CONTROL OF LASER RADIATION PARAMETERS

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Compression of a Gaussian pulse in two-mode periodic optical waveguides with a complex refractive index

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Abstract. Using a FM Gaussian pulse travelling in a two-mode periodic optical fibre as an example, it is shown that dispersion parameters caused by the complexity of the refractive index substantially affect the pulse dynamics. In particular, the imaginary part of the effective dispersion enables one to compress a pulse in an amplifying medium without its initial frequency modulation.

Structures with a strong linear coupling between unidirectional waves travelling there attract interest because of a multitude and a variety of effects observed upon propagation of short optical pulses. The presence of these effects suggests that such structures can be used to control parameters of optical radiation. Among these structures are tunnel-coupled optical fibres [1, 2], media with gyration [3, 4], etc.

Of particular interest are fibres possessing periodicity along their length, where strong interaction between unidirectional modes is realised [5 – 7]. The analysis of linear and nonlinear regimes of transformation of optical modes in a periodic two-mode optical fibre with a real refractive index shows that such fibres have unique dispersion properties [8 – 10], which enables the efficient compression of a pulse travelling in a fibre and formed by its modes.

Real fibres have a rather low loss that, however, can affect their dispersion characteristics. Also of particular interest are amplifying optical fibres, which found a wide application as effective fibre amplifiers of laser radiation [11, 12].

Because of this it seems important to study the effect of the complexity of the refractive index and of related absorption or gain on dispersion properties of a periodic optical fibre and the transformation of optical pulses in it. Here, we report the results of our study of these problems.

Consider a periodic two-mode optical fibre whose dielectric constant is a complex quantity and depends on the coordinates as

$$\varepsilon(r,z)=\varepsilon_0\{1-f(r)[1+\gamma\cos(2\pi z/\Lambda)]\}. \quad (1)$$

Here, $\varepsilon_0=\varepsilon_0'+\mathrm{i}\varepsilon_0''$ is the dielectric constant of the fibre axis, with $|\varepsilon''|\ll|\varepsilon_0'|$ for real fibres; $f(r)$ is the function describing the distribution of optical nonuniformity over the fibre section; $\gamma\ll 1$ is its modulation degree and Λ is the period of optical nonuniformity along the fibre.

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To find the imaginary part ε'' of the dielectric constant, we neglect the small quantity $\gamma\varepsilon_0''$, which eliminates modulation of ε'' along the fibre. The complexity of the dielectric constant leads to the complexity of mode propagation constants $\beta_j=\beta_j'-\mathrm{i}\beta_j''$, where $|\beta_j''|\ll|\beta_j'|$ $(j=1,2)$. The field in the fibre can be represented as a superposition of the fields of two eigenmodes of the fibre with the unperturbed dielectric constant

$$\boldsymbol{E}(t,r,z)=\frac{1}{2}\sum_j[\boldsymbol{e}_j\mathscr{A}_j(t,z)\boldsymbol{R}_j(r)\exp\mathrm{i}(\omega_0t-\beta_j'z)+\mathrm{c.c.}], \quad (2)$$

where $\boldsymbol{e}_j$ are unit polarisation vectors of modes; $R_j(r)$ are profile functions describing the mode field distributions over the fibre section; and ω_0 is the carrier frequency of the wave packet injected into the fibre. Taking into account the complexity of mode propagation constants, the time envelopes of mode amplitudes have the form

$$\mathscr{A}(t,z)=A(t,z)\exp(-\beta_j''z). \quad (3)$$

Efficient coupling between the modes travelling along the fibre is obtained in the case of their phase matching at the carrier frequency. Taking into account the fibre periodicity and the complex nature of propagation constants, the coupling conditions are determined by the relations

$$\delta'(\omega_0)=0,\ \delta''(\omega_0)\approx 0,\ \delta(\omega)=\beta_1(\omega)-\beta_2(\omega)-2\pi/\Lambda. \quad (4)$$

