ACOUSTIC MEASUREMENTS OF THE ENERGY DISTRIBUTION IN THE TRANSVERSE CROSS SECTION OF A LASER BEAM

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The relative distributions of the light energy in the cross section of a beam which are reconstructed from measurements of the pressure in sound pulses generated when light is absorbed in a liquid are compared with the distributions measured by the photometric method. The profiles of the energy distribution measured by the two methods are in good agreement with one another.

In studies of the propagation of a laser pulse over long atmospheric paths difficulties arise in measuring the energy distribution in the transverse cross section of the beam; this distribution can change significantly in the course of propagation. Both the beam aperture and the position of the center of gravity can vary within wide limits, the former owing to beam divergence and the latter owing to the regular and random refraction. All this makes it difficult to aim beams (especially IR beams) on the optical components of energy meters.

In this connection it is of interest to use remote methods for measuring the energy distribution in a beam. In particular, measurements of sound pulses, which arise when laser radiation is absorbed, can be employed for this purpose.[1,2] The results of a theoretical study of the possibilities of reconstructing the energy distribution in light beams, from acoustic measurements were published in Ref. 3. In this paper the results of a model experiment illustrating these possibilities are presented.

As done in Ref. 3, the pressure generated in a medium by short laser pulses whose duration τ is less than the characteristic time over which the pressure in an acoustic pulse varies $\tau_{ac} = l/u$, where l is the minimum spatial size of the nonuniformities of the light intensity and u is the velocity of sound, was measured as a function of time under the condition that the thermal relaxation time τ_{rel} of the absorbed light energy is short compared with τ_{ac}. In a weakly absorbing medium with an absorption coefficient α such that the attenuation of the light energy at a distance r from the illuminated region to the point at which the acoustic pressure is measured is small ($\alpha r \ll 1$) the change in the pressure in time $P(t)$ and the integral

$$W(\rho) = \int_0^{2\pi} Q(\rho,\varphi)d\varphi \tag{1}$$

of the energy density $Q(\rho, \varphi)$ in a polar coordinate system centered at the point where the pressure is measured are related by the relation[3]

$$\alpha W(\rho) = k\int_0^{\rho/u} \frac{P(t)}{\sqrt{\rho^2-u^2t^2}}\,dt, \tag{2}$$

where k is the coefficient of proportionality.

In measuring the pressure at a distance r, much greater than the characteristic size of the transverse cross section of the beam, from the illuminated region the function

$$W(\rho) \simeq W(x) = \frac{1}{x}\int_{-\infty}^{\infty} Q(x,y)dy, \tag{3}$$

where x and y are the Cartesian coordinates centered at the point $\rho = 0$ and $\varphi = 0$, i.e., the function $W(\rho)$ is proportional to the integrals of the energy density over straight lines and carries the same information about the quantity Q as do, for example, measurements performed with the help of bolometric wires or photometric measurements with a narrow silt whose length is greater than the width of the light beam.

The purpose of this work was to study experimentally the possibility of reconstructing the spatial distribution of the intensity characterized by the function W from acoustic measurements.

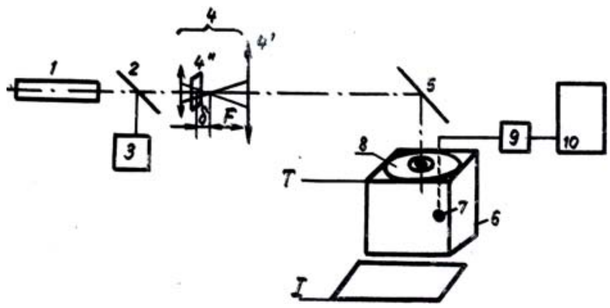

FIG. 1. Experimental arrangement.

The experimental arrangement is shown in Fig. 1. The radiation was provided by an OGM-20 ruby laser 1, which produced multimode radiation at the wavelength 0.69 μm with a pulse duration of 30 ns and energy up to 0.3 J. The energy in a light pulse was monitored with an IKT-1K calorimeter 3 by measuring the energy of the radiation reflected from a half-transmitting plate 2.

The beam passed through the forming collimator 4 was reflected from the rotating mirror 5, and was directed vertically into the cell 6 holding ethyl alcohol, the propagation velocity of sound waves in which is equal to 1160 cm/s. The alcohol was colored with methylene blue in order to obtain the required absorption (in a layer of liquid 20 cm thick the energy of the radiation was reduced by a factor of 1.5). The sound pressure generated in the liquid was recorded with a spherically shaped piezoelectric-ceramic hydrophone 73 mm in diameter whose frequency response had a nonuniformity of not more than 6 dB in the frequency band 30 kHz–600 kHz. The hydrophone was attached to a metal rod. The distance from it to the top surface of the liquid was the same as that to the bottom of the cell, and was equal to 10 cm. The rod holding the hydrophone was rigidly fastened to a rotating platform 8, which consisted of a circular 22 cm in diameter disk mounted in the cover of the cell and containing an opening at the center for injecting the beam. The acoustic signals at any point in the medium can be recorded by turning the platform around the axis and positioning the hydrophone at different distances from the center of the disk. From the output of the hydrophone the signal was fed through sin amplifier 9 to an S8-13 storage oscillograph 10, whose sweep was triggered by the delayed pulse triggering the electrooptical shutter of the laser.

