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Frequency modulation and compression of optical pulses in an optical fibre with a travelling refractive-index wave

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Abstract. **We have studied the conditions for spectral broadening, frequency modulation and compression (both temporal and spectral) of Gaussian pulses propagating in a fibre with a travelling refractive-index wave. Analytical expressions have been derived for the dependences of pulse duration, chirp and spectral width on the distance travelled through the fibre, parameters of the fibre and radiation launched into it. Based on the numerical analysis we have studied the behaviour of these characteristics by changing the coefficient of the refractive-index modulation and other parameters of the travelling refractive-index wave.**

Keywords: *frequency modulation, compression of optical pulses, travelling refractive-index wave.*

1. Introduction

It is known that when a light pulse propagates through an optical fibre, in which a travelling refractive-index wave (TRIW) is generated, one can observe the effects that are absent both in homogeneous fibres and in fibres with a static inhomogeneity or periodicity [1, 2]. The authors of Refs [3 – 5] studied the effects related to a change in polarisation and carrier frequency offset of quasi-monochromatic wave packets under the TRIW influence. Pulsed regimes of light propagation in optical fibres with a TRIW are characterised by a several-fold increase in the pulse power with a corresponding reduction of its duration [1, 2, 5]. However, despite the abovesaid, current publications (except for a relatively small number of papers; see e.g. [2, 6, 7]) lack a detailed examination of the possibility of the control of the frequency modulation rate and the spectral width of pulses interacting with a TRIW.

In this paper we investigate the conditions for temporal and spectral compression of frequency-modulated (FM) Gaussian pulses propagating in a fibre with a TRIW. It is shown that such a fibre can be characterised by a strong pulse frequency modulation at a constant linear velocity. This fact can be used for the subsequent strong spectral or temporal compression. We present analytical expressions for the dependences of duration, spectral width and initial rate of frequency modulation of a (chirp) pulse on the distance travelled along the fibre. Based on the numerical analysis we have studied the behaviour of these characteristics by changing the coefficient of the refractive-index modulation and other parameters of the TRIW. To modulate pulses with their subsequent compression in dispersing elements (optical fibres or diffraction gratings) one can use not only fibres [1 – 5], but also planar structures [8].

2. Basic equations

We assume that a travelling refractive-index wave, in which the refractive index varies according to the law

$$n(t,z) = n_0[1 - m\cos(\Omega t - qz)] \quad (1)$$

is excited in a fibre, where Ω is the modulation frequency; $q = 2\pi/\Lambda$ is the wavenumber; Λ is the spatial inhomogeneity period; $v_m = \Omega/q$ is the velocity of the TRIW 'movement'; $m = \Delta n/n_0$ is the modulation coefficient; and Δn is a maximum change in the refractive index in a TRIW. Consider a one-way propagation of a frequency-modulated Gaussian pulse with the initial conditions

$$A(t, z = 0) = A_0 \exp[-(\tau_0^{-2} + iC_0)t^2/2], \quad (2)$$

where A_0 is the peak value of the pulse amplitude at the input to the optical fibre; τ_0 is the initial duration of the pulse; and C_0 is the initial velocity of the FM pulse (chirp). Note that in English literature, in the expression for the temporal envelope of the FM pulse, the chirp usually has a negative sign [9].

For a wave packet propagating with the group velocity $v_g = (\partial\omega/\partial\beta)_{\omega_0}$, equal to the velocity of the TRIW movement, the equation for the envelope can be written as

$$\frac{\partial A}{\partial z} + v_g^{-1}\frac{\partial A}{\partial t} - iD\frac{\partial^2 A}{\partial t^2} = i\Delta\beta A, \quad (3)$$

where D is the parameter of the group velocity dispersion;

$$\Delta\beta = n_0 k_0 m \cos(\Omega t - qz) \quad (4)$$

is the parameter defining a change in the propagation constant of a waveguide eigenmode of the optical fibre as a result of the refractive-index modulation in the TRIW.

