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Deformations of the time-space structure of a laser pulse due to two-photon absorption

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Starting with paraxial equations for intensity, an eikonal of the light wave and the kinetic equation for the difference of level population, deformations of the space-time structure of a laser, pulse performed in two-photon absorbing medium under the condition of noncoherent interaction are studied. The functions of time and space compression, as well as the results of numerical solutions of the two-dimensional equations of propagation are used in the analysis. The basic features of the changes in space and time of radiation intensity distribution were determined for the cases of quasi stationary and nonstationary interactions and that of weak signal. It has been shown that the two photon absorption leads to essential heterogeneity in the time-space pulse structure. The results of the experimental examinations of time, space and energy changes of neodymium laser pulse due to two-photon absorption in the gallium arsenide are shown.

1. Introduction

Two-photon absorption is one of the interesting manifestation of the nonlinear interaction of radiation with the matter. In a series of both theoretical and experimental works it has been pointed out that the effectivity of this process is sufficient to be used in the laser technique, in particular, to control the parameters of strong pulse lasers [1–9]. In the papers devoted to this problem the attention is paid to analysis and examinations of changes in time-energy characteristic of pulses occurring due to two-photon absorption, whereas one dimensional models were used to describe these changes. In the teoretical considerations the existence of coupling between the time and space distribution of the field in nonlinear medium as well as the possibility of essential deformations of spatial structure of radiation were neglected. The exploitation of the two-photon absorbents in the laser techniques necessitates multi-sided and detailed examination of two-photon absorption influence on the parameters and time-space structure of radiation. The examination of this type is interesting also due to the fact that the two-photon absorption occurring in a number of materials used commonly in the laser technique to generate and amplify the radiation (for instance, the neodymium glass, rubin [10–12]), or to generate the harmonics [13–15] and the like, may change to a high degree the characteristics of radiation propagating in the media and modify the occurring processes. In the available elaborations the problem of time-space pulse structure deformation due to two-photon absorption both for coherent and noncoherent interactions has not been sufficiently analysed and described.

In this work the changes in time-space intensity distribution of radiation occurring in the two-photon absorbing medium under the condition of noncoherent radiation-matter interaction have been analysed, starting with paraxial equations for intensity and the light wave eikonal as well as the kinetic equation for differences in the level populations. The basic features concerning these changes for quasi-stationary and nonstationary interactions as well as for small signal are determined. The time and space compression functions are employed in the analysis [5, 16], while the main results of the latter are illustrated by numerical solutions of the propagation equations. The results of experimental examinations of changes occurring in time, space and energy characteristics of neodymium laser pulses due o two-photon absorption in gallium arsenide are presented.

2. Basic equations and relative dependences

The subject of the considerations presented below will be the changes in time-space distribution of the radiation propagation in the two-photon absorbing medium ($E_2 - E_1 = 2h\omega$, where E_2, E_1 — energy levels, ω — central frequency of radiation) under the condition of noncoherent interaction*. Phenomenological description of this changes in an isotropic and uniform medium characterized by a weak dependence of the refractive index upon the field applied may be obtained from the equations for intensity I and eikonal Ψ and the effective difference in the population density N of the levels considered, which in the system of axial symmetry have the forms (for instance, [16]):

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

$$\frac{\partial \Psi}{\partial z}+\frac{1}{v}\frac{\partial \Psi}{\partial t}+\frac{1}{2}\left(\frac{\partial \Psi}{\partial r}\right)^2 = \frac{1}{4k^2 I}\left[\Delta_{\perp} I - \frac{1}{2I}\left(\frac{\partial I}{\partial r}\right)^2\right], \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{N-N^e}{T_1} = -s\sigma N I^2, \tag{3}$$

$$K(I) = -2\sigma N(I)I-\varrho, \tag{4}$$

where: r, z — variables in the directions parallel and perpendicular to that of the radiation propagation, respectively, t — time, $\Delta_{\perp} = \frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}$, v — light velocity in the medium, $k = 2\pi/\lambda$ — wave number, $N^e > 0$ — population difference in the state of equilibrium, T_1 — relaxation time, σ — cross-section for two-photon transitions, s — parameter depending upon the relaxation scheme (for two-level scheme $s\hbar\omega = 2$), ϱ — linear loss coefficient. The eqs. (1), (2) may be easily obtained from the parabolic equation**, for the complex slowly varying amplitude of the electric field E by the substitution

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

where a — constant depending upon the choise of units.

*I.e. in the case when the pulse duration is much longer than the elongation relaxation time of the medium.

**For the conditions of applicability of parabolic equation for E and by the same means for eqs. (1), (2), see [16, 17], for instance.

The basic features of the changes in the time and space distribution of radiation intensity, due to nonlinear resonance interaction with the medium, may be determined–without solving the eqs. (1)–(4)–by using the time $T \equiv -\frac{1}{\tau_p}\frac{d\tau_p}{dz}$ and space $S \equiv -\frac{1}{r_p}\frac{dr_p}{dz}$ compression functions [5, 16] (τ_p — effective width of the time distribution of intensity at the distance r from the beam axis, r_p — effective width of the spatial distribution of intensity at the moment $\tau = t - \frac{z}{v}\Big)$. These functions determine the relative rate of the respective changes in the width of both time and space radiation intensity distributions in the medium. In accordance with [16], for $\Psi \approx$ constant and in a uniform medium we have

$$T = \frac{\delta_1}{2}\left[K(I_h, \tau_h) - K\left(\frac{1}{2}I_h, \tau_1\right)\right] + \frac{\delta_2}{2}\left[K(I_h, \tau_h) - K\left(\frac{1}{2}I_h, \tau_2\right)\right], \tag{5}$$

where $I_h = I(\tau_h, r, z)$ — intensity at the time distribution maximum, τ_h, τ_1, τ_2 — points corresponding to the time maximum of intensity and to the half-width of its front and back slope, respectively, $\delta_1, \delta_2 > 0$ — coefficients of respective slopes for the time distribution dependence are determined by the relationship $\frac{I}{\partial\tau}\Big|_{\tau_{1(2)}} = (\pm)\frac{I_h}{\tau_p}\frac{1}{\delta_{1(2)}}$ and

