EFFECT OF A LASER BEAM ON PLEXIGLAS

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An analysis is given of the optical effects during the focusing of a laser beam inside a transparent dielectric (plexiglas). Two types of damage were established. One is connected with the appearance of microcracks and the other with large plane cracks. Transition from one type of damage to the other is observed when the focal length of the lenses (energy density in the specimen) is varied and the pulse length is changed from 10^{-3} to 10^{-8} sec. The effect of a laser beam on metals and ionic crystals was investigated in [1–3]. A number of effects associated with structural changes and a specific material damage were found. There is also some interest in the effects of laser light on transparent dielectrics (glasses and polymers). In the present paper we report results of an investigation of the effect of laser beams on plexiglas.

A detailed account of the beam geometry and of the absolute distribution of the light field focused by real systems is given in [4].

We shall investigate the following special case. A plane wave S passes through an ideal optical system L (Fig. 1) and enters a medium 3 with refractive index n. We shall consider the geometry of the focal region. The notation shown in the figure is as follows: 1 is the parallel beam, L is the lens, 2 is the region between the lens and the medium, 3 is the region occupied by the medium, R_0 is the focal length of the lens in air (radius of the spherical wave), d is the part of R_0 lying in the medium, θ is the angle between the lens axis and a ray in air, and θ' is the angle between the lens axis and a ray in the medium. It follows from Fig. 1 that

$$\frac{\sin\theta}{\sin\theta'} = n, \qquad n > 1, \quad \theta > \theta', \tag{1}$$

i.e., the ray cuts the optical axis not at the point f but at some other point x. To find the function $x = x(\theta)$ we must write the two obvious relations

$$\operatorname{tg}\theta' = y/x, \quad \operatorname{tg}\theta = y/d \tag{2}$$

or

$$x = d\operatorname{tg}\theta / \operatorname{tg}\theta', \tag{3}$$

where d is the "depth of immersion" of the medium along the focal length of the lens, which is assumed to be known. If we transform Eq. (3) so that it is a function of the single argument θ, and suppose that θ is small, we obtain

$$x = x_0 + B\theta^2 \qquad (x_0 = dn, \quad B = d(n^2 - 1)/2n). \tag{4}$$

This leads to the following conclusions.

1) The focal length for paraxial rays in the medium is increased by $\Delta L = d(n - 1)$, which must always be taken into account when radiation is focused at a given point.

2) As the angle θ is increased there is also an increase in the distance x, and this means that the focal point degenerates into a line (axial caustic). This is particularly important when the laser has a large-diameter rod and the radiation is focused by a large-aperture optical system.

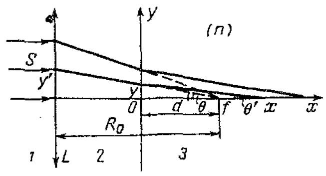

Fig. 1. Ray paths in the lens–plexiglas system.

The relation given by Eq. (4) must be taken into account in the analysis of the geometry of damage in transparent dielectrics in the focal region. The field of the axial caustic (whose length is usually between a few hundredths of a millimeter and 1 mm; see table) helps us to fulfill the conditions for the onset of self-trapping [5].

There is very little information in the published literature on the effect of laser radiation on transparent materials. Hercher [6] has examined the effect of focused laser radiation on some transparent dielectrics. Microphotographs of the damage show that it mainly consists of combinations of large cracks and lines, the latter being made up of very small bubbles. It was reported in [7] that the damage in glass consists of a region with a number of lines running out of it (the length of the main line is approximately 7 mm) where the material has been reduced to powder. Geometric optics is unable to explain the appearance of such lines (the axial caustic extends at best to 1 mm; see table). A theoretical interpretation of the appearance of such lines in the damaged region is given in [4] in terms of the self-trapping of light. We note that the idea of self-trapping of light in the case of a high-intensity laser beam was predicted earlier by Askar'yan [8].

The divergence of the laser beam (assuming that it corresponds to a spherical divergent wave with $R \approx 2$m) leads only to a displacement of the focus by $1.025\ R_0$ and cannot explain the above picture.

