Optica Applicata, Vol. XXV, No. 1, 1995

M^2 parameter of multimode laser diode beam transformation in real asymmetric optical systems*

J. JABCZYŃSKI

Institute of Optoelectronics, Military University of Technology, ul. Kaliskiego 2, 01–489 Warszawa, Poland.

Generalization of the M^2 parameter in such a way that it is valid in the case of asymmetric, multimode laser beam and array of laser beams is proposed. The geometrical method of propagation of beams of this type in real asymmetric optical systems, not restricted to paraxial approximation, is presented. The quality of lens design destined for transformation of this type of beam is discussed and the appropriate criterion based on transformation of the M^2 parameter is proposed. The examples of application of this method to the problem of diode laser beam formation are presented and discussed.

1. Introduction

Multimode, asymmetric and astigmatic light beams, generated by laser diodes (LD) and LD arrays, are the subject of this paper. Methods of transformation, collimation and circularization of such beams are of great importance to the increase of the efficiency of several devices as diode pumped solid state lasers, optoelectronic sensors, *etc.* The commercially available edge emitting LD can be divided, with respect to beam propagation parameters, into three groups:

– single multimode diodes up to 3–5 μm long junction,
– multimode stripe 1D linear arrays up to 500 μm long junctions,
– multielement 1D and 2D bars and stacks of arrays with low packing density.

Special means to form a beam are necessary for each group of diodes. The classical elements such as high speed diffraction limited collimators, prism or cylindrical anamorphic expanders, cylindrical or circular micro lenses, GRIN or diffractive optics, *etc.*, (see of *e.g.*, [1]–[4]), are widely known and used mainly for the first group diodes.

The classical elements, arrays of microlenses, binary optic arrays [5], arrays of GRIN lenses [6], bundle of tapered fibres [7] can be used in order to transform the beams of the second and third groups.

As a rule, the efficiency of the optics of such type is not high. For example, as it is presented in [5], a total transmission of diffractive optics system, transforming the beam of the 10 mm aperture 1D laser diode bar into circular shape, is about 25%.

---

* This paper was presented at the International Optical Design Conference in Rochester in June 1994.

The quasi-geometrical approach to the description of propagation of astigmatic beam or arrays of astigmatic beams in classical, real, asymmetric optical systems is presented in this paper. This approach is the generalization of the same method proposed by the author in [8] for an axial symmetric case. In Section 2, the idea of the method is described. The results of calculations for a few practically realized cases of the LD beam transforming optics are presented and discussed in Sect. 3.

2. Method of calculations

Our purpose is to describe the propagation of the array of laser beams, generated by an LD array using a modified ray tracing method. First, let us try to define the properties of an entrance beam. Usually, the parameters of intensity distribution in LD array facet are known. They are as follows: sizes of emitting area, number of elements of array, the divergence angles in both perpendicular and parallel directions to the junction plane. We can calculate the normalized volumes of beam, named M^2 parameters (see [8], [9]), in the following way:

$$M_{x,0}^2 = \eta_x w_{x,0} \sin\theta_{x,0} \pi/\lambda,$$
$$M_{y,0}^2 = \eta_y w_{y,0} \sin\theta_{y,0} \pi/\lambda \tag{1}$$

where $\theta_{x,0}$, $\theta_{y,0}$ denote the half divergence angles in the directions parallel and perpendicular to junction plane, respectively; $w_{x,0}$, $w_{y,0}$ denote sizes of emitting area; λ denotes wavelength; normalized factors η_x, η_y are calculated in such a way that the M^2 parameters are equal to 1 for diffraction limited elliptical Gaussian beam. As a rule, the M_y^2 parameter, defined in direction perpendicular to junction plane, is slightly greater than 1, whereas the M_x^2 can be significantly larger for very long junctions.

