Journal of Physics D Applied Physics 32, (1999), p. 2871-2875.

Generation of high power radially polarized beam

A.V. Nesterov, V.G. Niziev, V.P. Yakunin
Institute on Laser & Information Technologies of Russian Academy of Sciences,
Shatura 140700 Russia

Abstract Radially polarized radiation was first obtained in an industrial high-power CO_2-laser. Special reflective elements with axial polarization selectivity 22% were used as total mirrors in the laser. The output radiation consisted mainly of an unpolarized mode TEM_{00} and a radially polarized mode R-TEM_{01*}. The degree of polarization of the beam measured in the far field was about 50%.

1. Introduction

The radiation of the modern gas lasers has homogeneous polarization, i.e. ellipsometrical parameters over the cross-section of the laser beam are constant. As a rule, the element determining the direction of plane polarization is placed inside the laser resonator. This can be the Brewster window in the low-power lasers or one or several turning mirrors in the high-power lasers.

The modes with inhomogeneous polarization in laser resonators are known [1]. The modes with the radial and azimuthal types of polarization look the most interesting for applications. In such fields like holography, interferometry, spectroscopy, photochemistry and acceleration technique it is often desirable to apply a laser beam with the parameters that are axially symmetrical, including polarization.

In particular, the laser beam polarized in the radial direction can be useful for laser cutting metals, in which the maximum absorption of radiation by the processed surface is necessary [2]. The azimuthally polarized beam shows minimum losses passing through the circular hollow metallic waveguide [3].

There exist two basic methods for generating radiation with axially symmetrical polarization. The first method consists in creating the axial symmetry of active medium. For example, laser modes with radial or azimuthal polarization were obtained in the solid state laser [4,5]. These modes appeared because of double refraction in the crystal at axially symmetrical optical pumping of the active element and intensive heat removal from its surface.

The second method consists in using axially symmetrical optical elements with polarization selectivity inside the resonator. It can be, for example, a conical Brewster window [6] or a conical reflector used as total mirrors of the resonator. Both the solutions are technically complicated. The above-sited optical elements exhibit low polarization selectivity and other disadvantages.

The other possibility of producing an axially polarized beam is offered and realized in the present study. This possibility is based on using a polarization-selective diffraction element with axially symmetrical groove structure inside the resonator. Such elements could be used for generating radially or azimuthally polarized beams, depending on the groove structure on the working surface of the element. Besides, the shape of the element and its location inside the resonator do not present additional technical difficulties in its use in comparison with the conical Brewster window or the conical reflector. This method can be applied to high power gas lasers and, therefore, promote the use of beams having these types of polarization.

In the study [7], diffraction gratings with polarization selectivity were used for fixing a direction of plane polarization. A metallic diffraction grating with a groove spacing 12 μm was installed in the resonator of the industrial CO_2-laser. The radiation was incident upon the grating at a zero angle. The degree of polarization 98.5% was achieved for maximum output radiation 2.3 kW.

Journal of Physics D Applied Physics 32, (1999), p. 2871-2875.

All the below discussed aspects concerning generation of radially polarized radiation (degree of polarization, mode structure, etc.) equally relate to the case of generating azimuthally polarized beams.

2. Experimental setup

The experiments for generating radially polarized beam were carried out on an industrial CW CO_2-laser with transverse gas flow and transverse discharge. The length of the resonator is 8 m, one mirror is flat, the radius of curvature of the second mirror is 30 m, diameter of the beam is 35 mm, the Fresnel number is 15. The laser equipped with conventional mirrors generates multi-mode radiation with the output power 2.5 kW and divergence 3.3 mrad. The scheme of the measurements is shown in figure 1. A special diffraction element providing maximum quality of resonator for radially polarized modes was installed instead of a conventional total mirror. The radiation was incident upon turning mirrors in the resonator at the angle less than 1^o, therefore they did not influence polarization of the radiation. The output mirror was made from ZnSe. The output radiation was divided by a diffraction beam splitter forming two beams. The main beam was directed on the cooled absorber. The second beam carrying 0.1% of laser radiation output power was directed into the measuring system. Passing through the polarizer, the second beam was focused on the camera of Mode Analyze Computer (MAC-2) which measures intensity distribution over cross-section of the beam. The degree of polarization was estimated using intensity distributions at different angles of the polarizer axis. The intensity distribution was measured in far and near fields.

