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Phase correction of radiation emitted by a powerful industrial laser with higher mode selection

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Abstract. **Special features of operation of a high-power industrial CO_2 laser with selection and correction of the phases of higher transverse modes are investigated theoretically and experimentally. An effective conversion of the higher-mode oscillation field into a narrow beam with in-phase optical oscillations with an output power up to 1 kW with the help of a phase corrector is reported for the first time. The angular divergence is reduced to one-third of the value typical of a multimode beam. The physical origin of intracavity aberrations, which deteriorate the beam quality, is analysed. It is shown that the most significant effect is produced by an optical wedge-type aberration emerging due to transverse circulation of the active medium and transverse discharge. The prospects of application of this method for obtaining more powerful narrow laser beams are discussed.**

Keywords: *industrial laser, optical resonator, radiation quality*.

1. Introduction

The problem of improving the quality of radiation and increasing the energy extraction efficiency of the active medium in high-power industrial lasers has not been solved completely as yet. When stable resonators are used, the solution of the problem is limited by a transition to the multimode lasing regime with increasing the resonator aperture. Alternative schemes of optical cavities proposed for this purpose have along with certain advantages a number of inevitable drawbacks. For example, the classical scheme of an unstable resonator [1] is often ineffective for high-power gas lasers because of relatively low gains of the active medium. The popular scheme of a stable – unstable resonator [2, 3] does not allow the formation of an axially symmetric output radiation. The characteristics of an unstable resonator can be noticeably improved by using a modification of this scheme [4], in which a semitransparent output mirror possesses a weakly reflecting peripheral zone. However, the large cross section of the beam emerging from such a resonator makes it more sensitive to aberrations of subsequent transmission and beam-shaping optics.

Among other types of resonators used in industrial lasers, cavities with spatial filtration of radiation are worth noting [5, 6]. However, although such cavities provide high-quality radiation, their tuning and maintenance are more complicated because of their multicomponent structure. Restricted potentialities of alternative schemes of resonators stimulate attempts at improving the parameters of resonators with a stable geometry. One of the methods of improving the properties of stable resonators involves a spatially nonuniform extraction of energy of higher (including multipass) modes excited in such resonators [7 – 9]. However, the practical realisation of this method is complicated by the fact that the density of radiation power extracted from high-power lasers may exceed the radiation damage threshold for resonator mirrors.

There exists another method for improving the quality of the laser beam formed in a resonator and its matching with the gain profile of the active medium. This method is based on selective excitation of a certain high-order mode in the resonator, followed by conversion of its field with the help of a special phase corrector into a beam with in-phase optical oscillations [10 – 13]. This technique was used in lasers with a moderate output power. However, the application of this method for high-power lasers was not discussed in the literature. At the same time, the application of this method in high-power industrial lasers would make it possible to improve the beam quality considerably by a simple modification of the optical tract. In this paper, we consider a physical model describing the operation of a high-power industrial CO_2 laser with selection and correction of the phase of higher transverse modes and present the experimental results characterising the features of lasing.

2. Basic parameters of the laser

Experiments were made with a 10.6-μm TL-2.5 electric-discharge CO_2 laser with a transverse circulation of the active medium and a transverse discharge. The ratio of the working mixture components was $He : N_2 : CO_2 : O_2 = 15 : 4 : 1 : 0.2$ for a total pressure of 25 – 30 Torr in the discharge chamber. The rate of circulation of the active medium through the resonator was 50 – 60 m s^{-1}. The transverse discharge was initiated using a multisegment anode connected with a set of ballast resistors. The cathode was made in the form of a small-diameter copper cylinder

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cooled by running water. The lengths of the anode and cathode were equal to 1 m and their separation was 39 mm. The discharge current could be varied from 3 to 15 A.

The schematic of the stable optical resonator used in the laser is shown in Fig. 1a. The multipass resonator is formed by spherical (*1*), and plane (*4*) mirrors, and two deflecting mirrors (*2*) and (*3*). The total number of radiation trips through the active medium is equal to five for a total resonator length of 8 m. The resonator axis was at a distance of 22 mm from the anode.

