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The effect of nonlinear losses on the energy extraction from the amplifying medium

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In this paper an analysis of the energy extraction from the amplifying medium is given for the case of quasi-stationary nonlinear losses of radiation. The general expressions found for the extraction coefficient became a basis for a detailed analysis of the energy extraction from the medium with losses proportional to the radiation intensity. The influence of parameters of both medium and the pulse (so far as the length and the shape of the latter is concerned) on the extraction efficiency was shown, and the conditions under which the efficiency is maximal were detrmined. The results of experimental examinations of the extraction coefficient dependence upon the length and energy of the pulse and upon the amplification coefficient in the system of neodymium glass amplifiers are presented.

Introduction

One of the factors deciding about the laser system efficiency is the extraction effectivity due to stimulated emission of the energy accumulated in the amplifying medium. The determination of the optimal conditions for energy extraction from the amplifiers is of particular importance in big laser systems, since it allows to obtain the required laser pulse energy from the systems of essentially reduced sizes and lowered costs of their construction and exploitation. High efficiency of the laser system is one of the conditions of its application to the energy production in the proposed thermonuclear devices [1].

In a number of works devoted to the analysis of energy extraction efficiency from the amplifying medium (for instance, [2-4]) this problem was considered under assumption of the absence of nonlinear losses of radiation in the amplifying medium. This assumption allows to obtain sufficiently accurate results at a relatively low radiation intensity. In some big laser systems, for instance neodymium glass laser, the radiation intensity takes, however, so great values that the nonlinear losses of radiation may influence essentially the parameters of the amplified pulse [5-9]. These losses may not only lower the total extraction coefficient but also change the optimal conditions of amplification, as compared with the case when there exist only linear losses in the system. Thus, the determination of the effect of nonlinear losses on the energy extraction from the medium is indoubtly of importance from the viewpoint of optimization of the big laser system.

In the present paper the problem of energy extraction from the amplifying medium under the quasi-stationary nonlinear losses of radiation has been analysed basing on the equation of energy balance. Taking the neodymium glass amplifier as an example we have shown the influence of the medium and pulse parameters on the efficiency of the energy extraction from the amplifiers. The results of experimental examinations of the extraction coefficient dependence upon the length and energy of pulse and the amplification coefficient in the system of neodymium glass amplifiers are presented.

The basic equations and relations

The problem of energy extraction from the amplifying medium, in the case of its noncoherent interaction with radiation, may be analysed basing on the energy balance equation*:

$$\frac{1}{v}\frac{\partial I}{\partial t}+\frac{\partial I}{\partial z}=\left(\varkappa-\gamma-\frac{a}{z}\right)I, \qquad \frac{\partial \varkappa}{\partial t}+\frac{\varkappa-\varkappa^e}{T_1}=-\frac{1}{\varepsilon^s}\varkappa I, \tag{1}$$

where I — the radiation intensity (in W/m^2), $\varkappa$ — the amplification coefficient ($\varkappa^e$ — that in the equilibrium condition, at $I=0$), γ — the coefficient of losses, ε^s — the effective energy density of amplification saturation, T_1 — the relaxation time of the population inversion, v — the light velocity in the medium, $a = 0, 1, 2$ — for the radiation with plane, cylindric or spherical wavefront, respectively. We assume that the losses in the medium are of quasi-stationary nature and that they may be described by a function of the form of power series:

$$\gamma(I)=\beta_0+\beta_1 I+\beta_2 I^2+\ldots, \tag{2}$$

where β_i — the time-independent development coefficients. The above form of $\gamma(I)$ describes, in particular, the nonlinear radiation losses evoked by multiphoton absorption. Taking into account that usually $\tau_p \ll T_1$ (τ_p — the pulse duration time) and taking z, $\tau = t-\frac{z}{v}$, instead of z, t, we obtain from (1) and (2):

$$\frac{\partial I}{\partial z}=\left[\alpha\exp\left(-\frac{1}{\varepsilon^s}\int\limits_{\tau'}^{\tau} I d\tau\right)-\sum_{i=0}^{N}\beta_i I^i-\frac{a}{z}\right]I, \tag{3}$$

where τ' — the local time corresponding to the pulse origin, $\alpha = \varkappa(\tau')$ — the amplification coefficient of small signal. By introducing the energy of radiation

$$\varepsilon=\int\limits_{\tau'}^{\tau''} I(\tau)d\tau,$$

* For the applicability conditions of this equations see [10, 11], for instance.

