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Three-fold effective brightness increase of laser diode bar emission by assessment and correction of diode array curvature

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Abstract

An optical arrangement is used to characterize diode bar curvature which is known to limit the effective brightness achievable with such devices. By introducing an inclined, cylindrical collimating lens in front of the diode bar, the curvature of the diode's beam can be reduced by more than 60%. The correct inclination angle for this method is derived. Using a beam shaper together with this correction mechanism we achieve a homogeneous beam profile with low M^2 values in orthogonal directions and an effective brightness increase of more than 200%. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Diode lasers; Laser beam shaping; Diode pumped lasers

1. Introduction

Diode laser bars are nowadays the basic elements of high power semiconductor lasers. They continuously emit 5–60 W at specific visible to near infrared wavelengths and find their main applications in materials processing and optical pumping of solid state lasers. A single diode bar is a linear array of 20–50 individual diode emitters of 50–200 μm width and 100–400 μm center to center spacing. The overall emitting area of a diode bar has generally a width of 1 cm and is about 1 μm high. In this work, the term effective brightness is defined as the intensity per steradian radiated by the overall emitting area of the bar, which includes the non-emitting area in between the individual diode emitters. Due to the small height, comparable to the emission wavelength, the emitted beam diverges strongly in this direction (fast divergence axis) whereas in the other direction, given by the array of emitters, the divergence is smaller (slow divergence axis) [1]. As a result, the combined output beam is almost diffraction limited in the fast direction but has divergence that is more than thousand times that of a diffraction limited beam in the other direction. This very poor beam quality hampers the usefulness of diode bars in many applications. Specifically, when trying to focus the beam tightly, very different waist sizes, waist positions and depth of foci are obtained for the fast and slow axis, which makes e.g. end-pumping of solid-state lasers difficult. Several beam-shaping techniques have been proposed which generate approximately equal beam quality factors in orthogonal planes, permitting thereby smaller focus diameters [2–4]. Most of these techniques are accompanied by a strong brightness decrease and only a few are suitable for end-pumping of solid-state lasers [5]. Of these, two of the most well known techniques use either two parallel, high-reflectivity mirrors [6] or two series of micro mirrors (about 20) arranged in a special manner [7] to transform geometrically the diode radiation into a more circular beam with similar beam quality factors in orthogonal transverse directions. Both techniques are based on the same principle, which is cutting the approximately 1 cm wide beam emitted by the diode bar into a series of smaller beams (about 20–30) and then stacking them on top of another thereby achieving a more square and compact beam profile.

The brightness of the laser beam becomes significantly degraded if the diode array is curved. Array curvature, also called "smile", is mainly a function of the manufacturing process [8]. Once the diode is manufactured, the bar curvature is fixed (Fig. 1). This defect is introduced during the manufacturing process when the laser bar is bonded onto

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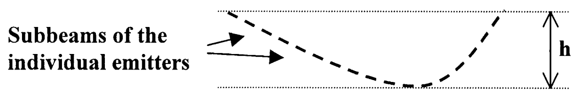

Fig. 1. Concave curvature of a diode bar. Typically h is about 5 μm at the bar.

the sub-mount which is then bonded to the copper heat-sink. Some manufacturers also bond the diode bar directly to the copper heat-sink which is referred to as "direct bonding".

The beam quality becomes even more degraded upon passage of the radiation through the fast-axis collimating lens and the beam shaper. To collimate the fast-axis radiation of a diode bar, with its divergence angle of up to 50°, very high numerical aperture collimating optics is required. When beam quality is not of critical importance, common plano-convex cylindrical lenses of long focal length can be used. However, when the preservation of the diode brightness is of importance, low optical aberrations are required. Because geometrical aberrations depend on lens shape, but not on focal length, they become less important, compared to the diffraction limit, for very short focal length [9]. Therefore, micro-lenses are indicated as fast-axis collimators whenever high brightness is necessary, for example when end-pumping laser rods [10]. These 1 cm long, cylindrically shaped lenses, have diameters of several hundreds of microns and are attached directly to the diode heat-sink, parallel to the array of diode emitters. Good collection efficiency and little cylindrical aberration are obtained with factory installed micro-lenses [11], although an overall brightness decrease of at least 3 times due to aberrations is the case no matter what lens design is chosen [12]. Additional aberrations are introduced due to misalignment of the micro-lens and will be treated at a later point.