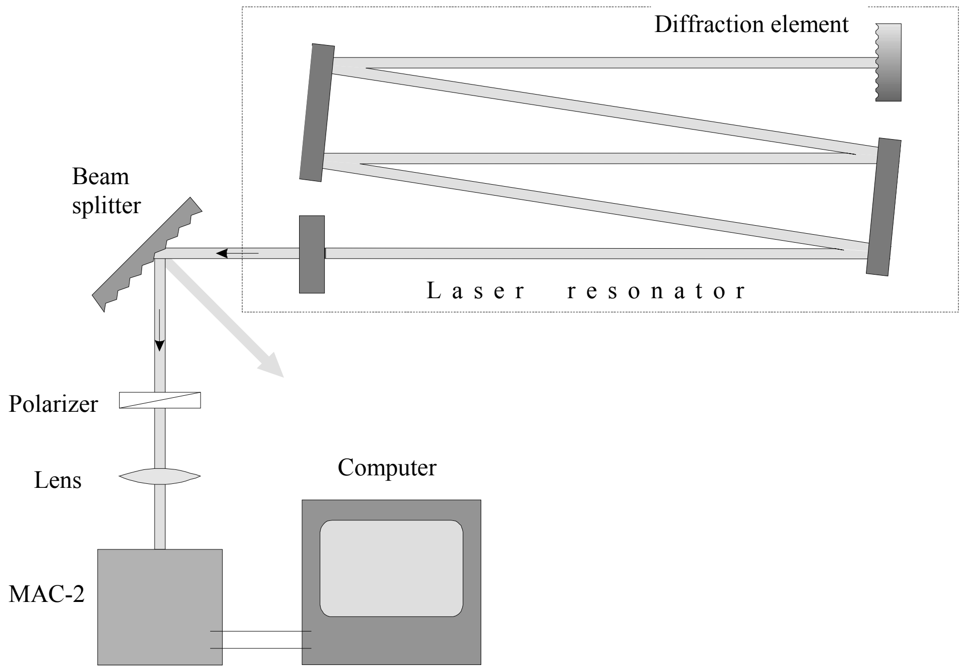


Fig.1. The optical scheme of the experimental setup.

3. Diffraction element of laser resonator

Special diffraction elements with polarization selectivity were used as total mirrors for generating the beam with radial or azimuthal polarization (figure 2a,b).The grooves on the surface of these elements had the form of lines along the radius (R-element) or of concentric circumferences (A-element).

The structure of the elements is shown in figure 2c. The adhesion Ti-layer 0.2 μm and Cu-layer 0.65 μm were deposited on the silicon flat substrate with diameter 50 mm and thickness 10 μm. The relief was fabricated using photolithography and chemical etching and covered by protection layer 0.4 μm.

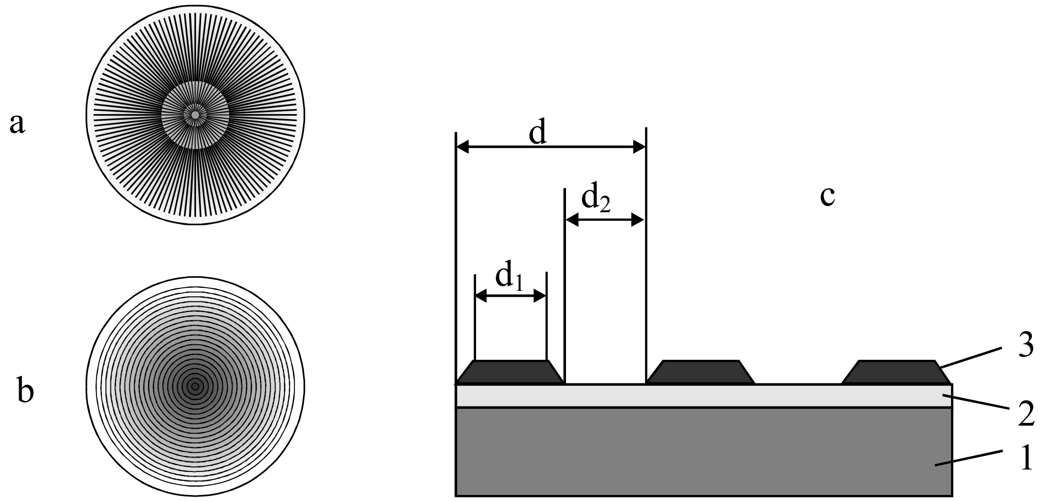


Fig.2. The structure of grooves of the optical elements for generating radially (a) and azimuthally (b) polarized radiation. The structure of the optical element (c): silicon substrate 1, adhesion Ti-layer 2, relief Cu-layer 3.

