GENERATION AND AMPLIFICATION OF HIGH-INTENSITY LIGHT PULSES IN NEODYMIUM GLASS

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Experimental investigation of nonlinear amplification of high-intensity light pulses in a neodymium glass active medium is reported. The shift of pulse maximum as a function of gain is measured and the energy of gain saturation of neodymium glass is estimated. Conditions are obtained for pulse shortening in nonlinear amplification. The oscillator and multistage amplifier generating light pulses with the energy of 100 J and a length of 5 nsec are described.

1. INTRODUCTION

THE theoretical and experimental investigation of nonlinear amplification of light pulses is reported in [1,2]. This research led to a method of increasing the laser power by shortening the pulse in the course of nonlinear amplification. Experimental realization of this method yielded light pulses of 7–8 GW [2] from ruby crystals used as the active medium. However the light flux of such power damaged the crystals and this damage prevented the achievement of higher power levels.

The present paper reports on the investigation of nonlinear amplification of light pulses in glass activated by neodymium [3,4]. This research was undertaken to increase the output power of a laser and resulted in the construction of a laser capable of emitting a 100 J light pulse 5 nsec long at half amplitude with a divergence angle not exceeding 20′.

A series of properties of neodymium glass renders it particularly attractive for use in high-power lasers. Neodymium glass can be used to prepare rods of practically any length and cross section. The length of the rods yields the required gain. An increase of the cross section of the amplifier rod makes it possible to pass high-power light fluxes without significant damage. As compared to ruby, glass has a higher optical quality that secures a considerably lower divergence of the output emission.

The $\lambda = 1.06\ \mu$ Nd^{3+} ion line in glass has a width of about 200 Å that is due to the splitting of the ion levels in glass and to inhomogeneous broadening caused by field differences at the Nd^{3+} ion sites. Homogeneous broadening has a width of about 20 Å for this line at room temperature. Consequently considerable energy can be stored in neodymium glass for a given gain and population inversion losses due to spontaneous emission gain [5].[1)]

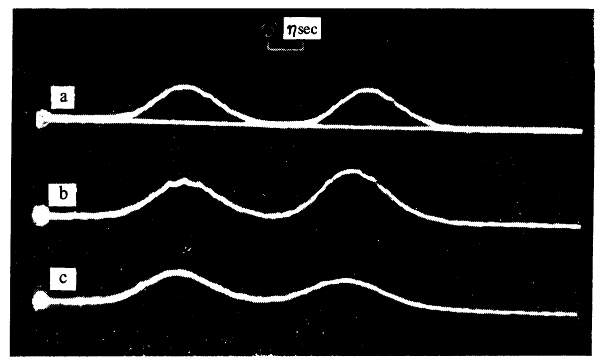

FIG. 1. Oscilloscopic traces of the input (left) and amplified (right) light pulses. (a) signal attenuated at input 3800 times; (b) signal attenuated 5 times; (c) full signal at input.

2. EXPERIMENTAL INVESTIGATION OF NONLINEAR AMPLIFICATION OF LIGHT PULSES IN NEODYMIUM GLASS

The propagation of a light pulse was investigated in an amplifier consisting of three neodymium glass rods 30 mm in diameter and 600 mm long each. The ends of the rods were cut at the Brewster angle. Each rod was pumped by four straight lamps with a total pump energy of 60 Kj. At this energy level the total gain K of the three rods was K = 5000 for a weak signal. A light pulse from a laser with a Kerr cell similar to that described in [6] was admitted to the input of the amplifier. The pulse length at half amplitude was 30 nsec in our experiments. The light beam from the oscillator passed through an additional Kerr cell synchronized with the laser shutter and serving to decouple the oscillator from the amplifier during the pumping period. At the input to the amplifier the beam was limited by a diaphragm with a diameter $d_{in} = 5$ mm in order to keep the diverging beam away from the lateral walls of the amplifier. The output diameter of the beam was $d_{out} = 15$ mm. The energy density at the input to the amplifier was $\epsilon_0 = 0.5\ J/cm^2$. The input signal was attenuated with calibrated neutral filters.

