Importance of Beam Circularization

- The beams output by edge-emitting laser diodes have different parallel (θ_{slow}) and perpendicular (θ_{fast}) divergence angles, Figure 1. This results in an elliptical beam spot, instead of one with a circularly symmetric Gaussian (TEM_{00}) profile.

- Elliptical beam shapes can be undesirable
  - The focused spot size is larger than if the beam were circular.
  - Larger spot sizes have lower irradiances (power per area). If a certain irradiance is needed, and the laser beam is not circularized, it will be necessary to increase the laser power.

- Figure 2 shows images of an elliptical laser diode beam before (left) and after (right) it was circularized.

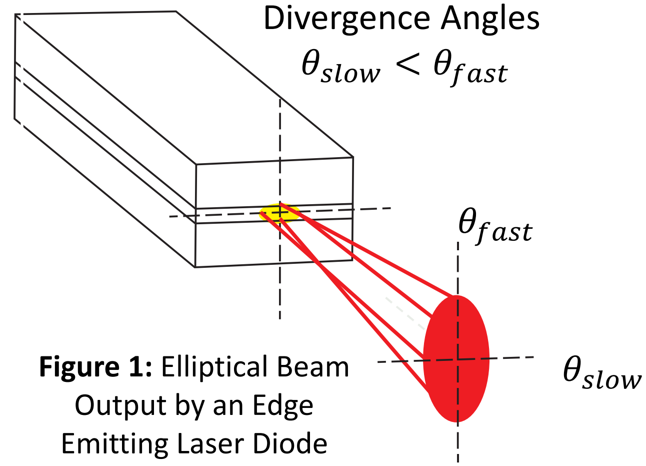


Figure 1: Elliptical Beam Output by an Edge Emitting Laser Diode

Before Circularization:

After Circularization:

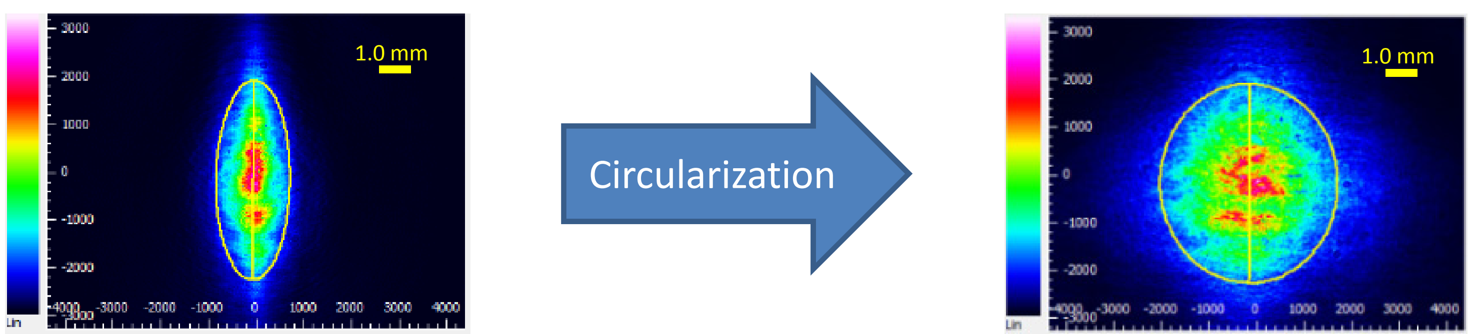
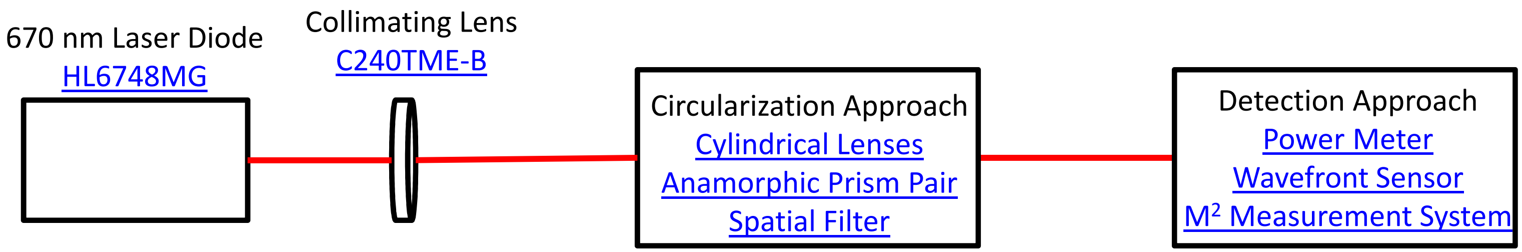


Figure 2: The Effect of Circularizing an Elliptical Beam

Overview of the Experiment

Different approaches exist for circularizing a collimated laser diode beam. Three were investigated and compared using the same collimated input beam and measurement techniques. Each of the experimental components and circularization methods are individually discussed in slides that follow.

- General Layout of Experimental Setup
  - Collimated optical output of a 670 nm laser diode was input into each collimation system.
  - Detection / measurement was performed using a power meter, wavefront sensor, and M^2 system.



