High-power laser beam shaping using apodized apertures

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(Received 19 February 1989)

This paper gives the results of the investigations of four types of apodized (soft) apertures for beam shaping of UV, visible and IR high-power lasers with near-Gaussian and flat-top transmittance. The apodized apertures (AA) are ≈3–45 mm in diameter, but the principles of fabrication of such apertures lends the possibility of apodizing beams with diameter <1 mm and >200 mm. The examples of studies of the AA in high-power lasers are presented. The possibility of avoiding the Fresnel diffraction ripples is proved experimentally.

1. Introduction

In classical optics, apodization is known to be a modification of the pupil function resulting in a partial suppression of the Fraunhofer diffraction secondary maxima or, on the contrary, a reduction of the central maximum width up to a value smaller than the diffractional one, owing to the extraction of some part of the energy to the side lobes. In the first case, it facilitates the detection of satellites of spectral lines in spectroscopy and the resolution of double stars of appreciably different apparent brightness in astronomy. In the second case, there is the possibility of better resolution for point sources (Jacqunot et al. 1964; Slusarev 1960; Maréchal et al. 1960).

In laser physics the same concept has been widely used since the early 1970s in the case of avoiding hard-edge Fresnel diffraction effects in the beam cross-section by rounding the uniform spatial intensity profile at the edges (Lawrence Livermore National Laboratory (LLNL) 1973). In high-power Nd:glass laser systems the diffraction ripples inside the glass may decrease the small-scale self-focusing threshold in glass, resulting in radical reduction of brightness of laser systems and damage to the output active elements (Fleck et al. 1973; Baranova et al. 1974; Zherikhin et al. 1976). On the contrary, in order to extract as much energy as possible, the beam profile must be almost uniform. Such a profile is usually described by a function called a super-Gaussian:

\[ I(r) = I_0 \exp\left[-\frac{(r/r_0)^N}{N}\right] \]

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where \( I(r) \) = intensity distribution depending upon the distance from the aperture centre \( r, I_0 \) = the intensity in the beam centre, \( r_0 \) = the distance from aperture centre at which \( I(r_0) = I_0/e, N \) = the numeral coefficient.

The calculations of beam propagation through a typical high-power laser for high-temperature heating of plasma showed that optimal value of \( N = 5-10 \) (LLNL 1973, 1977).

An ideal AA has a smooth monotonic (soft) profile without ripples and steps, high optical quality, and laser radiation tolerance. Besides it should be as easily made for a small diameter as for a large one.

There are many types of AA for laser beam shaping: photographic plates, shaped solid or liquid absorbers, metal films, single dielectric film, multilayer dielectric films, fringing field Pockels cells, fringing field Faraday rotators, phase-scattering on the edges, population inversion profiling, ion diffusion in melt glasses and others. The reviews of many such types of AA are presented by Costich et al. (1974) and Lukishova et al. (1987).

Beam shaping with the use of AA is also required for compensation of the large-scale inhomogeneities in beam cross-section, for given field distribution creation in a laser cavity, for laser welding, and for increasing the second harmonic conversion efficiency of laser radiation.

In this paper four types of AA for high-power lasers are presented, namely: induced absorption (IA), photodestruction (including photooxidation) (PHD) and additive coloration (AC) AA work in UV, visible, near and partially mid-IR regions. The working principle of frustrated total internal reflection (FTIR) AA is valid for the large spectral region including UV, visible, IR, submillimeter and millimeter spectral bands.

2. Induced absorption AA (IAAA)

It is well known that transparent materials change their absorbing properties under the irradiation of the ionizing radiation. The necessary transmission profile of such an AA is fabricated by the choice of the ionizing radiation source or by putting a copper, lead or duraluminium mask of changing thickness which absorbs the ionizing radiation between a transparent sample (glass or crystal) and a source of ionizing radiation (Krasjuk et al. 1976; Belyaev et al. 1976; Vinokurov et al. 1976).

The IAAA were fabricated with the use of various silicate and phosphate glasses and some crystals, e.g. calcium fluoride (CaF₂) with impurities.

Figure 1 presents the absorption spectra of a CaF₂:Pr sample before (curve 1) and after the exposure of \( \gamma \)-radiation (curve 2) in the region 0.25–2.2 \( \mu \)m (a) and in the region 2–3.8 \( \mu \)m (b). The ionizing radiation dose was \( 10^7 \) roentgen. The crystal sample had 7 mm thickness. The Pr concentration in CaF₂ and 0.2 Mol.%. The spectral resolution in the region 0.25–2.5 \( \mu \)m was 0.2–0.5 \( \mu \)m and in the region from 2.5 \( \mu \)m up to 3.8 \( \mu \)m was \( 1 \) cm⁻¹.