In the region of parameters where phase-matching conditions are nearly fulfilled $(\omega\approx\omega_0)$, coupled wave equations for the time envelopes of modes in a pulse, written in terms of the running time $\tau=t-z/u$ $(u^{-1}=(\partial\beta/\partial\omega)_0$ and $2\beta=\beta_1+\beta_2)$, have the form

$$\frac{\partial A_1}{\partial z}-\frac{1}{v}\frac{\partial A_1}{\partial\tau}-\mathrm{i}\frac{d_1}{2}\frac{\partial^2A_1}{\partial\tau^2}=-\mathrm{i}\sigma_{12}A_2\exp(\mathrm{i}\delta z),$$
$$\frac{\partial A_2}{\partial z}+\frac{1}{v}\frac{\partial A_2}{\partial\tau}-\mathrm{i}\frac{d_2}{2}\frac{\partial^2A_2}{\partial\tau^2}=-\mathrm{i}\sigma_{21}^*A_1\exp(-\mathrm{i}\delta z). \quad (5)$$

Here, $1/v=(u_1-u_2)/2u^2$; $u_j=(\partial\beta_j/\partial\omega)_0^{-1}$ and $d_j=(\partial^2\beta_j/\partial\omega^2)_0$ are the mode group velocity and the mode material dispersion;

$$\sigma_{ij}\approx\left[k_0^2\varepsilon_0\gamma\int e_ie_jf(r)R_iR_jr\mathrm{d}r\right]\left(2\beta_i\int R_i^2r\mathrm{d}r\right)^{-1} \quad (6)$$

are intermode coupling coefficients, which are determined by the overlap integrals of the profile mode functions; $k_0 = \omega/c$; ω and c are the frequency and speed of light in vacuum, respectively.

The initial time envelopes of mode amplitudes for a pulse at the input of the fibre are determined by its excitation type and can be represented in the form $A_j(t,0) = A_{j0}\phi(t)$. The most frequently used excitation types are the one-mode excitation, with $A_{10} \neq 0$ and $A_{20} = 0$ (or vice versa), and the two-mode excitation, with $A_{20} = \psi A_{10}$. If $\psi = \pm 1$, we have symmetric or antisymmetric fibre excitation. The time function for a FM Gaussian pulse is

$$\phi(t) = \exp\left[-(1 + i\alpha_0\tau_0^2)t^2/2\tau_0^2\right], \quad (7)$$

where τ_0 is the pulse duration at the fibre input and α_0 is the degree of frequency modulation.

In the case of strong intermode coupling, when $|A_1|^2 + |A_2|^2 =$ const with a high accuracy on the length $L_\sigma = 1/|\sigma|$ of intermode beats and $|\sigma_{12}| \approx |\sigma_{21}^*| \equiv |\sigma|$ there, the solution of system (3) can be represented in the form

$$A_1 = a_1(\tau, z)\exp[(iq - \delta/2)z] + a_2(\tau, z)\exp[(-iq - \delta/2)z],$$

$$A_2 = \varkappa a_1(\tau, z)\exp[(iq + \delta/2)z] \quad (8)$$

$$-\varkappa^{-1} a_2(\tau, z)\exp[(-iq + \delta/2)z].$$

Here, a_f are the amplitudes slowly varying with the coordinate z; $f = 1, 2$;

$$\varkappa = \frac{(2q + \delta)A_{20} - 2\sigma A_{10}}{(2q - \delta)A_{10} - 2\sigma A_{20}} \quad (9)$$

is a parameter determined by the initial fibre excitation conditions; and $q \equiv (\sigma^2 + \delta^2/4)^{1/2}$. The pulse formed by the interacting modes represents a superposition of partial pulses whose amplitudes, in view of (5) and (8), satisfy the equations

$$\frac{\partial a_f}{\partial z} - \frac{(-1)^f \delta}{2qv}\frac{\partial a_f}{\partial \tau} - \frac{iD_f}{2}\frac{\partial^2 a_f}{\partial \tau^2} = 0, \quad (10)$$