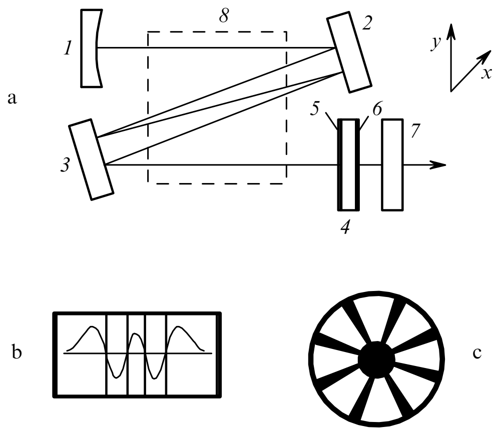

Figure 1. (a) Schematic of an optical resonator and (b, c) configurations of selecting masks: (*1*) totally reflecting spherical mirror, (*2*, *3*) deflecting mirrors, (*4*) plane output mirror, (*5*) mask, (*6*) phase compensator, (*7*) output window, (*8*) active medium; the curve in Fig. 1b describes the spatial distribution of the mode being selected.

The x and y axes shown in Fig. 1a determine the direction of the electric discharge and the gas mixture flow, respectively. A plane mirror (*4*) used as the output mirror and having a transmission of 50 % was deposited on a zinc-selenium substrate transparent in the IR range. An amplitude mask (*5*) intended for selecting a certain mode of the resonator was mounted near the reflecting surface of the mirror, while a phase corrector (*6*) was installed at the rear surface of the mirror. The mask had the form of an opaque screen mounted near the output mirror and having apertures of a special configuration. Internal opaque elements of the mask were in the regions of the nodes in the transverse field distribution of the mode being selected.

In some experiments, an output mirror technologically combining a selecting mask and a phase corrector was used. In this case, the shape and position of apertures of the mask corresponded to the zones on the reflecting surface, which ensured the optimal transmissivity and reflectivity for obtaining the maximum input power. The remaining (selecting) part of the mirror surface was completely transmitting in this case. The alignment of the phase corrector with the mirror was attained by an appropriate deposition of transparent coatings having an optical thickness equal to half the wavelength on the rear face of the substrate.

For small discharge currents (up to 8 A), the laser usually generated a superposition of the TEM_{00} and TEM_{01} modes, the nodal line of the TEM_{01} mode coinciding with the y axis (flow direction). The latter circumstance indicates that the effective size of the TEM_{00} mode, which determines its interaction with the active medium, is considerably larger in the direction of the y axis than along the x axis due to the flow of the medium. For higher values of the discharge current and a corresponding increase in the output power, the laser radiation was a more complex superposition of higher modes.

To analyse the transverse structure of the output laser radiation, we used the Mode Analysis Computer-2 diagnostic system. The radiation was supplied to the input aperture of this system after a reduction of its power with the help of a diffraction coupler.

3. Calculation of a resonator with higher mode selection

The computational model used for a resonator with higher-order mode selection was based on the requirements ensuring

(i) the best matching of the volumes of the mode being selected and the active region of the resonator;

(ii) the required selectivity of the amplitude mask for minimum additional losses;

(iii) the most favourable technological conditions for manufacturing and the radiation resistance of elements of the resonator and the phase corrector; and

(iv) the stability of the parameters of the mode being selected and of the phase compensator to optical aberrations in the resonator.

