

DOI: 10.1070/QEL16218

Fibre laser system providing generation of frequency-modulated pulses with a spectral width exceeding the gain linewidth

I.O. Zolotovskii, D.A. Korobko, D.A. Stoliarov

Abstract. **We propose an improved scheme of an amplifier similariton laser with a spectral width of the output significantly exceeding the gain linewidth. In the system, an additional dispersion element is inserted into the cavity to provide a local increase in the peak pulse power. The proposed scheme allows a reduction of pulse duration and an increase in peak power of the output pulse after compression.**

Keywords: *frequency-modulated pulses, fibre laser, dissipative solitons.*

Among the problems of modern laser physics one can distinguish the important line of research related to the development of sources of ultrashort pulses having a high peak power, demanded in a variety of applications, e.g., materials processing, optical communications, medicine, etc. One of the most widespread approaches to generation of ultrashort pulses is the generation of pulses possessing a wide spectrum and linear frequency modulation (chirp) followed by compression using an external compressor at the expense of chirp compensation. As a compressor one can use a pair of diffraction gratings or prisms, as well as an optical fibre with anomalous dispersion [1–3].

Promising sources of pulses with a wide spectrum are fibre lasers with mode locking and strong normal cavity dispersion [4–6]. The advantage of this type of lasers as compared to fibre lasers generating soliton pulses is a high threshold of the transition to the multipulse oscillation regime and, correspondingly, a higher energy of a single pulse [7]. The main types of these lasers are generators of dissipative soliton pulses, generators of stretched dissipative solitons, and lasers with self-similar pulse evolution in a passive fibre. It is important that such lasers can be implemented in the oscillation range of both the Yb fibre lasers (1040–1080 nm) [4–6] and the Er fibre lasers (1530–1600 nm) [8–10].

In recent years, the development of fibre lasers with strong normal cavity dispersion has been closely related to the concept of the so-called amplifier similariton lasers. A distinctive feature of these lasers is that the parameters of the pulse, i.e., the spectral width, the duration and the energy, strongly vary during each cavity roundtrip. The present approach was implemented for fibre lasers based on both ytterbium [11, 12], and erbium [13]. The active fibre in this case acts as a strong nonlinear attractor, in which the short initial pulse is transformed into a parabolic-shaped pulse with linear frequency modulation. The resulting parabolic pulse is characterised by the self-similar evolution, which allows its attribution to the class of similaritons [14]. An important element of such lasers is the strong spectral filter placed before the active fibre. Its role consists in the stabilisation of the pulse parameters before amplification, which finally allows the pulse to approach the similariton asymptotic behaviour within the active fibre [11, 15].

The similariton pulse propagation under the amplification is accompanied by an exponential growth of its parameters, i.e., the energy, the duration, and the spectral width. The final spectral width of the gain line limits the spectrum of a similariton and the path length of its propagation in the active fibre. One of the possible ways to alleviate this limitation in the optical fibre amplifiers is the use of the active fibres with the dispersion growing along the fibre [16, 17]. An alternative variant is to generate a parabolic similariton with a maximally wide spectrum in the fibre and then to broaden this spectrum in a passive nonlinear element with normal dispersion, e.g., a strongly nonlinear optical fibre [18, 19]. This construction of an amplifier similariton laser (Fig. 1) was numerically and experimentally considered in Ref. [12].

The principle of the laser operation is as follows. When the pump power exceeds a certain threshold value, the laser is

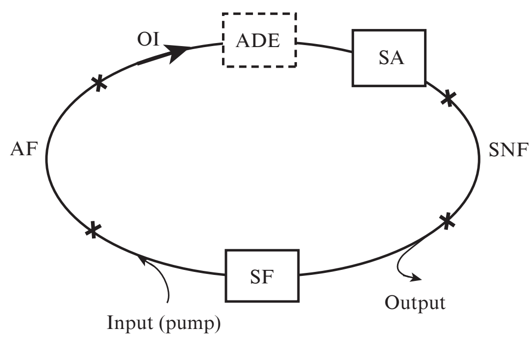

Figure 1. Schematic of an amplifier similariton laser with the spectral width of the generated pulses exceeding the gain linewidth: (OI) optical isolator, (ADE) anomalous dispersion element; (SA) saturable absorber; (SF) spectral filter; (AF) amplifying fibre; (SNF) strongly nonlinear fibre. The dashed line shows the element proposed for additional introduction into the construction. The crosses show the points of fibre welding.

