Optica Applicata, Vol. XXVI, No. 2, 1996

Shaping of laser diode beams for end pumped lasers

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Methods of laser beam transformations in optical systems are reviewed. Quasi-geometrical approach for highly divergent astigmatic laser beam transformation in real optical systems is presented. The appropriate software intended for evaluation of laser beam propagation in real optical systems has been developed. The criteria of laser optics quality based on the concept of M^2 parameter are proposed and discussed. The scope of the present work focuses on laser diode optics intended for end pumped solid state lasers. Classification of such optical systems is proposed. The examples of three practically verified systems to be used in three different types of laser diodes are presented.

1. Introduction

Impressive progress in diode pumped lasers, observed in the last 10 years, was possible due to development of efficient laser diode arrays, as well as methods of shaping their radiation. Performance of diode pumped lasers significantly depends on the quality of pump beam. Although the requirements on pump sources for such lasers were formulated a few years ago [1]–[3], the problem of shaping such highly divergent, astigmatic light sources is not trivial and is a subject of extensive research nowadays. A review of the methods of laser beam transformation in paraxial framework is presented in Section 2. In Section 3, a quasi-geometrical approach not restricted to paraxial approximation is developed, including quality evaluation criteria for laser optics schemes. Classification of laser diode beam shaping systems is proposed and some more interesting systems of laser diode optics are described in the next section. Results of practical verification of three laser diode shaping systems worked out at the Institute of Optoelectronics for end pumped lasers are presented in the last part of the paper.

2. Paraxial *ABCD* matrix method

Since the birth of laser the geometrical optics and paraxial wave methods in propagation of laser beam have been developed in several works [4]–[14]. The majority of works were devoted to exploration of the circular or astigmatic Gaussian beams in paraxial approach, although several works concerned the beams beyond paraxial limit (see, *e.g.*, [15]–[17]). The same well-known *ABCD* law introduced by Kogelnik in [5] can be applied in geometrical and paraxial wave approaches.

To describe the amplitude and phase distributions of multimode beam several approaches have been developed. The most widespread method based on the decomposition of beam into the orthogonal basis of Laguerre–Gaussian or Hermite–Gaussian beams was developed and used with success in many practical applications (see, *e.g.*, [5], [8], [9], [18], [19]).

On the other hand, a new theory of partial coherence based on the cross spectral density function was developed by WOLF [20]–[22]. This theory can also be applied to the multimode beams (see, *e.g.*, [23]–[27]). SIMON *et al.* [23] derived the generalised *ABCD* law which describes the propagation of general partially coherent beam in the *ABCD* system. One of the forms of the generalised *ABCD* law is as follows:

$$\begin{aligned} \langle x'^2\rangle &= A_x^2\langle x^2\rangle + 2A_xB_x\langle xp_x\rangle + B_x^2\langle p_x^2\rangle, \\ \langle p_x'^2\rangle &= C_x^2\langle x^2\rangle + 2C_xD_x\langle xp_x\rangle + D_x^2\langle p_x^2\rangle, \\ \langle x'p_x'\rangle &= A_xC_x\langle x^2\rangle + (A_xD_x+B_xC_x)\langle xp_x\rangle + B_xD_x\langle p_x^2\rangle \end{aligned} \tag{1}$$

where x, x' – locations in input and output planes, respectively, p_x, p_x' – angles, A_x, B_x, C_x, D_x – parameters of transfer matrix in the x-plane, and $\langle\ \rangle$ denote weighted averages, second or mixed central moments of intensity distributions in a given plane. The same law may be written in the y-plane of the system. To determine the waist location we have to find the plane where the mixed moments vanish. The condition of waist location in the output plane, assuming that the waist is also located in the input plane, is as follows:

$$Z_{R,x}^2 = \frac{\langle x^2\rangle}{\langle p^2\rangle} = -\frac{B_xD_x}{A_xC_x} \tag{2}$$