In the calculation of the optimal configuration of the selecting mask, the initial parameters were the diameters of confining diaphragms mounted in the standard manner near the output plane mirror of the resonator, as well as the radius of curvature of the totally reflecting spherical mirror. One of the diaphragms used in our experiments was rectangular in shape (the size in the direction of the x and y axes was 39 mm and 19 mm, respectively), while the other was circular (with a radius of 12 mm). We calculated the optimal configuration of the Hermite–Gauss mode for the rectangular diaphragm and of the Laguerre–Gauss mode for the circular diagram. The radius of curvature of the totally reflecting spherical mirror was $R = 30$ m. For a known resonator length ($L = 8$ m) and the wavelength $\lambda = 10.6$ μm, this radius unambiguously defines the beam radius w_0 of the fundamental mode at the output mirror:

$$w_0 = (\lambda/\pi)^{1/2}[L(R-L)]^{1/4} = 6.7\ \text{mm}\,. \tag{1}$$

The diffraction losses at the intracavity diaphragm and at the elements of the mask were estimated from expressions obtained in Ref. [8] in the preset field approximation. In this approximation, we can assume that the wave incident on the output mirror corresponds to a 'pure' mode being selected, $\Psi_{mn}(x,y,z)$ in the rectangular system of coordinates. If we neglect the energy losses at the totally reflecting mirror, the losses δ_{mn} of this mode are determined by the expression [8]

$$\delta_{mn} = 1 - r_{mn}\,, \tag{2}$$

where

$$r_{mn} = (\rho_1 \Delta_1 + \rho_2 \Delta_2)^2 \tag{3}$$

is the coefficient of reflection from the system formed by the selector and the output mirror to the mode being selected; ρ_1 and ρ_2 are the amplitude coefficients of reflection from the working surface of the mirror and from elements of the selector (we also assume that the coefficient of reflection from the confining diaphragm is also equal to ρ_2, thus treating the diaphragm as an element of the selecting mask);

$$\varDelta_1 = \int_{S_1} |\varPsi_{mn}^2| \mathrm{d}x\mathrm{d}y; \qquad (4)$$

$$\varDelta_2 = \int_{S_2} |\varPsi_{mn}^2| \mathrm{d}x\mathrm{d}y; \qquad (5)$$

S_1 is the area of the working surface of the mirror, and S_2 is the area of the opaque regions of the mask (we assume that the power of the mode being selected is equal to unity).

The losses determined by expression (2) are the sum of the transmission losses of the output mirror, the losses due to absorption in the mirror and the elements of the mask, and the losses associated with the dissipation of energy of the working mode distorted by the selector to the resonator modes with other transverse indices.

Using relations (1)–(5) and taking into account the above requirements, we carried out a multiparametric optimisation of the parameters of the selective resonator, during which the indices of the modes excited in the resonator were varied, as well as the shape and size of elements of selecting masks. The amplitude distributions were calculated for various modes on the basis of the theory of a 'cold' resonator [14]. We found that, for given sizes of the intraresonator diaphragms, the selection of the Hermite–Gauss mode TEM_{40} is optimal for the rectangular diaphragm, while the selection of the Laguerre–Gauss mode TEM'_{04} is optimal for the circular diaphragm. The configurations of the masks used for selecting these modes are shown in Figs 1b and 1c. The sizes of the inner apertures of the masks correspond to the sizes of the intracavity confining diaphragms, which ensures the best filling of the active region of the resonator with radiation. The width of the inner waists of the rectangular mask is $2d = 0.54$ mm (d is the distance from the waist edge to the nodal line of the mode being selected). The angular size of radial waists of the circular mask is $2\varphi_0 = 0.16$ rad for a diameter of the inner opaque circular zone equal to 8 mm.

The selectivity of the rectangular mask is characterised by the curves shown in Fig. 2a. These curves determine the dependence of the losses σ_{m0} upon the reflection of a wave from the mirror–selector system on the indices m of the TEM_{m0} modes excited in the resonator for various widths of waists. One can see that the waist width $2d = 0.54$ mm (0.08 in the units of w_0), chosen as the optimal width, ensures a selectivity, which is determined by the difference between the losses in the selected mode and other modes of the resonator, not worse than 10 % without any noticeable increase in the intracavity losses. The selectivity of the circular mask is determined by the curves in Fig. 2b, which characterise the ratio of the losses in the system formed by the mirror and the TEM'_{0l} mode selector, which differ in the index l. One can see from the shape of the curves that the azimuth size of radial waists ($2\varphi_0 = 0.16$ rad), which was chosen for manufacturing the circular mask, ensures a selectivity ~ 15 %, increasing the total losses only slightly.

