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STUDY OF DIRECT AMPLIFICATION OF ULTRASHORT LIGHT PULSES IN A LASER AMPLIFIER WITH A VIEW TO OBTAINING HIGH RADIATION CONTRAST

V. V. Ivanov, A. V. Koutsenko, A. A. Matsveiko, Yu. A. Mikhailov, A. I. Popov, G. V. Sklizkov, and A. N. Starodub

P. N. Lebedev Physical Institute, Russian Academy of Sciences
Leninskii Pr. 53, Moscow 119991, Russia
e-mail: mikh@sci.lebedev.ru

Abstract

An amplification scheme for ultrashort laser pulses of high radiation contrast was used to perform experiments on ablation pressure symmetrization using a prepulse upon acceleration of thin foils. It is shown that the spontaneous radiation of the regenerative amplifier restricts the energy contrast in the amplification of chirped pulses at a level of $10^{-4} - 10^{-3}$. The possibility of direct amplification of a short pulse with a view to increasing the energy contrast ratio was considered. Experiments were performed on the "PICO" laser facility to demonstrate that a 10-ps pulse amplification achieved an intensity $\geq$100 GW/cm^2, a gain factor of 1.2, and an inversion dumping factor >30%.

Keywords: ultrashort laser pulses, chirped pulses, energy contrast, symmetrization, direct amplification.

1. Introduction

Modern pico- and femto-second solid-state laser facilities are built on the basis of amplification of the so-called chirped pulses [1–3]. This technique allows one to obtain laser pulses of petawatt power with energy above a kilojoule at target intensity $>10^{21}$ W/cm^2. However, the realization of high-energy contrast at the irradiated target is a serious problem for such facilities. High laser-radiation contrast is important as in studies of heating and compression of thin shell targets (see, for example, [4]) and in experiments on modeling physical processes accompanying target compression. In particular, the investigations on ablation pressure symmetrization performed on the "PICO" laser facility [5] using a prepulse upon acceleration of thin foils, which resemble shell targets, have shown that a high contrast of the fundamental (heating the target) laser pulse is very important for the correct analysis of its influence on symmetrization. Symmetrization using a controllable prepulse is presumed to be an effective method to suppress the appearance of nonhomogeneous target heating due to the presence of laser beam speckles [6].

If the intensity contrast is on the level of 10^{-7}–10^{-6} one can observe the appearance of a parasitic pedestal and prepulses due to several reasons. First, the spectral limitation at stretching and compression of the pulse and the phase distortions in the optical path are responsible for a pedestal with a duration of tens and hundreds of picoseconds. Second, the limited contrast of a Pockels cell in the regenerative amplifier leads to pulse "leakage" and the appearance of a background prepulse. Third, the pedestal of a

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femtosecond oscillator and the "noise" of spontaneous radiation of the regenerative amplifier are amplified in the process of amplification of the "chirped" nanosecond pulse. This results in the appearance of a noncontrollable nanosecond pedestal after compression [1–3, 7–9].

The increase in the spectral transmission band of the pulse stretching and compression system and the compensation of higher-order dispersions and phase distortions in the system make it possible to decrease the first factor to an acceptable level [2]. Using additional high-contrast Pockels cells one can suppress a prepulse produced by the regenerative amplifier. However, it is difficult to eliminate the third factor in traditional schemes of generation and amplification of the chirped pulse. Being compressed, an amplified spontaneous radiation of a few nanosecond duration may contain an energy comparable to the energy of the fundamental femtosecond pulse.

A method for increasing the contrast ratio was realized in [7]. In this method, a 3-nJ pulse of a femtosecond generator was amplified up to the microjoule level, then it was filtered by a saturable absorber to suppress the background pedestal, and finally extended to nanosecond duration to be amplified by a regenerative amplifier. The amplification of the refined pulse with energy three orders higher than that formed by a traditional scheme made it possible to increase the contrast ratio 10^2 times. The spontaneous radiation noise in the regenerative amplifier and the possibility of direct amplification to increase the energy contrast ratio are considered, and the direct amplification of picosecond pulses at an output radiation flux density greater than 100 GW/cm^2 is demonstrated.

