Role of self-focusing in the damage to transparent dielectrics by laser radiation

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A study was made of the appearance and development of damage in transparent media as a result of focusing giant ruby laser pulses. Investigation of a wide range of transparent dielectrics indicated that when the laser energy exceeded the damage threshold, the process started with the formation of filamentary structures, irrespective of the nature of the focusing lenses. The damage process in glass was attributed to the accumulation of energy.

INTRODUCTION

A considerable experimental body of data is now available on laser damage in transparent dielectrics. Attention is drawn in[1-5] to the influence of the self-focusing of laser radiation on the damage to matter under certain experimental conditions. Depending on these conditions, one may observe filamentary damage regions, which are attributed to the self-focusing, and "bulk" damage regions whose longitudinal and transverse dimensions are of the same order of magnitude. It is held that the bulk damage is not influenced by the self-focusing.

We used the method of pulse holography in a study of the dynamics of the development of laser damage, beginning from the moment of its appearance. We found experimentally that, under all the investigated conditions, the damage was always preceded by the appearance of an opaque filament in the focal region of a lens. A filament also appeared when the final "cooled" damage region was of bulk type.

We investigated different transparent dielectrics and focused the radiation using lenses of different focal lengths. The influence of the multimode nature of the radiation on the damage process was allowed by carrying out control experiments in which single-mode laser radiation was used. Filaments which appeared in these cases could be due to the self-focusing effect. It was found that the damage threshold of glass and fused quartz was governed by the laser radiation energy and the threshold of lithium niobate by the radiation power.

1. EXPERIMENTAL METHOD

The damage was produced and recorded using a Q-switched ruby laser emitting pulses of ~2 J energy and ~15 nsec duration (at mid-amplitude). This laser could emit multimode and single-mode radiation. The damage was recorded by the method of pulse holography with a two-frame scan, described in[6].

The moment of the appearance of a filament had to be known exactly in a study of the dynamics of the damage process. The duration of the recording pulses was ~15 nsec, but the time resolution of the method used in the determination of the moment of appearance of a filament was ~1 nsec. We reached this conclusion as follows.

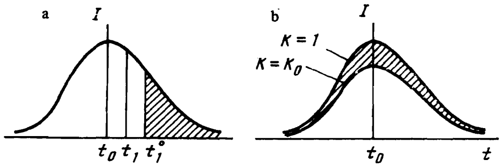

FIG. 1. Ruby laser pulse producing an image of an object.

Let us assume that a hologram records an opaque object which appears instantaneously at some moment t_1 (Fig. 1a). In this case, the contrast in the reconstructed image of the object is governed by the ratio of the energy transmitted after the moment t_1 to the total pulse energy. Obviously, at some moment of appearance t_1^0, this object becomes indistinguishable from the bright background of the reconstructed image. The difference $t_1^0 - t_0$ represents the threshold contrast for the visual observation of the object.[7,8] It is equal to the ratio of the shaded area in Fig. 1a to the total area under the recorded pulse.

Let us now consider a hologram recording a stationary partly transparent object. In this case, the threshold contrast is governed by the threshold transparency coefficient of the object K_0 (Fig. 1b). When this transparency increases, the object becomes indistinguishable from the bright background of the reconstructed image (equality of the background and object brightness corresponds to $K = 1$). Obviously, in this case, the threshold contrast is equal to the ratio of the area shaded in Fig. 1b to the total energy of the recording pulse.

If we assume that the reciprocity law is not violated in ~1 nsec, the density of the developed photographic emulsion should be governed only by the total energy received during the recording time. Thus, $t_1^0 - t_0$ and K_0 are related because of the equality of the shaded areas in Figs. 1a and 1b. The value of K_0 was determined by recording holograms of partly transmitting objects. These were filters of known optical density, covering part of the beam. In the case of a filter with a transmission coefficient of ~0.8, the brightness of the reconstructed image of the filter was indistinguishable from the background brightness. This transmission coefficient was equal to the required value of K_0. Knowing K_0 and the pulse shape, we could determine $t_1^0 - t_0$, which was 3 ± 1 nsec. The measured shape of the pulses could be described by a Gaussian curve with different dispersion at the leading and trailing edges. The error in the determination of $t_1^0 - t_0$, equal to 1 nsec, was governed by the error in finding K_0 and represented the time resolution of the method.

