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PRODUCTION OF POWERFUL ULTRASHORT LIGHT PULSES IN A NEODYMIUM GLASS LASER

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Experimental investigation of the generation and amplification of ultrashort light pulses in neodymium glass is reported. A laser capable of emitting light pulses up to 10^{12} W has been built as a result of this research. Phenomena indicating the presence of nonlinear interaction between the amplified radiation and the active medium of the amplifier are detected.

1. INTRODUCTION

THE production of short light pulses have attracted the attention of investigators during the entire period of development of quantum electronics. The interest in high-power light pulses is due to the wide applicability of such pulses in physics research and in other areas.

At the present time the highest laser emission powers are reached in pulses shorter than 10^{-6} sec. The pulse peak power can be increased either by increasing pulse energy or by shortening pulse length. For solid-state laser pulses 10^{-7}–10^{-9} sec long, the energy density per pulse is limited mainly by laser damage from its own radiation. The method to increase output energy by increasing the cross section and volume of the laser medium entails considerable technical difficulties.

The considerable recent progress in the attempts to increase laser peak power[1-5] is associated with the shift to sub-nanosecond (ultrashort) pulses. This has been made possible by the creation of the neodymium glass generator of ultrashort pulses[1]. The experimental work reported in many papers (see, for example,[5,6]) showed that the generator pulse length lies within the limits 10^{-11}–10^{-12} sec.

Our studies carried out with such a generator showed that the time structure of the emission is not reproducible from flash to flash. Only in sporadic cases did the generator emission represent a periodic sequence of isolated ultrashort pulses[6]. According to measurements of the generator pulse length made with a fast electron-optical camera[7] the pulse length does not exceed 2×10^{-11} sec. Using such a laser as a driving generator we succeeded in reaching, after amplification, the power of $\sim 10^{12}$ W[3]. When this power was focused on a lithium deuteride target we recorded neutron radiation from the plasma formed in the focal region[8].

The present paper describes the laser setup for the production of light pulses up to 10^{12} W. The study of the factors capable of limiting the power increase of such pulses during amplification is an important aspect of the production of powerful ultrashort pulses. Our experimental research in this area carried out in the course of building the laser showed that nonlinear interaction between radiation and the amplifying medium can cause such a limitation.

2. THE LASER SETUP FOR THE PRODUCTION OF HIGH-POWER ULTRASHORT PULSES

A neodymium glass laser generator[1] used in this work as the source of ultrashort pulses can emit a precisely periodic sequence of picosecond pulses with a bell-shaped envelope. The energy contained in even the most intense pulses emitted by the generator does not usually exceed 0.01 J[6]. A laser amplifier can be used to increase this energy. When the entire pulse sequence is amplified the amplifier output contains a range of pulse powers from zero to the maximum power of the most intense pulse. Such a composition of the emission makes it difficult to study the emission power dependence of various phenomena. Furthermore, if the phenomenon under consideration has a typical relaxation time that is longer than the pulse repetition period in the sequence, then the behavior of the phenomenon is distorted by the presence of numerous pulses with different power.

In our work we amplified a single pulse separated out of the sequence of generator pulses. The experiments showed that the amplification of a single pulse imparts to it a larger energy than the energy obtained in any pulse when the entire sequence is amplified, without damaging the amplifier rods.

The experimental setup for the production of high-power ultrashort light pulses in neodymium glass consisted of a driving generator, a multi-stage laser amplifier, and a control circuit. It is shown in Fig. 1, where 1—active neodymium glass rods; 2, 4—mirrors and beam splitters; 3—cells with nonlinear absorber solution; 5—calorimeter; 6—gas laser (emission wavelength of 1.15 μ) used to align the setup.

The driving generator contained a KGSS-7 neodymium glass rod of 10 mm dia and 180 mm long, with ends cut at the Brewster angle (1). The rod was placed in a cylindrical reflector with an IFK15000 helical pump lamp. The generator resonator, ~2.1 m long, consisted of dielectric mirror surfaces 2 with reflection coefficients R = 40% (on a wedge substrate) and R = 99.5% (on a substrate with a dulled rear surface).

