Formation of the radial distribution of intensity in a laser beam by "soft" apertures

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The results are given of theoretical and experimental investigations of "soft" apertures whose action is based on the dependence of the transmission of light by a three-layer medium on the thickness of the layer separating the surfaces on which light is incident at an angle exceeding the angle of total internal reflection. It is shown that such apertures can be used to form a beam with a specified radial intensity profile from beams with Gaussian and uniform profiles. The high optical strength of such apertures and the possibility of forming a radial profile with a high spatial fill factor without formation of diffraction rings makes them suitable for use in high-power laser systems.

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The development of high-power laser systems has drawn attention to the methods for forming the radial distribution of the intensity in a light beam being amplified. According to theoretical calculations, the optimal intensity is

$$I(\rho) = I_0 \exp \left[-\left(\rho/\rho_0\right)^{N} \right], \quad N = 5 - 10, \quad (1)$$

where the parameter $\rho_0$ is selected on condition that $R(r) = 10^{-3}I_0$, where $2r_1$ is the entry aperture of the amplifier. This results in a significant increase of the filling of the amplifier aperture without formation of diffraction rings in the working zone because such rings reduce the self-focusing threshold and, consequently, can facilitate damage to the optical elements at relatively low intensities.

The method of producing the required radial intensity distribution is based on the use of "soft" apertures, i.e., of apertures whose transmission varies radially with a specified law which differs from the usual aperture with a step-like distribution.

The present paper gives the results of an investigation of a soft aperture shown schematically in Fig. 1. The action of this aperture is based on the dependences of the reflection and transmission coefficients on the thickness of the layer formed between two surfaces each of which reflects totally in the absence of the other. A suitable selection of the profile of this layer ensures the desired transformation of the radial distribution of the intensity in the incident beam as a result of passage through such a layer or on reflection from it.

The expressions describing the modulation and phase of the reflection and transmission coefficients of a layer separating identical media are as follows:

$$\rho = \frac{\rho_0}{\sqrt{(\rho^2 - \delta^2) + (\rho^2 + \delta^2) \cos \phi}}; \quad \rho_0 = \frac{2\rho \tan \delta}{2\rho_0}; \quad (2)$$

$$t = \frac{\rho_0}{\sqrt{\rho^2 + (\rho^2 - \delta^2) \cos \phi}}; \quad (3)$$

where

$$\delta = \frac{2\lambda}{n \sin \theta_0} \frac{1}{(n \cos \theta_0 \cos \theta_1 + n \cos \theta_1 \cos \theta_0) \sin \theta_1} \sin \theta_1 \sin \theta_0 \cos \theta_0 \cos \theta_1 \sin \theta_1$$

$n$ is the refractive index of the prism material; $d$ is the thickness of the separation layer; $\lambda$ is the wavelength of the radiation interacting with the layer; $\theta_0$ is the angle of incidence.

The power reflection $R$ and transmission $T$ coefficients are related to $\rho$ and $t$ by $R = \rho^2$ and $T = t^2$.

Figure 2 shows possible curved surfaces needed to obtain a radial distribution of the type given by Eq. (1) with $N = 10$, calculated using Eqs. (2) and (3). The results show that if one of the surfaces of the layer is spherical and its radius of curvature is $R$, radiation with $R(r) = \text{const}$ entering a soft aperture is transformed into a beam whose radial intensity distribution is nearly

FIG. 1. Schematic diagram of a soft aperture.

FIG. 2. Shapes of surfaces for transforming a beam with a uniform radial intensity distribution into a beam with a distribution $I = I_0 \exp[-(r/r_0)^{10}]$ ($r_0$ is the thickness of stressed layer): 1) soft aperture operating in transmitted light; 2) soft aperture operating in reflected light; 3) transformation of a Gaussian beam $I = I_0 \exp[-(r/r_0)^{10}]$ into a beam with a radial distribution $I = I_0 \exp[-(r/r_0)^{10}]$; 4) transformation surface of the experimental aperture.
Gaussian with $r_0 = 0.8\sqrt{K3}$ (curve 2 in Fig. 3). An analysis of the expressions (2) and (3) describing the phases of the reflection and transmission coefficients shows that the radial phase change in the reflected signal is slight: $|\Delta \varphi_{\max}| < 0.05$ for $\theta_0 = \pi/4$ and $n = 1.52$. However, in a transmitted beam the phase changes are mainly due to the presence of a curvilinear boundary in the path of the beam.

The experimental system used is shown in Fig. 4. Two types of aperture were investigated: one with a curved surface of shape represented by curve 4 in Fig. 2 and the other with a surface of an ellipsoid of revolution with a radius of curvature of 9 m. The apertures were formed by two total internal reflection prisms made of glass K3. A film of SiO, with a suitable profile and elliptic cross section, was deposited on the contact surface by vacuum evaporation. The shape of the evaporated surface was determined interferometrically from the displacement of equal-optical-thickness fringes. One of the interferograms and the evaporated surface profile calculated from it are shown in Fig. 5e and in Fig. 2 (curve 4), respectively.

A photoelectronic method was used to record the cross section of the investigated beam. A rotating mirror scanned the beam relative to a fixed diaphragm with a small aperture behind which a photomultiplier was placed (Fig. 4). The photomultiplier signal appeared on the screen of an oscilloscope which was triggered by a synchronizing pulse from a second photomultiplier. The radial distribution in the plane of the soft aperture was determined by projecting this distribution with an objective 6 onto the entry aperture or on a photomultiplier 7.