Proceeding from the experience gained in the application of spatial selection of the modes excited in the resonator of a CO_2 laser [8], the above values of selectivity can be regarded as admissible. Since the sensitivity of the mechanism of

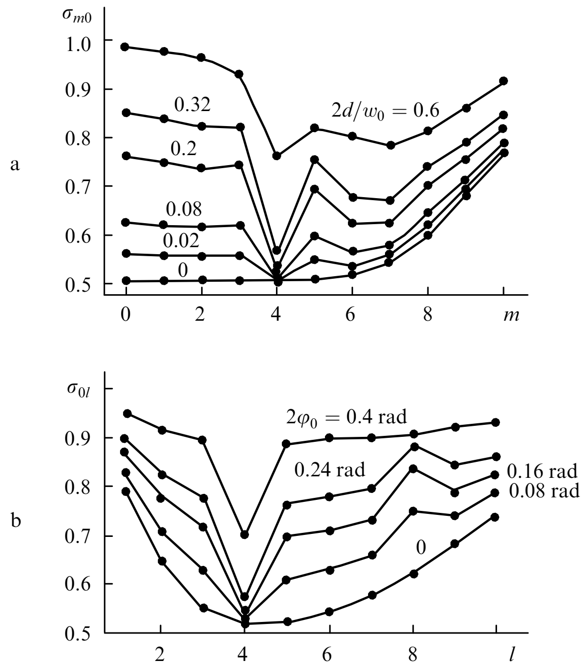

Figure 2. Losses of (a) the Hermite–Gauss TEM_{m0} modes and (b) the Laguerre–Gauss TEM'_{0l} modes for selector tuning to the TEM_{40} and TEM'_{04} mode, respectively, for different waist widths $2d/w_0$ and azimuth sizes $2\varphi_0$ of radial waists.

mode competition to the ratio of the losses in these modes is high, the final conclusion concerning the sufficiency of the selectivity of a chosen mask for obtaining a single-mode lasing can be drawn only as a result of experiments (see below).

To verify the model used for estimating losses and based on the preset field approximation, we calculated the structure of the intracavity field for optimal configuration and position of the selecting mask by using the iterative method [15].

The calculated distributions of intensity and phase for a wave incident on the plane mirror are shown in Figs 3a and 3b for a rectangular mask with the above-mentioned optimal width of the waist. These distributions exhibit weak perturbations caused by the diffraction of the laser beam by the mask elements. Nevertheless, they are close to the corresponding distributions for the modes of an 'empty' resonator, which confirms the correctness of the model used for computations. Fig. 3c shows the distribution of the intensity of the light beam formed in the resonator and passed through a phase compensator in the far-field zone. A comparison of this distribution with the intensity profile for lasing at the fundamental mode (dashed curve) readily shows the narrowing of the radiation diagram for the phase compensation of phase variations in adjacent segments of the transverse structure of the higher mode being selected.

Using the iterative method, we also investigated the sensitivity of the resonator mode selection to a deviation of the size of the waists of the intracavity masks from the optimal value. The calculations proved that the selectivity of the masks is not very sensitive to the sizes of the waists. For example, their increase by a factor of two or three as compared to the optimal value did not noticeably affect the characteristics of the intracavity field being selected.

