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Spectral broadening and compression of high-intensity laser pulses in quasi-periodic systems with Kerr nonlinearity

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Abstract. **We report the results of theoretical studies and numerical simulations of optical high-power pulse compression systems based on the spectral broadening in a Kerr nonlinear medium with subsequent pulse compression in a dispersive delay line. It is shown that the effective spectral broadening requires suppressing a small-scale instability arising due to self-focusing, which is possible in quasi-periodic systems consisting of a nonlinear medium and optical relay telescopes transmitting images of the laser beam through the system. The numerical calculations have shown the possibility of broadening the spectrum, followed by 15-fold pulse compression until the instability is excited.**

Keywords: *Kerr nonlinear medium, relay telescopes, self-phase modulation.*

1. Introduction

Ultra-high-power femtosecond laser pulses of the petawatt range are usually generated using the phase-modulated (chirped) pulse amplification and compression technique [1], which is based on amplification of relatively long laser pulses (~0.1–1 ns) and their subsequent compression to pico- and femtosecond pulses in dispersive elements, e.g., diffraction gratings. Amplifiers in these laser systems are either classical quantum amplifiers [1–9] or optical parametric amplifiers based on KDP/DKDP crystals [7, 10]. In this case, the highest energy of output radiation (a few tens of kJ) is obtained in neodymium glass lasers. However, a sufficiently large pulse duration of such lasers (~0.3–1 ps) [9], determined by the finite bandwidth of the gain, also limits the peak output power.

Application of additional techniques of output laser pulse compression would allow a significant (by an order or more) increase in power. One such method is based on self-phase modulation in a bulk nonlinear (in the simplest case, Kerr) medium with the subsequent compression of the pulses [11].

Spectral broadening of a Gaussian pulse in a passive Kerr nonlinear medium that determines the pulse compression can be estimated by using the expression [12]

$$\frac{\Delta\omega}{\Delta\omega_0} \approx (1 + 0.88B^2)^{1/2}, \tag{1}$$

where $\Delta\omega_0$ and $\Delta\omega$ are the initial and finite widths of the spectrum; B is the nonlinear phase incursion, or the so-called B integral defined in CGSE units by the expression:

$$B = \frac{8\pi^2 n_2}{\lambda c n_0}\int_0^L I(z)\,\mathrm{d}z, \tag{2}$$

where n_0 and n_2 are the linear and nonlinear parts of the refractive index $n = n_0 + n_2|E|^2/2$; λ is the wavelength; I is the radiation intensity; L is the length of the nonlinear medium; and E is electric field amplitude.

According to (1), a high degree of compression of the pulse after its phase modulation is achieved only for sufficiently large values of the B integral: $B \gg 1$. However, the value of this integral in bulk integral media is usually limited to the value $B <$ 1–3 [2] due to the small-scale self-focusing (SSSF), which leads to the beam filamentation impairing the beam brightness and eventually causing the breakdown of optical components due to a strong increase in intensity in the self-focusing filaments. It is for this reason that a high degree of compression still cannot be achieved in one nonlinear element [13–15].

Noticeable phase modulation, and therefore significant broadening of the spectrum, is possible by taking measures to suppress the SSSF [11].

Below we consider pulse compression by a system of nonlinear elements (without amplification), in which the spectrum is broadened due to the self-action with a significant decrease in the SSSF influence caused by the use of relay telescopes – a system consisting of a pair of lenses.

According to the simplest theory of self-focusing suppression with relay telescopes [16], with decreasing pulse duration and increasing pulse power, the B-integral value can be preserved by reducing the nonlinear element length and the relay telescope length until the focal length becomes significantly shorter than the beam radius. The latter, obviously, cannot be realised. Therefore, in practice, one can use nonlinear quasi-optical waveguides consisting of units, each of which has gaps filled with a linear medium, relay telescope and nonlinear elements (Fig. 1). Pulses generated due to phase modulation in the system can be compressed in the compressor, which consists of diffraction gratings [17] or chirped mirrors [14, 18]. The total B integral in such a system, characterising the spectral broadening, is $B_N = NB_1$, where B_1 is the B integral for one element, and N is the number of elements.

This paper presents the results of a study on suppression of the solution instability of a plane wave in the systems under consideration [19–22], with account for radiation diffraction in linear elements and relay telescope and for additional dis-

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tortions due to the Kerr nonlinearity in the nonlinear elements. We also discuss the features of propagation of wave beams and present the results of calculations of compression of pulses after their propagation in such systems.

2. Description of propagation of light beams in a nonlinear quasi-optical waveguide

Consider a quasi-optical waveguide (Fig. 1), in which propagation of pulses is accompanied by broadening of their spectrum with the SSSF suppression. Each period of the waveguide consists of a relay telescope formed by lenses with a focal length F_r (placed at a distance $L_{tr} = 2F_r$) and a nonlinear element of thickness L_{dr} with a refractive index $n = n_0 + n_2|E|^2/2$ (located at a distance L_{lr} from the relay telescope lenses). Reflection from the boundaries of the elements is neglected in the study, and the lens is assumed to be a linear phase corrector.