where

$$D_f = d + \frac{(-1)^f}{2vq}\left(1 - \delta p v^2\right) \quad (11)$$

is the effective dispersion of the corresponding partial pulse; $d = (d_2 + d_1)/2$; $p = (d_2 - d_1)/2$. Because of (8), the initial conditions for the amplitudes of partial pulses $a_f(\tau, 0) = a_{f0}\phi(t)$ take the form

$$a_{f0} = \frac{1}{2}\left[A_{10} + (-1)^f\left(\frac{\delta}{2q}A_{10} + \frac{\sigma}{q}A_{20}\right)\right]. \quad (12)$$

For the initial conditions presented above, the solutions of equations (10) can be represented in the form

$$a_f(\tau, z) = a_{f0}\xi_f^{-1/2}\exp\left[-\frac{(1 + i\alpha_0\tau_0^2)\tau_f^2}{2\tau_0^2\xi_f}\right], \quad (13)$$

where

$$\xi_f = 1 - (\alpha_0 - i\tau_0^{-2})D_f z; \;\; \tau_f = \tau + (-1)^f \delta z/2qv.$$

Thus, the general solution of system of equations (5) with initial conditions (12) can be represented in the form of system (8), i.e., as a simple superposition of noninteracting partial pulses whose dynamics is totally described by relations (13).

In the case of complete phase matching ($\delta = 0, \varkappa = -1$), the effective dispersion of partial pulses is determined by the expression

$$D_f = D_f' - iD_f'' = d' + \frac{(-1)^f}{v'^2|\sigma|} - i\left[d'' + \frac{2(-1)^f}{v'v''|\sigma|}\right], \quad (14)$$

and the solution of equations (10) is written in the form

$$a_f = \left(\frac{\tau_0}{\tau_{uf}}\right)^{1/2} a_{f0}\exp\left[i\theta_f + (1 + s^2)\frac{\tau''^2}{2\tau_{uf}^2} - \frac{(\tau' - s_f\tau'')^2}{2\tau_{uf}^2}\right]. \quad (15)$$

Here, $\tau' = t - z/u'$; $\tau'' = u''z/u'^2$; $a_{f0} = 0.5(A_{10} + (-1)^f \times A_{20})$ are initial pulse amplitudes. The pulse durations are determined by the expression

$$\tau_{uf} = \tau_0\left[\frac{(1 - b_1 z)^2 + b_2^2 z^2}{1 + D_f''(\tau_0^{-2} + \alpha_0^2\tau_0^2)z}\right]^{1/2}, \quad (16)$$

where

$$b_1 = \alpha_0 D_f' - \tau_0^{-2}D_f''; \;\; b_2 = \alpha_0 D_f'' - \tau_0^{-2}D_f';$$

$$s_f = \frac{(b_1\alpha_0\tau_0^2 + b_2)z - \alpha_0\tau_0^2}{1 + (\alpha_0\tau_0^2 b_2 - b_1)z}.$$

In the case of symmetric or antisymmetric two-mode excitation of an optical fibre, which are important in practice, the total pulse formed by two modes is represented only by one of the partial pulses (8)–(10). In this case, its duration becomes equal to the partial-pulse duration ($\tau_{uf} = \tau_p$), the intensities of mode components $I_j = |\mathscr{A}_j|^2$ are identical, and the intensity of the total pulse is determined by the expression

$$I = \left(\frac{\tau_0}{\tau_p}\right) I_0 \exp\left[-2(\beta'' - \Delta_1)z - \frac{(\tau' - \Delta_2)^2}{\tau_p^2}\right], \quad (17)$$

where $I_0 = |A_{10}|^2 + |A_{20}|^2$; $\Delta_1 = (1 + s^2)\tau''^2/\tau_p^2 z$; $\Delta_2 = s\tau''$. Below, we will analyse precisely this type of excitation, and because of this, we omit the subscript f in (17) and in further formulas.

