Quantum Electronics **45** (1) 75 – 77 (2015)

PACS numbers: 42.79.Sz; 42.81.Uv
DOI: 10.1070/QE2015v045n01ABEH015635

Numerical simulation of current experimental 100 Gbit s^{-1} DWDM communication lines*

O.V. Yushko, O.E. Nanii, A.A. Redyuk, V.N. Treshchikov, M.P. Fedoruk

Abstract. **We report the results of experimental and numerical studies of the maximum length of multi-span DP-QPSK DWDM communication lines (channel rate of 100 Gbit s^{-1}) with 100-km-long uniform and combined spans. The use of the combined spans (50 km of SSMF fibre and 50 km of NZDSF fibre) has allowed the maximum line length to be increased up to 6700 km, which is 60% higher than in the case of homogeneous SSMF- and NZDSF-based spans.**

Keywords: *coherent communication lines, polarisation division multiplexing, numerical modelling, nonlinear Schrödinger equation.*

1. Introduction

Nowadays, with the annual traffic increase to 40%, the bandwidth capacity of optical communication systems increases by only 20% per year. In this scenario, in the next few years the amount of traffic would exceed the capacity of existing lines [1]. In recent years, next generation fibre-optic communication systems with data rates of 100 Gbit s^{-1} and higher have been intensively studied and developed. Next generation communication networks are based on such technologies as coherent detection, digital processing of optical signals and spectrally-efficient formats of signal modulation. A symbiosis of these technologies can provide a further development of fibre-optic communication systems. From this perspective, the coherent communication lines with electronic dispersion compensation and four-level phase format of signal modulation with polarisation multiplexing [2 – 6] are to date the most successful in terms of commercial use.

The maximum operating range of fibre-optic communication lines is determined by several factors. One of them is the signal distortion caused by noise accumulation in amplifiers and by nonlinear effects. In the coherent communication lines with electronic dispersion compensation, a no less important factor is the maximum admissible accumulated chromatic dispersion, which is limited by the performance of available digital signal processors. In this respect, the design of fibre-optic communication lines (optimisation of dispersion maps, amplification schemes, etc.) has been and remains a highly important direction of studies.

In the present work, we have studied experimentally and numerically the transmission of information via a DWDM line with no optical dispersion compensation. In using the four-level phase modulation format with DP-QPSK polarisation multiplexing, the symbol efficiency constitutes 4 bits per symbol. At a symbol rate of 30 Gbaud, the total channel rate is of 120 Gbit s^{-1}. The rate of useful information transmission through the channel is 100 Gbit s^{-1}, 5 Gbit s^{-1} are used to transmit the service information and 15 Gbit s^{-1} provide the error correction circuit operation. The span length is 100 km, and we consider three different span configurations: uniform spans based on SSMF fibre, uniform spans based on NZDSF fibre and combined spans. A good agreement is shown between the results of numerical modelling and experiment. The use of combined spans allows one to increase the maximum line operation range by 60% with an acceptable error level and thus to exceed the range of 6000 km.

2. Experimental setup

The line under investigation is schematically shown in Fig. 1 and incorporates an optical signal transmitter Tx, a multiplexer MUX for combining different spectral channels, 100-km-long SSMF optical fibre spans (Fig. 1a), an erbium doped optical amplifier EDFA for compensating optical signal loss in the spans, a demultiplexer DEMUX for splitting the combined signal, an optical signal receiver Rx, a digital DSP processor for dispersion compensation and circuits for measuring the optical signal-to-noise ratio (OSNR). The performance of the DSP processor used in the experiment provides electronic compensation for accumulated dispersion in the range of 0 – 70000 ps nm^{-1}.

Basic parameters of SSMF and NZDSF fibres used in the line spans are given in Table 1. The limitation on possible electronic compensation for accumulated dispersion by the value of 70000 ps nm^{-1} entails the limitation on the maximal communication line length. Based on the parameters of fibres, the maximum line length with SSMF fibre is $L_{\rm DSP}^{\rm SMF}$ = 4200 km, whereas for the NZDSF fibre $L_{\rm DSP}^{\rm DSF}$ = 17500 km.

