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Waveguide CO_2 laser with a quasi-homogeneous distribution of the output radiation intensity

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Abstract. **An experimental sample of a waveguide CO_2 laser with a quasi-uniform profile of the output radiation intensity is designed on the basis of a waveguide quasi-optical cavity of a new type comprising the generic confocal cavity with a nonuniform mirror and the hollow waveguide with the dimensions satisfying the conditions for self-imaging the quasi-uniform field. The surface of the mirror has the discrete large-scale absorbing nonuniformities. Results of theoretical and experimental investigations of spatial-energy characteristics of the laser in using uniform or amplitude-stepped reflecting mirrors are presented.**

Keywords: *field formation, infrared range, waveguide CO_2 laser, quasi-optical combined cavity, Fourier optics, field self-imaging.*

1. Introduction

Waveguide gas lasers are widely applied in technology, medicine, spectroscopy, and space communication [1, 2]. Problems in these fields are optimally solved by employing the beams with a quasi-uniform cross-section distribution of the radiation intensity. There are methods for obtaining such beams in open laser cavities based on transformation of the field of a particular transverse mode by various optical elements and nonuniform laser mirrors [3]. In waveguide gas lasers the combined quasi-optical cavities are used, which comprise multimode waveguides and segments of free space. In such cavities, non-Gaussian radiation beams may be formed not only by the mirrors but also due to a coherent summation of an ensemble of transversal modes of the oversized waveguide disposed between the mirrors [4]. It was shown [5, 6] that at certain length of a multimode waveguide the wave fields are transferred without distortion at a given wavelength (polyharmonic waveguide). The concept was suggested in [7, 8] for fabricating laser cavities on the basis of self-imaging properties of multimode waveguides. In [9], the submillimeter laser was described with the quasi-homogeneous output beam on the basis of the waveguide cavity folded by means of a deflecting mirror system (DMS). In that construction, the DMS serves as an open generic confocal cavity (GCC) [10]. Such schemes provide small dimensions of the unit, increase selectivity with respect to the fundamental mode and have quasi-homogeneous output beam in solid-state and gas IR lasers [11 – 13].

By employing these approaches to building laser cavities one can realise the method for obtaining a close-to-uniform output profile of the radiation intensity of an IR laser based on a new type of the combined cavity, which includes a GCC with a non-uniform mirror and a multiharmonic waveguide. The present work is aimed at development, fabrication, and study of an experimental sample of the waveguide CO_2 laser with a quasi-uniform output beam.

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2. Theoretical relations

Theoretical consideration is based on the methods of Fourier optics and eigenoscillations [14, 15]. The process of formation of cavity oscillation types is interpreted as the result of various diffraction interactions of the waves with the optical elements comprised in the cavity. Due to these interactions, the eigenwaves recover the relative spatial amplitude and phase distributions and the polarisation state in a cavity cross-section in each successive transit. The lens corrector and mirror nonuniformities we will describe by the amplitude – phase correction function [16]. The scheme of the cavity under study is given in Fig. 1. One arm of the cavity near the output semitransparent reflector (*1*) has a circular dielectric waveguide. The waveguide dimensions should correspond to the self-imaging conditions for the radiation beams with the super-Gaussian field amplitude distribution in hollow waveguides. These conditions have been obtained in [17]. We denote the diameter of the output mirror and waveguide by $2a_1$ and the waveguide length by L. At a distance L_1 from the waveguide end, the thin lens corrector (*3*) of radius a_3 and focal length F is placed, which performs Fourier transformation of the field at the waveguide output. At a distance L_2 from the phase corrector, there is the nonhomogeneous mirror (*2*) of diameter $2a_2$ with a spatial filter characterised by the amplitude correction function $T(\rho_2)$ ($\rho_2 = r_2/a_2$ is the dimensionless radial

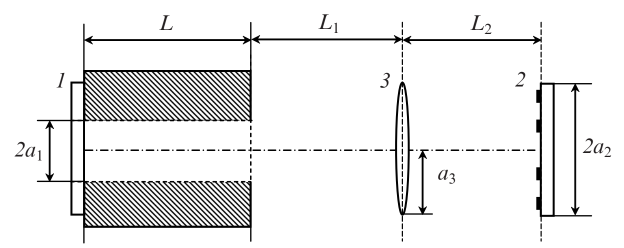

Figure 1. Schematic diagram of a waveguide quasi-optical cavity.