Taking into account (15), the condition of compression of the wave packet injected into the fibre $(d\tau_p/dz)_{z=0} < 0$ is given by the inequality

$$2\alpha_0\tau_0^2 D_f' + (\alpha_0^2\tau_0^4 - 1)D_f'' > 0. \quad (18)$$

In this case, the length on which a pulse reaches a minimum duration (the compression length) is determined by the expression

$$L_s = -\frac{\tau_0^2}{(1+\alpha_0^2\tau_0^4)D''}\left[1 - \frac{|D' + \alpha_0\tau_0^2 D''|}{|D|}\right], \tag{19}$$

and the minimum pulse duration is

$$\tau_{min} = \tau_0\left[\frac{D'^2 + D''^2}{(D' + \alpha_0\tau_0^2 D'')^2}\right]^{1/4}\left[(1 - b_1 L_s)^2 + b_2^2 L_s^2\right]^{1/2}. \tag{20}$$

In the limiting case of the zero imaginary part of the refractive index (i.e., $D'' = 0$), we have

$$L_s = \frac{\tau_0^2}{D'}\frac{\alpha_0\tau_0^2}{1+\alpha_0^2\tau_0^4},\ \tau_{min} = \frac{\tau_0}{(1+\alpha_0^2\tau_0^4)^{1/2}}. \tag{21}$$

Similar relations describe the behaviour of a pulse in a single-mode optical fibre with material dispersion d [13].

It follows from these relations that, in the general case, the complexity of the dielectric constant of a fibre material leads to the presence of both the imaginary part of the propagation constant and the imaginary components of the group velocity and the effective dispersion, which, in turn, cause a shift of the carrier frequency of a wave packet and a decrease in the damping parameter.

The analysis made for absorbing fibres shows that the effect of ε'' on their transformation and dispersion properties is insignificant. Indeed, present-day optical fibres have the absorption coefficient $\alpha = 2\beta'' \leqslant 10^{-4}$ m^{-1}, and its presence, according to (17), leads only to a small decrease in the pulse intensity on rather large lengths. For the imaginary components of the group velocity and the effective dispersion of a typical silica fibre with loss, we have the estimates $u'' \approx (\partial\beta''/\partial\omega)_0(u'^2) \approx u'^2\beta''/\omega_0 \leqslant 10^{-2}$ m s^{-1} and $|D''| \approx (\partial^2\beta''/\partial\omega^2)_0 \approx \beta''/\omega_0^2 \approx 10^{-35} - 10^{-33}$ s^2 m^{-1}. In this case, $u' \approx 10^8$ m s^{-1} and $|D'| \approx 10^{-26}$ s^2 m^{-1}.

Because u'' and $|D''|$ are so small, the effect of absorption on the pulse dynamics is insignificant, and, therefore, we will cinsider below only dispersion properties of an amplifying fibre made, for example, of a neodymium glass [14].

Let a pulse be formed by a combination of LP_{10} and LP_{20} modes of a fibre core. In this case, we have $\beta_1'' = \beta_2'' = \beta_{10}''$ with a high accuracy. For active fibres of this kind, $2\beta''(\omega)$ represents the linear gain and can be defined by the relation [15]

$$2\beta''(\omega) = -\rho N\left[1 + \frac{I_0}{I_{sat}} + \left(\frac{\Delta\omega}{\Delta\omega_I}\right)^2\right]^{-1}, \tag{22}$$

where $\Delta\omega = \omega - \omega_r$ is the detuning from the induced-transition frequency; ω_r and ρ are the frequency of the induced transition and its cross section; N is the concentration of active particles in the absence of lasing; $\Delta\omega_I$ is the spectral line width; and I_{sat} is the saturation intensity. In amplifying optical fibres, the imaginary part D'' of the effective dispersion is equal to the imaginary part d'' of material dispersion with a high accuracy because the cases of most interest (when $|D''| \geqslant |D'|$) satisfy the inequality $|d''| \gg 2/|v'v''\sigma|$, and, therefore, $D'' \approx (\partial^2\beta''/\partial\omega^2)_0$. As a result, we have