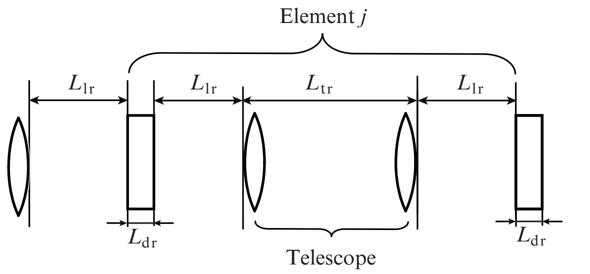

Figure 1. Fragment of a transmission line (quasi-optical waveguide) with a relay telescope.

Consider the propagation of a pulse, defined on a limited time interval $-1 < t/\tau < 1$ at the input of the system as

$$E = E_0 \exp\left[-\left(\frac{r_{\perp r}^2}{2a^2}\right)^m\right]\cos\left(\frac{\pi}{2}\frac{t}{\tau}\right), \tag{3}$$

where E_0 is the initial amplitude of the field; a is radius of the beam; 2τ is the pulse duration; $\boldsymbol{r}_{\perp r}$ is the radius vector in the plane perpendicular to the direction of the pulse propagation; and m is the number characterising a 'super-Gaussian' beam. We restrict ourselves to the simplest case and do not take into account the time dispersion, which is valid for 0.5–1-ps pulses. Consequently, we may assume the propagation of each temporal pulse cross section

$$t_i = 2\tau i/M \tag{4}$$

(M is the number of points in time, included in the calculation, and $i \leqslant M$ is the number of the cross section) to be independent of the propagation of other cross sections, which allows the calculation of the structure of the field in each cross section using the steady-state equations

$$\Delta_\perp E - 2\mathrm{i}k_\mathrm{d}\frac{\partial E}{\partial z} + k_\mathrm{d}^2\frac{n_2}{n_0}|E|^2 E = 0 \tag{5}$$

in a nonlinear medium and

$$\Delta_\perp E - 2\mathrm{i}k_0\frac{\partial E}{\partial z} = 0 \tag{6}$$

in a linear medium with the initial conditions at the input of the system (at $z = 0$)

$$E = E_0 \exp\left[-\left(\frac{r_{\perp r}^2}{2a^2}\right)^m\right]\cos\left(\frac{\pi}{2}\frac{t_i}{\tau}\right) = E_i \exp\left[-\left(\frac{r_{\perp r}^2}{2a^2}\right)^m\right],$$

$$E_i = E_0\cos\left(\frac{t_i}{\tau}\right).$$

In (5) and (6), k_0 is the wave number in a linear medium and relay telescope; k_d is the wave number in a weak field in a dielectric. Radiation given by expression (3) at the input of the system is assumed transform- and diffraction-limited. When considering the propagation of the pulse, its duration does not change, but in each section of the stationary beam described by systems (5) and (6), there occurs a change due to the nonlinearity and diffraction of the complex field amplitude, and because of the nonlinearity of the frequency-angular spectrum of the pulse broadens. Using the appropriate phase correction of the pulse spectrum, one can reduce the pulse duration.

In this system, localised wave beams may propagate under certain conditions [23–25]. However, we restrict ourselves to a particular case, which is of most interest from the point of view of the instability suppression when there exists a relatively simple unperturbed solution in the form of a plane wave in a nonlinear dielectric system. For the system in Fig. 1 the field at distances L_{dr} and L_{lr} is described by a plane wave, and in a relay telescope of length L_{tr} due to the lenses the field 'contracts' to a point on a plane halfway between the lenses. After passing through the plane, the beam propagates in the form of a spherical wave, whose phase front is corrected by the next lens; as a result, the wave in a nonlinear dielectric again becomes plane. The field compression in the middle of the relay telescope is determined by its structure at the system input.

In studying systems (5) and (6) we pass to the dimensionless variables $\boldsymbol{r}_\perp = k_\mathrm{d}\boldsymbol{r}_{\perp r}$, $z_\mathrm{n} = k_\mathrm{d} z_\mathrm{r} + C_\mathrm{n}$ (in a nonlinear medium) and $z_\mathrm{lin} = k_\mathrm{d} z_\mathrm{r} + C_\mathrm{lin}$ (in a linear medium), as well as to $L_\mathrm{d} = k_\mathrm{d} L_\mathrm{dr}$, $L_\mathrm{l} = k_\mathrm{d} L_\mathrm{lr}$, $L_\mathrm{t} = k_\mathrm{d} L_\mathrm{tr}$, $k_\perp = k_{\perp r}/k_\mathrm{d}$, $\psi = \sqrt{n_2/n_0}\,E$, where C_n and C_lin are the constants depending on the number of the element in the structure. After this, equations (5) and (6) take the form

$$\Delta_\perp\psi - 2\mathrm{i}\frac{\partial\psi}{\partial z} + |\psi|^2\psi = 0, \tag{7}$$

$$\Delta_\perp\psi - 2\mathrm{i}\frac{k_0}{k_\mathrm{d}}\frac{\partial\psi}{\partial z} = 0. \tag{8}$$

Before carrying out numerical calculations of the beam propagation in the system in question, we investigate the stability of the above solution.