I.O. Zolotovskii, D.A. Korobko, D.A. Stoliarov Ulyanovsk State University, ul. L. Tolstogo 42, 432017 Ulyanovsk, Russia; e-mail: korobkotam@rambler.ru

Received 30 September 2016; revision received 21 October 2016
Kvantovaya Elektronika **46** (12) 1092–1096 (2016)
Translated by V.L. Derbov

mode-locked and the pulse is formed. In the steady-state regime of oscillation, the evolution of the pulse in the cavity can be presented step by step as follows: 1) the small initial pulse with a narrow spectrum is amplified in the active fibre and transformed into a parabolic pulse; 2) the spectrum is further broadened due to nonlinear phase modulation in the strongly nonlinear modulator fibre; 3) the dominant part of the pulse is extracted from the cavity through the exit device; and 4) the residual part of the pulse in the cavity is subject to strong spectral filtering. Due to the spectral broadening in the strongly nonlinear fibre, the spectral width of the output pulse exceeds by several times both the pulse spectral width at the output and the gain linewidth as well. The output pulse demonstrates high linearity of frequency modulation. The experiment shows that after the modulation compensation in the external compression element, the pulse with the energy about 1 nJ can be compressed to a duration of ~20 fs.

In the present paper, we propose further improvement of the construction of the amplifier similariton laser. Using the fact that that the active fibre is a strong nonlinear attractor and provides the stable parabolic shape of the pulse with linear frequency modulation at its output, we introduce into the laser cavity an additional compression element, a delay line with anomalous dispersion, that locally increases the peak pulse power. As such an element one can use a pair of diffraction gratings, as well as a fibre with anomalous dispersion and weak nonlinearity. In Fig. 1, the dashed line shows this element. The growth of the pulse peak power is accompanied by an increasing level of self-phase modulation in the nonlinear fibre, which facilitated further broadening of the pulse spectrum. The proposed method is actually an inversion of the known method of 'chirped pulse amplification' aimed at reducing the nonlinear distortions in the optical fibre amplifiers and implemented by stretching the amplified pulses [20].

To describe the pulse propagation in fibre elements, we make use of the standard approach based on the modified nonlinear Schrödinger equation (NSE) for the complex amplitude $A(z,t)$ [21]:

$$\frac{\partial A}{\partial z} - \mathrm{i}\frac{\beta_2 - \mathrm{i}(g/\Omega_{\mathrm{g}}^2)}{2}\frac{\partial^2 A}{\partial t^2} + \mathrm{i}\gamma|A|^2 A = \frac{g-l}{2}A. \quad (1)$$

Here, z is the longitudinal coordinate; t is the time in the accompanying system of coordinates; β_2 is the group velocity dispersion (GVD) coefficient; γ is the Kerr nonlinearity parameter of the fibre; and l is the loss. We neglect the dependence of GVD on the wavelength, i.e., the higher-order dispersion terms (the third- and higher-order ones), as well as the contributions of higher-order nonlinearities (nonlinearity dispersion and stimulated Raman scattering). This is possible since the length of the used fibre elements does not exceed 10 m, and the pulse duration during the most part of the propagation amounts to a few picoseconds. The gain g and the gain dispersion g/Ω_{g}^2, where Ω_{g}^2 is the gain linewidth, are nonzero only in the active fibre, and the saturated gain

$$g = g_0\left[1 + \frac{1}{E_{\mathrm{sat}}}\int |A(z,t)|^2 \mathrm{d}t\right]^{-1} \quad (2)$$

is determined by the small-signal gain coefficient g_0 and the saturation energy E_{sat}.

