

https://doi.org/10.1070/QEL16559

Nonlinear distortions as nonlinear noise in coherent fibre-optic communication lines

A.E. Zhitelev, V.A. Konyshev, S.N. Lukinykh, O.E. Nanii, V.N. Treshchikov, R.R. Ubaydullaev

Abstract. **A phenomenological model describing nonlinear distortions in coherent fibre-optic communication lines is investigated. This model makes it possible to extend the range of application of the nonlinear noise model as compared with the well-known GN model. A method for experimental determination of the main parameters of the proposed model is described, and the sources of possible errors are discussed.**

Keywords: *DWDM, nonlinearity, GN model, coherent communication systems.*

1. Introduction

In view of the constant rise in the traffic volume (according to different estimates, by 30%–60% a year), the traffic network throughput should correspondingly increase. To date, optical communication lines with 100G channels (with a data transfer rate of 100 Gbit s^{-1}) and higher rate channels (100+G) without instrumental distortion compensation have become a base of trunk networks. These lines have been investigated in many works [1–6]. At the same time, there are many heterogeneous lines in operation, in which coherent channels (100G and 100+G) neighbour channels with amplitude modulation (2.5G, 10G). Instrumental dispersion compensators are applied in these lines. The most complex problem in designing coherent communication lines is to calculate the nonlinear distortions for a multi-span line. Despite the existence of a model for calculating nonlinear noise in the case of a multi-span line with uncompensated dispersion (based on the theory of superlinear addition of noises from individual spans), no unified model have been developed to calculate heterogeneous lines with a complex dispersion pattern. The main purpose of this study was to develop a model for calculating nonlinear dispersions in heterogeneous lines with an arbitrary dispersion compensation scheme.

One can select four main sources of errors in optic-communication backbones: (1) non-optimal power on the optical detector (either too high, leading to detector overload, or too low, at which the detector intrinsic noises become significant); (2) chromatic and polarisation mode dispersions; (3) amplified spontaneous emission (ASE) noise, which is introduced into line by erbium-doped fibre amplifiers (EDFAs) (spontaneous Raman scattering noise, occurring under Raman pumping, can also be assigned to this group); and (4) nonlinear dispersions or impairments. The first two reasons can be completely eliminated by designing correctly the line (below, this situation is assumed to be implemented, and these error sources are excluded from consideration). The ASE noise and nonlinear impairments, which cannot be completely excluded at the modern technological level (primarily, that of digital signal processors), give rise to errors in line. To design a line and estimate (monitor) the reliability margin for an operating channel, one must be able to calculate the influence of these noises. Generally, the effect of ASE noise can easily be taken into account by calculating and/or measuring the $OSNR_{ASE}$ value*. At the same time, the evaluation of the influence of nonlinear impairments on the operation of coherent channel is a rather difficult problem. Some providers solve it by projecting a line for operation in the linear regime. This approach facilitates the design, but the solution obtained is less universal. When passing to transponders with multilevel modulation formats, it becomes even less efficient and, most likely, inapplicable because of the intolerable decrease in the communication range.

Thus, one needs a method for estimating the coherent-channel operation quality with allowance for the joint action of linear (ASE noise) and nonlinear impairments. It was shown that the classical method for estimating nonlinear impairments, developed for channels with amplitude modulation (modulation of signal power without phase control) and based on calculating the nonlinear phase delay, is inapplicable to coherent channels. To this end, a model considering nonlinear impairments as a nonlinear interference Gaussian noise (GN model) was proposed in [1]. This model is of little use for calculating real lines because of its extraordinary complexity and a limited range of application (it is valid for only long multi-span communication lines without dispersion compensation).

A.E. Zhitelev, R.R. Ubaydullaev T8 LLC, office 826, ul. Krasnobogatyrskaya 44/1, 107076 Moscow, Russia; e-mail: rustam2@mail.ru;
V.A. Konyshev T8 LLC, office 826, ul. Krasnobogatyrskaya 44/1, 107076 Moscow, Russia; Vavilov Institute of History of Natural Science and Technology, Russian Academy of Sciences, Staropanskii per. 1/5, 109012 Moscow, Russia;
S.N. Lukinykh, O.E. Nanii T8 LLC, office 826, ul. Krasnobogatyrskaya 44/1, 107076 Moscow, Russia; Faculty of Physics, M.V. Lomonosov Moscow State University, Vorob'evy gory, Moscow, 119991 Russia;
V.N. Treshchikov T8 LLC, office 826, ul. Krasnobogatyrskaya 44/1, Moscow, 107076 Russia; Kotel'nikov Institute of Radio Engineering and Electronics (Fryazino Branch), Russian Academy of Sciences, pl. Vvedenskogo 1, 141190 Fryazino, Moscow region, Russia