coordinate for mirror (*2*)]. The transversal dimensions of the cavity elements are assumed to satisfy the conditions of quasi-optical approximation $(ka_i)^2 \gg 1$ ($i = 1, 2, 3$), where $k = 2\pi/\lambda$ (λ is the wavelength), and paraxial conditions $k_{\parallel} \gg k_{\perp}$ (the longitudinal wavenumber is much greater than the transverse one).

The method for calculating the characteristics of lower cavity modes is based on the quasi-stationary condition for the transversal structure of the mode field in the cavity [18]. In this case, the field in the waveguide is presented as a superposition of eigenwaves and in the open parts of the cavity – as the diffraction integral in the Fresnel approximation [19, 20]. Finally, the problem of eigenoscillations in the considered cavity is reduced to the following system of linear algebraic equations:

$$\mu C_k = \exp(i\gamma_k L)\sum_{m=1}^{M} C_m \exp(i\gamma_m L)\int_0^1 V_m(\rho_1)Q_k(\rho_1)\rho_1 d\rho_1, \quad (1)$$

where

$$Q_k(\rho_1) = \int_0^1 Q^0(\rho_1, \rho_1')\, V_k(\rho_1')\rho_1' d\rho_1';$$

$$Q^0(\rho_1,\rho_1') = \frac{N_1 N_2}{(1-G_1)(1-G_2)} \times \int_0^1 Q(\rho_1,\rho_2)Q(\rho_2,\rho_1')T(\rho_2)\rho_2 d\rho_2;$$

$$Q(\rho_p,\rho_n) = -4\pi^2 N_0 \exp[ik(L_1+L_2)]\exp[i\pi(N_1\rho_p^2 + N_2\rho_n^2)] \times \int_0^1 \exp(i\pi N_0 Z\rho_3^2) J_0(2\pi N_1 \xi_1 \rho_p \rho_3)\, J_0(2\pi N_2 \xi_2 \rho_n \rho_3)\rho_3 d\rho_3;$$

ρ_1 and ρ_1' are the dimensionless (normalised to a_1) radial coordinates on the mirror (*1*) at the start and finish of a round trip in the cavity; ρ_3 is the dimensionless radial coordinate (normalised to a_3) on the phase corrector (*3*); J_0 is the zero-order Bessel function of the first kind; $p = 1, 2$ is the mirror number; $n = 3 - p$; $k = m = 1,\ldots,M$; M is the number of modes for the waveguide laser tube; and γ are waveguide wave propagation constants [21]:

$$N_{1(2)} = \frac{a_{1(2)}^2}{\lambda L_{1(2)}};\ N_0 = \frac{a_3^2}{\lambda F};\ \xi_{1(2)} = \frac{a_3}{a_{1(2)}};$$

$$G_{1(2)} = 1 - \frac{L_{1(2)}}{F};\ Z = \frac{1 - G_1 G_2}{(1-G_1)(1-G_2)}.$$

The solution to system (1) yields M eigenvalues μ, determining the relative energy losses for cavity modes and their additional phase intrusion over the cavity round trip and the same number of eigenvectors C_k whose components determine the profiles of the corresponding transversal cavity modes. The relative energy losses, which include the mode energy losses in the waveguide and in free space segments per round trip, are defined, along with the phase shift of the modes, by the expressions

$$\delta_r = 1 - |\mu|^2, \qquad \Phi = \operatorname{Arg}\mu. \quad (2)$$

Assume that the distribution of a complex amplitude of field component at output mirror (*1*) of the waveguide quasi-optical cavity and, correspondingly, at the end of the multiharmonic waveguide is described, at the corresponding waveguide length, by the circular function

$$\operatorname{circ}\rho_1 = \begin{cases} 1, & \rho_1 \leqslant 1, \\ 0, & \rho_1 > 1. \end{cases} \quad (3)$$

In the approximation of infinite aperture of the phase corrector, the Fourier–Bessel transformation of this function, with the accuracy to an insignificant constant factor, has the form [22]

$$\operatorname{somb}\Theta = \frac{2J_1(\pi\Theta)}{\pi\Theta}, \quad (4)$$

where $\Theta = 2N_{12}\rho_2$; $N_{12} = a_1 a_2/[\lambda F(1 - G_1 G_2)]$ is the GCC Fresnel number.

