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Dynamics of pulses in optically coupled active optical fibres with different parameters

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***Abstract*. The dynamics of a wave packet formed by two modes propagating in optically coupled channels with different mode gain increments is studied. It is shown that in the case of a linear intermode coupling, radiation in such structures is decomposed into two autonomous partial pulses with different values of the effective dispersion parameters determining their dynamics. The conditions of the temporal compression and realisation of the superluminal velocity of the envelope maximum for partial pulses and the wave packet as a whole are also investigated.**

Keywords: *wave-packet dynamics, optically coupled fibres, active fibres.*

1. Introduction

Systems of optically coupled fibres (OCFs), which can provide a strong coupling of waves propagating in adjacent channels, attract permanent great attention due to the wide possibilities of their practical applications in devices for controlling laser radiation [1 – 4]. Optically coupled fibres can be fabricated both from fibre and planar structures [1, 5]. In recent years long-period fibre gratings, which can provide the coupling of modes in the fibre core (in particular, amplifying) and cladding (the core and cladding having different waveguiding parameters) attract the attention of researchers [6, 7]. Of great interest are also multicore fibre arrays providing multiwave coupling with one optical fibre [8, 9].

The effective dispersion parameters of wave structures in such systems considerably depend on the strength of a linear coupling between waves and the excitation conditions of a fibre, which allows the efficient control of the radiation dynamics, for example, the duration and velocity of the envelope maximum of wave packets. In this case, it is possible in principle to compress linearly a pulse of arbitrarily low power in the region of normal material dispersion in the absence of the initial frequency modulation [10, 11]. In addition, the velocity of the envelope maximum considerably exceeding the speed of light in vacuum can be achieved. Such a pulse dynamics is not related to energy transfer with the superluminal velocity but is caused by the change in the pulse shape due to the predominant amplification of its leading edge during propagation [12 – 19].

In most papers devoted to the discussion of the possibilities of obtaining superluminal velocities, exponential pulses with a sloping leading edge are considered. Such a pulse was experimentally observed for the first time in a laser amplifier [20]. The velocity of the envelope maximum of this pulse was a few times higher than the speed of light in vacuum. However, superluminal velocities can be also achieved for pulses of a Gaussian shape having steep leading and trailing edges. In this case, superluminal regimes can be obtained if the pulse has the quadratic initial rate of frequency modulation (FM) and propagates in a medium with the dispersion of the gain increment [21, 22].

The dynamics of wave packets formed by two interacting modes was studied, as a rule, for the case of real dispersion parameters and identical gain increments characterising the mode-propagation channels. At the same time, a number of possible dynamic effects can be related to the complex nature of these parameters and their difference. In this paper, we consider the dynamics of a two-mode wave packet propagating in a system of two optically coupled channels (one of which at least is amplifying) with substantially different material parameters. The possibility of obtaining the regimes of propagation of the envelope maximum of a wave packet at the superluminal speed in such systems is investigated.

2. Dynamic equations and their general solutions

The field of a wave packet propagating in a system of two active linearly coupled fibres (channels) can be written in the form

$$E(t,r)=\frac{1}{2}\sum_{j=1,2}\left(e_jR_j(x,y)B_j(t,z)\exp\left[\mathrm{i}(\omega_0 t-\beta_j' z)\right]+\mathrm{c.c.}\right), \quad (1)$$

where e_j are polarisation unit vectors; R_j are profile functions; B_j are time envelopes of the mode components of the wave packet; ω_0 is the carrier frequency of the wave packet; and β_j' is the real part of the propagation constant $\beta_j=\beta_j'-\mathrm{i}\beta_j''$.