- Circularization Techniques Investigated:
  - Cylindrical Lens Pair
  - Anamorphic Prism Pair
  - Spatial Filter
- Efficacy of each circularization approach was evaluated by investigating:
  - Quality of Beam Circularization
  - Deviation of the Resultant Wavefront from an Ideal Plane
  - Optical Power Transmitted by Each Beam Circularization System

Laser Diode Emission

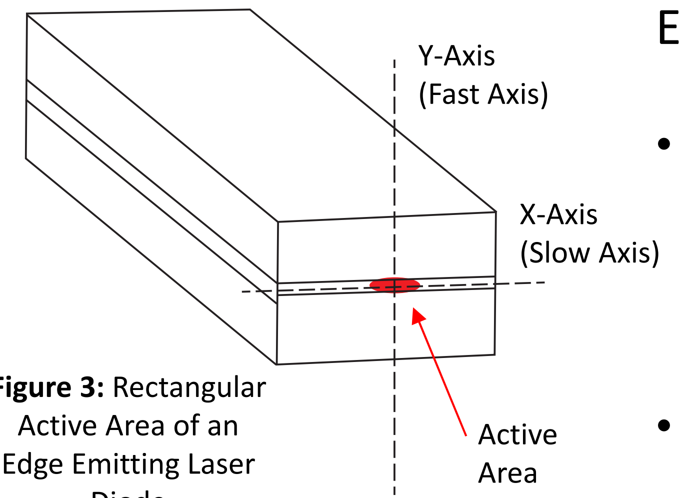


Figure 3: Rectangular Active Area of an Edge Emitting Laser Diode

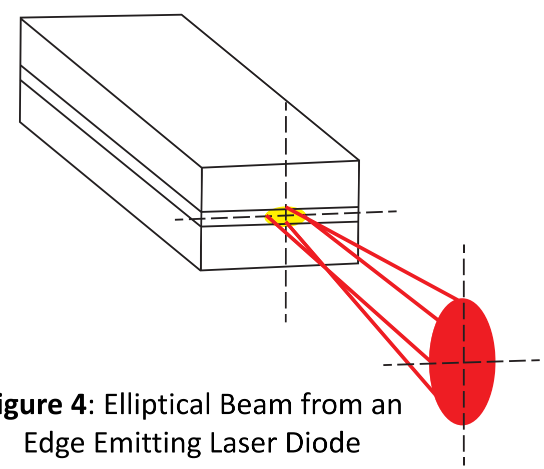


Figure 4: Elliptical Beam from an Edge Emitting Laser Diode

Edge-emitting laser diodes emit elliptical beams.

- The active cross-sectional area of edge-emitting laser diodes is typically rectangular, as is shown in Figure 3. The width and height of the emitter can differ by an order of magnitude or more.

- The aperture's different height and width dimensions result in different beam divergence angles.
  - Diffraction is greater when the dimension of the aperture is smaller.
  - The fast axis of the diode is the axis along which the beam is more highly divergent (Y-axis in Figure 3)
  - The slow axis is orthogonal to the fast axis (X-axis in Figure 3).

- The 670 nm laser diode used in this investigation has a typical full width half max (FWHM) slow axis divergence of 8° and a typical FWHM fast axis divergence of 25°.

Collimation Technique

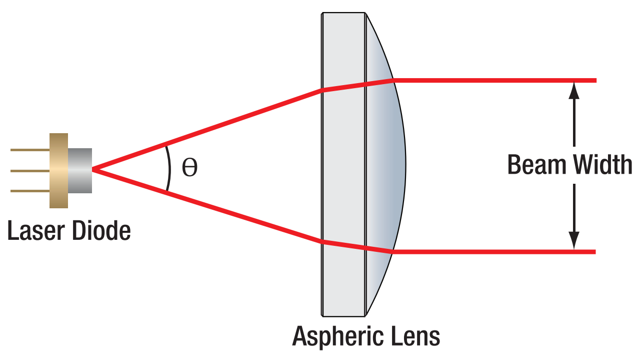


Figure 5: Collimating light from a laser diode. The divergence angle is θ and the beam height differs for orthogonal beam components.

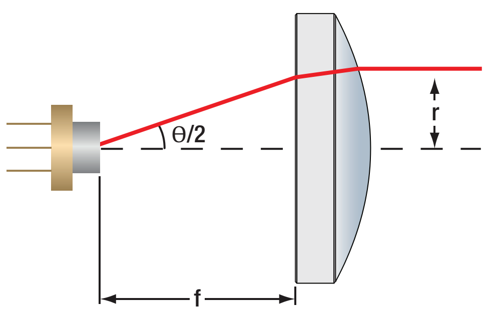


Figure 6: Evolution of the Beam from an Edge Emitting Laser Diode

- Optical applications typically require collimating the highly divergent laser diode beam.
- Collimating optics can be chosen with:
  - Different focal lengths for the fast and slow beam axes (for optimal collimation)
  - A circularly symmetric focal length (for ease of use)
- This application used a single aspheric lens with an 8.00 mm focal length and 0.5 numerical aperture.
- General guidelines, detailed here, recommend positioning the lens to collimate the light from the fast axis, which has the larger divergence angle, to maximize light collection.
- The relationship between the half height of the collimated beam, r, the focal length, f, and θ is:

$$f = \frac{r}{tan(\theta/2)}$$

Circularization System: Cylindrical Lens Pair

A cylindrical lens pair circularizes the beam by expanding one dimension.