$$S = \frac{\gamma}{2}\left[K(I_m) - K\left(\frac{1}{2}I_m\right)\right], \tag{6}$$

where $I_m = I(\tau, r = 0, z)$ — intensity at the spatial distribution maximum, $\gamma > 0$ — slope coefficient for the spatial distribution defined by the formula $\frac{\partial I}{\partial r}\Big|_{r_p} = -\frac{1}{\gamma}\frac{I_m}{r_p}$. The coefficients $\delta_1, \delta_2, \gamma$ are, in general, slowly varying functions of coordinates as compared with I_h, I_m, τ_p, r_p. In the case when the absorption function K is explicity time-independent (the quasi-stationary interaction) the function T takes the form

$$T = \frac{\delta_1 + \delta_2}{2}\left[K(I_h) - K\left(\frac{1}{2}I_h\right)\right], \tag{7}$$

which is analogical to the form of the spatial compression function S. This means that in this case the changes in time and space intensity distributions of radiation evoked by the resonance interaction occur in an analogical way. This analogy is no more valid for nonstationary interaction.

3. Deformations in time distribution of radiation

Let us consider the changes in the time and space intensity distributions of radiation occurring due to nonlinear interaction with the absorbent in the three limiting cases, namely: in quasi-stationary interaction ($\tau_p \ll T_1$), nonstationary interaction ($\tau_p \gg T_1$) and small signal $\big(N(I) \approx N^e = \text{const}\big)$. In the case when $\tau_p \gg T_1$, in accordance with (3) and (4), the absorption function of absorbent takes the form

$$K = -\frac{\beta_s P(r, \tau)}{1+P^2(r, \tau)} - \varrho, \tag{8}$$

where $P = I/I^s$, $I^s = (s\sigma T_1)^{-1/2}$ — intensity of absorption saturation, $\beta_s = 2\sigma N^e I^s$. The dependence $K(P)$ is nonmonotonous and has one minimum at $P = 1$. For this value of intensity the two-photon absorption is greatest, while $|K|_{\max} = \frac{1}{2}\beta_s + \varrho$. Due to the appearance of the extremum of the function $K(P)$, the central part of the pulse slopes will be most strongly absorbent in the case of the pulse of top intensity $I_h > I^s$, while the absorption at its top and bottom will be weaker.

The rate of changes in time intensity distribution of radiation is described by time compression function being, in accordance with (7) and (8), of the form

$$T = \frac{\delta_1+\delta_2}{2}\beta_s P_h(r)\frac{P_h^2(r)-2}{[1+P_h^2(r)][4+P_h^2(r)]}, \tag{9}$$

where $P_h = I_h/I^s$. The dependence of the function T upon the top intensity P_h is illustrated in fig. 1a. In the region $P_h < \sqrt{2}$ the time distribution (its half-width) is widened, while its compression takes place in the region $P_h > \sqrt{2}$. There exist optimal values of P_h close to 0.5 and 3.5, respectively, for which the spead of the widening and compression of distribution is the greatest. Figure 1b presents, in turn, the rate of changes in the width of time distribution as a function of the distance from the axis of the beam of Gaussian profile $I(r)$. The parameter is here the intensity at the maximum of the time-space distribution $P_{hm} = P(\tau = \tau_h, r = 0, z)$. In the case when $P_{hm} < \sqrt{2}$ a widening of the time distribution occurs within the whole range of r, for P_{hm} less or equal to the value optimal from the view-

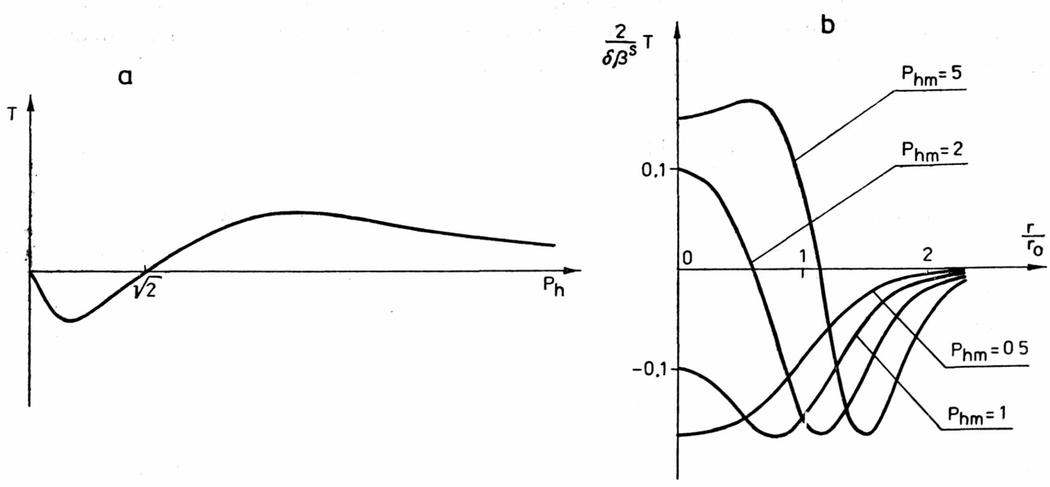

Fig. 1. a. Dependence of the time compression function of two-photon absorption upon the top pulse intensity, for the case of quasi-stationary interaction. b. Relative speed of changes in the width of the time intensity distribution of Gaussian profile $I(r)$ as a function of the distance from the beam axis

point of decompression ($P_{hm} \approx 0.5$) the maximum speed of widening occurs on the beam axis, and for P_{hm} greater than the optimal one – at the slope of the space distribution. In the case when $P_{hm} > \sqrt{2}$ the time distribution at the neighbourhood of the beam axis is subject to compression, being widened at the periphery of the distribution $I(r)$. For the values of P_{hm} greater than 3.5 the maxima of both the compression and widening speeds occur on the slopes of the space distribution. A consequence of the shown $T(r)$ dependence is the non-uniformity of the time-space structure of radiation. The intensity distribution at the output of absorbent may no more be written in the form $I(\tau, r) = af(\tau)g(r)$. It is also clear that the shape of the spatial distribution of radiation entering the medium under these conditions will essentially influence the character of time changes in the radiation power distribution $\mathscr{P}(\tau)$, (i.e., intensity integrated over the light beam cross-section). It is also possible that the compression of the time distributions of the power in the medium will occur for quasi-rectangular distribution of $I(r)$ and the widening of the same distribution for distribution of $I(r)$ with mild slopes.