The design parameters of the grating measured with profilemeter Talystep with precision up to 0.2μm were the following: h=0.65 μm, d=12 μm, d_1=5.2 μm, d_2=4.8 μm. The local reflectivities for radially directed electrical vector k_r and for azimuthally directed electrical vector k_φ measured by ellipsometer were 94% and 72% correspondingly.

4. Experimental results

Radiation of the CO_2-laser used without the diffraction element was unpolarized. The laser with the diffraction element generated mainly radially polarized radiation with output power up to 1.8 kW. The degree of polarization of beams with axial polarization is given by:

$$P(r) = (I_r - I_\varphi) / (I_r + I_\varphi) \qquad (1)$$

where I_r, I_φ are intensities of radial and azimuthal electric field components.
The quantities I_r and I_2 were measured with MAC-2. The typical picture of intensity distribution over the cross-section of the beam transmitted through the polarizer is presented in figure 3. Location of two spots on the axis of rotating polarizer evidenced the fact that the beam had mainly radial polarization (figure 4). The dependence of degree of polarization in the far field upon the radius calculated by formula (1) is illustrated in figure 5.

The analysis of the transverse structure of the beam showed that the intensity distribution over the cross-section is well approximated by the sum of two modes TEM_{00} and TEM_{01*} (figure 3a). The main mode is completely unpolarized, i.e. electrical vector has an accidental direction at every instant of time.

5. Discussion

The tasks of generating radially and linearly polarized beams differ substantially. Laser modes described in the framework of the scalar theory [1] have linear polarization. The direction of polarization may be accidental or determined by optical elements with polarization selectivity inside the resonator. It is known, that elements with very low polarization selectivity can provide the fixed direction of plane polarization. They often use conventional turning mirrors inside the resonator at the angle 45° for this purpose. The polarization selectivity of this element is less than 1%.

Journal of Physics D Applied Physics 32, (1999), p. 2871-2875.

While generating radially polarized radiation it is important to realize that not all the modes can have radial polarization. For example, the radially polarized mode TEM_{01*} results from superposition of plane polarized modes TEM_{01} if their planes of polarization are perpendicular and phase shift equals zero [1]. By analogy, there is the possibility of obtaining axially polarized modes TEM_{p1*}. Thus the general problem consist in selecting transverse modes with radial polarization.