The introduction of an additional regulatable delay in triggering the sweep made it possible to record the signal at the center of the screen of the oscillograph with maximum time resolution, irrespective of the time of arrival of the acoustic signal at the location of the hydrophone. Next the recorded signal was photographed, digitized, and processed on a computer. Since the spatial mode structure of successive laser pulses was unstable, additional beam formation was performed. For this a phase screen 4″, whose nonuniformities were much smaller than the characteristic scale of the intensity fluctuations in the laser beam, was placed in the collimator at a distance δ from the focal plane F. A mask which formed a fixed intensity distribution at the inlet into the medium was placed near the plane of the image of the screen U located at a distance L from the forming lens 4′ in the plane T coinciding with the surface of the disk.

This method for forming the beam makes it possible to obtain light radiation with small divergence outside the image plane of the screen and quite uniformly distributed over the cross section near the axis. In the experiment the focal length of the forming lens was $F = 8$ cm, $\delta = 0.8$ cm, $L = 88$ cm, and the distance from the forming lens to the plane T was equal to 60 cm. Comparing the photographs of the cross section of the beam obtained in such a manner, made near .the surface of the liquid and the bottom of the cell, showed that over the length of the layer of liquid (20 cm) the size of the beam changes insignificantly (by less than 10%); this makes it possible to regard it as collimated with known accuracy.

In the experiment a mask consisting of an elliptical opening, whose major and minor semiaxes were equal to 1.1 and 0.75 cm, respectively, cut out of an opaque screen was employed; the center of the opening was covered with an opaque circular disk 0.5 cm in diameter. Figure 2 shows a photograph of the cross section of the beam so formed in the plane of the hydrophone.

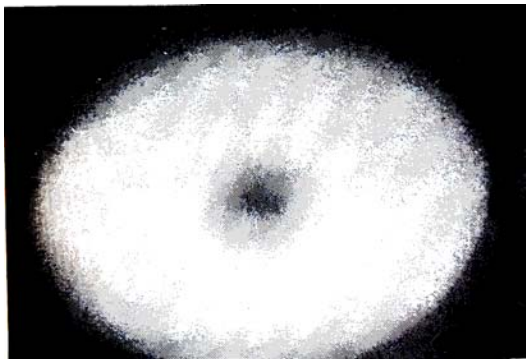

FIG. 2. Photograph of the cross section of the beam.

The center of the disk and the orientation of its axes were rigidly coupled to the center of the rotating platform; this made it possible to determine the coordinates of the beam with an accuracy of 0.5 mm. In order to be able to compare the results obtained by processing the acoustic signal with the starting parameters of the beam was photographed and photometric measurements were performed on the obtained negative on an MF-4 microphotometer in order to obtain the two-dimensional spatial distribution of the intensity in the cross section of the beam. For this the blackening of the film, averaged over a square window with 0.3 mm sides, was measured at the nodes of a grid with a step of 1 mm and the values of the intensity were calculated from its characteristic curve. Since absolute calibration of the entire channel of the measuring apparatus was not performed, only relative measurements were performed.

The function W was reconstructed from the measured acoustic pressure on a computer using a method analogous to that employed in Ref. 3. The pressure pulse was digitized with a resolution time of 0.88 μs, which corresponds to a spatial resolution $\Delta = 1$ mm, while the error in determining its amplitude did not exceed 10%, which, as one can see from the presented photographs of the form of the sound pulse (Fig. 3), was determined by the noise level in the measuring channel and the width of a line on the screen of the oscillograph.

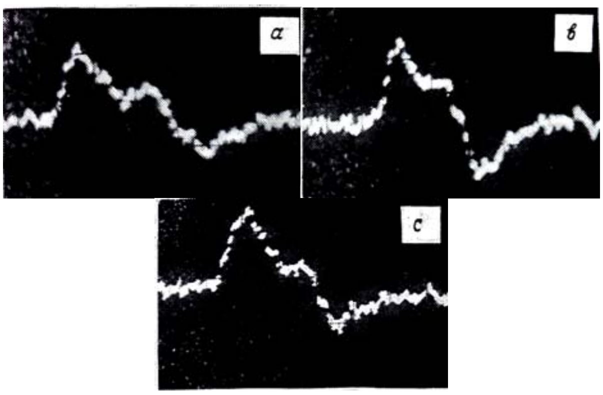

FIG. 3. Examples of sound pulses generated on absorption. The hydrophone was placed along the major axis of the ellipse (a), the minor axis of the ellipse (b), and at an angle of 45° (c).

