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On the possibility of using a corner-cube reflector in resonators of high-power repetitively pulsed lasers

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Abstract. **An optical cavity with a highly reflecting mirror in the form of a hollow corner-cube reflector (CCR) made of uncooled plane metal mirrors, which, in combination with a plane semitransparent output mirror, ensures complete filling of the output laser beam aperture, is studied. It is shown that, both in the pulsed and repetitively pulsed regimes of high-power far- and mid-IR lasers, it is possible to achieve beam divergence close to the diffraction limit (taking into account the drift of the radiation pattern axis) and dependent only on the quality of surfaces and accuracy of alignment of the hollow CCR mirrors and the resonator.**

Keywords: *corner-cube reflector, high-power laser, beam divergence.*

1. Introduction

The thermal self-action of radiation [1], which considerably increases the beam divergence of lasers with unstable telescopic resonators, is one of the main factors hindering the development of high-power repetitively pulsed gas lasers. Nonlinear wavefront correction in high-power gas lasers [2, 3] decreases the beam divergence to a value close to the diffraction limit, but, due to the complexity of the used optical schemes, this method has not yet found wide application. A divergence close to the diffraction limit was obtained using a self-filtering unstable resonator (SFUR) in a high-power electron-beam-controlled repetitively pulsed CO_2 laser, which was used as a master oscillator in [4, 5]. In this laser, an SFUR with the magnification $M = 2$ made it possible to achieve a near-diffraction beam quality (~$1.6\Theta_{\rm difr}$ for the full aperture) in the single-pulse regime with the beam aperture of ~53 mm. As was shown by theoretical [6] and experimental [7, 8] investigations, the beam divergence of lasers with an SFUR in both repetitively pulsed and single-pulse regimes in the case of slightly inhomogeneous medium was also close to the diffraction limit [did not exceed $(2-2.6)\Theta_{\rm difr}$].

However, in the presence of significant optical inhomogeneities, the diffraction beam quality in an SFUR may be lost since the beam after intracavity spatial filtering passes twice through the active medium [9].

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The schemes of unstable resonators with trihedral corner reflectors stabilising the radiation pattern axis were considered in [10]. The author of [10] believes that, if the optical axis in this resonator passes through the vertex of the triple-prism and the centres of curvature of the mirrors, then lasing may independently occur in separate regions of the resonator aperture, which may spoil the spatial coherence of the radiation. To eliminate this tendency, the authors of [11] used a double-pass unstable resonator with the magnification $M = 3$, in which a triple-prism composed of metal mirrors served as a deflecting mirror. The beam in the resonator fell onto the faces of the triple prism, sequentially passing over it in one direction. However, the authors of [11] restricted themselves to investigations of polarisation of laser radiation in the resonator.

As was shown in [12], a resonator composed of a corner-cube reflector (CCR) with plane faces and a plane output mirror is equivalent to an ordinary plane-parallel resonator and has similar beam matrices. If a CCR has no significant defects in the mirror surface quality and the mirrors are well aligned (or the CCR is made of a single block), then the resonator with the CCR can ensure not only a high beam quality but also a stability of the radiation pattern axis at any number of passes through the resonator.

In [13, 14], it was shown analytically and experimentally that elementary waves reflected by different sectors of a corner prism reflector with metalized faces and total internal reflection remain almost phase-matched. In this case, the Fraunhofer diffraction pattern corresponds to the classical Airy distribution and the kernel diameter is equal to the Airy disk diameter for the diffraction on a round hole with a diameter equal to the diameter of a circle inscribed in the reflector front face.

In this connection, it is of undoubted interest to study a laser resonator with a hollow CCR, composed of three plane metal mirrors, and a semitransparent plate as an output mirror in order to study the conditions of formation of a laser beam with a divergence close to the diffraction limit.

2. Experimental setup

The experiments on the effect exerted by a CCR on the laser beam divergence were performed using two laser setups. The first of them (see Fig. 1), which was previously studied in detail in [4, 5, 7–9] as a master oscillator, is a high-power repetitively pulsed electron-beam-controlled CO_2 laser operating at the atmospheric pressure of the laser mixture.