(τ'' — the time corresponding to pulse end) and integrating the equation (3) with respect to τ we obtain:

$$\frac{\partial \varepsilon}{\partial z} = a\varepsilon^s\left[1-\exp\left(-\frac{\varepsilon}{\varepsilon^s}\right)\right]-\left(\sum_{i=0}^{N}\beta_i A_i\frac{\varepsilon^i}{\tau_{ef}^i}+\frac{a}{z}\right)\varepsilon, \tag{4}$$

where $\tau_{ef} = \varepsilon/I_h$ — the effective pulse length,

I_h — the top intensity,

$$A_i = \frac{\int\limits_{-\infty}^{\infty} f^{i+1}(\tau)\,d\tau}{\int\limits_{\infty}^{\infty} f(\tau)\,d\tau},$$

$f(\tau) = \dfrac{I(\tau)}{I_h}$ — the normed function describing the pulse shape.

Let us introduce the differential coefficient of energy extraction from the medium defined by the formula [3]:

$$\eta = \frac{1}{\hbar\omega N^0}\left.\frac{d\varepsilon}{dz}\right|_{a=0}, \tag{5}$$

where $\hbar\omega N^0$ — the energy stored in a unity volume, N^0 — the initial population inversion, $\hbar\omega$ — the photon energy. The coefficient η determines the ratio of the radiation energy increment after passing through the layer of the thickness dz to the energy stored in this layer and is a measure of energy extraction efficiency in the medium. Taking into account that $a = \sigma N^0$ and $\varepsilon^s = \dfrac{\hbar\omega}{s\sigma}$, where σ — the stimulated emission cross-section, s — the parameter depending upon the amplification scheme*, we have $\hbar\omega N^0 = sa\varepsilon^s$. By dividing the equation (4) by the last equality and taking account of the definition (5) we obtain

$$\eta = \frac{1}{s}\left[1-e^{-X}-X\sum_{i=0}^{N}\frac{\beta_i A_i(\varepsilon^s)^i}{a\tau_{ef}^i}X^i\right], \tag{6}$$

where $X = \varepsilon/\varepsilon^s$.

To estimate extraction efficiency of the energy from the medium of finite length and to optimize its energy amplification it is convenient to introduce the average extraction coefficient defined by the formula

$$\bar{\eta} = \frac{1}{X_l - X_0}\int\limits_{X_0}^{X_l}\eta(X)\,dX, \tag{7}$$

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* For two-level scheme of amplification which is realized when $\tau_p \ll \tau_d$ (τ_d — the lifetime of the low laser level), $s = 2$, while in the three-level scheme which occurs if $\tau_p \gg \tau_d$, $s = 1$.

where X_0, X_l — the relative radiation energy density at the input and output of the medium of length l, respectively. The formulae (6) and (7) will be used in the next section to analyse the energy extraction efficiency from the amplifying medium with linear and nonlinear radiation losses. The detailed considerations will be carried out for the case of nonlinear losses proportional to intensity which corresponds to real situation occurring for instance, in the neodymium glass amplifiers. In these amplifiers $\beta_1 \approx \sigma_2 n$ is a two-photon absorption coefficient in glass [6, 8] (σ_2 — the cross-section for two-photon absorption, n — the ion concentration of neodymium), the higher terms of the expansion $\gamma(I)$ for the beams defocussed may be neglected.

The analysis of energy extraction from the medium with the nonlinear losses proportional to the intensity of radiation

In the case of an amplifier, with linear and nonlinear losses proportional to the intensity, the extraction coefficient η takes the form

$$\eta = \frac{1}{s}\left[1 - e^{-X} - \frac{\varrho}{\alpha} X - \frac{\beta A \varepsilon^s}{\alpha \tau_{ef}} X^2\right], \tag{8}$$

where $\varrho = \beta_0$ — the coefficient of linear losses, $\beta = \beta_1$ — the coefficient of nonlinear losses, $A = A_1$. From (8) it follows, among others, that:

— At the absence of nonlinear losses the extraction efficiency is determined uniquely by the ratio α/ϱ and by the relative density of the radiation energy (in the pulse duration intervals, for which the scheme of the amplification does not change essentially, i.e. $s \approx$ constant*).