The expression (9) allows us to obtain an approximate analytic expression, describing the dependence of width τ_p upon the top intensity of the pulse at the point r, useful for estimations. For $\beta_s \gg \varrho$ and small divergence of the beam we have

$$\tau_p \approx \tau_p^o \left(\frac{P_h^o}{P_h}\right)^{\delta/2} \left(\frac{P_h^2+4}{P_h^{o2}+4}\right)^{3/4\delta},$$

where $\delta = \overline{\dfrac{\delta_1+\delta_2}{2}}$ — average slope coefficient for the distribution in the discussed interval of the changes of P_h^*.

In case of quasi-stationary interaction and plane wavefront of radiation an analytical solution of the eq. (1) may be obtained. In particular, for $\varrho = 0$ and expressed in r, τ variables it has the form

$$P(\tau, r) = \frac{1}{2P^o(\tau, r)}\left[P^{o2}-P^o\beta_s l-1+\sqrt{(1-P^{o2}+P^o\beta_s l)^2+4P^{o2}}\right],$$

where l — length of the propagation path, $P^o(\tau, r)$ — input distribution. For beams of non-plane wavefronts the numerical methods must be unavoidably used. The exemplified results of numerical solutions of eqs. (1), (2) with the absorption function (8) are presented in fig. 2a; they illustrate the deformations of time distributions of power (4) and intensity (1)–(3) of radiation at different distances from the beam axis as compared to the input distribution (broken line). The input distributions were assumed in the forms:

$$I(\tau, r, z = z_o) = I_{hm}^o \exp\left(-\frac{\tau^2}{\tau_o^2}-\frac{r^2}{r_o^2}\right), \Psi(\tau, r, z = z_o) = \frac{r^2}{2z_o},$$

and the following values for parameters were accepted: $I_{hm}^o = 10I^s$, $r_o = 0.5$ cm, $z_o = 10^3$ cm, $k = 6\cdot 10^4$ cm^{-1}, $\beta_s = 0.2$ cm^{-1}, $\varrho = 0.01$ cm^{-1}.

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*As shown by numerical calculations the coefficient for input distribution may be also accepted for estimations in place of average coefficient.

From the graphs presented it may be seen, in particular, that the changes in the time distribution of intensity in different points r occur in different way: in the vicinity of the beam axis the distribution compression developes and a two-step profile $I(\tau)$ is formed, while the widening of the distribution $I(\tau)$ occurs on the slopes of the spatial distribution.

In the case $\tau_p \ll T_1$ the absorption function for the two-photon absorbent takes the form:

$$K = -\beta I(\tau, r)\exp\left[-s\sigma \int_{-\infty}^{\tau} I^2(\tau', r)d\tau'\right] - \varrho, \tag{10}$$

where $\beta = 2\sigma N^e$.

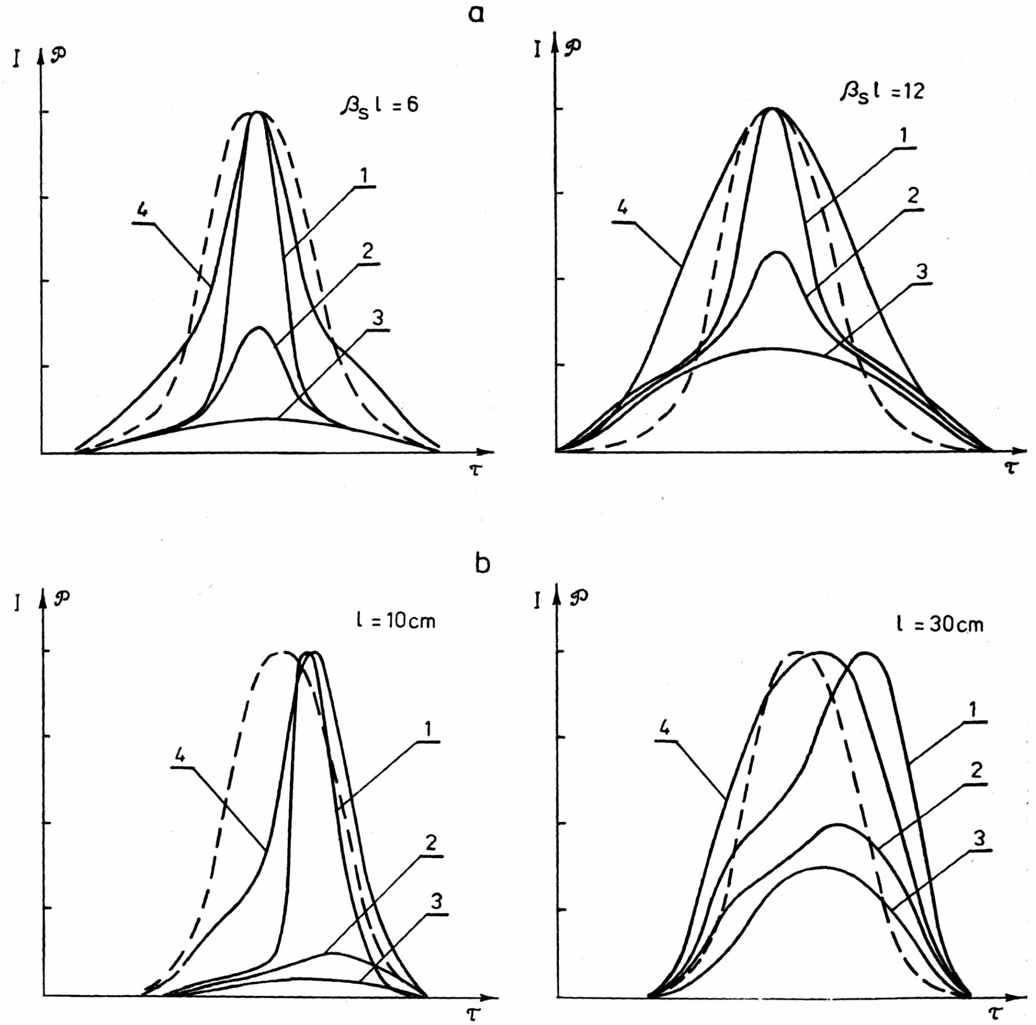

Fig. 2. Time deformation of the both power (4) and intensity (1, 2, 3) distributions of radiation at different distances from the Gaussian beam axis for the case of quasi-stationary (a), and nonstationary (b) interaction with two-photon absorbent. 1 — $r = 0$, 2 – $r = 3/5\ r_0$, 3 – $r = 6/5\ r_0$. Broken line denotes input distribution