It should be pointed out that the threshold contrast in the image and, therefore, the moment of detection of an object could depend on its dimensions and shape.[9,10] This dependence was particularly strong when the angular dimensions of the object approached the resolution limit of the optical system. In the present investigation, the investigated objects were filamentary damage regions and the precision of the measurements could be affected by the small angular dimensions of these regions. We carried out control experiments in which we deliberately made a scratch on a transparent rotating disk which was used as the object. The results of these experiments confirmed the applicability of the above method of measuring the threshold contrast to investigations of filamentary damage regions.

2. EXPERIMENTAL RESULTS

The application of the method described above gave us new information on the early stages of the laser damage process.

1. We found that, when laser pulses were focused in the bulk of transparent media (K-8 glass, fused quartz, lithium niobate, and water) by lenses with different focal lengths f (18, 36, and 85 mm), the damage process always began with a filament. Figure 2 shows the damage in K-8 glass caused by focusing radiation with an f = 36 mm lens and recorded at different moments. In 1-2 nsec after the appearance of the first filament at the center of the focal region (Fig. 2a), we found that lateral filaments appeared on both sides of the original filament and filled the focal region. The appearance of several filaments in the focal region was attributed to the multimode structure of the laser radiation. This was confirmed in experiments in which the distribution of the energy density in the focal spot was varied. The multimode radiation was used because of the higher energy provided in this way. When single-mode radiation was employed, the results were the same but only one shorter filament was observed.

At some points in the filaments there were discrete explosion regions which appeared simultaneously with the filaments themselves. The explosion regions in each filament grew gradually (Fig. 2b) and the damage was homogeneous at the end of the radiation pulse and filled the focal region of the lens (Fig. 2c). The later stages of the damage process were due to the action of a shock wave which caused the bulk damage (Fig. 2d). The role of a shock wave in the damage process was investigated in[11]. When other media and different focusing lenses were used, the early stages of the damage process were still the same.

However, when an f = 85 mm lens was used, the final damage was governed by the presence of long filaments. This was the pattern regarded in the literature as typical of the self-focusing effect. An investigation of the dynamics of the damage process at different stages thus indicated that, under the conditions employed by us, the damage of transparent dielectrics always started with a filament whose origin could be attributed to the self-focusing effect.

2. Measurements of the damage thresholds and filament diameters d of various media gave the results listed in Table I for a lens with f = 36 mm. The damage thresholds were calculated by averaging over the focal spot the pulse intensity I_{th} and the energy density E_{th}/S. The focal spot diameter was ~200 μ. The filament diameter increased with the damage threshold of a given substance.

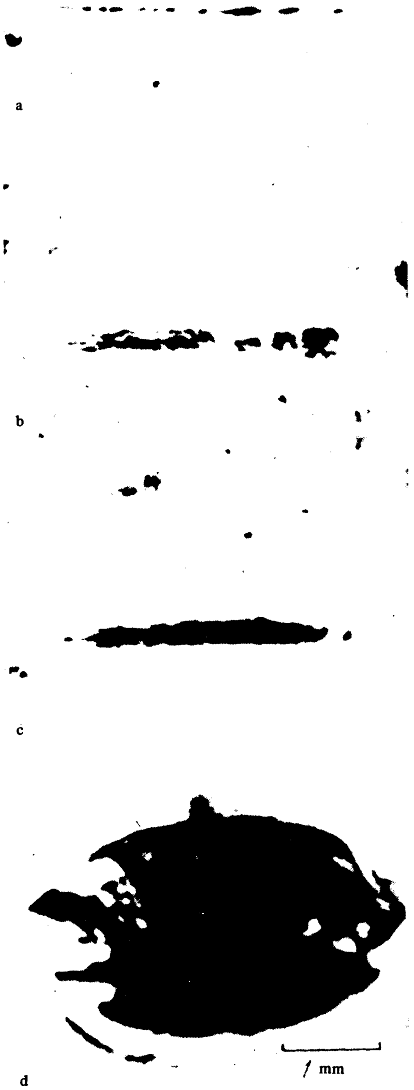

FIG. 2. Laser damage in K-8 glass, recorded at different moments: a) −4 nsec; b) −2 nsec; c) +12 nsec; d) final "cold" damage region (time was measured from the moment when the maximum intensity of the pulse was reached).

