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Direct amplification of picosecond pulses in neodymium glass with a power density above 100 GW cm^{-2}

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***Abstract*. A scheme for amplification of ultrashort laser pulses is studied, which is used in experiments on symmetrisation of ablation pressure with the help of a prepulse upon acceleration of foils by laser radiation of high brightness. The possibility of direct amplification of short pulses before their expansion in order to increase the energy contrast is considered. In experiments performed on the PICO facility, the amplification of a 10-ps pulse with a power density exceeding 100 GW cm^{-2} is demonstrated with the gain equal to 1.2 and the inversion drop above 30 %.**

Keywords: *ultrashort laser pulses, amplification of laser pulses, laser plasma heating, interaction of radiation with matter.*

1. Introduction

Modern picosecond and femtosecond solid-state laser facilities are based on the principle of amplification of chirped pulses [1 – 3]. This method provides the generation of petawatt laser pulses with the energy above one kilojoule, which produce the power density on a target exceeding 10^{21} W cm^{-2}. One of the important problems involved in these studies is the production of a high energy contrast for a laser pulse irradiating a target. A high contrast of laser pulses is important both in studies on the heating and compression of thin-wall shell targets (see, for example, Ref. [4]) and in experiments modelling physical processes in such targets. In particular, to analyse correctly the influence of the prepulse on symmetrisation processes in PICO experiments [5] on the symmetrisation of ablation pressure using a prepulse upon acceleration of thin foils imitating shell targets [5], it is very important to have the main (heating the target) pulse with high contrast. The theoretical analysis shows that the prepulse can reduce the inhomogeneity of the target heating caused by the presence of speckles in a laser beam [6, 7].

The appearance of a pedestal and prepulses, when the intensity contrast is equal to $10^{-7} - 10^{-6}$, is caused by several reasons. First, by the restriction of the spectrum during the pulse extension and compression and by phase distortions in the optical path, which produce a pedestal of duration of tens and hundreds of picoseconds. Second, by the limited contrast of the optical Pockels gate in a regenerative amplifier resulting in the pulse 'leakage' and the appearance of a prepulse. Third, by the pedestal amplification appearing upon generation of the driving femtosecond pulse and by the noise of spontaneous emission of the regenerative amplifier, which is amplified together with a chirped nanosecond pulse and produces a nanosecond pedestal after compression [1 – 3, 8, 9].

The influence of the first factor can be reduced down to the level of 10^{-8} in intensity by increasing the width of the transmission band of a system for extension and compression of pulses and compensating the higher-order dispersion and phase distortions in the optical path [2]. The use of additional Pockels cells with a high contrast provides the suppression of the prepulse appearing due to the pulse 'leakage' from the regenerative amplifier and ensures the contrast at a level of 10^{-9}. However, the third factor cannot be eliminated within the framework of a conventional scheme for generation and amplification of chirped pulses. After compression, amplified spontaneous emission of duration a few nanoseconds can contain the energy comparable with that of the main femtosecond pulse.

The authors of Ref. [8] enhanced the pulse contrast by amplifying a 3-nJ pulse from a femtosecond laser up to the microjoule level, then eliminating a pedestal using a saturable absorber, expanding the pulse to the nanosecond duration, and amplifying it again in the regenerative amplifier. The amplification in the regenerative amplifier of a 'pure' pulse with the energy three orders of magnitude greater than in a conventional scheme resulted in the contrast enhancement by a factor of 100. Taking into account the real pulse energy losses during chirping and phase-matching losses upon the signal injection into the regenerative amplifier, the spontaneous emission noise of the regenerative amplifier and the pedestal of the oscillator restrict the energy contrast of radiation at the level $10^{-4} - 10^{-3.}$ The contrast can be substantially improved by converting an ultrashort pulse into the second harmonic. However, this involves severe technical problems and can be performed at present only when the pulse energy does not exceed 20 J [10].

In this paper, we studied the possibility of a direct amplification of picosecond pulses in a neodymium glass to enhance the pulse contrast and demonstrated a direct amplification of picosecond pulses with a power density above 100 GW cm^{-2}.

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2. Direct pulse amplification as a method for the pulse contrast enhancement

The direct amplification of a femtosecond pulse up to the millijoule level allows one to exclude a regenerative amplifier from the optical scheme and amplify chirped pulses with contrast exceeding 10^{-9} directly in final cascades.