In the running time coordinates ($\tau = t - z/v_g$), equation (3) takes the form

$$\frac{\partial A}{\partial z} - iD(z)\frac{\partial^2 A}{\partial \tau^2} = i\beta m \cos[\Omega(\tau - \delta\tau)]A, \quad (5)$$

where $\beta = n_0\omega/c$ is the propagation constant of a wave packet in an unperturbed fibre; $k_0 = \omega/c$; c is the velocity of light in

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vacuum; and $\tau - \delta\tau = \tau - (v_{\rm m}^{-1} - v_{\rm g}^{-1})z$ characterises the temporary detuning associated with the mismatch of the pulse group velocity and the TRIW velocity. In considering pulses with a sufficiently small detuning ($\tau - \delta\tau \approx 10^{-10}$–$10^{-11}$ s), in the right-hand side of equation (5) we can use the expansion

$$\cos[\Omega(\tau - \delta\tau)] \approx 1 - \Omega^2(\tau - \delta\tau)^2/2. \quad (6)$$

In this case, equation (5) takes the form

$$\frac{\partial A}{\partial z} - {\rm i}D\frac{\partial^2 A}{\partial \tau^2} = {\rm i}(S_1 + S_2\tau + S_3\tau^2)A, \quad (7)$$

where the parameters S_j are defined by the expressions:

$$S_1 = m\beta(1 - \Omega^2\delta\tau^2/2),\ \ S_2 = m\beta\Omega^2\delta\tau,\ \ S_3 = -m\beta\Omega^2/2.$$

We represent the amplitude of the envelope of the wave packet in the form

$$A(z) = a(z)\exp[{\rm i}(\varphi(z) + b(z)\tau + \alpha(z)\tau^2)] \quad (8)$$

and substitute in equation (7). As a result, we arrive at the system of equations

$$\frac{\partial a}{\partial z} + 2D(b + 2\alpha\tau)\frac{\partial a}{\partial \tau} - {\rm i}D\frac{\partial^2 a}{\partial \tau^2} = {\rm i}\left(S_1 - \frac{\partial \varphi}{\partial z} - b^2D + 2{\rm i}\alpha D\right)a, \quad (9a)$$

$$\frac{\partial b}{\partial z} + 4\alpha Db = S_2, \quad (9b)$$

$$\frac{\partial \alpha}{\partial z} + 4D\alpha^2 = S_3, \quad (9c)$$

where the parameter α characterises the rate of frequency modulation (chirp) 'induced' by the TRIW, and b is the change in the velocity of the envelope maximum caused by a mismatch of the group velocity of the FM wave and the TRIW velocity in the TRIW field.

Next, using a simple substitution

$$a = \bar{a}\exp\left[{\rm i}\int\left(S_1 - \frac{\partial \varphi}{\partial z} - b^2D + 2{\rm i}\alpha D\right){\rm d}z\right] \quad (10)$$

equation (9a) is transformed into

$$\frac{\partial \bar{a}}{\partial z} + 2D(b + 2\alpha\tau)\frac{\partial \bar{a}}{\partial \tau} - {\rm i}D\frac{\partial^2 \bar{a}}{\partial \tau^2} = 0. \quad (11)$$

We proceed in this equation to the new running time coordinates:

$$\tau'(z) \equiv f(z)\tau - 2\int f(z)D(z)b(z){\rm d}z, \quad (12)$$

where for the parameter $f(z)$ the relations

$$f(z) = f(0)\exp\left(-4\int D(z)\alpha(z){\rm d}z\right),\ \ f(0) = 1$$

are valid. As a result, equation (11) takes the form

$$\frac{\partial \bar{a}}{\partial z} - {\rm i}D(z)f^2(z)\frac{\partial^2 \bar{a}}{\partial \tau'^2} = 0. \quad (13)$$

The initial conditions for the amplitude $\bar{a}$ are as follows:

$$\bar{a}(0) = A_0\exp[-(\tau_0^{-2} + {\rm i}C_0)\tau'^2/2], \quad (14)$$

The solution to equation (13) with the initial condition (14) can be represented in the form:

$$\bar{a}(\tau', z) = A_0F^{-1/2}(z)\exp\left[-\frac{(\tau_0^{-2} + {\rm i}C_0)\tau'^2}{2F(z)}\right]. \quad (15)$$

where

$$F(z) = 1 - 2g(z)(C_0 - {\rm i}\tau_0^{-2});\ \ g(z) = \int D(z)f^2(z){\rm d}z.$$

