LASER DIODE TECHNICAL NOTE 1

Beam Circularization and Astigmatism-correction

The Diode Optics Challenge

The use of diode lasers is becoming increasingly attractive in a wide range of applications. Diode lasers are small, efficient and available with outputs at several red and near-IR wavelengths. Their low-voltage dc power sources (frequently just a small battery) can be directly modulated or pulsed to similarly modulate or pulse the laser output beam. However there are difficulties associated with adopting diode lasers for specific applications. In particular, commercial diodes have very divergent output beams and the diodes can be only-too-easily damaged by electrostatic pickup etc. Such optical and electrical problems are most frequently overcome by incorporating the bare laser diode in a module which includes correcting optics and protective electrical circuitry. Most laser diodes are of the “edge-emitting” type and these have output beams with elliptical cross sections and some associated astigmatism. For many applications the ellipticity and astigmatism are not important, but in other applications they cause problems.

In this review we discuss the advantages and limitations of the various methods which can be used in modules to remove the astigmatism and convert the diodes elliptical output beam into a circular beam.

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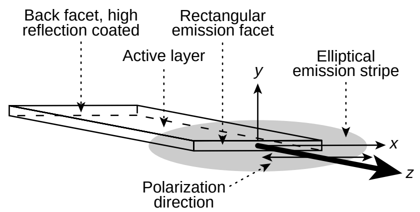

Figure1 - Laser diodes have a thin active layer with a rectangular cross section. The emission stripe at one end of the active layer has an elliptical cross section and is larger than the cross section of the active layer. The drawing is not to scale.

Optics of the Diode Laser Emission

Within a typical edge-emitting diode the light emission is created by an electrical current flow across a semiconductor active layer, ~0.1 μm thick, ~3 μm wide and ~100 μm long. The laser beam is emitted from one of the facets in the *x-y* plane at the end of the active layer and propagates in the *z* direction, as shown in Fig. 1. Because the laser radiation created inside the active layer leaks into the surrounding semiconductor volume, the laser output at the active layer facet (the emitting stripe) is larger than the size of the active layer facet and has an elliptical cross section. The output beam is linearly polarized in the *x* direction.

Two types of laser diodes are commonly used: ***index-guided*** and ***gain-guided***. In ***index-guided*** laser diodes the active layer material has a refractive index larger than that of the material surrounding the layer. This index difference guides the laser radiation within the diode and confines the beam to (and close to) the *x-y* cross-section of the active layer. The situation is similar to a piece of glass fiber confining and guiding a laser beam inside it. Because of the large confinement and good guidance of the beam, index-guided laser diodes are more likely to operate with a single longitudinal mode and a single transverse mode, and hence are widely used in those applications requiring good quality beams. Beam powers are typically in the range of a few milliwatts up to a few tens of milliwatts. In ***gain-guided*** laser diodes, the refractive indices of the active layer material and its surrounding material are the same. However the lasing process taking place inside the active layer will slightly increase the index of the active layer. The resultant weak confinement and guidance of the beam makes gain-guided laser diodes more likely to operate with multi-longitudinal modes and multi-transverse modes, which is not usually desirable. But since the active layer of gain-guided laser diodes can be fabricated to widths of hundreds of microns such diodes can generate powers up to 1 Watt or more, and they are used in applications where beam power is more important than modal quality. In this review we will not further consider gain-guided lasers.

As already noted, index-guided low power laser diodes typically have an active layer with a *x-y* cross section size of about 0.1 μm by 3 μm. But the ($1/e^2$) diameters of the emission stripe, d_{x0} and d_{y0}, are larger, due to the beam spreading into the surrounding lower index material. Typically $d_{x0} \approx 4$ μm and $d_{y0} \approx 1$ μm, an ellipticity of 4. Different commercial diodes have ellipticities varying from 2.5 to 6. Laser theory shows that the output beam has a Gaussian intensity profile in the *x-y* plane. The beam $1/e^2$ intensity diameters in the *x* and *y* directions are a function of *z* and are given, respectively, by