Taking into account the first- and second-order dispersion effects under the conditions of a considerable detuning from phase matching, the wave-packet dynamics can be described by the system of equations for the time

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envelopes of the mode components of the wave packet in each of the fibres:

$$\frac{\partial B_1}{\partial z}+\frac{1}{u_1}\frac{\partial B_1}{\partial t}-\frac{\mathrm{i}d_1}{2}\frac{\partial^2 B_1}{\partial t^2}=\mathrm{i}\sigma B_2\exp(\mathrm{i}\delta z)+\alpha_1 B_1,$$
$$\frac{\partial B_2}{\partial z}+\frac{1}{u_2}\frac{\partial B_2}{\partial t}-\frac{\mathrm{i}d_2}{2}\frac{\partial^2 B_2}{\partial t^2}=\mathrm{i}\sigma^* B_1\exp(-\mathrm{i}\delta z)+\alpha_2 B_2. \quad (2)$$

Here, d_j is the group velocity dispersion for the corresponding modes in each of the coupled fibres; $u_j=(\partial\beta_j'/\partial\omega)^{-1}_{\omega=\omega_0}$ are the group velocities of modes in each of the coupled fibres; $\delta=\beta_1'-\beta_2'$ is the detuning of the real components of propagation constants; σ is the linear intermode coupling coefficient; and $\alpha_j=-\beta_j''$ are the mode gains.

By making the change of variables $B_j=A_j\exp(\alpha_j z)$ and passing to the running coordinate system $\tau=t-z/u$, we obtain the system of equations

$$\frac{\partial A_1}{\partial z}-\frac{1}{v}\frac{\partial A_1}{\partial \tau}-\frac{\mathrm{i}d_1}{2}\frac{\partial^2 A_1}{\partial \tau^2}=\mathrm{i}\sigma A_2\exp(\mathrm{i}\Delta z),$$
$$\frac{\partial A_2}{\partial z}+\frac{1}{v}\frac{\partial A_2}{\partial \tau}-\frac{\mathrm{i}d_2}{2}\frac{\partial^2 A_2}{\partial \tau^2}=\mathrm{i}\sigma^* A_1\exp(-\mathrm{i}\Delta z), \quad (3)$$

where $u=2u_1u_2/(u_1+u_2)$; $v=2u_1u_2/(u_1-u_2)$; $\Delta=\delta-\mathrm{i}(\alpha_2-\alpha_1)$.

The system of equations (3) should be solved together with the initial condition for amplitudes $A_j(\tau,z)$. We assume that a frequency-modulated pulse is incident on the fibre input. The pulse amplitude is $A_j(\tau,0)=A_{j0}\theta(\tau)$, where A_{j0} are the amplitudes of pulses coupled to each of the fibres, and the function $\theta(\tau)$ determines the shape of a wave packet introduced to the fibre. We will consider below a Gaussian frequency-modulated pulse, for which this function has the form

$$\theta(\tau)=\exp\left[-\frac{(1+\mathrm{i}\alpha_0\tau_0^2)\tau^2}{2\tau_0^2}\right], \quad (4)$$

where τ_0 and α_0 are the duration and velocity of the frequency modulation of the pulse at the input to the fibre, which are assumed identical for both mode components of the wave packet.

The solution of system (3) in the general form can be represented as a superposition of two partial pulses with envelopes a_1 and a_2 for each of the fibres:

$$A_1(z,\tau)=\left[a_1(z,\tau)\exp(\mathrm{i}qz)+a_2(z,\tau)\exp(-\mathrm{i}qz)\right]\times\exp\left[(\alpha_2+\alpha_1+\mathrm{i}\delta)z/2\right],$$
$$A_2(z,\tau)=\left[\varkappa a_1(z,\tau)\exp(\mathrm{i}qz)-(1/\varkappa^*)a_2(z,\tau)\exp(-\mathrm{i}qz)\right]\times\exp\left[(\alpha_2+\alpha_1-\mathrm{i}\delta)z/2\right], \quad (5)$$

where the parameters $\varkappa=[(2q+\Delta)\psi-2\sigma^*][(2q-\Delta)-2\sigma\psi]^{-1}$ and $q=(|\sigma|^2+\Delta^2/4)^{1/2}$ are introduced, and the parameter ψ determines the excitation type of the fibre: $A_2=\psi A_1$. For $\psi=\pm 1$, symmetric or antisymmetric excitation takes place, and for $\psi=0$ – single-mode excitation. According to (3) and (5), the time envelopes of the corresponding partial pulses are determined by the equation