To study the resonator with a CCR, we replaced the SFUR in this laser by a double-pass resonator similar to the SFUR in efficiency and pump volume. In this resona-

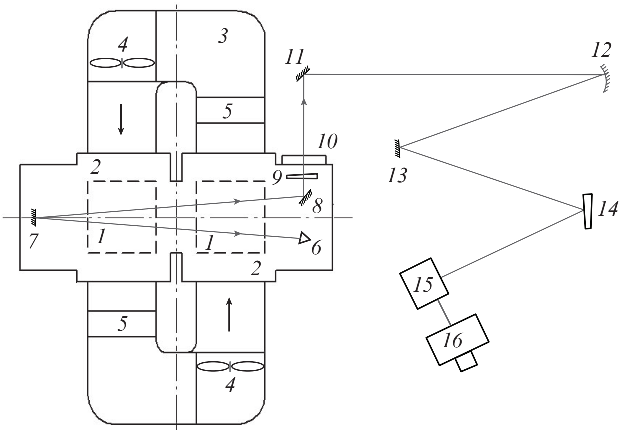

Figure 1. Scheme of the laser setup: (*1*) volumes in which the laser mixture is pumped; (*2*) laser chambers; (*3*) gas-dynamic channel; (*4*) centrifugal blowers; (*5*) water-cooled heat-exchangers; (*6*) hollow CCR; (*7*, *8*) plane deflecting mirrors of the resonator; (*9*) ZnSe wedge; (*10*) exit window made of a KCl crystal; (*11*–*13*) mirrors of the beam divergence measurement scheme; (*14*) KCl wedge; (*15*) bolometric detector measuring the beam divergence; (*16*) S8-11 two-beam oscilloscope with a FOR-2 photorecorder.

tor, the studied hollow CCR composed of three uncooled plane copper mirrors (Fig. 2) served as a highly reflecting mirror (*6*), while a wedge (*9*) made of a ZnSe single crystal was a plane output mirror. Since the apertures of deflecting mirrors (*7*) and (*8*), wedge (*9*), and exit window (*10*) were considerably larger than the CCR aperture, the resonator volume (~7.5 L) was calculated as a product of the CCR aperture area (the area of a hexagon with an edge of ~36 mm estimated by the burn spot on sensitive paper) and the total length of the active medium along the optical axis (~3000 mm). The resonator volume was calculated taking into account the partial overlap of beams at mirror (*7*). The resonator mirrors were fastened to positioners and placed into hermetic cells attached to the edges of gas-discharge chambers.

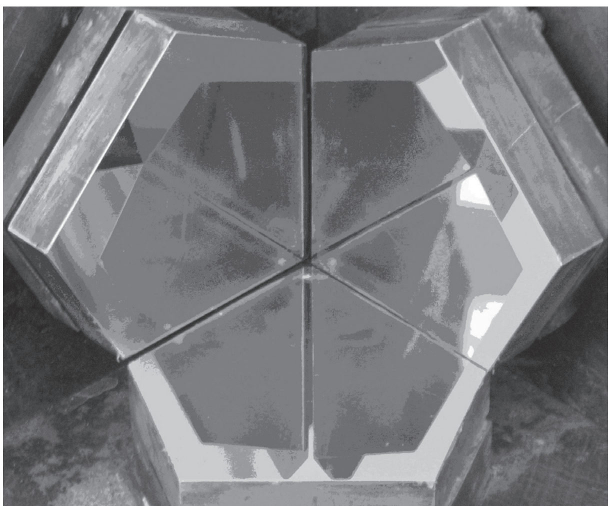

Figure 2. Photograph of the assembled cube reflector.

