LIGHT ABSORPTION IN RUBY IN THE PRE-BREAKDOWN STATE

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Submitted December 25, 1969

Zh. Eksp. Teor. Fiz. 58, 1898–1903 (June, 1970)

Intense light from a powerful ruby laser is found to induce in the ruby an absorption increase preceding destruction. The kinetics of this increase under the action of the pulse is investigated. Estimates are made of the dependence of the shock wave pressure on the absorption and intensity of the incident light.

WE investigated breakdown in ruby under the influence of light from a ruby laser operating in the single-pulse regime. In area investigations[1,2] it was established that at incident-radiation power densities 3×10^{10} W/cm^2 there occurs damage inside the ruby sample in the region where the laser beam is focused. The damage is accompanied by shock waves, the pressure on whose front reaches 3×10^6 atm[2].

One of the authors[3] proposed a mechanism for energy transfer from the light to the transparent dielectric. This mechanism consists of the development of an electron cascade in the medium as a result of absorption of light by the free carriers and shock ionization of the lattice. The purpose of the present paper is to determine the change of the light absorption in the substance during the time of action of the laser pulse and to establish a criterion for a breakdown in which the damage has a dynamic character.

EXPERIMENT

The investigations were performed with the setup illustrated in Fig. 1. Light from the Q-switched ruby laser 4–7 was focused by lens 10 into the interior of the ruby sample 11 measuring $4 \times 4 \times 15$ mm. Part of the light was diverted with a semitransparent plate 12 to a semitransparent mirror 13 and illuminated the ruby sample 11 through the side faces. This light was focused by lens 14 on diaphragm 15 and struck the photographic film 16. Diaphragm 15 eliminated the light from the flash lamp and the laser light scattered by the ruby sample.

The light pulse incident on the ruby was registered with an FÉK-09 coaxial photocell 17. The light pulse passing through the ruby was registered with a second FÉK-09 cell 18. The signal from the photocell 17 was fed to an S11-11 high-speed oscilloscope 19 directly, and the signal from photocell 18 was fed to the same oscilloscope through a delay line 20. The system was adjusted with the aid of a helium-neon laser 1, the divergence of which was made equal to the divergence of the ruby laser by means of a telescope system 2–2′ and a diaphragm 3.

The incident laser light was attenuated by combined filters 9. The same filters were used also to balance the sensitivities of the photocells. To increase the intensity of the light incident on the sample, the filters were moved to a position behind the sample, in position 9′ in front of the photocell, without disturbing the balance of the photocell.

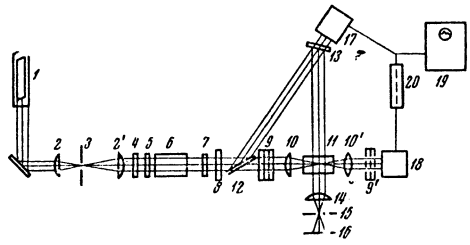

FIG. 1. Diagram of experiment aimed at investigating the absorption in ruby prior to breakdown.

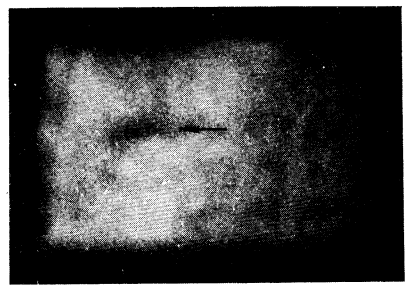

FIG. 2. Shadow picture of absorption in ruby prior to the occurrence of damage.

Figure 2 shows a shadow picture of the ruby sample with increased absorption in the region of the laser-beam focus[1)]. The absorbing region in Fig. 2 is marked by an arrow, which shows also the direction of the incident light. The dimension of the region of increased absorption corresponds to a zone of high power density of the incident light, determined by the caustic of the lens. This shadow picture was obtained with the aid of the same laser pulse which produced the change of the absorption, but delayed by 3 nsec. The attenuation of the transmitted light by the region of increased absorption is ~ 10%. An estimate of the absorption coefficient averaged over the pulse yields a value of several reciprocal centimeters.