We have investigated the effect of a high-intensity laser beam on plexiglas, using a Q-switched laser (pulse length of the order of 10^{-8} sec) and a regulated output power. The glow produced inside the transparent specimen by the light pulse was photographed with a camera, and the negatives were examined with a microphotometer. The results of measurements on some plexiglas specimens ($n = 1.5$) are given in the table, where w is the laser output power in MW (±10%), R_0 is the focal length of the lens (mm), d is the part of R_0 lying in the medium (mm), $x_0 = dn$ is the true position of the focus in the medium (mm), $B = d(n^2 - 1)/2n$ and is given in mm, θ_m is the angle between a peripheral ray and the axis (rad), and x is the point of intersection between the peripheral ray and the axis (mm).

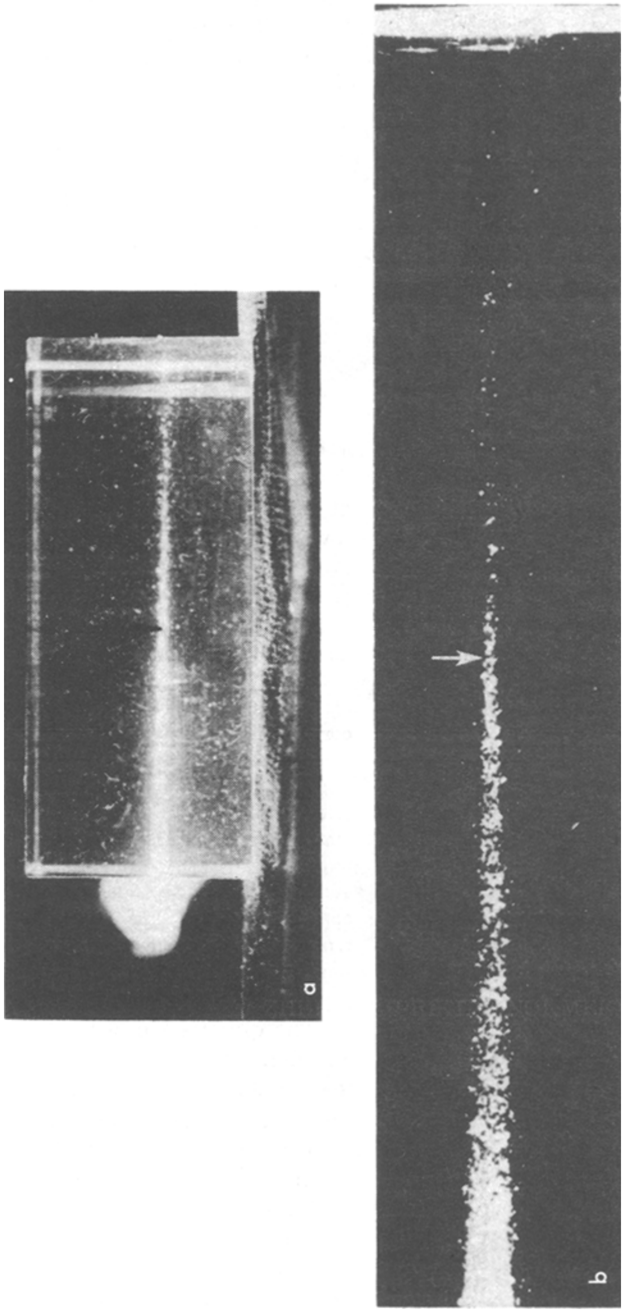

Fig. 2. Microcrack-type damage: a) photograph of the laser beam in the specimen, magnification ×1.5; b) damage along the beam, magnification ×3.

It follows from the table that, as a result of aberration, the focal point will be displaced in the forward direction along the ray by about 0.1–1 mm and that this displacement is measurable.

When the appearance of the damage in plexiglas is analyzed there are two clearly distinguishable types of damage, namely: 1) damage with the formation of a large number of microcracks; and 2) damage with the formation of extended plane cracks.