By analysing the expression (10) it is easy to show that the function K is, in general, a nonmonotonic function of both top pulse intensity and the time τ, and that the maximum absorption is associated with the front slope of the time distribution. For the value I_h exceeding several times the values characteristic of the saturation: $I_h^s = (s\sigma\tau_p)^{-1/2}$ a strong absorption will occur in the central part of the pulse front and a weaker one in its bottom, top and the back front.

By substituting (10) to (5) we get

$$T = \frac{1}{2}\beta I_h(r)\left\{\delta_1\left[\frac{1}{2}\exp\left(-\chi_1 I_h^2(r)\right) - \exp\left(-\chi_h I_h^2(r)\right)\right] - \delta_2\left[\exp\left(-\chi_h I_h^2(r)\right) - \frac{1}{2}\exp\left(-\chi_2 I_h^2(r)\right)\right]\right\}, \tag{11}$$

where

$$\chi_{1(2)} = s\sigma\int_{-\infty}^{\tau_{1(2)}} f^2(\tau, r)\,d\tau, \quad \chi_h = s\sigma\int_{-\infty}^{\tau_h} f^2(\tau, r)\,d\tau, \quad f(\tau, r) = \frac{I(\tau, r)}{I_h(r)}.$$

From eq. (11) it follows, in particular, that in contrast to the case of quasi-stationary interaction both the speed and the direction changes in the width of time intensity distribution depend essentially upon its shape and upon the symmetry, among others. In the case of sharp front slope ($\delta_1 \approx 0$) the nonstationary two-photon absorption leads to some broadening of distribution. For the symmetric distribution ($\delta_1 = \delta_2$) or asymmetric ones with sharp back slope ($\delta_2 \approx 0$) both the broadening and compression of the distribution may happen depending upon the value of I_h. The greatest speed of compresion may be obtained at $\delta_2 = 0$. The above considerations are illustrated in fig. 3. For the quasi-stationary inter-

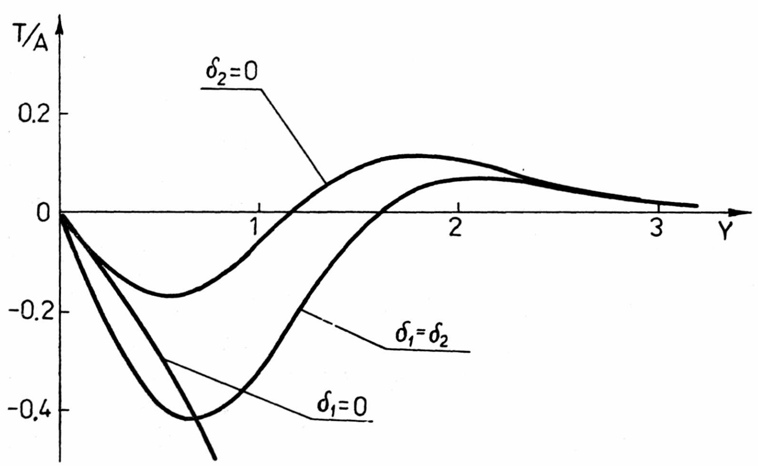

Fig. 3. Dependence of the time compression function upon the top pulse intensity for the case of nonstationary interaction with two-photon absorbent.

$\delta_1 = 0$ — pulse with sharp front slope, $\delta_2 = 0$ — pulse with sharp back slope, $\delta_1 = \delta_2$ — symmetric pulse.

$Y = (1/2s\sigma\tau_o)^{1/2} I_h$, $A = \dfrac{\beta}{(2s\sigma\tau_o)^{1/2}\ln 2}$

action, in general, much higher compressions may be achieved than for nonstationary interaction, since, in the first case the compression results from shortening of both front and back slopes, while in the second one it results from shortening of the front slope but widening of the back one.

In the nonstationary case, similarly as for $\tau_p \gg T_1$, the character of the changes in time distribution is different at different distances from the beam axis. This is illustrated in fig. 2b, representing the numerical results of the solutions of eqs. (1) and (2) with the absorption function (10) at $\beta = 2\cdot 10^{-10}$ cm/W, $I_{hm} = 2\cdot 10^{10}$ W/cm^2, $s\sigma\tau_o = 10^{-19}$ cm^4/W^2 and other parameters as in the quasi-stationary case.

The case is often in practice realized in which the radiation intensity is much less than intensity needed to saturate the two-photon absorption. In this case from (9) or (11) we may obtain:

$$T = -\frac{\delta_1+\delta_2}{4}\beta I_h(r), \tag{12}$$

which means that the speed of time distribution broadening at the point r is for small signal proportional to its top intensity at this point. On the base of (12) we may obtain the expressions describing the dependence of the distribution width τ_p upon the top intensity

$$\tau_p = \tau_p^o \left| \frac{\beta I_h^o + \varrho}{I_h + \varrho} \right|^{\delta/2}, \tag{13}$$

or

$$\tau_p = \tau_p^o \left[1 + \frac{\beta I_h^o}{\varrho}(1-e^{-\varrho l}) \right]^{\delta/2}. \tag{14}$$

By letting $I_h = 0$ in eq. (13) we obtain the expression determining the maximal pulse broadening in two-photon absorbent

$$\left.\frac{\tau_p}{\tau_p^o}\right|_{\max} = \left| \frac{\beta I_h^o + \varrho}{\varrho} \right|^{\delta/2}. \tag{15}$$

From this expression it follows in particular that the essential pulse broadening is possible only when the losses evoked by the two-photon transitions are much higher than the linear losses in the absorbent.

