

Research Article

Laser-Induced Defects in a Bulk GaAs Used as an Output Coupler in an Nd:YAG Laser Cavity

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Received 29 October 2010; Revised 23 January 2011; Accepted 22 February 2011

Academic Editor: Gregory Lapicki

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By using bulk GaAs as an output coupler as well as a saturable absorber, with changing of concentration of defects inside the laser cavity, Q-switching of flashlamp-pumped Nd:YAG laser has been studied. It is shown that the formation of the laser pulses, in a wide range of duration, which were reported in a lot of previous papers is caused by the intracavity changes of the defect concentration in GaAs. The factor of increase in defect concentration is estimated by modeling of the pulse formation process.

1. Introduction

Recently, GaAs crystals are frequently used as nonlinear-optical elements, saturable absorbers for passive Q-switching and mode locking, and an output mirror [1–10]. In comparison with active Q-switching, passive technologies can considerably simplify a design, improve the efficiency and reliability, and reduce the cost of the laser sources. In [6], a semiconductor GaAs crystal with a thickness of 0.5 mm is used as a saturable absorber, and the pulses as short as 10 ps are received while in other papers the obtaining of durations 3 ns [7], 15.5 ns [8], 78 ns [9], and from 90 up to 800 ns [10] is reported. Though in these papers, it is shown that GaAs can be effectively used as a saturable absorber, the mechanism of formation of pulses up to now is not found out in detail. So, for example, even if the distinctions in conditions of these experiments will be taken into account, it is difficult to explain such large differences in the results, as the initial parameters of the used crystals did not differ significantly. Note that in all these experiments were used either a focusing lens or a spherical mirror for increasing the intensity of radiation on the GaAs surface planes to reach optimum efficiency of a saturable absorber. It is also necessary to note that in all these experiments the concentration of defects was supposed to be constant. At the same time, from the experiments on research of laser-matter interactions, it is known that intensive laser radiation can result in formation of defects

in semiconductor crystals [11–15]. So, in [15], at a long irradiation of a GaAs crystal with the sequence of pulses of the Nd:YAG laser with an intensity lower than the threshold for an optical breakdown, the increase in concentration of defects more than one order was revealed. Since it is possible to assume that the use of GaAs in combination with a lens inside the resonator, during the operation of the laser, the increase in concentration of defects of a GaAs crystal is possible as well. This process would result in a change of the optical properties of GaAs and affect the output characteristics of the laser.

In this paper, the results of research on the possibility of formation of defects in a GaAs crystal at its use as the output mirror in the pulse Nd:YAG laser and a possibility of control of parameters of output radiation by the change of intensity of intracavity radiations on a surface of GaAs are reported.

2. Experiment

The schematic diagram of the experimental setup is shown in Figure 1. The resonator of the laser consists of a fully reflecting mirror (1), flashlamp-pumped Nd:YAG crystal (2), a bulk GaAs crystal (6) as an output mirror, a diaphragm (3), and a telescope consisting of two focusing lenses (4, 5). The telescope was used to increase the intensity of the intracavity radiations on the surface of the GaAs crystal. The pump repetition rate was 1 Hz.

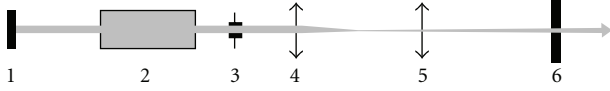


FIGURE 1: Block diagram of the experimental setup, (1) fully reflecting mirror, (2) Nd:YAG-active element, (3) a diaphragm, (4,5) lenses, and (6) GaAs crystal as an output mirror.

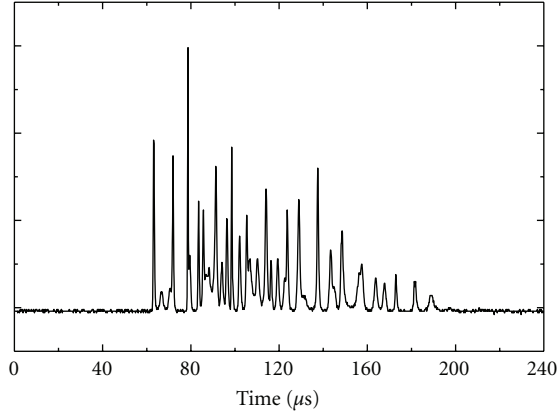


FIGURE 2: Sequence of output pulses of the radiation obtained with unirradiated bulk GaAs. Time scale: 20 μ s.