The laser system was designed as a classical closed-loop wind tunnel (*3*) with two identical laser chambers (*2*) connected to each other by a tube along the optical axis. The laser mixture was blown (shown by arrows) with an average rate of 60 m s^{-1} through gas-discharge volumes (*1*) in opposite directions using blowers (*4*) located in the corners of the gas-dynamic channel. The laser mixture temperature was kept constant by water-cooled heat exchangers positioned at the exits of the laser chambers. Each laser chamber was equipped with two electrodes, the upper one (cathode) being permeable for fast electron beams emitted by an electron gun located above the laser chamber (the electron gun is not shown in the scheme). The electron beam size was 150×650 mm (across and along the optical axis, respectively).

The lower electrode (anode) was made in the form of the Rogowski profile with a 140-mm plane part along the flow and with a 100-mm radius of curvature of the edges. The length of the electrodes along the optical axis (taking into account the curvatures) was 800 mm, and the interelectrode distance was 100 mm. A dc voltage was applied to the laser anode, and the pump current pulse duration of 45 μs in all the experiments was achieved by modulating the accelerating voltage of the electron gun. The active medium volume receiving 80% of the pump energy was estimated to be ~22.5 L, the discharge electric field strength was varied from 3 to 5.5 kW $cm^{-1}atm^{-1}$, and the laser was able to operate with repetition rates from 1 to 200 Hz in cycles with a duration of tens of seconds.

In all experiments, the CCR was placed in the resonator such that the radiation axis propagated through the point of contact of the three sides of the reflector and the centre of its front plane. The length of the resonator with the CCR was 9.6 m and equal to the SFUR length [7, 8]. The CCR and the resonator were aligned with an accuracy no worse than 2×10^{-5} by an autocollimation method in a laboratory environment. The laser beam was coupled out of the resonator through a plane-parallel plate (*10*) made of a KCl single crystal. To avoid parasitic lasing, plate (*10*) was placed at a small angle to the resonator axis.

The beam divergence was measured by an aperture technique, as well as by a wire multichannel bolometric detector with an angular resolution of ~0.02 mrad, whose receiving aperture was located in the focal plane of mirror (*12*) with a focal length of 40 m. The receiving aperture of the bolometric detector had a diameter of 65 mm and was made of two rows of thin nickel wires.

Each row contained 64 wires spaced by 1 mm. The first-row wires were mutually perpendicular to the wires of the second row, each wire being connected to its own cell of a fast memory device. The bolometric detector allows one to record simultaneously the far-field radiation intensity distribution over two mutually perpendicular coordinates and the drift of the radiation pattern axis both in the pulsed and repetitively pulsed regimes. Signals from the memory device were recorded by a S8-11 two-beam oscilloscope, whose screen was photographed by a FOR-2 recorder. To calculate the diffraction divergence of this resonator, the beam aperture was assumed to be a circle with a diameter equal to the diameter of a circle inscribed in a hexagon, which, in our case, is ~62 mm.

At the second stage, investigations were performed on a non-chain electric-discharge HF laser, whose design is described in detail in [15]. At the unchanged resonator length (3.5 m), a highly reflecting mirror was replaced by a CCR and, in contrast to the first setup, the exit window served simultaneously as the second mirror of this resonator. The CCR and the resonator were aligned using an autocollimator, the accuracy of alignment of resonator mirrors at this stage being no worse than $(2-5)\times10^{-5}$ rad. To adjust the laser exit aperture to the apertures of the measuring devices (TPI-2M and IMO-2N calorimeters), a round aperture with a diameter of 50 mm was placed in front of the exit window of the resonator.

3. Experimental results and discussion

(1) On the first setup, the resonator with the CCR was studied using pump pulse repetition rates from 1 to 200 Hz with the specific energy contribution of 50–200 J $L^{-1}atm^{-1}$ in a pulse. In experiments, we used laser mixtures of the $CO_2:N_2:He$ = 1:2:4, 1:3:4, and 1:5:2 compositions. The laser energy varied from 20 to 150 J; taking into account the resonator volume (~7.5 L), the specific laser output energies were calculated to be 3–20 J L^{-1} atm^{-1}. It was found that the lasing threshold in the case of a resonator with the CCR remains the same as in the case of unstable telescopic resonators, and the resonator efficiency corresponds to the calculated value. The burn spots obtained on sensitive paper in both near- and far-field zones show no laser beam separation into individual spots, which means that the radiation wavefront is almost phase-matched [13, 14]. Figure 3 presents a typical intensity distribution in the focal spot recorded by the bolometric detector. Similar distributions were observed in experiments with a SFUR.

