Quantum Electronics **48** (12) 1157–1159 (2018)

https://doi.org/10.1070/QEL16848

Suppression of nonlinear interaction in a high-speed optical channel with dispersion compensation

E.G. Shapiro, D.A. Shapiro

Abstract. **Transmission of optical pulses with a large positive chirp is simulated numerically in a 40 Gbit s^{-1} communication link with high average negative dispersion. It is shown that the use of these mechanisms effectively suppresses the nonlinear interaction of pulses and significantly improves the quality of signal transmission.**

Keywords: *fibre-optic communication links, mathematical modelling, nonlinear Schrödinger equation.*

1. Introduction

The growing need to increase the rate and volume of transmitted information requires an increase in the capacity of communication links. The task becomes particularly relevant, since according to forecasts, the required information capacity of trunk lines will exceed the Shannon limit in the next few years [1, 2]. This problem can be solved using coherent detection, multichannel transmission, new modulation formats, and an increase in the transmission rate in one channel. The design of fibre-optic communication lines (methods of signal amplification, optimisation of dispersion maps, etc.) can also increase the information capacity [3, 4].

In this paper, a new regime of signal transmission is proposed, in which large average negative dispersion and large positive chirping are used. The main factors of signal distortion are the amplifier noise and nonlinear interaction. To suppress the Kerr nonlinearity, the soliton format with managed dispersion has been previously used [5, 6]. The proposed design of the communication channel is new. In such a channel, there are no solitons with controlled dispersion. We numerically simulated single-channel transmission of Gaussian optical pulses with a bit interval of 25 ps within the framework of the nonlinear Schrödinger equation. The numerical calculation was performed for a four-level amplitude modulation with a large variation in the power of optical pulses. It turned out that the simultaneous use of large average negative dispersion and large positive chirping significantly improves the quality of signal transmission.

E.G. Shapiro, D.A. Shapiro Institute of Automation and Electrometry, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Koptyuga 1, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia;
e-mail: shapiro@iae.nsk.su

Received 9 October 2018
Kvantovaya Elektronika **48** (12) 1157–1159 (2018)
Translated by I.A. Ulitkin

2. Numerical modelling

The communication link consisted of 20 periodic SMF-type spans (100 km) + EDFA + DCF + EDFA, where SMF is a standard single-mode fibre, EDFA is an erbium-doped fibre amplifier (a noise factor of 4.5 dB), and DCF is a dispersion compensating fibre. The parameters of the circuit elements are given below.

	SMF	DCF
Attenuation at $\lambda = 1550$ nm/dB km^{-1}	0.2	0.65
Effective area/μm^2	80	19
Chromatic dispersion/ps nm^{-1} km^{-1}	17	–100
Dispersion slope/ps nm^{-2} km^{-1}	0.07	–0.41
Nonlinear refractive index/10^{-20} m^2 W^{-1}	2.7	2.7

The average dispersion of the communication link depends on the length of the DCF span. The accumulated dispersion was compensated for at the receiver. We considered the transmission of information, which is encoded by four levels of amplitude of 8.3-ps-wide Gaussian pulses.

The signal was set in the form

$$S(t) = \sum_n a_n(t - nT), \quad a_n(\tau) = B_n \exp\left(-\frac{\tau^2 - 2\mathrm{i}\varphi_n\tau^2}{2T_0^2}\right),$$

where $T = 25$ ps is the bit interval; $B_n = B\xi_n$ is the amplitude; $\xi_n \in \{1, 2, 3, 4\}$ is a random variable taking one of the indicated values with a probability of 1/4; T_0 is a pulse width parameter equal to 4 ps; and φ_n is the chirp. Thus, the pulse occupied about a third of a bit interval. The powers of the transmitted pulses differed significantly, with the smallest average power corresponding to $\xi_n = 1$. In the numerical calculation, $B = 0.0065$, which corresponds to an average pulse power of 1.3 mW at $\xi_n = 1$. We denote by $\varphi_n = c_i$ the pulse chirp, corresponding to $\xi_n = i$ ($i = 1, 2, 3, 4$), i.e., c_1 is the pulse chirp with the lowest power ($\xi_n = 1$), and c_4 is the pulse chirp with the greatest power ($\xi_n = 4$). We set $\boldsymbol{\varphi} = (c_1, c_2, c_3, c_4)$.

To suppress the Kerr nonlinearity, we used large negative dispersion of the communication link and large positive chirping. To demonstrate the influence of these mechanisms on the suppression of nonlinear distortion, we calculated the distribution functions of the average bit powers at the receiver for links with and without the use of these mechanisms. The sample size was 20 400.

