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Polarisation properties of radiation of high-power industrial multitubular CO_2 lasers

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Abstract. **The polarisation of radiation of high-power industrial multitubular, diffusion-cooled CO_2 lasers is studied. The conditions of the appearance of linear and elliptic polarisation and of polarisation instability are determined. The relation between the laser parameters and its polarisation characteristics is established.**

Keywords: *CO_2 laser, radiation polarisation, polarisation instability, industrial CO_2 laser.*

1. Introduction

Radiation of modern industrial lasers should satisfy high requirements, which include not only a low angular divergence of the laser beam but also the beam stability and control of its parameters, in particular, of the beam polarisation. For example, circular polarisation is preferable for cutting details of complicated profiles because it allows one to avoid the machining defects such as the slanting of edges, different widths of the cut produced during cutting in different directions, the formation of burs, etc. Linear polarisation oriented along or perpendicular to the direction of a laser movement is used in laser welding. For these and other reasons, the problem of formation of the polarisation state in CO_2 lasers has attracted a great attention [1 – 4]. In Ref. [1], fluctuations of polarisation in a pulsed low-pressure unstable-resonator CO_2 laser were investigated. The influence of the resonator misalignment and of other factors on the polarisation of radiation from a low-power $\sim$ 5-W cw laser was studied in Ref. [2]. Unlike CO_2 lasers investigated in these papers, the polarisation state in high-power cw industrial lasers is formed under more complicated conditions [4, 5].

Common factors affecting a polarisation state in gas lasers are as follows:

(i) Different losses for radiation with s- and p-states of linear polarisation upon reflection from deflecting mirrors;

(ii) Polarisation anisotropy of the gain of a laser medium produced due to the phase shift of the s-polarised radiation with respect to the p-polarised radiation upon reflection of radiation at some angle from metal mirrors. This phase shift can be quite large upon reflection from mirrors with protecting reflecting coatings and depends on the manufacturing technology of the mirrors. It is known that this phase shift results in different shifts of axial modes with s- and p-polarisations.

(iii) Rotation of the field with the help of turned dihedral reflectors with the angle between facets equal to 90°.

Although these factors are known, they are manifested differently in CO_2 lasers of different types, which leads to a variety of polarisation states in these lasers: from the simplest case, when stable s-polarised linear radiation is emitted, to the case of polarisation instability of the bifurcation type [4].

In this paper, we study experimentally and theoretically the polarisation properties of high-power cw multitubular, single-beam, diffusion-cooled CO_2 lasers and compare their polarisation states with those of high-power transverse-flow CO_2 lasers.

2. Experimental results

We studied single-mode, 500 – 700-W, diffusion-cooled CO_2 lasers developed and recently modified at IPLIT, RAN, in collaboration with 'TechnoLaser' Joint-Stock Company. These lasers produce high-quality single-mode radiation, have a sufficiently large operating resource under industrial conditions, are very compact due to the absence of a system for fast gas circulation, and have a relatively low cost.

An important component of single-beam multitubular CO_2 lasers is an optical scheme for turning the laser beam, from which the spatial arrangement of gas-discharge tubes (GDTs) depends. At present, there are three types of the spatial arrangement of GDTs:

(i) GDTs are arranged equidistantly in a plane. The optical resonator is formed by the end plane mirrors and two deflecting dihedral reflectors displaced with respect to each other in the GDT arrangement plane by half the distance between their centres (Fig. 1) [6, 7].

(ii) All GDTs are arranged with the same step on the cylinder surface. The resonator is also formed by the end mirrors and two dihedral reflectors turned with respect to

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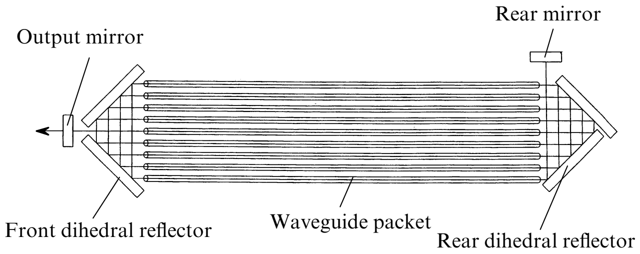

Figure 1. Scheme of a CO_2 laser with GDTs arranged in one plane and parallel dihedral reflectors.