We found that a soft aperture of the first type with $2r_1 = 5$ mm transformed a Gaussian beam with $r_0 = 2.6$ mm into a beam in which the radial distribution (at the

FIG. 3. Graphs of the functions $I/I_0 = 0.722[(r/\varphi)^2 - 0.276]$ (curve 2) and $I/I_0 = \exp[-8.91 (r/\varphi)^2]N$ with $N = 2$, 5, and 10 (curves 1, 5, and 7, respectively). Curves 3, 4, and 6 are explained in text.

FIG. 5. Oscillograms of radial intensity distribution in a Gaussian beam transformed by a soft aperture, recorded in the plane of the aperture (a), at a distance of 80 cm from the aperture (b), and at a distance of 8 m (c), along side an oscillogram of the radial intensity distribution in a beam with an initially uniform distribution after passing through a soft aperture with a spherical surface (d), an interferogram of the evaporated surface of the investigated aperture (e), and a photograph of the cross section of the transformed beam at a distance of 8 m (f).

exit from the aperture) was of the form shown in Fig. 5a. A photograph of the density distribution in the transformed beam is shown in Fig. 5f. The intensity profile, plotted in the coordinates $I/I_0, r/\varphi$, was the same as that represented by curve 6 in Fig. 3. The fill factor, defined as the ratio $r_0^2/\varphi$, was 0.6. It should be noted that in the case of a Gaussian distribution (curve 1 in Fig. 3), the spatial fill factor was 0.145. This indicated that use of a soft aperture of this type should make it possible to increase considerably the output energy of the radiation. An important point was also the smoothness of the distribution in the transformed beam over a fairly large diameter (compare oscillograms in Figs. 5b and 5c and curves 3 and 4 in Fig. 3). The absence of inhomogeneity in the radial distribution over the whole propagation path avoided small-scale self-focusing.

The second soft aperture (with a spherical profile of the gap) transformed a beam with a uniform radial distribution into a beam with an almost Gaussian distribution (Fig. 5d). The initial uniform distribution was achieved by a system of confocal lenses 2 and a diaphragm 3 with an aperture of 30 $\mu$m in diameter.

Our investigations demonstrated the usefulness of soft apertures of the type described above. They could be used to produce a laser beam with any desired radial distribution of the intensity. A distinguishing feature of these apertures was their stability in relation to optical damage. The necessary shape of the surfaces in contacts could also be obtained by chemical or ion etching.

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Jet dye laser pumped by copper vapor laser


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An investigation was made of the energy and time characteristics of a jet dye laser pumped by a copper vapor laser. The average output power of tunable dye laser radiation was 0.2 W, the peak power was 1.8 kW, and the efficiency was 12%.

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Successful applications of coherently pumped dye lasers may be helped by investigations of ways of increasing the practical efficiency, i.e., the ratio of the dye laser radiation energy to the electrical energy consumed by the pump laser. At present this efficiency does not exceed 0.01%, which is due to the fairly low efficiency of the gas and solid lasers used as pump sources.

One of the possible ways of increasing the efficiency of such a system is to use a metal vapor (copper, manganese, lead) laser as a pump source, because such lasers have quite good energy characteristics. This was put into practice in Ref. 3, where a dye laser was pumped with a copper vapor laser. However, good results were not obtained because of the low power of the pump source and only the laser action in the dye solution was noted.

We investigated the energy and time characteristics of a jet dye laser pumped a copper vapor laser.

We used the arrangement shown schematically in Fig. 1. A copper vapor laser 1 had a gas-discharge tube 70 cm long and 2 cm in diameter. The pulse repetition frequency was 10 kHz. The dye laser was excited with λ = 510.6 nm radiation deflected by a prism 2. An unstable telescopic resonator was used in the copper vapor laser and this made it possible to generate a beam with a diffraction-limited divergence. The pump radiation was focused by a lens 3 in a planar jet of rhodamine 6G dissolved in ethylene glycol 4. This free jet was produced by forcing the solution through a nozzle of 0.5 x 6 mm dimensions. The flow velocity in the jet could be varied smoothly within the range 2–10 m/sec. A confocal resonator was used in the dye laser: it consisted of a spherical mirror 5 (radius of curvature 30 mm), a lens 6 (focal length 32 mm), and a plane mirror 8 (reflection coefficient ~ 60%). The emission band width was reduced by introducing additionally a prism 7. The angle between the plane of the jet and the pump beam was 35°. We determined both energy and time characteristics of the jet laser. The average output power of this laser was measured with a KIM-1 calorimeter. The shape and duration of the output and pump pulses were recorded with an FEK-16 photodetector 10.

We determined the dependence of the average output power $P_{\text{out}}$ (curves 1 and 3 in Fig. 2) and of the efficiency (curves 2 and 4) of the jet laser on the average pump power $P_p$ of the copper vapor laser. When the average pump power was increased from 20 mW to 2 W, the output power of the jet laser increased linearly. Its average output power and efficiency depended on the

![FIG. 1. Schematic diagram of the apparatus.](image)

![FIG. 2. Dependences of the average output power (curves 1 and 3) and of the efficiency (curves 2 and 4) of the jet dye laser on the pump power.](image)