$$\frac{\partial a_f}{\partial z}-(-1)^f K\frac{\partial a_f}{\partial \tau}-\mathrm{i}\frac{D_f}{2}\frac{\partial^2 a_f}{\partial \tau^2}=0, \quad (6)$$

where $f=1,\ 2$. Here, the effective parameters are also introduced: the first dispersion parameter $K=\Delta/2qv$ and the group velocity dispersion (GVD) of partial pulses

$$D_f=d+\frac{(-1)^f}{q}\left[\frac{|\sigma|^2}{q^2v^2}+\frac{\Delta(d_1-d_2)}{4}\right], \quad (7)$$

where $d=(d_1+d_2)/2$. The initial conditions (for $z=0$) for each of the pulses, taking (4) into account, can be written in the form

$$a_f(\tau,0)=\frac{1}{2}\left[A_{10}+(-1)^f\left(\frac{\Delta}{2q}A_{10}+\frac{\sigma}{q}A_{20}\right)\right]\theta(\tau). \quad (8)$$

The dispersion parameters introduced above, which determine, finally, the dynamics of the wave-packet produced by two coupled modes, depend both on the parameters of each of the waveguide channels and the parameters of incident radiation. If even all the dispersion parameters in initial system (2) are real quantities (which is the case when $\partial\alpha_j/\partial\omega\simeq 0$, i.e. $\alpha_j=$ const in the frequency range under study), but $\alpha_1\neq\alpha_2$, then the parameters Δ and q, as well as the first- and second-order effective dispersion parameters are complex quantities. If, however, $\alpha_2=\alpha_1=\alpha$ and $\partial\alpha/\partial\omega\simeq 0$ near the carrier frequency, then all the dispersion parameters are real. Thus, in the case of different gains in OCFs, the effective dispersion parameters of partial pulses are complex. However, it is the presence of the imaginary components of these parameters that leads to a number of interesting and important effects: the time compression of arbitrarily-low-power pulses without the initial frequency modulation, the appearance of pulses with the superluminal speed of the envelope maximum, and the shift of the carrier frequency of the wave packet [22, 23].

3. Dynamics of partial pulses

The solution of Eqn (6) taking into account the boundary conditions (8) for the complex amplitudes of the corresponding partial pulses can be written in the form

$$a_f(\tau,z)=\rho_f(\tau,z)\exp\left[\mathrm{i}\phi_f(\tau,z)\right], \quad (9)$$

where the amplitude of the time envelope of a partial pulse $a_f(\tau,z)$ is determined by the expression

$$\rho_f(\tau,z)=a_{f0}\left(\frac{\tau_0}{\tau_{\mathrm{d}f}}\right)^{1/2}\exp\left[\frac{(1+S_f^2)K''^2z^2-\tau_{\mathrm{s}f}^2}{2\tau_{\mathrm{d}f}^2}\right], \quad (10)$$

and $a_{f0}=a_f(\tau,0)/\theta(\tau)$. We do not present here the expression for the phase ϕ_f of the time envelope of a partial pulse, which is not significant for our analysis. The pulse duration introduced in (10) is

$$\tau_{\mathrm{d}f}=\tau_0^2\left[\frac{(1-\chi_{1f})^2+\chi_{2f}^2}{\tau_0^2+D_f''(1+\alpha_0^2\tau_0^4)z}\right]^{1/2}, \quad (11)$$

and $\chi_{1f} = (\alpha_0 D_f' - D_f''\tau_0^{-2})z$, $\chi_{2f} = (\alpha_0 D_f'' + D_f'\tau_0^{-2})z$, and $\tau_{sf} = \tau + (-1)^f(K' + S_f K'')z$,

$$S_f = -\frac{(\alpha_0^2\tau_0^2 + \tau_0^{-2})D_f' z - \alpha_0\tau_0^2}{1 + (\alpha_0^2\tau_0^2 + \tau_0^{-2})D_f'' z}.$$

