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Deformation of the time-space structure of radiation in the absorbing-amplifying laser systems

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An analysis of deformation of the time and space distribution of radiation in the absorbing-amplifying systems, based on numerical solutions of equations for both intensity and eikonal of the light wave, as well as on the time and space compression function, has been performed, under the conditions of single-photon noncoherent interaction of the radiation with the matter. The characteristic properties of these deformations and the conditions of effective shaping of the distributions are determined. Some analogies, and as basic differences of the changes in time and space distributions, as well as the existence of a coupling between these distributions in the case of non-stationary interaction are indicated. It has been pointed out that under the condition, typical of a number of experiments, the nonlinear interaction of the radiation with the absorbing-amplifying matter may lead to essential non-uniformity of the time-space structure of the radiation.

1. Introduction

The development of both the theoretical and experimental investigations of the laser absorbing-amplifying systems dates back to the year 1966, when for the first time picosecond light pulse generation was achieved in a laser that, beside the amplifying medium, contains a nonlinear single-photon absorbent [1, 2]. The research works carried out by many authors on the systems of this kind were aimed first of all at both determination of mechanisms and finding the optimum conditions of ultra-short pulses in laser with nonlinear absorbent. The extended bibliography on this subject is, for instance, given in [3–6]. The examinations of generation in two-component absorbing-amplifying systems were made in parallel with the works on pulse amplification in these types of systems. These works, on the one hand, allowed to recognize more generally the mechanisms of ultrashort pulse formation and, on the other hand, showed other possibilities of applications of the systems with nonlinear absorbents. The papers [7–14], in which the changes in time and energy characteristics of pulses in amplifying systems of the type considered were analysed and examined, should be mentioned. A number of important regularities concering these changes have been determined, and some aspects of practical applicability of the systems discussed. In the course of last years the examinations referring to the two-component dye systems enabling, among others, the generation of subpicosecond pulses, have been developed particularly intensively, e.g. [15–17].

The absorbing-amplifying laser systems are at present exploited in many fields of physics and technology. The wide applicability of the radiation amplified or generated in the systems with nonlinear absorbents necessitates the detailed recognition of the processes accompanying the radiation propagation in these kinds of systems. The recognition of these processes provides information, sometimes inaccessible in directed measurements, about the time-space structure of radiation, which may determine to a high degree the course of the physical phenomena occurring during the interaction of radiation with a variety of objects, on the one hand, and creates the possibility of programming the parameters of radiation to be fitted to definite practical purposes, on the other. As already mentioned, the theoretical analyses concerning the problem of generation and amplification of the radiation in the absorbing-amplifying systems aimed first of all at determining the influence of the nonlinear absorption on the time characteristics of radiation. For this – among others – reason they were based on one-dimensional models ignoring the fact that there exist a transversal structure of radiation and a coupling between the time and space distribution of the field in nonlinear medium. In this paper, starting with nonlinear wave equation in paraxial approximation and with kinetic equations for both amplification factor and absorption coefficient, the changes in time and space distributions of radiation in absorbing-amplifying systems have been analysed under the conditions of single-photon noncoherent interaction of radiation with matter. Both the characteristic properties of this distribution and basic regularities concerning the mutual coupling between these distributions in the systems considered have been determined. The analysis was aided with results of numerical solutions of two-dimensional equations of propagation and with function of time and space compression.

2. Basic equations and relations

The change in time and space distributions of radiation in an isotropic and uniform absorbing-amplifying* system will be described by the equations for intensity I and eikonal Ψ, which in the system of axial symmetry have the forms [18]:

$$\frac{\partial I}{\partial z}+\frac{1}{v}\frac{\partial I}{\partial t}+\frac{\partial I}{\partial r}\frac{\partial \Psi}{\partial r}+I\Delta_{\perp}\Psi = K(I)I,$$

$$\frac{\partial \Psi}{\partial z}+\frac{1}{v}\frac{\partial \Psi}{t}+\frac{1}{2}\left(\frac{\partial \Psi}{\partial r}\right)^2 = \frac{\delta n'}{n_0}+\frac{1}{4k^2 I}\left[\Delta_{\perp}I-\frac{1}{2I}\left(\frac{\partial I}{\partial r}\right)^2\right], \tag{1}$$

where z, r – variables in the directions parallel and perpendicular to the

* I. e., in the system containing two kinds of independent active centra: absorbing centra and radiation amplifying centra (with population inversion).

radiation propagation direction, respectively, $\Delta_\perp = \frac{\partial}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}$, n_0, $\delta n'$ — real and, correspondingly, linear and nonlinear parts of refractive index in the medium, $v = c/n_0$ — light velocity in the medium, $k = 2\pi/\lambda$, λ — wavelength, $K(I)$ — amplification function of the system. The equations (1) may be easily obtained from the parabolic equation* for complex slow-varying amplitude of electric field E, by substituting

$$E(t, z, r) = A(t, z, r)e^{ik\varphi(t,z,r)}, \quad I = aA^2$$

where a — constant depending on the choice of units.

In the case of noncoherent, single-photon interaction of radiation $K(I)$ has the form

$$K(I) = \beta_1(I) - \beta_2(I) - \varrho, \tag{2}$$

where $\beta_1, \beta_2 > 0$ — coefficients of amplification and absorption, respectively, described by the kinetic equation [8, 18]:

$$\frac{\partial\beta_i}{\partial t} + \frac{\beta_i - \beta_i^e}{T_i} + s_i\sigma_i\beta_i I = 0, \quad i = 1, 2, \tag{3}$$

T_i — relaxation time for difference in level population, σ_i — active cross-section, β_i^e — amplification (absorption) coefficient of the system in equilibrium state, s_i — parameter depending on the working scheme of the active centra (in a two-level system $s_i\hbar\omega = 2$); ϱ — linear loss coefficient. The index $i - 1$ concerns the amplifying centra, while $i = 2$ — the absorbing ones.