Experimental examinations of deformation of the time distribution of radiation were carried out in the system composed of three amplifiers based on the neodymium glass and four plates of gallium arsenide (two-photon absorbent) each of thickness 0.05 cm. The amplifiers and absorbents were positioned alternatively. The laser pulse of effective length ~10 ns entering the system came from the YAG:Nd^{3+} crystal generator completed by two preamplifiers and an electrooptical pulse forming system. The measurements were carried out according to typical methodology that consisted in recording the energy, length and shape (on an oscilloscope) of both the input and output pulses for the two-component system under test. The parameters of the input pulse were chosen so that after replacing the gallium arsenide plates by linear damping elements no essential pulse deformation was obtained.

The results of pulse deformation tests and their comparison with the results of numerical calculations are shown in fig. 4. The calculations were made taking the parameters measured in the experiment and assuming that the wavefront is plane, while the spatial distribution of radiation is rectangular and $I^s = \infty$.

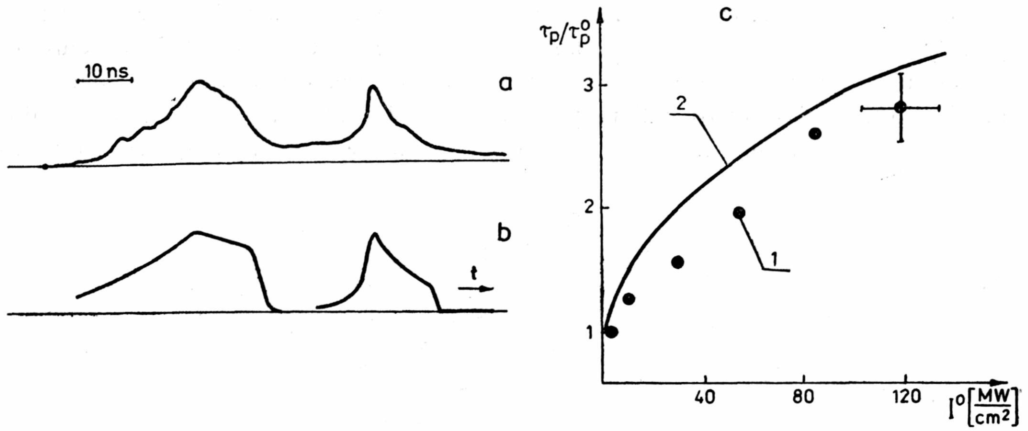

Fig. 4. Deformation of time shape of pulse in the system with two-photon absorbent obtained from experiment (a), and from calculations (b). The input pulse situated on the right hand side. c — dependence of the pulse length at the output upon the input pulse intensity:
1 — experiment, 2 — theory

In the case when the radiation intensity is much less than the saturation intensity I^s the two-photon absorption may lead to stability of the top power in the pulse leaving the system containing two-photon absorbents (for instance, [5, 8]). The effect of power stabilization due to two-photon absorption in gallium arsenide is illustrated in fig. 5 presenting he dependences of energy and power of the pulse leaving the examined two-component system upon the input intensity obtained from the measurements (5a) and calculations (5b).

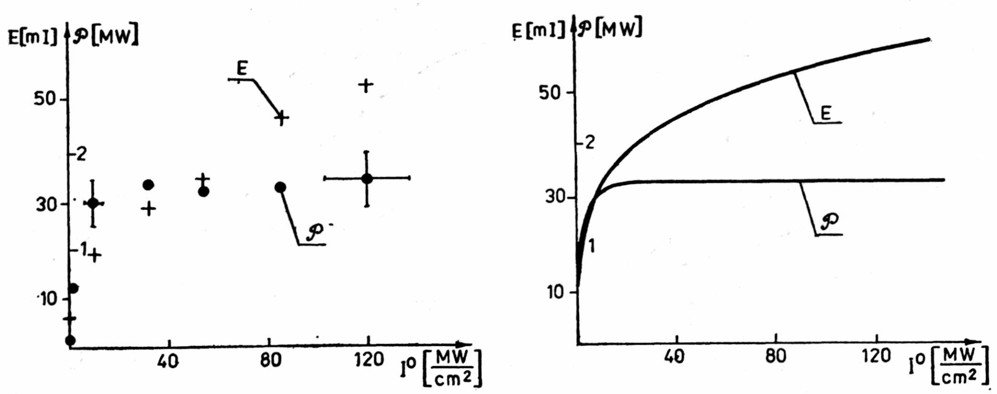

Fig. 5. Energy and power of the pulse emerging from the two-component system as a function of intensity of the input pulse.
a — results of measurements, b — results of calculations

4. Deformation in space distribution of radiation

In case of quasi-stationary interaction of radiation with the matter the expression for the functions of time and space compressions (6) and (7) are of analogical form, which means that the changes in the time and space distributions of radiation intensity evoked by two-photon absorption occur in an analogical way. These expressions become identical if $\tau_p(r)$, $P_h(r)$, $\delta_1+\delta_2$ is replaced by $r_p(\tau)$, $P_m(\tau)$, γ. By the same means all the conclusions and formulae obtained in Section 3 and concerning the changes in time distribution of radiation in the case of quasi-stationary interaction and small signal level are correct also with reference to the changes of space distribution (in the formulae only the mentioned