3. Spatial instability of a plane wave in a periodic system

Let a plane wave $\psi = \psi_0\exp\left[-(\mathrm{i}/2)\int|\psi_0|^2\mathrm{d}z\right]$ with an amplitude ψ_0 and phase $\Phi = -(\mathrm{i}/2)\int|\psi_0|^2\mathrm{d}z$ propagate in a periodic system (Fig. 1). Integration is carried out only over a nonlinear medium. We investigate the stability of this field structure to perturbations of the transverse structure. To do so, we first represent the field in a nonlinear medium in the form convenient for multiple transitions between nonlinear and linear elements. Let

$$\psi = (\psi_0 + e)\exp\left(-\frac{\mathrm{i}}{2}\int|\psi_0|^2\mathrm{d}z\right), \tag{9}$$

where the field perturbation e is a small quantity [26]. For the field e we have the equations:

$$\Delta_\perp e - 2i\frac{\partial e}{\partial z} + |\psi_0|^2 e + \psi_0^2 e^* = 0 \quad (10)$$

inside a nonlinear medium and

$$\Delta_\perp e - 2i\frac{k_0}{k_d}\frac{\partial e}{\partial z} = 0 \quad (11)$$

in a linear medium. Let us find the field structure of the perturbations. According to [26, 27], the perturbations in a nonlinear medium represent a superposition of waves of the form $\exp(\mp ik_\perp r_\perp)$:

$$e = A(z)\exp(-ik_\perp r_\perp) + B(z)\exp(ik_\perp r_\perp).$$

Convenient is the investigation of the functions $A(z)$ and $B^*(z)$, for which we have a system of equations with constant coefficients:

$$\Delta_\perp A - 2i\frac{\partial A}{\partial z} + |\psi_0|^2 A + \psi_0^2 B^* = 0,$$
$$\Delta_\perp B^* + 2i\frac{\partial B^*}{\partial z} + |\psi_0|^2 B^* + \psi_0^{*2} A = 0. \quad (12)$$

The solution to equation (12) has the form

$$A(z),\ B^*(z) \propto \exp(\pm iHz),$$

where

$$H = \frac{\sqrt{k_\perp^4 - 2k_\perp^2|\psi_0|^2}}{2};$$

in this case, we selects $\mathrm{Re}H > 0$, if $k_\perp^4 - 2k_\perp^2|\psi_0|^2 > 0$, and $\mathrm{Im}H > 0$, if $k_\perp^4 - 2k_\perp^2|\psi_0|^2 < 0$. Using the relation

$$B = A^*\frac{\psi_0}{\psi_0^*}\frac{1 + 2H^*/k_\perp^2}{1 - 2H^*/k_\perp^2},$$

following from (12), we introduce new amplitudes

$$\bar{A} = A\frac{2}{\psi_0(1 - 2H/k_\perp^2)}, \quad A^* = \bar{A}^*\frac{\psi_0^*(1 - 2H^*/k_\perp^2)}{2}$$

and rewrite (9) as

$$\psi = \psi_0\exp\left(-\frac{i}{2}|\psi_0|^2 dz\right)\left\{1 + \left[\bar{A}_+\frac{1 - 2H/k_\perp^2}{2}\exp(-ik_\perp r_\perp)\right.\right.$$
$$\left. + \bar{A}_+^*\frac{1 + 2H^*/k_\perp^2}{2}\exp(ik_\perp r_\perp)\right]\exp(-iHz) + \left[\bar{A}_-\frac{1 + 2H/k_\perp^2}{2}\right.$$
$$\left.\left.\times\exp(-ik_\perp r_\perp) + \bar{A}_-^*\frac{1 - 2H^*/k_\perp^2}{2}\exp(ik_\perp r_\perp)\right]\exp(iHz)\right\}. \quad (13)$$