Figure 2 shows spatial intensity profiles at the output of some fabricated IAAA for the wavelength \( \lambda = 1.06 \mu \)m (solid lines), \( \lambda = 2.8 \mu \)m (dashed lines). The Gaussian curves are given for the comparison (dotted lines). The ionizing radiation dose at the edges was \( 10^5–10^6 \) roentgen. Crystal samples had 30 mm thickness. The beam that came to the AA had uniform intensity profile. The measurements were made by microdensitometry method with the use of "E-1070" film (\( \lambda = 1.06 \mu \)m) or by utilizing a pyroelectrical sensor (\( \lambda = 2.8 \mu \)m). In figure 2, \( I \) is the intensity of the uniform input beam.

In order to characterize a degree of approximation of the beam cross-section intensity to the uniform profile, the fill-factor is used, which we define as:

\[
F = (I_0 \pi a^2)^{-1} \int_0^a 2\pi r I(r) \, dr
\]
Figure 1. Absorption spectra of CaF$_2$:Pr sample for IAAA before and after the irradiation of ionizing radiation.

Figure 2. Transmission profiles of IAAA.
Figure 3. Photographs of beam cross-section at various distances from the IAAA and hard-edge aperture.

where \( a = \) distance from the aperture centre at which \( J(a) = 10^{-2} I_0 \). For the uniform profiles \( F = 1 \), for the Gaussian beams \( F = 0.215 \). The fill-factors produced IAAA that reached 0.68-0.71. These AA permit a more effective employment of amplifier cross-sections than that in the Gaussian beams, avoiding at the same time a possibility of Fresnel diffraction spikes formation from sharp edges of optical elements of amplifiers. The latter fact is illustrated by photographs of beam cross-sections taken at the output of AA: at the AA plane (figure 3a) and at a distance of 1.5 m (figure 3b) from it. A diffraction photo of sharp-edge aperture of 7 mm diameter at distance 1.5 m from it is presented as a comparison (figure 3c). The measurements were made at \( \lambda = 1.06 \mu m \). The transmission profile of this AA we approximate by the super-Gaussian profile with \( N = 4 \) and \( r_0 = 2.2 \text{ mm} \).

It should be mentioned that we had samples of CaF\(_2\):Pr of 200 mm diameter with induced absorption coefficient \( K \approx 1.8 \text{ cm}^{-1} \) at \( \lambda = 1.06 \mu m \). We also had samples of CaF\(_2\) with a small value of unknown impurities with \( K \approx 6 \text{ cm}^{-1} \) at \( \lambda = 1.06 \mu m \).

Glasses and CaF\(_2\) rectangular cross-section IAAA have also been fabricated. Figure 4 shows a photograph of a part of the beam cross-section at the distance 1 m from the output of square IAAA (30 \( \times \) 30 mm\(^2\)) made of glass (\( \lambda = 0.63 \mu m \)).

The IAAA were used in various powerful lasers. At \( \lambda = 1.06 \mu m \) these apertures were not damaged, neither at the density of irradiation energy of 3 J/cm\(^2\) (pulse duration 3 ns) and AA diameters of 25 and 45 mm, or at the density of irradiation energy of 1 J/cm\(^2\) (pulse duration 300 ps) and AA diameter of 10 mm.

In focused laser beams at \( \lambda = 1.06 \mu m \) the surface damage of these apertures is observed at \( 5 \times 10^9 \text{ W/cm}^2 \), bulk damage at \( 2 \times 10^{11} \text{ W/cm}^2 \) (duration of smooth bell-form
pulse is 10 ns at half-height, beam diameter at focal plane 27 \( \mu \text{m} \) and 4.6 \( \mu \text{m} \) at 1/e level in the first and second cases, respectively). The study of the enlightenment of such AA in focused beams at \( \lambda = 1.06 \mu \text{m} \) showed that AA does not become enlightened until the samples are damaged.

The surface damage \( \approx 0.4 \text{ mm} \) in diameter was observed under the irradiation of \( \text{CaF}_2: \text{Pr} \) IAAA with 1.315 \( \mu \text{m} \) photodissociation iodine laser radiation at energy density \( > 100 \text{ J/cm}^2 \) (pulse duration 10 \( \mu \text{s} \), spot diameter 0.5 mm).

At \( \lambda = 0.342 \mu \text{m} \) (molecular iodine laser) IAAA were not damaged at 3 J/cm\(^2\) (pulse duration 10 \( \mu \text{s} \), spot size 3 \( \times \) 3 mm\(^2\)).