Figure 4 shows the values of the function W reconstructed from the form of the acoustic signal and corresponding to measurements performed for three positions of the receiving hydrophone: along the major and minor semiaxes of the beam as well as at an angle of 45° with respect to the semiaxes. In all three cases the distance from the center of the beam to the hydrophone was the same and was equal to 7 cm. The figure also shows the function W measured by the photometric method for all three cases. The function W was normalized to the total energy, i.e., to the integral $\int W(x)dx$. In spite of the fact that the results agree well with one Mother there is some discrepancy along the abscissa axis (see Fig. 4b). The discrepancy is associated with the fact that the sweep of the oscillograph was triggered with an accuracy of 0.5 μs (this introduced an error of 0.55 mm in the determination of the spatial coordinate) as well as with the presence of a small air gap between the disk and the rotating platform, which gave a total lead or delay of 1.5 cm in the recorded signal relative to the true signal. The small rise in the trailing edge of W near zero is caused by errors in determining the amplitude of the pressure pulse owing to the presence of low-frequency jitter of the zero level of the measuring channel (not more than 5% of the maximum value of the signal amplitude), which could affect appreciably the accuracy with which the "tail" of the sound pulse was digitized.

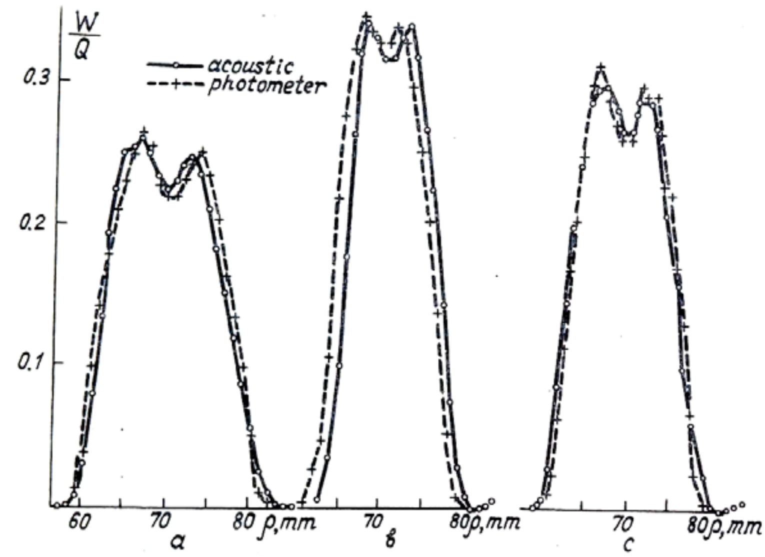

FIG. 4. The reconstructed profiles of the energy distributions corresponding to the sound pulses (see Fig. 3).

It should also be pointed out that the use of integration along straight lines, as done in (3), and not along circles, as done in (1), in determining the function W by photometric and acoustic methods does not introduce any significant errors for the given geometry of the experiment, since the maximum deviation of the circle from the straight line on the edges of the beam does not exceed 0.8 mm, which falls within the limits of the resolution of the microphone. The fact that the energy of the beam varies along the z-axis (in the direction of propagation of the beam) is neglected also introduces a small error in the reconstruction. Qualitative considerations show that a linear change in the energy Q along the z-axis does not result in any change in the form of the sound pulse as compared with the form of the pulse generated by a cylindrical beam (if Q is independent of z), since the pressure disturbances arriving at the point of measurement from points lying symmetrically about the plane Z_0, passing through the measurement point, together produce twice the disturbance from points in the plane Z_0, like in a cylindrical beam. The form of the sound pulse is therefore affected only by the nonlinear terms in the dependence $Q(z)$. In the case of exponential attenuation $Q(z) \sim \exp(-\alpha z)$ the deviation ΔP of the form of the pressure from that in a cylindrical beam $P_0(t)$ will be of the order of $\alpha^2 l^2$, $l^2 = r^2 - (r - a)^2$, where a is the radius of the beam l is the length of the region of the beam that is important for sound generation.

Numerical calculations performed for a Gaussian beam taking into account the dependence $Q(z)$ confirmed this result.

In particular, the ratio $\Delta P/P_0$ at the minimum of $P_0(t)$ satisfies the relation

$$|\Delta P/P_0| = 0.8\alpha^2 l^2.$$

In the experiment the quantities α and l were equal to 0.02 cm^{-1} and 3.6 cm, respectively, so that the relative error in reconstructing the function W does not exceed 0.4% in the region $r - 2a \le \rho \le r + 2a$.

The presented results of the laboratory experiment allow us to draw the conclusion that the optical-acoustic method proposed in Ref. 3 for determining the energy distribution over the cross section of a pulsed laser beam is promising.

The chief advantage of this method lies in the fact that there is no need to introduce radiation from the components of the measuring instruments into the channel, i.e., it is nonperturbative, and it permits monitoring the parameters of radiation in real time (the measuring time is determined by the passage time of the sound wave from the beam to the microphone, the triggering time of the ADC, and the computing time).

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