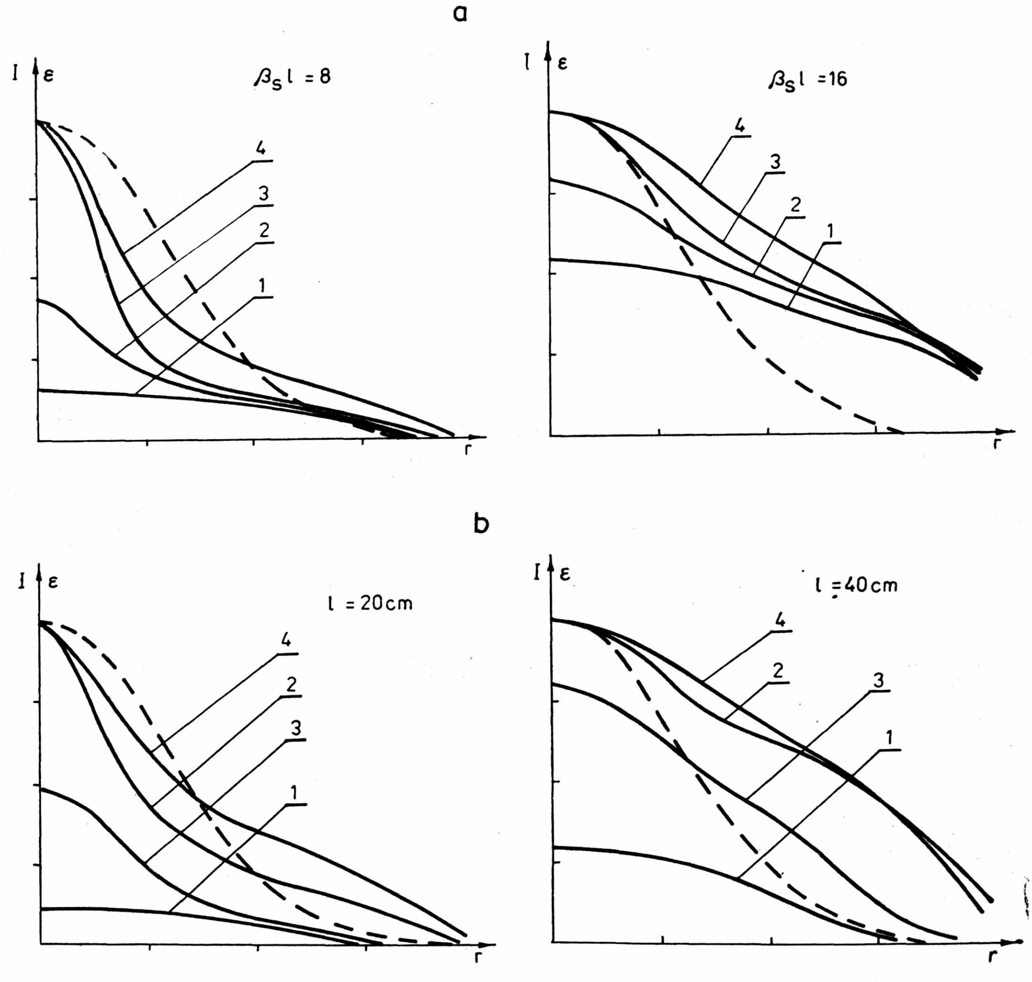

Fig. 6. a. Deformations of the spatial energy density distributions (4) and the radiation intensity on the front slope (1, 2) as well as those in the time maximum (3) of the pulse in the case of quasi-stationary interaction with two-photon absorbent. b. Deformations of the space energy density distributions (4) and of the radiation intensity on the front slope (1) in the time maximum (2) and on the back slope (3) of the pulse in the case of nonstationary interaction. Broken line denotes the input distribution

transformation of variables should be performed). This is confirmed by the detailed numerical results (1), (2). The examplified results are shown in fig. 6a presenting the deformations of the spatial distribution of the energy density $\varepsilon(r) = \int_{-\infty}^{\infty} I(\tau, r)\, d\tau$ and the radiation intensity at various moments of time τ. The input distributions and parameters are here the same as in fig. 2a. Below we shall concentrate our attention to the case of nonstationary interaction.

By substitution (10) to (6) we obtain

$$S = \frac{\gamma}{4} \beta f(\tau) I_{hm} \left\{ \exp\left[-\frac{1}{4} \chi(\tau) I_{hm}^2 \right] - 2\exp[-\chi(\tau) I_{hm}^2] \right\}, \tag{16}$$

where

$$\chi(\tau) = s\sigma \int_{-\infty}^{\tau} f^2 d\tau.$$

In fig. 7a the function of spatial compression at the time maximum of pulse normed to the value $B = \frac{\gamma}{4} \beta \chi_h^{-1/2}$ is presented as related to the relative intensity $Z = \chi_h^{1/2} I_{hm}$. Similarly, as in the case of quasi-stationary the regions of compression and decompression of the distribution $I_h(r)$ appear on the intensity axis, but both value and the direction of changes in this distribution depend essentially upon the effective length slope. For infinitely short front slope the distribution $I_h(r)$ is broadened with the speed proportional to I_{hm}: $S_h = -\frac{\gamma}{4} \beta I_{hm}$. If $\chi_h \neq 0$ the maximum speed of decompression is greater than the maximum speed of broadening (in the case of time distribution the situation is reversed). The compression of the space distribution at the vicinity of the time maximum may be obtained at lower top intensities in the case of pulses with long front slope. Figure 7b presents the relative speed of changes in the width of the spatial intensity distribution at various moments τ for a pulse of Gaussian time shape. For great values of $Z (Z \gg 1)$ both the maximum speed of broadening and that of compression occur on the front slope of the pulse. The reduction of Z is accompanied by a shift of these maxima in the direction of increasing values of τ and by a decrease of compression region on the axis τ so, that for certain Z only the back slope of the pulse occurs. After reduction of Z to the values less than $\sqrt{\frac{2}{3} \ln 2}$ (for the symmetric pulse) the broadening of space distribution takes place within the whole range of τ. For $Z \ll 1$ the greatest speed of the spatial distribution broadening occurs at the vicinity of the time maximum of the pulse. From the formula (16) and the graphs shown it follows that in the case of nonstationary interaction the time characteristics of radiation decide, to an essential degree, about the character of changes in the space distribution.

The conclusions following from the analysis of the function S confirm fully the results of numerical solutions of eqs. (1) and (2) with the absorption function (10). Some examples of numerical calculations are presented in fig. 6b (the parameters as in fig. 2b).