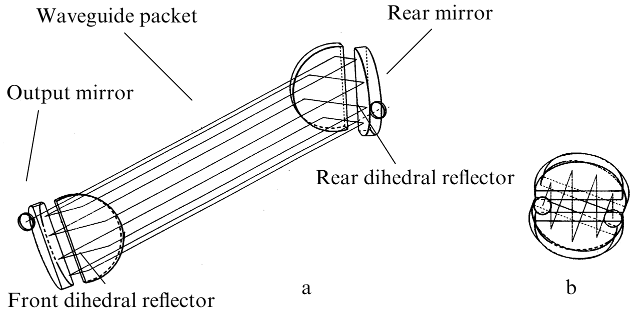

Figure 2. Scheme of a CO_2 laser with circularly arranged GDTs and crossed dihedral reflectors: general view (a), end view (b). Only nine tubes are shown for clarity.

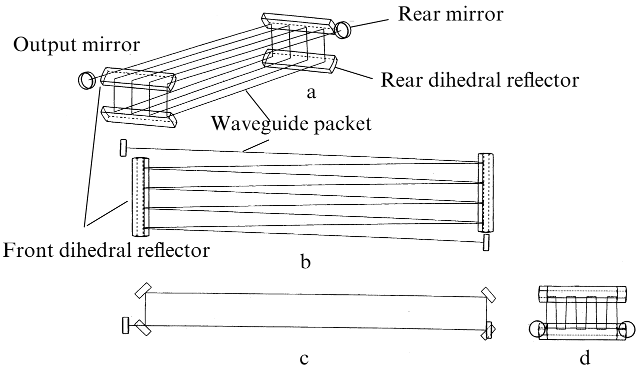

Figure 3. Scheme of a CO_2 laser with GDTs arranged in two planes and parallel dihedral reflectors: general view (a), top view (b), side view (c), end view (d).

each other through the angle equal to half the angular distance between the tubes (Fig. 2) [8].

(iii) GDTs are arranged in two parallel layers along the laser beam between two parallel dihedral reflectors, as shown in Fig. 3. The resonator is formed by two plane mirrors and dihedral reflectors, which provide the propagation of the laser beam through all GDTs [9].

There exists the scheme of the GDT arrangement without dihedral reflectors, in which the latter are replaced by two spherical mirrors or one spherical and one plane mirror. In the latter case, GDTs are placed between the mirrors along the laser beam, as in a resonator with multipass modes (M modes) [10].

In each of the cases considered above, polarisation parameters were measured with a specially designed power meter, whose readings depend on the direction of oscillations of the electric field [11]. The radiation power was measured simultaneously with a conventional polarisation-isotropic power meter. Table 1 presents the parameters of CO_2 lasers with three types of the spatial arrangement of GDTs, which we studied. The parameters of coatings on the reflecting surfaces of deflecting prisms are presented in Table 2.

Our measurements with CO_2 lasers of the first type showed that radiation of the lasers had stable linear s-polarisation, i.e., the direction of oscillations of the electric field was parallel to the edge of reflecting prisms. In lasers of the second type, elliptic polarisation was observed, but with a very strongly prolate ellipse with the axial ratio equal to 1/100. Such polarisation can be considered almost linear. When mirrors with the phase shift $\Delta\varphi = 7^\circ$ were used, the direction of polarisation was oriented at the angle $\Theta = 23^\circ$ with respect to the edge of a dihedral reflector. With time,

Table 1.

Parameters of the waveguide mulitubular CO_2 laser	CO_2 laser type		
	first	second	third
Wavelength/μm	10.6	10.6	10.6
Output power/W:			
Maximal	600	700	1000
Nominal	500	600	700
Parameters of the repetitively pulsed regime*:			
frequency/Hz	–	$\leqslant 2000$	$\leqslant 2000$
pulse duration/μs	–	$\geqslant 250$	$\geqslant 250$
Lasing mode	TEM_{00}	TEM_{00}	TEM_{00}
Number of tubes N	9	20	20
Tube length/mm	2000	1800	1800
Total resonator length L/m	18	36	36
Inner diameter of the waveguide tube/mm	7	7	7
Output beam diameter at the $1/e^2$ level/mm	4	4	4
Working pressure of the $CO_2:N_2:He = 1:2:10$ mixture/Torr	40	40	40
Gas flow rate/L h^{-1}	2–3	2–3	2–3
Laser dimensions/mm	200 × 200 × 2100	200 × 200 × 2100	200 × 200 × 2100
Laser head mass without coolant/kg	15	15	15

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*Note: CO_2 lasers of all types can operate in the cw regime.

Table 2.

