer technologies attract great attention [1 – 4]. DWDM systems assume, of course, a narrow filtering of signals to suppress the interaction between them. However, this leads to the distortion of the temporal shape of signals. The transmission of spectrally limited signals at 40 Gbit s^{-1} per channel was studied earlier in [5], but the pulse shape was not specially controlled.

In this paper, we propose and study the DWDM system providing the $N \times 40$-Gbit s^{-1} data transmission (N is the number of channels) by using the flat-top format along the frequency band B and the temporal signal profile sinc(πBt). Pulses of such a shape allow the suppression of a strong interaction between adjacent bits due to the location of zeroes of the function sinc (πBt) in the middle of bit intervals.

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2. Flat-top format

To obtain the sinc-shaped carrier signals with the limited spectrum, a short 1.7-ps Gaussian pulse was transmitted through a super-Gaussian optical filter. Figure 1 shows the temporal profiles of the pulse before and after the optical filter. Note that the filter bandwidth B is selected so that zeroes of the function sinc(πBt) are located in the middle of bit intervals. This reduces the interaction between adjacent bits. Figure 2 shows the formation of a WDM signal by using spectrally limited pulses.

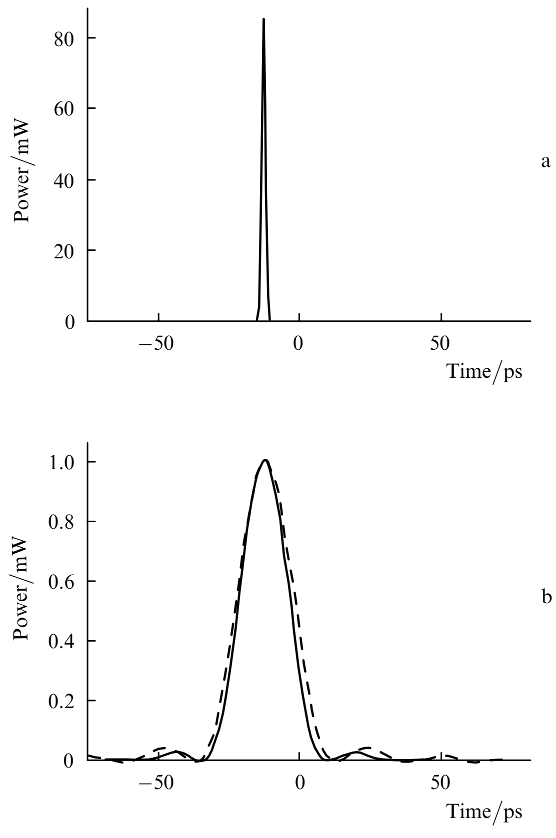

Figure 1. Temporal profile of a pulse before (a) and after a super-Gaussian optical filter (b, solid curve), and the function sinc(πBt)/t (b, dashed curve).

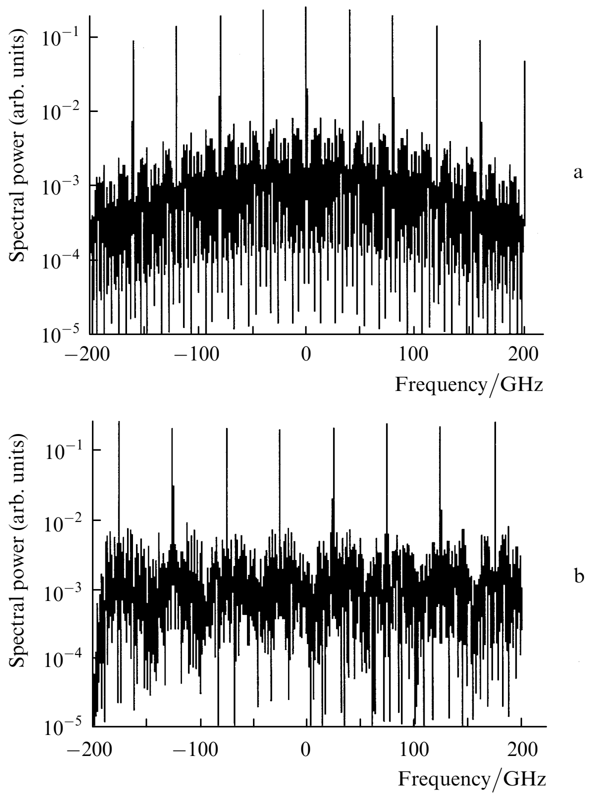

Figure 2. Spectra of signals of one frequency channel before the use of an optical filter (a) and of eight frequency channels after its use (b).