Received 30 October 2017
Kvantovaya Elektronika **47** (12) 1135–1139 (2017)
Translated by Yu.P. Sin'kov

* $OSNR_{XYZ}$ is the ratio of the optical signal power to the power of noise induced by the XYZ factor.

At the same time, it was shown in some experimental studies that the nonlinear noise model can be applied to calculate nonlinear impairments in single-span communication lines [7–9].

A phenomenological model (based on the main postulates of the classical GN model), which implies experimental determination of nonlinear coefficients, was proposed in [10] to describe nonlinear impairments as a nonlinear noise. Here, we investigated the experimental conditions allowing one to obtain correct results in measurements.

The basic statements of the model analysed are as follows.

(i) Nonlinear impairments in coherent optical channels can be interpreted as nonlinear interference Gaussian noise. Its power P_{NL} in the range under consideration is proportional to signal power cubed, P_S:

$$P_{NL} = \eta P_S^3. \tag{1}$$

The influence of nonlinear impairments (nonlinear noise) can be estimated by the value of nonlinear OSNR:

$$\mathrm{OSNR}_{NL} = \frac{P_S}{P_{NL}} = \eta P_S^{2}, \tag{2}$$

where η is the nonlinearity coefficient.

(ii) The ASE noise (whose influence is characterised by the classical ratio $\mathrm{OSNR}_{ASE} = P_S/P_{ASE}$) and the nonlinear noise are summed additively. The number of errors (pre-FEC BER) is affected by the ratio of signal power to the sum of linear and nonlinear noise powers (total inverse OSNR_{BER} value):

$$\frac{1}{\mathrm{OSNR}_{BER}} = \frac{P_{ASE} + P_{NL}}{P_S} = \frac{1}{\mathrm{OSNR}_{ASE}} + \frac{1}{\mathrm{OSNR}_{NL}}. \tag{3}$$

In this connection, the first task is to measure the nonlinearity coefficient η.

A schematic of the experiment is shown in Fig. 1. A signal from a coherent transponder 100G successively arrives at a multiplexer (MUX), a dispersion introduction unit [set of fibre coils and erbium-doped amplifiers, operating in the linear (in power) regime], and the main power amplifier. Then the signal is split by a coupler, and its main part arrives at a standard single-mode fibre under test (F.U.T.), in which nonlinear effects arise. In addition, a small fraction of the signal from the coupler output is fed through a demultiplexer (DEMUX) to a power meter (PM), which measures the optical power introduced into the fibre under test (a calibration is performed when adjusting the system). The signal transmitted through the fibre under test is amplified by a preamplifier and is fed through a demultiplexer to the linear detector of the transponder. The OSNR_{ASE} value is measured by an optical spectrum analyser (OSA), connected to the preamplifier monitor output.

The essence of the experiment is as follows: nonlinear impairments arise in the fibre under test, which depend on the power introduced into the fibre. In addition, ASE noise is also present in the scheme. Both these factors give rise to errors when receiving a signal; i.e., they determine the pre-FEC BER value. The contribution of the ASE noise (OSNR_{ASE}) is directly measured by the spectrum analyser. To find the value of nonlinear impairments, one must know the relation between the pre-FEC BER value and the total OSNR_{BER}, i.e., the calibration function of the transponder. Thus, the experiment is performed in two stages.

The transponder calibration function is measured in the first stage. If a low-power signal is introduced into the fibre under test, nonlinear effects do not arise, and the entire line operates in the linear regime. In this case, the single source of errors is the ASE noise. Let us change the OSNR_{ASE} value of the line (for example, by adding ASE noise from the generator to the line end, before the preamplifier; there are also some other ways). The pre-FEC BER will change correspondingly (Fig. 2). Since nonlinear effects are absent, the inverse nonlinear OSNR is zero, and the total inverse OSNR is equal to the inverse OSNR for the ASE noise.