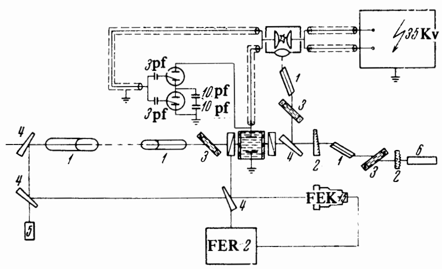

FIG. 1. Diagram of the neodymium glass laser setup for the generation of powerful ultrashort light pulses.

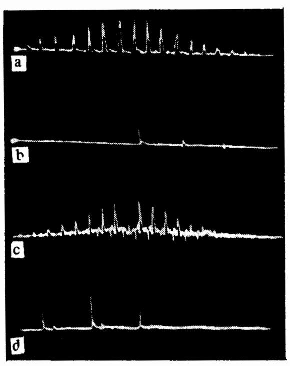

FIG. 2. Oscillograms of generator pulses and pulses that passed through the electro-optical shutter (oscillogram sweep duration was 300 nsec): a – periodic generator pulse sequence at the input to the electro-optical shutter; b – single pulse at shutter output; c – sequence of pulses separated by shutter; d – group of pulses at shutter output.

The nonlinear absorber 3, a cell containing No. 3955 dye solution in nitrobenzene, was placed at the mirror with R = 99.5%. The initial transmission of the solution was T = 60%.

The periodic pulse sequence emitted by the generator (Fig. 2 a) was aimed at the electro-optical shutter consisting of two crossed Glan-Thomson polarizing prisms and a Kerr cell (Fig. 1). To isolate a single pulse from the sequence a high-voltage electrical pulse was delivered to the Kerr cell that opened the shutter for ~15 nsec. This time interval corresponded to the pulse repetition period in the sequence. The electric pulse was generated by a long-line discharge circuit (Fig. 1). The two-electrode discharge chamber was filled with gaseous nitrogen at 7 atm. The discharge was started with a portion of the generator emission that passed an additional amplification stage and was focused by a lens on the interelectrode gap.

The arrival time of the electric pulse at the Kerr cell can be controlled by selecting the transmission of the nonlinear filter cell with the dye solution in front of the discharge chamber and adjusting the length of the discharge cable. The operation of the control circuit is illustrated by the oscillograms in Fig. 2 obtained with an FÉK-15 coaxial photocell and S1-14 fast oscillograph (not shown in Fig. 1). The polarized (in the horizontal plane) generator emission does not pass through the shutter when there is no control pulse at the Kerr cell. This emission (full pulse sequence in Fig. 2a) is directed to the photocell by means of a polarizing prism and a plate. When the control pulse arrives the polarization plane of the emission passing through the Kerr cell rotates through 90° (becomes vertical) and the emission is allowed to pass through the shutter to the amplifier input. Figure 2b shows an oscillogram of a single pulse (maximum in the sequence) isolated by the shutter. This pulse is of course absent in the radiation diverted by the polarizing prism (Fig. 2c).

A reflection quenching circuit of vacuum discharge tubes (see Fig. 1) was used to prevent a secondary operation of the shutter by pulses reflected from the cable ends. The tubes were started ~15 nsec after the arrival of the control pulse at the shutter and shorted the Kerr cell to the ground. If the quenching circuit was disconnected from the Kerr cell, reflections in the cables caused secondary operation of the shutter so that several pulses were isolated from the sequence emitted by the generator (Fig. 2d). The time separation of these pulses (~56 nsec) equalled twice the time of flight of the electric signal reflected from the Kerr cell along the long-line cables. Isolation of several (two or three) pulses with the subsequent amplification was used in our experiments on high-speed shadowgraphy of plasma formed by focusing the generator emission on a solid target[9,10]. The first pulse was used to obtain the plasma, while the following pulses served as light source for the shadowgraphy.