Let us consider two practically most interesting limiting cases: the case $T_2 \ll \tau_p \ll T_1$ (τ_p — the FWHM of the time distribution of the radiation intensity at the distance r from the beam axis) in which, according to (2) and (3) and after introduction of the variable $\tau = t - \frac{z}{v}$

$$K = a\exp\left[-\frac{1}{\varepsilon_1^s}\int_{-\infty}^{\tau} I(\tau', r)d\tau'\right] - \frac{\varkappa}{1 + \frac{I}{I_2^s}} - \varrho, \tag{4}$$

where $a = \beta_1^e = \beta_1(t = -\infty)$ — amplification factor for weak signals, $\varkappa = \beta_2^e = \beta_2(t = -\infty)$ — absorption coefficient for weak signals, $\varepsilon_1^s = 1/s_1\sigma_1$ — saturation energy density, $I_2^s = (s_2\sigma_2T_2)^{-1}$ — absorption saturation intensity; and the case $\tau_p \ll T_1, T_2$, in which

$$K = a\exp\left[-\frac{1}{\varepsilon_1^s}\int_{-\infty}^{\tau} I(\tau', r)d\tau'\right] - \varkappa\exp\left[-\frac{1}{\varepsilon_2^s}\int_{-\infty}^{\tau} I(\tau', r)d\tau'\right] - \varrho, \tag{5}$$

where $\varepsilon_2^s = \frac{1}{s_2\sigma_2}$.

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* For the conditions of applicability of parabolic equation for E and by the same means the equations (1), see, for instance, [18, 19].

The characteristic properties of changes in the time and space distributions of radiation occurring in the system considered due to nonlinear resonance interaction, dominating at $\delta n' = 0$ and small beam divergence, will be defined by taking advantage of numerical solutions of equations (1) as well as both the time compression function [18, 20]: $T \equiv -1/\tau_p \cdot d\tau_p/dz$ and the space compression function [18, 20]: $S \equiv -1/r_p \cdot dr_p/dz$ (r_p – half-width of the space distribution of radiation intensity at the moment τ). These functions determine the relative rate of changes in the respective widths of time and space radiation intensity distributions in the medium. In accordance with [18, 20], for $\Psi \approx$ const we have

$$T = \frac{\delta_1}{2}\left[K(I_h, \tau_h) - K\left(\frac{1}{2} I_h, \tau_1\right)\right] + \frac{\delta_2}{2}\left[K(I_h, \tau_h) - K\left(\frac{1}{2} I_h, \tau_2\right)\right], \tag{6}$$

where $I_h = I(\tau_h, r)$ – intensity at the maximum of the time distribution, τ_h, τ_1, τ_2 – points corresponding to the maximum of time distribution and to the half-heights of its face and back fronts, respectively, $\delta_1, \delta_2 > 0$ – inclination coefficients for slopes of the time distribution determined by the dependence

$$\left.\frac{\partial I}{\partial \tau}\right|_{\tau_{1(2)}} = \mathop{}^{+}_{(-)} \frac{1}{\delta_{1(2)}} \frac{I_k}{\tau_p},$$

and

$$S = \frac{\gamma}{2}\left[K(I_m) - K\left(\frac{1}{2} I_m\right)\right], \tag{7}$$

where $I_m = I(\tau, r = 0)$ – intensity at the maximum of spatial distribution, $\gamma > 0$ – inclination coefficient of spatial distribution slopes defined by the formula

$$\left.\frac{\partial I}{\partial r}\right|_{r_p} = \frac{-1}{\gamma} \frac{I_m}{r_p}.$$

3. Deformation of the time distribution of radiation

In the case $T_2 \ll \tau_p \ll T_1$, in accordance with (4) and (6), the time compression function for the case considered may be written in the form

$$\begin{aligned} T = &\frac{1}{2} a\delta_1 \{\exp[-bR_h(r)] - \exp[-b_1 R_h(r)]\} \\ &+ \frac{1}{2} a\delta_2\{\exp[-bR_h(r)] - \exp[-b_2 R_h(r)]\} \\ &+ \frac{\delta_1 + \delta_2}{2} \varkappa \frac{R_h(r)}{[1 + R_h(r)][2 + R_h(r)]}, \end{aligned} \tag{8}$$

where $R_h = I_h/I_2^s$, $\quad b = \frac{I_2^s}{\varepsilon_1^s}\int\limits_{-\infty}^{\tau_h} f(r,\tau)\,d\tau$, $\quad b_1 = \frac{I_2^s}{\varepsilon_1^s}\int\limits_{-\infty}^{\tau_1} f(r,\tau)\,d\tau$,

$$b_2 = \frac{I_2^s}{\varepsilon_1^s}\int\limits_{-\infty}^{\tau_2} f(r,\tau)\,d\tau,\quad f(r,\tau) = \frac{I(r,\tau)}{I_h}.$$

In the expression (8) the first two components of the sum describe the changes in time distribution of radiation (the lengths of the face and back pulse fronts) evoked by the nonlinear amplification, while the third component represents the nonlinear absorption. It may be seen that both the rate and the direction of the changes in the pulse length caused by nonlinear amplification depends on the pulse shape, and that not only the shape of the factor is essential, as was pointed out in earlier works, for instance, in [8], but also the pulse symmetry. In the case when the face front is much sharper than the back one ($\delta_1 \ll \delta_2$) the nonlinear amplification will lead to the pulse compression. In the opposite case we will have to do with its elongation. The compression rate in the amplifying medium is the greater the more asymmetric the pulse, i.e. the smaller the ratio δ_1/δ_2. In the limiting case $\delta_1 = 0$, for $\varkappa = 0$,. the following expression may be obtained from (8):

$$T = \frac{1}{2}\,a\delta_2[1-\exp(-b_2R_h)], \tag{9}$$

from which it follows that the compression rate for asymmetric pulse with sharp face front increases with the increase of its energy density. If this density exceeds several times ε_1^s the second component of the sum in (9) is considerably less than 1 and practically $T \approx \frac{1}{2}\,a\delta_2$. This is the maximal rate of compression in an amplifying medium. Taking advantage of the formula obtained and the definition of the function T the following approximate expression may be obtained for the pulse length after its passing the distance l in the amplifying medium

$$\tau_p \approx \tau_p^0 \exp\left(-\frac{1}{2}\,a\delta l\right), \tag{10}$$

where δ — average inclination coefficient of the pulse slope. Since usually $\delta \sim 1$, the compression of the pulse in the amplifying medium at its optimal (highly asymmetric) shape may be considerable.

