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***FIBRE-OPTIC COMMUNICATION LINES***

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# Nonlinear noise suppression in a high-rate optical channel with phase modulation and dispersion compensation

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***Abstract.*** **We have performed a numerical simulation of transmission of optical DP QPSK signals at a rate of 40 Gbaud over a distance of 2000 km. It is shown that a channel with large negative dispersion and preliminary large positive pulse chirping significantly reduces nonlinear distortion and improves the signal quality. To further reduce the probability of recognition error, it is proposed, instead of a negative dispersion fibre, to use compensators with low attenuation.**

***Keywords:*** *fibre-optic communication lines, mathematical simulation, nonlinear Schrödinger equation, chromatic dispersion.*

## 1. Introduction

Currently, there is a rapid annual growth in traffic in optical communication lines. It is expected that in the coming years, existing lines will no longer be able to cope with the amount of transmitted data [1]; therefore, the task of increasing the line's throughput capacity is put to the fore. To solve this problem use is made of coherent detection, multichannel transmission, new modulation formats [2], polarisation multiplexing, high channel rate, etc. Signal amplification and optimisation of dispersion maps can also increase the information capacity of optical lines, and so these areas of research are also relevant.

For coherent communication lines with electronic dispersion compensation [3], significant factors are the accumulated dispersion and data transfer rate, which are limited by the capabilities of digital signal processors [4]. From this point of view, for extended lines with a high symbol rate (40 Gbaud), it is promising to use a dual polarisation quadrature phase shift keying (DP QPSK) modulation format [5].

Signal distortions are mainly caused by amplifier noise and nonlinear effects. The regime of the pulse compression point sliding along the periodic section of the communication line was considered in [6] for binary OOK format. In the case of quadrature phase shift keying, the use of large negative dispersion only slightly improves the signal quality, and so positive chirping of the input pulses is additionally required. The latter causes rapid pulse broadening, which reduces the signal degradation due to Kerr nonlinearity. A combination of these two methods for suppressing nonlinear signal distortion has been proposed for a multilevel amplitude format [7]. It is shown that they reduce nonlinear amplitude distortions. However, the amplitude and phase modulations are fundamentally different; in particular, with the QPSK signal in an ideal optical system, the amplitudes of the transmitted symbols are the same. Therefore, the issue of the possibility of suppressing nonlinear phase noise during the QPSK signal transmission remains important.

The purpose of this work is to test the proposed methods of distortion suppression for the QPSK format. Moreover, in this work, the transmission of optical pulses was simulated using the coupled Schrödinger equations for polarisations, that is, in the DP-QPSK format, in contrast to the model [7], where the interaction of polarisations was not considered. A model of coupled Schrödinger equations for orthogonal polarisations was tested by Yushko et al. [4], who obtained a good agreement between the results of numerical calculation and laboratory experiment for a 1200 km long line. We have numerically simulated the single-channel propagation of Gaussian optical pulses with a bit interval of 25 ps in the framework of coupled nonlinear Schrödinger equations [4, 8].

## 2. Numerical simulation

The communication line contained 20 periodic spans consisting of the following elements:

SMF (100 km) + EDFA + DCF + EDFA,

where SMF is a standard single-mode fibre; EDFA is an erbium-doped fibre amplifiers (the noise ratio is 4.5 dB); and DCF is a dispersion-compensating fibre. A white Gaussian noise model was used to describe the amplified spontaneous emission (ASE) noise of the point-like EDFAs [4]. Distortions caused by polarisation mode dispersion were not taken into account. Technical specifications for SMF and DCF 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 |
| Refractive index/10$^{-20}$ m$^2$ W$^{-1}$ | 2.7 | 2.7 |

The mean dispersion of the communication line depends on the DCF span length. The accumulated dispersion was compensated for at the receiver. We have considered the information transmission that is encoded by four phase levels of the Gaussian pulses with amplitudes $A_x$ and $A_y$ polarised along the $x$ and $y$ axes, respectively.

The signal was set in the form

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$$A_x(t) = \sum_n a_{x_n}(t - nT),\ A_y(t) = \sum_n a_{y_n}(t - nT),$$

$$a_{x_n}(\tau) = B\xi_{x_n}\exp[-(\tau^2 - 2\mathrm{i}C\tau^2)/(2T_0^2)],$$

$$a_{y_n}(\tau) = B\xi_{y_n}\exp[-(\tau^2 - 2\mathrm{i}C\tau^2)/(2T_0^2)],$$

where $\xi_{x_n}$ and $\xi_{y_n}$ are the independent random variables which take one of the values of the set {exp(iπ/4), exp(–iπ/4), exp(3iπ/4), exp(–3iπ/4)} with a probability of 1/4; $T = 25$ ps is the bit interval; $T_0 = 5$ ps is the pulse width parameter; and $C$ is the chirp parameter. Thus, the pulse width at half maximum constituted approximately 0.47 of the bit interval. In the calculation, $B = 0.075$ W$^{1/2}$, which corresponds to an average pulse power of 2 mW.