As the passive strongly nonlinear fibre in the considered model we propose to use a fibre with the GVD decreasing with length. In this fibre the coefficient of the normal GVD decreases according to the hyperbolic law

$$\beta_{2\mathrm{HNLF}} = \frac{\beta_{20\mathrm{HNLF}}}{1+\theta z},$$

where θ is the GVD decrement. It is known that the propagation of a pulse through such fibre is equivalent to its propagation through an active fibre with the gain $g = \theta$ [22]. Thus, the second nonlinear attractor is created in the cavity, in which the pulse asymptotically acquires the shape of a parabolic similariton having linear frequency modulation. The high nonlinearity factor γ_{HNLF} and the local increase in the peak power of the pulse facilitate the acceleration of this asymptotic convergence.

The lump elements are introduced into the model by means of a transfer function T. The transfer functions of the dispersion delay line with the anomalous dispersion $\beta_{2\mathrm{r}}$ ($T_{\mathrm{DDL}} = \beta_{2\mathrm{r}}\Omega^2/2$) and the spectral filter with the Gaussian profile and the width Ω_{f} ($T_{\mathrm{f}} = \exp[-\Omega^2/(2\Omega_{\mathrm{f}}^2)]$) relate the Fourier transforms of the pulse $\hat{A}_{\mathrm{f}}(\Omega) = T\hat{A}_{\mathrm{i}}(\Omega)$, where $\Omega = \omega - \omega_0$, and ω_0 is the carrier frequency. The transfer function of the output coupler is merely the coefficient T_{c} of transmission of part of the pulse into the cavity: $A_{\mathrm{f}}(t) = T_{\mathrm{c}}A_{\mathrm{i}}(t)$.

One of the problems typical for mode-locked lasers is the transition into the regime of multi-pulse oscillation with increasing pump. An obvious negative effect of this phenomenon is the reduction of the individual pulse energy [23]. In the proposed construction, we tried two types of saturable absorbers. The first one is a standard fast saturable absorber, and the second one is described by the coefficient of nonlinear absorption

$$\alpha = \frac{\alpha_0}{1+|A|^2/P_{\mathrm{s}}}, \quad (3)$$

where P_{s} is the saturation power; α_0 is the modulation depth. The second version implies the use of a pair of coupled symmetric fibres (or a double-core fibre) of the length L with the coupling coefficient $\sigma = \pi/(2L)$ [24, 25]. The propagation of the pulse in this structure is described by the system of NSE-type equations

$$\frac{\partial A_j}{\partial z} - \mathrm{i}\frac{\beta_{2j}}{2}\frac{\partial^2 A_j}{\partial t^2} + \mathrm{i}\gamma_j|A_j|^2 A_j = \mathrm{i}\sigma A_{3-j} - \frac{l_j}{2}A_j\,, j = 1,2. \quad (4)$$

The initial conditions are such that the pulse input into one of the coupled fibres (conditionally $j = 1$), returns into the cavity; the radiation from the second fibre is removed from the cavity. The symmetry of the structure implies the equality of the GVD parameters ($\beta_{2j} = \beta_{2\mathrm{SA}}$), nonlinearity ($\gamma_j = \gamma_{\mathrm{SA}}$) and losses ($l_j = l_{\mathrm{SA}}$) of the coupled fibres. In this case, the saturable absorption effect arises due to the nonlinear phase shift that inhibits the transfer of radiation into the linearly coupled fibre.

The analysis has shown that at the gain level corresponding to the generation of pulses with the energy of a few nanojoules in the case of a fast saturable absorber (3), the single-pulse regime is maintained only at a large modulation depth, $\alpha_0 \to 1$. Thus, for solving our problem we cannot use semiconductor saturable absorbers that possess an essentially smaller modulation depth. At the same parameters, the saturable absorber based on the coupled fibres (4) demonstrated the capability to support the single-pulse oscillation regime. This shows that the use of such saturable absorbers is promising. The widespread version of a saturable absorber based on the nonlinear rotation of polarisation is largely similar in mechanism to the second version considered here. Thus, we can expect that this version is also promising from the point of view of providing the single-pulse oscillation regime at significant pulse energies.