- A cylindrical lens focuses the component of light in the lens' plane of curvature and does not magnify the orthogonal component of light (Figure 7).
- While it is possible to use cylindrical lenses to both collimate and circularize the light emitted by the laser diode, the other techniques do not have this capability. In order to directly compare the three circularization techniques, the aspheric collimating lens was left in place and the cylindrical lenses were used only to circularize the collimated beam.
- The cylindrical lens pair was used to expand the narrow dimension of the beam, which corresponds to the slow axis.
- The focal lengths of the two lenses, f_1 and f_2, were chosen such that: $\theta_{fast} = \theta_{slow} \frac{f_2}{f_1}$

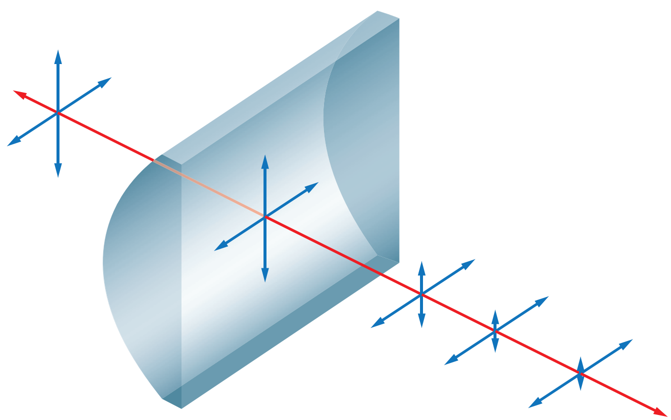


Figure 7: A cylindrical lens focuses light in one dimension.

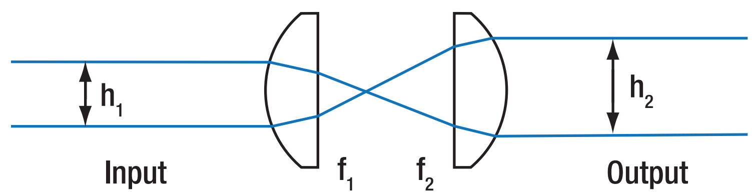


Figure 8: A beam expander used to increase the collimated beam diameter (h_1, h_2) in one dimension.

Circularization System: Anamorphic Prism Pair

An optical element with planar front and back surfaces can be used to expand or reduce one dimension of a transmitted light beam, without affecting the beam's orthogonal dimension. This beam shaping is not a result of focusing the beam.

- **Refraction that does not result in beam shaping:** For each optical element in Figure 9, the beam intersects the external front and back surfaces at the same angle ($\phi_1 = \phi_2$). The areas of intersection between the beam and the two sides are also the same. These symmetric conditions give equal input and output beam heights ($h_1 = h_2$).
- **Refraction resulting in beam shaping:** For the anamorphic prism in Figure 10, the beam intersects the external front and back surfaces at a different angles ($\phi_1 \neq \phi_2$). The areas of intersection between the beam and the two sides are also different. These asymmetric conditions result in different input and output beam heights ($h_1 \neq h_2$).

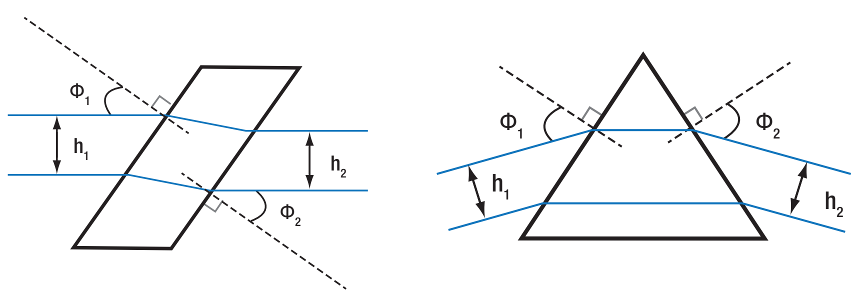


Figure 9: Refraction with no beam expansion. As $\phi_1 = \phi_2$, input and output beam heights (h_1, h_2) are the same.

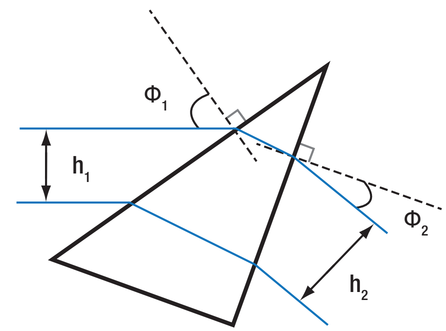


Figure 10: Refraction with beam expansion. As $\phi_1 \neq \phi_2$, input and output beam heights (h_1, h_2) are different.

Circularization System: Anamorphic Prism Pair

Anamorphic Prism Pair Circularizes the Beam by Expanding One Dimension

- While a single anamorphic prism is all that is required to expand, or reduce, one dimension of a laser beam, the resultant output beam will travel in a different direction than the input beam. (Note that if the beam is expanded when it travels through the prism(s) in one direction, the beam will be reduced when it travels through the prism(s) in the other direction.)
- With an anamorphic prism pair, the input and output beams can be made parallel; however the output beam will be offset from the input beam, as is shown in Figure 11. The second prism can also be used to further expand or reduce the beam dimension of interest.
- Different magnification ratios are achieved by adjusting the orientation of the prisms with respect to the incoming beam, which is typically described using the angles α_1 and α_2 shown in Figure 11.
- Prisms exhibit wavelength-dependent performance due to the chromatic dispersion of the prism material, which may be unacceptable in broadband applications.