According to (13), perturbations in a nonlinear medium represent a superposition of two waves of the form $\exp(\pm iHz)$. The amplitude of each wave is proportional to the sum

$$\bar{A}_\pm\frac{1 \mp 2H/k_\perp^2}{2}\exp(-ik_\perp r_\perp) + \bar{A}_\pm^*\frac{1 \pm 2H^*/k_\perp^2}{2}\exp(ik_\perp r_\perp) \quad (14)$$

and depends on the transverse coordinate $r_\perp$. In the instability region ($k_\perp^4 - 2k_\perp^2|\psi_0|^2 < 0$), the field ψ can be written as

$$\psi = \psi_0\exp\left(-\frac{i}{2}\int|\psi_0|^2 dz\right)\left[1 + |\bar{A}_+|\frac{1 - 2i\tilde{H}/k_\perp^2}{2}\cos(k_\perp r_\perp - \varphi_+)\right.$$
$$\left.\times\exp(\tilde{H}z) + |\bar{A}_-|\frac{1 + 2i\tilde{H}/k_\perp^2}{2}\cos(k_\perp r_\perp - \varphi_-)\exp(-\tilde{H}z)\right], \quad (15)$$

where $\tilde{H} = \sqrt{2k_\perp^2|\psi_0|^2 - k_\perp^4}$; $\varphi_\pm$ are the phases of the amplitudes $\bar{A}_\pm = |\bar{A}_\pm| \times \exp(i\varphi_\pm)$. It follows from (15) that the perturbations, which have the phase $-\arctan(2\tilde{H}/k_\perp^2)$ with respect to the phase of a high-power wave, increase exponentially, while the perturbations, which have phase $\arctan(2\tilde{H}/k_\perp^2)$ with respect to the phase of a high-power wave, decrease exponentially. During propagation in a linear medium, the phase difference between the waves (15) and a high-power wave change, so that the wave, amplified in one nonlinear layer, can have an adverse phase for amplification in the next nonlinear layer, and its amplitude will decrease. The phase mechanism of self-focusing suppression is based on this phenomenon. In the stability region the perturbation waves (13) represent a superposition of waves of the form $\exp(\mp ik_\perp r_\perp)$ with coupled amplitudes and phases.

We define the wave transmission matrix of the form $\exp(ik_\perp r_\perp)$ through the system where linear and nonlinear element alternate. In a linear medium, the solution is

$$\psi = \psi_0[1 + A_{+\chi}\exp(-ik_\perp r_\perp) + A_{-\chi}\exp(ik_\perp r_\perp)].$$

This yields the relation between the amplitudes $A_{\pm\chi}$ and $\bar{A}_\pm$:

$$A_{+\chi} = \bar{A}_+\frac{1 - 2H/k_\perp^2}{2} + \bar{A}_-\frac{1 + 2H/k_\perp^2}{2},$$

$$A_{-\chi} = \bar{A}_+^*\frac{1 + 2H^*/k_\perp^2}{2} + \bar{A}_-^*\frac{1 - 2H^*/k_\perp^2}{2}.$$

We pass in the second equation to conjugates:

$$A_{-\chi}^* = \bar{A}_+\frac{1 + 2H/k_\perp^2}{2} + \bar{A}_-\frac{1 - 2H/k_\perp^2}{2},$$

and, therefore, the matrix of transition from $\bar{A}_\pm$ to $A_{\pm\chi}$ has the form

$$\hat{L}_{\mathrm{ln}} = \begin{pmatrix} \frac{1}{2}\left(1 - \frac{2H}{k_\perp^2}\right) & \frac{1}{2}\left(1 + \frac{2H}{k_\perp^2}\right) \\ \frac{1}{2}\left(1 + \frac{2H}{k_\perp^2}\right) & \frac{1}{2}\left(1 - \frac{2H}{k_\perp^2}\right) \end{pmatrix}.$$

The inverse matrix, the matrix of transition from $A_{\pm\chi}$ to $\bar{A}_\pm$, will be written in the form

$$\hat{L}_{\mathrm{nl}} = \begin{pmatrix} \frac{1}{2}\left(1 - \frac{k_\perp^2}{2H}\right) & \frac{1}{2}\left(1 + \frac{k_\perp^2}{2H}\right) \\ \frac{1}{2}\left(1 + \frac{k_\perp^2}{2H}\right) & \frac{1}{2}\left(1 - \frac{k_\perp^2}{2H}\right) \end{pmatrix}.$$

The matrices $\hat{L}_L$, $\hat{L}_d$ и $\hat{L}_t$, describing the propagation of perturbations to a distance L in a linear medium, L_d in a nonlinear medium and L_t in the transponder, respectively, have a diagonal form:

$$\hat{L}_L = \begin{pmatrix} \exp\left(\frac{ik_\perp^2 k_d L}{2k_0}\right) & 0 \\ 0 & \exp\left(-\frac{ik_\perp^2 k_d L}{2k_0}\right) \end{pmatrix},$$

$$\hat{L}_d = \begin{pmatrix} \exp(-iHL_d) & 0 \\ 0 & \exp(-iHL_d) \end{pmatrix},$$

$$\hat{L}_t = \begin{pmatrix} \exp\left(-\frac{ik_\perp^2 k_d L_t}{2k_0}\right) & 0 \\ 0 & \exp\left(-\frac{ik_\perp^2 k_d L_t}{2k_0}\right) \end{pmatrix}.$$

The relay telescope matrix differs from the matrix of a linear medium by the sign in the exponent of the diagonal element.