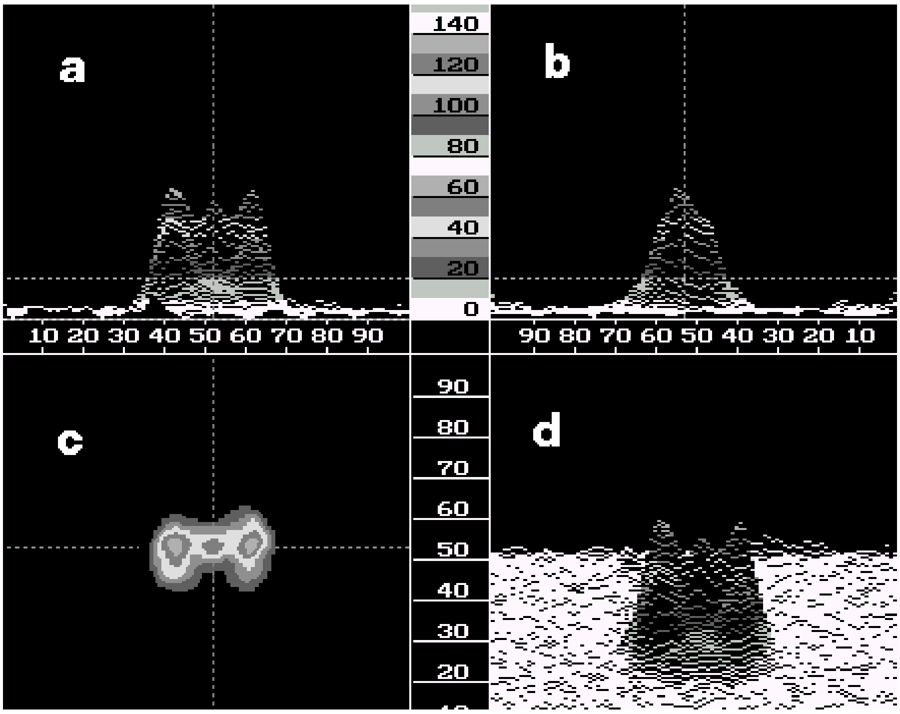


Fig.3. A typical picture of intensity distribution of the laser beam transmitted through the polarizer obtained with MAC-2. The axis of the polarizer is directed a flat in the picture c.

For convenience, let us supplement the letters corresponding to the types of polarization to the system of mode designation: L - linear, C - circular, R - radial, A - azimuthal. So the designation R-TEM_{01*} denotes "radially polarized mode TEM_{01*}".

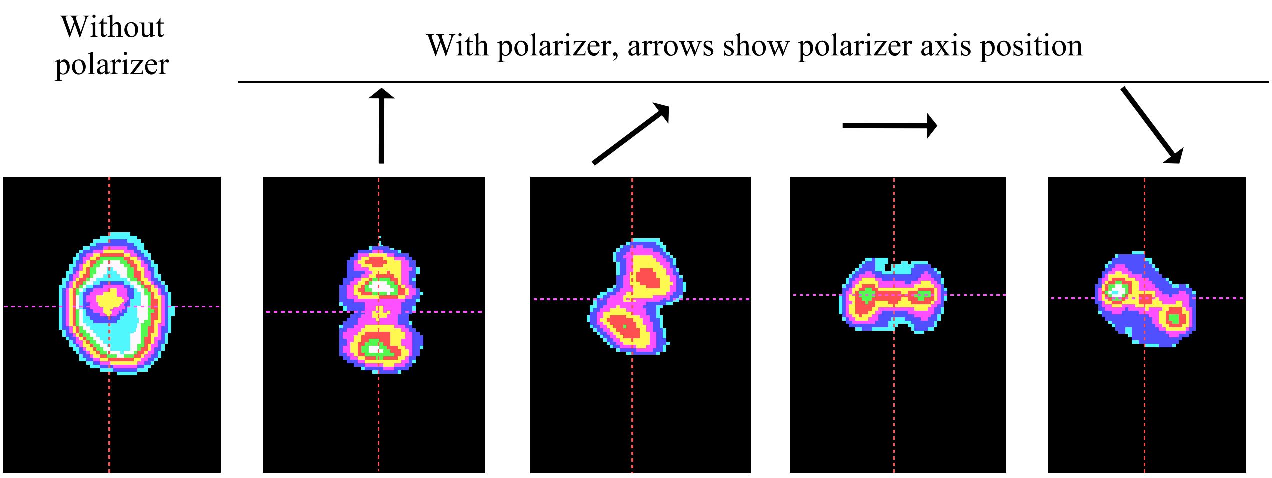


Fig.4. Diagnostics of an radially polarized beam. The arrow shows positions of the polarizer axis.

The substantial differences in the structure of the modes L-TEM_{01*} and R-TEM_{01*} are shown in Fig. 6. The oscillation phase of the mode R-TEM_{01*} is constant over the cross-section of the beam. The mode L-TEM_{01*} is spiral [8]: its local oscillation phase is equal to the azimuthal angle. This means that two spots of the mode L-TEM_{01} retaining the direction of polarization rotate with the frequency of radiation. Selecting this mode is a difficult physical task. There is no reason for generating this very mode in the lasers which have no elements providing the selection of mutual mode orientation and their appropriate phase shift. The superposition of two modes L-TEM_{01} with any phase shift can not give instantaneous ring intensity distribution. The designation TEM_{01*} used for the modes generated in such lasers has another meaning. The TEM_{01*} has "doughnut" like intensity distribution resulting from time-averaged generating modes L-TEM_{01} with an arbitrary angle of orientation and an arbitrary phase.