$$D'' = \frac{\rho N}{\Delta\omega_I^2}\,\frac{1 + I_0/I_{sat} - 3(\Delta\omega^2/\Delta\omega_I)}{\left[1 + I_0/I_{sat} + (\Delta\omega/\Delta\omega_I)^2\right]^3}. \tag{23}$$

In what follows, we assume that $I_{sat} \gg I_0$. When $|\Delta\omega| = \Delta\omega_I/\sqrt{3}$, the parameter D'' changes its sign, which substantially determines the character of pulse transformation. For typical parameters of a neodymium glass $\rho N \approx 10^{-2} - 10^0$ m^{-1} and $\Delta\omega_I \approx 10^{12}$ s^{-1} [14], we have $|D''| \approx 10^{-24}$ s^2 m^{-1}. Because the imaginary component of the effective fibre dispersion is so large, this parameter should have a substantial effect on the radiation dynamics in amplifying fibres.

Let us analyse in greater detail some scenarios of pulse behaviour in the case of complete phase matching and find the dependence of the pulse duration and the conditions under which pulse compression takes place on the parameters of a fibre and radiation injected into it.

(1) Let $\alpha_0 = 0$, i.e., a pulse at the fibre input has no initial frequency modulation of phase. In this case, as follows from (18), compression is also possible provided $D_f < 0$. The compression length and the minimum pulse duration are determined by the relations

$$L_s = L_0\left[1 - \frac{1}{(1+\eta^2)^{1/2}}\right],$$
$$\tau_{min} = \frac{\sqrt{2}\tau_0}{\eta}\left[\left(1+\eta^2\right)^{1/2} - 1\right]^{1/2}, \tag{24}$$

where $L_0 = \tau_0^2/|D''|$; $\eta = |D''/D'|$. If $\eta \gg 1$, then $\tau_{min} \approx \tau_0(2/\eta)^{1/2}$. Fig. 1 presents the dependence of the normalised pulse duration on the reduced length z/L_0 for $\eta = 1, 2, 10$, and 100. One can see that each value of η is characterised by the minimum pulse duration $\tau_{min}(\eta)$, and when the length tends to L_0, the pulse duration tends to infinity for all η.

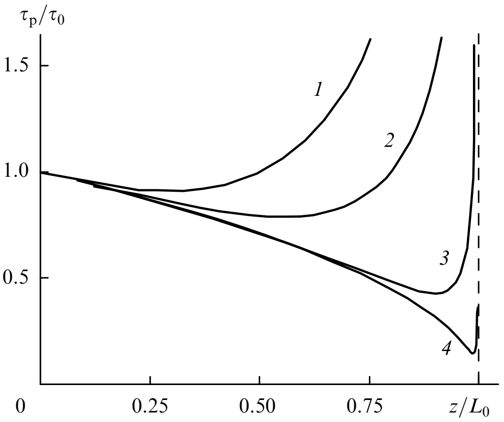

Figure 1. Dependences of the reduced pulse duration τ_p/τ_0 (for a pulse without initial frequency modulation) on the normalised coordinate z/L_0 for $\eta = 1$ (*1*), 2 (*2*), 10 (*3*), and 100 (*4*).

In the general case, one should take into account for $z \approx L_0$ the dispersion terms of third and higher orders, which makes it possible to avoid an infinite pulse spread on a finite length. It is possible to obtain $D' \leqslant 10^{-26}$ s^2 m^{-1} and, consequently, $\eta \approx 100$ by choosing the fibre parameters (its thickness and profiles of refractive indices of a core and a cladding). For the initial pulse duration $\tau_0 \approx 10$ ps and the imaginary part of the effective dispersion of a partial pulse in an amplifying medium $|D''| \approx 10^{-24}$ s^2 m^{-1}, the normalised length is $L_0 \approx 100$ m.