3. Results of numerical simulation

We described the dynamics of optical pulses in a fibreoptic communication link using the nonlinear Schrödinger equation for the complex envelope $E(z,t)$ of an electromagnetic field

$$\mathrm{i}\,\frac{\partial E}{\partial z}-\frac{1}{2}\,\beta_2(z)\,\frac{\partial^2 E}{\partial t^2}+\sigma(z)|E|^2E$$

$$=\mathrm{i}\Big[-\gamma(z)+r_k\sum_{k=1}^{N}\delta(z-z_k)\Big]E=\mathrm{i}G(z)E.$$

Here, z is the propagation distance of a signal; t is time; $|E|^2$ is the optical pulse power; $\beta_2(z)$ is the group-velocity dispersion coefficient; $\sigma(z)=2\pi n_2(z)/[\lambda_0 A_{\mathrm{eff}}(z)]$ is the nonlinearity coefficient; n_2 is the nonlinear refractive index; λ_0 is the carrier wavelength; $A_{\mathrm{eff}}(z)$ is the effective cross sectional area of the fibre; and z_k is the position of optical amplifiers.

Consider for simplicity a periodic amplification with the period Z_{a}. If the loss coefficient γ between two adjacent amplifiers is a constant, the gain is $r_k=[\exp(\gamma_k Z_{\mathrm{a}})-1]$. The loss coefficient on the kth segment is $\gamma_k=0.05\ln(10)\alpha_k$, where the signal attenuation α_k is expressed in dB km^{-1}. This equation was simulated numerically by the Fourier method of splitting over physical processes [6].

Consider, without loss of generality, the propagation of sinc-shaped signals in a $N\times 40$-Gbit s^{-1} WDM system with 50-GHz-spaced channels. A periodic section of the fibreoptic communication link consists of two fibres [single-mode fibre (SMF) and dispersion-compensating fibre (DCF)] and a lumped erbium-doped fibre amplifier (EDFA): SMF (20 km) + DCF (6.8 km) + SMF (20 km) + EDFA (the total length is 46.8 km). The parameters of the fibres are: SMF: $\lambda=1550$ nm, dispersion $D=17$ ps nm^{-1} km^{-1}, dispersion slope $S=0.07$ ps nm^{-1} nm^{-1} km^{-1}, losses 0.2 dB km^{-1}; DCF: $\lambda=1550$ nm, $D=-100$ ps nm^{-1} km^{-1}, $S=-0.41$ ps nm^{-1} nm^{-1} km^{-1}, losses 0.65 dB km^{-1}. The noise coefficient of the lumped EDFA is 4.5 dB.

We studied transmission in eight 50-GHz-spaced channels in the wavelength range between 1548.78 and 1551.98 nm. The average dispersion of the communication link was $\langle D\rangle=-0.03$ ps nm^{-1} km^{-1}. The channels were mixed and separated using a super-Gaussian filter (of the six order) with a bandwidth of 43 GHz and specified optimal shift with respect to the channel centre. To produce the sinc-shaped sequence, very short 1.7-ps, 85-mW pulses were transmitted through an optical filter with a bandwidth of 43 GHz (Fig. 1). Note that the shift $\Delta\nu$ of the optical filter band with respect to the channel centre is a very important parameter of the problem.

Figure 3 shows the eye diagrams of a signal transmitted through the super-Gaussian optical filter whose band was shifted by zero and -6 GHz with respect to the channel centre. One can see that the shape of pulses for this data format strongly differs from their shape both for the returning-zero (RZ) format considered in [5] and the non-returning-zero (NRZ) format. A more open eye diagram corresponds to the optimal shift $\Delta\nu=-6$ GHz. This results in a strong dependence of the initial Q factor of the system on $\Delta\nu$. Recall that the value of the Q factor characterises the data transmission error coefficient BER, which is equal to 10^{-9} for $Q_{\mathrm{cr}}=6$ [7]. These dependences for the flat-top format and usual RZ format are presented in Fig. 4. One can see that the initial value of the Q factor for

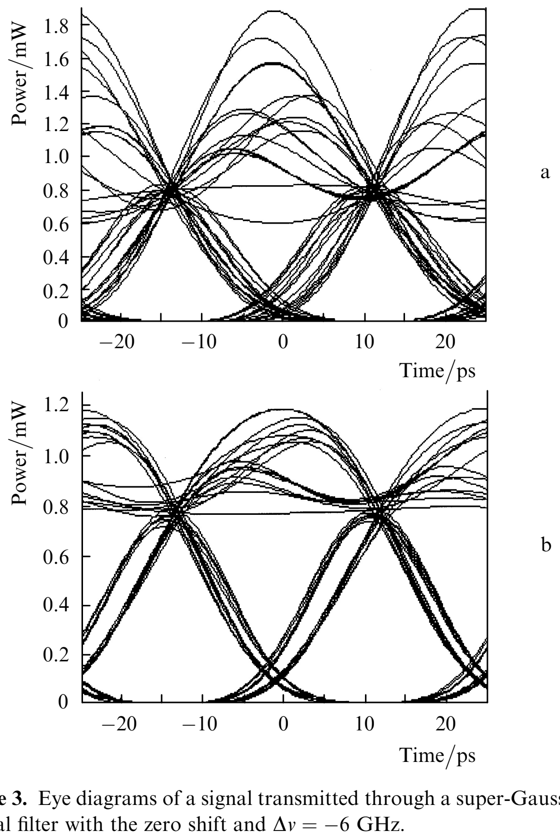

Figure 3. Eye diagrams of a signal transmitted through a super-Gaussian optical filter with the zero shift and $\Delta\nu=-6$ GHz.