Diode array curvature greatly increases off-axis aberrations introduced by the fast-axis collimator depending on the type of collimating lens used. A 5 μm displacement may reduce the beam quality by a factor of 2. It is therefore very important that the lens shows as little sensitivity to array curvature as possible. In at least one publication it has been tried to compensate smile by adjusting the curvature of the flexible fiber-lens with a piezo-electric actuator [12], but we do not know if this procedure has any long term success.

Due to the intrinsic way that beam shapers work, the beam emitted by curved diode bars gets either clipped by the mirrors [6], causing a power loss, or the total area occupied by the beam after it has been re-shaped by the device increases [13]. Either effect results in an effective brightness decrease of the diode radiation. Because array curvature becomes significant at the focus, relative to the spot size, it is also a problem when side-pumping solid-state lasers [14].

This is to our knowledge the first time that the consequences of array curvature are analyzed for the purpose of pumping solid-state lasers and that a simple method is proposed and analyzed which can improve the effective brightness obtained in common diode pumping schemes.

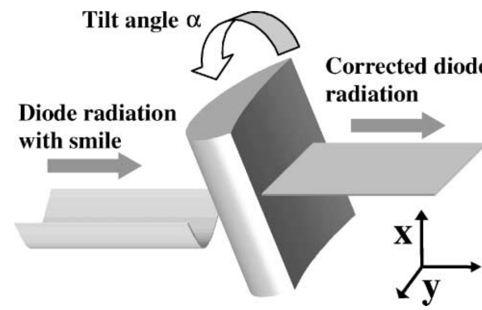

Fig. 2. Schematic of the working principle of the inclined cylindrical lens.

2. Theory

Diode array curvature is a translation of the individual emitters of the diode array along the fast divergence axis (x-axis). Therefore, a cylindrical, slow divergence axis (y-axis) collimating lens, inserted parallel to the fast axis in front of the diode has no effect on the relative position of the sub-beams emitted by the individual emitters. Only rotation around one or more of its axes can introduce a correction to the diode array curvature (see Fig. 2). An exception to this is a pure rotation around the x-axis which introduces only off-axis aberrations.

Rotating the lens by α around the y-axis causes a displacement of the beam in the x-direction which depends upon the thickness t of the lens. In the paraxial approximation we may write:

$$x \approx t\alpha(1 - 1/n), \tag{1}$$

where n is the index of refraction of the lens. Because the diode projects a highly elongated beam along the y-direction of the cylindrical lens, the thickness t experienced by the diode emission varies considerably. This effect can be exploited to level the individual emitter images by translating the sub-beams by different amounts along the x-axis. In the case of a plano-convex lens, where the convex side has a spherical curvature r, the relative x-axis translation is quadratic, as seen in Eq. (2). The translation is the highest for the sub-beams in the middle of the array in the case where the image on the lens is well centered and the lens has no tilt around the x-axis (see Fig. 2).

In order to correct for the diode curvature, what matters is the relative difference, Δd, between the lens thickness introduced for the ends and for the center of the elongated beam. For a beam, which has the half-width y at the lens position and for a lens of focal length f this difference is given by (see also Fig. 3)

$$\Delta d = r(1 - \sqrt{1-(y/r)^2}) \approx \frac{y^2}{f}\left(1 + \frac{y^2}{f^2}\right), \tag{2}$$

where we have expanded to second order and made use of the "lens-maker formula" [15] for plano-convex lenses with index of refraction close to 1.5

$$f = r/(n-1) \approx 2r. \tag{3}$$

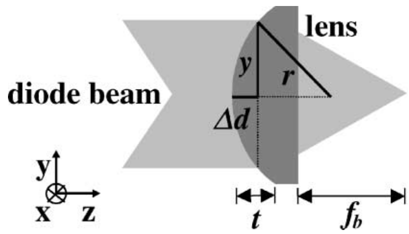

Fig. 3. Schematic of a highly elongated beam of a diode bar of half width y passing through a cylindrical lens of thickness t, back focal length f_b and whose convex side has a radius of curvature r.