The intensity of laser radiation in a short ($L \sim 1$ cm) amplifier is restricted by the disintegration of the laser beam due to small-scale defocusing and optical breakdown of a surface. The surface radiation resistance of fused silica and laser glasses irradiated by 10-ns – 100-fs laser pulses was studied in papers [11 – 13]. The threshold density E_d of the optical breakdown for 10-ps – 10-ns pulses is proportional to the square root of the laser pulse duration $\Delta t_\mathrm{p}^{1/2}$. For $\Delta t_\mathrm{p} < 5$ ps, the dependence $E_\mathrm{d}(\Delta t)$ is saturated and the damage threshold proves to be constant and equal to $E_\mathrm{d} \geqslant 2$ J cm^{-2} for 100-fs – 1-ps pulses. Thus, the damage threshold for a 10-ps pulse exceeds 200 GW cm^{-2}, while for 100-fs pulse this threshold is 2×10^4 GW cm^{-2}.

Let us estimate the restriction imposed on the radiation intensity by small-scale self-focusing from the value of the decay integral B. In the case of direct amplification of a femtosecond pulse, the restriction on the integral B is eliminated because of phase modulation. In the approximation of exponential amplification and a small value of the product of the gain α by the active medium length L, we have

$$B = \frac{2\pi}{\lambda}\frac{\gamma I_0}{\alpha}\left(\mathrm{e}^{\alpha L} - 1\right) \approx \frac{2\pi}{\lambda}\gamma I_0 L. \qquad (1)$$

For neodymium glasses and a sapphire crystal, $\gamma = (1.5 - 2.5) \times 10^{-16}$ [14] and 3.3×10^{-16} cm^2 W^{-1} [9], respectively. For $B = 2$ and $L = 1$ cm, we obtain $I_0 = 100$ GW cm^{-2}.

Let us estimate from (1) the integral B in a multistage (or multipass) amplifier. If the radiation intensity, the decay integral, and the gain in the last stage are I_0, B_0, and G, respectively, then these quantities in a previous stage are I_0/G, B_0/G, etc. As a result, we obtain that the integral accumulated after all the passes is $B_\Sigma = B_0 G/(G-1)$. Assuming that $B_\Sigma = 3$ and reducing this value by the factor $G/(G-1) = 3$, we obtain $B_0 = 1$ for $G = 1.5$ and the radiation intensity in the last stage is $I_0 = 50$ GW cm^{-2}.

3. Specific properties of direct amplification in Nd : glass lasers

Consider the possibility of direct pulse amplification in a neodymium glass. The transmission band of a neodymium glass makes it possible to obtain 150-fs pulses [15], and a combination of glasses of different types allows the generation of even shorter pulses [16]. Neodymium glass is the only active medium in which 300 – 500-fs pulses can be obtained with energies of up to kilojoule [1, 3]. Because Ti : sapphire amplifiers have a low cross section for stimulated emission at the 1.055-μm wavelength of a neodymium laser ($\sigma = 2.6 \times 10^{-20}$ cm^2 [9]), it is worthwhile to use them for direct amplification to enhance the contrast only at a wavelength of 800 nm [8]. The stimulated emission cross section of a phosphate glass is almost half as much, so that a neodymium glass is a good medium for the contrast enhancement.

Upon pumping by a nanosecond second-harmonic pulse from a neodymium laser, the gain per unit length is

$$\alpha = \frac{\sigma E_{0.53}}{h\nu L} K_1 K_2 K_3, \qquad (2)$$

where $E_{0.53}$ is the pump energy density; K_1 is the absorption coefficient for pump radiation; $K_2 = 0.5$ is the coefficient of pump-photon utilisation; and $K_3 = \exp(-\tau_1/\tau)$ is the coefficient taking into account the decay of inversion of a metastable level with the lifetime τ at the instant delayed by τ_1 with respect to the pump beginning. The coefficient K_1 depends on the type of the active neodymium glass element and its length. For $K_1 = 0.5$, $K_3 = 1$, $\sigma = 3.2 \times 10^{-20}$ cm^2 and $L = 1$ cm, we obtain $\alpha \approx 0.04 E_{0.53}$ cm^{-1}. For $E_{0.53} = 10$ J cm^{-2}, the gain G over the length 1 cm is $\exp(\alpha L) \approx 1.5$.

When the intensity of radiation in a neodymium glass is high, nonlinear processes and absorption from the metastable level can reduce the gain of short pulses. In addition, for $\sim$ 10-ps pulses, the gain can be reduced because the lifetime of the lower $^4I_{11/2}$ laser level is substantially longer than the pulse duration, and the four-level scheme of laser levels of the Nd^{3+} ion will operate as a three-level scheme. For this reason, we measured the inversion drop and the gain of a 10-ps pulse for the radiation intensity exceeding 100 GW cm^{-2}.