The input and output signals were recorded on the oscilloscope screen. The output signal was delayed 96 nsec by a delay line. Figure 1 a shows an oscilloscope trace of the input and output pulses when the attenuation of the input signal was $\eta = 3800$, Fig. 1 b

[1)]In the case of inhomogenous broadening of the line the change in pulse energy with nonlinear amplification is somewhat different than in the case of a homogeneous broadening. For example nonlinear amplification of a monochromatic signal results in a "hole" burned in the amplification line and the width of the "hole" increases with rising pulse energy. We can show that this causes an almost quadratic dependence of pulse energy on the amplification length in the nonlinear region until the "hole" width approaches the total width of the amplification line. After that the energy increase is linear just as in the case of homogeneous broadening until energy saturation due to emission losses is reached reached.

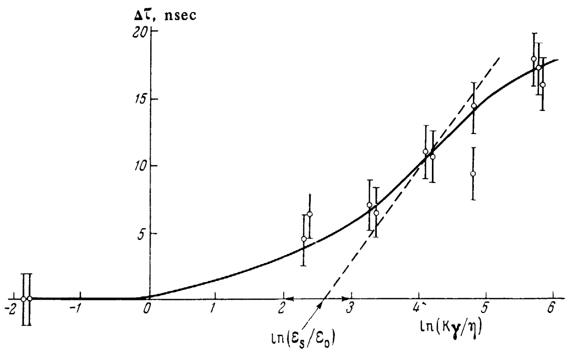

FIG. 2. Shift between the peaks of input and output pulses as a function of input energy density.

shows the traces for $\eta = 5$ and Fig. 1c shows the case of an unattenuated input signal. These traces show that the shape of the amplified pulse is similar to that of the input pulse. The peak of the output pulse of the unattenuated input signal is shifted 17 nsec backward in relation to the signal that was attenuated 3800 times.

Figure 2 shows the shift $\Delta\tau$ between the peaks of the input and output pulses as a function of the input signal energy. The backward shift is absent in the linear amplification region where the pulse energy density at the amplifier output, $\epsilon = \epsilon_0 K\gamma/\eta$ (ϵ_0 is the energy density at amplifier input, and $\gamma = (d_{in}/d_{out})^2$ accounts for the attenuation of energy density due to divergence), is much lower than the gain saturation energy ϵ_S.[2)]

A shift appears as the pulse energy rises and within the region of nonlinear amplification where $\epsilon > \epsilon_S$ the shift $\Delta\tau$ as a function of the nonlinear amplification length L_{nl} can be described by[1]:

$$\Delta\tau = \tau_0 \alpha_0 L_{nl}, \tag{1}$$

where τ_0 is the slope of the exponent of the leading pulse edge, α_0 is the initial gain per unit length, and L_{nl} is the distance traveled by the pulse with energy $\epsilon > \epsilon_S$ in the medium. In our case this shift depends linearly on $\ln(K\gamma/\eta)$:

$$\Delta\tau = \tau_0 \ln\left(\frac{\varepsilon_0}{\varepsilon_s} K \frac{\gamma}{\eta}\right). \tag{2}$$

This linear region on the experimental curve (Fig. 2) occupies a small interval of values of $\ln(K\gamma/\eta)$. The observed deviation of the experimental points from a straight line in the case of small attenuation of the signal can be explained by a coupling between the amplifier and oscillator. The coupling occurs after the synchronized opening of the electrooptical shutters and reduces gain because of supperradiance when the filter attenuation is small.

The saturation energy ϵ_S can be estimated when the remaining parameters are known by using (2) to approximate the experimental points in the nonlinear amplification region. The measurement of the rate of increase τ_0 contributes the greatest error here. This is due to the fact that the value of $\tau_0 \approx 10$ nsec as measured on the oscilloscopic trace of Fig. 1 is really a cross sectional average of the beam, while in (1) and (2) τ_0 is the rate of intensity increase at a point in the cross section. As we know[7,8] the rate of intensity increase of the emission from the entire rod end can be significantly different from that at a point due to the transverse development of generation. To obtain a more accurate value of τ_0 we recorded the pulse shape in various regions of the cross section of the input beam using the 0.5 mm diameter diaphragm. The resulting values of τ_0 ranged from 5 to 10 nsec. Taking the average value of 7 nsec as τ_0 we plot function (2) which is the dashed straight line in Fig. 2. The point of intersection of this line with the abscissa yields the value of saturation energy $\epsilon_S \approx 7$ J/cm^2. The low accuracy in the determination of τ_0 defines a range of values of $\epsilon_S = 7 \pm 3$ J/cm^2. The obtained value of the saturation energy is in agreement with Mauer's data on the absorption cross section for Nd^{3+} ions in glass at the wavelength $\lambda = 1.06\ \mu$[9] and with the data of Young and Kantorski[10].[3)]