A lens with high NA is needed to collect at a short distance the light from a 1 cm wide diode bar with 10° slow-axis divergence angle (FWHM). Also, the beam-width at the lens is close to the lens-width. Therefore, the difference Δd approaches the lens thickness t (which is the center thickness minus the edge thickness)

$$t \approx \Delta d \approx \frac{y^2}{f} \quad \text{for } y/f \ll 1, \tag{4}$$

where we have used Eq. (2). For plano-convex lenses the position of the principal plane, d_p, with respect to the flat side of the lens is given by [15]

$$d_\mathrm{p} = ft(n - 1/r) \approx t, \tag{5}$$

we may now rewrite Eq. (2)

$$\Delta d \approx \frac{y^2}{f - t} = \frac{y^2}{f_\mathrm{b}}, \tag{6}$$

where f_b is the back focal length which comprises the distance from the flat side of the lens to the focus with the lens's flat side facing the focus. This approximation is easy to use because most lens-manufacturers indicate the back-focal length of their lenses. The difference between Eqs. (4) and (6) is shown in Fig. 4 where we demonstrate the relative error between calculated and measured value of the thickness of several plano-convex lenses.

A rotation of α around the y-axis introduces a relative shift of the sub-beams at the center of the diode emission of

$$\Delta x \approx \alpha \frac{y^2}{3 f_\mathrm{b}}, \tag{7}$$

where we have made use of Eqs. (1) and (6) and $n \approx 1.5$. If the image of the curved bar has a height h at a distance z from the diode, the angle α necessary for correction of the curvature is given by

$$\alpha = \frac{h 3 f_\mathrm{b}}{m y^2}, \tag{8}$$

where m is the magnification of the image between the lens position and z.

An important consequence of Eq. (8) is, that correction of diode array curvature works better with lenses of short focal length, as can be seen in Fig. 4. In this figure we used Eq. (7) to calculate the tilt angle necessary to introduce a 1 mm height difference between center and border of the diode emission when placing the lens at a distance f_b from the diode. For strong curvature, correction becomes impossible with long focal length collimating lenses. It follows from Eq. (7) that this method works best if the array shows a parabolic curvature.

3. Experimental set-up

An optical arrangement serves to analyze the array curvature of a total of four diodes bars, two emitting at 960 nm and two at 792 nm, and measure the total height of the laser beam (see Fig. 1) at a fixed distance from the diode bar. It allows to correct for the deviation from linearity of the arrays with a slow axis collimating lens and to compare the results. In a second step, a beam-shaper is added to the optical arrangement in order to measure the effective brightness of a 792 nm diode, with and without correction for the bar curvature.

The 20 W diode bars used in this experiment (Opto-Power-Corporation model OPC-A020-mmm-CS), have 24 emitters each, measuring 1 μm × 200 μm, with center to center spacing of 400 μm. The emitted beam is collimated in the fast direction (x-axis) by a factory installed, AR-coated non-cylindrical fiber lens of 440 μm diameter. To characterize the collimation of the diode emission in the x-direction by the diode's micro-lenses, the M^2 value in this direction was measured and values of 2.9 (±0.5) were obtained.

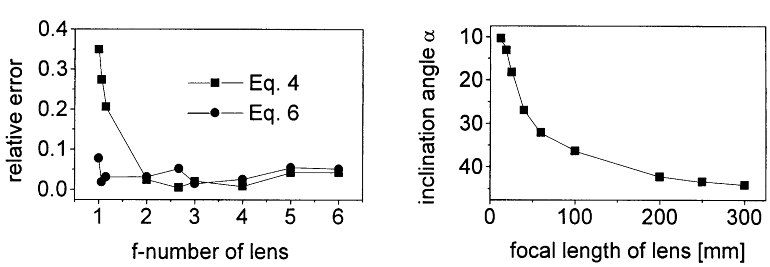

Fig. 4. Left: relative error introduced when calculating the thickness of plano-convex lenses with Eq. (4) and (6). Right: calculated tilt angle of slow-axis collimating lens necessary to introduce a 1 mm difference between center and border of diode emission.

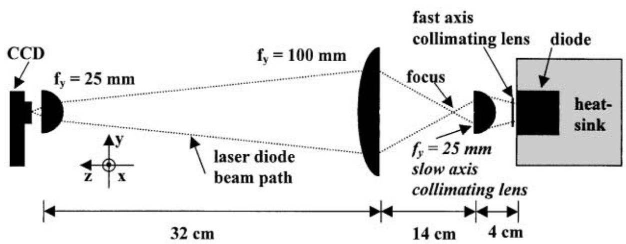

Fig. 5. Top-view of the optical arrangement used to measure the curvature of the diode emission.