Nonlinear quasi-stationary absorption, as it follows from (8), leads to compression of pulse of arbitrary time shape. The latter influences only the compression rate which is the higher the milder are slopes of the pulse, being weakly dependent on pulse symmetry ($\delta_1 + \delta_2 \approx$ const at the change in pulse symmetry). The changes in the pulse length evoked by absorption occur most quickly at the top intensity $R_{hm} = \sqrt{2}$, while the maximum compression rate amounts to $T = (\delta_1+\delta_2)\varkappa/2(1+\sqrt{2})^2$, being three times less than the maximal rate of compression in the amplifier with a equal to $\varkappa$.

Some of the regularities discussed above and concerning the change of the pulse length in the two-component system are illustrated in fig. 1. The curve

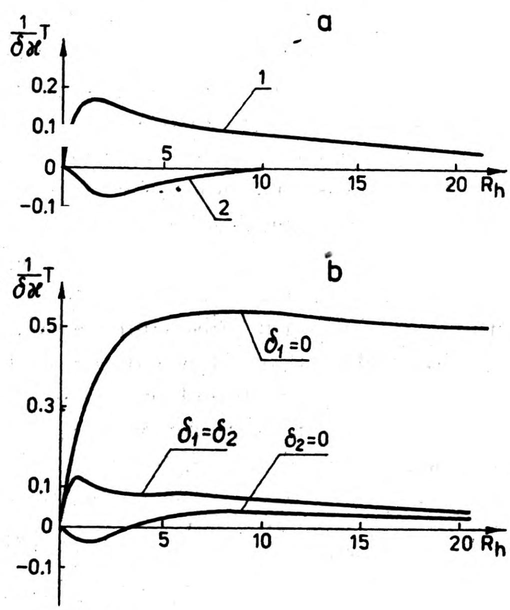

Fig. 1.a. The time compression function for an absorbing (1) and amplifying (2) medium. b. Time compression function for the absorbing-amplifying system in the case of quasi-stationary interaction with the absorbent. $b = 2$, $b_1 = 2$, $b_2 = 1$

1 in fig. 1a presents the dependence of the time compression function upon the top pulse intensity for single-photon absorbent, while the curve 2 shows an analogical dependence for the amplifier in the case of pulse with exponential slopes for $b = 1$. Fig. 1b illustrates the influence of symmetry of the pulse on the rate of its length change in a two-component system with $a = \varkappa$. The symmetric pulse with exponential back fronts ($\delta_1 = \delta_2$), the asymmetric pulse with a jumping face front and exponential back front ($\delta_1 = 0$) and asymmetric pulse with exponential face and jumping back fronts ($\delta_2 = 0$) are illustrated in the graphs. It may be seen that the change in the pulse symmetry leads not only to quantitative but also to qualitative changes in the time evolution of the radiation distribution in the system. For $\delta_1 = 0$ or $\delta_1 = \delta_2$ the compression of the pulse occurs for arbitrary values R_h while for $\delta_2 = 0$, a pulse elongation occurs in the region of small intensities and the pulse compression in the region of great intensities.

Characteristic properties of pulse shape changes in the absorbing-amplifying system under the conditions of quasi-stationary interaction with the absorbent are illustrated in fig. 2. The figure 2a presents the dependence of the amplifying function upon the local time τ for $a < \varkappa+\varrho$, while the fig. 2b shows the direction of changes in radiation intensity at different moments τ. It may be easily pointed out [13], that in a system with threshold amplification the pulse compression may occur independently of its shape at the system input, provided that propagation path is sufficiently long. If $\alpha > \varkappa + \varrho$ this shape is the more essential the greater the ratio $\alpha/\varkappa$.

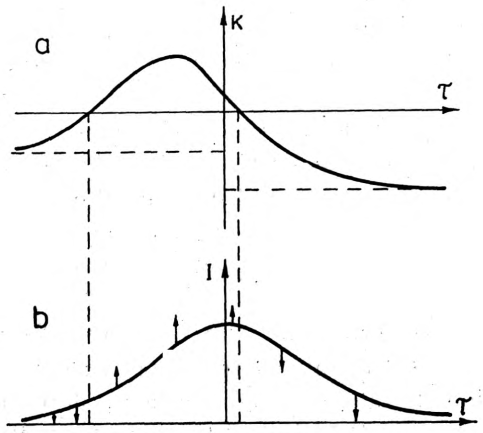

Fig. 2. a. The dependence of the amplifying function for the absorbing-amplifying system upon the local time at quasi-stationary interaction with the absorbent and $\varkappa > \alpha - \varrho$. b. The direction of changes in radiation intensity

As it follows from eq. (8) the time compression function, in general, depends on r. This means that for spatial radiation distribution, different from rectangular, the rate of changes of the intensity distribution at different points r of the beam cross-section is different. In figure-3 the dependence $T(r)$ is shown

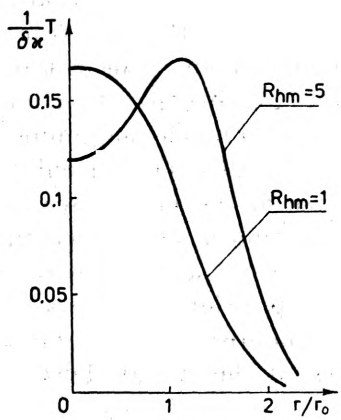

Fig. 3. Relative rate of width changes in the time distribution of radiation intensity in an absorbent as a function of the distance from the beam axis

for single-photon absorbent in the case of Gaussian distribution of $R(r)$ and two top intensity values on the beam axis $R_{hm} = 1$ and $R_{hm} = 5$. The dependence $T(r)$ for these two values has a qualitatively different course. For the value R_{hm} less than optimal (equal to $\sqrt{2}$) the maximal rate of time distribution compression occurs on the beam axis. For $R_{hm} > \sqrt{2}$ the dependence $T(r)$ is non-monotonic and the compression rate maximum appears on the slope of the space distribution of radiation. The minimum of the function $T(r)$ on the beam axis deepens with the increase of R_{hm}, its maximum value being independent of R_{hm}. The existence of the dependence $T(r)$ leads to some time-space heterogeneity in the radiation structure, i.e. the intensity distribution at the output of the system may be unrepresentable in the form: $I(r, \tau) = af(\tau)g(r)$. It results also in appearence of the dependence of time changes on the radiation power distribution (intensity integrated with respect to beam cross-section) upon its spatial distribution.