Figure 1 shows the signal distribution function for a link without a chirp and with zero mean dispersion. It can be seen that the histogram peaks merge and the pulses cannot be correctly recognised. Figure 2 shows a histogram of a signal with

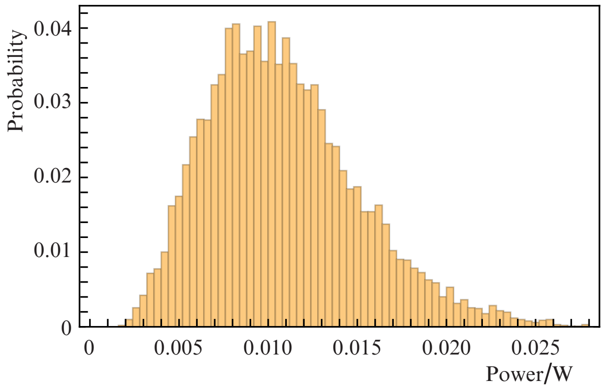

Figure 1. Histogram of a signal with average chromatic dispersion $\langle D \rangle = 0$ and $\boldsymbol{\varphi} = (0, 0, 0, 0)$.

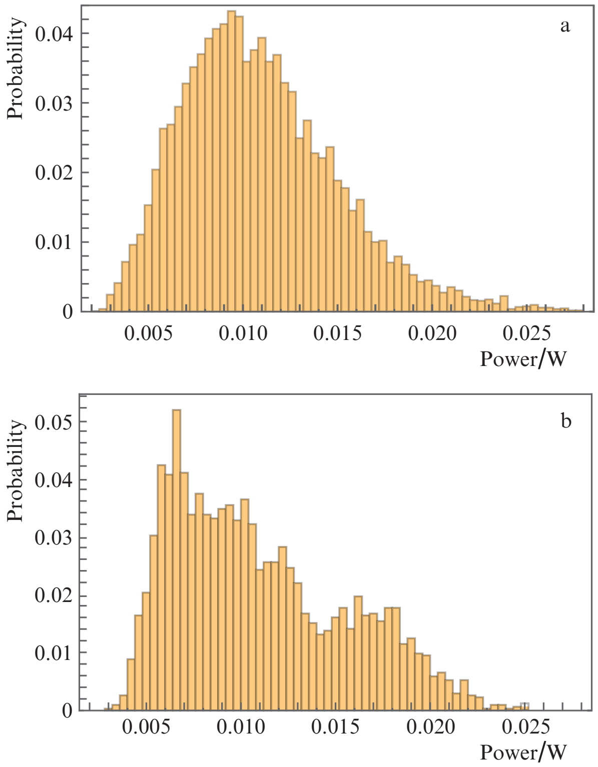

Figure 2. Histograms of signals with (a) $\langle D \rangle = -1.2$ ps nm^{-1} km^{-1}, $\varphi = (0, 0, 0, 0)$ and (b) $\langle D \rangle = 0$, $\varphi = (15, 13, 19, 7)$.

only a positive chirp or only with average negative dispersion. The peaks here are also impossible to distinguish.

Figure 3a shows a histogram of the signal at the receiver with the simultaneous action of negative dispersion and the chirp. The peaks corresponding to the four levels of amplitude modulation are clearly distinguishable. Therefore, the use of high negative dispersion and positive chirping significantly improves the quality of signal transmission. The maximum probability of incorrect recognition corresponds to small values of amplitude ($\xi_n = 1$ and 2). The total number of errors is 165, which for a sample of 20 400 corresponds to the probability of an error of 8.1×10^{-3}. The number of recognition errors in the region of the first two peaks of the histogram is 142.

The parameters c_i of positive chirping of optical pulses can be considered as parameters for further optimisation of the communication link in terms of signal transmission quality. Figure 3b shows a histogram of the signal, in which the chirp is selected individually for each level of the signal amplitude. In this case, the total number of errors is 15, which gives the probability of an error of 7.1×10^{-4}. Therefore, if one uses different chirps for pulses of different power, the probability of error can be significantly reduced.