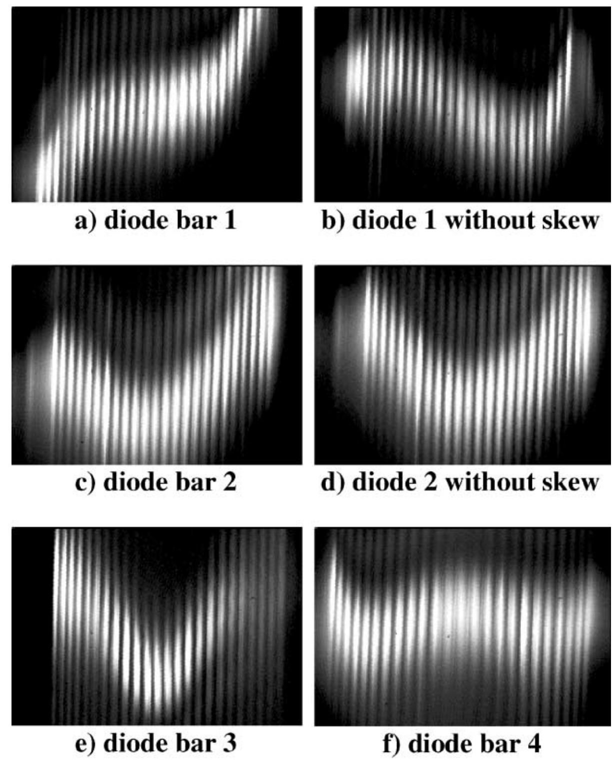

Fig. 6. Images of the 24 sub-beams emitted by the 20 W diode bars. Pictures (a) and (e) are from diodes emitting at 792 nm, whereas pictures (c) and (f) are from diodes emitting at 960 nm. Pictures (b) and (d) are obtained from (a) and (c), respectively, by rotating the $f = 100$ mm lens in Fig. 5 around its z-axis by 1°–2°.

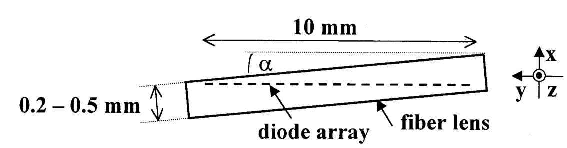

Fig. 7. Misaligned fiber lens. The beam of the emitters on the left side will be diffracted downwards whereas the beam on the right side is diffracted upwards (skew), thereby increasing the total beam divergence and off-axis aberrations.

The M^2 value of the slow axis was in between 1600 and 2200 for the four diodes. All measurements were done at a distance of 20 cm from the diode bar. The measured values of the beam-quality factors in the fast and slow direction are in good agreement with previously reported values [6,7].

An optical arrangement was built to de-magnify the slow axis of the diode emission by a factor of 2 whereas the fast direction of the emission is magnified by a factor of 1000 (Fig. 5). This arrangement serves also to correctly rotate the slow-axis collimating lens in order to maximize the linearity of the diode emission in the y-direction. The diode bars are tested on a leveled pneumatic table, one after another, on top of a water cooled heatsink, whose parallelism with the table surface has been verified. The slow-axis collimating lens, with 25 mm focal length, is inserted in front of the diode with its cylindrical axis parallel to the x-axis and its flat side parallel to the x–y-plane. After centering its y-position with the diode emission, the z-position is adjusted in order to generate a sharp, magnified image of the bar's emitting region at a distance of approximately 50 cm from the diode. The only purpose of the two plano-convex, cylindrical lenses in front of the CCD (Merchantek Inc. model Wincam.) is to create an image inside the CCD of the 24 individual diode emitters after they have passed through the slow-axis collimating lens, without influencing the measurement in the x-direction (fast axis). Both lenses were arranged with their cylinder axis parallel to the x-axis, with an error of less than 1.5°. Also, the flat side of the plano-convex lenses was aligned parallel to the y-axis to less than 1° error. The CCD, mounted on a x–y–z translation stage at a distance of 52 cm from the diode, was protected by a neutral density filter and a mirror with high reflectivity either at 792 or 960 nm. The picture captured by the CCD is the image of the far field created after the focus which is situated immediately behind the slow-axis collimating lens. With the help of the camera's computer based software which is specific for laser beam characterization, calibrated measurements of the relative separation in the x-direction between the images of the individual sub-beams could be taken. The images taken had an area of 6.2×4.1 mm^2 (width x height). With the exception of some images with extreme off-axis aberration, the computer software permitted determination of the relative x-axis position of the center of the individual emitter image with a precision of better than 100 μm. After inserting the other two y-axis collimating lenses into the beam path and slightly readjusting their y-position, an uncorrected image of the emitters is obtained (Fig. 6). This figure shows that some bars are concave ("smile" in Fig. 6e), some convex ("frown" in center part of Fig. 6f) and some are both (Fig. 6b). In Fig. 6, images (a) and (c) show a vertical translation of the emitter image, also called "skew", which is probably due to the fast-axis collimating micro-lens not being exactly parallel with the diode array [8], as shown in Fig. 7. Although the skew has no effect on the amount of curvature we corrected it with a small rotation (between 1° and 2°) around the z-axis of the $f = 100$ mm lens in Fig. 5 as shown in Fig. 6. One major difficulty in using micro-lenses resides in aligning the fast-axis collimating lens parallel to the bar to better than 200 μrad [12]. If the lens is not parallel with