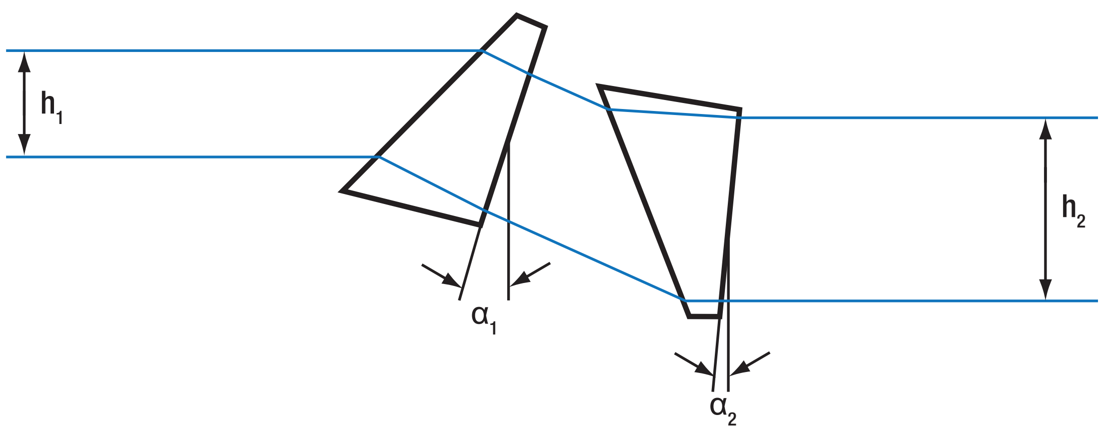
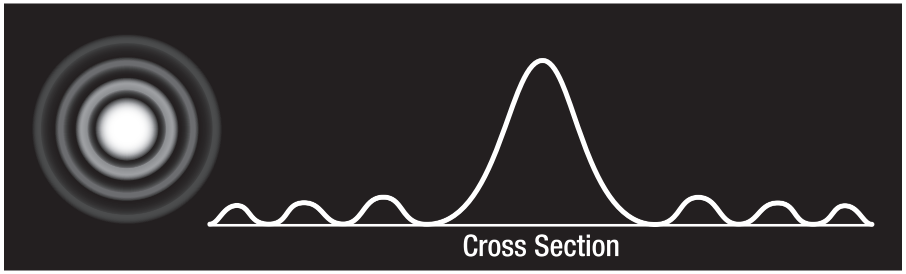


Figure 11: Beam expansion using an anamorphic prism pair.

Circularization System: Spatial Filter

Spatial filters used for beam circularization purposes are small, round apertures, such as pinholes. Incoming light focuses to a spot on the spatial filter. The filter blocks the transmission of all but the center portion of the beam. The spatial filter circularized the beam by apodizing the elliptical spot to a circular spot.

- A Gaussian beam, sometimes called a TEM_{00} beam after the Gaussian-shaped fundamental mode of a perfect laser, is typically considered to be a beam with ideal properties. When focused, its spot size is circular and will pass cleanly through the circular aperture of a spatial filter.
- The spatial filter blocks transmission of the non-ideal components of the beam, such as aberrations, which result from various optical imperfections in the system. The spatial filter transmits a circular beam regardless of the incident spot cross section.
- The filter's aperture is typically chosen to be slightly larger than the spot size of a focused beam with ideal properties, which results in the transmission of only the center portion of the focused beam spot.



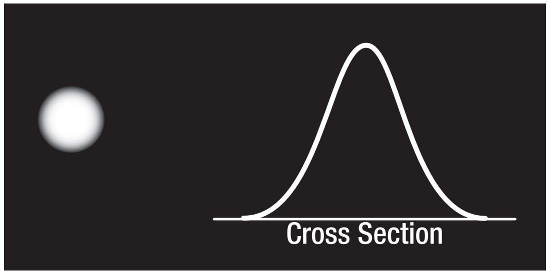


Figure 12: Apodization changes the intensity profile of the optical signal. In this case, apodization is used to filter the structure surrounding the central spot (left) and transmit only the center portion (right).

Circularization System: Spatial Filter

Spatial Filter Circularizes the Beam by Apodizing the Elliptical Spot

- The diameter, d, of a focused beam spot is inversely proportional to the diameter, D, of the beam before the aspheric focusing lens (Figure 13): $d = (M^2)\frac{2f\lambda}{D}$, where M^2 is the beam quality factor, λ is the wavelength, and D is the size of the input beam at the focusing lens.
- The focused dimension of the beam measured along the fast axis is narrower than measured along the slow axis. This is a result of $D_{fast} > D_{slow}$.
- Choosing a spatial filter requires balancing beam quality and transmitted intensity, which are inversely related. In order to transmit a circular beam, the aperture of the spatial filter should have a diameter no larger than the width of the focused width the beam in its narrowest (fast axis) direction.
- A lens must be placed after the spatial filter to collimate the circularized beam transmitted by the spatial filter (Figure 14).