Now, let us consider the case $\tau_p \ll T_1, T_2$. The analysis of the changes in the time distribution of radiation in this case may be carried out analogously to what was done above by using the time compression function. We shall restrict our consideration to an indication of only some features of the distribution deformation under the conditions of nonstationary interaction of radiation with the two-component medium.

The function T for absorbent may be obtained from expression (8) by omitting in the sum its last term and a respective substitution of parameters (a for $\varkappa$, R_h for I_h, and so on). From this expression it follows, among others, that in the case of a pulse with face front much sharper than its back front ($\delta_1 \ll \delta_2$) the nonstationary single-photon absorption leads to pulse elongation The maximum rate of elongation occurring at $\delta_1 = 0$ for $\varepsilon \gg \varepsilon_2^s$, is equal to $\frac{1}{2}\ \delta_2 \varkappa$. For $\delta_1 \gg \delta_2$ the nonstationary absorption leads always to the pulse compression, whereby for $\varepsilon \to 0$ and $\varepsilon \to \infty$ the compression rate tends to 0.

For nonstationary radiation-absorbent interaction the change in the pulse length is a resultant of two opposite processes: shortening of the face front and back elongation of the front of the pulse. Applying of an absorbent of long (with respect to τ_p) relaxation time is usually less effective than that for absorbent of short relaxation time. In practice, it is not this much the diminishing of the total pulse length, which is often desirable, but rather the shortening of its face front (for instance, to achieve a quicker rise of the pulse laser in the amplifiers). In this case an absorbent of long relaxation time is more effective, since it allows to obtain the required shortening of the front at considerable less losses of power than in the case of $\tau_p \gg T_2$. The expression (8) allows to determine the optimal conditions for the face front compression. It implies that the rate of shortening of the front is the greatest if the energy density of this front $\varepsilon_h = \int_{-\infty}^{\tau_h} I(\tau)d\tau$, satisfies the condition

$$\varepsilon_h = \frac{\ln \dfrac{b}{b_1}}{1-\dfrac{b_1}{b}}\ \varepsilon_2^s.$$

During the propagation the pulse shape suffers from alternations and by the same means the ratio b/b_1 is also changed. Since the optimal value of ε_h is a low-varying function of this ratio, it may be pointed out that for a broad class of the face front shapes it lies within interval:

$$\varepsilon_2^s < \varepsilon_h^{op} < 2\varepsilon_2^s,$$

whereby for mild fronts it is positioned close to the lower limit of this interval, while for the sharp fronts – to the upper limit (for instance, for the exponential front $\varepsilon_h^{op} = 2\varepsilon_2^s \ln 2$). The condition given above determines with the sufficient accuracy the energy density of the face front at which the shortening rate of this front is the highest.

The ratios $a/(\varkappa+\varrho)$ and $\varepsilon_1^s/\varepsilon_2^s$ decide predominantly about the properties of this system in the case of nonstationary interaction. For the given values of these ratios the character of changes in the time distribution of radiation is determined by its shape and the energy density. The character of the influence of the energy density on the evolution of time distribution of the intensity I and power P of radiation in the system is illustrated by the graphs in fig. 4,

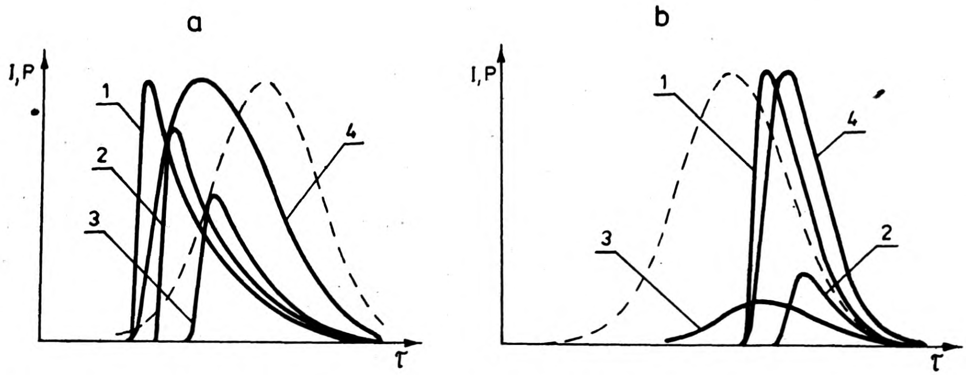

Fig. 4. Time distribution of intensities (1, 2, 3) and power (4) of radiation at the output of an absorbing-amplifying system in the case of the nonstationary interaction with the absorbent.

$a = 0.12\ \mathrm{cm}^{-1}$, $\varkappa = 0.2\ \mathrm{cm}^{-1}$, $\varrho = 0.02\ \mathrm{cm}^{-1}$, $r_0 = 0.5$ cm, $z_0 = 10^3$ cm, $\varepsilon_1^s/\varepsilon_2^s = 4\cdot 10^3$. a. $\varepsilon_2^s \ll \varepsilon_m^0 < \varepsilon_1^s$, $1 - r = 0$, $2 - r = \frac{6}{5} r_0$, $3 - r = \frac{9}{5} r_0$. b. $\varepsilon_2^s < \varepsilon_m^0 \ll \varepsilon_1^s$, $1 - r = 0$, $2 - r = \frac{3}{5} r_0$, $3 - r = \frac{6}{5} r_0$