4. Experimental results

4.1 Measurement of the inversion drop

Fig. 1 shows the optical scheme of the setup for measuring the inversion drop produced by a 10-ps pulse. The inversion drop was measured from luminescence of Nd^{3+} ions from the metastable $^4F_{3/2}$ level. To avoid the distortion of results caused by hole burning in the luminescence band, we detected luminescence at the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition at a wavelength of 0.88 μm. This transition is weakly correlated with the operating 1.06-μm $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition [17] and the corresponding luminescence band is not distorted during the inversion drop.

The inversion drop was produced by a high-power 10-ps pulse from a Nd : phosphate glass laser included in the PICO facility. Spatial filter (*1*) with the collimation coefficient 3 : 1 defocused to obtain a weakly convergent

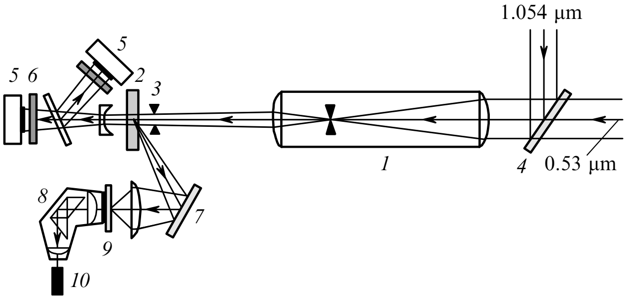


Figure 1. Optical scheme of the setup for studying the inversion drop: (*1*) spatial filter; (*2*) neodymium glass sample; (*3*) aperture; (*4*) selective mirror; (*5*) calorimeters; (*6*) optical filter; (*7*) aluminium mirror; (*8*) prism monochromator; (*9*) narrow-band filter; (*10*) photomultiplier.

beam was used to increase the intensity and eliminate the wave-front perturbations appearing upon self-focusing. In front of neodymium glass sample (*2*), 2.5-mm aperture (*3*) was mounted, which separated the central region of the picosecond beam with a homogeneous spatial profile. This aperture was also used for the spatial combining of the picosecond pulse with the 0.53-μm pump pulse. In this scheme, the inversion drop occurred within the entire pumped volume of the neodymium glass.

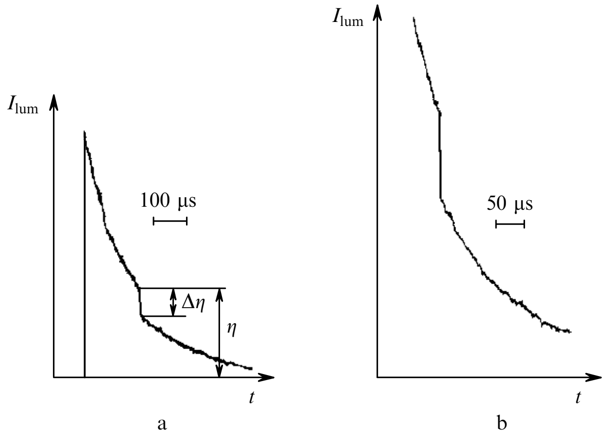
Pump radiation was directed to the spatial filter through selective mirror (*4*) by the same optical path as the picosecond pulse. The energy of the pulse dropping the inversion in sample (*2*) was measured with calorimeters (*5*).

Luminescence of the sample was collected with spherical aluminium mirror (*7*) and focused on the entrance slit of prism monochromator (*8*). The stray laser light at 1.054 μm was rejected by narrow-band optical filter (*9*) mounted in front of the entrance slit of the monochromator. The luminescence at a wavelength of 0.88 μm was detected with photomultiplier (*10*) and a storage oscilloscope with the time resolution no more than 1 μs. The monochromator was tuned to the centre of the luminescence band of a neodymium glass under study by pumping the glass by the green harmonic from a repetitively pulsed Nd^{3+} : YAG laser.

The delay between the pump pulse and the inversion-drop pulse was 200 μs. Upon narrow-band laser pumping, the initial shape of the luminescence band can differ from the stationary band shape [18]. However, after $\sim 10^{-4}$ s, due to cross relaxation energy transfer between Nd^{3+} ions in the glass, the luminescence band acquires the stationary shape. In this case, we can compare our results with the data [19] obtained upon flashlamp pumping.

Fig. 2 shows the oscillograms of the inversion-drop pulse in a GLS21 phosphate glass. A sharp leading edge corresponds to pumping by the 20-ns pulse and fast relaxation to the metastable $^4F_{3/2}$ level for the time no longer than 10^{-9} s. The time of the exponential decay equal to 350 μs corresponds to the relaxation time of the metastable level in the GLS21 glass. A step in the decay curve corresponds to the drop of inversion by the picosecond pulse.