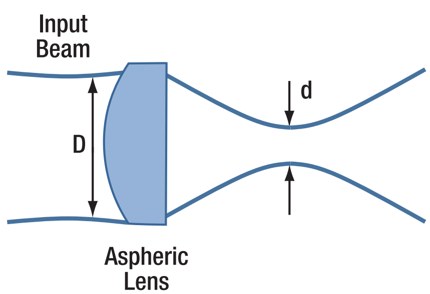


Figure 13: The focused beam diameter, d, depends on the input beam diameter, D, and lens properties.

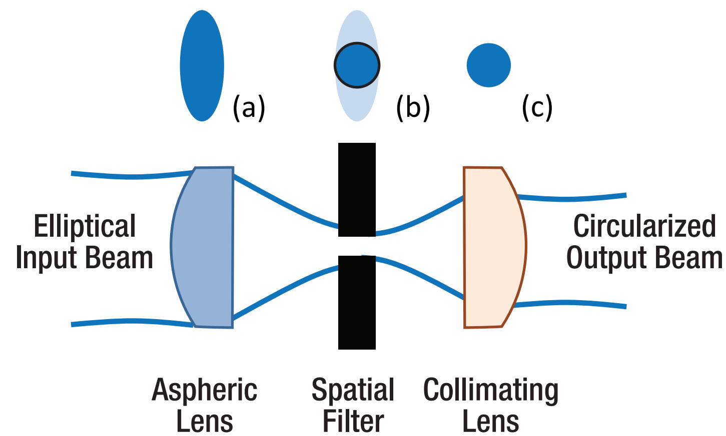


Figure 14: Spatial filter implementation, with the ellipses at the top showing the beam shape immediately before (a), at (b), and immediately after (c) the spatial filter.

Measurements of Circularization and Beam Quality

- **Beam Quality Factor (M squared, or M^2)** M^2 is the ratio of the beam parameter product (BPP) of a given beam and the BPP of an ideal Gaussian beam of the same wavelength. M^2 quantifies the beams' similarity to a perfect single mode Gaussian beam (TEM_{00}), whose $M^2 = 1$. The BPP is the product of the beam waist radius and the beam divergence half angle measured in the far field (Figure 15). Lower quality beams have higher BPPs, and therefore higher M^2 parameters.

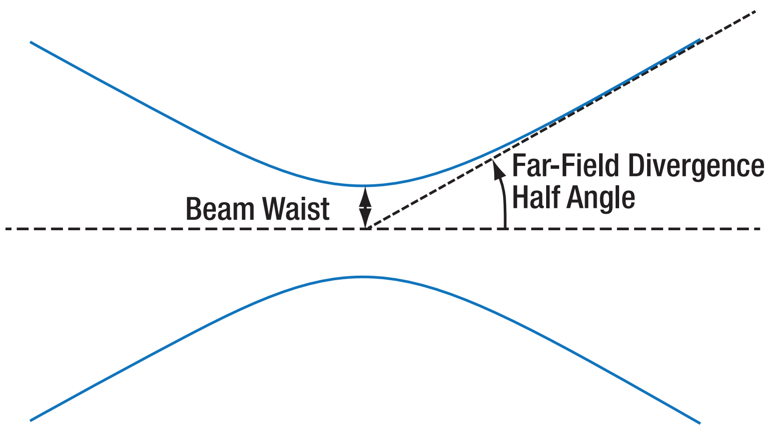
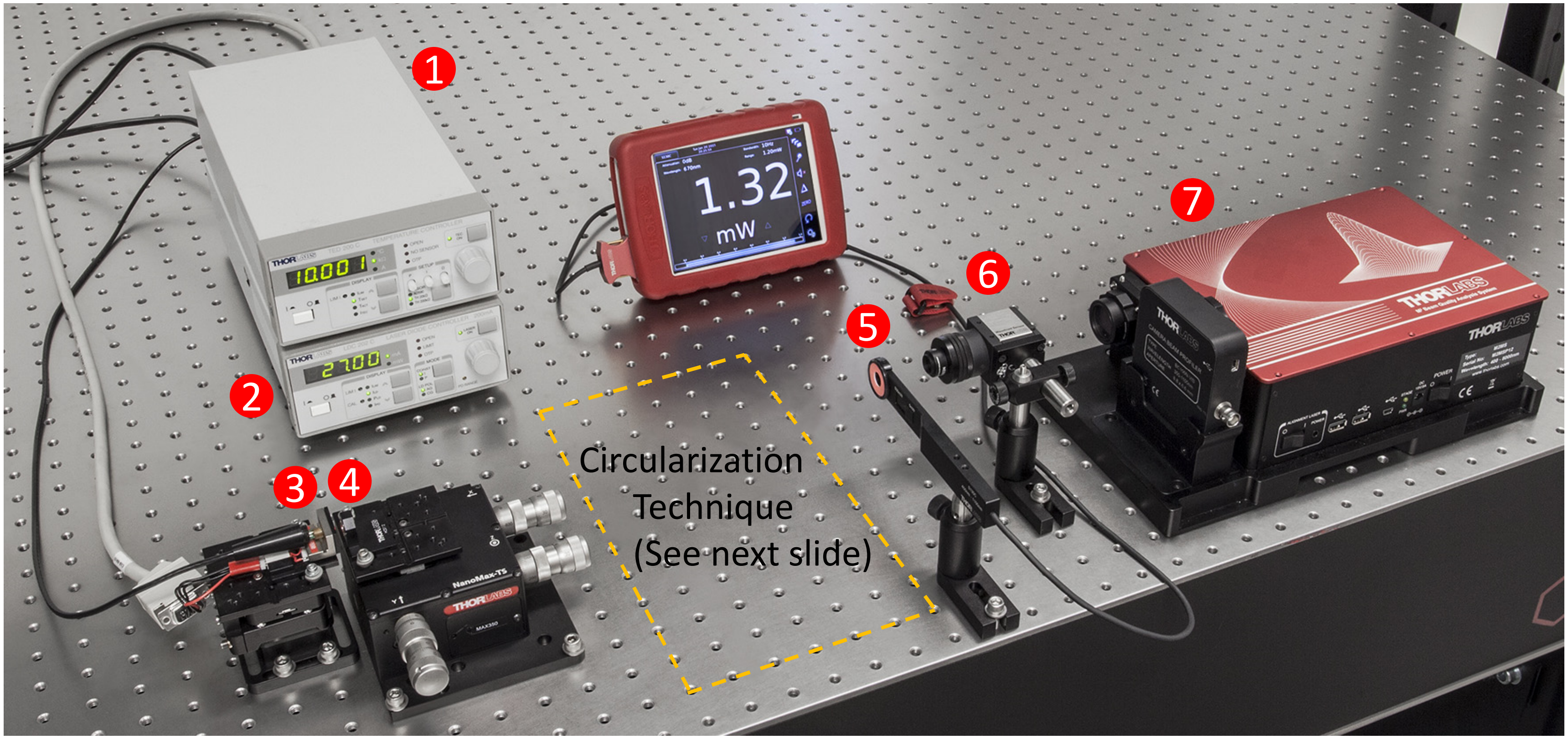