obtained from numerical solutions of equations (1) for $\delta n' = 0$, $R(r, \tau, z = z_0) = R_{hm}^0 \exp(-\tau^2/\tau_0^2 - r^2/r_0^2)$, $\Psi(r, \tau, z = z_0) = r^2/2z_0$. Fig. 4a concerns the case $\varepsilon_2^s \ll \varepsilon_m^0 < \varepsilon_1^s$, and fig. 4b the case $\varepsilon_2^s < \varepsilon_m^0 \ll \varepsilon_1^s$. The curves 1, 2, 3 present the intensity distribution at the output of the two-component medium of the length $l = 80$ cm, while the curves 4 show the output distribution of the radiation power. The broken line gives the input distribution. The distributions 1, 4 and the input distribution are normed to the same value. It may be seen that in the case when radiation energy density is comparable with the energy density of the amplification saturation and it is much greater than the energy density of the absorbtion saturation, the maximum of the time distribution is shifted in the direction of diminishing values τ (maximum of distribution propagates in the medium with the superlight velocity), the shift being the greatest on the beam axis. This results from the dominating influence of the amplification saturation on the radiation propagation. In the case shown in Fig. 4b we observe an opposite situation – the maxima of distribution are shifted to the back front of the input distribution (and propagate with the sublight velocity), while the greatest shift occurs on the slope of the space distribution of radiation. In this case the absorption saturation effects decide about the character of the radiation evolution. In both the cases shown in Figs. 4a and 4b the nonlinear interaction of radiation with the medium leads to some splitting of the initially uniform time-space structure of radiation. Nonuniformity of this structure will be the less the closer is the input space distribution of radiation to rectangular form. The input space distribution of radiation influences essentially also the time distribution of the radiation power at the system output. In the case of quasi-rectangular distribution $R^0(r)$ the output power distribution will be close to the intensity distribution on the beam axis (curves 1 in fig. 4) and thus may differ considerably from the power distribution for Gaussian distribution of $R^0(r)$.

4. Deformations of space distribution of radiation

The analysis of the space distribution of radiation due to resonance interaction with the two-component medium will begin — as previously — with considering the case $T_2 \ll \tau_p \ll T_1$. In accordance with (4) and (7) the space compression function in this case has the form*

$$S = \frac{\gamma}{2}\, a\left\{\exp\left[-\eta_1 \int\limits_{-\infty}^{\tau} R_m(\tau')\,d\tau'\right] - \exp\left[-\frac{1}{2}\eta_1 \int\limits_{-\infty}^{\tau} R_m(\tau')\,d\tau'\right]\right\}$$
$$+\frac{\gamma}{2}\varkappa \frac{R_m(\tau)}{[1+R_m(\tau)][2+R_m(\tau)]}, \tag{11}$$

where $R_m(\tau) = I_m(\tau)/I_2^s$ — relative intensity on the beam axis at the moment τ, $\eta_1 = I_2^s/\varepsilon_1^s$. The first term of the sum (11) describes the changes in the space distribution of radiation occurring at the moment τ due to the interaction with the absorbing centra. Nonlinear amplification leads, as may be seen, to a broadening of spatial distribution, while the nonlinear absorption – to its compression.

In the case of quasi-stationary interaction the function of space compression for the absorbent has the form analogous to the time compression function (comp. (8)). Hence, all the conclusions obtained in the Section 3 and concerning the changes in the time distribution of radiation for the case $a = 0$ or $\varepsilon \ll \varepsilon_1^s$ are valid also for the changes in spatial distribution.

* For the sake of simplicity it has been assumed that $f(\tau, r = 0) \approx f(\tau, r = r_p)$.

There is no symmetry in the changes in both time and space distribution of radiation in the amplifying medium due to nonstationarity of interaction. The rate of changes in the space distribution of intensity at the moment τ depends upon the energy density of radiation which passed through the given point in the medium till the moment τ. By virtue of (11) it may be shown that the rate of the instantaneous intensity broadening is the greatest when

$$\varepsilon_m(\tau) = 2\varepsilon_1^s \ln 2, \tag{12}$$

where $\varepsilon_m(\tau) = \int\limits_{-\infty}^{\tau} I_m(\tau')\,d\tau'$. For $\varepsilon_m \dashrightarrow 0$ and $\varepsilon_m \dashrightarrow \infty$ the rate of broadening tends to zero. From (12) it follows in particular that the broadening of space distribution intensity in the time maximum of the pulse occurs most quickly when the top intensity on the beam axis I_{hm} fulfils the condition

$$I_{hm} = \frac{2\varepsilon_1^s}{\tau_f} \ln 2, \tag{13}$$

where $\tau_f = \int\limits_{-\infty}^{\tau_h} f(\tau)\,d\tau$ — effective length of the face front of the pulse. From the above it follows that at the fixed value of I_{hm} the changes in the space distribution of intensity at the moment τ depend on the time shape of the pulse.

In the two-component system the changes in space distribution of radiation result from two opposite processes, i.e. compression due to nonlinear absorption, and broadening due to nonlinear amplification. This leads to a complex dependence of the kind of the distribution deformation upon the parameters of both the system and pulse. The expression (11) allows to reveal the features of these deformation and to determine the basic regularities concerning the influence of both system and pulse parameters on the character of the changes occurr'ng. The figure 5 presents the dependence of the space compression

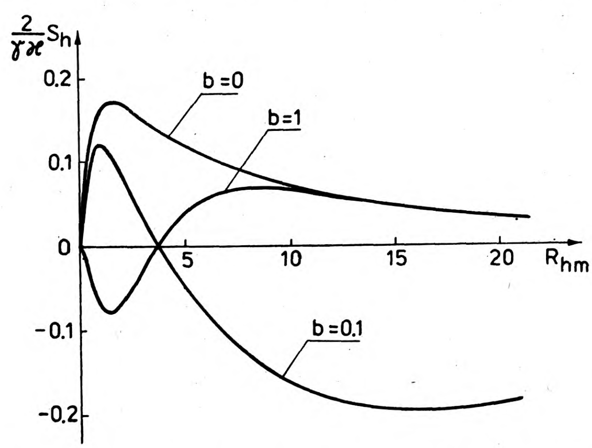

Fig. 5. Relative rate of changes in the width of the space distribution of radiation intensity at the time maximum of the pulse in the case of quasi-stationary interaction with the absorbent in two-component system

function at the time maximum of the pulse S_h upon the top intensity on the beam axis for different values of the parameters $b = \eta_1 \tau_f$ and $a = \varkappa$. For $b = 0$, which corresponds to the lack of amplification saturation, or $a = 0$, the space distribution of intensity in the time maximum of the pulse suffers from compression for arbitrary R_{hm}, and the maximum rate of compression occurs at $R_{hm} = \sqrt{2}$. The increase of the parameter b, thus, for instance, the increase of the face front of the pulse, leads to the occurrence of a decompression region in the range of great values of R_{hm}. After a definite value of b is exceeded, the situation changes essentially; the compression of the distribution occurs in the range of great values of R_{hm}, while its broadening at small values of R_{hm}.