The size of the GaAs plates was 30 mm in diameter and 0.4 mm in thickness. The flashlamp of IFP-800 was used as a pump source. The half-height duration of the discharge impulse was ~ 0.2 ms, and the mean electrical power dissipated in a discharge circuit was about 23 W. The reflection factor for the GaAs wafer is $R \sim 50\%$ on the wavelength of a generation $1.06 \mu\text{m}$. As an active element, the Nd:YAG crystal (2) with sizes of $\phi 5 \times 65$ mm was used. For registration of output radiation, the high-speed photodiode LFD-2 with a rise time of ~ 0.5 ns and digital oscilloscope RIGOL DS5152C with a bandwidth of 150 MHz were used.

For finding out the mechanism of the processes taking place in a GaAs crystal, it has been carried out the set of experiments with various durations of an operating time of the laser, at different magnitudes of a telescoping factor and lengths of the resonator. As have been shown in the numerous experiments in the beginning of the experiment, until the GaAs crystal has not been irradiated for a sufficient time, the laser generated sequences of casual pulses with partial Q-switching, practically without mode locking in multimode regime, irrespective of telescoping factor. In Figure 2, the sequence of pulses of output radiation per one pump pulse is presented at a telescoping factor of 1 and a resonator lengths of 1.5 m.

Apparently from Figure 2, the pulses have different amplitudes and stochastic sequence in time. In Figure 3, the expanded view of the first pulse of a sequence is presented. The pulse duration varied in small limits, and it was approximately 400 ns. In the beginning of the experiments with different values of telescoping factor, the careful alignment has not given an essential modification of an oscillating mode, that is, it did not reduce in mode-locking regimes.

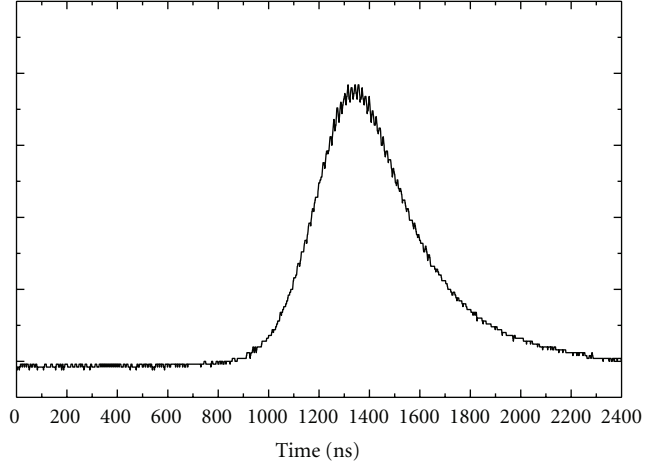


FIGURE 3: Profile of the first pulse for a sequence in a time scale of 200 ns.

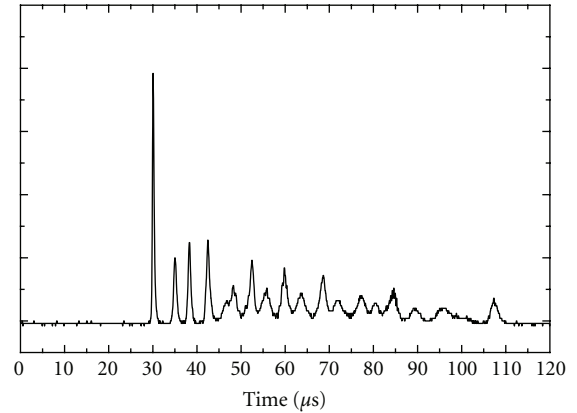


FIGURE 4: Sequence of laser pulses in a mode-locked regime with $k = 3$ and round-trip time of 8 ns.

We guess it is associated with the fact that the defect concentration in the GaAs wafer is not high enough yet.