where $Z_{R,x}$ denotes the Rayleigh range of input beam defined in x-plane. For y-plane due to different Rayleigh ranges or input waist locations, the output waist can be placed in another location. Thus, we obtain the transformation law of generally astigmatic, multimode beam in the first order, asymmetric systems. It can be shown that the product of variances of x given in the waist and p_x is an invariant of beam transformation in the first order, aberration-free systems. Such a product can be expressed in terms of M^2 parameter introduced by SIEGMANN in [28] as follows:

$$M_m^2 = \sqrt{M_x^2 M_y^2} \tag{3}$$

where:

$$M_x^2 = \frac{4\pi}{\lambda}\sqrt{\langle x^2\rangle\langle p_x^2\rangle}, \quad M_y^2 = \frac{4\pi}{\lambda}\sqrt{\langle y^2\rangle\langle p_y^2\rangle}. \tag{4}$$

The square of parameter M_m^2 is proportional to étendue of the beam. According to fundamental law of geometrical optics, it should be invariant in perfect systems. The aim of this work is to develop a method of analysis which could be applied beyond the paraxial limit for real systems with aberrations, asymmetries, *etc.*, and to analyse the properties of highly divergent, asymmetric beams and arrays of beams generated by medium and high power laser diodes (LD).

3. Quasi-geometrical approach

The genesis of the proposed approach can be found in geometrical construction of Gaussian beam. To describe the propagation of Gaussian beam (see, *e.g.*, [8], [10], [13], [14]) it is sufficient to perform the transformation of one skew ray intersecting the waist plane at the height equal to waist radius and inclined to the meridional plane at the divergence angle. This ray rotated about optical axis in centred optical system draws the hiperboloid of Gaussian beam. In an axially symmetric case, it was proposed (see details in [29]) to construct the one parameter family of entrance skew rays, whose variances of locations and angles are equal to squares of beam radius and divergence, respectively. Each ray is transformed in real optical systems according to rigorous refraction laws. Analysing variances of ray heights one can find beam sizes and waist locations in the image space.

The same idea can be applied to asymmetric beams [30]. However, in this case, a two, three or four parameter family of rays should be defined, so the computation effort is much more extensive. The input beam of ordinary geometrical rays should fill the whole étendue of real beam. After propagating through the optical system the statistical parameters of output beam should be calculated. In this way, we can obtain a computational method of transformation of any beam in any optical system, similar to the paraxial *ABCD* law determined by (1). This approach can be used in many applications, especially for beams with weak spatial coherence. An output of multimode waveguide, a beam generated by vertical cavity surface emitting laser array, an array of high power non-coherently summed beams of CO_2 or Nd:YAG lasers are the typical examples. In this paper, we focus on the beams generated by arrays of edge emitting LD's.

There were carried out the extensive theoretical and experimental investigations of beam parameters generated by LD (see, *e.g.*, [31]–[33]). The parameters of emitting area and divergence angles in both x-parallel to junction and y-perpendicular to junction planes depend mainly on the technology and can vary in the wide range. Although the progress in operational characteristics of LD's is tremendous (see [35]–[38]), the basic geometrical characteristics remain the same. The medium and high power arrays consist of subarrays (see Fig. 1) formed by the spatially coherent elementary emitters distant about 10 μm from each other. The subarray can have 50–200 μm width and the far field divergence angles of about 10 degrees in x-plane and 40 degrees in y-plane. A single mode LD with powers of about few hundreds mW consists of a single elementary emitter. The medium power diodes with powers of up to 3–5 W consist of one (very seldom two) subarray which can be treated as a quasi-continuous linear source of light. High power bars of cw LD's consist of several (10–20) subarrays separated by the distances needed to efficiently remove the heat. The quasi-cw bars, contrary to cw ones, are made of quasi-continuous line of elementary emitters [36].