2. Spontaneous Radiation and Contrast of the Regenerative Amplifier

At present, regenerative amplifiers using a sapphire crystal activated by titanium ions as the active medium are the most widespread. The contrast of such an amplifier is determined by the ratio of the input signal energy to the spontaneous radiation energy. The power of spontaneous radiation per unit volume of the active medium is equal to

$$\rho_0 = \frac{d\varepsilon}{dt} = \frac{\varepsilon}{\tau}\,, \tag{1}$$

where τ is the ion lifetime at a metastable level, ε is the metastable specific energy that can be found from a weak signal amplification coefficient $G_0 = \exp\left(l\sigma\varepsilon \,/\, h\nu\right)$, σ is the stimulated radiation cross section, $h\nu$ is the photon energy, and l is the amplifier active medium length. Integrating the radiation over the volume of the homogeneous active medium $V = S_0 l = \pi d^2 l\,/4$, where d is the beam diameter, and taking into account signal amplification along its propagation, one can evaluate the spontaneous radiation power after the first passage P_{nl} into a small solid angle $\Delta\Omega$ within a spectral interval $\Delta\nu$:

$$P_{n1} = \frac{S_0 h\nu\,\Delta\nu}{\sigma\tau\nu_{\text{eff}}}\,\frac{\Delta\Omega}{4\pi}\,(G_0 - 1)\,, \tag{2}$$

where ν_{eff} is the effective luminescent linewidth of the amplifying medium. In a multi-passage amplifier, the spontaneous radiation noise is added to the amplified signal at any passage. The intensity of spontaneous radiation is decreased with every passage by the value of the gain coefficient. The spontaneous radiation power after m passages is equal to

$$P_n = \left(P_{nl} + \frac{P_{nl}}{G_0} + \ldots + \frac{P_{nl}}{G_0^{m-1}}\right) G_0^{m-1} \approx P_{nl}\,\frac{G_0^m}{(G_0 - 1)}\,. \tag{3}$$

Let us substitute Eq. (2) into Eq. (3). Dividing the expression obtained by the gain coefficient value G_0^m and by the factor of 2, which takes into account the linear polarization, we obtain the noise power of the multi-passage amplifier normalized to the input power:

$$P_n = \frac{\Delta\Omega}{4\pi} S_0 \frac{h\nu\,\Delta\nu}{\sigma\tau\nu_{\text{eff}}}\,. \tag{4}$$

Let us use the relation between parameters Ω, τ, and λ^2 [6, 7]

$$\sigma = \frac{1}{8\pi c n^2} \frac{\lambda^4}{\lambda_{\text{eff}}\tau} = \frac{1}{8\pi n^2} \frac{\lambda^2}{\tau\nu_{\text{eff}}}\,, \tag{5}$$

where λ_{eff} is the effective luminescence linewidth. Substituting (5) into (4), we obtain

$$P_n = \Delta\Omega\, S_0 \frac{h\nu\,\Delta\nu\, n^2}{\lambda^2}\,. \tag{6}$$

As is shown in [10], the value $\lambda^2/(S_0 n^2)$ corresponds to the solid angle of a blackbody single-mode radiation, i.e., the noise power per one mode of the radiation equals

$$P_0 = h\nu\,\Delta\nu. \tag{7}$$

The noise power per single-mode radiation does not depend on the parameters of the active medium and amplifier parameters and is determined by the transmission band and quantum energy.

Let us consider a plane wave passing through the aperture d. The solid angle $\Delta\Omega = \pi\alpha^2/4 \approx 0.61^2\pi\lambda^2/(dn)^2$ corresponds to the plane-wave diffraction divergence $\alpha \approx 1.22\lambda\,/\,(dn)$. Substituting the value of the solid angle into Eq. (6), we obtain

$$P_0 = \left(\frac{0.61\pi}{2}\right)^2 h\nu\,\Delta\nu. \tag{8}$$

The coefficient $(0.61\pi/2)^2 \approx 0.92$ corresponds approximately to a single radiation mode. For a real amplifier, it is necessary to take into account the resonator mode, shape of the spatial distribution of the pumping radiation, and the solid angle selected by spatial filters placed between amplifiers.

2.1. Sapphire:Ti Amplifier at $\lambda = 1054$ nm (Band $\Delta\lambda = 5$ nm)

As Eqs. (7) and (8) correspond to the radiation at the maximum of the luminescent line, we shall make estimates using formula (4). Let us substitute the value of the solid angle, which corresponds to the plane wave diffraction divergence in Eq. (4),

$$P_n = \frac{0.62^2\pi}{32} \frac{\lambda^2}{n^2} \frac{h\nu}{\sigma\tau} \frac{\Delta\nu}{\nu_{\text{eff}}}\,. \tag{9}$$

Using the data of [8], one obtains $\sigma = 2.6 \cdot 10^{20}$ cm^2 with account for the superluminescence lifetime $\tau = (1/\tau_0 + 0.0137E_p)$. Here $\tau_0 = 3.1$ μs, $E_p = 2 \cdot 4.7$ J/cm^2, $n = 1.76$, and the luminescence line profile is characterized by $\Delta\nu/\nu_{\text{eff}} \approx 1.9 \cdot 10^{-3}$. Substituting these parameters in Eq. (6), we obtain