We propose to simulate the propagation properties of such a beam by the beam of the ordinary geometrical rays which satisfies the following relations:

$$w_{x,0}^2 = \sum_i g_i(x_{i,0} - x_{c,0})^2,$$
$$w_{y,0}^2 = \sum_i g_i(y_{i,0} - y_{c,0})^2, \tag{2}$$
$$\sin^2\theta_{x,0} = \sum_i g_i(\sin\theta_{x,i,0} - \sin\theta_{x,c,0})^2,$$
$$\sin^2\theta_{y,0} = \sum_i g_i(\sin\theta_{y,i,0} - \sin\theta_{y,c,0})^2$$

where:

$$x_{c,0} = \sum_i g_i x_{i,0},$$
$$y_{c,0} = \sum_i g_i y_{i,0} \tag{2a}$$

$$\sin\theta_{x,c,0} = \sum_i g_i \sin\theta_{x,i,0},$$

$$\sin\theta_{y,c,0} = \sum_i g_i \sin\theta_{y,i,0},$$

$$\sum_i g_i = 1, \tag{2a}$$

and $x_{i,0}$, $y_{i,0}$ denote the point of intersection of the i-th ray and entrance plane; $\theta_{x,i,0}$, $\theta_{y,i,0}$ denote the angles of the i-th ray with respect to x and y axes, respectively; and g_i denotes the weight coefficient of the i-th ray. The distribution of rays in the beam may be uniform or of any kind (Gaussian, *etc.*). The choice of weight coefficients enables the "realization" of any profile of intensity distribution in the junction plane and in the far field. The main, statistical parameters of this beam, *i.e.*, r.m.s. sizes, angles and the M^2-parameters, are the same as for the given real beam. In the case of multielement bars and stripes of LD, 1D or 2D array of these beams should be defined, taking into account the spaces between the following bars and stripes.

To calculate the same parameters after passing the beam through any generally asymmetric optical system, the exact formulae for skew ray transformation (see, *e.g.*, [10]) were applied. In the image space, the w_x^2 and w_y^2 parameters can be calculated from Eqs. (2) and (2a) for a given distance z. The locations of horizontal x-waist and vertical y-waist planes are calculated from the criterion of minimum of w_x^2 or w_y^2, respectively. Moreover, the plane of a minimum spot, *i.e.*, the minimum of sum of w_x^2 and w_y^2, is determined. The M^2 parameters can be determined in the image space of lens in the same way as in the object space:

$$M_{x,1}^2 = \eta_x w_{x,1} \sin\theta_{x,1} \pi/\lambda,$$

$$M_{y,2}^2 = \eta_y w_{y,2} \sin\theta_{y,2} \pi/\lambda \tag{3}$$

where $\theta_{x,1}$, $\theta_{y,2}$ denote r.m.s. half divergence angles, and $w_{x,1}$, $w_{y,2}$ denote r.m.s sizes of beam in the x-waist and y-waist planes in the image space, respectively. The effective M_e^2 parameter for astigmatic beam is proposed to be defined as

$$M_e^2 = \sqrt{M_x^2 M_y^2}. \tag{4}$$

This parameter can be calculated in both object and image spaces of any lens system. The basic rules of transformation of the M^2 parameters in generally asymmetric optical systems are not known. It is possible that after passing a beam through any optical system, the M^2 parameter can decrease in one direction and increase in the other. It is supposed (but not shown) that the effective M_e^2 parameter cannot decrease during the transformation in the classical optical systems similarly as in the axial symmetric case (see [8]).

Let us introduce the beam transformation parameters Q_e, Q_x, Q_y as follows:

$$Q_e = M_{e,1}^2 / M_{e,0}^2,$$

$$Q_x = M_{x,1}^2 / M_{x,0}^2,$$

$$Q_y = M_{y,2}^2 / M_{y,0}^2 \tag{5}$$

where $M_{e,1}^2$ and $M_{e,0}^2$ denote the effective parameters defined in the image and object spaces, respectively.

The Q parameters give information about the quality of a transformation of the LD beam in the lens systems. The Q_e parameter can be treated as a merit function. During the optimization procedure it should decrease tending to unity for ideal system.

3. Examples of application

To show the advantages of the method described above, three examples of the LD beam transformation for various LD beam parameters, shown in Table 1, were calculated. It was assumed that the period of stripe was 10 μm and the width of elementary emitter is about 4 μm. For the second and third arrays the horizontal spacing between subarrays was 0.5 mm. In the third case, the vertical pitch was 0.4 mm. For each diode there were worked out the special optical systems delivering the maximum of power to laser rod by the end facet (see Figs. 1**a**, 2**a**, 3**a**). Each system consists of the first cylindrical lens which collimates the radiation in the vertical direction. Further, the combination of axially symmetric and cylindrical elements enables us to deliver the LD radiation to the laser rod. The x-waist and y-waist locations are inside the rod. It was assumed that the length of caustics should be approximately 1–2 mm and the divergence angles should not be too large (<400 mrad).