The nonlinearity coefficient is measured in the second stage. To this end, the input power introduced into the fibre under test is increased, with the additional noise source switched off. The pre-FEC BER and OSNR_{ASE} values are measured for each power. The found calibration function is used to determine the total OSNR_{BER} value from pre-FEC BER. Then the dependence of $\mathrm{OSNR}_{NL}^{-1} = \mathrm{OSNR}_{BER}^{-1} - \mathrm{OSNR}_{ASE}^{-1}$ on the squared input power P_S^2 is plotted (Fig. 3). The nonlinearity coefficient η is found as the slope of the approximating straight line passing through zero [see formula (2)].

The main error sources in this experiment are as follows.

(1) Systematic error in measuring the power introduced into the fibre. Any deviation of the real power introduced into the fibre under test from the calculated value leads to a tilt of the approximating straight line (Fig. 4).

(2) Incorrect choice of the measurement range. A channel in a real communication line is optimised using some technique, for example, by providing the maximum margin with respect to OSNR. Generally, the higher the power introduced into a span, the larger the OSNR_{ASE} value at the output of the

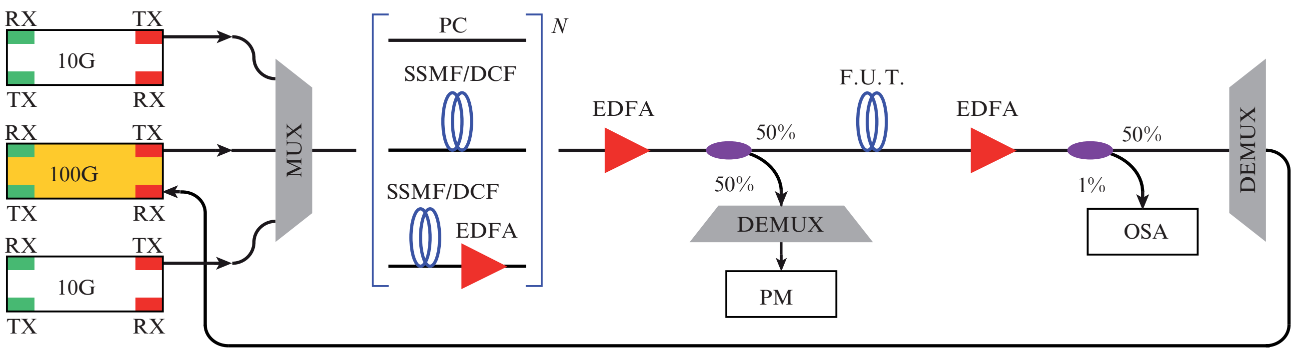

Figure 1. Schematic of the experiment on measuring the nonlinearity coefficient (PC is an optic patch cord and N is the number of spans).

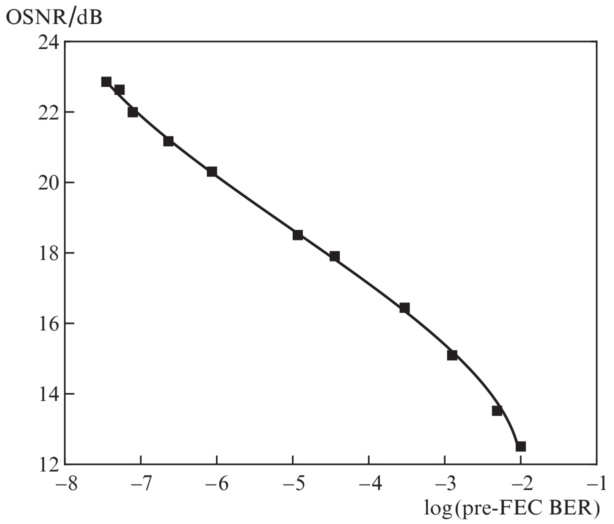

Figure 2. Transponder calibration function.