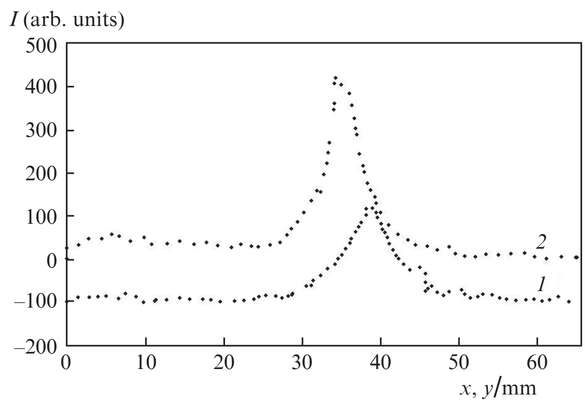

Figure 3. Laser beam intensity distribution in the focal spot recorded by a bolometric detector along the horizontal (for clarity, the curves are shifted by –100) (*1*) and vertical (*2*) axes.

Figure 4 shows the dependences of the beam divergence measured at the level 0.5 of the total energy on the output energy in the single-pulse and repetitively pulsed regimes. The beam divergence of the laser with the CCR remains almost the same (within the measurement accuracy) in both regimes and does not depend on the output pulse energy. We also observed no influence of the composition of the used laser mixtures on the beam divergence. For comparison, Fig. 4 also shows the divergence measured for SFURs in [4, 5, 7–9]. While the beam divergence in the cases of single pulses was almost the same for both types of resonators, the beam divergence of lasers with SFURs in the repetitively pulsed regime at output energies exceeding 20 J was two times larger.

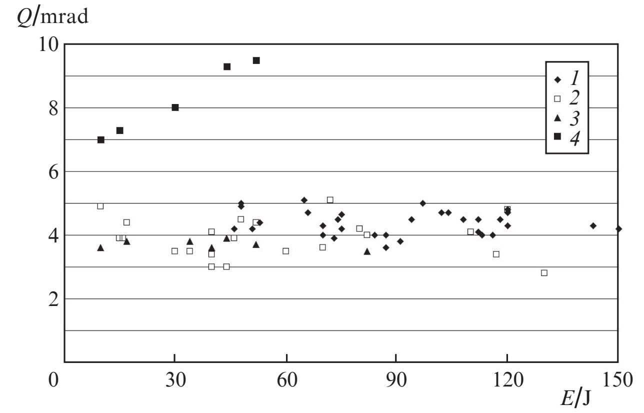

Figure 4. Dependences of the beam divergence (at the level 0.5 E) on the output energy for the resonator with the CCR in the single-pulse (*1*) and repetitively pulsed (f = 100 Hz) (*2*) regimes, as well as for a SFUR in the single-pulse (*3*) and repetitively pulsed (f = 100 Hz) (*4*) regimes.

Figure 5 presents the calculated and experimental data for the portion of energy (in relative units) contained in a cone with a vertex angle θ. The calculation was performed for the diffraction of a 10.6-μm laser beam on a round hole 53 mm in diameter (SFUR aperture); points correspond to experimental data averaged over a large number of experiments.