We have found that, in the above range of beam power and optical-system parameters, the type of damage depends only on the focal length of the lens and is independent, for example, of the laser output power.

The microcrack-type damage is characteristic for lenses with long focal lengths. Figure 2a shows a photograph of the laser beam for a typical experiment in this series. The photograph shows a number of characteristic features. We note, first of all, that the focal point should lie in the region indicated by the arrow. In reality, a narrower and less divergent part of the light beam occurs further on. It is important to note that there is a characteristic glow in the air as the beam passes from air into the plexiglas specimen. There is also a bright region at the point of exit. A part of the beam energy is lost in forming this glow which is connected with the formation of plasma. This means that the energy density inside the specimen cannot be calculated. However, a change in the emitted power within a small range does not affect the appearance of the plasma cloud, i.e., the amount of energy taken up by the plasma remains approximately constant. Figure 2b shows the type of damage occurring in such a specimen. It is clear from this photograph that the region of damage has a conical shape and consists of individual points which scatter light (the photograph was obtained by illuminating the specimen with a narrow beam through one of its ends. At the point of entry and in the zone near the focus the density of the points is higher. It is important to note again that the region of damage extends well beyond the focus, which is indicated by the arrow. Finally, photographs taken from the end show that the cone of damage has a nearly circular base.

The density of radiation at the entrance to the medium in cases 2, 3, and 4 (see table) (microcrack-type damage) was 10^8 W/cm^2.

As the focal length is reduced the appearance of the damage undergoes a gradual change, and there is a gradual increase in the number of large cracks. As expected, the beam is then concentrated in the region of the focus. Moreover, it is important to note that a narrow region of high-intensity emission extends beyond the focus. Microphotography has shown that the region of damage in cases 5, 6, and 7 consists of a large number of nearly plane cracks of different sizes, ending on a common edge which extends in the forward direction beyond the focus. The length of the thread-like damage is about 6 mm for a mean crack size of about 10 mm.

The formation of plane cracks is also observed when a pulsed laser (pulse length 10^{-3} sec) operating under the conditions of free generation is employed. However, for a giant pulse (10^{-8} sec) the cracks have a common line of intersection which lies along the laser beam. The cracks themselves form a star-like figure when viewed along the beam. For an ordinary pulse (10^{-3} sec) the cracks are inclined to the axis at an angle of about 45° (see, for example, [9]). Photographs of the process of formation of the plane cracks show that, when the pulse length is 10^{-3} sec, practically all damage occurs during the actual pulse. This conclusion is based on the fact that photographs of the region of damage obtained during and after the pulse are practically the same. Moreover, secondary damage is often observed, i. e., sets of cracks lying along the axis at an angle of about 90° to the primary beam.

N	w	R_0	d	x_0	B	θ	$B\theta_m^2$	x_m
	1	2	3	4	5	6	7	8
1	20	80	20	30	8.35	0.075	4.7	30.05
2	80	80	20	30	8.35	0.075	4.7	30.05
3	80	55	20	30	8.35	0.107	9.6	30.10
4	80	55	15	22.5	6.26	0.107	7.4	22.57
5	30	18	13	19.5	5.42	0.333	60	20.10
6	90	18	15	22.5	6.26	0.333	70	23.20
7	90	18	15	22.5	6.26	0.333	70	23.20

In such cases, it is always clear that secondary damage is connected with the reflection of light from cracks produced earlier. For giant pulses (10^{-8} sec), photographs of the region of damage, obtained during and after the pulses, are not the same. During the pulse the damage is conical in shape and the plane cracks grow after the end of the pulse.

We note, finally, that studies of various types of transparent polymers have shown that each of them exhibits a specific type of damage. For example, in polystyrene exposed to an ordinary pulse (10^{-3} sec), the plane cracks form an angle with the beam which is less than in the plexiglas. For giant pulses in this material there is a conical damage without plane cracks (even for short focal-length lenses) which also extends well beyond the focus. Measurements have shown that the size of the region of damage is always greater than the shift of the focus due to lens aberration, and is apparently connected with the self-trapping effect in solids.

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