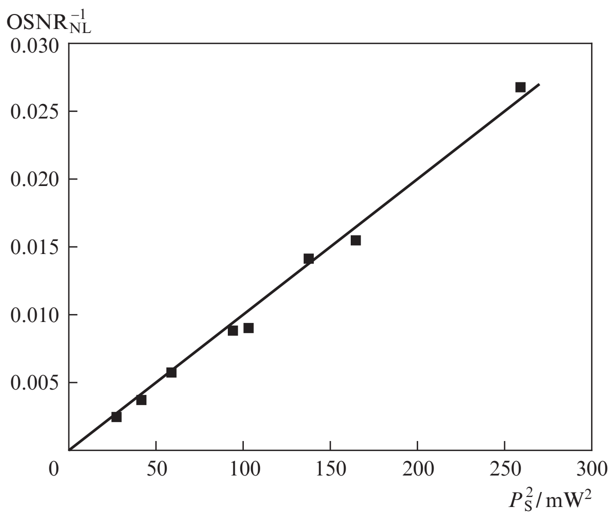

Figure 3. Dependence of inverse nonlinear $OSNR_{NL}$ on squared input power.

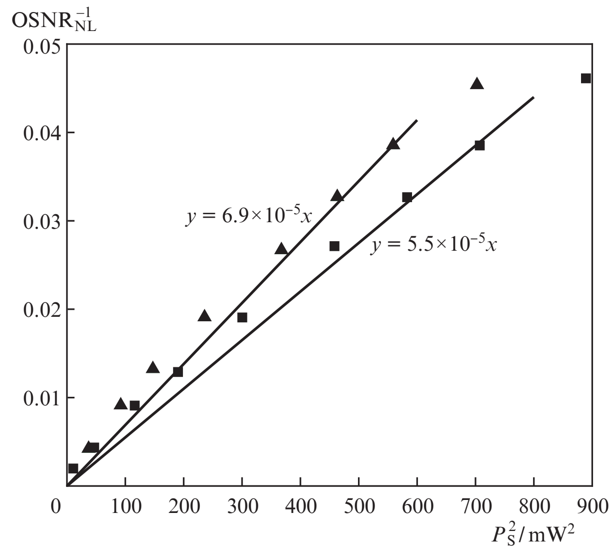

Figure 4. Influence of systematic error in measuring the power introduced into fibre: (▲) experimental values and (■) values calculated with allowance for the change in input power by +0.5 dB.

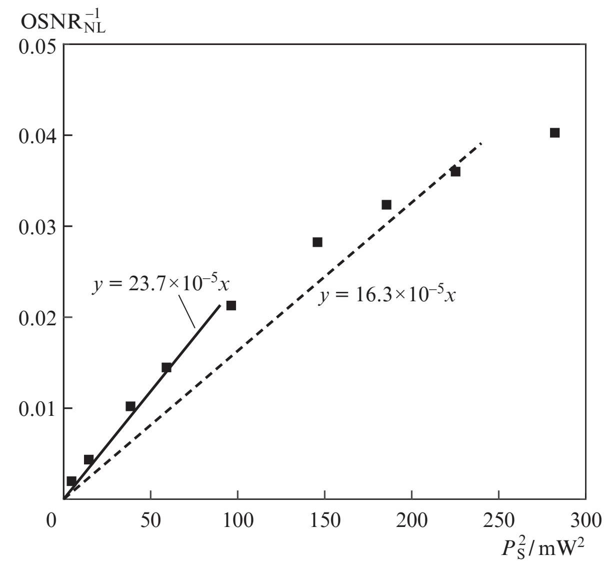

Figure 5. On the correct choice of measurement range.

span (and the line as a whole) and, at the same time, the stronger the influence of nonlinear impairments in the beginning of this span is. Vice versa, a decrease in the power introduced into the fibre weakens the influence of nonlinear impairments but enhances the effect of the ASE noise introduced by subsequent amplifiers. The maximum margin with respect to OSNR is obtained at a specified relation between the powers of linear and nonlinear noises in the line (due to the cubic dependence of the nonlinear noise power on the signal power, the power ratio for the ASE and nonlinear noises is 2:1). Therefore, when calculating lines, it is important to measure nonlinear coefficients in a specified working range of channel powers/OSNR values (although the measurement in the strongly nonlinear regime, aimed at reducing the error arising during differential measurement, appears attractive for an experimenter). The expansion of the working range beyond the range of optimal values gives rise to a systematic error, related to the inaccuracy of the GN model (Fig. 5).

(3) Signal power oscillations on a linear detector, which are typical of coherent formats with multilevel modulation.