To determine the influence of the intensity of radiation and duration of an intracavity exposure on the formation process of lattice defects in GaAs, the experiments for different telescoping factors with constant remaining parameters have been carried out. The experiments have been conducted for different lengths of the resonator. The telescoping factor k varied from 1 upto 5. At $k > 3$ in a short time, there are optical breakdowns that increased the losses on the crystal and led to a diminution of the intensity of the output radiation, and in some cases to an interruption of generation. At $k = 3$, within ~ 30 minutes, the laser generated the pulses with Q-switching, but without mode locking, then the pulses with interior structure, that is, the regime with mode locking started to appear. Eventually, the quality of mode locking improved. Approximately in 1.5 hours of operation of the laser with the repetition rate of 1 Hz and at little change of the alignment, the outcomes shown in Figure 4 have been obtained. Thus, the profile of the first pulse in a sequence was reproduced with the high enough accuracy in each pumping

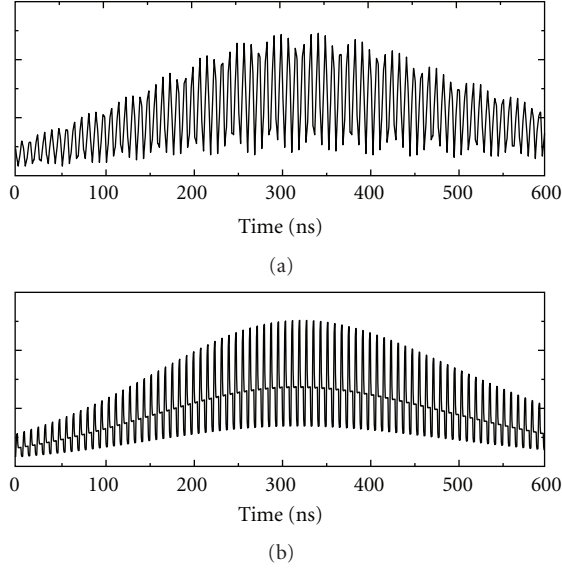


FIGURE 5: (a) Expanded view of a pulse from a sequence in the increased scale in a mode-locked regime of generation for $k = 3$. Round-trip time is 8 ns. (b) Mode-locked output pulse obtained as a result of modeling for an increase of the GaAs defects concentration by a factor of 5 and for the scheme with a telescope with $k = 3$.

pulse. In Figure 5(a), the expanded view of a pulse from a sequence which represents the train of nanosecond pulses with a modulation depth of $\sim 60\text{--}70\%$ is presented. The duration of the single pulses in a train was about 5 ns, and the interval between them accounts for ~ 8 ns that corresponds to the round-trip time of the resonator.

However, approximately after 3 hours of laser operation, a small spot appeared on the GaAs surface. The spot size increased with further laser operation and led to deterioration of the pulses quality.

The same experiments were carried out with a telescope at $k = 2$, but in this case the optical breakdowns during the experiments were not observed. However, to achieve a transition into a mode-locking regime, more time was required in comparison with $k = 3$, that is, about 1.5 hours. In this case, similar results with a little bit smaller modulation depth have been obtained, and approximately after 3 hours of laser operation, no further change was observed. We assume that it is connected with the saturating character of a defect formation process. Further, in the next experiment for the check of the assumption of increase in concentration of defects under the influence of the intracavity radiations, the telescope was removed after irradiation in order to switch the laser to the mode with $k = 1$ where the sensitivity to the defects concentration is less. Thus, the use of the irradiated area of the GaAs crystal where we assume that the concentration of defects is increased was provided. As it was supposed, the laser continued to work steadily enough in a mode-locked regime and generated the train of pulses, one of which is presented in Figure 6(a). Let us note that at $k = 1$ without a preliminary irradiation of a crystal, the laser generated the pulses similar to what are resulted in Figure 3, that is, without mode locking.