Assuming $b = 0$ and $S_2 = 0$ (i.e. in the case where the group velocity of the wave packet and the TRIW velocity are equal and, consequently, $\delta\tau = 0$) for the pulse duration in a medium with a TRIW we obtain an expression for the FM pulse duration,

$$\tau_{\rm p}(z) = \frac{\tau_0}{f(z)}\sqrt{(1 - 2C_0g(z))^2 + \frac{4g^2(z)}{\tau_0^4}}, \quad (16)$$

and its real current chirp:

$$C_{\rm eff}(z) = \bar{C}(z) - 2\alpha(z). \quad (17)$$

Here

$$\bar{C}(z) = \frac{C_0 - 2(C_0^2 + \tau_0^{-4})g(z)}{(1 - 2C_0g(z))^2 + 4\tau_0^{-4}g^2(z)}f_1^2(z). \quad (18)$$

3. Chirp dynamics and pulse duration

The dependence $\alpha(z)$ in (17) can be found from the solution of equation (9c). For example, if D and S_3 are constant and do not depend on z, for the induced frequency modulation rate [taking into account the initial condition $\alpha(0) = 0$] we have the solutions:

at $DS_3 < 0$

$$\alpha(z) = \pm\sqrt{|S_3/D|}\,\tan(\sqrt{|S_3D|}z); \quad (19)$$

at $DS_3 > 0$

$$\alpha = \pm\frac{\exp(4\sqrt{S_3D}z) - 1}{\exp(4\sqrt{S_3D}z) + 1}\sqrt{\frac{S_3}{4D}}. \quad (20)$$

In both cases, the sign '+' corresponds to $S_3 > 0$, and the sign '–' corresponds to $S_3 < 0$.

The solutions obtained show that when a wave packet interacts with a TRIW, its superfast modulation is possible at the same linear frequency modulation and large spectral width. This in turn allows the pulse compression to continue. Thus, with a positive chirp the compression can be performed on diffraction gratings. If the pulse has a negative chirp, then a conventional optical fibre with normal material dispersion can be used for its further compression. In both cases, after compression (when the pulse becomes transform-limited and $C_{\rm eff} \to 0$) the pulse duration

$$\tau_{\min} = \frac{\tau_{\rm p}(z)}{\sqrt{1 + C_{\rm eff}^2(z)\tau_{\rm p}^4(z)}} \cong \frac{1}{\left|2\alpha(z)\tau_{\rm p}^2(z)\right|}. \quad (21)$$

It can be seen that at the initial duration of a transform-limited ($C_0 = 0$ and $\alpha_0 = 0$) pulse (at $\tau_0 = 10^{-11}$ s, depth and modulation frequency of $m\beta = \pm 10^4$ m^{-1} and $\Omega = 5\times10^{10}$ s^{-1}) launched into a waveguide modulator, as well as at the group velocity dispersion $|D| = 10^{-26} - 10^{-27}$ s^2 m^{-1} for a waveguide modulator length $z = 4$ cm, the FM pulse velocity is $|C_{\rm eff}| \approx 10^{24}$ s^{-2}. Moreover, its duration does not substantially change. As a result, after the transmission of the pulse through a dispersing element providing a temporary pulse compression, its duration $\tau_{\rm p}$ may be reduced by 100 times, to 10^{-13} s. If the pulse is synchronised with a 'dip' of the refractive-index wave, the pulse compression should be carried out in a medium with normal material dispersion. In this case, the compressor may be a conventional optical fibre with normal dispersion. If the pulse is synchronised with a TRIW 'ascent', its compression should be performed in a medium with anomalous dispersion, and then at a peak pulse power of less than 100 W as a compressor we can also use a conventional optical fibre, but with anomalous dispersion. If the peak power is much greater than 1 kW, it is preferable to use a pair of diffraction gratings for the 'neutralisation' of undesired nonlinear effects.

4. Spectral compression

Of interest is also the possibility of spectral compression of a FM broadband pulse in a TRIW medium. Thus, one of the most important problems of modern laser physics is the development of systems for amplification and generation of high-energy pulses required in a wide range of applications – in materials processing, optical communication and medicine. Specificity of fibre amplifier systems is associated with strong nonlinear effects, mainly self-phase modulation (SPM) of a propagating pulse. One of the main factors limiting the generation of pulses of high (over 100 nJ) energies in such amplifiers is a high positive FM arising because of SPM, which leads to the overrunning of the spectrum outside the gain band, to a distortion of the envelope and, finally, to a decay of the pulse. A standard way to reduce the negative nonlinear effects is the use of a well-known technique of chirped pulse amplification (CPA), which consists in a preliminary (before amplification) FM pulse stretching to reduce the peak power [10–12]. The application of specially designed Yb fibres with a large mode area ('cores') and the use of several amplification stages allow one to obtain pulses with energies up to a few mJ and peak powers of more than 1 GW [13–16]. In this case, the most effective techniques, which can be used to reduce the spectral broadening caused by SPM, is a spectral compression (SC) of the pulse [17–29]. As a rule, its essence consists in imparting first a negative chirp to the pulse and then its 'decay' due to SPM during the propagation in a nonlinear medium.