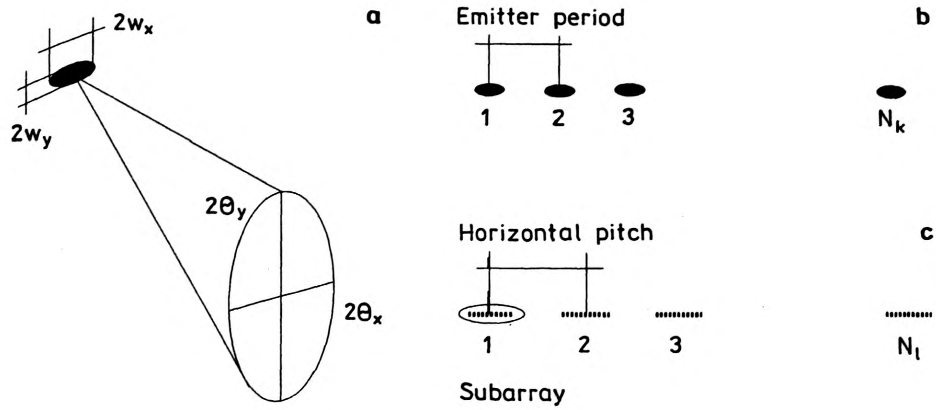

Fig. 1. Geometry of diode array: **a** — elementary emitter, **b** — scheme of subarray, **c** — scheme of bar

In all cases, we analyse the radiation of coherent elementary emitter with about 3 μm × 1 μm emitting area and almost diffraction limited divergence angles. The general condition on the construction of an elementary emitter beam of geometrical rays is to preserve the same waist and divergence statistical estimations as the real beam parameters as follows:

$$
\begin{aligned}
&w_x^2 = \eta\langle x_0^2\rangle_{l,m}, \quad w_y^2 = \eta\langle y_0^2\rangle_{l,m}, \\
&\sin^2\theta_x = \eta\langle p_{x,0}^2\rangle_{l,m}, \quad \sin^2\theta_y = \eta\langle p_{y,0}^2\rangle_{l,m}
\end{aligned}
\tag{5}
$$

where: w_x, w_y denote the half-width of emitter area in x and y directions, respectively, θ_x, θ_y denote the half-angles of divergence, subscript 0 denotes the parameters given in object waist plane, and $\langle\ \rangle_{l,m}$ denote the weighted averages over the two parameter l, m family of elementary emitter beams.

The factor η depends on geometry and intensity distribution, and for Gaussian distribution it is equal to 4. The choice of ray distributions and weighting factors in the elementary emitter beam enables several shapes of intensity distribution to be simulated. The input beam is composed of the incoherent sum of elementary emitter beams $(x, y, p_x, p_y)_{i,k,l,m}$, where index i represents the number of subarray, index k represents the number of consecutive emitter in this subarray. It should be noted that in the beam thus defined there are "empty" places corresponding to not emitting areas of diode array. The effective M_m^2 parameter is the geometrical medium of M^2 parameters of elementary emitter multiplied by the special factor $\Lambda(N_k, N_l)$ depending on array geometry

$$
M_{x,0}^2 = \frac{\pi}{\lambda} w_x \sin\theta_x; \quad M_{y,0}^2 = \frac{\pi}{\lambda} w_y \sin\theta_y; \quad M_{m,0}^2 = \sqrt{\Lambda(N_k, N_l) M_{x,0}^2 M_{y,0}^2}
\tag{6}
$$

where N_l denotes number of subarrays, N_k denotes number of elementary emitters in subarray.

3.1. Beam parameters in the image space

After passing through the optical system we have the 4-parameter bundle of rays $(x', y', p'_x, p'_y, z)_{i,k,l,m}$, where z denotes the plane which is intersected by the ray in the point (x', y'). We have to calculate the second central moments of ray distribution in a given plane. In the case of paraxial approximation, the variances of ray family can be calculated from formulas (1). In general case, we have to calculate ray parameters in image space using rigorous ray transfer procedures (see, *e.g.*, [39]). To determine the divergence in image space we have to calculate the variances of p'_x, p'_y over the whole 4-parameter family of rays as follows:

$$\sin^2\theta'_x = \eta \langle p'^2_x \rangle_{i,k,l,m}, \quad \sin^2\theta'_y = \eta \langle p'^2_y \rangle_{i,k,l,m}. \tag{7}$$