The change in the perturbations on the period of the system (Fig. 1) is described by the product of the matrices

$$\hat{L}_\Sigma = \hat{L}_{L1} \times \hat{L}_{nl} \times \hat{L}_d \times \hat{L}_{ln} \times \hat{L}_{L2} \times \hat{L}_t.$$

Let us find the eigenvalues of the matrix Λ

$$\hat{L}_\Sigma = \begin{pmatrix} L_{\Sigma 11} & L_{\Sigma 12} \\ L_{\Sigma 21} & L_{\Sigma 22} \end{pmatrix}$$

from the determinant

$$\begin{pmatrix} L_{\Sigma 11} - \Lambda & L_{\Sigma 12} \\ L_{\Sigma 21} & L_{\Sigma 22} - \Lambda \end{pmatrix} = 0. \qquad (16)$$

Periodic systems are stable if the roots of the determinant $|\Lambda_{1,2}| = 1$, and unstable if $|\Lambda_{1,2}| \neq 1$; in this case $|\Lambda_1 \Lambda_2| = 1$.

It was shown in [19, 27] that if $L_1 = L_2 = 0$, the system is stable if the conditions

$$|\psi|^2 L_d \leqslant \pi, \text{ or } B_1 \leqslant \pi/2, \qquad (17)$$

$$L_d = L_t \qquad (18)$$

are fulfilled. The last equation in dimensionless variables has the form $k_d L_{dr} = (k_d^2/k_0) L_{tr}$, or $L_{tr} = \sqrt{\varepsilon_0/\varepsilon_d}\, L_{dr}$, where ε_0 and ε_d are the dielectric constants of a linear medium and a dielectric, respectively.

In the system in Fig. 1 inequality (17) for the stability should be also met, and equality (18) is replaced by the expression

$$L_d + 2L_l = L_t, \qquad (19)$$

or

$$2L_{lr} = L_{tr} - \frac{L_{dr}\sqrt{\varepsilon_0}}{\sqrt{\varepsilon_d}}.$$

Note that the expression (19) corresponds to a condition of continuous transmission of the beam image by the relay telescopes throughout the system.

Figure 2 shows the region of stability of the system in the parameter plane B_1, L_{lr} for the following values of other parameters: L_{tr} = 10 cm, n = 1.46 (silica glass), and L_{dr} = 5 cm. One of the boundaries of the region (the top) is given by (17), the other lies below. The width of the region of stability for $B_1 \approx 1.5$ is a small part of the thickness of the dielectric.

One can see from Fig. 2 that the suppression of instability arising due to self-focusing (self-focusing instability) in the system under study is possible while strictly observing the distances between the linear and nonlinear elements, the requirements for accuracy increasing with decreasing thickness of the nonlinear element.

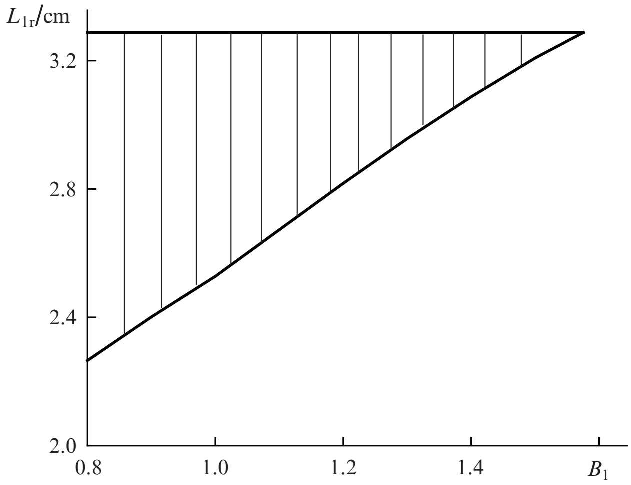

Figure 2. Stability region (shaded) in the coordinates L_{lr}, B_1 for the thickness of the nonlinear element, L_{dr} = 5 cm, at the relay telescope length L_{tr} = 5 cm and the refractive index of the nonlinear element n = 1.46.

4. Numerical modelling of wave beam propagation and pulse compression

The most detailed numerical calculations were performed for the following parameters: L_{tr} = 10 cm, n = 1.46, L_{dr} = 5 cm, a = 1 cm, λ = 1000 nm. The beam size is limited by the computing power of the self-focusing instability calculation. In the parameters B_1 and L_{dr}, the spatial scale of the perturbations with the maximum growth rate is $\Lambda_\perp = \pi\sqrt{L_{dr}}/(a\sqrt{k_d B_1})$, and on this scale it is needed to have several points of subdivision of the beam in its calculation, which limits the transverse beam size in the calculation on a grid of about $\sim 10^3 \times 10^3$ points.