The dependence of the function S upon time for a pulse of Gaussian time distribution: $f(\tau) = \exp(-\tau^2/\tau_0^2)$ (describing the rate of changes in the width of space distribution at different points τ of the pulse) is shown in fig. 6. For $R_{hm} = \text{const}$, and $b = 0$ the function $S(\tau)$ is symmetric and positive, while the maximum rate of distribution compression occurs at the time maximum of the pulse*. The decompression region resulting from the increase of the parameter b appears first on the back front of the pulse and next also on its face front. For sufficiently great values of b (in the region of strong saturation of amplification) the broadening of the distribution occurs only in a part of the face front pulse, while in the surrounding of its maximum and on the back front the compression takes place. The influence of intensity R_{hm} on the dependence $S(\tau)$ for $b = \text{const}$ is illustrated in fig. 6b. It may be seen that the

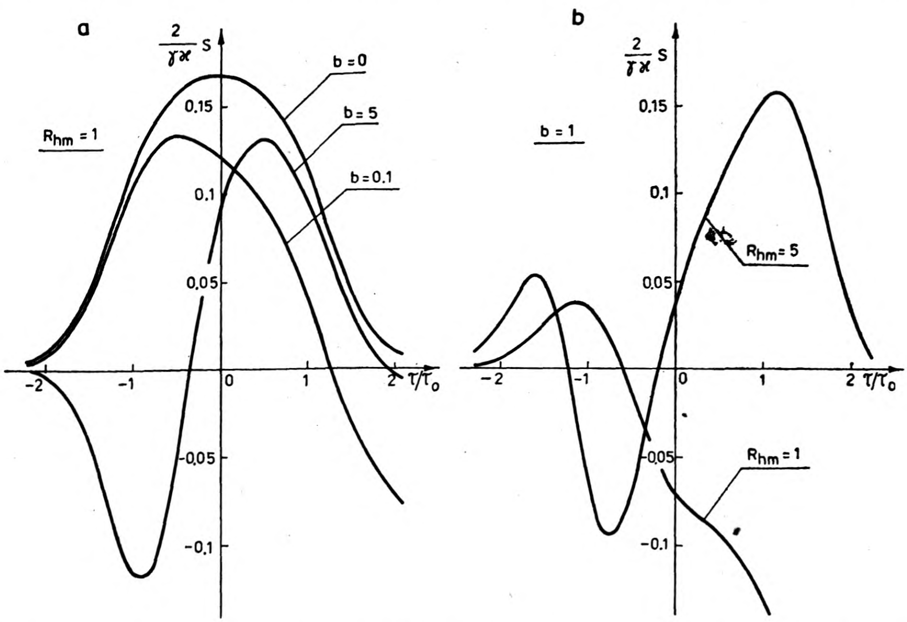

Fig. 6. Relative rate of change in the width of the space distribution of radiation intensity at different moments τ in the case of quasi-stationary interaction with the absorbent in the two-component system

* For $R_{hm} \leqslant \sqrt{2}$. If $R_{hm} > \sqrt{2}$ the maximum rate of compression appears symmetrically on the face and bock fronts of the pulse.

change of R_{hm} may lead to substantial changes in the character of the spatial distribution deformation occurring in the system.

The influence of the third of parameters deciding about the character of the space distribution changes, namely of the ratio $\varkappa/a$ is quite obvious. The increase of this ratio leads to an increase of the compression region both on the axis R_{hm} and τ, while its diminishing results in an increase of the decompression region.

The numerical solutions of equations (1), with $\delta n' = 0$ and the function K given by the formula (4), illustrating the change in the width of space intensity distribution in the time maximum of the pulse r_h and the spatial distribution of the energy density r_ε for two values of parameter $b' = \eta_1 \tau_0$, are shown in fig. 7. The input distributions are accepted to be the same as those

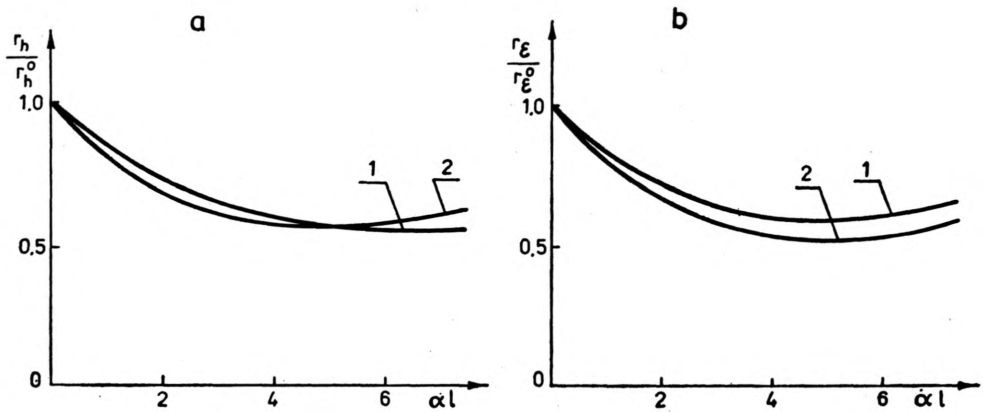

Fig. 7. Evolution of the space intensity distribution width (a) and the energy density (b) of radiation in the absorbing-amplifying system in the case of quasi-stationary interaction with the absorbent.
$a = 0.12$ cm^{-1}, $\varkappa = 0.2$ cm^{-1}, $\varrho = 0.02$ cm^{-1}, $r_0 = 0.5$ cm, $z_0 = 10^3$ cm. $1 - b = 0.1$, $2 - b = 0.001$

in fig. 4. The curve 1 concerns the case $b = 0.1$, and the curves 2 correspond to $b = 0.001$. At the initial stage of amplification, when the pulse energy is still relatively small, the absorption saturation effect, leading to the compression distribution, decides about the changes in the space distribution. After the pulse achieves a sufficiently high power and energy, the effect of amplification saturation begins to dominate causing the broadening of the distribution. This is manifested in a nonmonotonic character of the respective curves. The shapes of intensity distributions and radiation energy density at the output of a two-component medium ($l = 80$ cm), as compared to the input distribution (broken line), are shown in fig. 8. The curves 1, 2, 3 illustrate the intensity distributions on the face pulse front, in the maximum surrounding and in the back pulse front, respectively, while the curve 4 represents the energy density $\varepsilon(r) = \int_{-\infty}^{\infty} I(\tau, r) d\tau$. In the case $b = 0.1$ (fig. 8a), the distribution width is the least on the face front and the greatest in the back front of the pulse. A distribution minimum appearing simultaneously on the back front results from differences in the rate of shifting the time maximum of radia-