In practice, we usually deal with the radiation distributions, in which there exist a number of fluctuations, which result, for instance, from diffraction from heterogeneities and apertures of optical system, the statistical nature of the generation and the like. The regularities described above, concerning the changes both in spatial and time radiation distributions, should in this case refer to their envelopes. The influence of the two-photon absorption on the character of changes in the fluctuations (their contrast with respect to the back-

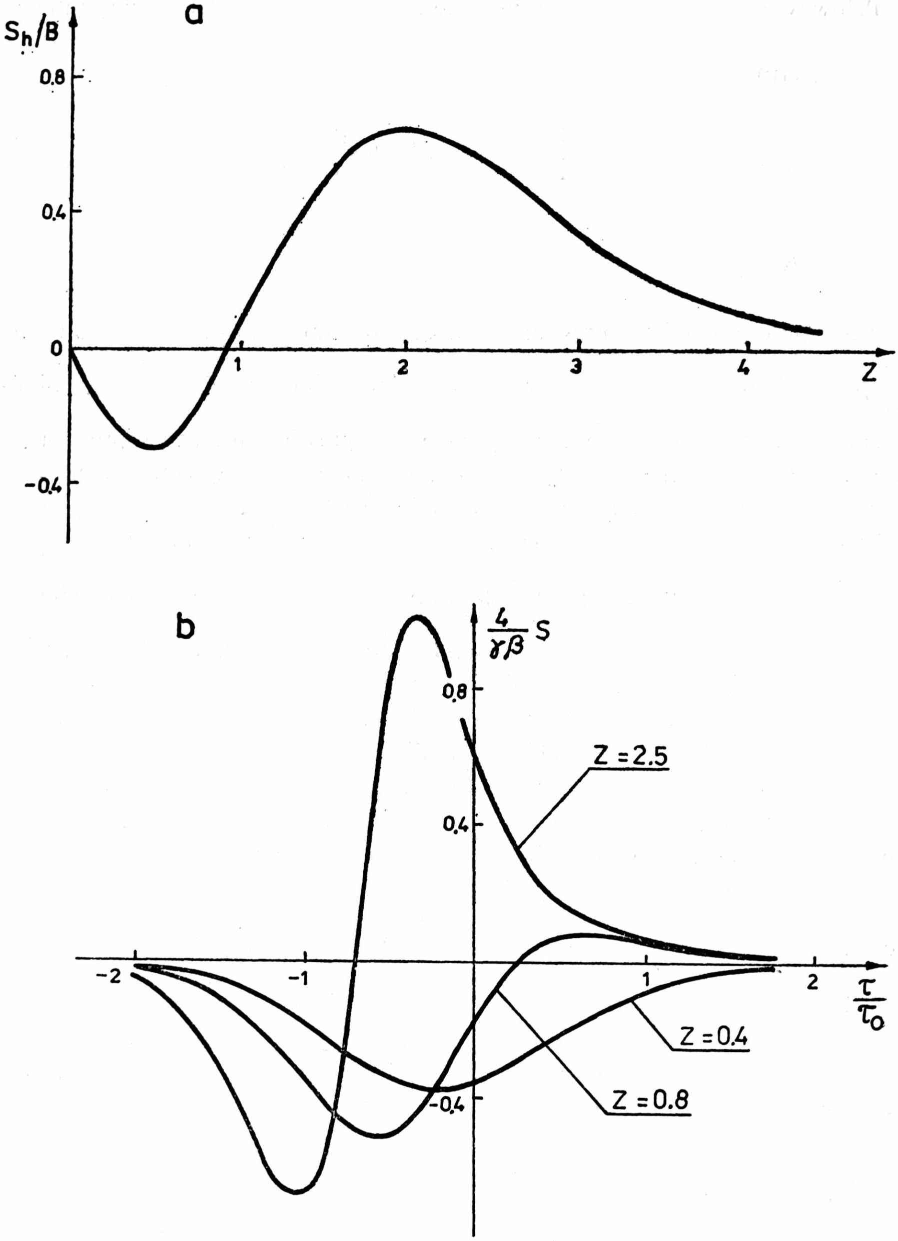

Fig. 7. The function of spatial compression in two-photon absorbent in the case of nonstationary interaction. a — relative speed of changes in the intensity distribution width as a function of ntensity on the axis. b — relative speed of change s in the intensity distribution at various time moments τ

ground) may be of two types. In the case when the intensity of fluctuations is higher than the intensity necessary to saturate the absorption the nonlinear interaction with two-photon medium will lead to an enhancement of their contrast. On the other hand, for the fluctuation intensities less than the saturation intensity the two-photon absorption will result in their smoothing. The smoothing effect in the spatial distribution of radiation is illustrated in fig. 8 presenting the results of numerical solutions of eqs. (1), (2) for $I_{hm} \ll (s\sigma\tau_0)^{-1/2}$, $\beta l = 2.5 \cdot 10^{-9}$ cm^2/W, and the other parameters as in fig. 2b.

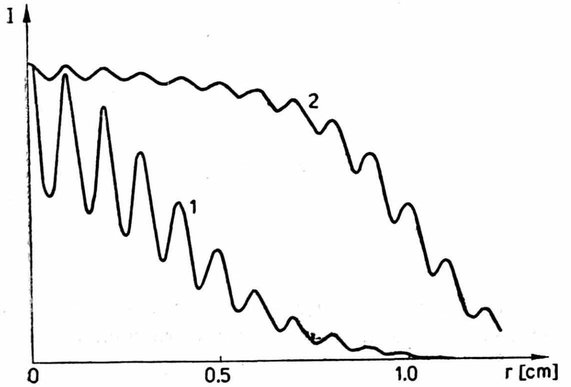

Fig. 8. The smoothing of the nonuniformities in the spatial distribution of radiation due to two-photon absorption.