For the pulse maximum we used B_1 = 1.4, which is rather close to the instability boundary $B_1 = \pi/2$. This value of the B integral for 5-cm-thick nonlinear elements is reached at a light intensity $I \approx 15$ GW cm^{-2} in silica glass ($n_2 = 0.72 \times 10^{-13}$ CGSE units [28]). For 1-ps pulses typical of neodymium glass laser with pulse compression, this corresponds to the energy density of 0.015 J cm^{-2}, which is two orders of magnitude less than the radiation strength of reflection and anti-reflection coatings [29]. The distance L_{lr} was chosen in the middle of the stability region: L_{lr} = 3.2 cm. The calculations were performed for different values of the 'super-Gaussian' m. The field after passing through the relay telescope was recalculated by the formula

$$E_{out}(r_{\perp r}) = \frac{1}{2\pi L_{tr}} \int_S E_{in}(r'_\perp) \exp\left[ik_0 \frac{r_{\perp r}^2}{2F_r} + ik_0 \frac{r'^2_{\perp r}}{2F_r} - ik_0 \frac{(r'_{\perp r} - r_{\perp r})^2}{2L_{tr}}\right] dr'_\perp$$

$$= \frac{1}{2\pi L_{tr}} \int_S E_{in}(r'_\perp) \exp\left[ik_0 \frac{(r'_\perp + r_\perp)^2}{2L_{tr}}\right] dr'_\perp, \qquad (20)$$

where $E_{\text{in}}(r_\perp)$ is the field at the relay telescope input and $E_{\text{out}}(r_{\perp\text{r}})$ is the field at the relay telescope output; the integration is performed over the entire cross section. Note that the use of (20) is possible in the absence of the diaphragms inside the relay telescope.

The field structure, which represents the dependence of the field amplitude on the radius $r_{\perp\text{r}}$ in the cross section of the beam passing through the centre ($r_\perp = 0$), at the output of the 22nd stage of this quasi-periodic system of nonlinear elements and relay telescopes is shown in Fig. 3. One can see that there is optimal $m \approx 5$. At large m, the self-focusing instability develops earlier; at lower m, the field amplitude of the beam in the maximum decreases due to the diffractional spreading of the beam.

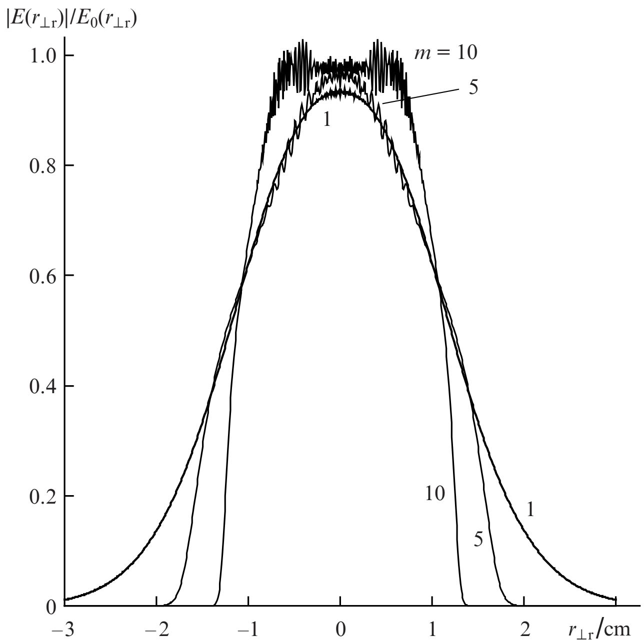

Figure 3. Cross sections of the electric field of the laser beam after the 22th stage.

Figure 4 shows the degree of distortion of the beam structure due to the development of the self-focusing instability at the optimal $m = 5$. It has an 'explosive' character and develops on two or three stages after the twentieth stage. This behaviour is different from that presented in [30], where the instability develops on fewer stages, which, in our opinion, is due to the larger value of the B integral, and the presence of the seed phase–amplitude perturbations at the input to the system.

After calculating all the beam cross sections we performed processing as follows. At the central point ($r_\perp = 0$) is the pulse spectrum

$$F(0, \Omega) = \frac{1}{\sqrt{2\pi}} \int \exp(-\mathrm{i}\Omega t) E_{\text{out}}(0, t)\, \mathrm{d}t\,. \tag{21}$$

For pulse compression with the help of dispersion elements, very important is the phase of the spectrum. Its evolution at different stages of the system is shown in Fig. 5. Up to the 20th–25th stages, when the self-focusing instability has not yet developed, the dependence of the phase on the frequency