$P^{1054}_{\text{Ti:Sa}} = 0.8 \cdot 10^{-6}$ W. For the spontaneous emission time Δt_{se} and for the signal energy E_0 the energy contrast ratio is equal to

$$K_{\text{se}} = \frac{P^{1054}_{\text{Ti:Sa}} \Delta t_{\text{se}}}{E_0}\,. \tag{10}$$

As is measured in [1], the spontaneous radiation pulse fractional energy is $2 \cdot 10^{-5}$–$2 \cdot 10^{-4}$ relative to the main pulse energy. Substituting the data of [1], $\Delta t_{\text{se}} = 4$ ns, $E_0 = 0.3$ nJ, and $P^{1054}_{\text{Ti:Sa}} = 0.8 \cdot 10^{-6}$ W, in relation (10) we obtain, in this case, the maximum contrast ratio $K_{\text{se}} = 1.1 \cdot 10^{-5}$.

2.2. Sapphire:Ti Amplifier at $\lambda = 780$ nm (Band $\Delta\lambda = 20$ nm)

Substituting the values $\sigma = 2.6 \cdot 10^{-19}$ cm^2, $\tau = 2.2$ μs, and $K_{\Delta\nu} \approx 0.077$ from [8] in formula (9), one obtains $P^{1054}_{\text{Ti:Sa}} = 2.4 \cdot 10^{-6}$ W. At the same time, using formula (8), we obtain $P^{780}_{\text{Ti:Sa}} = 2.3 \cdot 10^{-6}$ W, which is close to the above one. In accordance with Eq. (10), the radiation contrast ratio is equal to $3.2 \cdot 10^{-5}$ when the spontaneous radiation pulse duration is about 4 ns and the input pulse energy is about 0.3 nJ.

2.3. Nd-Glass Amplifier at $\lambda = 1054$ nm (Band $\Delta\lambda = 2.3$ nm)

For neodymium glass active media, it is necessary to take into account the branching of spontaneous emission through several channels, and the nonradiative quenching of excitation from the metastable level. For phosphate glass active media, the branching coefficient is $K_b = 0.46 - 0.51$ and the nonradiative transition coefficient is $K_n = 0.6 - 1$, that is, $P_{\text{Nd}} = P_\Sigma = K_n \cdot K_b$. Choosing $K_b = 0.48$ and $K_n = 0.8$ and using the parameters of LG750 phosphate glass $\sigma = 3.7 \cdot 10^{-20}$ cm^2, $\tau = 347$ μs, and $K_{\Delta\nu} = 0.088$, one obtains, from Eqs. (8) and (9), $P_{\text{Nd}} = (0.8 - 1.7) \cdot 10^{-7}$ W. The immediate measurements of the spontaneous radiation power in a regenerative multipassage phosphate-glass amplifier (without considering the amplification saturation) resulted in the value $P_{\text{Nd}} = 4 \cdot 10^{-7}$ W [11].

3. Optical Parametric Amplifier

Optical parametric amplifiers based on LBO or KDP crystals can have a gain coefficient of the order of 10^3–10^5 [12]. In the majority of cases they are used instead of a regenerative amplifier. The noise of a parametric amplifier is caused by quantum-mechanical disintegration of the pump-wave quantum [10, 13]. It can be reduced to the noise at the amplifier input with zero oscillation energy $h\nu/2$ for every oscillation mode of the signal and idle waves or with an energy equal to the quantum $h\nu$ for every mode of the input signal wave. The number of oscillation modes in k-space is about $dN = Vk^2 dk/\left(2\pi^2\right)$; then the noise power at the signal input is

$$P = dN\, h\nu\, \frac{c}{Vn}\, \frac{\Delta\Omega}{4\pi}\, S_0 = \frac{n^2}{\lambda^2}\, h\nu\, \Delta\nu\, \Delta\Omega. \tag{11}$$

The substitution of the solid angle corresponding to the diffraction of a plane wave, $\Delta\Omega \approx 0.61^2 \pi \lambda^2/(dn)^2$, into the last equation yields formula (8).

4. Influence of Oscillator Contrast

Let us consider the contribution of the oscillator to the general contrast of the laser system based on amplification of a “chirped” pulse. The measurements performed for oscillators with Kerr lens mode-locked synchronization revealed a pedestal at the level $K_i = 10^{-8} - 10^{-9}$ [7, 14]. Pulse stretching up to 2–3 ns by a pair of diffraction gratings showed that a part of the pedestal (half duration of the stretched pulse) entered in the same time interval as the main pulse, i.e., the pedestal turns out to be inside the chirped pulse. At a pedestal intensity level $K_i = 10^{-9}$, pedestal duration $\Delta t_n = 1$ ns, and pulse duration $\Delta t_p = 100$ fs, the pulse energy contrast can be evaluated as $K_e = K_i \Delta t_n / \Delta t_p = 10^{-5}$. The oscillator pedestal is summed up with the spontaneous emission noise and is amplified concurrently with the main pulse.