At \( \lambda = 2.79 \mu \text{m} \) (the laser utilizing the chromium and erbium-doped yttrium-scandium-gallium garnet crystals) these AA were not damaged, neither at 1.5 J/cm\(^2\) (beam diameter 1 mm), nor at 8 J/cm\(^2\) (beam diameter 0.25 mm). The train consisted of 18 ultrashort 150 ps spikes separated by a 6.7 ns interval.
3. Photodestruction AA (PHDAA)

The PHDAA were fabricated using γ-irradiated crystals and glass samples with color centers. In the many cases of crystals we used for this purpose, we observed the phenomenon of photooxidation of divalent rare-earth ions (TR²⁺) up to the three-valent state. It is well known that TR²⁺ have wide band absorption spectra different from the spectra of TR³⁺, which consist of groups of narrow discrete lines (figure 1).

Figure 5 shows the relative changes of transmittance T at λ = 0.488 μm of a γ-colored CaF₂:Pr sample after the irradiation of a cw 0.488 μm beam with 2W output power (h = hours). Sample length was 30 mm.

The transmission profile of such AA for λ = 0.63 μm is presented at figure 6 (curve 1). Curve 2 in figure 6 shows the transmission profile of another AA for λ = 1.06 μm. The absolute transmittance value of the second AA (curve 2) at 1.06 μm is 0.72 at the AA centre and 6.25·10⁻³ at its edges.

The second PHDAA has been employed for 2 years at the laser system output of 25 J energy and 25 ns pulse duration (λ = 1.06 μm). In this case, the second harmonic conversion efficiency increased from 40% up to 55% due to the better beam cross-section fill-factor. At λ = 1.06 μm these AA are not enlightened until the samples are damaged.

4. Primary results of additive coloration AA (ACAA)

A known method of additive coloration of transparent crystals (Mollenaer 1978) is carried out by heating (the temperature t = 400–800°C) of transparent crystals in alkaline or alkaline-earth metal vapors atmosphere. Alkaline or alkaline-earth metal is in the same vessel with the transparent crystal.

Additive coloration takes place up to a certain depth in the transparent crystal (depending on crystal temperature, the alkaline-earth metal vapors pressure and the duration of coloration process). The transparent crystal temperature determines the diffusion velocity from the surface to the volume, and the metal vapor pressure determines the value of absorption coefficient K in the coloured part of crystal. Independent variation of these parameters in time makes it possible to create the necessary profile of the coloured part of the crystal. The uncoloured part of the crystal does not change its optical properties.

In this way the ACAA for the UV and visible regions were produced. One such AA was fabricated with the use of a CaF₂:Sm sample of 10 mm primary diameter. The AA diameter was ≈3 mm. The transmittance in the centre of AA was 94%, the absorption coefficient of edges >8 cm⁻¹ (λ = 0.63 μm).

The ACAA were also fabricated to work in UV, visible and near-IR regions (up to 2–3 μm). At λ = 1.06 μm an AC part of these crystals has the value of K ~ 15–20 cm⁻¹, at the same time the uncoloured part of the crystals is absolutely transparent. Figure 7 (curve 1) shows the transmission profile at 1.06 μm of one of such samples which has the rectangular cross section (9 × 4.5 mm²) and 1 mm thickness (l = the length along one side of the rectangle). This profile was defined with the use of CCD by L.N. Ionov and V.B. Shilov (State Optical Institute).

In many cases the ACAA were fabricated with almost step-like profiles (figure 7, curve 2, λ = 0.63 μm). The sample thickness was 1 mm. In this case the value of Δl was ~30 ± 10 μm. The measurements were carried out by Yu.N. Orlov (Institute of Radio-engineering and Electronics) with the use of FEAG-200-300 (VEB Carl Zeiss JENA-DDR).
Figure 6. Transmission profiles of PHDAA.

Figure 7. Transmission profiles of additive coloured crystals.
5. Frustrated total internal reflection AA (FTIRAA)

The FTIR device (Krasjuk et al. 1976a) is presented in figure 8. As a rule, the FTIRAA were made of two right-angle total internal reflection prisms so that their hypotenuse faces are near the optical contact. One of these hypotenuse faces (or the plane substrate optically contacted with one of the faces) is covered with a thin layer (>1.5\(\lambda\)) of homogeneous transparent dielectric, meeting the requirement of smooth changing of thickness along two coordinates. It results in smooth changing of transmittance along the cross-section due to the gradual layer thickness variation under the conditions of total internal light reflection on the contact surfaces of two prisms. The spacial vacuum deposition techniques were used for dielectric layer profiling. There are two types of such AA with the convexity or the concavity on the surface of one of two prisms (figure 8a). In the first case the AA works in the transmitted beam, in the second case in the reflected light.