— Under the condition of nonlinear losses this efficiency depends also on the absolute values of amplifier parameters and on the length and the shape of pulses.

— For three-level amplification scheme a higher extraction efficiency may be expected than in the two-level scheme (at the absence of nonlinear losses–twice).

The dependence of the coefficient η on the relative energy density for several pulse durations of Guassian shape and for the case $\beta = 0$ is shown in fig. 1. Typical parameters of the neodymium glass amplifier: $\alpha = 0.06$ cm^{-1}, $\varrho = 0.01$ cm^{-1}, $\varepsilon^s = 4$ I/cm^2, $\beta = 2 \times 10^{-12}$ cm/W** are assumed as the medium parameters. As it is seen, in the case of pulses of length exceding several nanoseconds, the influence of nonlinear losses on the energy extraction from the discussed amplifier is relatively small. In the case of subnano- and picosecond pulses the influence is very significant. The

* For the neodymium glass amplifiers the characteristic time, in the surrounding of which a change of amplification scheme occurs, is $\tau_d \gtrsim 10^{-8}$ s [12].

** This value of β corresponds to $\sigma_2 = 10^{-32}$ cm^4/W [6], $n = 2 \cdot 10^{20}$ cm^{-3}, for instance.

decrease of τ_{ef} is followed by the reduction of the extraction coefficient and a shift of optimal and limiting values of X towards its smaller values. The dependences of the maximal extraction coefficient η_{max}, and the optimal (X_{opt}) and of limiting (X_{lim}) energy densities on the pulse duration are shown in figs. 2 and 3 (parameters as in fig. 1). The optimal value of energy may be determined from the equation

$$e^{-X} = \frac{\varrho}{a} + \frac{2\beta A\varepsilon^{s}}{a\tau_{ef}} X, \tag{9}$$

while the limiting value is determined by the positive root of the equation

$$\eta(X) = 0. \tag{10}$$

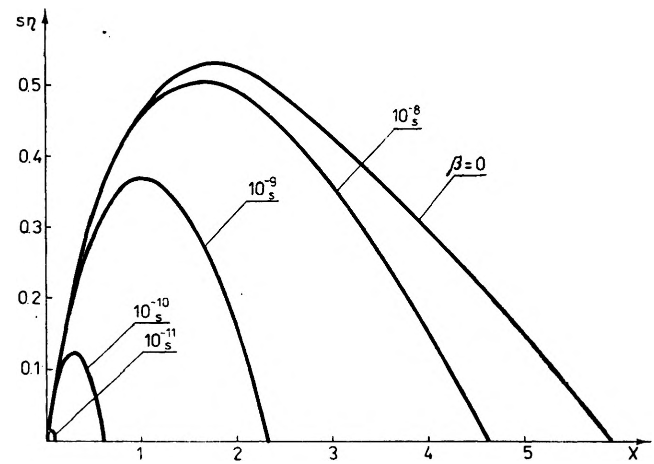

Fig. 1. The dependence of the extraction coefficient on the relative energy density of pulses of various duration

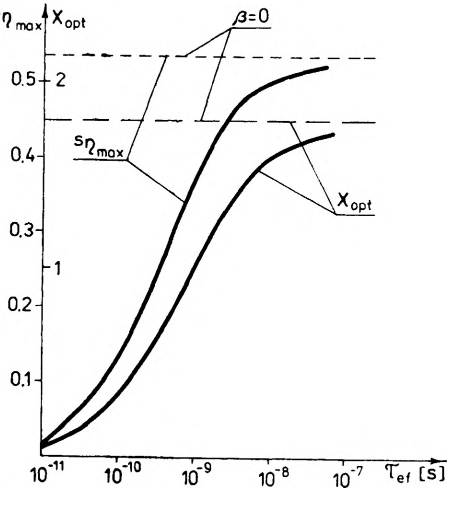

Fig. 2. The dependence of maximal coefficient of extraction and optimal energy density of radiation on the pulse duration