The numerical modelling shows that for the proposed construction in a wide range of parameters, a stable solution exists in the form of a single pulse propagating in the laser cavity. It is important that the parameters of the pulse passing throught the cavity are subject to strong variation. Let us consider these variations for one of the parameter sets, presented below.

Parameters of the active fibre

L/m	10
β_2/ps^2 km^{-1}	20
γ/W^{-1} km^{-1}	3
g_0/m^{-1}	0.5
E_{sat}/nJ	3
Ω_s/ps^{-1}	9 or 18

Parameters of the strongly nonlinear fibre with decreasing GVD and delay line

L_{DDF}/m	10
$\beta_{20\,HNLF}$/ps^2 km^{-1}	40
γ_{HNLF}/W^{-1} km^{-1}	8
θ/m^{-1}	0.5
l_{HNLF}/nJ	0.001
β_{2r}/ps^2	−0.09 or −0.0975

Parameters of the fibre saturable absorber, spectral filter and output coupler

L_{SA}/m	1.5
β_{2SA}/ps^2 km^{-1}	20
γ_{SA}/W^{-1} km^{-1}	3
l_{SA}/m^{-1}	0.001
Ω_f/ps^{-1}	1.5
T_c	0.3

The considered approach is universal with respect to the operating wavelength; however, it is convenient to express the widths of the gain line and filtering pass band in terms of the centre wavelength λ_0 at which the laser operates: $\Delta\lambda = \Omega_g \lambda_0^2 \times (2\pi c)^{-1}$. For Er lasers ($\lambda_0$ = 1.55 μm) the parameter Ω_g corresponds to the half-maximum gain linewidth 16 or 32 nm, and the parameter Ω_f corresponds to the filter half-maximum bandwidth 3.2 nm. For Yb lasers λ_0 = 1.06 μm) these quantities equal 7.5, 15, and 1.5 nm, respectively.

Figure 2 presents the evolution of the pulse envelope in the course of propagation through the cavity in the steady-state oscillation regime for Ω_g = 9 ps^{-1} and β_{2r} = −0.09 ps^2. It is seen that when passing through the active fibre, the pulse acquires the shape close to the parabolic one that insignificantly changes in the saturable absorber. The pulse possesses a strong nonlinear chirp, the compensation of which in the dispersion delay line leads to the compression of the pulse and the peak power strongly increases (to tens of kilowatts). Then the pulse passing through the strongly nonlinear fibre with a decreasing normal GVD again acquires the shape close to the parabolic one (see the inset in Fig. 2b). It is important that the high peak power provides the strong self-phase modulation and the enhanced broadening of the pulse spectrum. After the exit of the dominant part of the pulse from the cavity and strong spectral filtering, the pulse shape again approaches the Gaussian one.