To suppress nonlinear phase distortion, we used:

1) large negative dispersion of the communication line; and

2) large positive chirping.

Below are the constellation diagrams of bit sequences at the receiver in cases when the specified methods of nonlinearity suppression are used and without them. The pulses were averaged over the bit interval, and the sample size contained 10200 values.

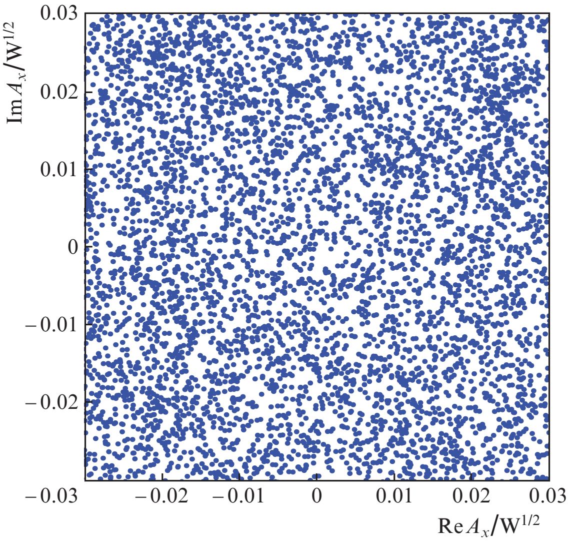

**Figure 1.** Constellation diagram for $A_x$ polarisation, $D = 0$, $C = 0$.

Figure 1 shows a constellation diagram for $A_x$ in cases of zero mean dispersion of the communication line and without pulse chirping.

The diagram for $A_y$ polarisation along the $y$ axis is similar. Note that the points corresponding to different bit sequences are mixed, and the signal cannot be correctly recognised. The BER probability is 0.23.

The use of large positive chirping improves the signal quality. This follows from Fig. 2, where the $A_y$ diagram for a chirped signal is displayed. It is seen that the cloud of points splits into four regions corresponding to four levels of phase modulation, and these regions, in contrast to Fig. 1, are distinguishable. The BER probability in this case is $4 \times 10^{-2}$.

With a positive chirp, the initial pulses expand faster, which reduces the impact of nonlinear effects. Figure 3 shows the diagrams for $A_x$ and $A_y$ of a signal with a chirp and a non-