The equations (9) and (10) are the transcedental ones and only their approximate analytic solutions are available. In particular the approximate expression for X obtained from (10) by the method of subsequent approximations has the form

$$X_{\lim} = \frac{1}{2D}\left[\sqrt{B^2+4D-4D\exp\left(\frac{\sqrt{B^2+4D}-B}{2D}\right)}-B\right], \tag{11}$$

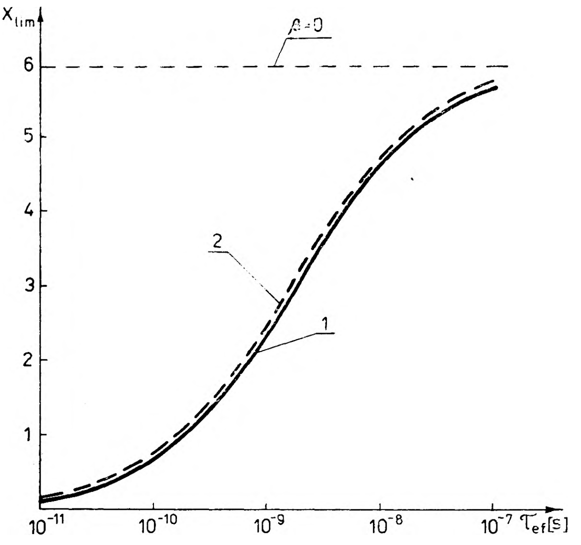

Fig. 3. The limiting energy density of radiation vs. the pulse duration
1 — rigorous relation, 2 — approximate relation

where $B = \varrho/a$, $D = \dfrac{\beta A \varepsilon^s}{a\tau_{\mathrm{ef}}}$. The dependence $X_{\lim}(\tau_{\mathrm{ef}})$ obtained from (11) is presented in fig. 3 with a broken line 2. For typical parameters of the neodymium glass amplifier the formula (11) describes well this dependence for $\tau_{\mathrm{ef}} \gtrsim 10^{-10} s$. At the absence of nonlinear losses the limiting and optimal values of X and the maximal coefficient of extraction are determined by the ratio a/ϱ. The last two quantities are expressed by simple formulae:

$$X_{\mathrm{opt}}(\beta = 0) = \ln\frac{a}{\varrho}, \qquad \eta_{\max}(\beta = 0) = \frac{1}{s}\left[1-\frac{\varrho}{a}\left(1+\ln\frac{a}{\varrho}\right)\right].$$

The influence of the pulse shape (parameter A in the formula (8)) on the efficiency of the energy extraction from the amplifying medium is illustrated in fig. 4. The curves 1, 2, 3 in this figure refer to rectangular, Gaussian, and exponential pulses, respectively, with $\tau_{\mathrm{ef}} = 10^{-10}\ s$. The parameters of the amplifiers are assumed as in fig. 1. The energy extraction efficiency and the optimal and limiting energy densities are here the greater the smaller the slopes of the amplified pulse.

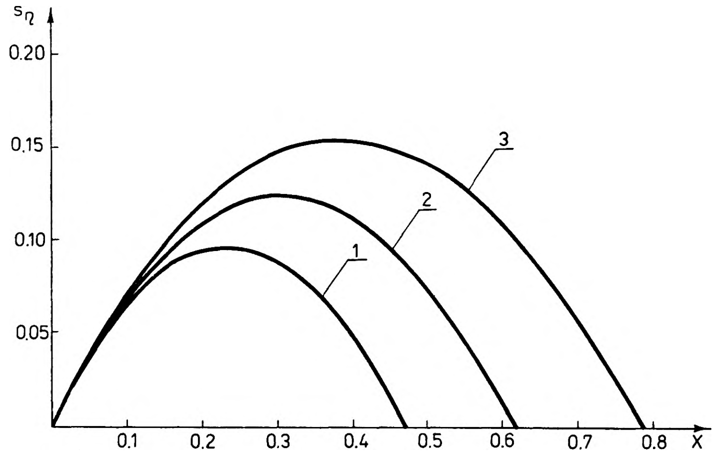

Fig. 4. The extraction coefficient as a function of relative energy density in subnanosecond pulses of various shape