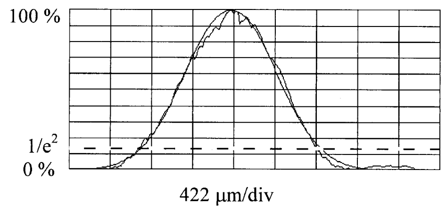

Fig. 8. Gaussian fit along the fast axis of the smallest, single sub-beam emitted from diode bar 1. Measured width is 1.83 mm between $1/e^2$ points.

the diode array astigmatism and coma is produced which degrades the beam quality but does not introduce additional curvature to the emitter image. Another angular error may occur when the distance between the lens and the array on one side of the bar is smaller than on the other side. This relative focus error manifests itself as differing spot size and shape of the emitter image. The image seems "blurred" on one side of the diode bar and "sharp" on the other. In some cases the diode array also shows curvature within the y–z plane. In this case, the error shows up as a sharp emitter image at the center and a blurred image at both ends of the diode array or vice versa as seen for example in Fig. 6f. If skew or relative focus error is detected after purchasing the diode it is possible to try to correct it by re-lensing the diode, which is generally done at the factory [8]. During this procedure, the fast axis collimating lens which is installed in front of the emitters is detached and then bonded again in a position such as to increase its parallelism with the diode array.

4. Assessment and correction

Depending upon the sum of the effects described above, an image height (at $1/e^2$ points) between 1.83 and 4.6 mm was measured for a single sub-beam. The camera's built in software was used to determine how close to a Gaussian the images of the sub-beams are along their fast axis. This software displays the normalized residuals of a least squares fit with a gaussian. Experimentally, we measured values closer to unity for smaller image heights as shown in Fig. 8. Minimum measured heights for the sub-beams from diode bars emitting at 792 and 960 nm were 1.83 and 2.3 mm, respectively. The image peak-to-peak heights (difference between intensity peaks of lowest and highest sub-beams in Fig. 6), h, were measured for all diode bars. They are 1.62, 1.88, 2.09 and 0.9 mm for diode bars 1–4, respectively. All measurements were done with the diode operating at 20 A current and after correction of the skew in the emitter image.

The dashed lines in Fig. 9 are gaussian fits ($M^2 = 1$) through the minimum measured height for individual sub-beams (1.83 mm at 792 nm and 2.3 nm at 960 nm). These fits generate a value for the beam waist w_0 at the micro-lens of 139(5) µm. The solid line is a fit of the overall

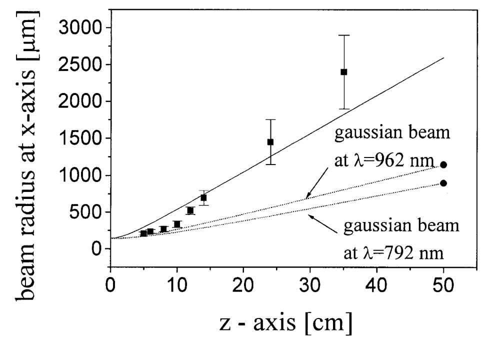

Fig. 9. Measured overall beam radius at $1/e^2$ (black squares) and calculated radius for a beam with $M^2 = 2.4$ (solid line). The upper and lower dashed lines represent fits of gaussian beams ($M^2 = 1$) which have their waist at the diode bar ($z = 0$), and a radius at $z = 50$ cm equal to the smallest sub-beam image recorded (see also Fig. 8).