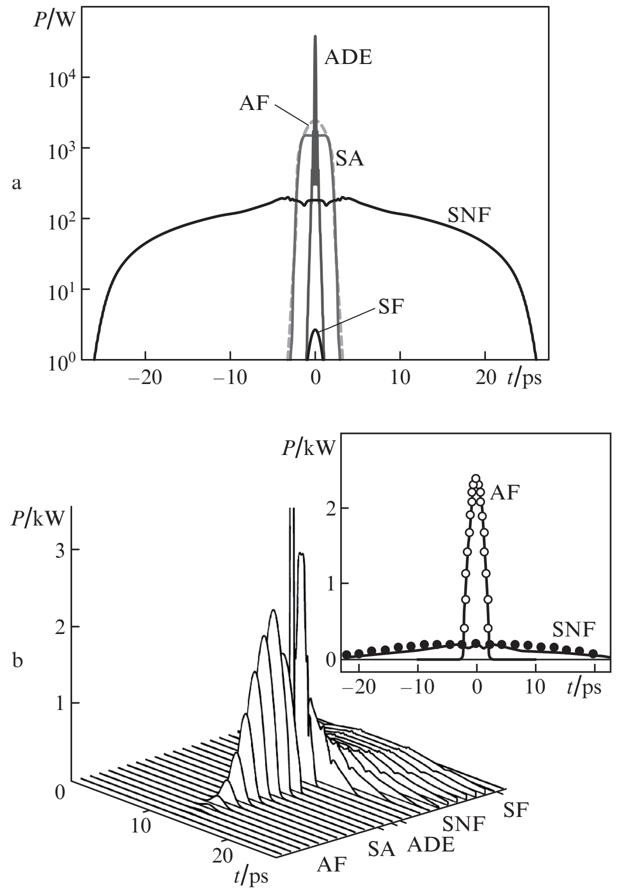

Figure 2. Steady-state oscillation regime. (a) The pulse shape after passing through different elements of the cavity (see Fig. 1); (b) the pulse evolution during a single cavity roundtrip. The inset shows the pulse shape after passing through the active fibre and the strongly nonlinear fibre. The points show the parabolic envelopes $|A(t)|^2 = P(1 - (t/\tau)^2)$, $|t| < \tau$.

The presence of a dispersion delay line in the cavity also allows a certain possibility of tuning the cavity parameters in order to generate a maximally broad spectrum. Figures 3a and 3b show the envelopes and the dependence of the laser pulse frequency modulation after passing through the active fibre for two different values of the gain linewidth. As one could expect, for a wider line the envelope is closer to the parabolic shape. In the second case, one can see essential deviations from this shape, mainly due to a grater gain in the central part of the pulse spectrum. Nevertheless, choosing the parameter of anomalous dispersion β_{2r} (β_{2r} = −0.0975 ps^2 for the linewidth Ω_g = 18 ps^{-1} and β_{2r} = −0.09 ps^2 for the linewidth Ω_g = 9 ps^{-1}), one can implement high-quality compression of the pulse in the dispersion delay line due to high linearity of frequency modulation. As shown by Figs 3c and 3d, this optimisation of the parameters allows achieving high peak