1 – rectangular pulse, 2 – Gaussian pulse, 3 – pulse with exponential slopes

The energy extraction efficiency, both at the presence and absence of the nonlinear losses, increases with the amplification coefficient a. The full curve in fig. 5 shows the influence of this coefficient on the value $\eta_{\max}$ in the case of Gaussian pulse with $\tau_{ef} = 10^{-10}$ and parameters ϱ, ε^s, β specified above. For comparison the dependence $\eta_{\max}(a)$ for the amplifier without nonlinear losses is shown in the same figure with the broken line. The increase of a leads also to the increase of both X_{opt} and X_{lim}. The described above influence of the coefficient a on the parameter characterizing the energy extraction efficiency means that it is more advantageous to concentrate the given pumping energy within a small volume and to

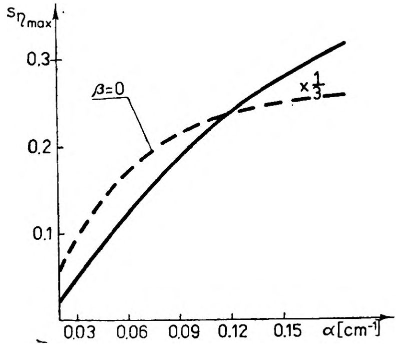

Fig. 5. The dependence of maximum extraction coefficient on the amplification coefficient for subnanosecond pulse

amplify within those volume the radiation of great energy density ($X < X_{opt}$) than to amplify the radiation of small energy density respectively greater aperture in the region of great volume. Of course, there appear some restrictions connected, among others, with the damages in the active material due to its irradiation, thermal deformations of the medium or the existence of parasitic generation in the medium.

As it follows from the formula (8) the energy extraction efficiency from the neodymium glass amplifier depends also upon the cross-section for stimulated emission σ and on active ion concentration n (this last dependence does not exist at the absence of nonlinear losses). Since an increase of n leads to an increase of the loss coefficient β then for subnano- and picosecond pulses a higher amplification efficiency may be obtained in glasses of small ion concentration of neodymium, provided that the lowering of the coefficient a connected with the reduction of n is compensated by an increase of energy density of the pumping radiation or with the increase of the cross-section σ. An increase in values of σ may be obtained by a suitable choice of the glass kind [13, 14]. The increase of σ is also advantageous due to respective lowering of the absolute value of optimal energy density, which has an essential importance in the face of the fact that there exist some restrictions for radiation energy density connected with the damage of the active material.

The differential coefficient of extraction η allows to determine the optimal conditions for energy extraction from the medium and enables the analysis of the influence of parameters of both the medium and pulse on the extraction process. It does not give, however, the complete information about the process of energy extraction from the amplifying system as the whole. Some additional information, important from the practical viewpoints, may be obtained from the analysis of the average coefficient of extraction defined by the formula (7). By substituting the expression (8) to this formula we obtain:

$$s\bar{\eta} = 1 - \frac{1}{2}B(X_1 + X_0) - \frac{1}{3}D(X_l^2 + X_l \cdot X_0 + X_0^2)\frac{e^{-X_0} - e^{-X_l}}{X_l - X_0}, \qquad (12)$$

where $B = \frac{\varrho}{a}$, $D = \frac{\beta A \varepsilon^s}{a\tau_{ef}}$. The formula (12) allows, in particular, to analyse the influence of the energy density of the radiation entering and leaving the system on the efficiency of energy extraction from the amplifiers.