Calculations showed that to obtain a spatial-intensity profile close to uniform, at the output of the FTIRAA, however, without any diffraction ripples at a distance of several meters from the aperture, it is necessary that the surface separated by two media has a flat top smoothly descending on the sides (figure 9, curve 1). When AA are used in Gaussian beams the layer profile in the central part should have a pit (figure 9, curve 3). The optical glass substrate was covered by vacuum sprayer with \(H \sim 1-2\ \mu m\) thick MgF\(_2\)-layer.

Figure 8. a) The FTIRAA structure scheme; b) Photograph of FTIRAA device.
with a pit in the central part. The profile of one of these layers is shown in figure 9 (curve 4) and in the interferogram (figure 10a).

Figure 11 (curves 3, 4, 6) presents intensity profiles at 8 m, 80 cm and in the output of fabricated AA with dielectric layer shown on the interferogram of figure 10a. As the Gaussian beam with $r_0 = 2.6$ mm comes to this AA, the intensity profile at its output may be approximated by super-Gaussian function (curve 6) with $N = 6$ and $r_0 = 1.94$ mm ($\lambda = 0.63$ $\mu$m). The curves with $N = 2$ (curve 1), $N = 5$ (curve 5), $N = 10$ (curve 7) are given for comparison. Note that at figures 9 and 11 $I(r_{\lambda}) = 10^{-3}I_0$. 

**Figure 10.** Interferograms of various internal layers for the FTIRAA.
The experiment and calculations have shown that, in order to have beams without flat top (close to the Gaussian profiles) at the output of FTIRAA with uniform input beam flat-convex lenses may be used. However, in this case it results in elliptical cross-section beams (figure 12a for $\lambda = 0.63 \, \mu\text{m}$ at 8 m distance). Instead of using the cylindrical lens we made the intermediate layers with elliptical cross-sections (e.g. interferogram at figure 10b) with AA transmission profile expressed by the curve 2 in figure 11. Figure 12b shows the corrected beam spot at the distance of 8 m from such AA.

The FTIRAA suitable for the work in the reflected light were manufactured too. The curve 2 in figure 9 expresses the intermediate layer surface profile when the uniform intensity beam comes to the aperture and the super-Gaussian profile with $N = 10$ is ob-

Figure 12. Photographs of typical spots of the beam transformed by FTIRAA.
tained at the aperture output. The calculations of curves 1–3 in figure 9 were made for the case of electric field component perpendicular to the incidence plane, refractive index \( n = 1.52 \), incidence angle \( \theta = 45^\circ \), \( I/I_0 = \exp[-6.91(r/r_t)^{10}] \). The fabricated FTIRAA had the right-angle glass prisms \( (n = 1.52) \) and \( \theta = 45^\circ \).

The FTIRAA damage threshold in focused laser beams at \( \lambda = 1.06 \mu m \) and pulse duration of 10 ns is \( 1.7 \times 10^9 \) W/cm², in the case of contact of two glass surfaces, and \( 1.4 \times 10^9 \) W/cm², in the case of contact of glass surface and MgF₂-layer.

The FTIRAA were also fabricated by Diels (1975) and Armandillo et al. (1985).

6. Conclusions

The experiments showed that IA, PHD, and FTIRAA may be successfully used in high power lasers. Crystals of doped CaF₂ made it possible to apodize beams up to 200 mm in diameter. The PHDAAA diameter may be smaller than 1 mm. This type of AA may be used inside the laser cavity.

Easily made small and large AA are of high optical quality. They provide the required beam profiles and have high tolerance to the laser radiation.

The method of AC can also produce AA. The absorption coefficients at the edges of ACA are much greater than at the edges of IAAA, but the required beam profile creation in the case of ACA is a more difficult problem than in the case of IAAA.

Acknowledgment

The authors wish to thank V. A. Sokolov, E. A. Simun, V. K. Karpovich of State Optical Institute for fabricating CaF₂:Pr samples up to 200 mm in diameter; V. D. Terekho, V. K. Ivanchenko of Ya. M. Karpov Physical and Chemical Institute for technical aid in fabricating IAAA; A. V. Shirkov, K. B. Andreeva, I. K. Krasjuk of General Physics Institute for technical aid in spraying on the profiled layers for FTIRAA; L. V. Chernysheva, Yu. K. Nisienko, M. V. Brenner, V. V. Aleksandrov of I. V. Kurchatov Institute of Atomic Energy; B. V. Gorshkov, A. V. Kili'pio, K. L. Vodop'yanov of General Physics Institute; O. Yu. Nosach, L. D. Mikhee of Lebedev Physical Institute for providing the opportunity to study the manufactured AA in powerful laser systems.

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