(2) Let $\alpha_0 \neq 0$, i.e., we have a FM pulse at the fibre input. In this case, compression can be obtained for $D'' > 0$ as well (in particular, at the carrier frequency $\omega \approx \omega_0$, which is characterised by the maximum gain of a wave packet). If $D' = 0$, i.e., if the contributions of the real parts of the material and intermode dispersion to the effective dispersion compensate one another, the compression condition has the form

$$(\alpha_0^2\tau_0^4 - 1)D'' > 0. \tag{25}$$

From this, it follows that compression is obtained for $|\alpha_0|\tau_0^2 > 1$ and $D'' > 0$ and $|\alpha_0|\tau_0^2 < 1$ and $D'' < 0$. In this case,

$$L_s = \frac{\tau_0^2}{D''}\frac{|\alpha_0|\tau_0^2 - 1}{\alpha_0^2\tau_0^4 + 1}, \quad \tau_{\min} = \tau_0\left(\frac{2|\alpha_0|\tau_0^2}{\alpha_0^2\tau_0^4 + 1}\right). \tag{26}$$

Fig. 2 presents the dependences of the normalised compression length L_s/L_0 and the minimum pulse duration $\tau_{\min}/\tau_0$ on the parameter $|\alpha_0|\tau_0^2$. $D'' > 0$ corresponds to the region $|\alpha_0|\tau_0^2 > 1$, and $D'' < 0$ corresponds to the region $|\alpha_0|\tau_0^2 < 1$. As the parameter $|\alpha_0|\tau_0^2$ is increased, pulse compression is enhanced in the region $D'' > 0$, and when this parameter is decreased, it is enhanced in the region $D'' < 0$. If $\alpha_0 = 0$, 'supercompression' takes place at the length $L_s = L_0$, i.e., $\tau_{\min} \to 0$.

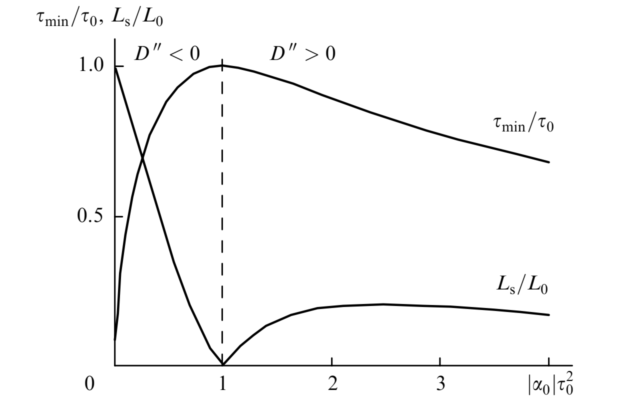

Figure 2. Dependences of the reduced compression length L_s/L_0 and the minimum pulse duration $\tau_{\min}/\tau_0$ on the rate of frequency modulation at the fibre input $|\alpha_0|\tau_0^2$.

(3) Let $D' + \alpha_0\tau_0^2 D'' = 0$. If $D'' < 0$, this case also leads to 'supercompression', i.e., the situation when $\tau_p \to 0$. In this case, the pulse duration is determined by the expression

$$\tau_p = \tau_0[1 + D''\alpha_0(1 + \alpha_0\tau_0^2)z]^{1/2}, \tag{27}$$

from which follows that the minimum duration ($\tau_p \to 0$) is obtained on the compression length

$$L_s = L_0(1 + \alpha_0^2\tau_0^4)^{-1}. \tag{28}$$

Note that in the wavelength region $z \approx L_s$, one should take into account, as in the case of an infinite pulse spread (Fig. 1), dispersion parameters of third and higher orders.