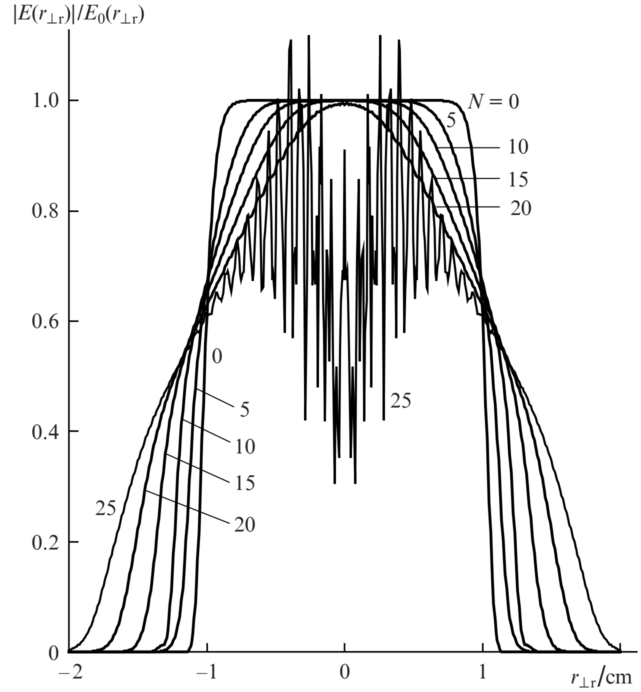

Figure 4. Cross sections of the field after passing through a different number of stages N.

Ω can be approximated by a polynomial of the fifth degree. The resulting spectrum was analysed according to the scheme, which simulates compression of the pulse in a grating compressor [31]. The approximating value of the phase was subtracted from the initial phase and the spectrum is convoluted with some residual phase in time. For comparison, we also zeroed completely the phase.

The examples of the pulses calculated in this way are shown in Fig. 6. Note that we observed side subpulses with a rather large (~20 dB) amplitude, which is caused by the nonlinear dependence of the frequency on the time. This, obvi-

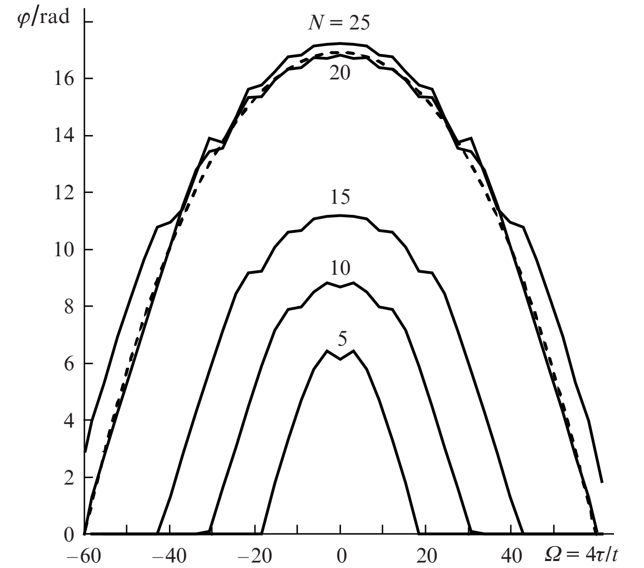

Figure 5. Phase φ of the pulse spectrum for different number of stages N. Dashed curve is approximation for $N = 20$.

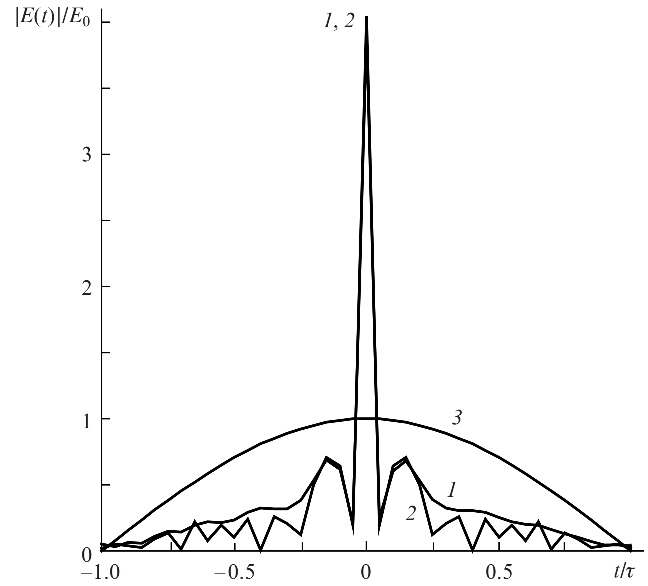

Figure 6. Structure of the pulse after compression at the 22nd (optimal) cascade: minus the total phase of the spectrum (*1*) and the phase, approximated by a polynomial of the fifth degree (*2*). Curve (*3*) is the initial pulse.

ously, decreases the time contrast of the pulse. Figure 7 shows the dependence of the intensity at the maximum of the pulse on the number of stages in the quasi-periodic system of nonlinear elements and relay telescopes. One can see that the intensity increases up to 22th stage; in this case, the residual phase obtained after phase correction by the polynomial of the fifth degree slightly reduces the intensity. Comparison of the obtained intensity with that calculated using formula (1) shows that the latter gives a value overestimated by about 1.6 times for the parameters used in the present study. Comparison of the results for the field structure as a function of the transverse coordinates (Fig. 3) and for the degree of the intensity growth in the compressed pulse shows that relatively small structural distortions of the field structure (on the 22th stage, see Fig. 3) can stop the intensity growth.