$$d_x = d_{x0}\,[1 + (\frac{M^2 z}{z_{Rx}})^2]^{1/2} \qquad (1)$$

$$d_y = d_{x0}\,[1 + (\frac{M^2 z}{z_{Ry}})^2]^{1/2} \qquad (2)$$

where $z_{Rx} = 4\lambda/\pi d_{x0}^{\,2}$ and $z_{Ry} = 4\lambda/\pi d_{y0}^{\,2}$ are the two Rayleigh Ranges of the beam in the *x* and *y* directions, respectively, λ is the laser wavelength and M^2 is a factor describing the deviation of the beam from a fundamental transverse mode Gaussian beam. For laser diode beams, we have $M^2 \approx 1.2$. The terms “far field” and “near field” are often used in literature and are defined as $z >> z_{Rx}$ (or $z >> z_{Ry}$) and $z \sim z_{Rx}$ (or $z \sim z_{Ry}$), respectively. It can be seen that at $z = z_{Rx}$ (or $z = z_{Ry}$), $d_x = 2^{1/2} d_{x0}$ (or $d_y = 2^{1/2} d_{y0}$). The beam far field $1/e^2$ full divergent angles θ_x and θ_y, in the *x* and *y* directions respectively, can be obtained by inserting a large *z* value into Eqs. (1) and (2). Then

$$\theta_x = \frac{4\,M^2\lambda}{\pi d_{x0}} \qquad (3)$$

$$\theta_y = \frac{4\,M^2\lambda}{\pi d_{y0}} \qquad (4)$$

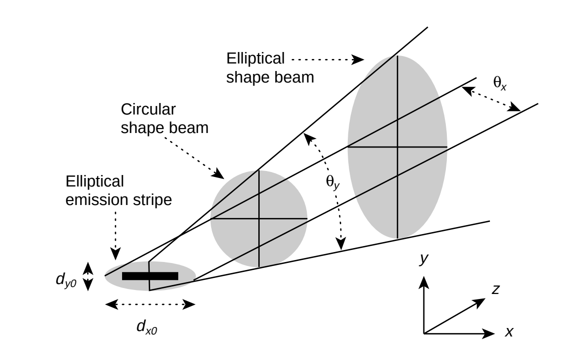

Figure 2 - The output beam from the emission stripe diverges rapidly and the beam shape changes as the beam propagates.

where θ_x and θ_y are in radians. Obviously, since $d_{x0} > d_{y0}$, $\theta_x < \theta_y$ and the output beam will be elliptical. For our typical example, from Eqs. (3) and (4) and assuming $\lambda = 0.67\ \mu m$ we find that $\theta_x \approx 13^o$ and $\theta_y \approx 53^o$, with equivalent 50% intensity divergent angles of 8^o and 31^o, respectively. Clearly the emitted beam is elliptical in shape and highly divergent. As the beam propagates in the *z* direction, the beam increases its size faster in *y* direction than in *x* direction because θ_y is larger than θ_x as shown in Fig. 2.

At a distance of several microns from the active layer facet, the beam size in the *x* direction equals the beam size in the *y* direction and the beam cross section becomes circular. Beyond this distance, the beam cross section is again elliptical, but with the major diameter in the *y* direction.

Beam Collimation and Truncation

Because of the very large divergence of the diode emission a collimating lens must be situated within several millimeters of the emission stripe, close to the window in the diode cap. A simple convex lens or GRIN lens can be used, but in most applications, to obtain a reasonable quality beam, either an aspheric lens or a lens group is used. Both the aperture and the focal length of most diode beam collimating aspheric lenses are several millimeters. Usually the numerical aperture of the lens is smaller than θ_y and the lens aperture clips or truncates the beam in the *y* direction.