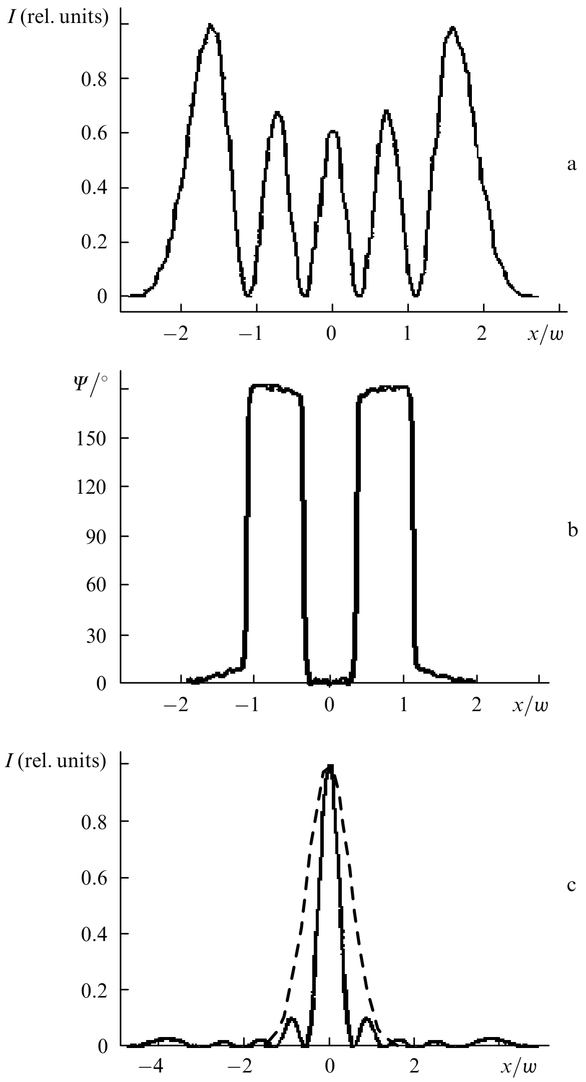

Figure 3. Distributions of (a, c) intensity I and (b) phase Ψ near the output mirror (a, b) and in the far-field zone (c). The dashed curve describes the fundamental-mode radiation; w is the radius of the fundamental-mode beam.

4. Effect of optical aberrations and errors in the compensation of phase variation on the laser beam quality

The above results of calculation of the selectivity of masks were obtained by neglecting the effect of various optical aberrations distorting the amplitude–phase profile of a wave incident on the selector. Among the factors causing aberrations, we should single out (according to their importance) the effects associated with the thermal self-action of radiation in the active medium and with spatial nonuniformity of the energy contribution to the discharge [16]. These factors cause aberrations of the optical-wedge type, tilting the resonator axis. Measurements of the angle of inclination of the resonator axis [16] showed that the angular displacement $\Delta\varphi$ may attain values of 1.6×10^{-4} rad in an industrial CO_2 laser with transverse circulation of the active medium and an output power of 5 kW. The angular displacement leads to a transverse displacement Δx of the resonator axis in the mask plane, which can be estimated approximately by the formula $\Delta x = (R - L)\Delta\varphi$. If $\Delta\varphi = 1.6 \times 10^{-4}$ rad, we have $\Delta x = 3.5$ mm. Therefore, the transverse displacements of the axis are comparable with the fundamental mode beam radius at high powers.

The transverse displacement of the resonator axis may considerably deteriorate the selectivity of the mask and distort the radiation structure in the resonator and in the far-field zone. This can easily be seen in Fig. 4 showing the distributions of the intensity and phase of radiation at the laser output in the near- and far-field zones, which were calculated using the iterative method in the case when the