5. Direct Amplification as a Method for Laser Contrast Enhancement

As is mentioned above, the presence of the noise of the regenerative amplifier spontaneous emission and the pulse radiation pedestal restricts the level of the radiation energy contrast ratio to a value of the order of 10^{-4}–10^{-3}. A major improvement in the contrast ratio can be achieved by transformation of the femtosecond pulse radiation into the second harmonic [15], but this is accompanied by sophisticated experimental difficulties and a decrease in energy efficiency.

Another method was proposed in [7] for improvement of the pulse radiation contrast ratio relative to both the oscillator noise and the laser short pulse pedestal. The femtosecond-pulse radiation of the oscillator was amplified up to 3 μJ and then it was “purified” of the pedestal by a saturable absorber filter. After that, a “pure” laser pulse with energy about a microjoule was extended to nanosecond duration and then amplified by a regenerative amplifier. In such a scheme, one could achieve both a suppression of the oscillator pulse radiation pedestal and a significant decrease of the regenerative amplifier noise. The direct amplification of the femtosecond-pulse radiation up to the millijoule level should allow one to exclude the regenerative amplifier from the optical scheme and to obtain pulses with a contrast ratio better than 10^{-9}.

The laser radiation intensity in a short amplifier of optical length $L \sim 1$ cm is limited by beam disintegration due to the small-scale self-focusing and by the optical breakdown at the surfaces of the optical elements. Data on the radiation strength of a fused quartz and a few laser glasses were obtained in [16–18] for the range of light pulse duration from 10 ns to 100 fs. It was observed that the threshold energy density E_d of the surface optical breakdown within the range of pulse duration from 10 ps to 10 ns is proportional to Δt_p, where Δt_p is the half height laser pulse duration. The curve of the dependence of the breakdown energy density on the pulse duration goes to saturation at $\Delta t < 5$ ps. The threshold intensity of the surface damage due to breakdown $E_d \geq 2$ J/cm^2 is within the range of pulse duration from 100 fs to 1 ps. Thus, the surface damage threshold exceeds, by intensity, 200 GW/cm^2 for a 10-ps pulse and $I_d > 2 \cdot 10^4$ GW/cm^2 for a 100-fs pulse.

Let us evaluate the limitation of the radiation intensity by small-scale self-focusing through the delay integral B. The integral B is no longer limited due to the phase modulation when a femtosecond pulse is amplified directly in a linear system of successive amplifiers. In the exponential amplification approximation and for a small value of αL we obtain

$$B = \frac{2\pi}{\lambda}\,\gamma \int\limits_0^L I\,dl = \frac{2\pi}{\lambda}\,\frac{\gamma I_0}{\alpha}\left(e^{\alpha L} - 1\right) \approx \frac{2\pi}{\lambda}\,\gamma I_0 L. \tag{12}$$

For neodymium glass $\gamma = (1.5 - 2.5) \cdot 10^{-16}$ cm^2/W [9] and for sapphire crystal $\gamma = 3.3 \cdot 10^{-16}$ cm^2/W [8]. For $B = 2$ and active optical length $L = 1$ cm, we obtain the allowable value of the flux density $I_0 = 100$ GW/cm^2.

We shall use Eq. (12) to determine the B-integral in a multistage (or multipassage) amplifier. If the radiation intensity at the last stage is I_0 and the integral is B_0, then in the preceding cascade these values are less by a factor G, that is, I_0/G and B_0/G, etc. By analogy with Eq. (5), we obtain the total decay integral $B_\Sigma = B_0 G/(G-1)$ accumulated in all passages through every active media. Assuming the complete final integral $B_\Sigma = 3$ and decreasing it by the factor $G/(G-1) = 3$ with $G = 1.5$, one obtains $B_0 = 1$. As a result, the radiation intensity in the last amplifier is $I_0 = 50$ GW/cm^2.

6. Experimental

Let us consider the possibility of direct amplification using as an example a neodymium glass active medium. The transmission band of the neodymium glass makes it possible to achieve a 150-fs pulse duration [19]. The amplification band can be extended up to 5–8 nm by a combination of different types of the glass [20]. At present neodymium glass is the only active medium that allows one to obtain radiation pulses of 300–500-fs duration at the kilojoule energy level (see, for example, [1, 3]).