As follows from Fig. 2, no mechanical damage occurs

[1)]The attenuation of the light incident on the receiver could not be due to nonlinear refraction, since the change of the refractive index, measured by an interferometry method, was $\sim 10^{-2}$. Such a change did not bring the beam outside the limits of the aperture diaphragm of the setup.

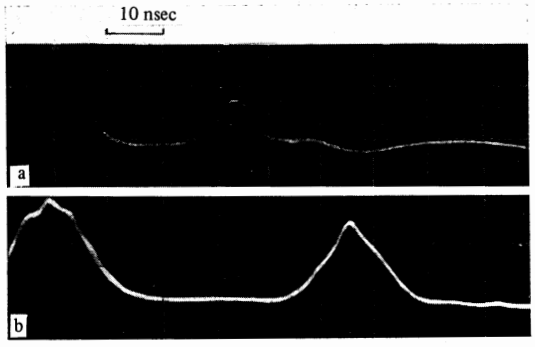

FIG. 3. Oscillograms of laser pulses of different duration, incident on the ruby and passing through it: a) τ = 12 nsec (at half-width), E = 0.3 J; b) τ = 35 nsec (one division corresponds to 20 nsec), E = 0.5 J.

as yet at a time t = 3 nsec. The time variation of this absorption was investigated by means of the oscillograms of the incident and transmitted light pulses.

Typical oscillograms are shown in Fig. 3 for generation pulses of equal duration. It is seen from Fig. 3 that the transmitted pulse (right-hand side) has a shorter duration in amplitude than the incident pulse. In the case when the incident pulse was small (all filters in position 9), the transmitted pulse coincided with it in shape and in amplitude.

We denote the intensity of the incident light by $J_0(t)$ and then the intensity of the transmitted light is $J(t) = J_0(t)e^{-k(t)x}$, where k is the absorption coefficient of the ruby and x is the length of the absorbing region. Hence

$$k(t)=\frac{1}{x}\ln\frac{J_0(t)}{J(t)}$$

Figure 4 shows plots of the absorption coefficient against the time for the oscillograms of Fig. 3. It is seen from the curves of Fig. 4 that the absorption coefficient amounts to $k \sim 10$ cm^{-1} (it is impossible to trace the subsequent increase of the absorption, owing to the insufficient sensitivity of the apparatus).

DISCUSSION

If we used for the absorption coefficient the formula[4]

$$k=\frac{4\pi Ne^2}{m\omega^2 c}\nu_{\text{eff}}, \qquad (1)$$

then we can calculate the carrier density N, which turns out to be 10^{19} cm^{-3} (the effective collision frequency for ruby is $\nu_{\text{eff}} \sim n^{14}$ sec^{-1} [2,5]). In the measured interval of absorption coefficients, the density N increases by a factor e within the time ~2 nsec. This cascade-development constant agrees qualitatively with the calculations of Molchanov[5]. The discrepancy may be due to the rapid thermalization and the settling of the conduction electrons on the traps, a factor not taken into account in[5]. This is confirmed qualitatively by the character of the curve of Fig. 4b, which shows that the absorption coefficient follows the oscillations of the incident-light intensity. One can speak only of qualitative agreement, since the temporal resolution of the apparatus (~2 nsec) does not make it possible to determine accurately the course of the absorption coefficients.

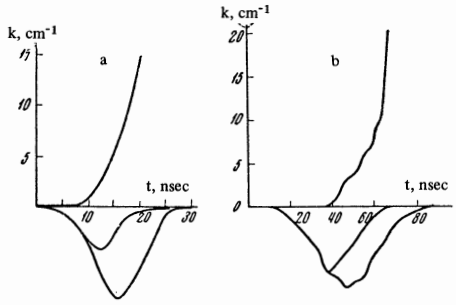

FIG. 4. Time dependence of the absorption coefficient for generation pulses of different durations: a) τ = 12 nsec, b) τ = 35 nsec. The generation pulse waveform is shown below the abscissa axis.

It is also seen from Fig. 4 that the absorption becomes significant in the second half of the generation pulse. This means that the substance acquires the basic energy within a time shorter than the duration of the generation pulse. This is the cause of the dynamic character of the damage. Let us estimate the critical rate of the energy acquisition leading to the formation of the shock wave.