Let us introduce the following parameters describing the beam in image space:

i) Beam radius in x-waist plane w'_x given at z_x-distance to the plane, where the minimum of $\langle x^2 \rangle_{i,k,l,m}$ occurs

$$w'^2_x = \eta \langle x^2 \rangle_{i,k,l,m}. \tag{8a}$$

ii) Beam radius in y-waist plane w'_y given at z_y-distance to the plane, where the minimum of $\langle y^2 \rangle_{i,k,l,m}$ occurs

$$w'^2_x = \eta \langle y^2 \rangle_{i,k,l,m}. \tag{8b}$$

iii) Beam sizes in best focus plane $w_{b,x}, w_{b,y}$ given at z_b-distance to the plane, where the minimum of the product of $\langle x^2 \rangle_{i,k,l,m} \langle y^2 \rangle_{i,k,l,m}$ occurs

$$w^2_{b,x} = \eta \langle x^2 \rangle_{i,k,l,m}; \quad w^2_{b,y} = \eta \langle y^2 \rangle_{i,k,l,m}. \tag{8c}$$

iv) The astigmatism of beam

$$\Delta z = z_x - z_y. \tag{8d}$$

v) Caustics lengths l_x, l_y:

$$l_x = \frac{2w_{b,x}}{\sin\theta'_x}, \quad l_y = \frac{2w_{b,y}}{\sin\theta'_y}. \tag{8e}$$

The M^2 parameters in the image space were defined in the following way:

$$M^2_{x,1} = \frac{\pi}{\lambda} w_{b,x} \sin\theta'_x; \quad M^2_{y,1} = \frac{\pi}{\lambda} w_{b,y} \sin\theta'_y; \quad M^2_{m,1} = \sqrt{M^2_{x,1} M^2_{y,1}}. \tag{9}$$

The caustics volume was defined in the following way:

$$V_{\text{caust}} = \frac{\pi}{3} w_{b,x} w_{b,y} \sqrt{l_x l_y} = \frac{\lambda}{3} l_x l_y M^2_{m,1}. \tag{10}$$

To estimate the quality of transformation there were proposed in [29], [30] the following quality factors:

$$Q_x = \frac{M^2_{x,1}}{M^2_{x,0}}; \quad Q_y = \frac{M^2_{y,1}}{M^2_{y,0}}; \quad Q_m = \sqrt{Q_x Q_y}. \tag{11}$$

From the fundamentals of geometrical optics it can be shown that in lossless systems the Q_m factor should satisfy the following relation:

$$Q_m \geqslant 1. \tag{12}$$

The increase of $M_{m,1}^2$ parameter is mainly caused by aberrations. The divergence angles, beam parameters in the best waist plane, caustics sizes and quality factors can be treated as the elements of a merit function in the process of optimisation of laser beam forming system.

4. Classification of laser diode shaping systems

The three requirements for LD's beam forming optics can be laid down:

a) correction of astigmatism, $z_x = z_y$,
b) equalisation of beam sizes in the waist, $w_{b,x} = w_{b,y}$,
c) equalisation of divergence angles, $\sin\theta'_x = \sin\theta'_y$.

The aim of LD's optics design is to satisfy one, two or three of these requirements, minimising the merit function at the same time. In paraxial, aberration-free systems the $M_{m,l}^2$ parameter is an invariant of transformation. In the framework of paraxial approximation, the equation satisfying these requirements can be derived explicitly from the generalised $ABCD$ law (1). Assuming that the input plane of $ABCD$ system is the waist plane for x- and y-directions, and the system conserves the M^2 parameters in x- and y-plane separately, the equations on matrix elements of optical system were derived as follows:

a) Paraxial conditions on correction of astigmatism

$$A_x C_x \langle x^2 \rangle + B_x D_x \langle p_x^2 \rangle = 0, \tag{13a}$$

$$A_y C_y \langle y^2 \rangle + B_y D_y \langle p_y^2 \rangle = 0. \tag{13b}$$

b) Paraxial condition on equalisation of waist sizes

$$A_x^2 \langle x^2 \rangle + B_x^2 \langle p_x^2 \rangle = A_y^2 \langle y^2 \rangle + B_y^2 \langle p_y^2 \rangle. \tag{14}$$

c) Paraxial condition on equalisation of divergence angles

$$C_x^2 \langle x^2 \rangle + D_x^2 \langle p_x^2 \rangle = C_z^2 \langle y^2 \rangle + D_y^2 \langle p_y^2 \rangle. \tag{15}$$

In the case of single mode beams it is possible to satisfy requirements a), b) and c) simultaneously in lossless, aberration-free optical system. There were developed several optical schemes realising these requirements (see, *e.g.*, [40]–[44]) for single mode LD's. The complex systems with prism or cylindrical lens expanders were typically applied to equalise the divergence angles in both x and y directions [41], [42]. The single cylindrical [43] or GRIN microlens [44] can perform the same task.

The scope of this work is focused on the systems intended to transform beams of multimode LD's. Such systems can be divided into two separate groups:

– classical systems without decreasing the M^2 parameters in x and y planes separately,

– beam equalisers.

The classical systems, in terms of our paper, consist of elements of axial or cylindrical symmetry. The cylindrical elements have to be aligned to x or y directions. Such systems can be analysed separately in each direction in paraxial approach, but when the ray beam is transformed in a real optical system, the influence of aberration disables the use of such a simple method. The optical schemes used for single mode beams can also be applied to the multimode ones. There were made several optical schemes to transform the beams of medium power cw LD's for end pumped lasers. As a rule, the paraxial formulas are satisfactorily fulfilled to define the basic parameters of a system. Moreover, due to high $M^2_{m,1}$ parameter of input beam, these systems need not be well corrected in comparison to the ones intended for single mode beams. Depending on the required caustics length and size, the simple spherical lens followed by cylindrical one is satisfactory. In order to raise the quality, more sophisticated systems should be used. One of such systems is presented in the next section.

The beam equalisers are the optical systems which change the M^2_x to M^2_y ratio to achieve the equal or near equal values of these parameters in both directions. The quality of beam equaliser can be determined by quality factor Q_m. The simplest way to equalise the beam is to use a fiber. The fiber coupled medium power LD's have been commercially available over the last few years, with NA of 0.2–0.4 and core diameters ~100 μm. The output M^2 parameter is almost equal to the M^2_x parameter of the diode, so the quality is not high. It is theoretically possible to achieve the square root of this value. A good deal of effort was directed towards the fiber coupled diode bars (see, *e.g.*, [45]–[48]). The brightness of fiber coupled bar is significantly lower compared to medium power diode beam. Nowadays, there are commercially available [48] fiber coupled bars with over 10 W output power and NA of ~0.2.

It can be shown [49] that the beam equalisation can also be realised in the system consisting of the cascade of cylindrical elements crossed and rotated to x plane at 45 degrees. Diffractive optics elements [50], GRIN microlens array [51], array of rotated microprisms [52] were used in other types of beam equalisers. The most attractive seem to be the beam shaper invented by CLARKSON [53], [54] and the lens duct developed by FEUGNET *et al.* [55] for end pumping of the media of short absorption length (*e.g.* Nd:YVO_4).

5. Examples of end-pumping schemes

There were examined in this work three types of LD beam forming systems designed to shape the radiation of three types of LD's (see Tab. 1 and Figs. 2**a**–**c**). The results of calculations for these systems are presented in Tab. 2 and in the following figures (Figs. 2–5).