When the second harmonic of Nd-laser radiation with nanosecond pulse duration is used to pump a Nd-glass active medium, the amplification gain α per unit length can be estimated as follows:

$$\alpha = \frac{\sigma E_{0.53}}{h\nu\,L}\,K_1 K_2 K_3, \tag{13}$$

where $E_{0.53}$ is the pumping energy density of the second harmonic radiation, K_1 is the pumping radiation absorption coefficient, $K_2 = 0.5$ is the pumping quantum efficiency, and the coefficient $K_3 = \exp\left(-\tau_1/\tau\right)$ takes into account the decay of inversion from a metastable level with time τ to the moment of inversion dumping, which is delayed by the time τ_1 relative to the pumping pulse. The coefficient K_1 depends on the type of neodimium glass and its active thickness. For $K_1 = 0.5$, $K_3 = 1$, $\sigma = 3.2 \cdot 10^{-20}$ cm^2, and active optical length $L = 1$ cm, one obtains $\alpha \approx 0.04 E_{0.53}$ cm^{-1}. This results in the value of the amplification gain coefficient $G = \exp(\alpha L) \approx 1.5$ at unit length ($L = 1$ cm), when the pumping energy density equals $E_{0.53} = 10$ J/cm^2.

The nonlinear processes occurring in the active medium along the amplification path and the absorption from the metastable level can reduce the efficiency of the short-pulse amplification when the Nd-glass radiation intensity is rather high. Moreover, when the pulse duration $\tau_p < 10$ ps, the lifetime of the lower laser level $^4I_{11/2}$ is significantly higher than τ, whereas the Stark-sublevel relaxation time is less than $\tau_s < 10^{-12}$ s. In this connection we conducted measurements of the inversion dumping time evolution at a radiation intensity greater than 100 GW/cm^2. Selective pumping with the second harmonic has been used in the experiments to make the value of the efficiency more accurate.

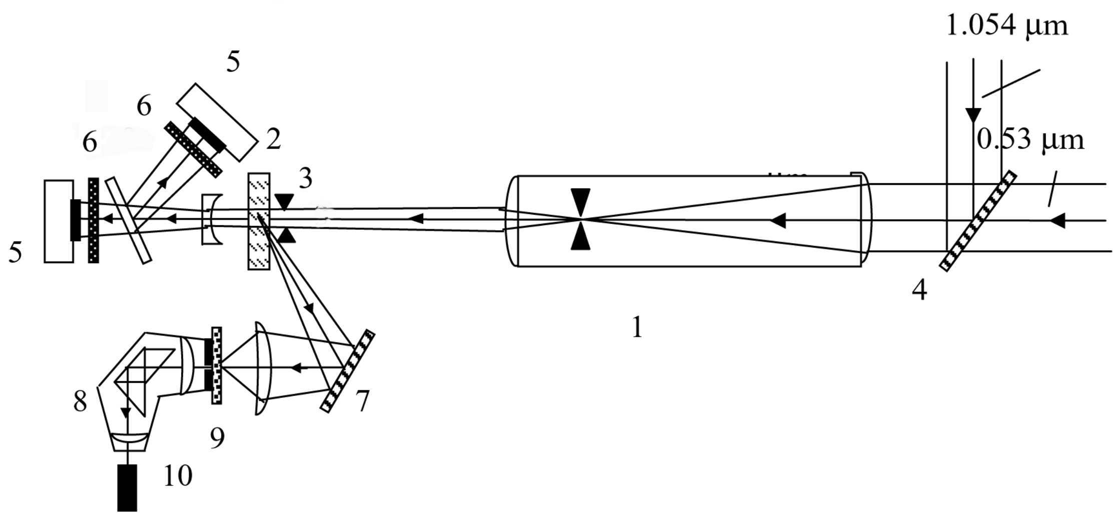

Fig. 1. Optical scheme of an arrangement for studying inversion dumping efficiency in a Nd-glass sample pumped by second-harmonic radiation.

6.1. Measurements of the Inversion Dumping

Figure 1 shows the optical scheme of the experimental set-up for measurements of inversion dumping by the action of a 10-ps pulse of coherent radiation. The population inversion density was observed from the temporal evolution of the luminescence from the ${}^4F_{3/2}$ metastable level of the Nd^{3+} ion. In order to avoid distortion of the final signal due to "hole burning" in the luminescence line shape, the transition ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ corresponding to a wavelength of 0.88 μm was used. This transition is weakly correlated with the main working transition ${}^4F_{32} \rightarrow {}^4I_{11/2}$ at the wavelength $\lambda = 1.06$ μm [21] and is not deformed with change in the population inversion density.

