ANGULAR DISTRIBUTION OF MATERIAL VAPORIZED BY A LASER BEAM

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The angular distribution of material vaporized by free-running and Q-switched laser beams is investigated. The target is β-active Tl^{204}. It is determined by experiment that the angular distribution can have a random character. It is assumed that the angular distribution resulting from Q-switched operation is mainly determined by the emission of target particles occurring after the action of the shock wave. Theoretical estimates are presented and agree with the experimental results.

THE ejection of material caused by laser radiation is a complex and little understood process. We know that in the case of a Q-switched laser the action of the beam is followed by the ejection of a plasma bunch from the solid target surface and by the generation of a powerful shock wave in the solid. The action of the shock wave is in turn followed by the ejection of material in the form of microscopic splinters. On the other hand a free-running laser causes the surface to eject material mainly in the form of vapor and liquid jets. The spatial distribution of electron density in the plasma flare was investigated by Basov and others,[1] and the angular distribution of electrons and ions was studied in [2].

In connection with the feasibility of sputtering films with the aid of a laser,[3] it is now worthwhile to consider the problem of the angular distribution of the ejected material. To solve this problem we measured the thickness of films formed on the surface of a spherical substrate enclosing the target in the center as a function of the angle between the normal to the target plane and the line pointing to the film region under consideration.

EXPERIMENTAL RESULTS

According to preliminary experiments the thickness of the film due to a single laser action does not exceed 100 Å even when the substrate is close to the target. The measurement of this order of thickness is known to be very difficult. Therefore we used a method based on sputtering solid radioactive material followed by dosimetric analysis of the resulting film. We assumed here that the activity is proportional to the film thickness.

The target was β-active Tl^{204} ($E_\beta = 0.765$ MeV) in the form of $3 \times 3 \times 1$ mm metal platelets. The platelets were fixed at the center of a spherical chamber 130 mm in diameter. A pressure of 1×10^{-3} mm Hg was maintained in the chamber. In various experiments the target plane was placed at 90, 60, and 30° to the direction of the ruby laser beam.

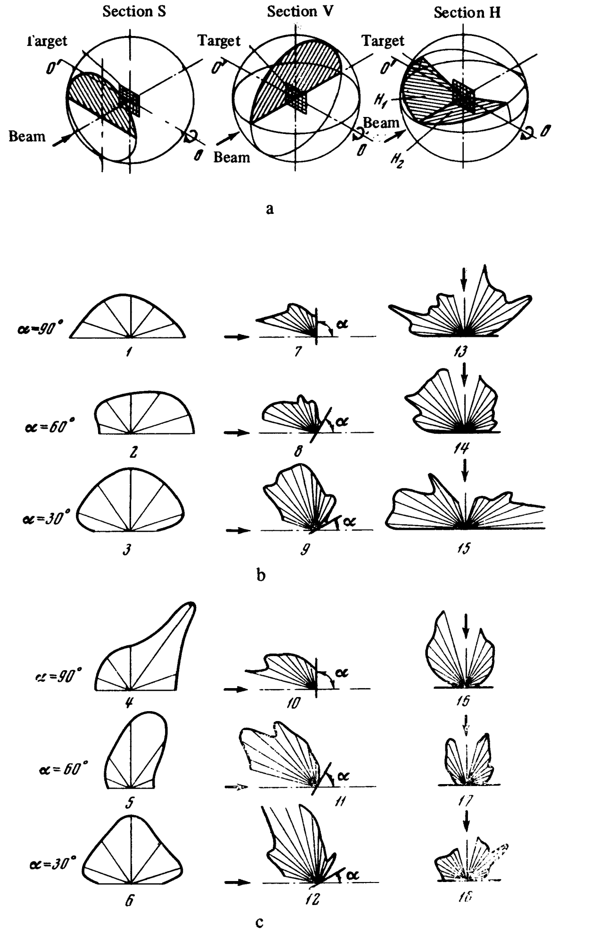
The energy density was 2×10^5 W/cm^2 in the free-running mode and 1×10^{10} W/cm^2 in the Q-switched mode. The thallium was deposited on substrates cemented to the surface of the chamber in the form of five meridional rings 5 mm wide. The substrate with the thallium film was cut into strips 10 mm long. The activity of each strip was measured with the SBT-7 counter and the PP-100 instrument. The statistical measurement error did not exceed 1%. Angular distribution diagrams were plotted for various cross sections from known angular coordinates and the measured activities of each strip. Some of these diagrams are shown in the figure. The experimental setup is shown in the upper part of the figure.