1 — distribution at the absorbent input, 2 — dis ribution at the absorbent output

The experimental examinations of the changes in the spatial distribution of radiation due to two-photon absorption have been carried out in a laser system containing: a YAG:Nd^{3+} crystal generator offering a possibility of single-pulse or multi-pulse generation of picosecond pulses, an electrooptical system short pulse separation, two YAG:Nd^{3+} crystal amplifiers and a neodymium glass amplifier. A plate of gallium arsenide dopped with neodymium of 0.5 cm thickness, polished on both sides and positioned perpendicularly to the direction of radiation propagation was used as two-photon absorbent. The examination of the plate damping showed the dependence of the damping upon the radiation intensity to be close to linear, which is typical of nonsaturated two-photon absorption. The examinations of changes in spatial distribution of energy density in the laser beam have been performed for nanosecond ($\tau_p \approx 4$ ns) and picosecond ($\tau_p \approx 5 \cdot 10^{-11}$ s) pulses. The distributions were recorded on the light sensitive plates situated at the distance of about 10 cm from the absorbent. In order to obtain approximately the same radiation intensities on the plates for various intensity values of the pulse entering the absorbent the radiation was suitably damped by using the proper linear filters. These filters did not cause observable changes in the radiation intensity distribution. Both in the case of nanosecond and picosecond pulses partial smoothing of nonuniformity in the distribution was observed as well as its broadening increasing with input pulse intensity. Typical densitograms of the spatial distributions of radiation energy at the input (a) and output (b) of the two-photon absorber and the dependence of the effective width of the output distribution upon the average intensity of the picosecond pulse are presented in fig. 9.

Finally, let us notice that the effect of nonuniform time-space structure of radiation occurring due to two-photon absorption and the existence of mutual relation between its

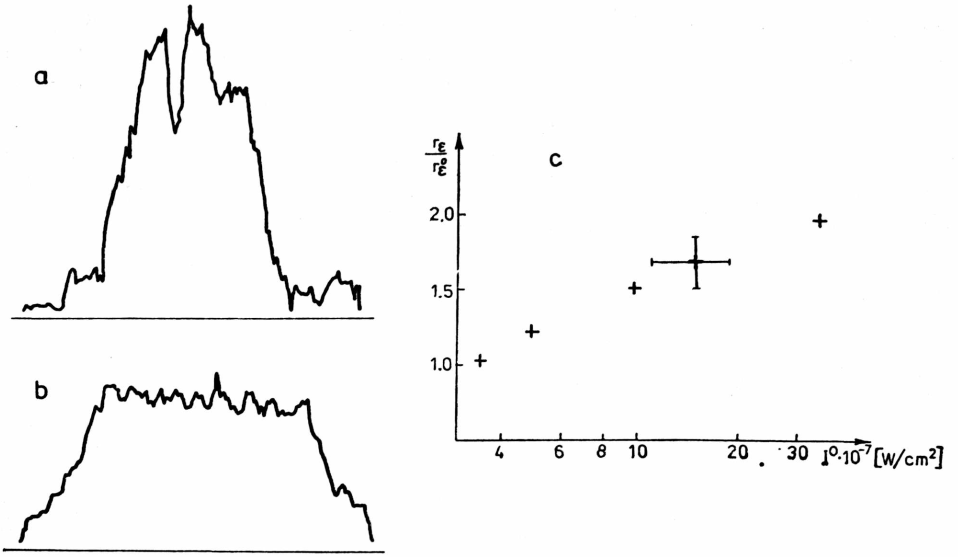

Fig. 9. The densitograms of the spatial distribution of the radiation energy density at the input (a), and output (b) of the GaAs plate and the dependence of the effective width of the output distribution upon the intensity (c) of the picosecond pulse

time and space characteristics under the nonstationary interaction reduces in an essential degree the applicability of the one-dimensional models to the description of pulse propagation in two-photon medium. These models, giving correct qualitative description, may simultaneously lead to significant quantitative errors and high divergences with the experimental results.

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References

[1] SCHWARTZ J., WEILER W., CHANG R. K., IEEE J. Quant. Electron. **6** (1970), 442.
[2] ARSENEV V. V., et all., Kvant. Elektron. No. 7 (1972), 33.
[3] POLUEKTOV I. A., et all., Zh. Eksp. Teor. Fiz. **18** (1973), 638.
[4] LISITSA M. P., et all., Kvatn. Elektron. (Kiev), No. 8 (1974), 35.
[5] BADZIAK J., JANKIEWICZ Z., J. Tech. Phys. **17** (1976), 85. Acta Phys. Polon. **A53** (1978), 99.
[6] WILHELMI B., et all., Kvant. Elektron. **3** (1976), 732.
[7] ELGIN J. N., OHARE T. B., Opt. Commun. **25** (1978), 263.
[8] BADZIAK J., J. Tech. Phys. **20** (1979), 91.
[9] MARTINEZ O. E., Opt. Quant. Electron. **11** (1979), 223.
[10] BIELIKOVA T. P., et all., Zh. Eksp. Teor. Fiz. **54** (1968), 39.
[11] PENZKOFER A., KAISER W., Appl. Phys. Lett. **21** (1972), 427.
[12] GRUDIN V. A., et all., Zh. Eksp. Teor. Fiz. **76** (1979), 1977.
[13] ARSENIEV V. V., et all., Zh. Eksp. Teor. Fiz. **56** (1969), 760.
[14] REINTJES J., ECKHARDT R. C., IEEE J. Quant. Electron. **13** (1977), 791.

[15] BITYURIN N. M., et all., Kvant. Elektron. **5** (1978), 2453.
[16] BADZIAK J., Optica Applicata X (1980), 119.
[17] LUGOVOI V. N., PROKHOROV A. M., Usp. Fiz. Nauk **111** (1973), 203.

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Деформации временно-пространственной структуры лазерного импульса в результате двухфотонной абсорбции

Исходя из параксьяльных уравнений для интенсивности и эйконала световой волны, а также кинетического уравнения для разности заполнений уровней проанализированы деформации временно-пространственной структуры лазерного импульса, происходящие в двухфотонной поглощающей среде в условиях некогерентного взаимодействия. Для анализа использованы функции временного и пространственного сжатия, а также результаты численных решений двумерных уравнений распространения. Определены основные закономерности касающиеся изменений временного и пространственного распределений интенсивностей излучения в случае квазистационарного и нестационарного взаимодействий, а также слабого сигнала. Показано, что двухфотонная абсорбция приводит к существенной неоднородности временно-пространственной структуры импульса. Представлены результаты экспериментальных исследований временных, пространственных и энергетических изменений характеристик импульса неодимногово лазера, полученных при двухфотонной абсорбции в арсениде галия.