Investigated substance	$I_{th} \times 10^{-8}$, W/cm²	E_{th}/S, J	d, μ
Quartz	400	600	~10
K-8 glass	200	300	5 – 10
H_2O bidistillate	80	120	~5
H_2O	40	60	1 – 5
Lithium niobate	6	10	~1

3. The dependence of the damage, threshold deduced from the energy density in the focal spot, on the focal length of the lens was determined for K-8 glass. This dependence is plotted in Fig. 3. The same dependence was obtained for K-8 glass when single-mode laser radiation was used. The latter dependence was similar to that shown in Fig. 3, apart from the scale. However, the absolute values of the threshold in the single-mode case were more than an order of magnitude higher than

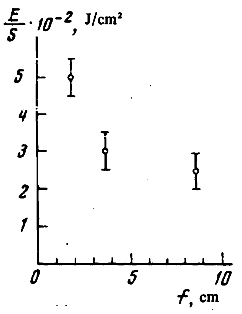

FIG. 3

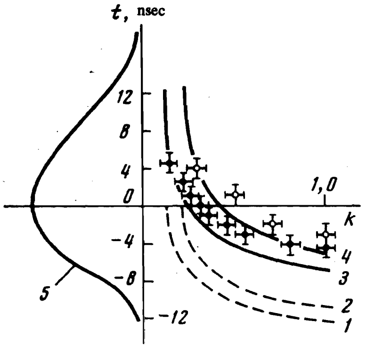

FIG. 4

FIG. 3. Dependence of the energy density corresponding to the damage threshold in the focal spot on the focal length of the lens.

FIG. 4. Dependence of the moment of the appearance of damage on the attenuation coefficient of a laser beam k: ●) K-8 glass; ○) fused quartz. Calculated curves: 1) "instantaneous" mechanism in K-8 glass; 2) "instantaneous" mechanism in fused quartz; 3) "delayed" mechanism in K-8 glass; 4) "delayed" mechanism in fused quartz. Curve 5 shows the laser pulse shape.

the corresponding values of the threshold in the multimode case (a similar observation was reported in[12]). The nature of the damage was basically similar in the single-mode and multimode cases.

4. The use of two-frame scanning in the holographic recording of filamentary damage regions demonstrated that a filament formed completely in a time not exceeding 1 nsec. Therefore, we could use the results presented in Sec. 1 to determine the moment of appearance of a filament. In the case of glass and fused quartz, we determined the dependence of the moment of appearance of a filament on the laser pulse energy. This energy was varied using neutral filters. The radiation was focused with an f = 36 mm lens. The results of the measurements are presented in Fig. 4.

3. DISCUSSION OF RESULTS

The main result of this investigation was the experimental information on the damage dynamics during a laser pulse. We found that, under all the conditions investigated, the damage began with the formation of a filament. A filamentary damage region probably represented the optical breakdown resulting from avalanche ionization.[13] The time needed for its development was much shorter than the time resolution of the method employed and, therefore, the avalanche ionization process could be regarded as instantaneous. However, experimental studies indicated the moment of appearance of damage in glass and fused quartz was subject to delay.

Knowing the damage threshold of a substance and the shape of a laser pulse, we could find for any substance the dependence of the moment of appearance of damage on the maximum laser pulse intensity and on its total energy. Figure 4 shows pairs of such curves for K-8 glass and fused quartz. The abscissa gives the transmission coefficients of neutral filters used to attenuate the laser beam and, therefore, the "delayed" and "instantaneous" dependences can be presented in the same figure. A comparison of the calculated and experimental results showed that the damage threshold of glass and fused quartz was governed by the accumulation of energy. This was also supported by the observation that, for a certain laser energy, the damage appeared immediately after the maximum intensity of the laser pulse was reached. This was also pointed out in[4]. (A similar method was employed in a study of the damage of lithium niobate; in this case, we found that the damage threshold was governed by the radiation power.) This experimental result indicated that the avalanche ionization was preceded by some other slower process. This could be the self-focusing of the incident radiation.