A light pulse of 10-ps duration generated by a high-power phosphate Nd-glass laser, which is an important component of the "PICO" laser installation, was used to trigger population inversion. A vacuum spatial filter 1 with a collimation number 3:1 was used to increase the light flux density and to diminish self-focusing perturbations of the wave front. The collimator is defocused to form a slightly divergent beam. A diaphragm 3 with a diameter of 2.5 mm was placed in front of a Nd-glass sample 2. The diaphragm cuts off the central part of a picosecond beam to provide a homogeneous spatial profile of the intensity distribution. This diaphragm also causes the picosecond beam to be spatially coincident with the pumping beam ($\lambda = 0.53$ μm). In such a scheme the overall inversion of the entire pumped volume of the Nd-glass sample was dumped in the same laser shot. The second harmonic of a silicate neodymium nanosecond pulsed laser was used to pump the Nd-glass sample. The pumping radiation was directed into the spatial filter through a selective dielectric mirror 4. This radiation propagated along the same optical path as the picosecond pulse. The energy of the laser pulse that duped the inversion in sample 2 was measured by calorimeters 5 with selective light filters 6 before them.

The luminescence of the sample under investigation was collected by a spherical aluminum mirror 7 and was focused on the slit of a prism monochromator 8. A narrow-band dielectric light filter 9 at the

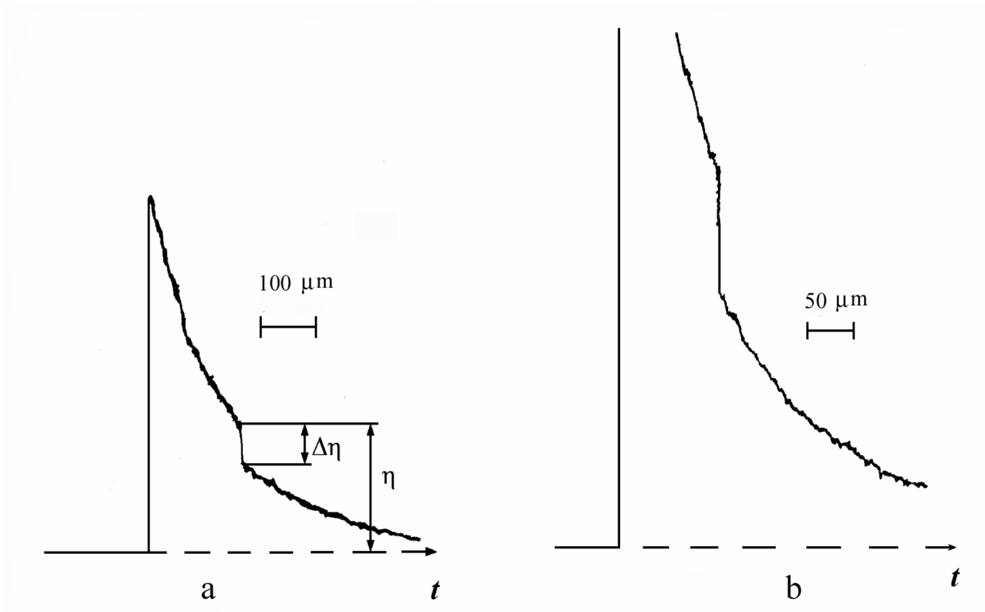

Fig. 2. Qualitative oscillograms of the luminescence time evolution in GLS21 (a) and KNFS8 (b) glasses (arbitrary units).

monochromator slit was used to diminish the influence of the background scattered powerful radiation at a wavelength $\lambda = 1.054$ μm. The 0.88-μm luminescence line was recorded by a photomultiplier 10 with an oscilloscope with time resolution ≤ 1 μs. The monochromator was tuned to the center of the Nd-glass luminescent line when the sample was pumped by the green harmonic of a repeatable YAG:Nd^{3+} laser used to adjust the laser system.

The time delay between the pumping pulse and the pulse that initiates the inversion dumping was 200 μs. In the general case, the initial profile of the luminescence line with narrow-band laser pumping can differ from the stationary profile [22]. It should be mentioned that the cross-relaxation processes of energy transfer between Nd^{3+} ions in the active medium reduce the luminescence line to its stationary form in a time of the order of 10^{-4} s. In that case, one can compare the results obtained with the data of [23] obtained by flash-lamp pumping of a sample.

The typical inversion time evolutions in the phosphate glass samples under investigation are illustrated in Fig. 2. A sharp leading edge corresponds to pumping by a 20-ns laser pulse. Here we have assumed that fast relaxation to the metastable level $^4F_{3/2}$ of Nd^{3+} ion is not greater than 10^{-9} s. An exponential decrease with a characteristic time about 350 μs corresponds to the relaxation time from the metastable level of the GLS21 phosphate glass (Fig. 2a). The sharp vertical step on the left oscillogram is the result of the inversion dumping by the picosecond transmitting pulse.