In the first system (see Fig. 2**a**), a cylindrical microlens is used to collimate a beam in vertical direction, similarly as SNYDER proposed in [43]. Further, after passing

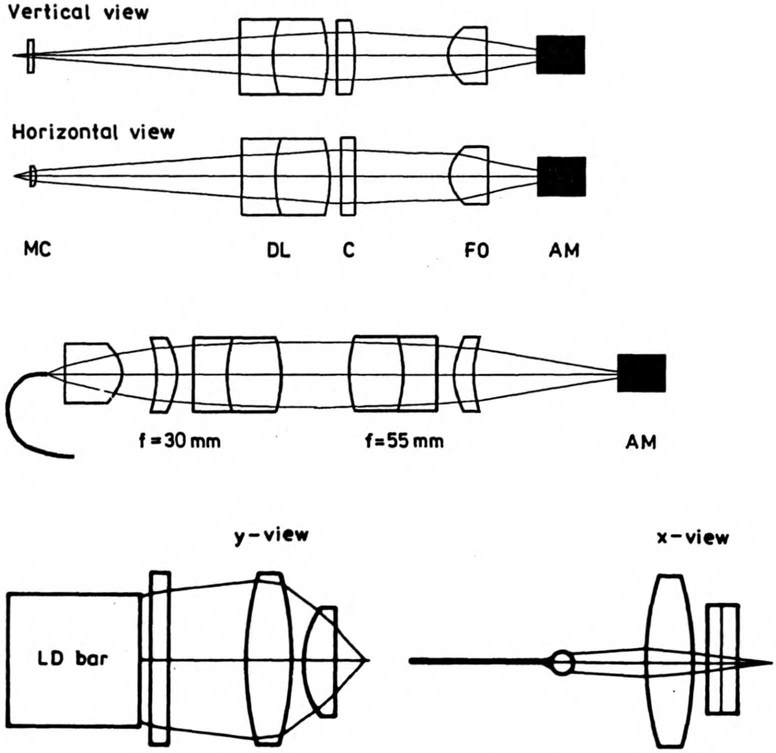

Fig. 2. Schemes of LD beam shaping systems designed for: **a** — 2 W diode with $200\times1\ \mu m^2$ emitting area and $10°\times40°$ divergence, **b** — 10 W fiber coupled bar with 0.4 mm diameter and 0.4 NA, **c** — 100 W quasi-cw bar with 1 cm × 1 μm and $10°\times40°$ divergence