As follows from the above relations, each of the partial pulses spreads or is compressed during its propagation, depending on the relation between parameters τ_0, α_0, D_f', D_f'', and also acquires the additional phase modulation. The condition under which the time compression regime is realised in the fibre is written in the general form as $\partial\tau_{df}/\partial z < 0$, and in the case of complex dispersion parameters, is determined by the inequality

$$2\alpha_0\tau_0^2 D_f' + (\alpha_0^2\tau_0^4 - 1)D_f'' > 0. \qquad (12)$$

It follows from (12) that for $\alpha_0 = 0$, the pulse compression regime is possible when $D_f'' < 0$, and for $D_f'' = 0$ the classical situation takes place in which the condition $\alpha_0 D_f' > 0$ corresponds to the pulse compression. In this case, the pulse compression occurs due to the change in the shape of the initial spectrum, when the predominant increase in the intensity of the parts of the spectrum removed from its maximum is observed. Such a time compression is not the classical pulse compression because the compressed pulse in this case is frequency-modulated with $\alpha(z) \neq 0$. However, by using dispersion elements of different types placed directly behind the system, the pulse chirp can be eliminated, thereby obtaining the classical pulse compression and simultaneously $\alpha(z) = 0$ [22].

The dynamics of each of the partial pulses is determined to a great extent by the values of the real and imaginary parts of dispersion parameters, which can be considerably different for different pulses. In this case, the situation is possible when one of the pulses is compressed, while the other rapidly spreads.

The distance at which the duration of the corresponding partial pulse become minimal is determined by the expression

$$z_{mf} = \frac{L_{0f}}{1 + \alpha_0^2\tau_0^4}\left|\frac{|D_f' + \alpha_0\tau_0^2 D_f''|}{|D_f|} - 1\right|, \qquad (13)$$

where the characteristic length is $L_{0f} = \tau_0^2/|D_f''|$. In this case, the minimal pulse duration is determined by the relation

$$\tau_{mf} = \tau_0\left\{\frac{|D_f|}{|D_f' + \alpha_0\tau_0^2 D_f''|}\left[(1 - \chi_{1f} z_{mf})^2 + \chi_{2f}^2 z_{mf}^2\right]\right\}^{1/2}. \qquad (14)$$

When $D_f'' > 0$, the pulse achieves the minimum duration at the point τ_{mf} and $z = z_{mf}$ then begins to broaden, and its broadening is described by the expression $z \gg z_{mf}$ for $\tau_{df} \simeq |D_f|(z/D_f'')^{1/2}$. When $D_f'' < 0$, the pulse achieves the minimal duration and then rapidly broadens when z tends to the value $L_{0f}/(1 + \alpha_0^2\tau_0^4)$, by experiencing a strong frequency modulation.

4. Optically coupled fibres with identical gain increments

Consider the simplest and important situation of identical gain increments in adjacent waveguide channels, i.e. $\alpha_1 = \alpha_2 = \alpha$. In this case, $D_f'' = 0$, $K'' = 0$, $\Delta = \delta$, and the solution of system (3) can be written in the form

$$|A_j|^2 = |\gamma_j a_{10}|^2 \frac{\tau_0}{\tau_{d1}}\exp\left(-\frac{\tau_{s1}^2}{\tau_{d1}^2} + 2\alpha z\right) + \left|\frac{a_{20}}{\gamma_j^*}\right|^2 \frac{\tau_0}{\tau_{d2}}\exp\left(-\frac{\tau_{s2}^2}{\tau_{d2}^2} + 2\alpha z\right) - (-1)^j \mathrm{sign}(a_{10}a_{20}) \times 2|a_{10}a_{20}|\left(\frac{\tau_0^2}{\tau_{d1}\tau_{d2}}\right)^{1/2}\exp\left(-\frac{\tau_{s1}^2}{2\tau_{d1}^2} - \frac{\tau_{s2}^2}{2\tau_{d2}^2} + 2\alpha z\right) \times \cos(\varphi_1 - \varphi_2 + 2qz), \qquad (15)$$