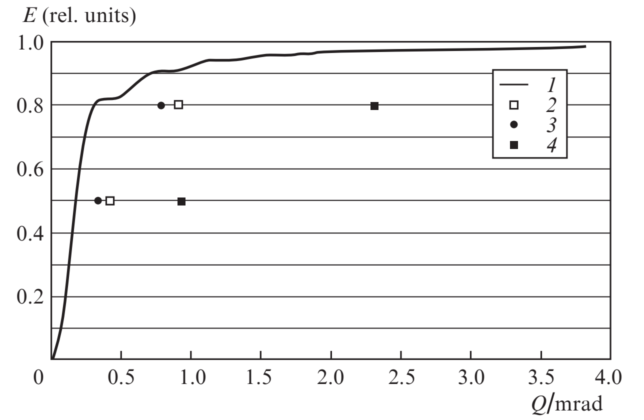

Figure 5. Laser beam angular divergence: calculation for D = 53 mm (*1*); resonator with a CCR (single pulse and f = 100 Hz) (*2*); SFUR (single pulse) (*3*); SFUR (f = 100 Hz) (*4*).

(2) A resonator with a CCR in a HF laser was investigated in the single-pulse regime with $(C_3H_8 + C_4H_{10})-SF_6$ and $C_2H_6-SF_6$ mixtures. In all the experiments, the pressure of laser mixtures was 55 Torr and the beam divergence was measured at specific pump energies from 10 to 150 J L^{-1} by the method of calibrated apertures using TPI-2M and IMO-2N calorimeters placed in the focal plane of a mirror with a radius of 14 m.

The resonator with the CCR and the total error in the alignment of mirrors of $(2-5)10^{-5}$ rad introduced no smaller than $\lambda/2$ distortions in the wavefront structure of a HF laser. As was expected, the beam divergence measured with these distortions considerably exceeded the diffraction limit calculated for a laser beam 50 mm in diameter. It was found that the beam divergence in our experiments does not depend on the mixture composition and, on average, is approximately

1.5×10^{-3} and 2.3×10^{-3} rad at the levels 0.5 and 0.8 of the total energy, respectively. Figure 6 demonstrates a spot burned on sensitive paper placed in the focal plane of a mirror with a radius of 14 m. Even at the relatively poor alignment of the CCR mirrors for a HF laser, the spot retains a round shape and has no visible disruptions.

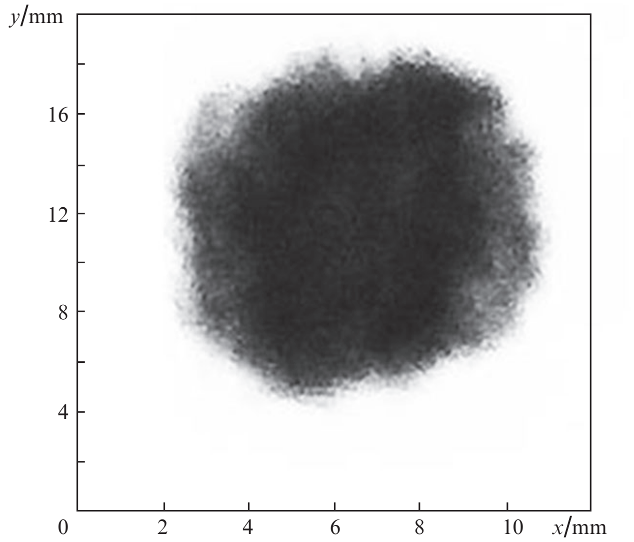

Figure 6. Burn spot of a HF laser in the focal plane of a mirror with a radius of curvature of 14 m.

(3) It is known that the laser beam divergence depends on a number of factors, because of which the real beam divergence, especially in the repetitively pulsed regime, is far above the diffraction limit.

In our case, the main effect on the beam divergence is exerted by static aberrations, i.e., by the accuracy of alignment of the CCR mirrors and by the quality of their surfaces. The dynamic aberrations caused by small-scale optical inhomogeneities appeared in the active medium and in the inactive regions of the resonator are, in our opinion, less important since the resonator with a CCR should exhibit no strong correlation between the wavefront structure and the positions of small-scale optical inhomogeneities. In this connection, we will estimate only the effect of static aberrations and determine the limits of reasonable application of CCRs in IR lasers.