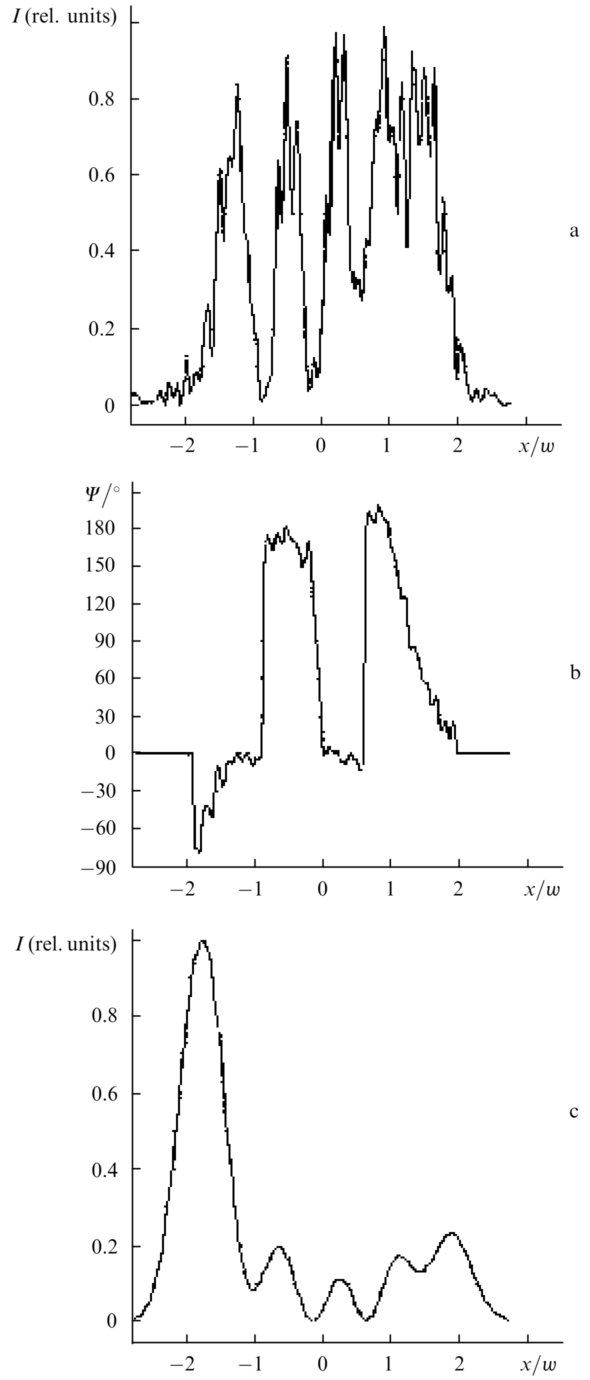

Figure 4. Distributions of (a, c) intensity I and (b) phase Ψ upon a displacement of the mask near the output mirror (a, b) and in the far-field zone (c) for $\Delta x/2d = 4$.

resonator axis is displaced during the TEM_{40} mode selection in the plane of the selecting mask by a value four times as large as the width of its waists. The beam displacement relative to the mask not only distorts the intensity profile, but also leads to considerable phase aberrations. The latter factor, in turn, hampers levelling out of the phase distribution with the help of the phase compensator. Calculations proved that a displacement of the resonator axis in the direction of the x axis strongly deteriorates the parameters of the intracavity field for $\Delta x = (0.15 - 0.2)w_0$. It should be noted that the displacement of the axis in the direction of the y axis does not noticeable affect the selectivity of the rectangular mask, leading only to a certain increase in the total losses.

Similar calculations were also made for a circular mask to estimate the effect of the displacement of the resonator axis. It was found that a circular mask loses its selective capacity for displacements $\Delta r = (0.15 - 0.3)w_0$. The displacement of the axis in the direction of the nodal line produces a stronger effect.

The estimates of the effect of nonuniformities in levelling out of the phase of optical oscillations in the output plane of the laser on the output beam parameters prove that the field of the mode being selected can be transformed qualitatively when the error δ in the phase compensation for the TEM_{40} mode does not exceed 20 % – 25 %. The sensitivity of the phase correction for cylindrical Laguerre – Gauss modes to the value of δ is manifested more strongly: the admissible values of δ must be smaller than 10 %. The difference in the estimates considered here is due to the fact that the correction of the phase distribution of the TEM_{40} mode is carried out in segments with a smaller relative area.

5. Experimental results and discussion

In experiments with TEM_{40} mode selection, the mask was first mounted so that its waists were oriented along the flow. It was found that for such a position of the mask, the optical diagram ensures effective TEM_{40} mode transformation into a beam with synphase oscillations for an output power of 700 – 800 W. The introduction of a selecting mask into the resonator for an unchanged resonator aperture lowered the input power by about 10 %. However, this decrease was accompanied by a strong increase (almost doubling) in the intensity in the axial region and could easily be compensated by an increase in the pumping current. This is confirmed by the radiation intensity distributions displayed on the monitor screen of the diagnostic system and presented in Fig. 5. The distributions shown in Figs 5a and 5b were recorded at the resonator exit, while the distributions presented in Figs 5c and 5d were recorded in the focal plane of a converging lens (far-field zone) for an output power of 700 W. A comparison of these diagrams clearly shows an improvement of the beam divergence in the case of compensation of phase variations.