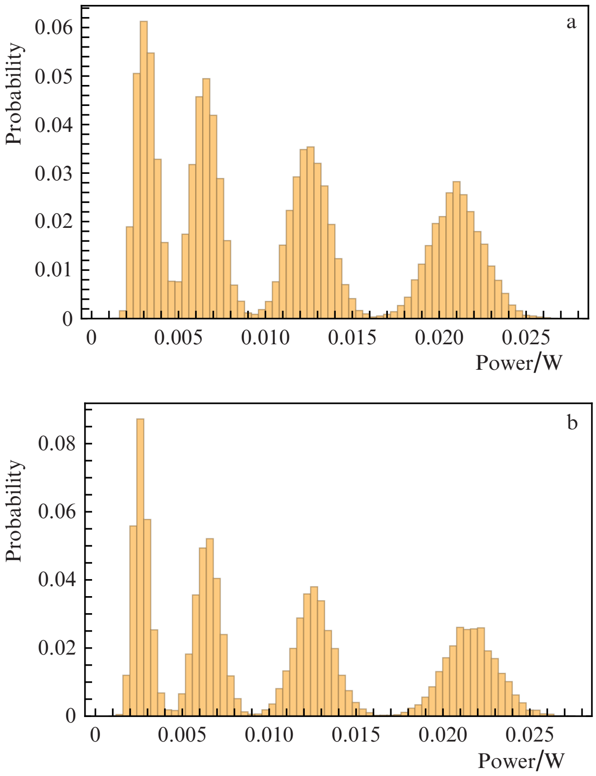

Figure 3. Histograms of signals with $\langle D \rangle = -1.2$ ps nm^{-1} km^{-1} and (a) $\varphi = (7, 7, 7, 7)$ and (b) $\varphi = (15, 13, 19, 7)$.

For a link with the OOK format (on – off keying) of data transmission, Shapiro et al. [7] showed that large negative dispersion improves the quality of signal transmission, but for a four-level amplitude format, one must use simultaneously the proposed mechanisms for the Kerr nonlinearity suppression. The suppression of the Kerr nonlinearity is due to the fact that the amplification of the signal and the compression of optical pulses occur at different points in space. Therefore, the compressed pulse has a relatively low power and is, conse-

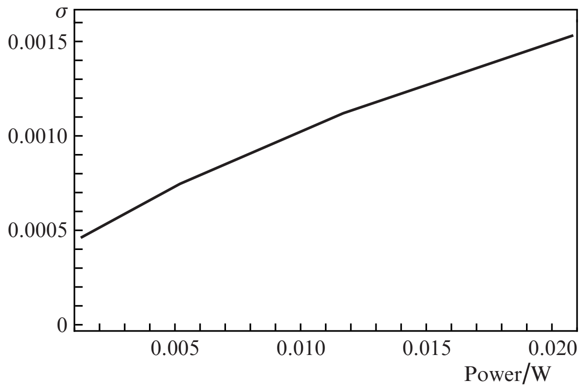

Figure 4. Standard deviation σ of the bit power.

quently, less affected to degradation due to self-action. Positive chirping causes rapid pulse broadening, which also reduces the nonlinear interaction.

The proposed signal propagation regime is nonlinear. In addition, unlike the model described in [8], nonlinear interaction is not a distortion caused by additional nonlinear noise. This is evident from the fact that the standard deviations of the recorded amplitudes differ markedly (Fig. 3) for optical pulses of different power. Figure 4 shows the dependence of the standard deviation on the power of the pulses. It is seen that this dependence monotonically increases.

3. Conclusions

The transmission of optical pulses with a large positive chirp in a link with large negative dispersion has been calculated for the first time. It has been shown that in a channel with a data transfer rate of 40 Gbit s^{-1}, the signal degradation caused by nonlinear effects is significantly reduced. The dependence of the dispersion of the distribution function of the recorded bits at the receiver on the power of optical pulses for a four-level amplitude format is calculated. The obtained results can be useful in choosing the design of the communication link. The possibility of selecting the power of transmitted symbols with allowance for their dispersion [9] under conditions of a balance of chirping and dispersion card of the communication link is an additional opportunity to optimise a fibre link with a high data transfer rate.

Acknowledgements. This work was supported by the Russian Science Foundation (Grant No. 16-11-10133).

References

1. Shannon C. *Bell Syst. Tech. J.*, **27**, 379; 623 (1948).
2. Richardson D.J. *Science*, **330**, 327 (2010).
3. Yushko O.V., Nanii O.E., Redyuk A.A., Treshchikov V.N., Fedoruk M.P. *Quantum Electron.*, **45** (1), 75 (2015) [*Kvantovaya Elektron.*, **45** (1), 75 (2015)].
4. Gurkin N.V., Konyshev V.A., Nanii O.E., Novikov A.G., Treshchikov V.N., Ubaidullaev R.R. *Quantum Electron.*, **45** (1), 69 (2015) [*Kvantovaya Elektron.*, **45** (1), 69 (2015)].
5. Gabitov I.R., Shapiro E.G., Turitsyn S.K. *Phys. Rev. E*, **55**, 3624 (1997).
6. Agraval G. *Applications of Nonlinear Fiber Optics* (Oxford: Acad. Press, 2008; St. Petersburg: Lan', 2011).
7. Shapiro E.G., Fedoruk M.P., et al. *Opt. Commun.*, **250** (1-3), 202 (2005).
8. Poggiolini P., Carena A., Curri V., Bosco G., Forghieri F. *IEEE Photonics Technol. Lett.*, **23**, 742 (2011).
9. Shapiro E.G., Shapiro D.A. *Optoelectron., Instrum. Data Process.*, **54** (4), 108 (2018) [*Avtometriya*, **54** (4), 108 (2018)].