The electro-optical shutter used in our work passed 40% of the incident radiation in the open state and 2% in the closed state if the energy of the pulse sequence passing through the Kerr cell did not exceed 0.1 J[1)]. At higher energies of the incident radiation we observed a strong attenuation of the radiation in the Kerr cell nitrobenzene. This phenomenon limited for us the possibility of increasing the energy of the isolated pulse at the amplifier input.

To increase the isolated pulse-to-background energy ratio, a nonlinear absorber cell (Fig. 1) was placed after the electro-optical shutter. Radiation that managed to pass through the closed shutter was almost completely absorbed in the cell. After passing through the shutter and the cell with nonlinear absorber, the energy in the isolated pulse at the amplifier input did not exceed 0.001 J.

The isolated pulse was amplified by a five-stage laser amplifier (Fig. 1). KGSS-3 neodymium glass rods with diameters of 20, 30, and 45 mm and 650 mm long each were used in the amplifier. The amplifier rods were pumped with IFP-20000 straight lamps. To prevent self-oscillation, the end faces of all rods were cut at the Brewster angle and the separate amplifier stages were decoupled from each other with bleachable filters. The amplifier stages were spaced 1.5–2 m from each other for the same purpose, so that the total length of the installation reached 15 m. The aperture of the amplifier was filled by virtue of the natural divergence of the generator emission. The amplifier rods were oriented in the vertical plane in accordance with the polarization of the amplified radiation (see Fig. 1). The total weak-signal gain of the amplifier was $\sim 10^4$. The gain could not be increased because of amplifier self-oscillation.

Amplifier self-oscillation and absorption in the electro-optical shutter limited the output energy of the amplified pulse. The maximum pulse energy measured

[1)] Closed-state transmission of the shutter is mainly due to a small intrinsic anisotropy created in the glass container of the Kerr cell in the course of its manufacture.

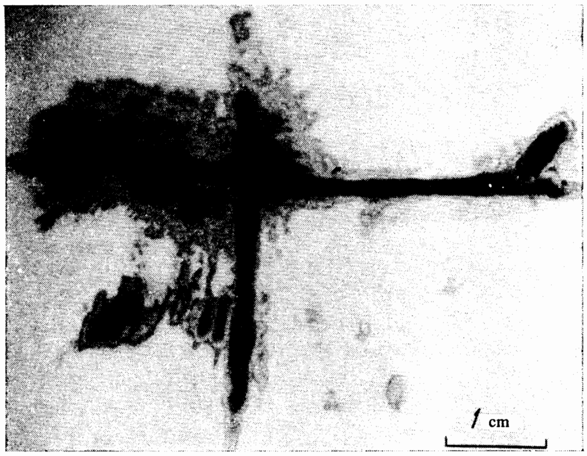

FIG. 3. Photograph of a radiation trace on film placed at a distance of m from the amplifier output.

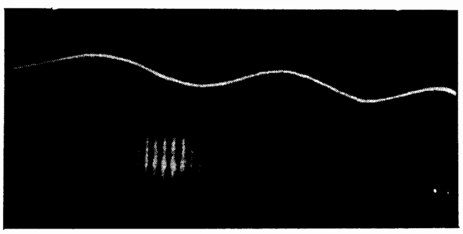

FIG. 4. Time structure of a single generator emission pulse recorded with the fast camera (period of the calibration sinusoid is 2 nsec).

with a calorimeter (Fig. 1) reached 20 J at the amplifier output. Background emission consisted of the amplifier's own emission and the amplified emission of the generator that passed through the closed electro-optical shutter. The total background radiation energy measured for a single flash did not exceed 0.1 J.

The radiation intensity distribution was strongly inhomogeneous over the end face of the output rod. We observed individual emitting spots, or points not exceeding 0.5 mm. The far-field radiation was also strongly inhomogeneous. Figure 3 shows a photograph of a radiation trace on film placed at a distance of 5 m from the amplifier output. The divergence of the emission ($\sim 3 \times 10^{-3}$ rad) was estimated from the measured dimensions of such prints. The cruciform shape of the intensity distribution is probably due to birefringence in the glass of the amplifying stages.