The results of calculations are collected in Table 2. As a rule, the radiation distribution in the rod is not axially symmetric (see Figs. 1**b**, 2**b**, 3**b**), but the shape and sizes of beam inside the rod are sufficient to pump effectively the laser rod. In the

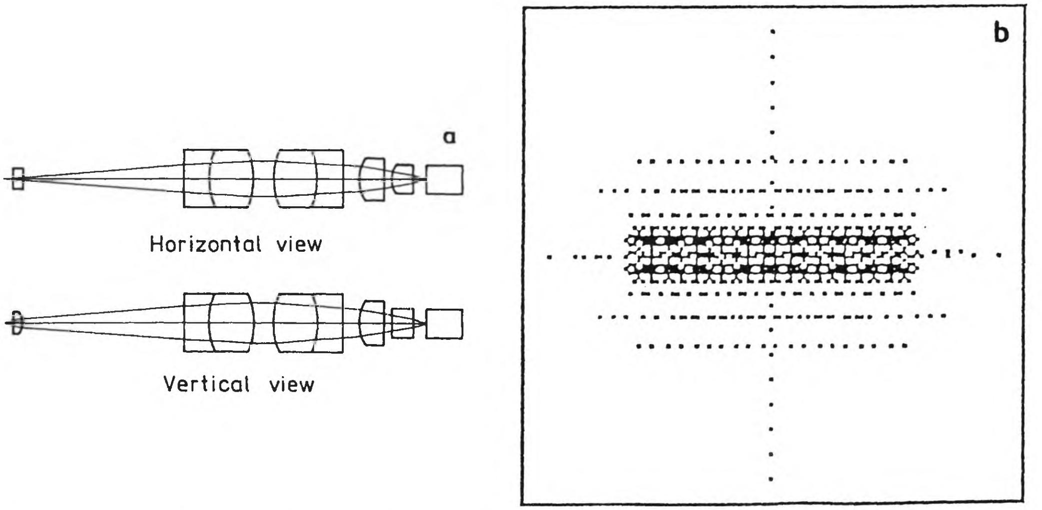
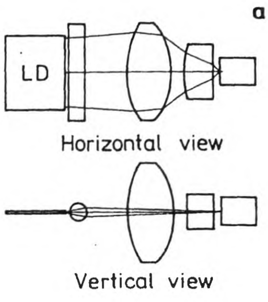


Fig. 1. Scheme of an optical system for the case No. 1 (**a**). Spot diagram of the waist for the case No. 1; frame size 1×1 mm (**b**)



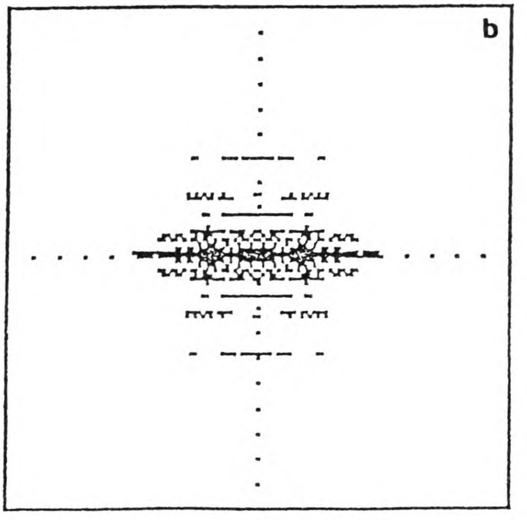
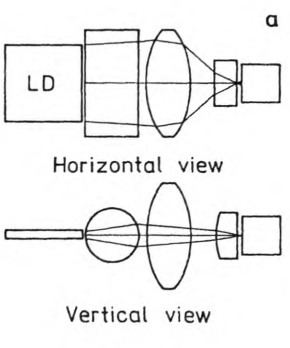


Fig. 2. Scheme of an optical system for the case No. 2 (a). Spot diagram of the waist for the case No. 2; frame size 4×4 mm (b)