where $\gamma_1 = 1$ and $\gamma_2 = \varkappa$. In the case of phase matching ($\delta = 0$) and symmetric or antisymmetric excitation of the fibre, the parameter $\varkappa = \pm 1$ and the degenerate single-partial regime takes place, in which $|A_1|^2 = |A_2|^2$, according to (15). Figure 1 shows the dependences of the square of the modulus $|a_f|^2$ of the envelope of partial pulses and the wave packet $|A|^2 = |A_1|^2 + |A_2|^2$ on the distance propagated by the pulse in the fibre obtained in the absence of the phase mismatch of the mode components of the wave packet ($\delta = 0$) for the antisymmetric ($\psi = -1$) and symmetric ($\psi = 1$) excitations of the fibre. The fibre parameters ($\sigma = 100$ m^{-1}, $d_1 = d_2 = 10^{-26}$ s^2 m^{-1}, $\alpha_1 = \alpha_2 = 10^{-3}$ m^{-1}) were chosen so that the effective GVD of the first nonzero partial pulse for $\psi = -1$ (see Fig. 1a) was zero: $D_1 = 0$. In this case, the dynamics of the partial pulse during its propagation remains invariable, and a single wave packet is formed by two modes with identical envelopes, i.e. $|A_1| = |A_2|$. The intensity of the wave packet increases during its propagation, while its duration does not change. In the case of symmetric excitation of the fibre ($\psi = 1$, see Fig. 1b), the second pulse is nonzero; in this case, $D_2 > 0$, which determines a strong spreading of the pulse and the wave packet as a whole.

For $\delta \neq 0$, the degeneracy is possible, when the wave packet is represented only by one partial pulse. This occurs when the condition

$$\psi = -\frac{\Delta}{2\sigma} - (-1)^f\frac{q}{\sigma} \qquad (16)$$

is fulfilled.

In the degenerate case, the dynamics of the whole wave packet is determined by the dispersion parameters of one pulse only. From the point of view of controlling the pulse behaviour, the degenerate situation is of most practical interest. Figure 2 presents the dependences of $|a_f|^2$ and $|A|^2$ on the coordinate z for three types of excitation of the fibre ($\psi = -1$, 0, 0.5) and $\delta = 10$; other parameters are as in Fig. 1. One can see that in the case of antisymmetric excitation of the fibre ($\psi = -1$), the single-partial regime is realised with $a_1 \neq 0$ and $|A_1| = |A_2|$. Because the effective GVD for these parameters in this case is very small ($D_1 = 3 \times 10^{-29}$ s^2 m^{-1}), the partial pulse in the wave packet as a whole are not virtually distorted during propagation and only shift to positive τ, which is caused by the presence of the phase mismatch δ. Upon single-mode excitation of the fibre ($\psi = 0$), the two-partial regime with $|a_{10}| = |a_{20}|$ is realised, and then the pulse a_2, for which