the usual format proves to be much smaller than the standard critical value $Q_{cr} = 6$. A third-order Batterworth filter with the 50-GHz bandwidth was used in front of a receiver. The transmission capacity of the system was defined as the distance for which $Q \geqslant 6$, and was calculated as the averaged distance for the propagation of twenty-one pseudo-random sequences containing $2^7 - 1$ bits each [8]. Figure 5 shows the distance over which a signal propagates as a function of the filter band shift with respect to the channel centre. Note that the optimal shift depends on the band shape of the filter. For example, for the six-order super-Gaussian filter, the optimal shift is -6 GHz.

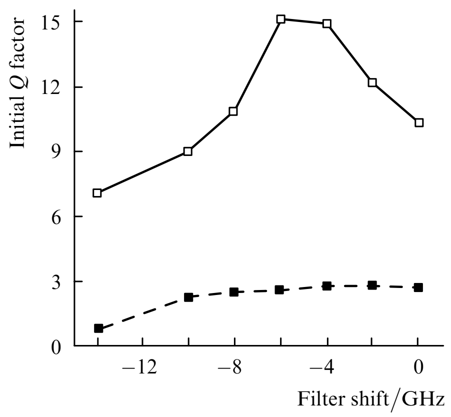

Figure 4. Dependences of the initial Q factor on the filter shift for the flat-top data format (solid curve) and usual RZ format (dashed curve) for optimal parameters for each format.

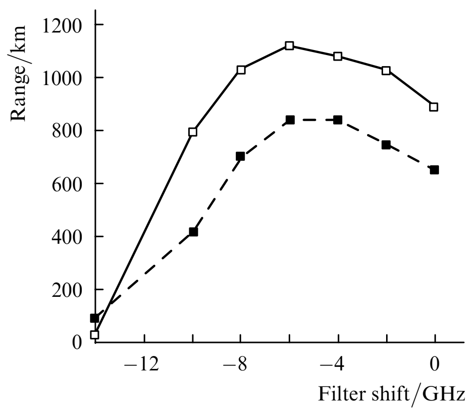

Figure 5. Dependences of the signal transmission range on the shift of the six-order super-Gaussian filter (solid curve) and on the shift of a rectangular filter (dashed curve) for optimal parameters for each format.

We also studied the dependence of the data transmission range on the bandwidth of an electric filter at a receiver (Fig. 6). The average power of a signal at the link input was -5 dBm.

4. Conclusions

We have studied the flat-top data format with sinc-shaped optical pulses. A rapid attenuation of the spectral power outside the signal band and the corresponding suppression of crosstalk between the channels provide the 0.8-bit$\times$ s^{-1} Hz^{-1} spectral efficiency without using polarisation WDM. A direct numerical simulation showed the possi-

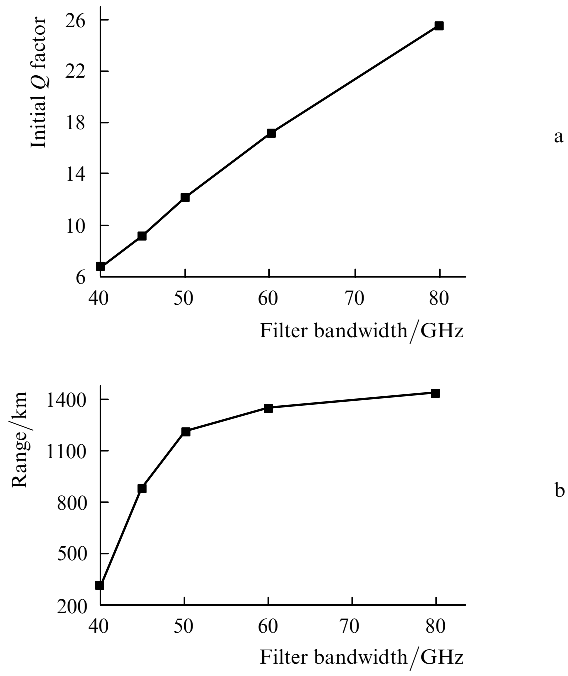

Figure 6. Dependences of the initial Q factor of the system on the electric filter bandwidth for the shift of the super-Gaussian optical filter $\Delta\nu = -6$ GHz (a) and of the signal transmission range on the electric filter bandwidth (b).

bility of error-free WDM transmission at $N \times 40$ Gbit s^{-1} over 1200 km with the 0.8-bit s^{-1} Hz^{-1} spectral efficiency.

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