<u>The collimated beam</u> has a waist size in the *x* direction smaller than in the *y* direction and the collimated beam divergence in the *x* direction is larger than the divergence in the *y* direction according to Gaussian optics theory. The collimated beam becomes circular at a certain distance beyond the lens and in the far field becomes elliptical with the major diameter in the *x* direction as shown in Fig. 3. Most importantly the elliptical ratio of the far field beam shape equals d_{x0}/d_{y0} since the far field beam shape is an image of the beam source, the emission stripe. The far field beam intensity profiles in the *x* and *y* directions are quasi-Gaussian. Fig. 4 shows typical far field intensity profiles of a collimated beam, these are also the typical intensity profiles of the spot of a focused beam. In the *y* direction the profile usually has two side lobes caused by the beam truncation of the collimating lens. The intensity profiles and their Gaussian fits are not distinguishable in most part of the profiles except near the side lobes. The side lobes cause problems in some applications, but since most lenses truncate the beam, it is difficult to eliminate them. Side lobes of the magnitude of a few percent of the main lobe are often seen. When a lens truncates much of the beam, the magnitude of the side lobes can be over 10% of the main lobe and additional side lobes appear, and of course the

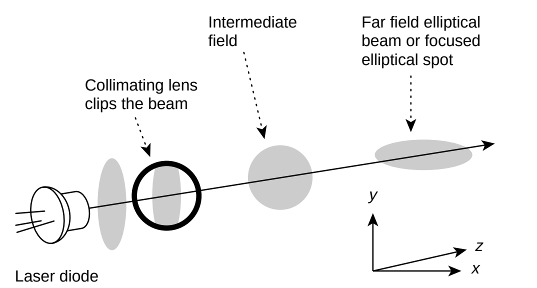

Figure 3 - The collimating lens usually clips the beam along the major axis and the shape of a collimated beam changes as the beam propagates

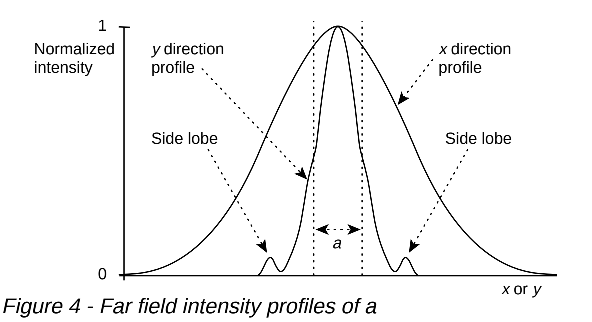

Figure 4 - Far field intensity profiles of a collimated beam. The two vertical dashed lines represent a circular aperture of diameter a for "circularizing" the beam.

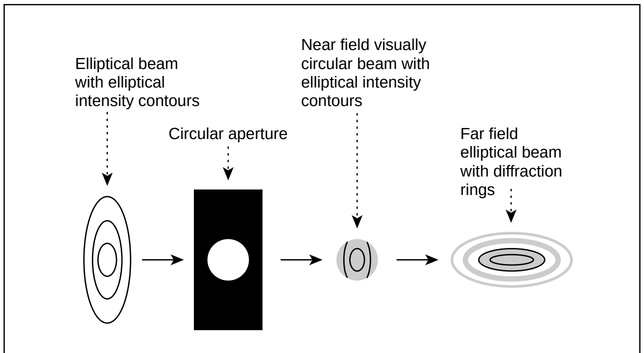

Figure 5 - Circularizing an elliptical beam with a circular aperture.

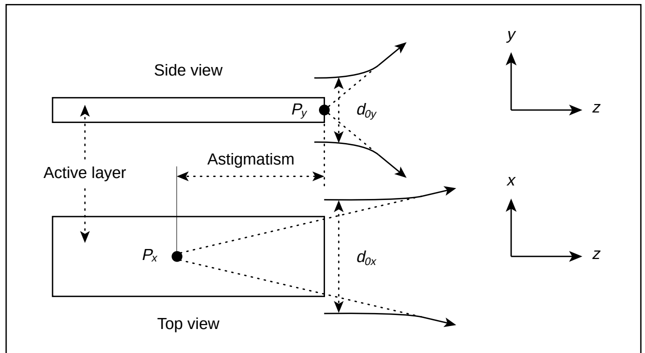

Figure 6 - Side view and top view illustrating the origin of astigmatism.

transmitted beam power is significantly reduced. However such truncation does suggest one simple method of circularizing a diode beam.