Mirror type	R_s	R_p	$\Delta\varphi/^\circ$
Standard mirror with a protecting coating	0.992	0.985	7
Highly reflecting mirror	0.995	0.993	0.3

Note: R_s and R_p are the radiation coefficients for the s- and p-polarisations.

approximately after 1500 h of the laser operation, the angle Θ increased up to 30°.

In some cases, when highly reflecting mirrors with $\Delta\varphi = 0.3^\circ$ were used, polarisation became temporarily unstable and the direction of the major axis of the ellipse was randomly changed by ±90°. As the input and, hence, the output power increased, these unstable states of polarisation repeated through certain current intervals. The time of the appearance (in current) of the unstable state of polarisation depends also on the mixture composition and pressure, the resonator length, and other factors.

In the laser of the third type, polarisation was always stable and linear, but the oscillations of the electric field were directed at a small angle to the edge of reflectors (s-polarisation).

3. Theoretical analysis

The polarisation state in lasers of the first type can be affected only by the first two of the factors considered above. Let us estimate them. When N tubes are used, the distributed reflection losses for dihedral reflectors are

$$\beta \approx \frac{N-1}{N}\frac{1-R^2}{L_a}, \tag{1}$$

where L_a is the active length of a GDT; R is the reflectivity of the optical surface of the dihedral reflector and $1 - R^2 \ll 1$. When the number N of tubes is great, the value of β is almost independent of N. Therefore, equality (1) can be written in the form

$$\beta \approx \frac{1-R^2}{L_a}. \tag{2}$$

The difference of losses for light waves with s- and p-polarisations is

$$\Delta\beta = \beta_p - \beta_s = \frac{R_p^2}{L_a}\left(\frac{R_s^2}{R_p^2} - 1\right). \tag{3}$$

On the other hand, it is known from the theory of reflection of light waves from absorbing media that the phase shift $\Delta\varphi$ appearing after reflection depends on the polarisation state:

$$\frac{\rho_s}{\rho_p} = \left(\frac{R_s}{R_p}\right)^{1/2}\exp(\mathrm{i}\Delta\varphi),$$

where ρ_s and ρ_p are the complex reflection coefficients for a light wave with s- and p-polarisations, respectively. Because the phase shift $\Delta\varphi = \varphi_s - \varphi_p$ is nonzero, the resonance lines of the optical resonator for the waves with s- and p-polarisations are separated by the interval

$$\Delta\nu = \nu_s - \nu_p = \frac{c}{2L}\frac{\Delta\varphi}{\pi}, \tag{4}$$

where c is the speed of light and L is the resonator length.

It is known that the frequency dependence of the gain per unit length for a homogeneously broadened spectral line is

$$g = \frac{\alpha}{1 + [(\nu - \nu_0)/\Delta\nu_0]^2}, \tag{5}$$

where α is the gain per unit length at the centre of the spectral line at frequency ν_0; $\Delta\nu_0$ is the half-width of this line.

It readily follows from (5) that the difference of the gains for the s- and p-polarised waves is

$$\Delta g = g_s - g_p$$
$$= \alpha\frac{[(\nu_0 - \nu_p) + (\nu_0 - \nu_s)](\nu_s - \nu_p)}{\Delta\nu_0^2\{1 + [(\nu_s - \nu_0)/\Delta\nu_0]^2\}\{1 + [(\nu_p - \nu_0)/\Delta\nu_0]^2\}}. \tag{6}$$

Because the maximum frequency detunings $\nu_0 - \nu_p$ and $\nu_s - \nu_p$ do not exceed the interval $c/(2L)$ between the axial modes, which is substantially smaller than $\Delta\nu_0$, expression (6) can be simplified:

$$\Delta g = \alpha\frac{[(\nu_0 - \nu_p) + (\nu_0 - \nu_s)](\nu_s - \nu_p)}{\Delta\nu_0^2}. \tag{7}$$

The coefficient α in (7) can be assumed equal to the saturated absorption coefficient

$$\alpha = \frac{1}{2NL_a}|\ln r|, \tag{8}$$

where r is the reflection coefficient of the output mirror.