The existence of a transverse structure in the oscillator emission pulse is revealed also by experiments in pulse amplification using amplifiers with thin rods. In these experiments there was another driving oscillator with a larger divergence and shorter pulse. If the laser pulse length in each point of the cross section is shorter than the length of the total pulse generated by the entire rod face, we can expect some shortening of the pulse length without having to sharpen the leading edge with an additional shutter. The sharpening of the leading edge can occur in this case because of the fact that the amplifier aperture cuts off a small portion of the cross section of the input pulse.

Figure 3 shows oscilloscopic traces of the input and output pulses for a thin rod amplifier (two rods 10 mm dia x 600 mm cut at the Brewster angle with a total gain up to 10^4). Fig. 3a corresponds to linear amplification (input signal has been weakened 3800 times) and Fig. 3b corresponds to nonlinear amplification (no weakening of the input signal). The shape of the output pulse appears in both cases to differ sharply from that of the input pulse: the length of the output pulse at half amplitude and the length of the leading edge are smaller than in the input pulse.

It is of interest to note that the thin rod amplifier can distort the output pulse because of inadequate alignment of the amplifier rods. Figure 3c shows an oscilloscopic trace of the output pulse with a weak input signal. In this case the input pulse fell on the walls of the amplifier, was partially scattered backward and again amplified, and thus passed through the amplifier

2)However, we have also observed an increase of up to 4 nsec in the distance between the peaks of the input and output pulses (negative shift) in the case of a weak input signal. This shift can be due to the absorption of the leading edge of the pulse by metastable centers with a saturation energy that is lower than that of the Nd^{3+} ions. Snitzer [5] noted the appearance of these centers when pumping neodymium glass. Shifts of this type were not subject to any special controls in our experiments.

3)When considering the data in [10], we should remember that the saturation energy of a four-level system irradiated with a light pulse whose length is $\tau_{pulse} \gg \tau_S$ is twice as high as the saturation energy from a pulse length $\tau_{pulse} \ll \tau_S$, where τ_S is the particle lifetime at the lower working level. For neodymium glass the ion lifetime at the $^4I_{11/2}$ level is $\tau_S \approx 60$ nsec [11]. The first case is the subject [10] while the present paper deals with the second.

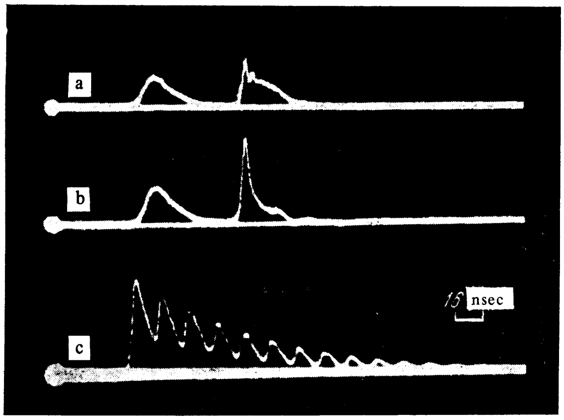

FIG. 3. Oscilloscopic traces of the input and output signals in a small-aperture amplifier.

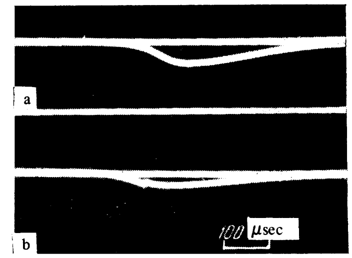

FIG. 4. Oscilloscopic traces of high-gain amplifier pulses. (a) sub-threshold; (b) above generation threshold due to emission scatter on the lateral surface of amplifier rods

many times. Since the total gain per pass is about 10^4 for a weak signal, oscillation requires a fairly small reflection coefficient of the order of 10^{-3}—10^{-4}. Exponential damping of oscillation is due to gain saturation effected by the pulses. A strong input signal does not produce oscillation because the first pulse is capable of exhausting the energy stored in the amplifier.