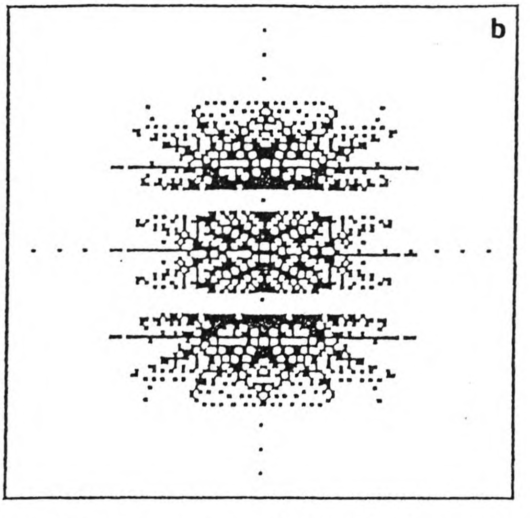


Fig. 3. Scheme of an optical system for the case No. 3 (a). Spot diagram of the waist for the case No. 3; frame size 4×4 mm (b)

Table 1. The parameters of LD beams

Case No.	Type of laser diode	Sizes of emitting area		Divergence angles	
		Horizontal [mm]	Vertical [mm]	Horizontal [deg]	Vertical [deg]
1	LDT 27004	0.2	0.001	10	40
2	SDL 3251-A1	10	0.001	10	30
3	SDL 3251-A3	10	0.8	10	30

Table 2. Results of calculations: $w_{m,1}$ denotes medium radius of beam in the minimum waist, $\theta_{m,1}$ denotes medium divergence angle in the image space, ΔZ denotes the distance between the x-waist and y-waist planes

	Case No.		
	1	2	3
$w_{x,1}$ [mm]	0.035	0.85	1.0
$\theta_{x,1}$ [mrad]	289	440	396
$w_{y,1}$ [mm]	0.012	0.27	1.34
$\theta_{y,1}$ [mrad]	222	60	181
$w_{m,1}$ [mm]	0.026	0.63	1.16
$\theta_{m,1}$ [mrad]	253	161	268
ΔZ [mm]	0.05	0.55	0.5
Q_x	2.54	1.86	0.66
Q_y	0.69	4.02	12.92
Q_e	1.33	2.74	2.92

case No. 1, the correction of astigmatism was achieved, while the beam in the waist is not circular (see Fig. 1b). In two latter cases, the beams in the image space are strongly astigmatic, but also in these cases they are significantly compressed to contain inside the rod with 4 mm diameter.

4. Conclusions

Three examples of relatively simple astigmatic optical systems, which enable efficient formation of arrays of beams, were shown. The method presented in Sect. 2 is convenient to evaluate this type of optical systems and beams. The quality of lens system can be estimated by the value of Q factors. It seems that for a beam with large M^2 parameters (1D and 2D bars and stacks of LD) it is impossible to correct completely the ellipticity and astigmatism, but reasonable compromise solution can be effectively found.

Acknowledgements — This work was sponsored by the State Committee for Scientific Research (KBN-93).

References

[1] FORKNER J. F., KUNTZ D. W., Proc. SPIE **740** (1987), 27.
[2] VANECK D. G., Proc. SPIE **1025** (1988), 20.
[3] REICHERT P., SNYDER J. J., Proc. SPIE **1544** (1991), 146.
[4] ALBERS P., HEIMBECK H. J., LAGENBACH E., Proc. SPIE **1780** (1992), 533.
[5] LEGER J. R., GOLTSOS W. C., IEEE J. Quant. Electron. **28** (1992), 1088.
[6] YAMAGUCHI S., IMAI H., IEEE J. Quant. Electron. **28** (1992), 1101.
[7] WILLING S., WORLAND P., HARNAGEL G. L., ENDRIZ J., Proc. SPIE **1418** (1991), 358.
[8] JABCZYŃSKI J., Opt. Appl. **22** (1992), 179.

[9] SIEGMAN A., Proc. SPIE **1224** (1990), 2.
[10] KINGSLAKE R., *Lens Design Fundamentals*, Academic Press., New York 1978.

Received October 20, 1994
In revised form January 9, 1995