Beam Circularization with an Aperture

A circular aperture is often used after the collimating lens to truncate an elliptical beam to visually circular. It can be seen from Fig. 4 that for a circular aperture with diameter *a* the ratio of the beam intensity in *x* and *y* directions at the aperture edge is about 2, and the smaller the aperture is, the closer to 1 the intensity ratio is and the more visually circular the beam is. However a small circular aperture can cause power loss as high as 80% and strong far field diffraction rings. The intensity contours of the beam after the aperture are still elliptical as shown in Fig. 5 and the beam is still astigmatic. The far field beam shape will become elliptical since the far field beam is the image of the emission stripe.

Astigmatism and its Correction

Consider the exact position of the emission from the diode front facet. As illustrated in Fig. 6, tracing the far field beam backwards, one can reach two different imaginary beam source points p_x and p_y for the *x-z* and *y-z* planes respectively, because $d_{x0} > d_{y0}$ and $\theta_x < \theta_y$. This phenomenon is called astigmatism and the linear distance between p_x and p_y is the magnitude of the astigmatism. For gain-guided diodes the astigmatism may be as large as 50 µm, but for index-guided, low power laser diodes the astigmatism is typically only 5 µm - 15 µm.

Even this small amount of astigmatism for index-guided diodes can cause problems for some applications, for instance when a good optical system is being used to focus the laser beam on a working plane to a very small spot only a few microns in size. Because of the astigmatism, the focusing lens cannot truly focus the beam in both the *x-z* and the *y-z* planes on the working plane. This is because p_x and p_y cannot be simultaneously positioned at the focal point of the optics. But the astigmatism can be corrected by the use of a weak cylindrical lens after the collimating lens as shown in Fig. 7. The focal length required for the cylindrical lens is about 2 m - 4 m, depending on the value of the astigmatism and the focal length of the collimating lens. But such a collimated and astigmatism-corrected beam still has an elliptical cross section and elliptical intensity contours.

Beam Circularization with Anamorphic Prisms

In many applications a circular cross-section beam is required. There are three commonly used methods to circularize an elliptical beam, they involve the use of a circular aperture, a pair of anamorphic prisms or a single-mode fiber. Each method has advantages and disadvantages.

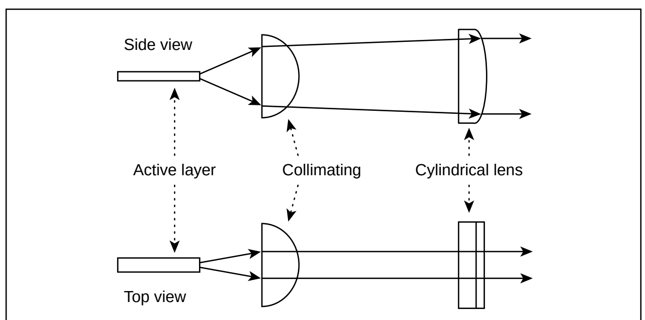

Figure 7 -Astigmatism can be corrected by the use of a cylindrical lens with long focal length.

Using a circular aperture is a low-cost technique, but as has been seen, it greatly reduces the power of the beam and adds side lobes and diffraction rings to the beam profile. A pair of anamorphic prisms can be used to circularize a beam with less power loss and without the imposition of strong diffraction rings and lobes. Anamorphic prisms can enlarge or reduce the size of a collimated beam along one axis (x or y) transverse to the beam direction (z) while keeping the beam size in the perpendicular transverse direction (y or x) unchanged as shown in Fig. 8. Thereby both the visual shape and the intensity contours of the resulting beam can be made circular. The enlargement or reduction can be adjusted by rotating the prisms. Because of the truncation of the collimating lens aperture, a circular aperture slightly smaller than the beam output from the prisms is used to finally circularize the beam as shown in Fig. 8. Although the prisms can change the beam size, they do not change the beam divergence. When the input beam is astigmatic, the output beam is also astigmatic. The reflectivity of each of the four prism surfaces can be reduced to ~1% by antireflection coating. However, the real reflectivity of these surfaces is much higher because of the varying incident angle of the beam, unless they are AR coated for actual angles of incidence. In practice the total power loss caused by such an optical system is about 50%. The four prism surfaces can also cause wavefront distortion and scattering and should be manufactured to a surface flatness of better than $\lambda/4$. The optical assembly is usually neither compact nor inexpensive.