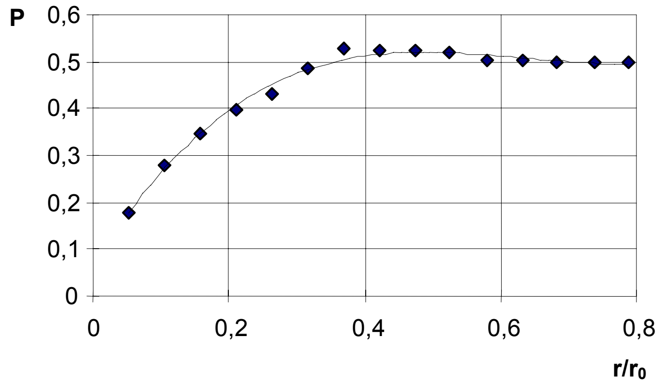


Fig.5. Dependence of the degree of polarization in far field upon radius (r_0 - the size of the beam)

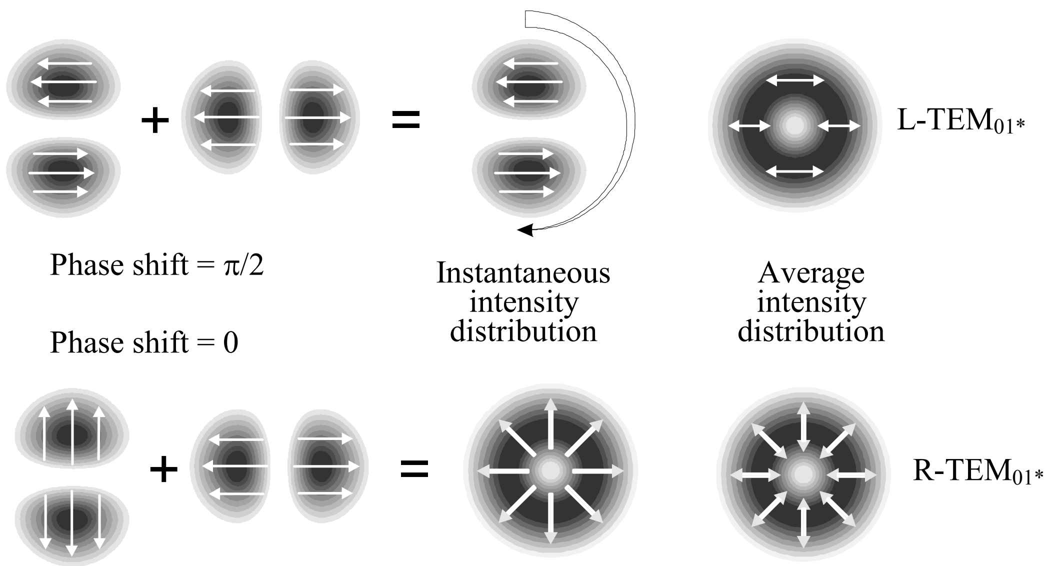
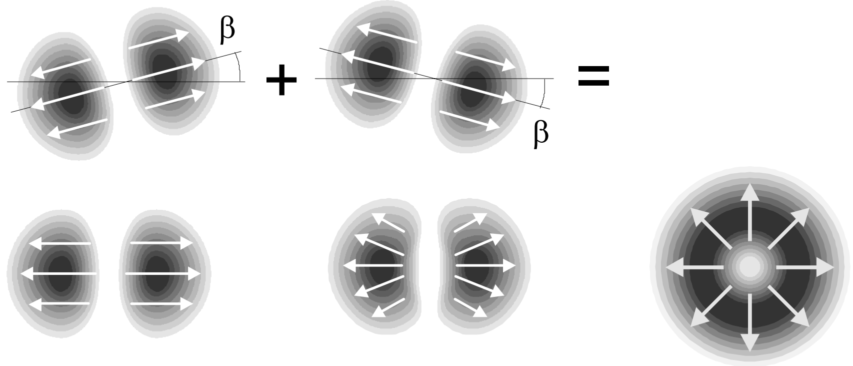


Fig.6. Formation of the radially and linearly polarized modes with ring intensity distribution.

As indicated above, the mode R- TEM_{01*} consists of two L- TEM_{01} with the appropriate mutual orientation and the appropriate phase shift. This mode can be generated by using an optical element providing minimum losses for radially polarized radiation. It is natural that the mode and phase selectivity of such an element depends upon its polarization selectivity and the groove structure.