Figure 15: Beam waist radius is measured at the narrowest point of the beam, and the far field divergence half angle is extrapolated back to the location of the beam waist.

- **Beam Profile Measurements** A measurement of the beam profile was used to estimate beam circularity. Circularity is expressed as a measurement of the diameter across the minor axis divided by the diameter along the major axis.
- **Wavefront Measurements** A perfectly collimated beam is a plane wave with a planar wavefront. Wavefront measurements quantify the deviation of the beam's wavefront from an ideal plane in units of the laser diode's wavelength (waves).
- **Power Measurements** Measurements of the beam power before and after circularization provide the power transmitted by each circularization system.

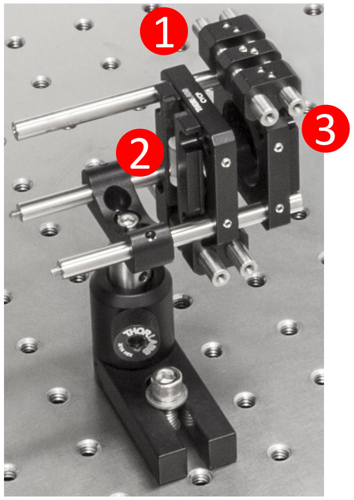
Experimental Setup



1) Temperature Controller: TED200C
2) Laser Diode Current Controller: LDC202C
3) 670 nm Laser Diode: HL6748MG
4) Laser Diode Collimating Lens: C240TME-B
5) 400 – 1100 nm Si Power Meter: S130C
6) Shack-Hartmann Wavefront Sensor: WFS150-7AR
7) M^2 and Beam Profiler: M2MS-BC106VIS

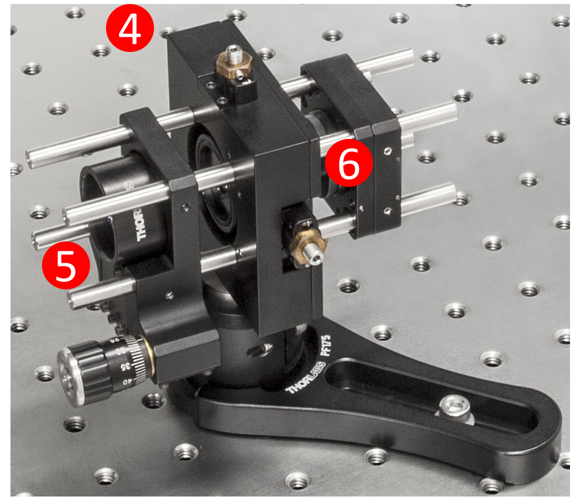
Circularization System Setups

Cylindrical Lens Pair



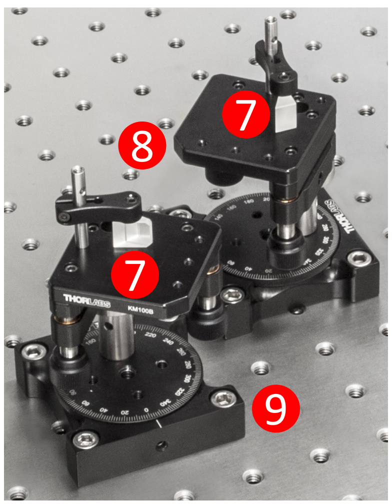
1) 30 mm Cage Mount for Cylindrical Lenses: CYCP
2) Plano-Convex Cylindrical Lens: LJ1874L2-A
3) Plano-Convex Cylindrical Lens (Not Visible): LJ1638L1-A