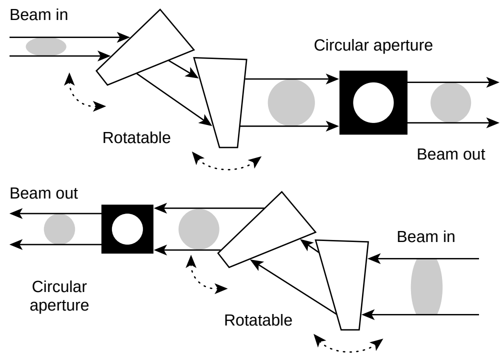

Figure 8 - A pair of anamorphic prisms can enlarge or reduce the beam size along one axis while keeping the beam size in the perpendicular direction unchanged.

Beam Circularization with a Single Mode Fiber

A length of single mode fiber can be used to both circularize an elliptical beam and correct the beam astigmatism. As shown in Fig. 9, a laser diode beam is coupled into a piece of single mode optical fiber with two aspheric lenses. Optical fiber theory indicates that a piece of single mode fiber much longer than the laser wavelength can sufficiently "mix" the beam that the output beam from the fiber has lost the transverse spatial characteristics the beam had on entering the fiber, but the beam coherence is retained. The spatial characteristics of the beam output from the fiber are determined by the shape of the output end of the fiber. The core of single mode fiber has a circular cross section and Eqs. (3) and (4) show that the beam output from the fiber will have a constant divergent angle in every radial direction. Tracing any beam output from the fiber backwards will reach the same imaginary beam source. Therefore the beam output from a single mode fiber has a circular cross section, no astigmatism and a good Gaussian intensity profile.

But there are practical difficulties. For single mode fiber with a cut off wavelength of 630 nm, the fiber core diameter is about 4 μm and the fiber acceptance numerical aperture is about 0.11 or, equivalently, about 12° of full acceptance angle. The ideal input beam focused onto the fiber should thus have a convergent angle smaller than 12° and a spot size smaller than 4 μm. However, laser diode beams cannot meet these specifications. The ratio of the two focal lengths of the input coupling lenses is usually chosen to be $f_2/f_1 \approx 3$. Theoretically, the focused elliptical spot of a laser diode beam has a major diameter of $(f_2/f_1)d_{x0} \approx 12$ μm and a minor diameter of $(f_2/f_1)d_{y0} \approx 3$ μm. The real spot size can be few times larger due to the lens diffraction and aberration.

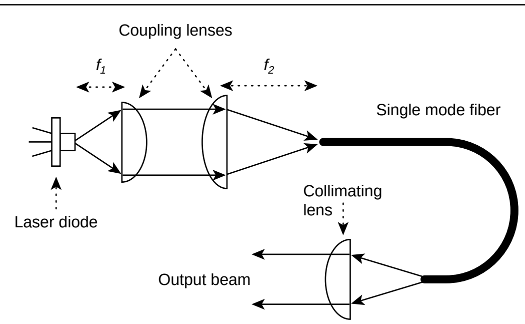

Figure 9 - Single-mode optical fiber can circularize and correct astigmatism of a laser diode beam.

The focused beam has in the *x* direction a convergence of $(f_1/f_2)\theta_x \approx 4^o$ and in the y direction a convergence of $(f_1/f_2)\theta_y \approx 18^o$.

So much of the beam power will not be captured by the fiber. In addition it requires skill and experience to couple a focused beam spot into a 4 µm fiber core. The total power loss is typically about 70% and the whole arrangement is usually significantly larger than a standard laser diode module.

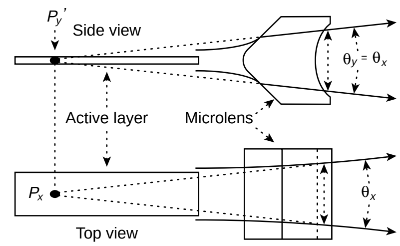

Figure 10 - An appropriate micro-cylindrical lens positioned properly can circularize an elliptical beam and correct the beam astigmatism.