Now we can estimate the relative role of the polarisation anisotropy of absorption and amplification by assuming in (7) that the maximum admissible detunings are

$$\nu_s - \nu_p = \frac{c}{2L}, \quad \nu_0 - \nu_p = \frac{c}{2L}, \quad \nu_0 - \nu_s = \frac{c}{L}.$$

As a result, we obtain

$$\Delta g_{\max} = -\frac{3}{4}\alpha\left(\frac{c}{L}\right)^2\frac{1}{\Delta\nu_0^2}. \tag{9}$$

We will use in calculations the following parameters of an industrial laser of the first type (Table 1): $L_a = 150$ cm, $R_s = 0.995$, $R_p = 0.993$, $L = 1800$ cm, $r = 0.13$, and $\Delta\nu_0 = 250$ MHz. Even for highly reflecting dihedral reflectors used in the calculation and in the case of the maximum possible polarisation anisotropy of the gain, we obtain for the CO_2 laser of this type that $\Delta g_{\max} < \Delta\beta$. Therefore, the main factor affecting the polarisation state is the polarisation anisotropy of absorption on the optical surfaces of dihedral reflectors, which leads to the generation of the s-polarised light wave with minimal losses, in which the electric field oscillates parallel to the edges of dihedral reflectors. This explains the stable linear s-polarisation of radiation of industrial CO_2 lasers of the first type.

Unlike transverse-flow industrial CO_2 lasers, in which the conditions appear that provide the fulfilment of the equality $\Delta\beta = \Delta g$, and, hence, lead to the appearance of polarisation instability, in particular bifurcations [4], this does not occur in lasers of the first type. This is explained by reflections at a comparatively large angle (45°) in dihedral reflectors, at which the difference $\Delta\beta$ of losses increases, and also by the large resonator length resulting in a decrease in the frequency interval between axial modes.

Let us analyse now the polarisation properties of CO_2 lasers of the second type. The main feature of these lasers is crossed dihedral reflectors in the resonator, which produce the rotation of the field. It is known that a polarisation mode, in the general case, with elliptic polarisation is established in such resonators even in the absence of losses [12]. In other words, the rotation of the field itself and the phase shift during the reflection of the s- and p-components of the electric vector become key factors forming the polarisation state.

In the resonator under study, all reflecting optical elements only transform polarisation, but do not violate it, i.e., for example, scattering elements are absent. Therefore, the polarisation state can be determined using the formalism of Jones matrices [13].

Let us first consider for clarity the case of three GDTs. Then, one can readily see that the matrix of the round trip of radiation in the resonator has the form

$$T = DB(AB)D(BA)^2, \tag{10}$$

where A is the rotation matrix; B is the matrix of reflection from the two mirror surfaces of the dihedral reflector; and D is the matrix of reflection from a plane mirror:

$$A = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix},$$

$$B = \begin{pmatrix} R_{\rm p}^{1/2} & 0 \\ 0 & R_{\rm p}^{1/2}\exp(-2{\rm i}\Delta\varphi) \end{pmatrix},$$

$$D = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

In the case of four tubes, the matrix of the round trip of radiation in the resonator takes the form

$$T = DB(AB)^2AD(BA)^3. \tag{11}$$

Expressions (10) and (11) can be readily generalised to the cases of odd and even numbers of tubes:

$$T = DB(AB)^{N-2}D(BA)^{N-1}, \ N \text{ is an odd number,}$$

$$\tag{12}$$

$$T = DB(AB)^{N-2}AD(BA)^{N-1}, \ N \text{ is an even number.}$$

The polarisation mode should satisfy the matrix equation

$$T\begin{bmatrix} e_{\rm p} \\ e_{\rm s} \end{bmatrix} = \lambda \begin{bmatrix} e_{\rm p} \\ e_{\rm s} \end{bmatrix}. \tag{13}$$

Let us denote the eigenvalues of this equation as λ_i ($i = 1, 2$), $1 - \lambda_i$ characterising the losses for each of the polarisation eigenstates. For $N = 20$, we found numerically the solutions for different phase shifts $\Delta\varphi$ using a PC.

Our calculations showed that the output radiation had elliptic polarisation, but with a strongly prolate ellipse (the ratio of the major and minor axes of the ellipse was 100/1). Such polarisation can be considered almost linear. Figure 4 shows the calculated dependence of the optical rotation angle on the phase shift $\Delta\varphi$. Thus, for the phase shift $\Delta\varphi = 7°$, which was used in experiments (Table 2), we obtain from Fig. 4 the optical rotation angle $\Theta = 20°$, in good agreement with the experimental value $\sim 23°$. Our calculations also agree with the optical rotation angle observed during operation of the laser for a long time, when the phase shift increased from the initial value 7° to $\sim 10°$ because of the ageing of the resonator mirrors. This resulted in the increase of the angle Θ up to $\sim 30°$ (Fig. 4).