Samples made of two types of phosphate glass, GLS21 and KNFS8, were studied in these experiments. The inversion dumping efficiency at energy density $E = 1 - 2$ J/cm^2 corresponding to light flux density $I = 100 - 200$ GW/cm^2 reaches 20–30% without detectable optical breakdown of the glass surface. The dependence of the inversion dumping $\Delta\eta$ for GLS21 on the energy density is illustrated by the open circles in Fig. 3. The filled circle denotes the burn on the glass surface resulting from optical breakdown at a flux density level greater than 200 GW/cm^2.

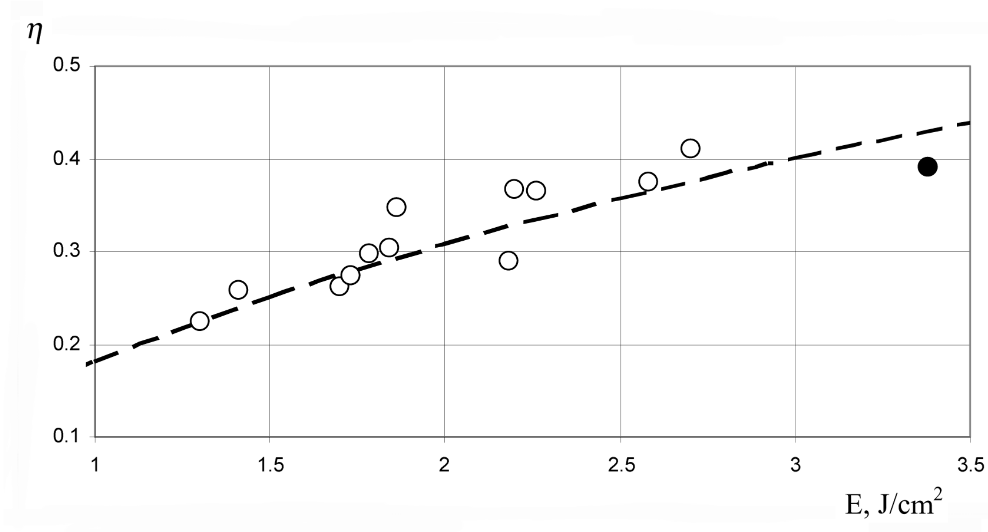

Fig. 3. Experimental dependence of the inversion dumping η (E) in GLS21 glass on the radiation energy density for a 10-ps laser pulse (circles). The dotted line demonstrates the dependence η (E) plotted from the data of [20] at σ $(0) = 4.2 \cdot 10^{-20}\, cm^2$.

A linear dependence of the value $N(0)/N(E)$ on the energy density for the phosphate and silicate glasses was derived in [21, 23]:

$$\frac{N(0)}{N(E)} = 1 + \sigma(0)\,\frac{E}{h\nu}\,, \tag{14}$$

where $N(0)$ and $N(E)$ are the initial and final inversion and $\sigma(0)$ is the constant derived from the experiment.

The dotted curve in Fig. 3 corresponds to the dependence of the inversion dumping factor $\eta = [N(0) - N(E)]/N(0)$ on the energy density. This dependence has been found experimentally using 50-ns and 6-μs pulse durations of the inversion dumping radiation (see, for example, [23]). Our data for a 10-ps pulse duration coincide with those within the experimental discrepancy. The samples of GLS21 and GLS22 glasses used had different concentrations of Nd^{3+} ions. The coincidence of our data with those mentioned above can be explained by fast relaxation between Stark components of the laser levels in spite of the fact that the radiation pulses were distinguished by pulse durations greater than three orders. The calculations performed using the numerical code described in [24] taking into account the luminescence line structure show that the difference in the inversion dumping factors for a long laser pulse (in comparison with the lifetime of the lower laser level) and for a short laser pulse averages between 10% and 15% at least at the level of the input energy density E of the order of 1 J/cm^2.

6.2. Amplification of a Picosecond Pulse in the Laser Pumped Nd Glass

The immediate measurements of a 10-ps light pulse amplification at laser pumping of a Nd-glass plate have been performed using calorimeters. The registration scheme is shown in Fig. 4. A laser beam with aperture 45 mm in diameter is introduced into the vacuum spatial filter 1. A phosphate Nd-glass plate 2 is placed instead of a lens at the output of the filter. The central part of the beam is cut off by a diaphragm 3 placed in front of the filter input that illuminates a small area of the plate 2. The diameter of the laser