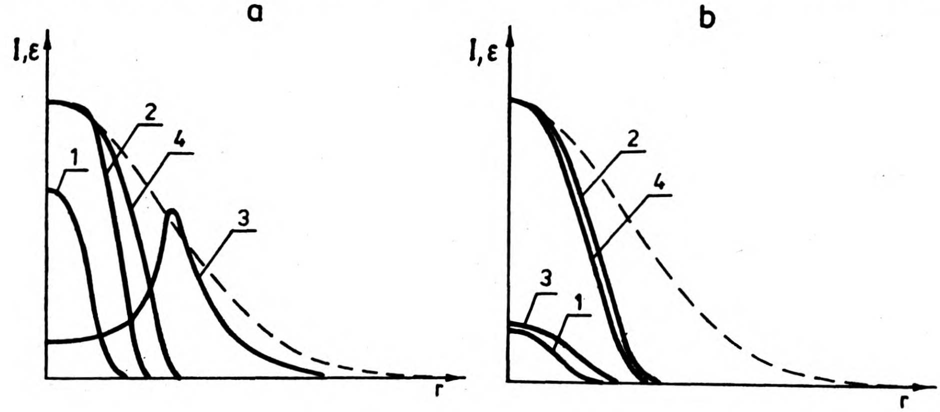

Fig. 8. The space distribution of intensity (1, 2, 3) and energy density (4) of the radiation at the output of the absorbing-amplifying system in the case of quasi-stationary interaction with the absorbent.

1 — on the face front, 2 — at the time maximum of the pulse, 3 — on the back front. $a - b = 0.1$, $b - b = 0.001$. Parameters as indicated in fig. 7

tion at different points r. In the case of $b = 0.001$, in which the nonlinear absorption decides about the changes in distribution, the compression of space distribution on the face and back fronts of the pulse is greater than at the surrounding of its time maximum.

The function of space compression for an absorbent in the case of nonstationary interaction ($\tau_p \ll T_1, T_2$) has the form analogous to that in the amplifying medium; therefore in the formula for S only the quantities a and ε_1^s should be replaced by $\varkappa$ and ε_s^2, respectively. Hence, it follows, among others, that the nonstationary absorption leads to space distribution compression of radiation intensity and that the rate of compression is maximal at $\varepsilon_m(\tau) = 2\varepsilon_2^s \ln 2$. In the two-component system the character of changes in space structure of radiation depends on the values of the ratios $\varkappa/a$ and $\varepsilon_2^s/\varepsilon_1^s$. The influence of the last magnitude is illustrated in fig. 9, which represents the dependence of

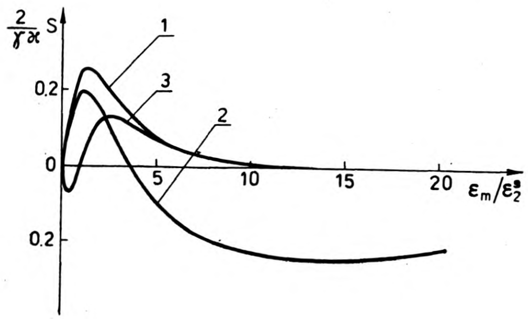

Fig. 9. Function of space compression for an absorbing-amplifying system in the case of nonstationary interaction with the absorbent.

1 – $\varepsilon_2^s = 10^{-3}\,\varepsilon_1^s$. 2 – $\varepsilon_2^s = 0.1\varepsilon_1^s$. 3 – $\varepsilon_2^s = 2\varepsilon_1^s$

the function S upon the normed radiation energy density on the beam axis at the moment τ. The graphs in this figure may be interpreted in two ways: as dependence of the function S at the moment $\tau = \tau'$ upon the energy density of radiation on the beam axis, which to the moment τ' passed the given point of the medium, or as the qualitative dependence of the function S upon the time τ, since the increase of ε_m may be treated as being equivalent to the increase of τ. If $\varepsilon_2^s \ll \varepsilon_1^s$ (curve 1) the space distribution of intensity is comprimed in arbitrary moments for the pulse energy density $\varepsilon_m(\tau = \infty)$ comparable to ε_2^s. An increase in the ratio $\varepsilon_2^s/\varepsilon_1^s$ leads to the appearence of the decompression region on the energy density axis in the range of the values ε_m comparable with ε_2^s, which may result in broadening of the intensity distribution on the back front of the pulse of sufficiently high energy. For $\varepsilon_2^s > \varepsilon_1^s$ (curve 3) the compression occurs for great values of ε_m (and thus on the back front of the pulse), while the decompression takes place for small values of ε_m (and thus on the face front of the pulse). The change of the ratio $\varepsilon_2^s/\varepsilon_1^s$ may thus lead to strong changes in the character of space distribution in the medium.

The influence of the energy density on the space distribution of radiation at the output of the two-component medium ($l = 80$ cm) is illustrated in fig. 10

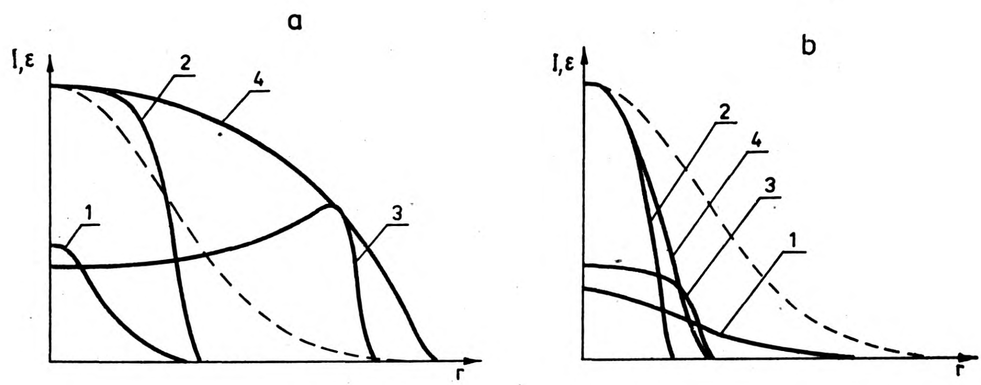

Fig. 10. Space distribution of intensity (1, 2, 3) and energy density (4) of radiation at the output of an absorbing-amplifying system in the case of nonstationary interaction with the absorbent.