The size of the spot in the focal plane of the lens in the direction of the x axis is found to be smaller than the size in the direction of the y axis since the effective cross section of the beam at the laser exit is larger in the x direction. An analysis of the profile of the beam depicted in Fig. 5d shows that its angular divergence in the direction of the x axis is approximately half the divergence of the fundamental mode. The angular width of the beam corresponding to half the intensity level is $\theta = 4 \times 10^{-4}$ rad. Such an angular divergence coincides with the above theoretical estimates (see Fig. 3c). If we characterise the radiation divergence in the xz plane by the angular width of the region containing a certain fraction of the total power, we find that the divergence of the transformed TEM_{40} mode corresponding to 0.5 of the total power is $\theta = 1.7 \times 10^{-4}$ rad, which amounts to 0.55 of the divergence of the TEM_{00} mode; at a level of 0.8, the divergences of these modes become identical and equal to 6×10^{-4} rad. The divergences level out due to the presence of side peaks in the beam of the corrected TEM_{40} mode. Note that the latter of the above values of divergence is equal approximately to one-third of the divergence of a multimode beam ($\theta = 2 \times 10^{-3}$ rad) formed in the resonator in the absence of a mask.

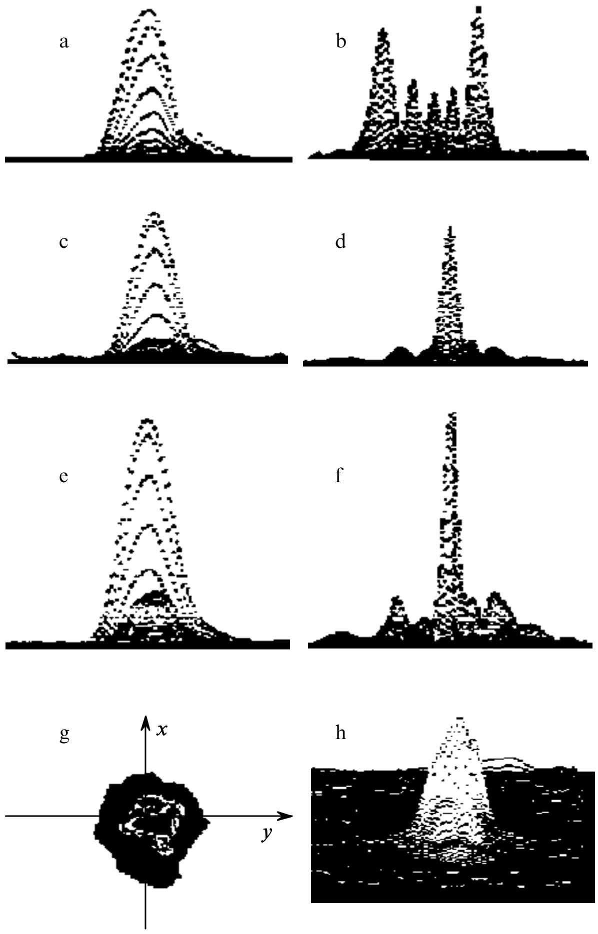

Figure 5. Structure of radiation emitted by a laser with a phase corrector for the selection of (a) the Hermite – Gauss TEM_{40} mode (a – f) and the Laguerre – Gauss TEM'_{04} mode in (g) 2D and (h) 3D representations, obtained along the y axis (a, c, e) and along the x axis (b, d, f) near the output mirror (a, b) and in the focal plane of a lens (c – h) for an output power of (a – d) 700, (e, f) 1000, and (g, h) 800 W.