The inversion drop in GLS21 and KNFS8 phosphate glasses achieved 20 % – 30 % for the energy density $E = 1-2$ J cm^{-2} ($I = 100-200$ GW cm^{-2}) without the optical breakdown of the glass surface. The dependence of the inversion drop η on the energy density E in the GLS21 glass for this case is shown by open circles in Fig. 3. The dark circle corresponds to the appearance of a burn on the rear surface of the glass.



a b

Figure 2. Oscillograms of luminescence in GLS21 (a) and KNFS8 (b) glasses.

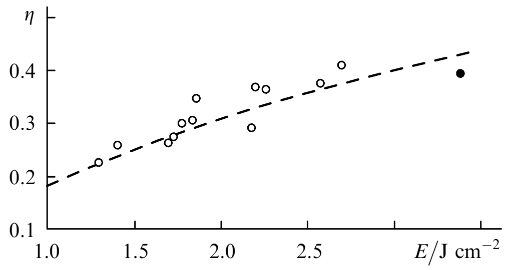


Figure 3. Experimental dependences of the inversion drop η on the radiation energy density E for a 10-ps laser pulse (circles) in the GLS21 glass. The dashed curve shows the dependence $\eta(E)$ for $\sigma(0) = 4.2 \times 10^{-20}$ cm^2 [17].

The authors of papers [17, 19] obtained the linear dependence of the ratio $N(0)/N(E)$ of the initial and final inversion levels on the energy density for phosphate and silicate glasses

$$\frac{N(0)}{N(E)} = 1 + \sigma(0)\,\frac{E}{h\nu}, \tag{3}$$

where $\sigma(0)$ is an empirical constant.

The dashed curve in Fig. 3 corresponds to the experimental dependence of the inversion drop $\eta = [N(0) - N(E)]/N(0)$ produced by 50-ns and 6-μs pulses in the GLS22 glass [19]. Our data obtained for the 10-ps pulse coincide with these data within the experimental error (GLS21 and GLS22 glasses differ by concentrations of Nd^{3+} ions), which can be explained by fast relaxation of excitation over the Stark components of laser levels. Numerical calculations performed using the model [20] taking into account the structure of luminescence bands show that, for $E = 1$ J cm^{-2}, the difference in the inversion drop produced by long (compared to the lower-laser level lifetime) and short laser pulses is 10 % – 15 %.

4.2 Amplification of picosecond pulses in a neodymium glass upon laser pumping

The amplification of a 10-ps light pulse in a neodymium glass plate pumped by a laser was measured with calorimeters on the setup shown in Fig. 4. The light beam of diameter 45 mm entered into vacuum spatial filter (*1*) with neodymium phosphate plate (*2*) mounted at

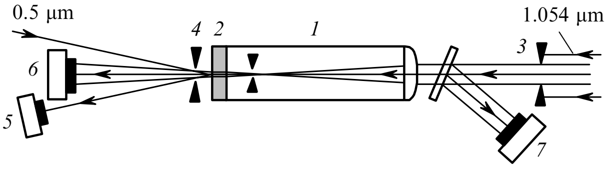


Figure 4. Optical scheme of the setup for measuring the amplification of the 10-ps pulse in a neodymium glass plate: (*1*) spatial filter; (*2*) phosphate glass plate; (*3*) aperture; (*4*) 3-mm aperture; (*5–7*) calorimeters.

its output instead of a lens. Aperture (*3*) placed in front of the spatial filter selected the central part of the beam, reducing the beam diameter on the plate down to 2 mm. 3-mm aperture (*4*), aligned with aperture (*3*), was placed directly behind plate (*2*). The pump energy incident on an area of diameter 3 mm and the gain of the system were measured with calorimeters (*5*), (*6*), and (*7*). The gain was averaged over five-six individual measurements.

We found from a series of measurements performed with the GLS21 glass plate of thickness 1 cm, when the amplified pulse was delayed by $\tau_1 = 200$ μs with respect to the pump pulse, that $G = 1.12$ and $\alpha = 0.113$ cm^{-1} for the pump energy equal to 5.1 J cm^{-2}. When the delay time was reduced down to 30 μs, the pump energy density being invariable, the value of α increased up to 0.17 cm^{-1}. The calculations by expression (2) give in these cases $\alpha = 0.12$ and 0.19 cm^{-1}, respectively. The radiation intensity did not exceed 100 GW cm^{-2}.