1 – on the face front, 2 – at the point of time maximum, 2 – on the back front. a. $\varepsilon_2^s \ll \varepsilon_m^0 < \varepsilon_1^s$, b. $\varepsilon_2^s < \varepsilon_m^0 \ll \varepsilon_1^s$
Parameters as indicated in fig. 4

for nonstationary case. The curve notations are the same as in fig. 8 and the input parameters of radiation are the same as those in fig. 4 Fig. 10a concerns the case $\varepsilon_2^s < \varepsilon_m^0 \ll \varepsilon_1^s$. In the first case the direction of changes in the intensity distribution on the face and back fronts of the pulse is different – on the face front the compression and on the back front the decompression of the distribution are observed. The energy density distribution suffers from considerable broadening. In the second case the compression of the intensity distribution occurs at arbitrary moments τ and the width of the energy density distribution is less than that at the input. The evolution of the width of the $I_h(r)$ and $\varepsilon(r)$ distributions in both the cases mentioned, as well as in the case when $\varepsilon_m^0 < \varepsilon_2^s$, is illustrated in fig. 11. The graphs presented confirm some conclusions drawn from the analysis of the function of space compression.

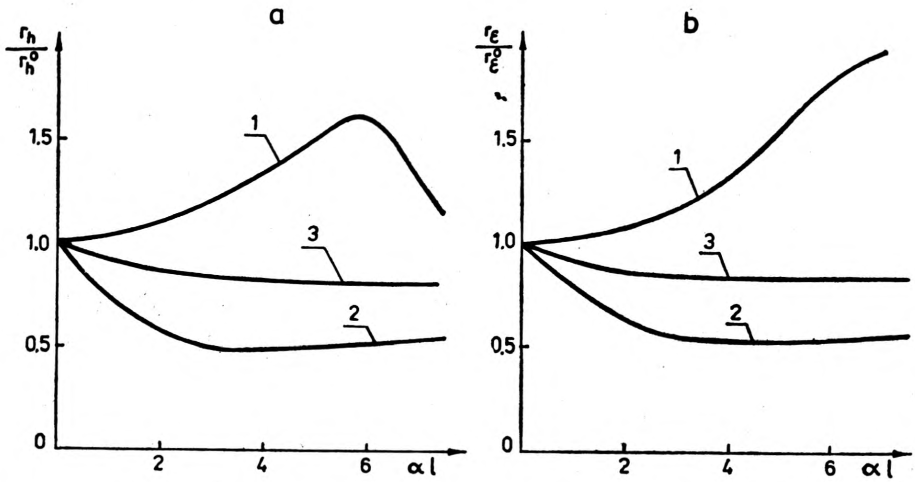

Fig. 11. Evolution of space intensity distribution width (a) and energy density (b) of radiation in an absorbing-amplifying system in the case of nonstationary interaction with the absorbent. $1 - \varepsilon_2^s \ll \varepsilon_m^0 < \varepsilon_1^s$, $2 - \varepsilon_2^s < \varepsilon_m^0 \ll \varepsilon_1^s$, $3 - \varepsilon_m^0 < \varepsilon_s^2$. Parameters as indicated in fig. 4

5. Recapitulation

In this work an analysis of the deformation of the time and space radiation distributions in the absorbing-amplifying laser system, made under the conditions of single-photon, noncoherent interaction of the radiation with the medium has been presented. The properties of these deformations have been determined and the conditions under which these deformations are the greatest – defined. The analysis carried out has indicated the appearence of both some analogies and essential differences of the changes in time and space distributions, as well as the existence of correlation between those distributions in the case of nonstationary interaction. The appearence of these correlation is one of the essential factors limiting the applicability of the stationary models to the analysis of changes in space distribution of radiation in the medium, as well as the applicability of the one-dimensional models to the analysis of time and energy changes in the characteristics of radiation in two-component laser system. The analysis has also pointed out that under conditions typical of a number of experiments the nonlinear resonance interaction of the radiation with the absorbing-amplifying medium may lead to an essential time-space nonuniformity of the radiation structure, i.e. the radiation intensity distribution after passage through the medium cannot be represented in the form $I(r, t)$

$= af(t)g(r)$. This restricts, among others, the applicability of the concept of transversal modes to the two-component pulse laser, in particular to the laser with self-synchronization of modes, as well as to the traditional (stationary) models and methods of focussing or self-focussing of the pulsed radiation realized in systems of this kind. To obtain accurate quantitative information about the distributions of this radiation in the surrounding of focus it is necessary to consider the focussing system together with the radiation generating system. The analysis carried out in this work indicates also that an effective shaping refers not only to the time profile of the pulse, as shown in the earlier works, but also to the space profile and, in particular, to the formation of the distributions of the radiation energy density of the "supergaussian" profile which is desired in a number of application of the high power laser radiation.

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Деформации временно-пространственной структуры излучения в лазерных абсорбционно-усиливающих системах

Используя численные решения уравнений для интенсивности и эйконала световой волны, а также функции временной и пространственной компрессии, был произведён анализ деформации временного и пространственного распределения излучения в абсорбционно-усиливающих системах в условиях однофотонного некогерентного воздействия излучения со средой. Определены характерные

свойства этих деформаций, а также условия эффективного формирования распределений. В статье указывается на наличие как некоторых аналогий, так и основных различий в изменениях временного и пространственного распределений, а также на существоввание связи между этими распределениями в случае нестационарного воздействия. Доказано, что в типичных условиях для ряда экспериментов нелинейное воздействие излучения с абсорбционно-усиливающей средой может вести к существенной неоднородности временно-пространственной структуры излучения.