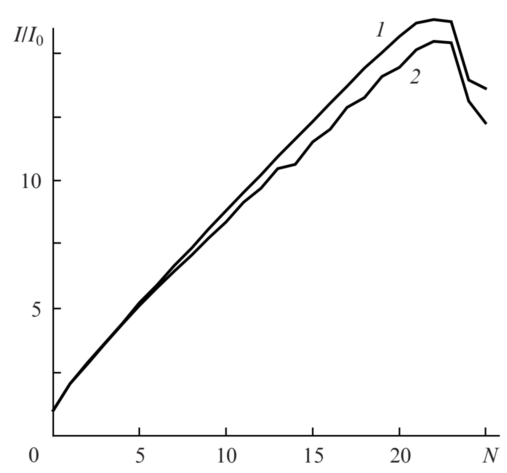

Figure 7. Dependences of the normalised intensity on the number of stages: minus the total phase of the spectrum (*1*) and the phase, approximated by a polynomial of the fifth degree (*2*).

As seen from the presented results, when a pulse, sufficiently smooth in transverse coordinates, is supplied into the system under consideration, the self-focusing instability is severely weakened and is manifested for the total B integral $B_N \approx 30$. When the real noise inherent in laser beams of high-power systems is taken into account [30, 32], the maximum value of the B integral will obviously decrease.

One of the drawbacks of the spectral broadening scheme is the limitation of the B-integral value in one of the elements of the system ($B_1 < 1.5$), which requires a large number of stages to increase B_N. Introduction of the diaphragms into the relay telescopes, i.e., use of spatial filters, can potentially increase the value of B_1 [32]. However, our calculations and the results of [30] show that when use is made of standard diaphragms, whose angular size exceeds by 10–20 times the diffraction divergence of the beam, spatial filters have no advantage over the relay telescopes. Perhaps, this is caused by the spatial intensity perturbations which are introduced into a beam by the diaphragms and increase due to SSSF.

5. Evaluation of the parameters of the system of spectral broadening and compression of ultra-high-power laser pulses

The quasi-periodic system of nonlinear elements considered in this paper can be used for spectral broadening and pulse compression of ultra-high-power neodymium-glass laser systems. Currently, the peak power of some lasers exceeds 1 PW for the pulse duration of ~1 ps.

As nonlinear elements of the spectral broadening system, the most suitable is quartz glass, which has the highest radiation resistance and the smallest nonlinear refractive index [28]. Nonlinear elements made of quartz glass should have AR coatings in order to minimise losses in the system. The damage threshold for AR coatings for the pulse duration of ~1 ps is ~2 J cm^{-2} [29], which makes it safe at an energy density of 0.2 J cm^{-2}, or intensity of 200 GW cm^{-2}. Note that the possibility of amplification of pulses with an intensity of 100 GW cm^{-2} was experimentally demonstrated in [33]. The safety value of the B integral $B_1 = 1.4$ is reached for a 0.5-cm-thick plate. Plates with a large aperture and good optical quality can be made of quartz glass. However, as follows from the results of the analysis, more stringent requirements are imposed on the accuracy of installation of nonlinear elements to ensure the system stability.

For a petawatt laser pulse the beam diameter will be about 50 cm, which is approximately equal to the beam diameter at the compressor output in 'large' laser systems. As relay telescopes spatial filters from laser systems can be used. Nevertheless, we still must find the answer to the question of how the lens nonlinearity of spatial filters affects the SSSF in the configuration under study. In principle, mirrors can serve as focusing elements of the relay telescopes.

To achieve high degrees of compression requires multielement systems, which are large enough. In principle, multielement systems can be replaced by multipass systems. As a decoupling element use can be made of a plasma-electrode Pockels cell [34], developed for laser fusion.

To compress the pulses with a broadened spectrum, the most suitable are the chirped mirrors, because the compression of short laser pulses does not need dispersive elements with large dispersion. These mirrors also have a significantly higher radiation resistance than the diffraction grating, and do not require an increase in the beam diameter before compression.

6. Conclusions

The theoretical analysis and numerical calculations have shown the possibility of significant broadening of the spectrum in the case of self-phase modulation of high-power laser pulses and SSSF suppression in a quasi-periodic system consisting of nonlinear elements and relay telescopes. In this case, the B integral in one nonlinear element is limited by the quantity $B_1 < \pi/2$, and the total B integral – by the quantity $B_N <$ 30 for the radiation parameters considered in this paper.

It is shown that phase-modulated pulses can be compressed by diffraction gratings or chirped mirrors, accompanied by an increase in the intensity by more than 15 times, if there are beams with sufficiently smooth transverse intensity distribution.

This scheme of spectral broadening and pulse compression can increase the power up to several petawatt and can be used in ultra-high-power laser systems.

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