Fig. 3 presents the dependences of the normalised pulse duration τ_p/τ_0 on the reduced length z/L_0 obtained for $D''/D' = -1$ and different values of the frequency modulation. Curve *3* corresponds to 'supercompression', i.e., for $z = L_0/2$, $\tau_p \to 0$. For this relationship between the dispersion parameters, one obtains the compression length L_s for each value of the parameter $\alpha_0\tau_0^2$ on which the pulse duration reaches a minimum and the length $L_{0\alpha}$ on which a pulse becomes infinitely long. For $z \geqslant L_{0\alpha}$, equations (5) have no solutions, which also shows that one should take into account for these lengths higher approximations of the dispersion theory.

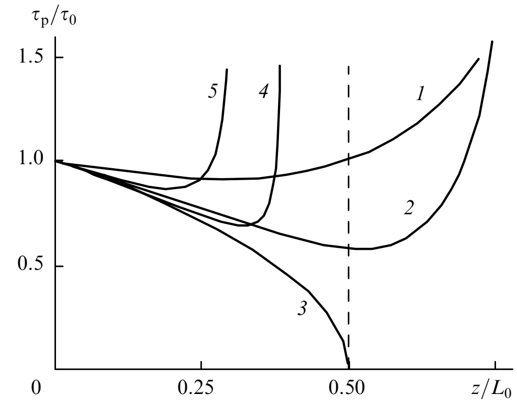

Figure 3. Dependences of the reduced pulse duration τ_p/τ_0 (for a pulse with initial frequency modulation) on the normalised coordinate z/L_0 for $D''/D' = -1$ and $|\alpha_0|\tau_0^2 = 0$ (*1*), 0.5 (*2*), 1 (*3*), 1.5 (*4*), and 1.75 (*5*).

Consider a Nb-doped two-mode step silica fibre with $\rho N \approx 0.1$ m^{-1}, core radius $r_0 = 10^{-5}$ m, $\gamma = 2 \times 10^{-5}$, period $\Lambda \approx 303$ μm providing phase-matching of LP_{01} and LP_{02} modes at the operating frequency $\omega_0 = 1.239 \times 10^{15}$ s^{-1} [16], $\omega_r \approx 1.24 \times 10^{15}$ s^{-1}, and $\Delta\omega_I \approx 10^{12}$ s^{-1}. Then, a frequency-unmodulated Gaussian pulse with duration $\tau_0 = 10^{-11}$ s at the input is compressed by a factor of ten on the fibre length $z = L_s \approx 100$ m.

It is reasonable to assume that systems using coupled unidirectional waves in media with complex dispersion parameters and gain can produce a considerable pulse compression. However, presently available data on periodic amplifying optical fibres are insufficient for obtaining – with a high accuracy – estimates of the parameter η required for determining the maximum potentialities of the compressors considered here. Nevertheless, we note that self-modulation in such fibres, in contrast to self-phase modulation in media with the refractive index possessing nonlinearity in intensity, appears for the input radiation intensity as low as is wished.

Our analysis shows that the dispersion parameters associated with the complexity of wave numbers of radiation travelling in an optical fibre are able to cause compression of an optical pulse without initial frequency modulation in a linear medium. This situation is radically different from the standard situation when the inclusion of dissipative properties of a medium is reduced to an additional linear term introduced into the wave equations. The presence of this term in the linear approximation of a medium, neglecting the complexity of dispersion parameters, leads only to an additional exponential increase (or decrease) in the amplitude of a pulse travelling along a fibre and has no effect on its duration. We showed that it is possible in principle to obtain 'supercompression', i.e., an extremely strong compression of a wave packet on a relatively small fibre length. Because of a strong intermode coupling, which is caused by the periodicity, the initial conditions of radiation injection strongly affect the effective fibre dispersion and, therefore, the pulse dynamics.

Our results show that periodic optical fibres offer much promise for the development of high-efficiency devices for controlling laser radiation.

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