Modes L-TEM_{pq} have the same losses on the R- or A-elements. Total reflectivity of the mode L-TEM_{pq} on the R-element is calculated by the formula:



Journal of Physics D Applied Physics 32, (1999), p. 2871-2875.

β=0°　　　　　　　　β=30°　　　　　　　　β=45°

Fig.7. Superposition of two plane polarized modes TEM_{01} with the angle shift 2β.

$$k = \frac{\int_0^{2\pi}\int_0^{\infty} \left|E_{pq}(r,\varphi)\right|^2 \cdot (k_r \cdot \cos^2(\gamma-\varphi) + (k_\varphi \cdot \sin^2(\gamma-\varphi) \cdot dr \cdot d\varphi}{\int_0^{2\pi}\int_0^{\infty} \left|E_{pq}(r,\varphi)\right|^2 \cdot dr \cdot d\varphi} \tag{2}$$

The table contains the results of calculating losses of the mode L-TEM_{pq} 1-k on the R-element with local polarization selectivity 100% (k_r=1, k_φ=0).

Table 1. Calculated losses of the mode L-TEM_{pq} on the R-element.

L-TEM_{p0}, p≥0	L-TEM_{p1}, p≥0	L-TEM_{pq}, p≥0, q≥2
50% not depending upon orientation of electrical vector	25%-75% depending upon orientation of electrical vector	50% not depending upon orientation of electrical vector

In accordance with the parameters of tested diffraction elements the calculated reflectivity of the main mode was 83.5%. Taking into account that the reflectivity of the main mode is rather high it is impossible to speak about fully suppression of this mode.

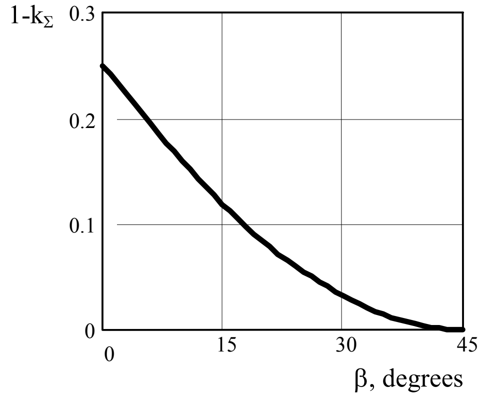


Fig.8. Dependence of losses of the "compound" mode TEM_{01*} formed by two plane polarized modes TEM01 with the angle shift 2β.

According to the results presented in the table, the modes L-TEM_{p1} when polarized as indicated in figure 7 have minimum losses (25%) on R-element.

It is interesting to calculate the losses of "compound" modes on R-elements. Such modes result from superposition of two modes L-TEM_{p1} with amplitudes E'_{p1}, E''_{p1} and the polarization direction as shown in figure 7:

$$E'_{p1}(r,\varphi) = E(r) \cdot \cos(\varphi-\beta),$$
$$E''_{p1}(r,\varphi) = E(r) \cdot \cos(\varphi+\beta), \tag{3}$$

where

$$E(r) = E_0 \cdot \sqrt{2} \cdot r \cdot L_p^1(2 \cdot r^2) \cdot \exp(-r^2),$$

$$L_p^1(x) = \sum_{\nu=0}^{p} \frac{(p+1)!}{(\nu-1)! \cdot (p-\nu)!} \cdot \frac{(-x)^\nu}{\nu!}.$$

The angle 2β in (2) determines the mutual orientation of two modes TEM_{p1}. We omit index p1 in the radial field component E(r) for simplification. An absolute value of electric field of "compound" mode E_Σ depending upon radius r, azimuthal angle φ and angle β is given by the formula:

$$|E_\Sigma|^2 = 4 \cdot E(r)^2 \cdot (\sin^2\varphi \cdot \sin^4\beta + \cos^2\varphi \cdot \cos^4\beta) \quad (4)$$

An angle γ(φ,β) between the electrical field direction and the x direction is defined by the equation:

$$tg\gamma = tg\varphi \cdot tg^2\beta \quad (5)$$

The total reflectivity for the "compound" mode k_Σ with an arbitrary angle β is defined by the expression (2) with E_Σ and γ(φ,β) instead of $E_{pq}(r,\varphi)$ and γ:

The calculated losses $1-k_\Sigma$ when $k_r=1$ and $k_\varphi=0$ are presented in figure 8. There results specify the selectivity of the R-element for "compound" modes. This losses are minimum when $2\beta=90^o$.