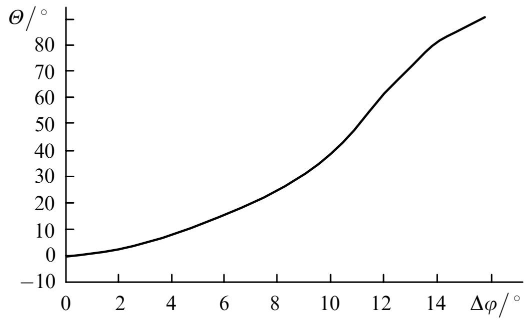

Figure 4. Calculated dependence of the optical rotation angle Θ on the phase shift $\Delta\varphi$ appearing after reflection of light from deflecting mirrors.

Figure 5 shows the losses γ after the round trip of two polarisation modes with mutually perpendicular directions of oscillations of the electric field in the resonator as functions of the phase shift $\Delta\varphi$. One can see that one polarisation state with lower losses is realised in a broad range of the values of $\Delta\varphi$. In this case, the polarisation anisotropy of the gain, i.e., the second of the three factors indicated above, can be neglected. However, there exist small intervals of $\Delta\varphi$ where the losses for the two polarisation states differ only slightly from each other. Near the values of $\Delta\varphi$ at which the two loss curves are intersected, polarisation instability can develop, when weak perturbations of the optical length of the resonator caused by the polarisation anisotropy of the gain can lead to switchings from one polarisation state to another, with the major axis of the ellipse turned by π/2.

It is important to note that the polarisation instability can have the bifurcation nature, appearing due to the photoinduced heat release according to the scheme [14, 15]

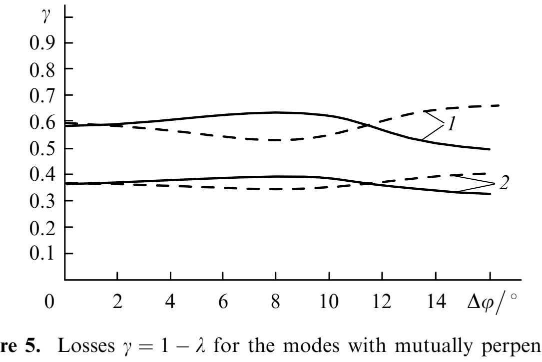

Figure 5. Losses $\gamma = 1 - \lambda$ for the modes with mutually perpendicular directions of polarisation appearing after the round trip of radiation in the resonator calculated as a function of the phase shift $\Delta\varphi$ produced upon reflection of radiation from deflecting mirrors with the reflection coefficients $R_{\rm s} = 0.992$, $R_{\rm p} = 0.985$ (*1*) and $R_{\rm s} = 0.995$, $R_{\rm p} = 0.993$ (*2*).

$$\delta I\uparrow\rightarrow\delta Q\uparrow\rightarrow\delta T\uparrow\rightarrow\delta\rho\downarrow\rightarrow\delta n\downarrow\rightarrow\delta L_{\mathrm{on}}\downarrow\rightarrow\delta(\alpha_{\mathrm{s}}-\alpha_{\mathrm{p}})\uparrow,$$

where the variations in the radiation intensity, heat release in an active medium, temperature, density, refractive index, the resonator optical length, and the difference between the gains for the s- and p-components of polarisation are presented.

When highly reflecting mirrors with the small phase shift $\Delta\varphi = 0.3^{\circ}$ are used in the experiment (Table 2), the difference of losses for the s- and p-polarised modes becomes very small, as follows from our calculations (Fig. 5), thereby producing the conditions for random switching between polarisation states.

Unlike CO_2 lasers with the circular arrangement, no rotation of the field occurs in lasers of the third type, and polarisation is formed almost under the same conditions as in lasers of the first type. In this case, laser radiation has stable linear polarisation with the rotation angle comparable to the angle of incidence of the laser beam on the dihedral reflector (Fig. 3).

4. Conclusions

The radiation of high-power, diffusion-cooled industrial CO_2 lasers can be either linearly s-polarised or elliptic, depending on the spatial arrangement of GDTs. For certain phase shifts between the s- and p-components of polarisation and reflection from the mirrors with protecting reflecting coatings, unstable polarisation is observed in multitubular CO_2 lasers with the spatial arrangement of the tubes on the surface of a cylinder with crossed dihedral reflectors. In the latter case, random switchings of the polarisation state are caused by the loss degeneracy of the two polarisation modes. In this case, the polarisation anisotropy of the gain can appear.

By controlling the phase shift and the parameters of a CO_2 laser in an appropriate way, the laser radiation with stable polarisation can be obtained, which can be conveniently converted with the help of phase-rotating mirrors to the polarisation state required for a particular technological operation.

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