In the case under study, an appropriate initial chirp can be obtained by synchronising FM wave packets with TRIW 'dips'. Let us assume that the above-described pulse with an initial duration $\tau_0 = 10^{-11}$ s has an initial negative chirp $C_0 = -10^{24}$ s^{-2}. In this case, the width of the spectrum of this pulse can be estimated using the expression

$$\Delta\omega = \sqrt{\tau_0^{-2} + C_0^2\tau_0^2} \approx 10^{13}\,{\rm s}^{-1}. \quad (22)$$

By synchronising the corresponding pulse with the TRIW 'dip' at a length of 4 cm, one can obtain a transform-limited wave packet with a zero effective chirp and as a result, $C_{\rm eff} \simeq 0$. In this case, the spectral width of the corresponding wave packet is $\Delta\omega = 1/\tau_{\rm p} \approx 1/\tau_0 \approx 10^{-11}$ s^{-1}.

Note that this kind of spectral compression can be extremely useful for a variety of technical applications – for high-power laser systems as well as optical communication systems and information processing systems. First of all, it opens the possibility of an effective amplification of picosecond pulses with an energy much greater than 1 nJ in the existing standard amplifying fibres (ytterbium, bismuth, and, most importantly, in a narrow band – erbium).

5. Numerical analysis

Below we present the results of the numerical analysis of the derived relations at a fixed TRIW frequency $\Omega = 5\times10^{10}$ s^{-1}, propagation constant $\beta = 10^7$ m^{-1} and input power $P_0 = 1$ W. Figure 1 shows the dependences of the maximum pulse power $P_{\max}$ and normalised propagating pulse duration $\tau_{\rm p}/\tau_0$ on the distance z travelled along the optical fibre at $\tau_0 = 10^{-11}$ s, $D = 10^{-25}$ s^2 m^{-1} and different m. One can see that with increasing

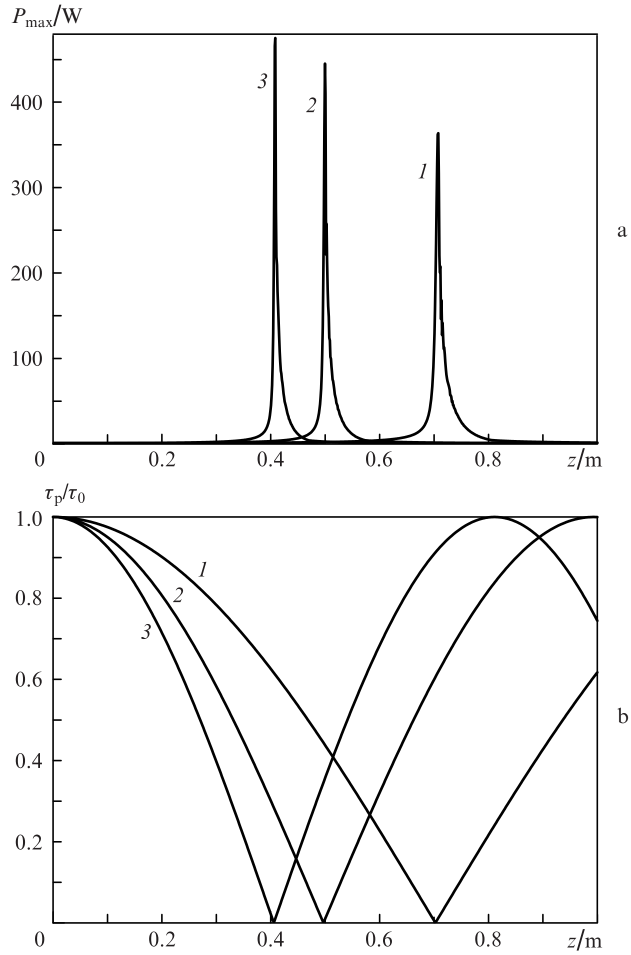

Figure 1. Dependences of (a) the maximum pulse power $P_{\max}$ and (b) normalised propagating pulse duration $\tau_{\rm p}/\tau_0$ on the distance z travelled along the optical fibre at $\tau_0 = 10^{-11}$ s, $D = 10^{-25}$ s^2 m^{-1} and $m = 10^{-3}$ (*1*), 2×10^{-3} (*2*), 3×10^{-3} (*3*).