Often, in practice, we have to deal with a situation, when — due to restrictions for the radiation energy density — the output energy density X_l is given. It may be, for instance, the maximum energy density which does not cause any damage (breakdowns) of the active medium. In this situation it is important to determine the input energy density X_0, for which the amplification efficiency in the system is the greatest. The dependence of the average extraction coefficient on the ratio X_0/X_{opt} for the subnanosecond pulse ($\tau_{ef} = 10^{-10}$ s) and four different values of X_l is shown in fig. 6*. The values of parameters α, ϱ, β, ε^s, are assumed as in fig. 1. As it may be seen, in the case when $X_l \leqslant X_{opt}$ the greater the energy density of the radiation at the input of the system the higher is the extrac-

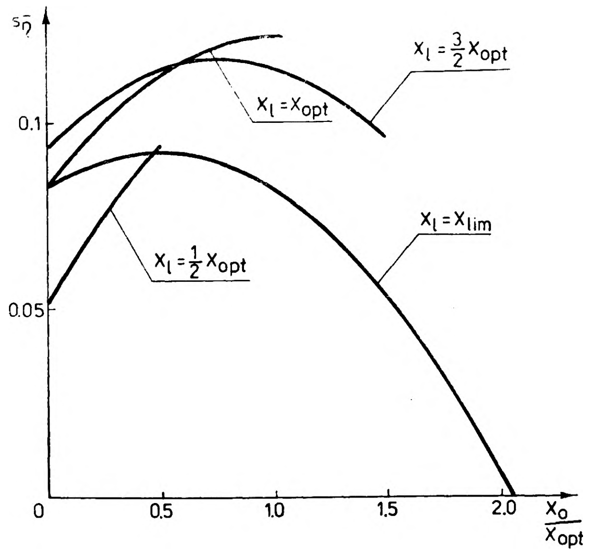

Fig. 6. The dependence of the average extraction coefficient on the radiation energy density at the amplifier input for different values of energy density at the output

tion efficiency (of course, if $X_0 < X_l$). However, if $X_l > X_{opt}$ there exists an optimal value of X_0, different from X_{opt}, for which the average efficiency is the greatest. The formula (12) allows in each concrete case to estimate this value. From fig. 6 and from the formula (12) it follows also that in the case $X_0 \ll X_{opt}$ frequently realized in experiment the highest extraction efficiency may be obtained when the output energy density lies within the range $X_{opt} < X_l < X_{lim}$. There exists also the optimal value X_l in this interval.

The average extraction coefficient depends upon the parameters of the medium and the time characteristic of the pulse in a similar way as the differential coefficient does. In particular, it increases with the increase of the amplification coefficient α and the pulse duration. This last dependence for the case $X_0 \ll 1, X_l$; $X_l = X_{lim}$, and the medium parameters given above is illustrated in fig. 7.

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* X_{opt} is, as previously, a value for which the differential coefficient of extraction is maximal.

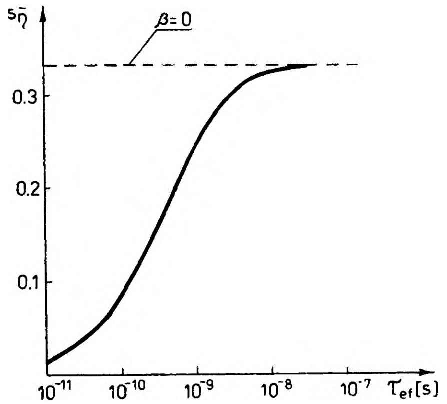

Fig. 7. The average extraction coefficient vs. pulse duration

Experimental results

As it was shown in the previous sections one of the most characteristic symptoms indicating the effect of nonlinear losses on the energy extraction from the amplifying medium is a strong dependence of the extraction coefficient on the pulse duration*. The basic purpose of the experiment described below was to examine this dependence for the amplifier system of neodymium glass.

The energy extraction from the system of four amplifiers (the total length of the active material being 60 cm) has been examined. The examinations were carried out for four kinds of amplified pulses: single picosecond pulse of $\tau_{ef} \approx 50$ ps, a series of picosecond pulses of the envelope length ~ 30 ns, and the single pulse of duration $\tau_{ef} \approx 4$ ns and $\tau_{ef} \approx 30$ ns. The YAG: Nd^{3+} crystal generator working in the regime of passive mode-locking (in the case of picosecond pulse) or active Q-switching (in the case of the nanosecond pulses) was used as the pulse source. The pulse energy at the input of the amplifier system was changed with the help of two amplifiers of the YAG : Nd^{3+} crystal and one amplifier of the neodymium glass. The measuring apparatus allows to measure the pulse energy at the input and output of the system as well as the pulse duration and shape**.