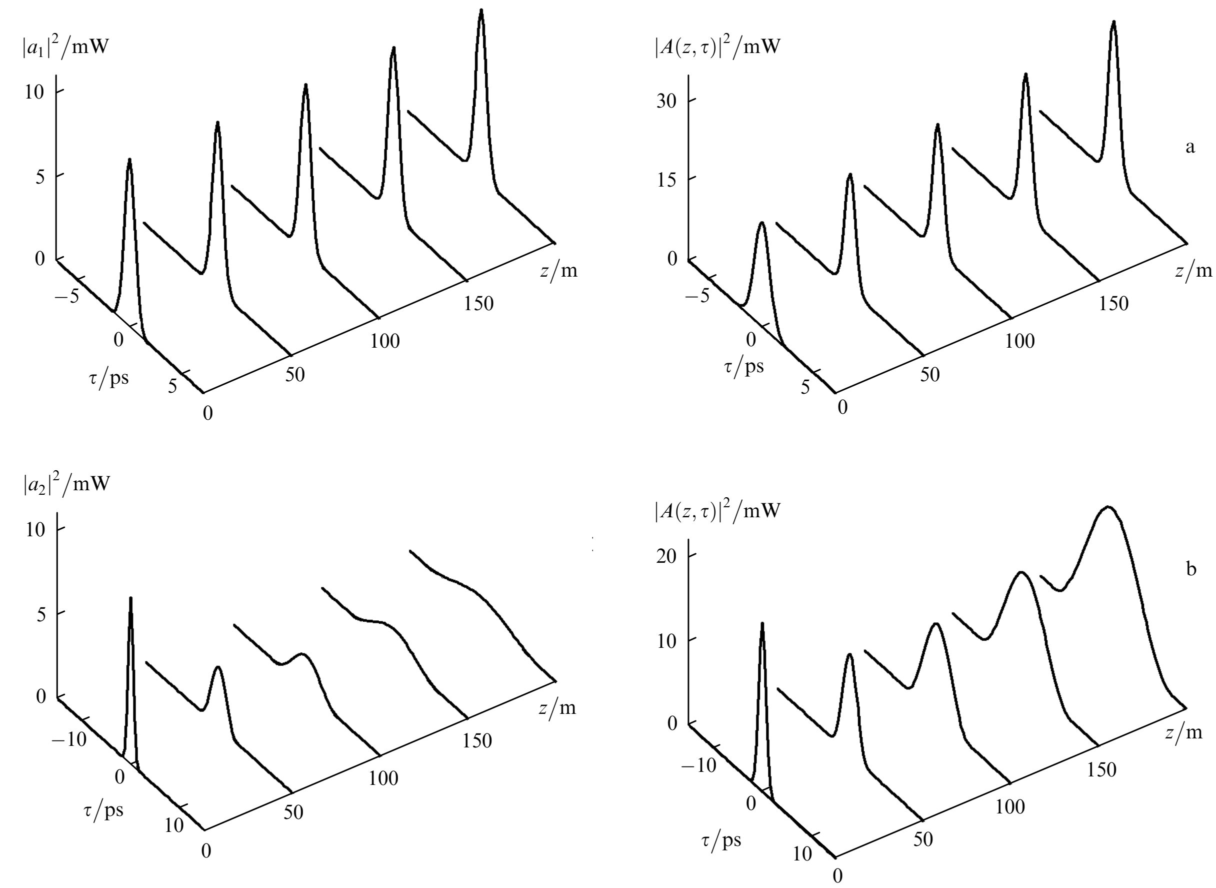

Figure 1. Dynamics of partial pulses $|a_{1,2}(z,\tau)|^2$ and a two-mode wave packet $|A(z,\tau)|^2$ in the case of phase matching ($\delta = 0$) and antisymmetric ($\psi = -1$) (a) and symmetric ($\psi = 1$) (b) excitation of a fibre.

$D_2 = 1.9 \times 10^{-26}$ s^2 m^{-1}, spreads rapidly, while the pulse a_1 broadens insignificantly because $D_1 \ll D_2$. In this case, the pulses move away from each other due to their phase mismatch. The total wave packet is also divided into two pulses moving away from each other; one of the pulses almost does not spread and is amplified, while the other strongly spreads. When the fibre is excited with $\psi = 0.5$, two partial pulses with different amplitudes appear, which move away from each other during propagation. The wave-packet dynamics in this case is similar to the pulse dynamics.

5. Superluminal coupled waves

Consider now the possibility of propagation of the wave-packet envelope maximum at the velocity exceeding the speed of light in vacuum. The general expression for the velocity of the envelope maximum of the corresponding partial pulse in a fibre with different gains in individual channels obtained from expression (10) for the amplitude ρ_f has the form

$$u_f = \frac{u}{1 - (-1)^f u(S_f K'' + K')}. \tag{17}$$

According to (17), the situation when $u_f > c$ is realised for one of the pulses if the inequality $(-1)^f u(S_f K'' + K') > 0$ is fulfilled. For simplicity, we will analyse the case when the dispersion parameters of the second and higher orders can be neglected. Such a situation is realised for pulses with $\tau_d \geqslant 10^{-9}$ s. In this case, we can assume with high accuracy that $S_1 = S_2 = \alpha_0\tau_0^2$. Let us also assume that $\delta \simeq 0$ (i.e. $K' = 0$) and $\alpha_1 \neq \alpha_2$. Then, expression (17) for the minimal pulse velocity will take the form