The alignment of amplifier rods in our experiments was performed quite rigorously with the aid of a narrow light beam from a gas laser operating at the wavelength of 1.15 μ.

3. METHOD OF SHORTENING THE LIGHT PULSE

As we know[1] we must cut off the leading sloping pulse edge in order to shorten the pulse in the course of nonlinear amplification. This can be done with an additional electro-optical shutter for example or with material that is bleachable when exposed to an intense light flux. The use of bleachable filters alone causes the output pulse length to remain approximately equal to the time of transverse development of generation over the cross section of the oscillator rod[2,12]. To avoid this limitation, a combined shutter consisting of a Kerr cell and a bleachable filter is used[2]. In our experiments we used a driving oscillator containing a thinner rod of neodymium glass 6 mm in diameter and 130 mm long with transparent ends. The small rod diameter made for a more homogeneous distribution of population inversion over the rod cross section. Therefore the time of transverse development of generation over the rod cross section apparently did not exceed a few nanoseconds and bleachable filters alone were sufficient to cut off the leading edge of the oscillator pulse[13].

The rod of the driving oscillator was pumped by a reflector with a helical lamp (the pump energy was 15,000 J). The resonator consisted of two mirrors with reflection coefficients of 99 and 37%. The oscillator emitted a pulse of linearly polarized light with an energy of 0.3 J and a length of 10—15 nsec. Larger diameter rods in this oscillator produced longer pulses since the population inversion in such rods was lower. For example, with the same pump energy the 6 mm rod had a gain of 0.2 cm^{-1}, while the 15 mm rod had a gain of 0.07 cm^{-1}.

The oscillator beam passed through a second Kerr cell, a saturable filter cell, and was admitted to the input end of a laser amplifier having a small-signal gain of about 500. Such a gain was reached by using a rod 10 mm in diameter and 600 mm long with ends cut at the Brewster angle to avoid oscillation. The rod was pumped by four straight lamps housed in an elliptic reflector (total pump energy was 60 kJ). At the output of the amplifier the pulse energy reached 3—5 J. Further amplification of the pulse was obtained in rods 30 mm in diameter since serious damage to the rods occurs at power levels of 0.5—1 GW/cm^2. To fill the rod cross section of the main amplifier we used a telescope capable of broadening the beam 2.5 times. The surfaces of the telescope lenses were coated to transmit at the wavelength of 1.06 μ.

The main amplifier consisted of four rods 30 mm in diameter and 600 mm long. The neodymium glass was of the KGSS-5 brand[14]. The ends of these rods were also cut at the Brewster angle. The total gain of the main amplifier reached 10^4.

The high value of gain can lead to oscillation and the resulting depletion of population inversion of the amplifier through scatter feedback from the lateral surfaces of the rods[15]. The depletion of population inversion can also be due to the amplified spontaneous emission. In both cases light fluxes 100—200 msec long appear at the amplifier output wasting the energy stored in the amplifier. There is a sharp drop in the energy of the useful signal passing through the amplifier under these conditions. Figure 4 shows oscilloscopic traces of the emission of a system with the gain of $\approx 10^4$ below threshold (Fig. 4a) and above threshold (Fig. 4b) that determines generation due to scatter at the lateral surface.

In addition, a high gain system can develop a photon avalanche when the electro-optical shutter is turned on[15]; the avalanche appears as a fairly short giant pulse of superradiance.

To prevent all these phenomena, which deplete the inverted population in the amplifier, the amplifier rods were moved away from each other by 0.7 meters, and cells with saturable dyes were placed between the stages of the amplifier[13].