The analysis of diagrams for the section V shows that the material is ejected mainly along the normal to the target surface and the angular distribution function as a whole (neglecting individual spikes) resembles the "cosine law." Maxima are observed in the free-running mode (diagrams 7–9) at 30° to the target surface. The maxima are due to the reflective action of the crater walls on the vapor jet. We note here that the crater profile varies within a single radiation pulse. The diagrams of sections H and Vare analogous.

Diagrams of section S are fairly smooth curves that are not symmetric with respect to the beam direction. We note that none of these diagrams is fully reproducible from experiment to experiment under the same conditions. Furthermore the diagrams of different sections parallel to the S plane obtained in the same experiment are not similar as a rule. Consequently the diagrams of all sections show that the angular distribution of the material has a random nature.

DISCUSSION OF RESULTS

The action of a powerful Q-switched laser on a solid target causes the formation of a plasma flare with a high thermal pressure.[4] The plasma pressure causes a high intensity shock wave to propagate in the solid. After termination of the pulse the pressure at the target surface drops and a relaxation wave travels into the interior of the solid. As the compressed body expands to its initial volume the elastic energy acquired earlier in compression is transformed into kinetic energy of the material which is then ejected ([5], p. 548). The mass of the ejected material can be approximately computed in the following manner ([5],



Geometry of the experiment (A) and experimental results in free-running (B) and Q-switched (C) operation. Diagrams of Section S show activity distribution along the line of intersection of the spherical chamber with plane S located 40 mm away from the target; diagrams V refer to intersection with plane V; and diagrams H refer to intersection with planes H_1 and H_2 inclined at 18° to the horizontal plane.

p. 614; [6], p. 745):

$$M \approx W / \varepsilon_{cr}, \qquad (1)$$

where ϵ_{cr} is the specific breakdown energy and W is the work performed by plasma pressure in compression of the material:

$$W = s \int_0^\tau pv \, d\tau'; \qquad (2)$$

Here s is the focal spot area, τ is the laser pulse length, p is the pressure at the solid surface, and v is the velocity of the material behind the shock wave front.

Using the mass and momentum conservation laws in the shock wave ([5], p. 505), and the equations of state for condensed matter ([5], p. 509), we find the relation between velocity v and pressure p:

$$v = p / c_0\rho_0,$$

where c_0 and ρ_0 are the velocity of sound and density of the material. Instead of (2) we then obtain

$$W = \frac{s}{c_0\rho_0} \int_0^\tau p^2 \, d\tau'. \qquad (3)$$

The pressure of plasma created on the surface of the target was computed in [7]:

$$p = 0.2 b^{-1/3} \tau^{-1/8} q^{3/4}, \qquad (4)$$

where q is the intensity of laser emission and b is a constant. The mass of the generated plasma was obtained from the same source:

$$m = 0{,}37 b^{-1/4} \tau^{3/4} q^{1/2} s.$$

Substituting (4) into (3) we obtain

$$W = 0{,}05 \frac{s}{c_0\rho_0} b^{-1/4} q^{3/2} \tau^{3/4}.$$

We are interested in the ratio of the mass of material ejected by the relaxation effect to the mass of plasma; this equals

$$M / m \approx q / 7 c_0\rho_0\varepsilon_{cr}. \qquad (5)$$

This ratio is of the order of unity at the energy flux density used in our experiments. Consequently the major portion of the mass of the material is ejected in the form of microscopic splinters. We indeed observed a large quantity of splinters that settled in the lower part of the chamber.

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[1] N. G. Basov, V. A. Gribkov, O. N. Krokhin, and G. V. Sklizkov, Zh. Eksp. Teor. Fiz. **54**, 1073 (1968).
[2] A. Decauze and P. Zanger, Compt. rend. **262**, 1398 (1966).
[3] H. M. Smith and A. F. Turner, Appl. Optics **4**, 147 (1965).
[4] N. G. Basov, V. A. Boĭko, V. A. Dement'ev, O. N. Krokhin, and G. V. Sklizkov, Zh. Eksp. Teor. Fiz. **51**, 989 (1966) [Sov. Phys.-JETP **24**, 659 (1967)].
[5] Ya. B. Zel'dovich and Yu. P. Raĭzer, Fizika udarnykh voln i vysokotemperaturnykh gazodinamicheskikh yavleniĭ (Physics of Shock Waves and High Temperature Gas Dynamic Phenomena), Nauka (1963).
[6] F. A. Baum, K. P. Stanyukovich, and B. I. Shekhter, Fizika vzryva (Physics of Explosion), Fizmatgiz, (1959).
[7] Yu. V. Afanasev, V. M. Krol', O. N. Krokhin, and I. V. Nemchinov, Prikl. Matem. Mekh. **30**, 1022 (1966).

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