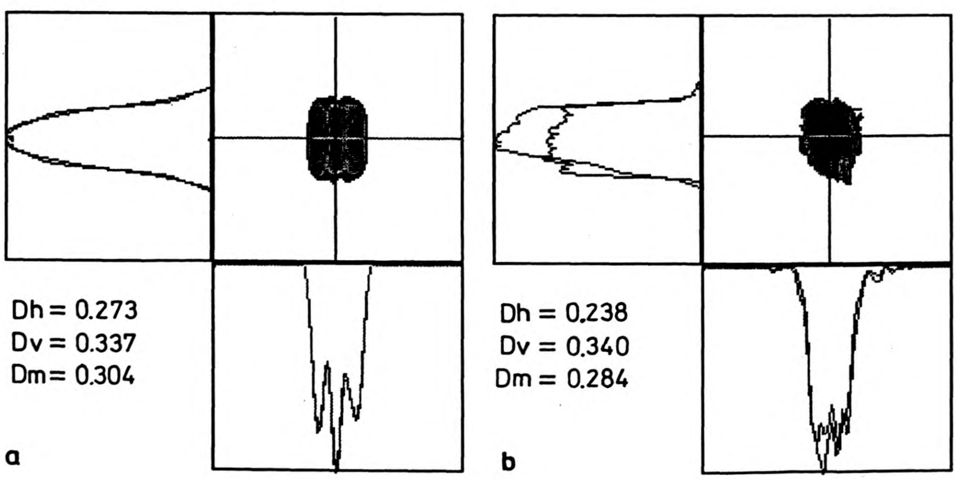

Fig. 3a, b

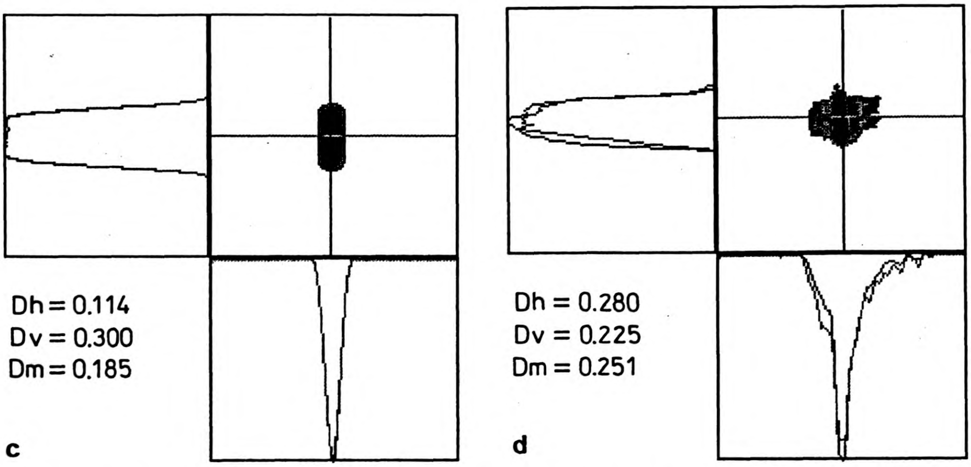

Fig. 3. Intensity distribution of pump volume for pump scheme I: **a** — at a distance of 1.5 mm from the best focus plane — computation, **b** — at a distance of 1.5 mm from the best focus plane — experiment, **c** — at the best focus plane — computation, **d** — at the best focus plane — experiment

Table 1. Parameters of pumping LD's

	LDT 27004	SDL 3450-P5	SDL 2351-A1
Type of LD	cw, array	cw fiber coupled bar	quasi-cw bar
Power [W]	2	10	100
b_x [mm]	0.2	0.4	10
b_y [mm]	0.001	0.4	0.001
θ_x [mrad]	100	400	100
θ_y [mrad]	400	400	400
M_x^2	47	358	2040
M_y^2	1.2	358	1.2
M_m^2	7.5	358	50

Table 2. Parameters of caustics of three LD shaping systems

Name of system	System I, Fig. 2a	System II, Fig. 2b	System II, Fig. 2c
l_x [mm]	1.12	1.6	1.38
l_y [mm]	0.32	1.6	2.52
V_{caust} [mm^3]	0.004	0.377	0.51
Δz [mm]	0	0	2.7
$w_{b,x}$ [mm]	0.14	0.47	0.97
$w_{b,x}$ [mm]	0.05	0.47	0.27
θ_x [mrad]	125	301	777
θ_y [mrad]	152	301	108
M_x^2	67	533	2647
M_y^2	28	533	115
M_m^2	44	533	551
Q_x	1.49	1.49	1.3
Q_y	22.59	1.49	92
Q_m	5.81	1.49	10.9

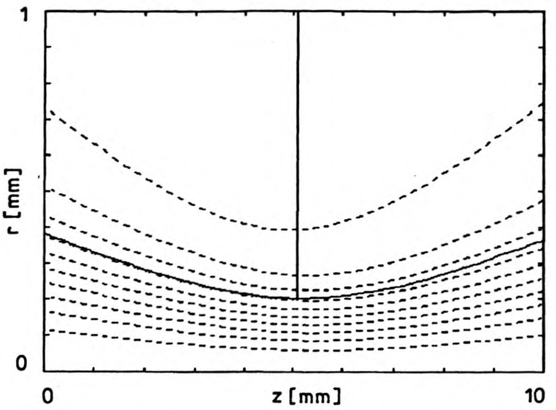

Fig. 4. Caustics plot inside the active medium for pump scheme II — computation

through the collimating doublet and additional correction of the cylinder "square" beam with the size of about 10 mm a distribution is obtained. As a focusing lens it is sufficient to use a singlet with focal length of about 30 mm to obtain beam size in the best focus plane with sizes of about 300×100 μm. Such a system satisfies the condition of equalisation of divergence with about 150 mrad of divergence angles in both directions. Results of experimental verification compared to spot diagrams obtained from calculations are shown in Figs. 3**a**—**d**. Such a pump system was used in several experiments of diode pumped lasers enabling laser operation in fundamental mode despite pump waist asymmetry. The best results were obtained for Nd:YVO_4 with output power of about 0.75 W and optical slope efficiency >50% [56].