In the second series of measurements with the KNFS8 glass for the delay $\tau_1 = 30$ μs, we obtained $G = 1.2$ and $\alpha = 0.182$ cm^{-1}. In this case, the pump energy density was lower than that in the GLS21 glass. However, due to a greater absorption coefficient K_1, the energy accumulated on the metastable level per unit volume remained the same. A greater amplification observed in the KNFS8 glass is explained by a greater cross section for the stimulated transition in this glass.

5. Conclusions

Our experiments have shown that pulses of intensity above 100 GW cm^{-2} can be directly amplified in a neodymium glass. The inversion drop produced by a 10-ps pulse of such intensity in a phosphate glass amounted to 30 % and the gain was 1.2. The gain $G = 1.5$ can be expected with increasing pump energy density and using two-side pumping.

For the power density of a 100-fs pulse equal to 50 GW cm^{-2}, the output energy 10 mJ corresponds to the area of 2 cm^2 and the beam diameter of 1.6 cm. At present, such parameters can be easily obtained because lasers are used for pumping amplifiers with an aperture up to 10 cm [2].

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References

1. Pennington D.M., Brown C.G., Cowan T.E., et al. *IEEE J. Sel. Topics Quantum Electron.*, **6**, 676 (2000); Key M.H., Cable M.D., Cowan T.E., et al. *Phys. Plasmas*, **5**, 1966 (1998).
2. Bonlie J.D., Patterson F., Price D., White B., Springer P. *Appl. Phys. B*, **70**, S155 (2001).
3. Blanchot N., Rouyer C., Sauteret C. *Opt. Lett.*, **20**, 395 (1995).
4. Basov N.G., Kalashnikov M.P., Mikhailov Yu.A., Sklizkov G.V., Fedotov S.I. *Trudy FIAN*, **203**, 3 (1990).
5. Ivanov V.V., Kutsenko A.V., Lebo I.G., Matsveiko A.A., Mikhailov Yu.A., Osetrov V.P., Popov A.I., Rozanov V.B., Sklizkov G.V., Statodub A.N. *Zh. Eksp. Teor. Fiz.*, **116** (10), 1287 (1999).
6. Lebo I.G., Rozanov V.B. *J. Russian Laser Research.*, **22** (4), 346 (2001).
7. Lebo I.G., Iskakov A.B., Mikhailov Yu.A., Rozanov V.B., Starodub A.N., Sklizkov G.V., Tishkin V.F., Zvorykin V.D. *Proc. SPIE XXVII ECLIM* (USA, 2003).
8. Itatani J., Faure J., Nantel M., Mourou G., Watanabe S. *Opt. Commun.*, **148**, 70 (1998).
9. Stuart B.C., Herman S., Perry M.D. *IEEE J. Quantum Electron.*, **31**, 528 (1995).
10. Neely D., Allott R.M., Clarke R.J., et al. *Laser Particle Beams*, **18**, 405 (2000).
11. Tien A.C., Backus S., Kapteyn H., Murnane M., Mourou G. *Phys. Rev. Lett.*, **82**, 3883 (1999).
12. Stuart B.C., Feit M.D., Herman S., et al. *Phys. Rev. B*, **53**, 1749 (1996).
13. Ivanov V.V., Mikhailov Yu.A., Osetrov V.P., et al. *Kvantovaya Electron.*, **22**, 589 (1995) [*Quantum Electron.*, **25**, 562 (1995)].
14. Brown D.C. *High-Peak-Power Nd:Glass Laser Systems* (Berlin, Heidelberg, New York: Springer-Verlag, 1981).
15. Keller U., Weingarten K.J., Kartner P., et al. *IEEE J. Sel. Topics Quantum Electron.*, **2**, 435 (1996).
16. Blanchot N., Rouyer C., Sauteret C., Migus A. *Opt. Lett.*, **20**, 395 (1995).
17. Rudnirskii Yu.P., Smirnov R.V., Sokolov V.I. Preprint IAE (3094) (Moscow, 1979).
18. Brawer S.A., Weber M.J. *Appl. Phys. Lett.*, **35**, 31 (1979).
19. Alekseev N.E., Gapontsev V.P., Zhabotinskii M.E. *Lazernye fosfatnye stekla* (Laser Phosphate Glasses) (Moscow: Nauka, 1980).
20. Ivanov V.V., Senatskii Yu.V., Sklizkov G.V. *Kvantovaya Elektron.*, **13**, 647 (1986) [*Sov. J. Quantum Electron.*, **16**, 422 (1986)].