It can be shown that "compound" modes (figure 7) at any angle β are self similar solutions of the vector wave equation and such modes can be obtained in open laser resonators.

In our laser there are selected directions determined by the gas flow and the anode-cathode geometry. In the experiments the mode R-TEM_{01*} had no ideal ring intensity distribution over cross-section of the beam. The intensity distribution was attenuated in the direction that is perpendicular to the gas flow direction. As for axial gas flow lasers with high axial symmetry, the task of generating R-TEM_{01*} modes seems to be less complicated.

One can state that increasing polarization selectivity of the element leads to reduction of the number of transverse modes in the output radiation. In our experiments the mode structure was practically reduced to two modes: an unpolarized TEM_{00} and a radially polarized TEM_{01*}. Divergence of radiation decreased from 3.3 mrad to 2.2 mrad.

The superposition of two modes TEM_{00} and R-TEM_{01*} according to the well known formulae [1] with the same parameter w_0 (w_0 is the geometrical size of the Gauss beam waist cross-section) do not give the intensity distribution with three peaks, obtained experimentally (figure 3a). This fact can be explained in the following way. The plane polarized mode TEM_{00} reflected on R-element has minimum losses in the direction of electrical vector oscillation and maximum losses in the perpendicular direction. This results in deformation of intensity distribution. The mode TEM_{00} shrinks in the direction that is perpendicular to electrical vector. Such a deformed mode has an arbitrary orientation at every moment of time. Time-averaged intensity distribution of the deformed modes with different orientations turns out to be more narrow in comparison with the intensity distribution of the classical mode. The above mentioned three-peak intensity distribution can be obtained analytically provided that the modes TEM_{00} and R-TEM_{01*} have different parameters w_0.

6. Conclusion

Journal of Physics D Applied Physics 32, (1999), p. 2871-2875.

Radially polarized radiation with output power 1.8 kW was obtained in industrial CO_2-laser. Special reflective diffraction elements for generating radially or azimuthally polarized laser beam were fabricated and tested. Their polarization selectivity is 22%. They were used as total mirrors in the laser. The number of transverse modes was reduced. The output radiation mainly consisted of an unpolarized mode TEM_{00} and a radially polarized mode TEM_{01*}. The degree of polarization of the beam measured in the far field was about 50%. Laser beams with axially symmetrical polarization can find a wide application.

Acknowledgment

The authors are grateful to A.A. Goncharsky, V.N. Glebov, L.V. Novikova for valuable assistance.

REFERENCES

1. Pressley R.J. (ed) 1971 *Handbook of Laser with Selected Data on Optical Technology* (Cleveland: Chemical Rubber Company)
2. Niziev V.G., Nesterov A.V. 1999 Influence of beam polarization on laser cutting efficiency. *J. Phys. D: Appl. Phys*, **32** (in press).
3. Power H.O., Gehringer E. 1992 Flexible hollow wavequides for CO_2-laser radiation *Laser Material Processing ICALEO, Orlando, Florida* 1992, *Proc. SPIE* **1990** 21-9
4. Vinokurov G.N., Mak A.A., Mitkin V.M. 1974 Generating azimuthal and radial modes in optical resonators. *Kvantovaja electronika* **8** 1890-1 (in Russian)
5. Pohl D. 1972 Operation of a ruby laser in the purely transverse electric mode. *Appl. Phys. Letters* **20** 266-7
6. Chen-Ching Shih, Palos Verdes Estates, Calif 1994 Radial Polarization Laser Resonator *United States Patent* #5,359,622
7. Jakunin V., Balykina E., Manankova G., Novikova L., Seminogov V. 1998 Diffraction polarizing mirror for resonators of high power CO_2-lasers. *Proc. of the VIth International conference «Laser Technology '98» (ILLA'98)*, Shatura: NICTL-RAN, p. 60. (in Russian).
8. Arsenyan T., Fedotov N., Korniemko L. et al. 1995 Laser beams with helical wavefront dislocations and their applications in the diagnostically and meteorological systems. *Proc. SPIE* **2713** 453-60.