(4) Influence of partially polarised ASE noise. When a partially polarised source of ASE noise is used, one can observe strong oscillations of the pre-FEC BER value at constant $OSNR_{ASE}$ even in the linear regime. Since conventional optical cords (with fibre that does not support polarisation) are used for connection, any their displacement causes rotation of the plane of polarisation of noise with respect to the plane of polarisation of signal (the DP *n*QAM modulation format), which leads to a change in the signal-to-noise ratio for this polarisation and, therefore, to a change in the number of errors. An additional experiment on measuring the dependence of pre-FEC BER on the rotation angle of the analyser was performed to estimate this effect (Figs 6, 7). A depolarised source of ASE noise must be used to obtain satisfactory results.

Thus, we found a fundamental nonlinearity coefficient η (denoted as $\eta_{100-100,\infty}$ below), which determines the self-action of a coherent (e. g., 100G) channel in the case of high input

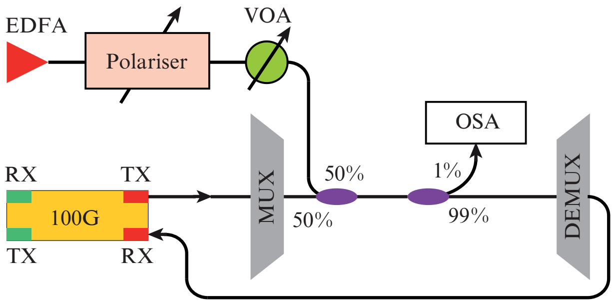

Figure 6. Schematic of the system for determining the influence of partially polarised ASE noise (VOA is a variable optical attenuator).

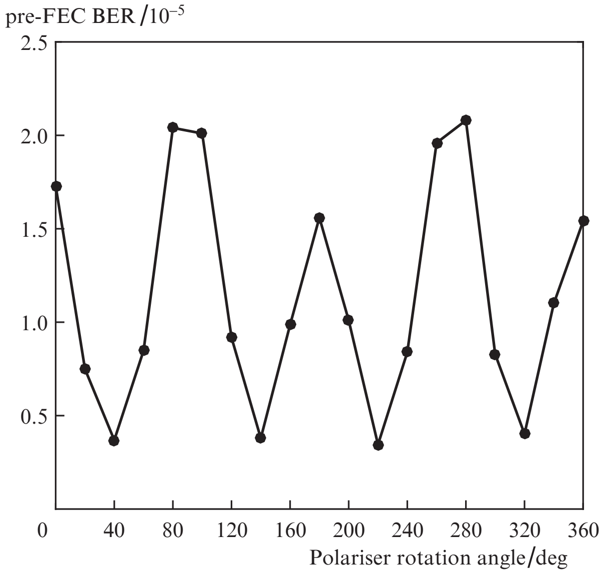

Figure 7. Dependence of pre-FEC BER on the polariser rotation angle (experiment with admixture of partially polarised ASE noise).

dispersion, providing the formation of nonlinear interference noise. However, it is insufficient for calculating real lines.

It is also necessary to take into account that, at a small value of accumulated dispersion, the nonlinear coefficient is much smaller in magnitude and depends on dispersion [10]. The experimental dependence of η on the accumulated dispersion is shown in Fig. 8.

An analysis of the interference of neighbouring channels shows that the nonlinear noise level depends strongly on the modulation format. Therefore, nonlinear coefficients of three types are introduced into the phenomenological model: $\eta_{100-100}$ (self-action of coherent 100G channel and influence of neighbouring 100G channels), η_{100-10} (influence of neighbouring 10G channels), and $\eta_{100-2.5}$ (influence of neighbouring 2.5G channels). In addition, one must take into account the case of a short (in comparison with nonlinear length) span, where nonlinear impairments have not enough time to be formed completely.

Thus, the following expression was derived to calculate the influence of nonlinear noise:

$$\eta(d, L, \alpha, K, \Delta f, \Delta f_{\rm p}) = \eta_\infty F(d) F(L, \alpha) F(K, \Delta f, \Delta f_{\rm p}), \quad (4)$$