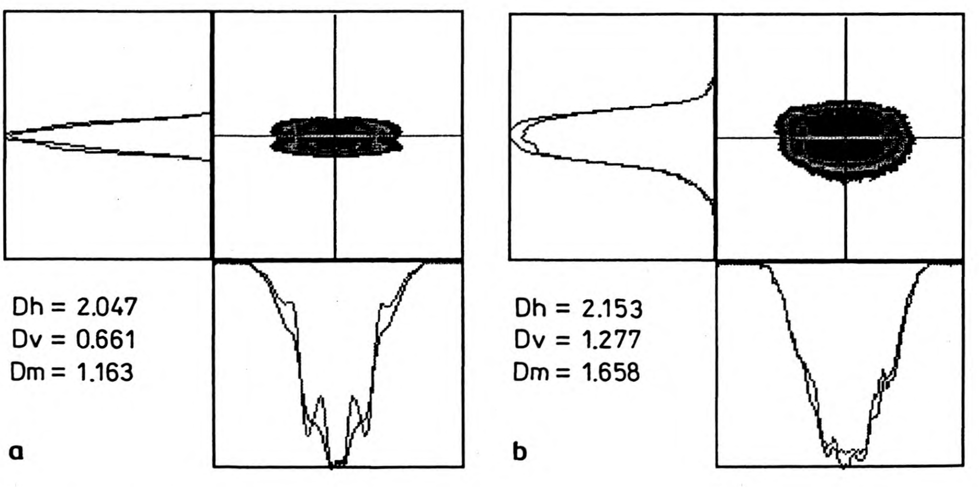

Fig. 5. Intensity distributions of 1 cm LD bar radiation for pump scheme III: **a** — at the best focus plane — computation, **b** — at the best focus plane — experiment

The second system designed for 10 W fiber coupled bar consists of two aberration-free objectives with focal lengths of 30 and 50 mm, respectively. As is shown in Fig. 4 and in Tab. 1, we achieved here the best quality factor and, of course, full equalisation of beam parameters because of axial symmetry of fiber output. Such a pump system was used to pump multimode Nd:YAG laser [57]. The 4.5 W cw output with 53% slope efficiency was obtained which seems to be one of the best results for such type of pumping diode.

The last system consists of a rod lens attached to the diode bar and spherical lens followed by cylindrical one. The results of computation (see Fig. 5**a**) were compared with measured intensity distribution near the waist (see Fig. 5**b**). This system was used in Nd:YVO_4 laser end pumped by 1 cm quasi cw diode bar [58], [59]. The output energy was 5 mJ for 15 mJ of incident pump energy, the optical slope efficiency of laser in free-running mode was 43%. For low and medium pump power the near diffraction limited output was achieved for resonator length of more than 150 mm and medium pump power. For higher powers and shorter resonator the output beam with $M_x^2 \simeq 2$ and $M_y^2 \simeq 1$ was observed.

6. Conclusions

The idea of quasi-geometrical approach to laser diode optics problems was presented. This method was applied to analyse the properties of several laser diode beam forming systems. Several parameters describing caustics sizes and quality of transformation were introduced and applied to analyse and optimise such systems. The software developed enables the analysis of a wide class of systems. The intensity distributions measured in practical models of such systems quantitatively verifies the results of computation. The construction of the pump shaping systems described above made it possible to build efficient diode end pumped lasers.

Acknowledgements — I would like to thank Dr. W. Żendzian and K. Kopczyński for help in investigations of the last two systems. All lenses were manufactured and coated by J. Firak from the Institute of Optoelectronics, Military University of Technology. This work was partly supported by the Polish Committee for Scientific Research (KBN) under the grant T11B00708.

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Received April, 22 1996