An FÉR high-speed electron-optical camera[7] was used to record the pulse lengths of both the driving generator and the amplifier output (see Fig. 1). The generator pulses and the isolated and amplified pulse at the amplifier output were recorded simultaneously. No significant difference in the time structure of the amplifier output pulses from that of the generator pulses was found within the limits of the camera resolution ($\sim 2 \times 10^{-11}$ sec). As a rule the time structure was complicated[6]. Only in isolated cases did we observe single pulses not longer than 20 picosec, and then the output power was not less than 10^{12} W. The time structure at the amplifier output corresponded to the wavelength-discriminating optical elements introduced into the resonator of the generator. Thus Fig. 4 shows a single generator emission pulse ~1.5 nsec long photographed with the FÉR camera; the pulse consists of a periodic sequence of shorter pulses. The length of the individual short pulses corresponds to the time resolution of the camera for a particular sweep. In order to obtain such a time structure of emission we replaced the output generator mirror on a wedge substrate by a mirror on a plane parallel substrate whose thickness (1 cm) corresponded[6] to the pulse repetition period (100 picosec) in the sequence shown in Fig. 3.

3. INTERACTION OF ULTRASHORT PULSES WITH THE AMPLIFYING MEDIUM

As we know, the power of nanosecond light pulses from ruby and neodymium glass lasers is limited by volume and surface damage of the active medium (see for example[10,11]). Usually 5—10 flashes with a power of $\sim 10^{10}$ W can destroy a neodymium glass rod with a cross section of ~ 7 cm^2[11].

It is of interest to analyze the factors capable of limiting the power increase of ultrashort light pulses. At the light flux densities attainable in a high-power generator of ultrashort pulses, the flux attenuation can be due to multiphoton ionization of the active medium atoms or to self-focusing of the amplified emission, for example. These phenomena can entail nonlinear (depending on power) absorption of the radiation and also damage to the active medium by the radiation. These are the phenomena that can impose a limit on the output power[12] and change the shape of the amplified pulse[13].

In our work with the amplification of ultrashort pulses, hundreds of flashes failed to bring the active rods out of commission in spite of higher radiation power at the amplifier output than in[10,11]. The maximum size of the volume damage (cracks) did not exceed 0.5 mm and the radiation did not dull the end faces of the output-stage rod made of KGSS-3 neodymium glass with a cross section of ~ 16 cm^2. In our experiments we also were unable to observe any significant limits to the amplified power: the radiation energy density at the amplifier output reached 1 J/cm^2 and corresponded to a linear amplification of the input signal. Nevertheless we observed phenomena that indicated the presence of nonlinear interaction between the amplified radiation and the active medium of the amplifier.

After polishing the lateral surface of the KGSS-3 glass rod that was subjected to hundreds of flashes in the output stage of the amplifier, we observed in the microscope numerous defects in the form of very fine (with a diameter up to several microns) and long (several cm) filaments inside the rod. Figure 5 shows a photograph of the filament damage (magnified ~57 times). Some filaments formed near the output ends of the neodymium rods terminated at the end surface. At the exit site of the filament there was a surface micro-defect with dimensions of several dozen microns. A considerably smaller amount of filamentary damage was found in the rods of two amplfier stages preceding the output stage. The quantity of volume defects and the number of filaments formed in the LGS-288-2 neodymium glass rods were considerably

FIG. 5. Filamentary damage of neodymium glass (arrow indicates direction of laser beam).

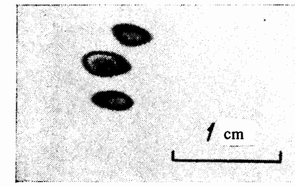

FIG. 6. Photograph of radiation trace on film placed at a distance of 25 m from the amplifier output.

smaller. Surface micro-defects are also formed on the end faces of these rods although the filamentary damage of the glass near such defects is often absent.