The absorption of light produces in the medium a heat source, the power of which is

$$W = k(t)J(t)V, \qquad (2)$$

where k(t) is the absorption coefficient, J(t) is the intensity of the incident light, V is the volume of the absorbing region of the substance. If we neglect the thermal conductivity of the medium, then the rate of its heating is

$$dT/dt = W/c_v\rho V, \qquad (3)$$

where c_v and ρ are the specific heat and density.

It can be assumed that heating within a time shorter than the time of propagation of the disturbance through the heated region occurred at a constant volume. The time of propagation of the disturbance is $t' = r/v_s \sim 10^{-8}$ sec (r—radius of focal region, v_s—speed of sound). Heating leads to an increase of the pressure in the volume V:

$$\frac{dP}{dt}=\frac{\beta}{\mu}\frac{dT}{dt}=\frac{\beta k(t)J(t)}{\mu c_v\rho}, \qquad (4)$$

where β and μ are the coefficients of volume expansion and the compressibility of the substance. If within a time $t' = r/v_s$ the pressure

$$P=\frac{\beta}{\mu c_v\rho}\int_0^{r/v_s} k(t)J(t)\,dt \qquad (5)$$

exceeds the pressure P_{crit} at which Hooke's law is violated, then a shock wave begins to propagate in the medium. The spreading of matter behind the front of the shock wave gives rise to a rarefaction zone.

When the negative pressure in this zone exceeds the strength of the substance, the latter is damaged. Substituting the numerical values for sapphire[7] in (5) we find that for dynamic destruction it is necessary that under our conditions ($\tau \sim 10$ nsec, V ~ 10^{-5} cm^3) the energy absorbed be $E > 10^{-1}$ J. This value agrees well with the values of E measured in our experiments.

Expression (5) contains the experimentally determined quantity k(t). If it is expressed in terms of the electron density in the conduction band N, then we can

obtain an expression connecting the pressure in the shock wave P with the density of the incident light J(t).

The powerful light causes the electron in the conduction band to acquire an energy at a rate

$$\frac{d\mathscr{E}}{at} = \frac{4\pi e^2 J(t)}{m\omega^2 c}\nu_{\text{eff}}.$$

If we neglect the energy losses on the phonon[5], then within a time

$$\gamma = m\omega^2 cI / 4\pi e^2 J(t)\nu_{\text{eff}},$$

where I is the lattice ionization potential, the electron acquires an energy sufficient to ionize the lattice, and causes a cascade-like growth of the number of electrons in the conduction band. The electron density N increases like

$$N(t) = N_0 \exp\left\{\int_0^t \frac{4\pi e^2 J(t')\ln 2}{I m\omega^2 c}\nu_{\text{eff}}\, dt'\right\}, \qquad (6)$$

where N_0 is the initial electron density in the conduction band. The connection between the pressure P and the light intensity J(t) is given by the following expression:

$$P = \frac{4\pi e^2}{m\omega^2 c}\frac{\beta}{\mu c_t \rho} N_0 \int_0^{r/v_s} J(t)\exp\left\{\frac{4\pi e^2 \nu_{\text{eff}}\ln 2}{Im\omega^2 c}\int_0^t J(t')dt'\right\} dt. \qquad (7)$$

At an initial electron density $N_0 \sim 10^{16}$ (this density can be produced by single-photon ionization of the impurities), the pressure on the shock wave front is $P \sim 10^6$ atm. This value agrees well with the estimate of P based on the shock-wave velocity[2].

In conclusion we wish to emphasize the following:

1) In the investigation of mechanical damage to transparent dielectrics by monopulse laser light, it is necessary to take into account the formation and development of shock waves.

2) Mechanical damage sets after the shock wave moves away, with a time delay exceeding 10 nsec. Thus, the main action of the laser light on the substance occurs prior to the occurrence of mechanical damage. This makes it possible to observe nonlinear effects such as stimulated Mandel'shtam-Brillouin scattering, the thresholds of which is higher than the damaged threshold, but the transient time is shorter than 10 sec.

The authors are grateful to M. D. Galanin for interest in the work and L. A. Pakhomycheva for help with the work.

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Translated by J. G. Adashko
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