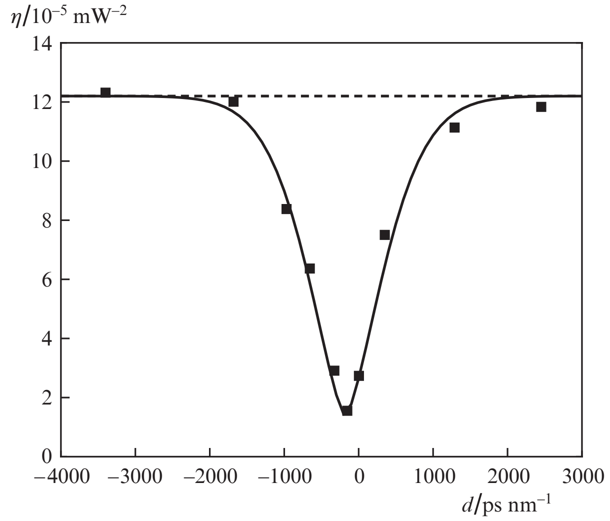

Figure 8. Dependence of the nonlinearity coefficient η on dispersion d.

where η_∞ is the fundamental nonlinearity coefficient for a specified channel rate and fibre type (SSMF or DCF); $F(d)$ is a function describing the dependence on the dispersion d; $F(L, \alpha)$ is a function describing the dependence on the span length L and fibre damping α; and $F(K, \Delta f, \Delta f_{\rm p})$ is a function describing the dependence on the number of actuating channels K, frequency plan Δf, and protective range $\Delta f_{\rm p}$ between the 100G channel under study and the group of actuating channels.

The accuracy of calculating OSNR within the proposed phenomenological model was estimated experimentally. It was shown that in the range of variation in parameters that is characteristic of real communication lines, the deviation of calculated values from experimental ones does not exceed 1.5 dB.

Thus, we proposed a phenomenological model, where nonlinear impairments are considered as a nonlinear noise induced by the channel self-action and the cross-interaction between channels. This model expands the range of application of the well-known model of nonlinear noise (GN model) and allows one to calculate the level of nonlinear noise in communication lines with small accumulated dispersion (including those with compensated dispersion) and heterogeneous DWDM communication lines, in which different transfer rates (100 Gbit s^{-1}, 10 Gbit s^{-1}, and 2.5 Gbit s^{-1}) and different modulation formats (DP 16QAM, DP QPSK, and NRZ ASK) are used to transmit data through different spectral channels. An experimental technique for measuring model parameters was developed, which makes it possible to estimate the quality of coherent operation of a channel in a line both in the design stage and during its operation. An experimental verification of the model proposed showed the calculation accuracy to be sufficient for its practical application in designing fibre-optic communication systems.

References

1. Poggiolini P., Bosco G., Carena A., Curri V., Jiang Y., Forghieri F. *J. Lightwave Technol.*, **32** (4), 694 (2014).
2. Carena A., Bosco G., Curri V., Jiang Y., Poggiolini P., Forghieri F. *Opt. Express*, **22**, 16335 (2014).

3. Konyshev V.A., Leonov A.V., Nanii O.E., Novikov A.G., Treshchikov V.N., Ubaydullaev R.R. *Opt. Commun*., **349**, 19 (2015).
4. Konyshev V.A., Leonov A.V., Nanii O.E., Treshchikov V.N., Ubaydullaev R.R. *Opt. Commun*., **355**, 279 (2015).
5. Gurkin N.V., Nanii O.E., Novikov A.G., Plaksin S.O., Treshchikov V.N., Ubaydullaev R.R. *Quantum Electron*., **43** (6), 550 (2013) [*Kvantovaya Elektron*., **43** (6), 550 (2013)].
6. Gurkin N.V., Mikhailov V., Nanii O.E., Novikov A.G., Treshchikov V.N., Ubaydullaev R.R. *Laser Phys. Lett*., **11**, 095103 (2014).
7. Redyuk A.A., Nanii O.E., Treshchikov V.N., Mikhailov V., Fedoruk M.P. *Laser Phys. Lett*., **12**, 025101 (2015).
8. Gainov V.V., Gurkin N.V., Lukinih S.N., Makovejs S., Akopov S.G., Ten S.Y., Nanii O.E., Treshchikov V.N., Sleptsov M. *Opt. Express*, **22**, 22308 (2014).
9. Gainov V.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**, 075107 (2013).
10. Konyshev V.A., Leonov A.V., Nanii O.E., Novikov A.G., Treshchikov V.N., Ubaydullaev R.R. *Quantum Electron*., **46** (12), 1121 (2016) [*Kvantovaya Elektron*., **46** (12), 1121 (2016)].