Figure 5a shows the oscilloscopic trace of the pulse of the driving generator and Fig. 5b a trace of the same pulse after passing through the entire amplifier. The length of the output pulse at half amplitude is 5 nsec and its energy reaches 100 J. The divergence does not exceed 20′ and the distribution of emission over the end face of the output rod is fairly uniform. When another driving generator emitting a 7 nsec pulse was used the amplified output pulse was 2.8 nsec long with

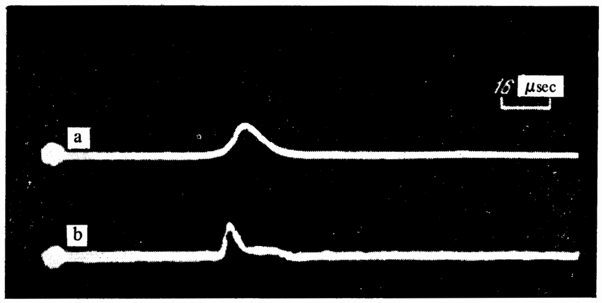

FIG. 5. Oscilloscopic traces of (a) driving oscillator pulses; (b) amplified pulses (100 J pulse energy).

an energy of 55 J. The oscilloscopic trace of this pulse is shown in Fig. 6. The energy density of the output pulse was 1.5—2 times higher than the saturation energy. Nevertheless the pulse length is significantly shortened upon amplification. It is possible that absorption of the trailing edge as well as shortening in nonlinear amplification plays a role in the formation of the pulse. For example such an absorption can occur during a spark breakdown at the end faces of the rods of the amplifier output stages. It is also possible that the transient processes in bleachable solutions affect the shape of the pulse.

At the energy levels obtained in the experiments we observed bubble damage within the last stage rod of the amplifier directly after the first flash. Each flash was accompanied by a spark breakdown on the surface of the output end; the end face was dulled in the process. After two or three flashes the output energy fell by one-half, while ten flashes completely destroyed the output end of the last rod. When the power did not exceed 5 GW the output end of the last rod was not damaged. Under these conditions the rod was capable of withstanding many more flashes whose number was limited by the volume damage to the rod.

The high power laser described in this paper is being used for a high-temperature heating of matter. We note that focusing the laser on a solid surface sometimes causes oscillation of the amplifier due to feedback in emission scattering by the target surface in the focal region. Oscillation of this type was noted by Hoffman.[4)] The scatter-induced generation damages the target, depletes the population in the amplifier stages, and can introduce error in the pulse energy measurements.

When the target feedback gain was high enough we also observed a "reversal" of the oscillator: a photon avalanche occurred in the system. The maximum energy concentration in the avalanche was reached in the first amplifier stage damaging the rod due to its small cross section. To avoid this undesirable generation in experiments with a solid target an additional cell with a bleachable filter was introduced between the last stages.

4. CONCLUSION

The present paper showed that the use of neodymium glass amplifiers operating in a nonlinear mode allows for a significant shortening and increase in the power of the pulse. This method makes it possible to reach a

4)A. H. T. Hoffman, private communication.

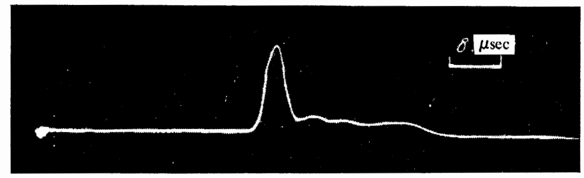

FIG. 6. Oscilloscopic trace of the amplified pulse (55 J energy).

peak power of 20 GW with an amplifier cross section of 7 cm^2. It is interesting to compare these results with the known data for high-power neodymium glass lasers. The light pulses obtained from large (15 cm^2 in cross section) neodymium glass rods have a maximum power of 6 GW with a pulse length of 20 nsec [16]. It is apparent that the nonlinear amplification method allows us to obtain light pulses that are much shorter at the same energy levels.

The method of amplifying light pulses has great potential. Thus the driving oscillator with a shorter emission pulse (for example pulses from an ultrashort pulse mode-locked oscillator) can produce short pulses of high energy [17]. Such pulses can be used to study the self damage threshold as a function of pulse length in the region shorter than 10^{-9} sec and to select the optimum pulse length of the driving oscillator for maximum power. The installation described here is now being used in work on this problem.

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