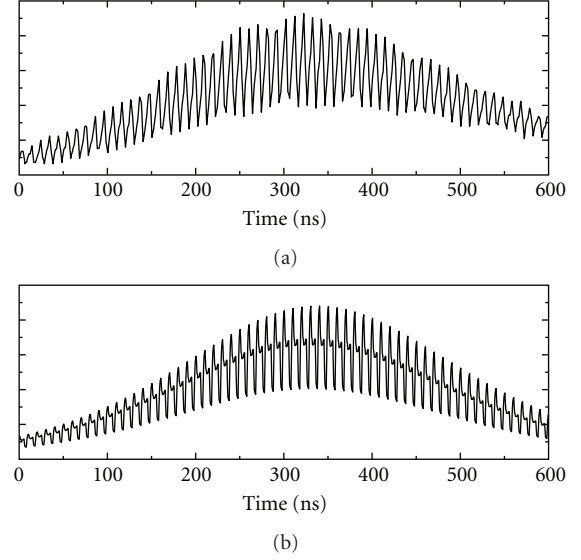


FIGURE 6: (a) The profile of the pulse obtained after removal of a telescope with a factor of 2. Round-trip time is 10 ns. (b) Mode-locked output pulse received as a result of modeling for the scheme without a telescope, but with the increased concentration of defects in GaAs.

The same experiments have been carried out for other lengths of the resonator and similar results have been obtained. This gives the basis to state that at use of the GaAs crystals inside a laser resonator, at intensities lower than the optical-breakdown threshold, the increase in concentration of defects without destruction of a surface is possible.

For deeper studying of the processes influencing the output radiation of the described laser, numerical experiments are carried out. For modeling the process of generation of the laser, the ways and equations in [5] have been used. In the model it has been used the approach, which is to determine the transfer function of each cavity element and follow step by step the evolution of the radiation in the cavity, starting from an arbitrary initial long and weak pulse. The gain coefficient has been determined by solving the rate equations for the four-level active medium [16]. To determine the transfer function of the GaAs crystal, the equation for intensity has been written as

$$\frac{dI}{dz} = -\alpha I - \beta I^2 - n\sigma_{fc}I, \quad (1)$$

where $\alpha = \sigma_n(N - N^+) + \sigma_p N^+$ is the single-photon absorption coefficient; σ_{fc} is the free-carrier absorption cross section; N is the density of neutral defect levels; N^+ is the density of ionized defect levels; n is the density of the free carriers; σ_n is the cross section of transition of an electron from the defect level to the conduction band; σ_p is the cross section of transition of an electron from the valence band to a defect level; I is the radiation intensity; β is the two-photon absorption coefficient, to determine α and n , a set of equations [5] describing the one-photon absorption at the defect levels, two-photon absorption, and the absorption at the free-carriers were numerically solved. In order to

take into account the changes in defects concentration, the initial single-photon absorption, which is defined by the density of the defect levels as $\alpha_0 = \sigma_n N$, has been varied. Numerical experiments were carried out for various values of defects concentration in a crystal GaAs. Telescoping factor is varied between 1 and 3.3. In Figure 5(b), the pulse received as a result of the modeling of the process at an increased concentration of defects in the GaAs crystal (5 times higher concentration than for nonirradiated crystal) is presented, for a telescoping factor of 3.3. This result consents satisfactorily with experimental result shown in Figure 5(a). As is seen from the Figure, the pulse represents train of subpulses in the nanosecond regime with a modulation depth of ~ 60 –70%. Results of the numerical experiments have shown that with the increase of concentration of defects in a crystal, the modulation depth increases.

For the case without a telescope after irradiation, the experimental result of which presented in Figure 6(a) the satisfactory consent of calculation results (Figure 6(b)) has been reached when the defects concentration was assumed to have increased by a factor of 10. These results of the numerical simulations show that the defects concentration can be increased by a factor of 5–10 while at calculations without increase in concentration of defects the results were similar to the experimental data obtained for a nonirradiated crystal (Figure 3).

3. Conclusion

On the basis of the analysis of the literary data and results of the carried out experiments, it is possible to draw a conclusion that under the influence of laser radiation with an intensity near and below the optical breakdown threshold, there can be changes in the structure of the GaAs crystal resulting in an increase in the concentration of defects and as a consequence in improving the saturable absorption of a crystal.

The mechanism of formation of the laser pulses in a wide range of duration is caused by the intracavity changes of the defect concentration in GaAs.

The process of formation of defects has a saturating character; the level of saturation depends on the intensity of radiation, and the formed defects are steady at intensities equal to or lower than intensity which created the given saturated concentration of defects.

The saturable absorbers received by the laser irradiation can be successfully applied for passive mode locking of solid state and other lasers, and it is possible to generate the laser pulses with the durations ranging from 10 ps to several hundreds of nanoseconds.

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