* Presented at the 6th Russian Workshop on Fibre Lasers, Novosibirsk, 2014.

O.V. Yushko, A.A. Redyuk, M.P. Fedoruk Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; Institute of Computational Technologies, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 6, 630090 Novosibirsk, Russia; e-mail: olesya.yushko@gmail.com, alexey.redyuk@gmail.com, mifester@gmail.com;
O.E. Nanii T8 LLC, Krasnobogatyrskaya ul. 44/1, office 826, 107076 Moscow, Russia; Department of Physics, M.V. Lomonosov Moscow State University, Vorob'evy Gory, 119991 Moscow, Russia; e-mail: naniy@t8.ru;
V.N. Treshchikov T8 LLC, Krasnobogatyrskaya ul. 44/1, office 826, 107076 Moscow, Russia; e-mail: vt@t8.ru

Received 16 July 2014; revision received 9 September 2014
Kvantovaya Elektronika **45** (1) 75 – 77 (2015)
Translated by M.A. Monastyrskiy

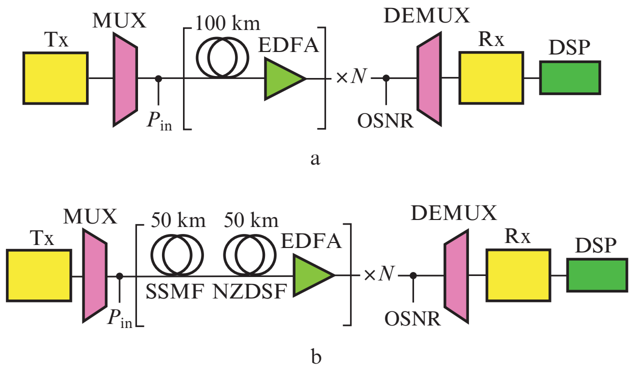

Figure 1. Configuration of communication lines with (a) uniform spans (SSMF) and (b) combined spans (SSMF + NZDSF).

Table 1. Parameters of the fibres used.

Fibre	D/ps nm^{-1} km^{-1}	γ/W^{-1} km^{-1}	S/ps nm^{-2} km^{-1}	α/dB km^{-1}
SSMF	16.5	1.2	0.07	0.2
NZDSF	4	1.84	0.45	0.2

In order, on the one hand, to increase the range of the line with $L_{\rm DSP}$ compared to the line with $L_{\rm DSP}^{\rm SMF}$, and, on the other, to reduce the influence of nonlinear effects typical of NZDSF fibre, we considered a communication line, the scheme of which is shown in Fig. 1b. This line is based on combined spans consisting of 50 km of SSMF fibre and 50 km of NZDSF fibre. The accumulated dispersion of a single span of such a line amounts to 1025 ps nm^{-1}, which allows the line range restricted by the DSP processor performance to be extended up to 6800 km.

3. Results of laboratory experiments and numerical calculations

With the use of three line configurations (spans based on SSMF and NZDSF fibres and on combined SSMF + NZDSF spans) 1200 km in length, we performed laboratory experiments and measured the dependence of the BER on the power $P_{\rm in}$ of radiation of one spectral channel, launched into the fibre. The experimental results are shown in Fig. 2. It can be seen that the curve with the highest values of the BER parameter, and hence with the worst signal quality at the receiver, corresponds to the configuration with NZDSF spans, which is due to its high nonlinearity. The results with the lowest value of the BER parameter – the best signal quality – are consistent with the configuration of SSMF spans, whilst the curve that corresponds to the communication line with combined spans occupies an intermediate position and is located between the two curves.