We also observed that the average (over the focal spot) threshold energy density decreased with increasing focal length of the lens (Fig. 3). Clearly, the electric field needed for the breakdown of a transparent dielectric at a given point in the focal spot was governed only by the properties of the substance investigated and was independent of the diameter of this spot.[13] This also suggested that the self-focusing effect took place.

As pointed out above, discrete explosion regions in the filaments played the dominant role in the damage process. Such regions had also been observed earlier.[14] They were the sources of the shock waves whose superposition produced a cylindrical shock wave.[11,14] The explosions could be due to the presence of foreign inclusions in the investigated medium. However, experiments carried out on different substances indicated that the frequency of explosions was independent of the degree of inhomogeneity of the substance. Moreover, the part of the damage region closer to the lens did not become thicker and this should have occurred during successive screening of the radiation by separate explosions. Thus, the influence of inhomogeneities on the explosions was doubtful. We could suggest that the observed explosions were the points of rest of traveling foci, resulting from the successive self-focusing of ring-like zones in the laser beam.[1]

Thus, on the basis of the results, we proposed the following sequence of the formation and development of damage caused to transparent dielectrics by focusing high-power laser radiation. When the threshold conditions were reached in most of the transparent dielectrics, the laser beam experienced the self-focusing effect irrespective of the beam geometry. The self-focusing produced filamentary damage regions with discrete explosion zones. During a pulse, these explosion zones increased and filled the whole focal region of the lens when the energy density was sufficiently high. It was these explosion zones that were sources of shock waves responsible for the damage outside the focal region of the lens. One should not exclude the possibility of conditions under which the breakdown threshold would be lower than the self-focusing threshold.

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[1] V. N. Lugovoĭ and A. M. Prokhorov, Usp. Fiz. Nauk 111, 203 (1973) [Sov. Phys.-Usp. 16, 658 (1974)].

[2] G. A. Askar'yan, Usp. Fiz. Nauk 111, 249 (1973) [Sov. Phys.-Usp. 16, 680 (1974)].

[3] A. J. Glass and A. H. Guenther, Appl. Opt. 12, 637 (1973).

[4] G. M. Zverev and V. A. Pashkov, Zh. Eksp. Teor. Fiz. 57, 1128 (1969) [Sov. Phys.-JETP 30, 616 (1970)].

[5] N. I. Lipatov, A. A. Manenkov, and A. M. Prokhorov, ZhETF Pis'ma Red. 11, 444 (1970) [JETP Lett. 11, 300 (1970)].

[6] I. I. Ashmarin, Yu. A. Bykovskiĭ, N. N. Degtyarenko, V. F. Elesin, A. I. Larkin, and I, P. Sipaĭlo, Zh. Tekh. Fiz. 41, 2369 (1971) [Sov. Phys.-Tech. Phys. 16, 1881 (1972)].

[7] A. V. Luizov, Priroda 40, 12 (1951).

[8] E. S. Ratner, Dokl. Akad. Nauk SSSR 105, 90 (1955).

[9] E. S. Ratner and Yu. Z. Matskovskaya, Dokl. Akad. Nauk SSSR 213, 313 (1973) [Sov. Phys.-Dokl. 18, 719 (1974)].

[10] A. V. Luizov and N. S. Fedorova, Opt.-Mekh. Prom.-st' No. 10, 12 (1973) [Sov. J. Opt. Technol. 40, 609 (1973)].

[11] I. I. Ashmarin, Yu. A. Bykovskiĭ, V. A. Gridin, V. F. Elesin, Ya. Yu. Zysin, A. I. Larkin, and V. A. Furmanov, Fiz. Tverd. Tela 16, 246 (1974) [Sov. Phys.-Solid State 16, 159 (1974)].

[12] G. M. Zverev, E. A. Levchuk, and É. K. Maldutis, Zh. Eksp. Teor. Fiz. 57, 730 (1969) [Sov. Phys.-JETP 30, 400 (1970)].

[13] N. Bloembergen, IEEE J. Quantum Electron. QE-10, 375 (1974).

[14] I. I. Ashmarin, Yu. A. Bykovskiĭ, V. A. Gridin, V. F. Elesin, A. I. Larkin, and I. P. Sipaĭlo, Kvant. Elektron. (Mosc.) No. 6, 126 (1971) [Sov. J. Quantum Electron. 1, 674 (1972)].

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