Spatial Filter System



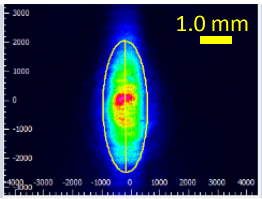
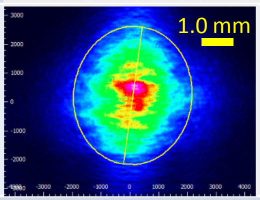
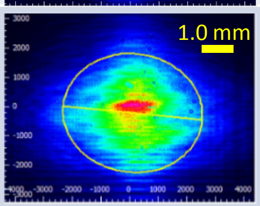
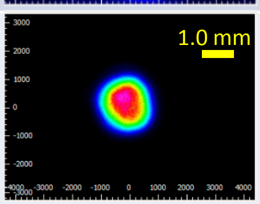
4) Spatial Filter System: KT310 with Ø5 µm Pinhole P5S
5) SM1-Threaded, Achromatic Doublet: AC254-030-A-ML
6) Mounted Geltech Aspheric Lens: C240TME-B

Anamorphic Prism Pair



7. Unmounted Anamorphic Prism Pair: PS873-A
8. 2" × 2" Kinematic Platform Mount: KM100B
9. Rotation Platform: RP01

Results: Beam Profile and Circularity

Method	Beam Intensity Profile	Circularity*
Collimated Source Output		0.36
Cylindrical Lens Pair		0.84
Anamorphic Prism Pair		0.82
Spatial Filter		0.93

*Circularity $= d_{minor}/d_{major}$,
where d_{minor} and d_{major} are minor and major diameters of fitted ellipse (1/e intensity) and Circularity = 1 indicates a perfectly circular beam.

- The table to the left compares the characteristics of the circularized beams with the initial beam.
- The cylindrical lens pair significantly improved the circularity of the beam. A wider selection of cylindrical lens focal lengths would enable further improvements to beam circularity.
- The anamorphic prism pair improved circularity to a degree similar to that achieved by the cylindrical lenses. The performance of the prism pair was tuned by varying the angle between the two prisms.
- Spatial filtering provided the beam with the highest circularity.

Results: Beam Quality and Performance

- The table on the right compares the performance of each technique by considering characteristics of the resultant circularized beam.
- Spatial filtering produced a beam with the best M^2 values and RMS wavefront error, yielding the result closest to a Gaussian collimated beam, but the transmitted power was low.
- The cylindrical lens pair provided the best balance between circularization, beam quality, and transmitted power.
- The beam output by the anamorphic prism pair had better M^2 values and less wavefront error compared to the cylindrical lens pair, but the prisms transmitted less power.

Method	Circularity	M^2 Values	RMS Wavefront	Transmitted Power
Collimated Source Output	0.36	X: 1.28 Y: 1.63	0.17	N.A
Cylindrical Lens Pair	0.84	X: 1.90 Y: 1.93	0.30	91%
Anamorphic Prism Pair	0.82	X: 1.60 Y: 1.46	0.16	80%
Spatial Filter	0.93	X: 1.05 Y: 1.10	0.10	34%

Results: Compensating for Astigmatism

- In addition to the fast and slow axes of the laser diode beam having different angles of divergence from the laser diode's output facet, the focal points of these orthogonal components of the beam do not overlap (i.e. laser diode beams are astigmatic).
- The internal architecture of the laser diode cavity determines the location and contours of the confined optical mode (Figure 16). The optical mode profile determines the degree to which the emitted laser beam is astigmatic. Different laser architectures exhibit different levels of astigmatism.
- One way of visualizing a laser diode's astigmatism is to show the fast and slow axes of the beam originating at different locations along the laser cavity, as is done in Figure 17.

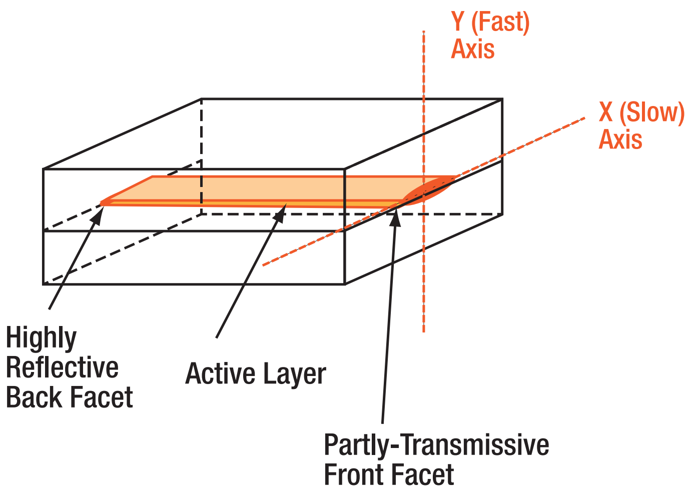


Figure 16: The characteristics of the confined lasing mode structure is heavily influenced by the optical properties and varied architecture of the active and surrounding layers.