By placing the absorbing elements on the nonuniform mirror (*2*) in such a way that $\rho_{2\chi} = \nu_{1\chi}/2\pi N_{12}$, where $\nu_{1\chi}$ are roots of function J_1, $\chi = 1, 2, 3\ldots$, and taking into account possible selection of transversal modes by the above mentioned elements [23] one may hope that a solution to system (1) will be formed from functions close to analytical forms (3), (4). In this case, the transverse dimensions of the uniform domains, in whose boundaries the matter constants experience discontinuity, should be noticeably greater than the wavelength.

System (1) can only be solved with the help of a computer. It was performed by the matrix method [24] by using the modified Rutishauser algorithm. There are three independent kinds of solutions of system (1): for hybrid (EH_{nm}-), transversal electric (TE_{0m}-) and transversal magnetic (TM_{0m}-) modes, where n and m are the azimuthal and radial mode indices, respectively. The results of calculations presented below refer to the practically important modes from the class of axisymmetric EH_{1m}-modes, which at $m \leqslant \sqrt{a_1/\lambda}$ [25] have a linear polarisation of the field. Their complex amplitudes are described by a complete system of orthonormalised functions $V_m(\rho_1) = \sqrt{2}\, J_0(Y_m\rho_1)/J_1(Y_m)$ [17], where J_0, J_1 are Bessel functions of the first kind, Y_m are roots of equation $J_0(Y_m) = 0$. The propagation constants for these modes are [21]

$$\gamma_m \approx k\left[1 - \frac{1}{2}\left(\frac{Y_m\lambda}{2\pi a_1}\right)^2\left(1 - \frac{i\nu_1\lambda}{\pi a_1}\right)\right],$$

where $\nu_1 = 0.5(\nu^2 + 1)/\sqrt{(\nu^2 - 1)}$ and ν is the refractive index of waveguide wall.

3. Experimental setup

The design of an experimental sample of a waveguide CO_2 laser is schematically shown in Fig. 2. The laser operated in the regime of slow gas mixture pumping (CO_2 : N_2 : He : Xe = 1 : 1 : 5 : 0.25). A longitudinal glow discharge was maintained by the DC power supply with a voltage of up to 26 kV. The discharge chamber was cooled by flowing water passing through fittings (*12*) into the water heat exchanger jacket (*2*).

The laser cavity is formed by two plane circular mirrors (*4*) and (*8*) with the diameter of 20 mm, the lens (*5*) is made of ZnSe (the phase corrector serving as the Fourier transformation element in the simulation model of the laser cavity) with the diameter of 19 mm, focal length of 76 mm, and a fraction of the hollow dielectric waveguide (*1*) with the diam-