image height of diode bar 4 (squares in Fig. 9), measured at different distances from the bar, with the diode's M^2 factor of 2.4. This fit generates a waist of 143 µm at the bar. Comparing the gaussian fit (dotted lines in Fig. 9) with the x-axis beam waist (squares), we can see that the emission, measured at the center of the diode beam, has gaussian beam characteristics along the x-axis close to the bar. The reason for this is, that only very few sub-beams overlap close to the bar. Farther away from the bar, all the sub-beams start to overlap because of their slow axis divergence (FWHM) of about 10° and cause the beam waist to increase strongly, approaching the solid line after about 10 cm of z-axis travel. Therefore, in order to achieve proper quality assessments of diode bar beams, the M^2 factor must be measured in the far field, after all the sub-beams have overlapped. A minimum distance of 20 cm should be maintained to properly assess the overall beam quality of the fast axis.

As already discussed, rotating the slow axis collimating lens around its y-axis shifts the sub-beams of the center of the array. This is obviously practical when the array curvature is in one direction only and less practical when it is both, convex and concave. It follows that we achieved good results with the diode bars 2 and 3 whereas only a small correction was achieved with diode bar 1 and 4 as shown in Fig. 10 and Table 1. Specially good results were obtained with diode bar 2 which showed an almost parabolic curvature and therefore permitted a 68% decrease of its initial curvature height.

5. Results with beamshaper

A two-mirror beam-shaper [6] was used, as shown in Fig. 11, to reconfigure the diode emission into a more circular beam with approximately equal M^2 factors in the x- and y-direction. The advantages of the corrected diode emission with less curvature are manifold in this application: (a) clipping of the diode emission by the mirrors is reduced and consequently power loss in the beam shaper is smaller and

Table 1
Overview of the curvature heights of the arrays before and after rotation of the slow axis collimating lens around its y-axis

Diode bar	1	2	3	4
Initial peak-to-peak height h of array curvature (mm)	1.62	1.88	2.09	0.9
Initial M^2 factor of fast axis	—	—	3.2(3)	2.4(3)
Experimentally determined rotation angle α (°)	5(2)	10(2)	10(3)	1(1)
With Eq. (8) calculated rotation angle α (°)	3	11	9	1
Peak-to-peak height h of curvature after rotation of lens (mm)	1.3	0.6	1.05	0.8
Height difference (mm)	0.32	1.26	1.01	0.1

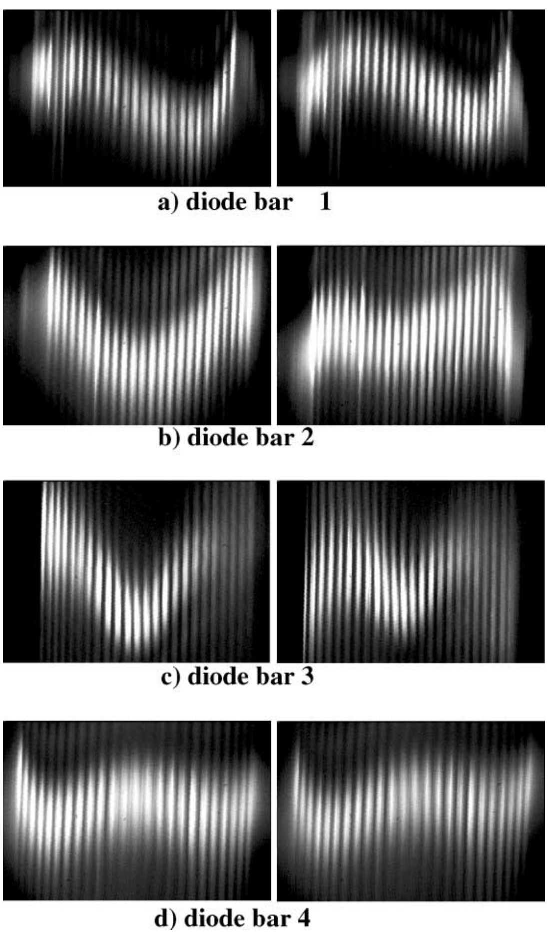

Fig. 10. Captured images of the diode arrays before (left) and after (right) rotation of the slow divergence axis collimating lens.