$$u_{\mathrm{m}f} = u\left\{1 + (-1)^f \frac{u_2 - u_1}{u_2 + u_1} \frac{(\alpha_2 - \alpha_1)\alpha_0\tau_0^2}{\left[4|\sigma|^2 - (\alpha_2 - \alpha_1)^2\right]^{1/2}}\right\}^{-1}, \tag{18}$$

which means that the superluminal propagation of one of the pulses is possible if $(-1)^f \alpha_0(u_2 - u_1)(\alpha_2 - \alpha_1) < 0$. As a rule, for $\alpha_j > \alpha_{3-j}$, the inequality $u_j < u_{3-j}$ takes place, and we can assume that $(u_2 - u_1)(\alpha_2 - \alpha_1) < 0$. Therefore, the condition of the superluminal regime in most cases is the inequality $(-1)^f \alpha_0 > 0$, i.e. this regime can be realised for the envelope maximum on the first partial pulse when $\alpha_0 < 0$ and for the second pulse when $\alpha_0 > 0$.

For the parameters of the fibre and wave packet $\alpha_1 \simeq 0$, $\alpha_2 \simeq 1$ m^{-1}, $|\sigma| \simeq 100$ m^{-1}, $u_1 \simeq 0.9c$, $u_2 \simeq 0.8c$, $\tau_0 \simeq 10^{-9}$ s, the superluminal regime for the first pulse is possible if $\alpha_0 < 0$ and lies in the interval 5.2×10^{20} s$^{-2} \leqslant |\alpha_0| \leqslant 3.4 \times 10^{21}$ s^{-2}. If $\alpha_0 > 0$, then under the same conditions the superluminal propagation regime can be realised for the second pulse. It is interesting that, when $|\alpha_0|\tau_0^2 \geqslant 3400$, the velocity of the envelope maximum for one of the pulses can become negative (for the first pulse if $\alpha_0 < 0$, and for the second pulse if $\alpha_0 > 0$). The superluminal velocity of the envelope maximum of a partial pulse in active media does not contradict to the conclusion of the theory of relativity about the limiting velocity of signal propagation