The dependence of the effective extraction coefficient

$$\eta_{ef} = \frac{\Delta E}{E_v} \approx \frac{\Delta E}{\bar{a}\dfrac{\hbar\omega}{\sigma}V}, \tag{13}$$

(where ΔE – the increment of the total pulse energy in the system, $E_v = \hbar\omega\overline{N^0}V$ – the energy stored in the amplifiers, V – the volume of

* For fixed parameters of the amplifier and the ratio $\varepsilon/\varepsilon^s$.

** A detailed description of the experimental system is presented in [9].

the active medium, $\bar{a}$ — the average coefficient of the system amplification for a small signals, σ — the cros-section for stimulated emission in the neodymium glass) on the effective length and energy of the pulse and on the amplification coefficient $\bar{a}$ has been examined. The coefficient $\bar{a}$ is determined from amplification and transmission measured in the system of amplifiers for small signal. The effective extraction coefficient defined by the formula (13) may be treated as proportional to the average coefficient $\bar{\eta}$ determined in the previous sections, thereby the fundamental qualitative features of the dependence of η_{ef} upon the pulse parameters and the amplifiers should be the same as for the coefficient $\bar{\eta}$*.

The dependence of the extraction coefficient η_{ef} on the effective pulse length is presented in fig. 8. The sets of points denoted by numbers 1, 2, 3 correspond to the following input pulse energies: 5 mJ, 20 mJ, and 50 mJ, the same for all the four kinds of pulses. In this figure the value of $\tau_{ef} \approx 2 \cdot 10^{-10}$ s is associated with the series of picosecond pulses (this is the effective pulse duration understood as the energy-to-power-ratio).

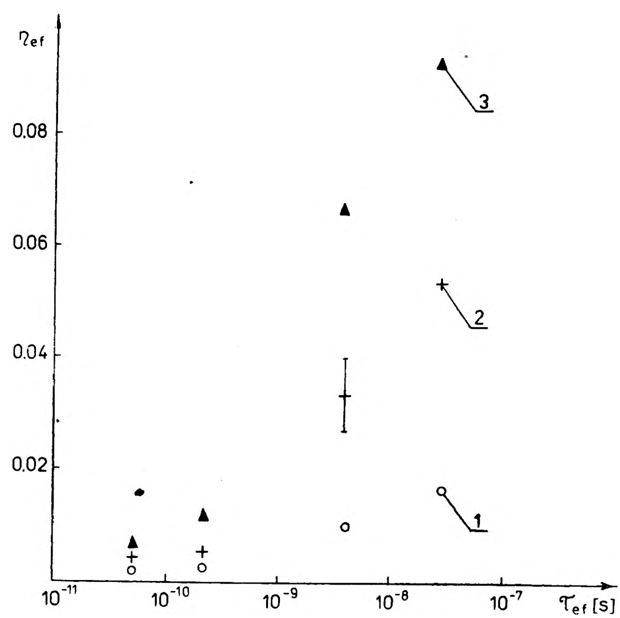

Fig. 8. Experimental dependence of the effective extraction coefficient upon the pulse duration for different values of radiation energy entering the system of amplifiers 1 — $E^0 \approx 5$ mJ, 2 — $E^0 \approx 30$ mJ, 3 — $E^0 \approx 50$ mJ

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* The values of η_{ef} are determined also by the spatial radiation characteristics and, in particular, by the shape of the transversal distribution and the ratio of the effective aperture of the beam to the amplifier aperture (which is, of course, not taken into account in $\bar{\eta}$, as it is the value obtained from the one-dimensional equation).