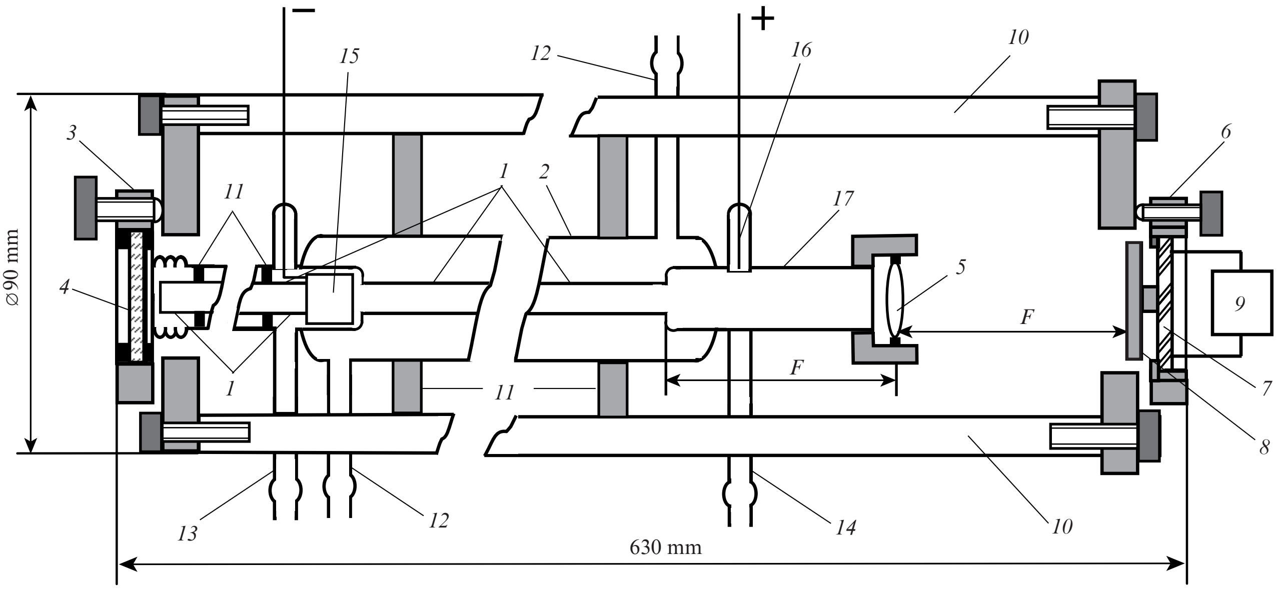

Figure 2. Construction of a waveguide CO_2 laser: (*1*) waveguide; (*2*) water heat exchanger jacket; (*3*) adjustment unit of a semitransparent mirror; (*4*) semitransparent mirror; (*5*) ZnSe lens; (*6*) adjustment unit of a nonuniform mirror; (*7*) KP-1 piezoelectric corrector; (*8*) nonuniform mirror; (*9*) DC source; (*10*) invar rods; (*11*) centring rings; (*12*) fittings of the water cooling system; (*13*) exhaust fitting; (*14*) working mixture puffing fitting; (*15*) cathode; (*16*) anode; (*17*) glass tube.

eter of 4 mm and length of 460 mm. The waveguide length $L \approx 1.2a_1^2/\lambda$ was chosen to satisfy the self-imaging conditions in a hollow dielectric waveguide for the radiation beams with a super-Gaussian field amplitude distribution [17]. The gap in the waveguide (the length of approximately 10 mm) did not affect the character of field replication in the waveguide and provided space for placing a hollow cylindrical cathode in the considered laser construction for obtaining a stable glow DC discharge. The discharge gap length was 370 mm.

The distance between the phase corrector and the nonuniform mirror from one side and the waveguide from the other side was chosen equal to the focal length. The inner diameter of the glass tube (*17*) is 15 mm and does not affect the field formation in the cavity. The radiation beam in this section propagates as in free space. In the experiments, for the mirror (*8*) we used the plane mirror made from stainless steel with gold deposited in vacuum, or the plane nonuniform amplitude-stepped mirror (ASM) made by the method of photolithography – by depositing thin annular strips from an absorbing material to a similar substrate. Parameters of the nonuniform mirror were preliminarily calculated according to (1). After fabricating the mirror, the widths of the reflecting and absorbing rings were measured and substituted again into (1) for recalculating the mode characteristics of the real cavity model.

The measured diameter of the central reflecting circle of the ASM was 0.743 ± 0.005 mm (70.1λ ± 0.5λ). The widths of the reflecting and corresponding absorbing rings are given in Table 1.

The radiation of laser was extracted through the plane semi-transparent germanium mirror (*4*) with the transmission coefficient of ~10%. The mirror was arranged at a distance not longer than 1 mm from the waveguide end. The highly reflecting mirror (*8*) and semi-transparent mirror (*4*) were mounted in adjustment units (*3*, *6*), which provided exact adjustment of the cavity by the radiation of a He–Ne laser. The cavity was supported by three invar rods (*10*), which provided the long-term stability of the cavity length. The construction was made rigid due to supports (*11*), which also made it possible to align the system comprising the waveguide, discharge chamber, phase corrector, ASM, and semitransparent mirror. The highly reflecting mirror was mounted on the piezoelectric corrector (*7*) of type KP-1, which served to remotely change the cavity length in the limits ±5 μm.

