A procedure for determining the diameter of a focused laser beam based on the measurement of laser damage to a thin film is described. This method has several advantages over the spatial methods of using calibrated diaphragms and the measurement of relative power density distribution with subapertures.

In all technical processes involving the use of laser light, great significance is placed on the measurement of beam diameter in the interaction region of the light and the work material. An error in the measurement of this quantity can have a fundamental influence on the accuracy of determining a key parameter of the optical interaction: the power (or energy) density of the beam at the object. A special approach is required for the solution of this metrologic problem when focused beams — used more and more frequently in laser technology — are considered.

Several methods have been used for the measurement of laser beam diameter. Among these are the widely used method of relative power (energy) density measurement [1] and the method of calibration apertures [2].

The first method uses a transducer to shift an aperture through a cross-sectional plane of the focused laser beam. This requires apertures and scanning systems [1] that cannot be realized in practice for small laser beam diameters. Even a matrix converter turns out to be ineffective. An optical system for relaying the image of the beam cross-section at the aperture plane can formally solve the problem, but introduces additional error that is especially significant and difficult to control for multimode irradiation.

Definite limitations arise with the measurement of beam diameter with calibrated apertures. These are based on the determination of the diameter of the aperture through which the energy (power) field of the laser passes [2].

In practice the fundamental difficulty with this method is the adjustment of the aperture position relative to the axis of the laser beam. The error arising from a shift in the center of the aperture can be as high as ± 8% [2]. For small diameter beams (less than 100 μm), this level of error can be even greater by 1.5 to 2.5 times, rendering this method unusable for the measurement.

In this paper a method for the measurement of laser beam diameter is proposed that uses an auxiliary medium — a disk of transparent material with an absorbing coating. For a certified coating which exhibits spatially uniform laser damage threshold, laser light interacts in such a way that its vaporization will occur so that the damage in various regions will show different contours of the reduced laser light $K_i = I_i/I_0$, where $I_0$ and $I_i$ are the peak intensities associated with the initial and reduced beams. It is apparent that in the case of a Gaussian beam, for example (with normal distribution of intensity in any cross-section) having peak intensity $I_i$ ($I_i > I^*$, where $I^*$ is the damage threshold of the coating) the damage region will be represented as a circular zone with diameter $d_i$, inasmuch as it bounds the curve for which the local intensity is equal to the damage threshold of the coating (Fig. 1). Since the damage at the diameter $d_i$ is obtained for the light reduction coefficient $K_i = I_i/I_0$, the initial beam has a diameter $d_i$ at the level $\mu = I^*/I_i$. In particular, continuing the measurements with $i = 1, 2, 3, \ldots$, one can examine the spatial distribution of the light intensity in a cross-section of a beam (Fig. 2). The data will be approximated by the function $d = F(\mu)$ for the determination of the beam diameter for any level of intensity, and, in particular, at the $\mu_c = 1/e \approx 0.37$ intensity level, the most often used level for characterizing the parameters of laser technology processes.
Fig. 1. Laser damage diameters $d_i$ for various levels of light reduction of a Gaussian beam.

The approach is also appropriate for multimode radiation. In Fig. 3 intensity contour in a cross-sectional plane of a focused laser beam are shown. The contour map was obtained by the superposition of images of damage regions taken with illumination at various light reduction levels. An effective diameter for the beam cross-section can be obtained from the following formula

$$d_{\text{eff}} = \sqrt{\frac{1}{\pi} S_i},$$

where $S_i$ is the area of the damage region corresponding to reduction coefficient $K_i$.

This method was used for the measurement beam diameter over a wide range of pulsed laser wavelengths: nitrogen ($\lambda = 0.337 \ \mu m$), Nd:YAG ($\lambda = 1.064 \ \mu m$) and its doubled frequency ($\lambda = 0.532 \ \mu m$), as well as erbium-doped ($1.540 \ \mu m$). Measurements of the diameters of focused laser beams were performed for diameters down to $30 \ \mu m$.

For certified samples of spatially homogeneous laser damage threshold (where the deviation from the mean value fell within a range $\delta_1 = \pm 5\%$), we used disks of K8 glass or polished quartz coated with the nonstoichiometric dioxides of titanium, silicon, or aluminum.

The measurement of the laser damage zones was done with a metrologic microscope with a maximum error of 1 $\mu m$, which in our case, translates to the range $\delta_2 = \pm 4\%$.

It is important to note that, with this method, it is not necessary to measure the intensity of the laser beam (this can contribute significant error to the total error [2]), rather one needs only to consider the ratio $I/I_0$. The reduction of the light can be accomplished by calibrated light filters such that errors in the beam measurement due to error in the reduction coefficient will not exceed $\delta_3 = \pm 1\%$.

Finally, the effect of error arising from the energy (power) instability in the laser is $\delta_4 = \pm 7\%$, and the errors of approximation in the reconstruction of the graphical function based on at least seven measurements is $\delta_5 = \pm 5\%$.

The formula for the total error $\delta$ in the measurement of beam diameter takes the following form,

$$\delta = \pm \alpha \sqrt{(\delta_1/\gamma_1)^2 + (\delta_2/\gamma_2)^2 + (\delta_3/\gamma_3)^2 + (\delta_4/\gamma_4)^2 + (\delta_5/\gamma_5)^2},$$

where $\alpha$, $\gamma_1$, ..., $\gamma_5$ are coefficients that depend on the distribution laws for the respective errors in measurement and the prescribed statistical confidence levels.

The distribution laws for the partial errors is taken to be uniform. The specific values for the coefficients $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = 1.73$. The distribution law for the total error yields $\alpha = 1.96$ for a statistical confidence level of 0.95.