modulation depth m, the distance z_m travelled by the pulse, at which its maximum compression and maximum pulse power are reached, is reduced. When the pulse travels a longer distance, i.e. at $z > z_m$, the pulse broadens and its power sharply decreases. The length of the maximum compression z_m with good accuracy (for the above parameters) satisfies the condition $1 - 2C_0 g(z_m) = 0$.

Figure 2 shows the dependences of the effective chirp C_{eff} and spectral width $\Delta\omega$ of the propagating pulse on the distance travelled along the optical fibre at $C_0 = 10^{24}$ s^{-2}, $D = -10^{-25}$ s^2 m^{-1} and different m. One can see that with increasing modulation depth the length z_m, at which the minimum spectral width of the FM pulse is implemented, decreases. The narrowing of the spectral width of the pulse occurs due to a decrease in the FM rate. In this case, the maximum spectral narrowing of the pulse is achieved at a complete 'decay' of the effective chirp. Note that except for a small area of the path lengths of the pulse near z_m the presented dependences are virtually linear at a given small interval of the lengths.

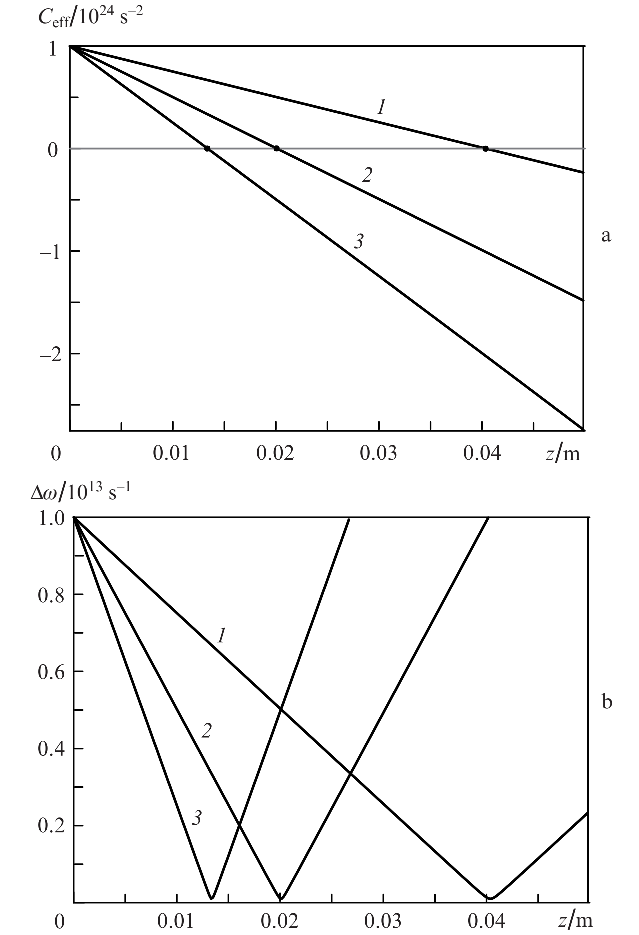

Figure 2. Dependences of (a) the effective chirp C_{eff} and (b) spectral width $\Delta\omega$ of the propagating pulse on z at $C_0 = 10^{24}$ s^{-2}, $D = -10^{-25}$ s^2 m^{-1} and $m = 10^{-3}$ (*1*), 2×10^{-3} (*2*), 3×10^{-3} (*3*).

Figure 3 presents the same dependence on a logarithmic scale on a longer section of the fibre. Note the presence of 'bursts', whose position is determined by equation (19), and a deep minimum in the effective chirp and its subsequent growth and a change in sign. This behaviour of the chirp affects the behaviour of the spectral width of the pulse, for which one observes 'bursts' at the same travelled distances.