The most characteristic feature presented in this dependence is the strong increase of the extraction efficiency when passing from the picosecond to nanosecond pulses, foreseen in the previous section. It is also visible that for the same length of the envelope (~ 30 ns) the pulse composed of a series of picosecond pulses is amplified much more weakly than a single pulse. This means that the differences in the amplification scheme and the values ε^s for the picosecond and nanosecond pulses have a secondary influence as compared with the effect of nonlinear losses on the extraction efficiency of this pulses. It seems that the change in the value of ε^s may be an essential cause of differences in η_{ef} values for the four-nanosecond pulse ($\tau_{ef} < \tau_d$) and thirty-nanosecond pulse ($\tau_{ef} \lesssim \tau_d$), for which the nonlinear losses are relatively low. The results presented in fig. 8 may be also influenced by the differences in the spectrum width of the examined pulses. Taking account of the fact that both for the picosecond pulses (used in the examinations) and for the nanosecond pulses the spectrum width is much less than the luminescence line width of neodymium glass, this influence should not be too strong.

The figure 9 illustrates the influence of the amplification coefficient $\bar{a}$ upon the extraction efficiency for a nanosecond pulse of energy ~ 40 mJ (the point set denoted by the number 1) and ~ 170 mJ (the point set denoted by number 2). In both cases the extraction coefficient increases distinctly with the increase of $\bar{a}$.

Both in fig. 8 and 9 it may be seen that the extraction efficiency increases with the increase of the input energy, which is in accordance with the theoretical picture of the phenomenon for the case of input radiation energy densities considerably less than the optimal ones realized in the experiment.

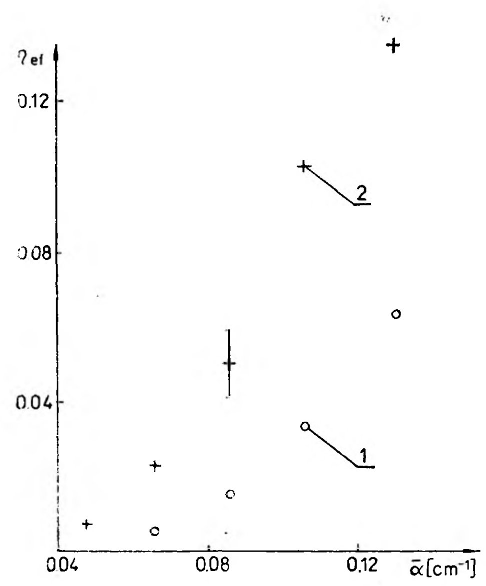

Fig. 9. Experimental dependence of the effective extraction coefficient upon the average coefficient of system amplification
1 – $E^0 \approx 40$ mJ, 2 – $E^0 \approx 170$ mJ

Concluding remarks

In this paper both the theoretical analysis and experimental investigations of the problem of energy extraction from the amplifying medium at the presence of nonlinear losses have been reported. The general expression for the extraction coefficient found from the energy balance equations was used to analyse in details the problem of energy extraction from the medium with losses proportional to the radiation intensity. It has been shown that the nonlinear losses lead to essential dependence of the extraction efficiency and the optimal and limiting radiation energy density upon the length and shape of the pulse. The conditions have been defined under which the energy extraction efficiency from the medium may be the greatest. The results of the experiment carried out in the system of neodymium glass amplifiers are qualitatively consistent with the results of calculations.

The theoretical considerations presented in this work were concerned with the case of the medium in which the dependence of the loss coefficient upon the intensity may be represented in the form of a power series. In the real systems this dependence may be also of a more complex nature. The analysis of such cases must be carried out separately, nevertheless some general conclusions reported in this paper and in particular the conclusions concerning the dependence of the extraction efficiency and the optimal and limiting radiation energy density upon its time characteristics may find an application also in those cases.

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Влияние нелинейных потерь на экстракцию энергии из усиливающей среды

В работе произведён анализ экстракции энергии из усиливающей среды в условиях наличия квазистационарных нелинейных потерь излучения. Найдено общее выражение для коэффициента экстракции, на основе которых подробно проанализирован вопрос экстракции энергии из среды с потерями, пропорциональными интенсивности излучения.

Показано влияние параметров среды и импульса, а в частности его длины и формы, на коэффициент полезного действия экстракции, а также определены условия, при которых к. п. д. является максимальным.

Приведены результаты экспериментальных исследований зависимости коэффициента экстаркции от длины и энергии импульса, а также коэффициента усиления в системе усилителей на неодимном стекле.