A further increase in the output power deteriorates the laser beam quality. Figs 5e and 5f show the structure of the laser beam in the focal plane of a focusing lens for a power ~ 1 kW. One can see that noticeable distortions of the beam profile start being manifested at such a power. A still further increase in the power led to a broadening of the spot in the focal plane, indicating the absence of phase locking at the laser output. The fact that the structure of radiation improved rapidly upon a sharp decrease in the pumping current and, hence, a decrease in the output power is important for interpreting the experimental results. It indicates that main aberrations affecting the selection of a definite type of oscillations in the resonator as well as phase compensation are due to heating of resonator elements to a smaller extent and are mainly due to self-action of radiation in the active medium and spatial nonuniformity of energy contribution in the discharge.

When the waists in a mask were perpendicular to the active medium flow, it was impossible to ensure the selection of the TEM_{04} mode and, accordingly, to obtain a directional radiation at the laser exit due to the emergence of the TEM_{14} mode impurity, which considerably distorts the structure of the intracavity field. The selection of the TEM'_{04} mode with the help of a circular mask also did not lead to a beam quality close to the theoretical estimates for a radiation power exceeding 700–800 W. Despite the closeness of the recorded intensity distributions to the 'classical' distribution for the TEM'_{04} mode, its wave front for the above values of power acquired considerable phase distortions. These distortions did not permit the formation of the beam intensity profile in the far-field zone, which would be narrower than the fundamental mode profile, although the beam intensity in the axial region increased steadily (see Figs 5g and 5h).

The decrease in the efficiency of a higher-order mode conversion into a narrow high-power beam, which was established in our experiments, can be unambiguously attributed to the negative effect of intracavity inhomogeneities. The theoretical estimates obtained in Refs [4, 16] indicate that light-induced optical inhomogeneities in a flowing active medium may cause an angular displacement of the axis of the order of 10^{-4} rad for a power of 1 kW. Such tilts of the axis in our geometry of the resonator lead to its displacement in the plane of the selector mask, which is close to the critical displacement as regards the manifestation of the selecting properties of the mask. The effects associated with nonuniformity of the energy contribution to the discharge lead to slightly smaller (half as large) tilts of the axis [4, 16]. Our theoretical estimates [4, 16] were confirmed by the measurements of the angular displacement of the output beam axis upon an increase in the power of the laser under investigation, in which a stable resonator was replaced by an unstable telescopic resonator.

6. Conclusions

The main conclusion that can be drawn by generalising the results of calculations and experiments is that the methods for computation and optimisation of the optical path of CO_2 lasers with transverse circulation of the active medium used in this study as well as the existing technological potentialities of manufacturing their optical elements make it possible to obtain narrow laser beams of power up to 1 kW by correcting the wave front of higher-order modes in the case of a good filling of the active medium with radiation.

The most significant obstacle for improving the output parameters of lasers with a higher radiation power are intracavity aberrations of the optical-wedge type, which are enhanced with increasing pump current. The physical nature of these aberrations is determined to a considerable extent by the transverse circulation of the active medium and the transverse discharge. On the one hand, aberrations of this type deteriorate the selectivity of the intracavity mask due to the displacement of the resonator axis; on the other hand, they cause wave front perturbations due to an increase in the role of diffraction of radiation by the elements of the mask, which cannot be compensated by a phase corrector.

Both numerical simulation and the results of experiments indicate that the negative effect of aberrations on the radiation structure is stronger in the case of selection of the Laguerre–Gauss modes than for the selection of the Hermite–Gauss modes. This is due, to a considerable extent, to a higher sensitivity to wave front perturbations of the phase compensator tuned to the modes with cylindrical geometry.

Thus, the efficient conversion of the higher-order mode radiation into a narrow beam at output powers exceeding 1 kW is possible only upon matching the position of the mask and the phase corrector in the operational mode for a given output power. The organisation of such a tuning in typical industrial lasers will require a more significant modification of the optical path and of the system controlling its parameters.

Finally, we must point out the advantage of the method of phase profile correction for higher modes in high-power industrial gas lasers with rapid axial circulation of the working mixture since there are no reasons for the emergence of aberrations of the optical-wedge type in such lasers.

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