Table 1.

N	Width of absorbing ring		Width of reflecting ring	
	/mm	in units of λ	/mm	in units of λ
1	0.043	4.05	0.171	16.13
2	0.057	5.38	0.157	14.81
3	0.043	4.05	0.157	14.81
4	0.043	4.05	0.157	14.81
5	0.043	4.05	0.150	14.15
6	0.043	4.05	0.157	14.81
7	0.043	4.05	0.164	15.47
8	0.043	4.05	0.143	13.49

Note: *N* is the serial number for reflecting and absorbing ring positions relative to the centre of the mirror.

4. Comparison of experimental and numerical results

Figure 3 presents the calculated relative transversal distributions of the intensity and phase of the field on the output mirror for the experimental model of laser at the amplitude spatial filter parameters given in Table 1. The absolute measure Π of distinct between the etalon circular function circρ_1 and the profile of field intensity $I(\rho_1)$ at the output mirror is defined, for the case of non-uniform mirror in the cavity, as [26]

$$\Pi = \frac{1}{S}\sum_{s=1}^{S}|1 - I(\rho_{1s})|,$$

where S is the number of points of the discrete set of the field intensity on the mirror between the maximal and 1/e^2 inten-

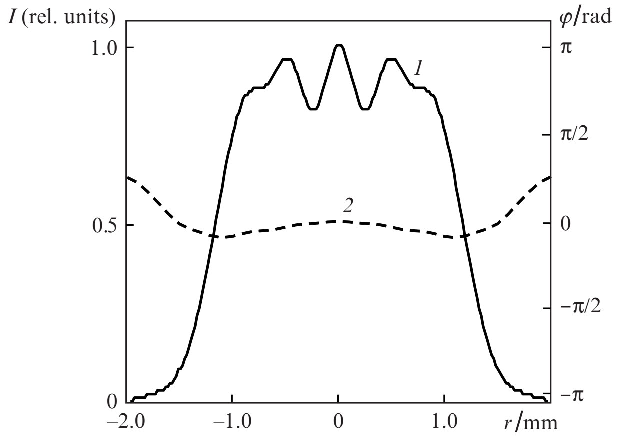

Figure 3. Calculated radial distributions of (*1*) intensity and (*2*) phase of the field on laser output mirror.

sity levels. The value of Π does not exceed 30%. The value of field quasi-uniformity is comparable to that obtained by other methods [27].

The measurements were performed at the total pressure of the working mixture in the discharge tube of 18 mm Hg and the discharge current of 10 mA. The laser operated in a single-mode regime. The radiation power of the laser measured by a calorimetric power meter of type IMO-2N was 2.5 W for the uniform mirror and 1.9 W for the amplitude-stepped mirror. The fall of power in the case of amplitude-stepped mirror is explained by greater waveguide and diffraction losses.

Due to constructive features of CO_2 laser it was impossible to measure the radiation intensity profile directly on the output mirror; thus, the experimental distributions of output beam intensity were recorded at various distances from the semi-transparent mirror in the near field. Experimental and the corresponding calculated intensity profiles are presented in Fig. 4. The experimental transversal intensity distributions of output radiation were recorded by a scanning pyroelectric detector (with the spatial resolution of 0.2 mm) in the plane normal to the radiation propagation direction. One can see that the profiles slightly differ. There are characteristic oscillations at the peak of both experimental and calculated transverse intensity distributions. A fall of the laser output power by 10% in detuning the cavity did not result in a noticeable change in the output field distribution. Calculations show that at the same parameters of the nonuniform mirror, the absolute distinct measure is changed by at most 5% for the two wavelengths corresponding to the neighbouring laser generation lines 10P(20) and 10P(22).