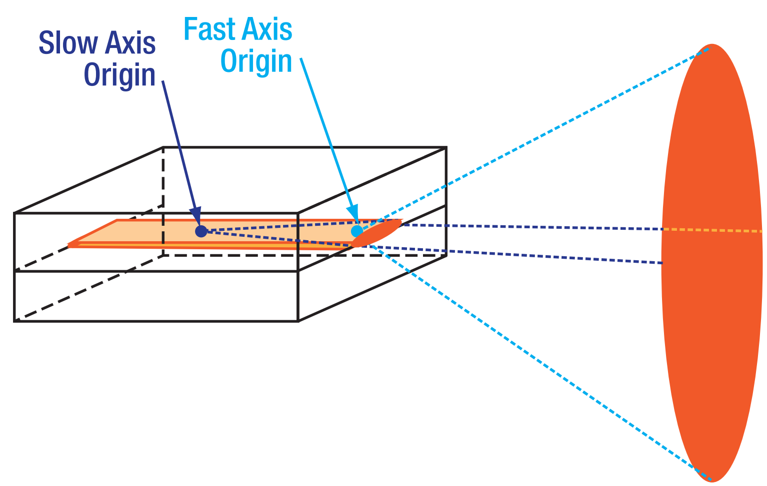


Figure 17: Visualization of astigmatism, in which different points of origin for the fast and slow axis components of the beam arise due to the characteristics of the confined optical mode.

Results: Compensating for Astigmatism

- Cylindrical lenses can provide astigmatism correction by precisely tuning the distance between the two lenses.
- Anamorphic prism pairs do not correct for astigmatism.
- Spatial filtering's astigmatism correction varies with pinhole and focusing lens configuration.

Method	Normalized Astigmatism*
Collimated Source Output	0.67
Cylindrical Lens Pair	0.06
Anamorphic Prism Pair	1.25
Spatial Filtering	0.36

- Normalized astigmatism is the difference in the waist positions of the two orthogonal components of the beam, divided by the Raleigh length of the beam component with the smaller waist.

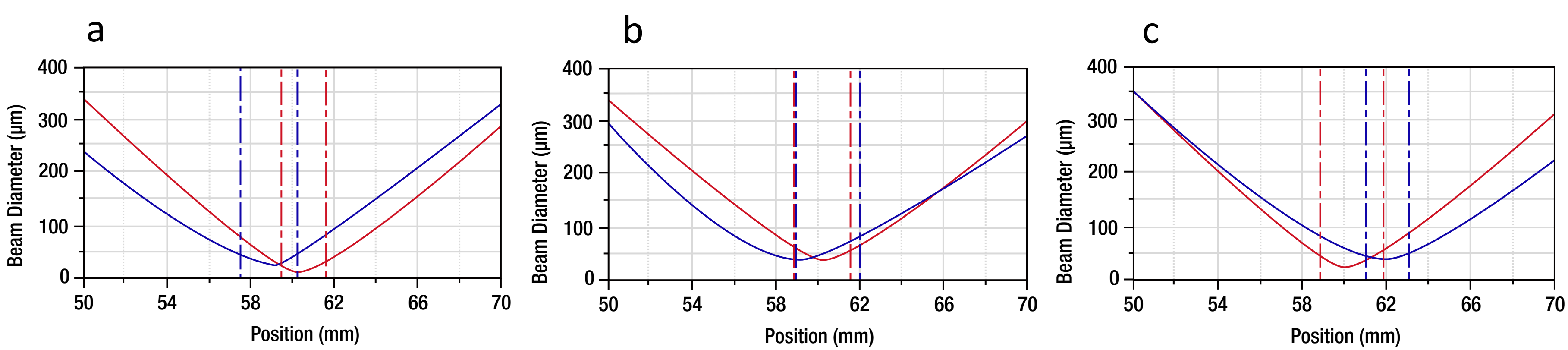


Figure 17: Data illustrating cylindrical lens astigmatism correction by varying distance between the lens pair. a) Astigmatism: -1.71 mm b) Astigmatism: -0.11 mm c) Astigmatism: 1.55 mm

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Experimental Limitations

- Experiments were performed using a single laser diode with divergence angles of 25° and 8°.
- Calculation of circularity was limited by the performance of the beam profiler software algorithm used to determine the beam radii.
- Components were chosen to allow the same experimental setup be used for all experiments. This had the desired effect of allowing the results of all circularization techniques to be directly compared; however, optimizing the setup for a circularization technique could improve its performance.
- The degree of circularization achieved using the cylindrical lens pair was limited by the inability to acquire lenses with custom focal lengths.
- Optomechanical components used to mount anamorphic prism pair provided limited flexibility in aligning the prims, which resulted in a limited ability to circularize the beam.
- The collimating lens mount provided limited ability to precisely position the lens along the optical axis.

Summary

- The performance of three different approaches for circularizing the elliptical output beam of a laser diode beam were investigated and the results compared.
- Each circularization approach was applied to the same collimated laser diode beam and evaluated using the same measurement techniques.
- The cylindrical lens pair provided a balance among beam circularization, quality and throughput.
- The anamorphic prism pair provided a circularized beam with quality comparable to that achieved by cylindrical lens pair, but its transmitted intensity was lower.
- Spatial filtering provides best beam quality at the cost of low transmitted power.
- It was demonstrated that the spatial filtering and cylindrical lens pair techniques are capable of reducing the astigmatism of the laser diode beam.
- Each circularization approach has its benefits. The best circularization technique for an application is determined by the system's requirements for beam quality, transmitted optical power, setup constraints.