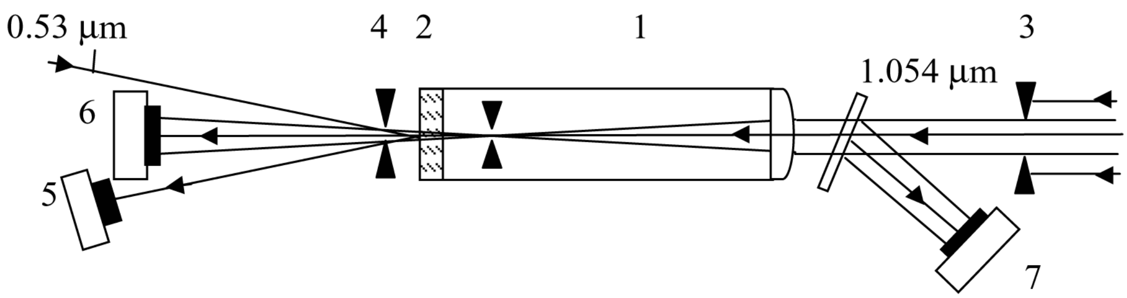

Fig. 4. Optical scheme of an arrangement for measuring the amplification gain of a 10-ps laser pulse in the Nd-glass plate at high radiation intensity density.

illuminated area at the plate plane is close to 2 mm. A diaphragm 4 of diameter 3 mm centered with the diaphragm 3 is placed just behind the plate 2. The pumping laser pulse is directed onto the output surface of the Nd-glass plate 2. The pumping radiation energy incident on an area of diameter 3 mm is measured with calorimeter 5 by reflection from the output surface of the plate 2. The transmission coefficient of the system is measured by calorimeters 6 and 7. The amplification factor is defined as the ratio of the transmission coefficient of the spatial filter with the pumped active element (plate 2) to its transmission coefficient in the absence of pumping. The value of the transmission coefficient has been averaged over a series of 5–6 independent shots.

The first series of measurements was taken with a plate of GLS21 glass of 1 cm thickness and with a delay of the amplified pulse relative to the pumping pulse equal to $\tau_1 = 200$ μs. The amplification factor $G = 1.12$ and the parameter $\alpha = 0.113$ cm^{-1} were measured at a pumping radiation energy density of 5.1 J/cm^2. The parameter α increases up to 0.17 cm^{-1} when the delay time τ_1 shortens to 30 μs at the same energy density. The calculations performed by Eq. (13) at these specified conditions yield the values $\alpha = 0.12$ cm^{-1} and 0.2 cm^{-1}, respectively. We emphasize that the radiation intensity is greater than or equal to 100 GW/cm^2.

The second series of measurements with KNFS8 glass and time delay $\tau_1 = 30$ μs gives $G = 1.2$ and $\alpha = 0.182$ cm^{-1}. In spite of the fact that in this case the radiation pumping energy density is less than in the GLS21-glass sample, the energy density per unit volume stored at the metastable level remained the same due to the large absorption coefficient K_1. The high gain coefficient of the KNFS8 glass results from the large cross section of the stimulated transition.

7. Discussion and Conclusions

The spontaneous radiation power emitted into the diffraction angle by a regenerative amplifier both with a sapphire crystal activated by titanium or with a neodymium glass rod and by a parametric amplifier ranges within $P \sim h\nu\,\Delta\nu$. The spontaneous radiation of the regenerative amplifier can limit the energy contrast by $10^{-4} - 10^{-3}$ depending on the pedestal duration, radiation beam divergence, and input laser-pulse energy density. One can achieve an increase in the contrast ratio by several orders by a preliminary amplification of a short pulse and by subsequent pulse "purification" by a saturable absorbing filter [7].

The experimental data and the appropriate estimates performed in the present work have shown that it is possible to realize the preliminary direct amplification of a short pulse with a radiation intensity density up to 100 GW/cm^2 by such a scheme. An inversion dumping in phosphate glass up to 30% and a gain of 1.2 have been achieved with a radiation intensity density greater than 100 GW/cm^2 when a 10-ps pulse was amplified. The increase in pumping energy density along with the two-lateral pumping show the promise of increasing the amplification gain up to $G = 1.5$.

At a radiation intensity of 50 GW/cm^2 and a pulse duration of 100 fs, an output power of 10 mJ corresponds to a laser beam area of 2 cm^2 and a diameter of 1.6 cm. At present, this is not a problem because the laser pumping is applied to pump amplifiers with an aperture up to 10 cm [2].

Note that, in such a scheme, one can apply a compact optical-fiber femtosecond generator with a low radiation contrast ratio. Moreover, one can use a parametric amplifier for preliminary amplification of a low intensity signal. When the parametric amplifier is pumped by a short picosecond pulse, the nanosecond pedestal of the master oscillator must be suppressed by a value of the gain coefficient up to 10^3–10^5 [12]. The inherent noise of the amplifier manifests itself only as a subpicosecond prepulse.

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