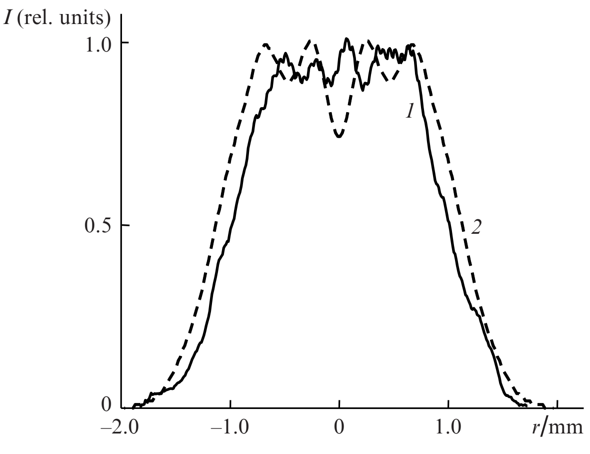

Figure 4. (*1*) Experimental and (*2*) calculated radial radiation intensity distributions of the laser with an amplitude-stepped mirror at a distance of 20 mm from the output mirror.

The transverse distributions of the radiation intensity at the output mirror in the experimental model of the laser in the near field are sufficiently well approximated by the six-order super-Gaussian beam profile. Presently, in describing the quality of laser beams, the parameter M^2 is widely used, which was introduced by Siegman in 1990 [28]. For super-Gaussian beams it may be defined from known relationship [29, 30] $M^2 = n\sqrt{\Gamma(4/n)}/[2\Gamma(2/n)]$, where n is the order of the super-Gaussian beam; Γ is the gamma-function. In our case the calculated beam quality parameter is $M^2 = 1.3$.

For testifying the close-to-uniform radial distribution of field intensity at the output of the waveguide CO_2-laser we investigated the intensity distribution at a focus of the positive lens with $f = 130$ mm. The latter was placed so that one of its focal planes coincided with the plane of laser output mirror. In this case the beam intensity distribution can be recorded in the other focal plane, which will be the Fourier-transform of the function, which describes the distribution of the field formed on the semi-transparent mirror. In our case it should be a curve close to the 'sombrero' function. The obtained experimental and calculated curves are presented in Fig. 5. A comparison confirms that there are no qualitative discrepancies as well. The amplitude of sidelobes in the experimental curve is comparable to the noise amplitude of the pyroelectric detector.

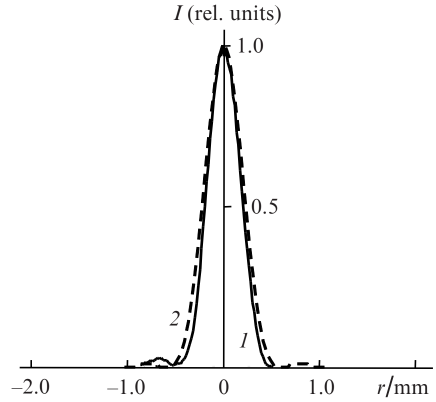

Figure 5. (*1*) Experimental and (*2*) calculated radial distributions of the radiation intensity at the lens focus.

Experimental and calculated relative radial distributions of radiation intensity for the laser with a uniform mirror are shown in Fig. 6 in the same cross-section as in Fig. 4. One can see that the radiation profile corresponds to a transversal distribution of the waveguide mode EH_{11}. Comparison of distributions in Figs 4 and 6 reveals that employment of the amplitude-stepped mirror makes it possible to obtain a quasi-uniform output beam in a waveguide laser.

Thus, the possibility of producing the waveguide CO_2 laser with a quasi-uniform profile of the output beam intensity on the basis of the combined waveguide quasi-optical cavity comprising the generic confocal cavity with a nonuni-

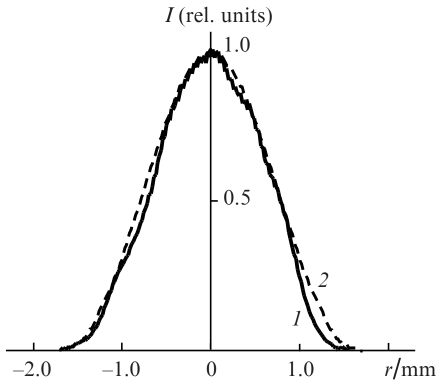

Figure 6. (*1*) Experimental and (*2*) calculated radial distributions of the radiation intensity of the laser with a uniform mirror at a distance of 20 mm from the output mirror.

form amplitude-stepped mirror and multiharmonic waveguide was shown theoretically and experimentally.

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