For numerical simulation of optical signal propagation in the optical fibre with regard to two signal polarisations, a system of coupled nonlinear Schrödinger equations (NSE) was used

$$\frac{\partial A_X}{\partial z} = -\mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 A_X}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A_X}{\partial t^3} + \mathrm{i}\gamma\Big(|A_X|^2 + \frac{2}{3}|A_Y|^2\Big)A_X - \frac{1}{2}\alpha A_X,$$

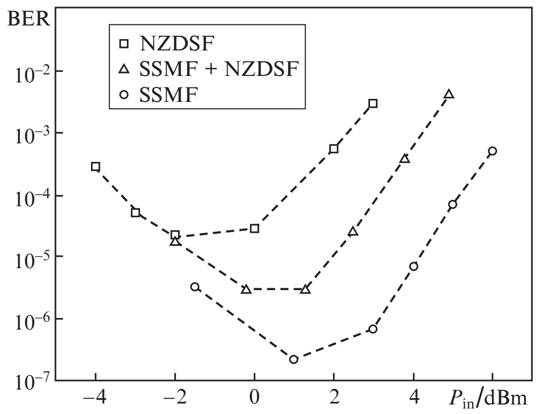

Figure 2. Experimentally measured dependences of the BER on the radiation power launched into a span of a 1200-km-long line, consisting of NZDSF spans, SSMF spans and SSMF + NZDSF spans.

$$\frac{\partial A_Y}{\partial z} = -\mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 A_Y}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A_Y}{\partial t^3} + \mathrm{i}\gamma\Big(|A_Y|^2 + \frac{2}{3}|A_X|^2\Big)A_Y - \frac{1}{2}\alpha A_Y,$$

where A_X, A_Y are the complex envelopes of the electromagnetic field amplitude; z is the distance along the fibre; t is time; β_2 and β_3 are the second- and third-order dispersions; γ is the nonlinearity coefficient; and α is the coefficient of optical losses. Erbium amplifiers are modelled as point devices, whilst a model of white Gaussian noise with the spectral polarisation density $N_{\rm ASE}^{\rm EDFA} = (\mathrm{e}^{\alpha L} - 1)h\nu n_{\rm sp}$ is used to describe the noise of the amplified spontaneous emission (ASE), where $n_{\rm sp}$ is the parameter of spontaneous emission, h is the Planck constant, ν is the signal frequency, and L is the span length. The initial signal was formed using the four-level phase modulation format based on NRZ DP-QPSK. In our calculations, we used random bit sequences of 2^{16} bits for each polarisation. The numerical solution of the NSE system was carried out by the method of splitting into physical processes [7].

Figure 3 compares the results of numerical simulations and laboratory experiments for the 1200-km-long line. It can

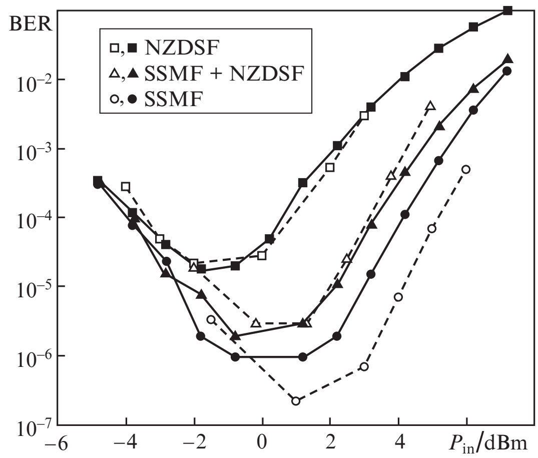

Figure 3. Comparison of numerical (solid lines) and laboratory (dashed lines) results of studying the dependence of the BER on the radiation power launched into a span of a 1200-km-long line.

be seen that the use of the model described ensures good qualitative and quantitative agreement between the results.

Having obtained the coincident results in numerical and laboratory experiments for the 1200-km-long line and a single spectral channel, we performed numerical calculations of the maximum line range of all configurations for eleven spectral channels with the interchannel spacing of 50 GHz. The threshold value of the bit error rate BER_{FEC}, which corresponds to the operating capability of the modern schemes of forward error correction (FEC), amounts to 2×10^{-2} (herewith the bit error rate after the forward error correction does not exceed 10^{-9}). In accordance with the bit error rate obtained in numerical calculations, the maximal line range L_{max} was determined. Figure 4 shows the results of numerical calculations of the dependence of the maximum line range on the radiation power that is introduced into the central spectral channel span. As can be seen from this Figure, for SSMF spans, the line range is limited by the DSP performance and constitutes 4200 km, although under the assumption of its performance being infinite, it can reach the value of 7500 km with the signal power of –1 dBm. For NZDSF spans, the line length is limited by the nonlinear signal distortion and does not exceed 3800 km, while the DSP processor power allows the range line to be more than 17000 km. Finally, for combined spans, the maximum range amounts to 6700 km which is 60% higher than the relevant results for the SSMF and NZDSF spans.