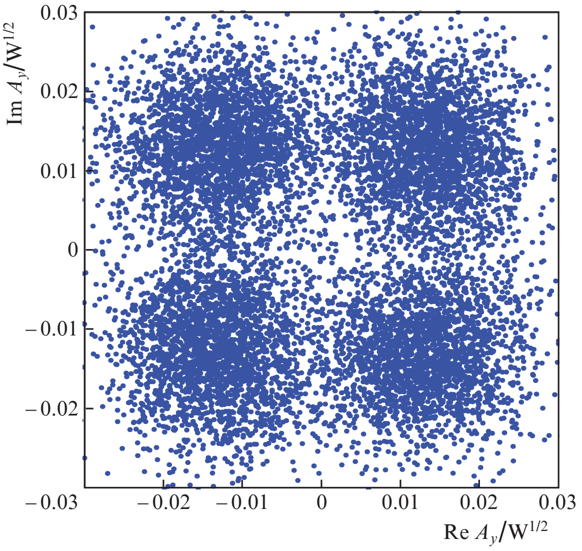

**Figure 2.** Constellation diagram for $A_y$ polarisation, $D = 0$, $C = 3.5$.

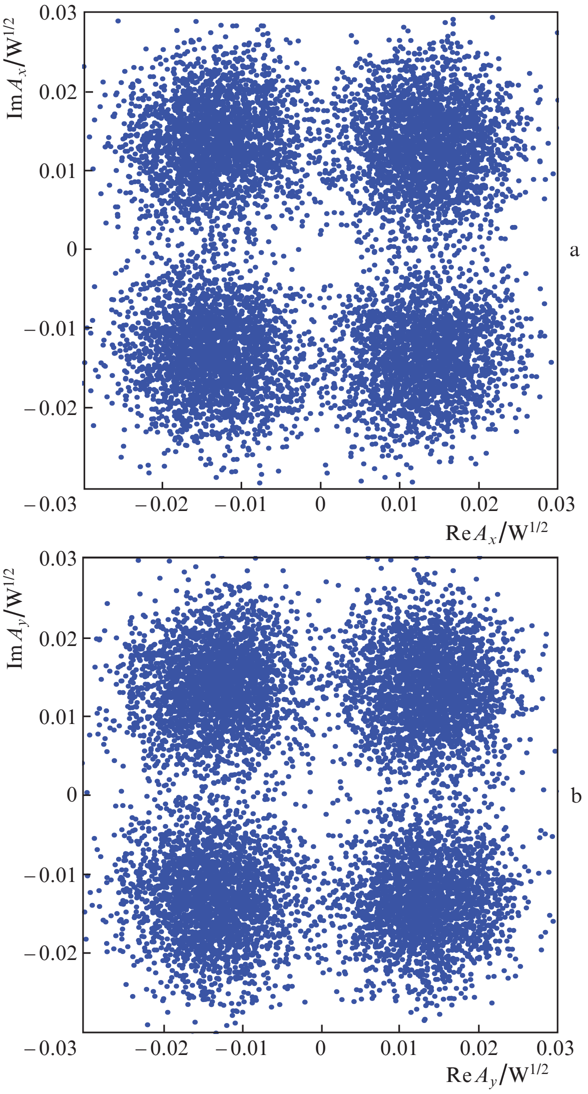

**Figure 3.** Constellation diagrams for (a) $A_x$ and (b) $A_y$ with $D = -1.4$ ps nm$^{-1}$ km$^{-1}$, $C = 3.5$.

zero mean dispersion of the communication line. It can be seen that the signal quality is higher compared to Fig. 2. The BER probability is now $1.2 \times 10^{-2}$.

Instead of using a DCF fibre span, the signal quality can be improved by periodic dispersion compensation using modern devices with low signal attenuation based on Bragg gratings [9, 10]. Unlike fibres with negative dispersion, these devices provide low power loss (~1 dB). Figure 4 shows constellation diagrams for the same set of parameters as in Fig. 3, when using low-attenuation dispersion compensators. It is seen that the grouping of points is improving, with the BER probability being reduced to $2 \times 10^{-3}$. In the communication line, the regions of periodic pulse compression and signal amplification are spatially separated due to nonzero mean dispersion, which reduces the nonlinear interaction.

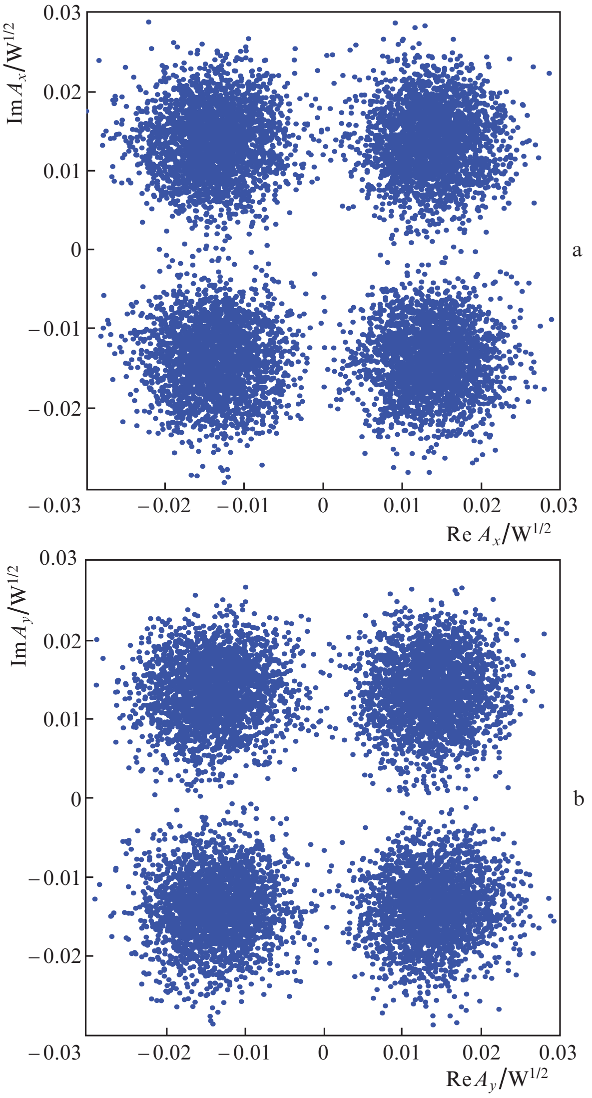

**Figure 4.** Constellation diagrams for (a) $A_x$ and (b) $A_y$ with with $D = -1.4$ ps nm$^{-1}$ km$^{-1}$, $C = 3.5$ and the use of a dispersion compensator with low attenuation.

## 3. Conclusions

We have calculated transmission of optical pulses in a DP QPSK communication line with large negative dispersion and large positive chirping. It is shown that in a channel with a rate of 160 Gbit s$^{-1}$, the use of these methods can significantly reduce the signal degradation caused by Kerr nonlinearity. The results obtained can be useful in choosing a high-rate communication line design.

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