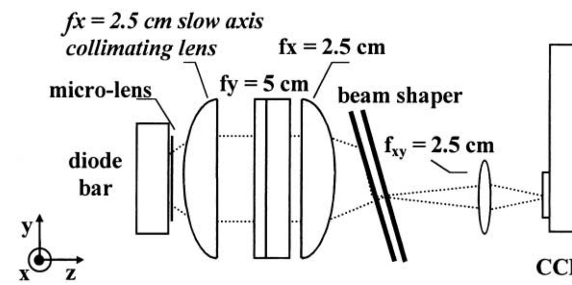

Fig. 11. Optical arrangement of the two mirror beamshaper.

(b) tighter stacking of the beams during the reshaping procedure permits a smaller beam cross-section. Both achievements result in an overall higher effective brightness of the beam when compared with the uncorrected diode emission.

We measured the quality factors at constant power for the corrected and uncorrected beams after the beam shaper. Between the measurements the beamshaper had to be re-aligned. The measurements were done with diode bar 3 and are summarized in Table 2. As seen in Table 1, diode 3 has the worst curvature. It is therefore no surprise that a strong power loss due to clipping at the beamshaper and a bad beam quality is obtained without the correction, as shown in measurement 1 of Table 2. In this configuration the beamshaper generated two columns containing 12 sub-beams each, corresponding to a total of 24 emitter images. After inclining the slow axis collimating lens by 10° the beamshaper was re-aligned into the same configuration (measurement 2 of Table 2). As an immediate result, 27% more output power was obtained and the brightness increased more than 100%, which is congruent with the decrease in the beam's curvature height (Table 1).

Because there was less clipping with the corrected diode beam, we were now able to realign the beamshaper (measurement 3 of Table 2) and stack all 24 sub-beams in one single column with only a small output power decrease. Without curvature correction the same procedure resulted in an output power of 7.8 W. Stacking all sub-beams in one single column has the additional advantage of generating a homogeneous beam profile at the focus, whereas two columns generate two distinct, separate features at the focus. The results of measurement 3 show excellent beam quality and also similar beam dimensions and quality factors in orthogonal directions. This beam quality increase is expected because, when generating a single column we eliminated the "dead" space between the two original columns which, as already pointed out, is twice as large at the focus as a single emitter beam.

Table 2
Quality factors and output power measured with diode bar 3 for different beam-shaper configurations and inclination angles of the slow-axis collimating lens

Inclination angle of low-divergence collimating lens (°)	Fast axis waist w_x/µm	Slow axis waist W_y/µm	Quality factor of fast axis M_x^2	Quality factor of slow axis M_y^2	Power (W)	Effective brightness (kW/cm^2)
Measurement 1: 0	120	200	56	120	14	15
Measurement 2: 10	97	140	41	78	17.8	33
Measurement 3: 10	107	82	50	29	16.1	46

6. Conclusions

The diode array curvature of four different bars, which use pre-assembled micro-lenses were analyzed and measured and it was demonstrated, that with the help of a slow-axis collimating lens it is possible to reconfigure the beam to achieve higher effective brightness. An approximate equation has been derived which shows, that short focal length lenses are needed for compensation of array curvature and which also permits to calculate the correct rotating angle of the lens. It follows, that this method works best if the diode's curvature is parabolic.

With the help of an optical arrangement we could magnify the array curvature and obtain images of the emitted sub-beams. The four tested diodes showed different levels of curvature ranging from parabolic to mixtures of negative and positive curvature within the same bar. Also, different levels of off-axis aberrations were present, although we demonstrated, that some sub-beams propagate almost Gaussian even in the presence of the micro-lens. Depending upon the curvature of the array, compensation by inclination of the lens was successful in reducing the height, *h*, by 10% to more than 60%. In the case of an almost parabolic curvature we achieved a reduction of 68% from the original height.

The technique was also applied to a beamshaper used to end-pump solid-state lasers. A reduction of about 50% in the curvature's peak-to-peak height was achieved after inclining the slow-axis collimating lens. This resulted in 27% more output power after the beamshaper and a better beam quality. After realigning the beamshaper, a threefold effective brightness increase and a homogeneous intensity distribution was achieved with only a small output power loss.

Finally, this correction mechanism should also prove useful for side-pumped solid-state lasers or whenever the curvature of the pump beam causes a bad overlap with the intra-cavity beam.

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