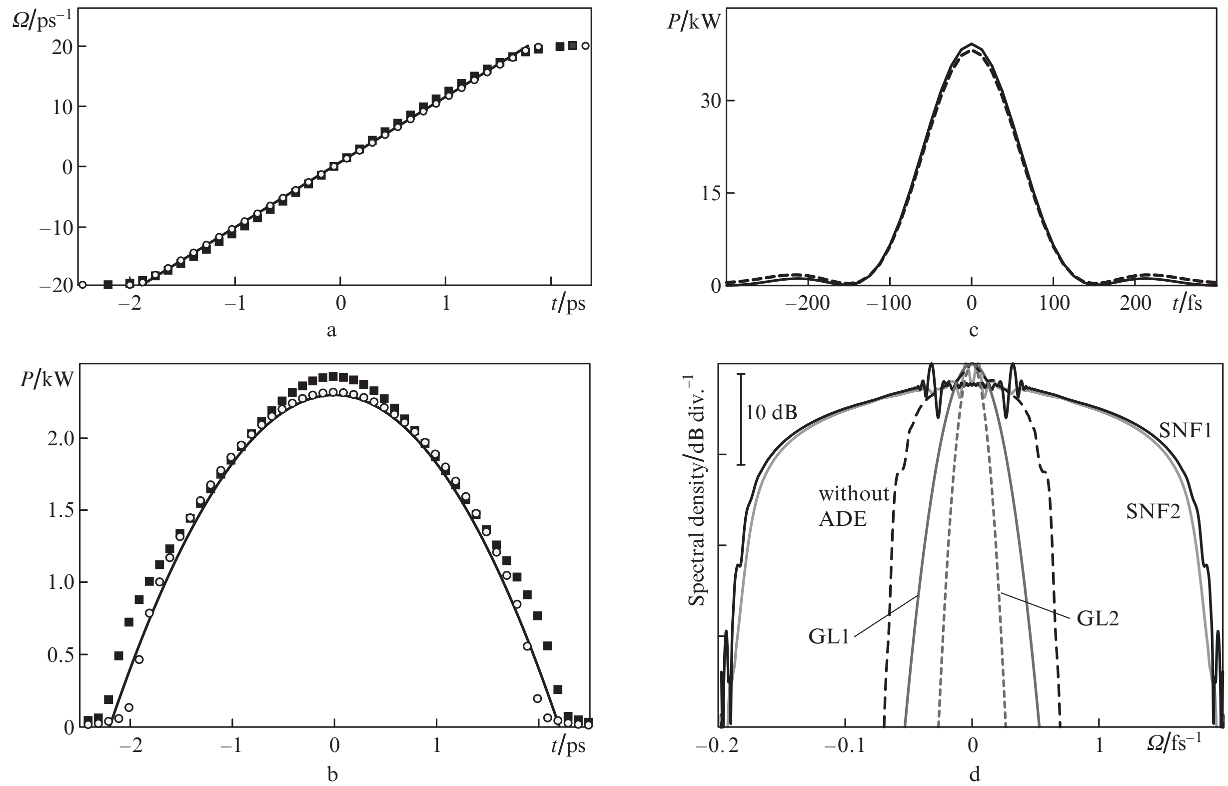

Figure 3. (a) Instantaneous frequency and (b) pulse envelopes after passing through the active fibre [the circles correspond to the gain linewidth $\Omega_g = 18$ ps^{-1}, the squares correspond to $\Omega_g = 9$ ps^{-1}, the solid lines show the linear dependence of (a) the frequency modulation and (b) the parabolic envelope]; (c) the pulse envelopes after passing through the dispersion delay line (the solid curve corresponds to the gain linewidth $\Omega_g = 18$ ps^{-1} and $\beta_{2r} = -0.0975$ ps^2, the dashed line corresponds to $\Omega_g = 9$ ps^{-1} and $\beta_{2r} = -0.09$ ps^2); (d) the pulse spectra normalised to the maximal values after passing through the strongly nonlinear fibre (SNF) and the gain lines (GLs), and the possible pulse spectrum after passing the strongly nonlinear fibre in the absence of the dispersion delay line (without ADE) (number 1 corresponding to the gain linewidth $\Omega_g = 18$ ps^{-1} and $\beta_{2r} = -0.0975$ ps^2, and number 2 corresponding to $\Omega_g = 9$ ps^{-1} and $\beta_{2r} = -0{,}09$ ps^2).

pulse powers after the dispersion delay line and, finally, the considerable broadening of the output pulse spectrum.

Comparing the results of modelling with and without a delay line (Fig. 3d), one can see that the delay line allows the output spectrum to be broadened by a few times. After the chirp compensation, the output pulse can be essentially compressed using the external dispersion element. Note that in a real experiment, besides the major contribution to the frequency modulation due to the linear chirp, it is also necessary to allow for the higher-order contributions, inevitably arising due to higher-order dispersions. Different methods exist to correct them, e.g., the multiphoton interpulse interference scanning [12, 26]. After correcting the phase, the compression is expected to provide the pulse durations of tens of femtoseconds and the peak powers of hundreds of kilowatts.

Thus, we have propose an improved construction of an amplifier similariton laser with the output spectrum width significantly exceeding the gain linewidth. The improvement consists in introducing a dispersion delay line into the cavity, aimed to increase the peak power of the pulse, and represents an inversion of the known method of 'chirped pulse amplification'. The proposed construction allows an essential increase in the output pulse spectrum and a reduction of the pulse duration after compression. The use of the proposed construction is not restricted to the problem of ultrashort pulse generation. Its application is also possible for the coherent supercontinuum generation.