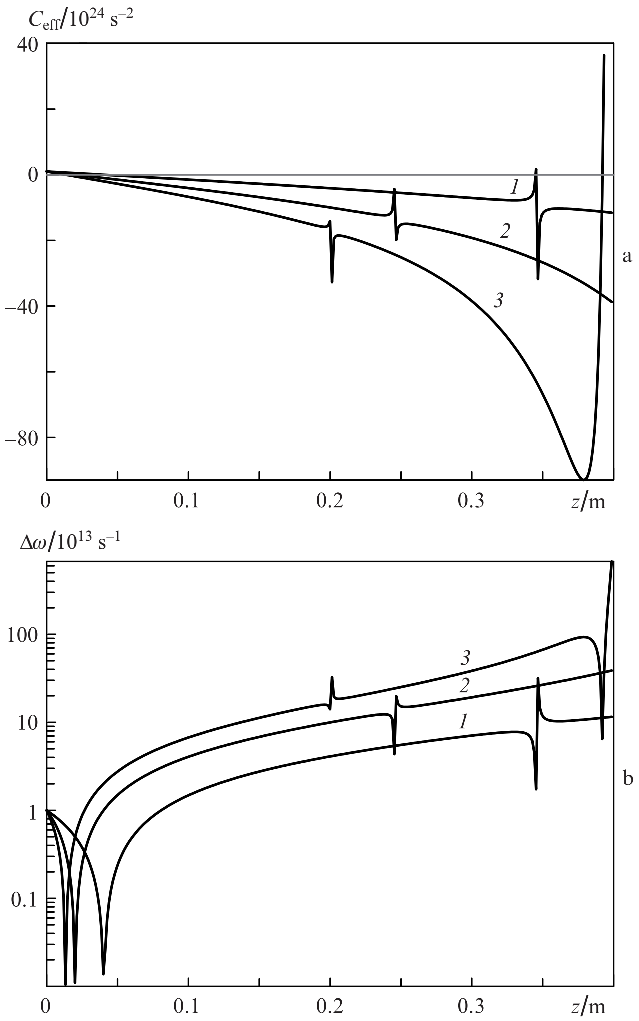

Figure 3. Dependences of (a) the effective chirp C_{eff} and (b) spectral width $\Delta\omega$ of the propagating pulse on z at $C_0 = 10^{24}$ s^{-2}, $D = -10^{-25}$ s^2 m^{-1} and $m = 10^{-3}$ (*1*), 2×10^{-3} (*2*), 3×10^{-3} (*3*) on a larger scale as compared to Fig. 2.

Figure 4 shows the dynamics of the pulse spectrum in the case of its passage through the optical fibre at the same parameters as in Figs 2 and 3. One can see that during the pulse propagation in a TRIW fibre the frequency modulation (chirp) is quenched and, as a consequence, the chirp is strongly (by about 10 times at a length of less than 4 cm) spectrally compressed. After passing through the point at which the pulse width is minimal, its spectral compression is replaced by strong broadening.

Figure 5 shows the behaviour of the temporal profile of the pulse with an increase in the distance travelled by the light in the fibre. The presented dependence of the relative power on the coordinate and the running time is obtained for an initially transform-limited pulse ($C_0 = 0$) with an initial duration $\tau_0 = 3\times10^{-12}$ s at a significant ($m = 10^{-3}$) modulation depth and dispersion $D = -10^{-25}$ s^2 m^{-1}. One can see that with increasing travelled distance there first occurs a sufficiently smooth (without a substantial change in the shape) temporary pulse compression and an increase in its peak power. Then, one observes a fast compression and maximal (for the

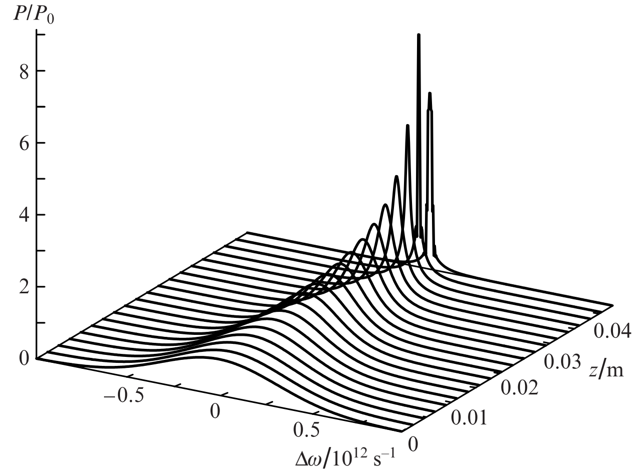

Figure 4. Dynamics of the pulse spectrum as it passes through the optical fibre at $C_0 = 10^{24}$ s^{-2}, $D = -10^{-25}$ s^2 m^{-1} and $m = 10^{-3}$.

chosen parameters) peak power, and after it – its fast decrease and rapid pulse broadening.