Similar filamentary damage in glass was observed earlier as a result of focused laser radiation. For example, this phenomenon is reported in[14]. The nonlinear self-focusing effect is considered to be the cause of the filamentary damage[14]. We could thus expect this effect to occur also in unfocused beams at the sufficiently high laser powers attainable by amplification of ultrashort pulses. Since in our case the emission power is large, we can assume that the filamentary damage observed in our experiments is an indication of the self-focusing of the divergent laser beam that is propagating in the amplifying medium. We performed additional experiments that showed that a single flash causes several filamentary defects at once, the defects being distributed over the entire cross section of the active rod. A simultaneous appearance of several filamentary defects shows that only individual, perhaps the most intense, portions of the beam are self-focused, rather than the beam as a whole. This concept of the spatial structure of the beam is in agreement with the strong inhomogeneity observed in our experiments in the distribution of the emission field over the end face of the output amplifier stage rods.

Filamentary damage was also observed by us in laser rods (ruby and neodymium glass) used previously in experiments with high-power nanosecond light pulses. We found that the self-focusing of a powerful laser radiation in the active laser material itself is a widespread phenomenon. Filamentary damage was observed in neodymium glass and ruby rods from output stages of powerful lasers emitting pulses with energies up to 100 J in ~5 nsec[11] and ~15 J in ~2 nsec[10] 2). This damage is also present in neodymium and ruby rods with diameters of 10—15 and length of 120—240 mm used in the generation of nanosecond pulses and ultrashort pulses[6,10].

Self-focusing should lead to a redistribution of energy over the beam cross section, to the absorption of energy (during the formation of filamentary damage), and consequently to a limitation of the power of laser radiation propagating in the amplifying medium. These processes should obviously be considered also in lasers emitting powerful light pulses.

We also observed anomalous propagation of a laser beam in air. Figure 6 shows a photograph of a trace left by the radiation on film placed 25 m away from the output end of the amplifier. The dimensions of the trace do not exceed 0.5 cm. According to theory, so small a trace cannot be obtained at such a distance from the source, i.e., output end face of the amplifier, even assuming the diffraction divergence of the beam. In our experiments the beam divergence past the amplifier was 10 times larger than the diffraction divergence. The cause of the anomalous propagation of the beam may be self-focusing of laser radiation in air. Self-focusing in air was observed in a focused beam in[15].

We were not able in this work to determine the power and energy of the radiation necessary to produce the observed nonlinear effects because of the instability of emission characteristics of the driving generator of ultrashort pulses. Therefore the obtained experimental data are insufficient to determine the physical mechanism responsible for these effects.

4. CONCLUSION

The method of nonlinear amplification of nanosecond light pulses allowed us to reach a pulse power over 10^9 W in ruby lasers[10] and over 10^{10} W in neodymium glass lasers[11]. In the present work we snow that it is possible to obtain light pulses with energy up to 20 J by linear (in terms of energy) amplification of a single pulse isolated from an ultrashort pulse sequence of a neodymium glass laser[1]. The length of the pulses does not exceed 2×10^{-11} sec (time resolution of the electron-optical camera). The energy density of ultrashort pulses in our experiments (not more than 1 J/cm^2) did not reach the saturation energy of the working transition in neodymium glass necessary to initiate nonlinear amplification[11].

We found, however, that a nonlinearity of another kind occurs in the amplification of ultrashort pulses—nonlinearity in terms of power. In our experiments the effect of self-focusing of the amplified radiation indicated such a nonlinear interaction between the amplified radiation and the active medium. No special experiments were performed by us to observe multiphoton absorption in the active medium of the amplifier.

Although we were not able to observe any significant limitation of the emission power in the course of amplification it is quite probable that with larger light flux densities nonlinear interaction may cause such a limitation.

Because of the unstable operation of the ultrashort pulse generator in our experiments we were unable to determine the dependence of the observed nonlinear effects on the emission power. Further investigation is therefore necessary to clarify the physical nature and the mechanism of the interaction between powerful ultrashort pulses and the amplifying medium.

2) The destruction of laser rods in these experiments was due mainly to the large volume and surface damage to the active medium.

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