Since the beam divergence measured in our experiments for CO_2 and HF lasers exceeded the diffraction limit by more than two times, then, to calculate the beam divergence of a laser with a CCR-based resonator, we can restrict ourselves to a semigeometric approximation and use the relation [10]

$$\Theta = \sqrt{\frac{2\Delta L}{L}}, \quad (1)$$

where $\Delta L = \varepsilon D$; D is the diameter of a circle inscribed in the frontal surface of the CCR; ε is the total angular error of alignment of the CCR sides; and L is the resonator length.

The divergence calculated by formula (1) is $\sim 5\times10^{-4}$ rad for a CO_2 laser and about 1.4×10^{-3} rad for a HF laser. The experimental values of the beam divergence at the level 0.8 of the total energy are $\sim 9\times10^{-4}$ rad for a CO_2 laser and approximately 2.3×10^{-3} rad for a HF laser.

It is of interest to estimate the maximum apertures of CCR-based resonators that can be used in high-power wide-aperture lasers of different spectral regions and whose beam divergence calculated by formula (1) must be no larger than the diffraction divergence,

$$2.44\lambda/D \geqslant \sqrt{\frac{2\Delta L}{L}}. \quad (2)$$

After some transformations, we obtain

$$D \leqslant \left(3\frac{L}{\varepsilon}\right)^{1/3}\lambda^{2/3}. \quad (3)$$

Let us find the wavelength dependence of the maximum diameter of the aperture of a resonator with a CCR. We performed calculations for the resonator lengths L = 1.5 and 10 m taking the practically achievable error in alignment of CCR sides ε to be 5×10^{-7} rad. The calculation results presented in Fig. 7 allow us to make two obvious conclusions: first, it is preferable to use resonators with a CCR in high-power long-wavelength lasers because of weaker static aberrations and, second, the direct power dependence of the maximum apertures D on L allows one to design a classical scheme of self-targeting of high-power laser radiation on remote objects similar to schemes with nonlinear elements (phase conjugate mirrors). For example, if an object is at a distance of $\sim10^5$ m and is illuminated by a CO_2 laser, then, using a high-power wide-aperture CO_2 amplifier with the end mirror in the form of a CCR with an aperture of 0.2 m [4], it is possible to obtain a self-targeting scheme with a beam divergence close to the diffraction limit at $\varepsilon \gg 5\times10^{-5}$ rad.

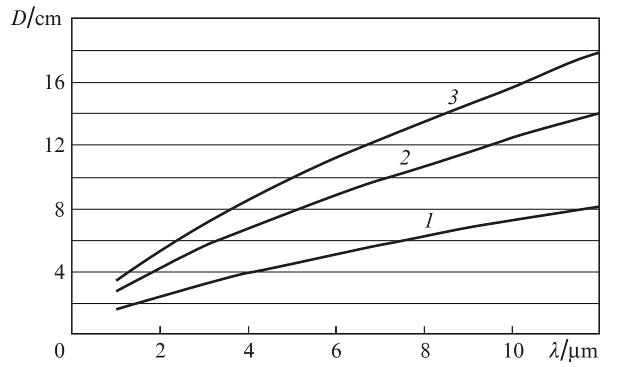

Figure 7. Dependences of the diameter of the CCR-based resonator aperture on the laser radiation wavelength at the error of alignment of CCR mirrors $\varepsilon = 5\times10^{-7}$ rad for L = 1 (*1*), 5 (*2*), and 10 m (*3*).

4. Conclusions

Our investigations of high-power CO_2 and HF lasers showed that the resonators with a CCR made of metal mirrors allow one to achieve a beam divergence close to the diffraction limit (no larger than two diffraction angles) for a uniformly illuminated aperture. At specific output energies of 3–20 J L^{-1} atm^{-1}, the main effect on the beam divergence in resonators with a CCR is exerted by static aberrations. These resonators are promising for application in technological lasers and laser complexes used for launching of Earth satellites, as well as in high-power lasers for long-distance radiation transport.

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