Beam Circularization with a Micro-cylindrical Lens

Recently there has been much research and development work on new and potentially more useful methods of circularizing laser diode beams in a cost-effective manner. Some techniques can also remove the beam astigmatism. These new techniques attempt to circularize the beam without significant beam power loss by re-shaping the beam profile with a diffractive or geometric (such as cylindrical) lens surface to obtain a pseudo point source or collimated beam as desired. In general it is difficult to manufacture a diffractive surface with the required sub-micron structure to obtain the necessary numerical aperture, or alternatively to figure the necessary asymmetric (hyperbolic-spherical, planar-elliptical etc.) transmissive surfaces. But one method of obtaining precision asymmetric surfaces at moderate cost has emerged, based on micro-cylindrical technology developed at Lawrence Livermore National Laboratory (US patent 5,181,224). This patent demonstrates that high quality micro-cylindrical lenses (with only ~200 µm cross-sectional size) can be manufactured and used to circularize the elliptical beams of laser diodes. The microlens is mounted inside the laser diode cap with the lens principle plane at the position (~10 µm from the emitting stripe) where the beam cross section is circular. The focal length of the micro-lens is so chosen that it makes $\theta_y \rightarrow \theta_x$ as shown in Fig. 10. Thereby the beam is circularized and the beam astigmatism is simultaneously corrected, as can be seen in Fig. 10. The shape of the microlens is also shown in Fig. 10. The two surfaces are aspheric to reduce the spherical aberration. Although it is probably impossible to directly polish such a microlens, the microlens can be made by drawing a precisely shaped large preform heated to an appropriate temperature. During the drawing process the preform shape is retained and the resulting microlens looks as if it is fire polished and its optical quality is better than the original preform by the ratio of the preform size to the microlens size. The wavefront distortion of a diode beam transmitted by a correctly aligned microlens is less than $\lambda/10$.

An aspheric collimating lens is used after the micro-cylindrical lens to collimate or focus the beam as required. The microlens can cause weak light scattering, so a circular aperture of appropriate size may be positioned after the collimating lens to block the scattered light, but not truncate the main beam. The beam is not truncated by the collimating lens since θ_x is smaller than the numerical aperture of the collimating lenses. Therefore the far field beam profile, or the focused spot, can be free of the side lobes shown in Fig. 4 and be near diffraction limited. Since the beam only passes through two lenses to be collimated and is not truncated, the total power loss of the optical system is only about 20%, much less than with systems using anamorphic prisms, a single mode fiber or a small aperture. The whole setup is compact, much smaller than arrangements using anamorphic prisms or single mode fibers.

The small size of a microlens and the short distance between the lens and the active layer facet of a laser diode require that the micro-lens be mounted precisely at the right position inside the diode cap. Successfully mounting a micro-lens requires skill, experience and the right tools. Under the Lawrence Livermore patent Blue Sky Research has developed the CircuLaser™ as a diode replacement incorporating a microlens inside the diode cap (this results in a divergent but circular beam) and Coherent Inc. has commercialized the MicroBlaze™ range of modules.

Each MicroBlaze module includes a laser diode, microlens, collimating lens, aperture and drive circuitry in one compact package, 15 mm diameter and 32 mm long. In 1997 the Coherent Auburn Group started the volume manufacture of the MicroBlaze modules in a purpose-designed facility in a new building. This facility incorporates state-of-the-art machine vision, microlens alignment and beam size and wavefront analysis equipment for complete manufacturing in a strictly-controlled cleanroom, along with module “burn-in” and lifetime and reliability verification test stations.

Comparison of Choices

The table below compares and contrasts the benefits and problems associated with the different diode laser circularization techniques. There is no perfect design to produce one module with attributes suitable for all applications, but there is a design solution available for almost every problem.

	Collimating Lens Only	Beam Circularizing Aperture	Anamorphic Prism Pair	Single-Mode Fiber	Module with Micro Cylinder
Astigmatism	5-15 µm	Can correct with additional lens	Can correct with additional lens	Corrected	Corrected
Beam Shape	Elliptical	Near field circular far field elliptical	Circular	Circular	Circular
Cost	Low	Medium	High	High	Medium
Power Transmitted	~80%	20-40%	~50%	~30%	~80%
Size	Compact	Compact	Large	Large	Compact
Wavefront Quality	1-20% Side lobes	Side lobes and diffraction rings	Moderate	Very good	Good

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