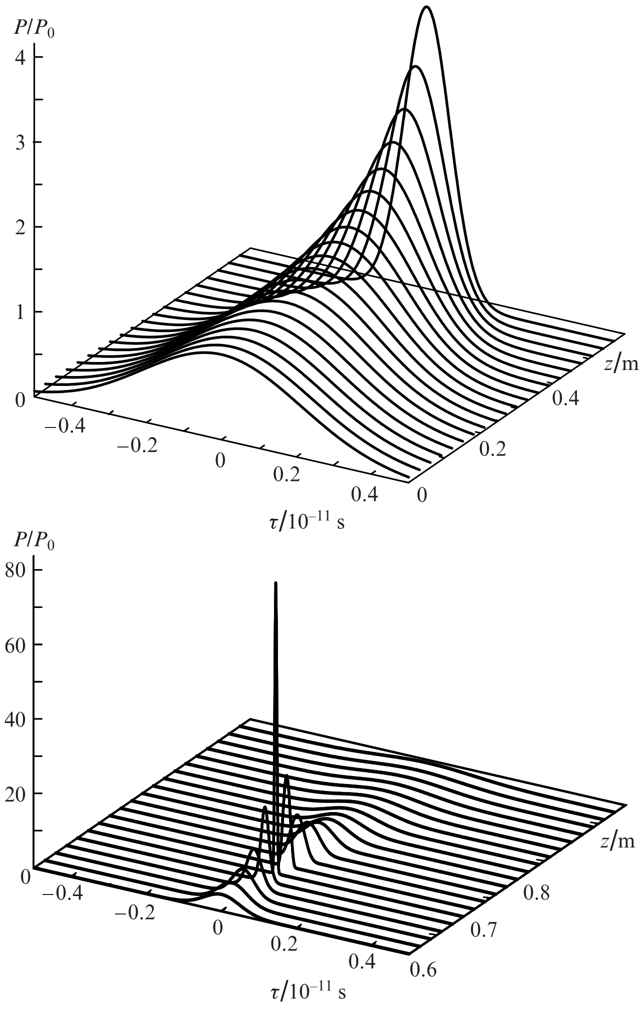

Figure 5. Changes in the temporal profile of a transform-limited pulse ($C = 0$) with an increase in the distance travelled by the pulse along the optical fibre at an initial duration $\tau_0 = 3\times10^{-12}$ s at $m = 10^{-3}$ and $D = -10^{-25}$ s^2 m^{-1}.

One can clearly see from Fig. 5 that the temporal envelope of the propagating pulse is extremely sensitive to the travelled distance. Note that with increasing length of the fibre the pulse compression is replaced by broadening, and near the maximum compression one can observe a violation of its shape, which is then restored in the process of broadening. The dependences in Fig. 5 correspond to the same set of parameters, and their sharp rise takes place near 0.6 and 0.7 m (point of maximum compression). These strong differences are due to the choice of calculation parameters [if we choose, for example, $\tau_0 = 3\times10^{-12}$ s rather than 10^{-11} s, the compression ratio decreases, and the original (Gaussian) pulse shape almost stops changing].

6. Conclusions

The analysis performed in this paper shows that optical fibres with a TRIW synchronised (by the propagation velocity) with the pulse launched into the optical fibre can be used for strong frequency modulation of the corresponding pulses at a small (less than 10 cm) length of the waveguide modulator. In this case, even at this length of the fibre, one can obtain a considerable spectral broadening of the pulse (by 1–3 orders of magnitude, up to $\Delta\omega \simeq 10^{14}$ s^{-1} inclusive) at a virtually ideal preservation of the chirp linearity.

The latter circumstance, in turn, makes possible the subsequent strong pulse compression (temporary compression) by 1–3 orders up to subpicosecond and femtosecond values (in the optical range). On the other hand, the corresponding waveguide modulators (such as fibre and planar ones) can be used for the spectral compression of initially frequency-modulated broadband pulses.

The set of appropriate techniques (both spectral and temporal compression) can be successfully used in CPA for amplification of frequency-modulated pulses in the high-power subpicosecond and femtosecond laser systems.

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