Acknowledgements. The work was supported by the Russian Science Foundation (Project No. 16-42-02012).

References

1. Shank C.V., Fork R.L., Yen R., Stolen R.H., Tomlinson W.J. *Appl. Phys. Lett.*, **40**, 761 (1982).
2. Tomlinson W.J., Stolen R.H., Shank C.V. *J. Opt. Soc. Am. B*, **1** (2), 139 (1984).
3. Smirnov S., Kobtsev S., Kukarin S. *Opt. Express*, **23** (4), 3914 (2015).
4. Renninger W.H., Chong A., Wise F.W. *Opt. Lett.*, **33**, 3025 (2008).
5. Ortac B., Plötner M., Schreiber T., Limpert J., Tünnermann A. *Opt. Express*, **15**, 15595 (2007).
6. Ilday F.O., Buckley J.R., Clark W.G., Wise F.W. *Phys. Rev. Lett.*, **92**, 213902 (2004).
7. Okhotnikov O.G. (Ed.) *Fiber Lasers* (Weinheim: Wiley-VCH, 2012).
8. Yan D., Li X., Zhang S., Han M., Han H., Yang Z. *Opt. Express*, **24**, 739 (2016).
9. Krylov A.A., Sazonkin S.G., Lazarev V.A., Dvoretskiy D.A., Leonov S.O., Pnev A.B., Karasik V.E., Grebenyukov V.V., Pozharov A.S., Obraztsova E.D., Dianov E.M. *Laser Phys. Lett.*, **12**, 065001 (2015).
10. Tang Y., Liu Z., Fu W., Wise F.W. *Opt. Lett.*, **41**, 2290 (2016).
11. Renninger W.H., Chong A., Wise F.W. *Phys. Rev. A*, **82**, 021805 (2010).
12. Chong A., Liu H., Nie B., Bale B.G., Wabnitz S., Renninger W.H., Dantus M., Wise F.W. *Opt. Express*, **20**, 14213 (2012).
13. Liu H., Liu Z., Lamb E.S., Wise F. *Opt. Lett.*, **39**, 1019 (2014).

14. Fermann M., Kruglov V., Thomsen B., Dudley J., Harvey J. *Phys. Rev. Lett*., **84**, 6010 (2000).
15. Bale B.G., Wabnitz S. *Opt. Lett*., **35**, 2466 (2010).
16. Korobko D., Okhotnikov O., Sysolyatin A., Yavtushenko M., Zolotovskii I. *J. Opt. Soc. Am. B*, **30**, 582 (2013).
17. Zolotovskii I., Korobko D., Sementsov D. *Phys. Wave Phenomena*, **21**, 110 (2013).
18. Inoue T., Namiki S. *Las. Photon. Rev*., **2** (1), 83 (2008).
19. Korobko D.A., Okhotnikov O.G., Stoliarov D.A., Sysoliatin A.A., Zolotovskii I.O. *J. Lightwave Technol*., **33** (17), 3643 (2015).
20. Galvanauskas A. *IEEE J. Sel. Top. Quantum Electron*., **7** (4), 504 (2001).
21. Agrawal G.P. *Nonlinear Fiber Optics* (Burlington – San Diego – London: Academic Press, 2006; Moscow: Mir, 1996).
22. Hirooka T., Nakazawa M. *Opt. Lett*., **29**, 498 (2004).
23. Shtyrina O., Fedoruk M., Turitsyn S., Herda R., Okhotnikov O. *J. Opt. Soc. Am. B*, **26**, 346 (2009).
24. Walton D.T., Winful H.G. *Opt. Lett*., **18**, 720 (1993).
25. Proctor J., Kutz J.N. *Opt. Express*, **13**, 8933 (2005).
26. Coello Y., Lozovoy V.V., Gunaratne T.C., Xu B., Borukhovich I., Tseng C.-H., Weinacht T., Dantus M. *J. Opt. Soc. Am. B*, **25**, 140 (2008).