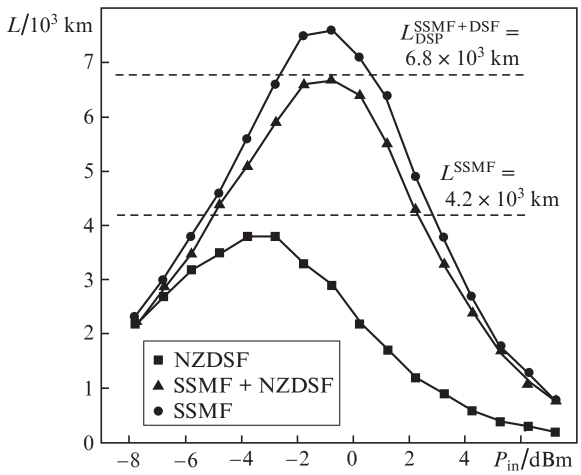

Figure 4. Calculated dependences of the maximum line range on the radiation power launched into a span at BER = 2×10^{-2}. Dashed straight lines show the maximum length of the communication lines based on SSMF and SSMF + NZDSF spans.

4. Conclusions

The linear and nonlinear distortions in multi-span DWDM communication lines with no optical compensation for chromatic dispersion have been experimentally and numerically studied by means of a coherent four-level phase format with polarisation division multiplexing (DP-QPSK format, the span length of 100 km). The qualitative and quantitative agreement between the results of numerical calculations and the experiment for 1200-km-long lines is demonstrated. Numerical simulations have shown that in using a low dispersion fibre (NZDSF, D = 4 ps nm^{-1} km^{-1}), the maximum transmission range (about 3800 km) is limited by nonlinear signal distortions and noise accumulation. In the communication lines based on standard fibre (SSMF, D = 16.5 ps nm^{-1} km^{-1}), the maximum transmission range (approximately 4200 km) is limited to the value of maximum admissible accumulated dispersion (70000 ps nm^{-1}), which is compensated for in real time with a digital processor. A numerical experiment has demonstrated that the use of combined spans (50 km of SSMF fibre and 50 km of NZDSF fibre) ensures a 60% increase in the maximum length of the DWDM communication line compared to the lengths of the lines employing single-type fibre.

Acknowledgements. This work was supported by the Ministry of Education and Science of the Russian Federation (Grant No 14.578.21.0029).

References

1. Richardson D.J. *Science*, **330** (6002), 327 (2010).
2. Xia T. *National Fiber Optic Engineers Conf.* (Anaheim: OSA Techn. Digest, 2013) Paper NW4E.6.
3. Yu J., Dong Z., Chien H., Jia Z., Gunkel M., Schippel A. *National Fiber Optic Engineers Conf.* (Los Angeles: OSA Techn. Digest, 2012) Paper PDP5D.3.
4. Zhang G., Nelson L., Pan Y., Birk M., Skolnick C., Rasmussen C., Givehchi M., Mikkelsen B., Scherer T., Downs T., Keil W. *National Fiber Optic Engineers Conf.* (Los Angeles: OSA Techn. Digest, 2012) Paper PDP5D.4.
5. Gainov V., Gurkin N.V., Lukinih S.N., Akopov S.G., Makovejs S., Ten S.Y., Nanii O.E., Treshchikov V.N. *Laser Phys. Lett.*, **10** (7), 075107 (2013).
6. Gurkin N.V., Kapin Yu.A., Nanii O.E., Novikov A.G., Pavlov V.N., Plaksin S.O., Plotskii A.Yu., Treshchikov V.N. *Kvantovaya Elektron.*, **43** (6), 546 (2013) [*Quantum Electron.*, **43** (6), 546 (2013)].
7. Agrawal G.P. *Nonlinear Fiber Optics* (New York: Acad. Press, 2001).