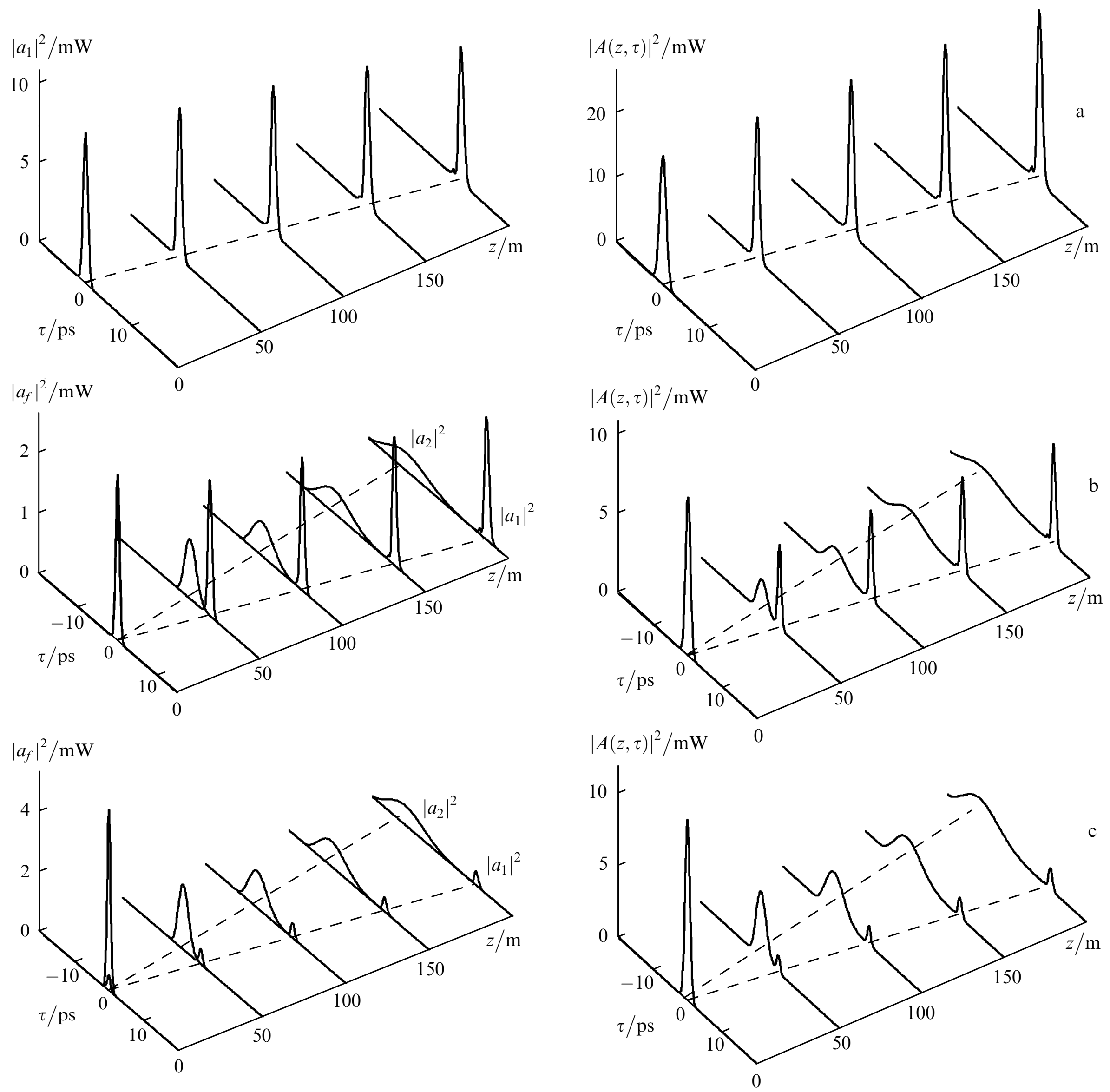

Figure 2. Dynamics of partial pulses and a wave packet in the case of detuning from phase matching ($\delta = 10$) and different excitation types $\psi = -1$ (a), 0 (b), and 0.5 (c).

because it is not related to energy transfer at this velocity but occurs due to the change in the wave-packet shape caused by a stronger amplification of its leading edge [12].

When condition (16) is fulfilled, only one pulse propagates in the system of coupled fibres under study; therefore, the situation can be realised in which only a superluminal pulse will propagate in one of the channels. The velocity of the envelope maximum of a partial pulse or of the whole mode (in the degenerate regime) can also become negative ($u_{\mathrm{m}f} < 0$). In this case, the wave-packet maximum is formed at the very beginning of the pulse and shifts oppositely to the propagation direction. Such a situation for an active medium was experimentally observed in [24].

It is interesting that for $\alpha_1 = \alpha_2$ and $\delta \neq 0$, according to (17), the velocities of the pulse envelope maxima are described by the expression

$$u_{\mathrm{m}f} = 2u_1u_2\left[u_1 + u_2 + (-1)^f \frac{\delta(u_2 - u_1)}{(4|\sigma|^2 + \delta^2)^{1/2}}\right]^{-1}. \qquad (19)$$

It follows from (19) that the velocity of any of the partial pulses in this case cannot exceed the speed of light in vacuum or be negative. In this case, velocities $u_{\mathrm{m}f}$ are no longer dependent of the initial frequency modulation and remain different for each of the pulses.

Our analysis has shown that a wave packet propagating in active fibres with the asymmetric gain in channels is decomposed into autonomous pulses with dispersion parameters dependent both on the parameters of each of the coupled fibres and on the conditions of radiation coupling in them. Therefore, by changing the excitation conditions of the fibre, we can efficiently control the dispersion parameters of the pulses and, hence, the dynamics (duration, the envelope maximum velocity, frequency modulation, etc.) of the wave packet as a whole.

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