Correcting Astigmatism In Diode Lasers

Knowing The Problem And How To Correct It Is Crucial To Wavefront Quality

by Michael Lang

Astigmatism is an inherent property of the output beam of diode lasers. In applications requiring collimation or transformation of the diode laser's beam, this astigmatism must be considered, and often corrected, if the final wavefront is even to approach the diffraction limit.

Diode lasers are p-n junction devices, where radiation created by injection of carriers across the junction is confined by a tiny optical waveguide. This waveguide, with its plano, partially reflecting end facets perpendicular to the junction, forms the Fabry-Perot cavity of the diode laser.

Two general types of optical waveguides may be found in diode lasers. The first is a dielectric slab, or index-guided, waveguide, in which the optical energy is confined through total internal reflection. This is achieved by surrounding the gain region with layers of material with a lower refractive index. In a gain-guided optical waveguide, in contrast, the energy is confined by surrounding the optical gain region with a region of optical loss. It is the guiding mechanism of the waveguide that determines how much astigmatism will be present at the output facet of a diode laser.

In index-guided diode lasers, index-guiding is the principal guiding mecha-

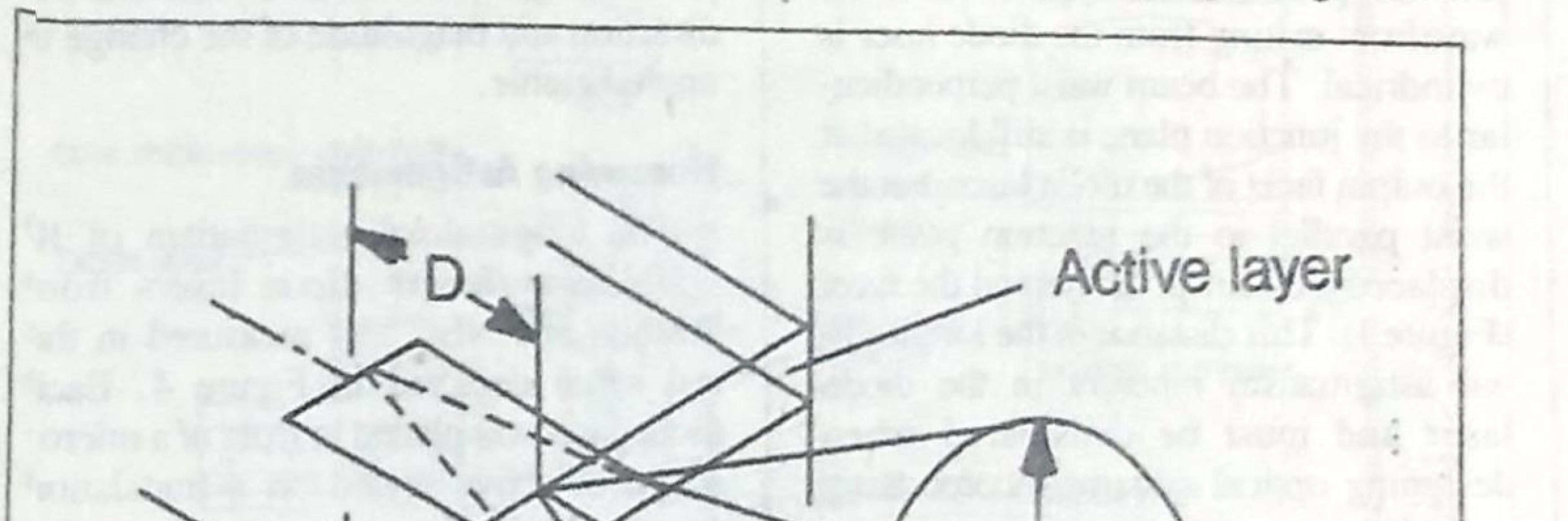

Figure 1. Schematic diagram showing the amount of astigmatism (D) in a diode laser.

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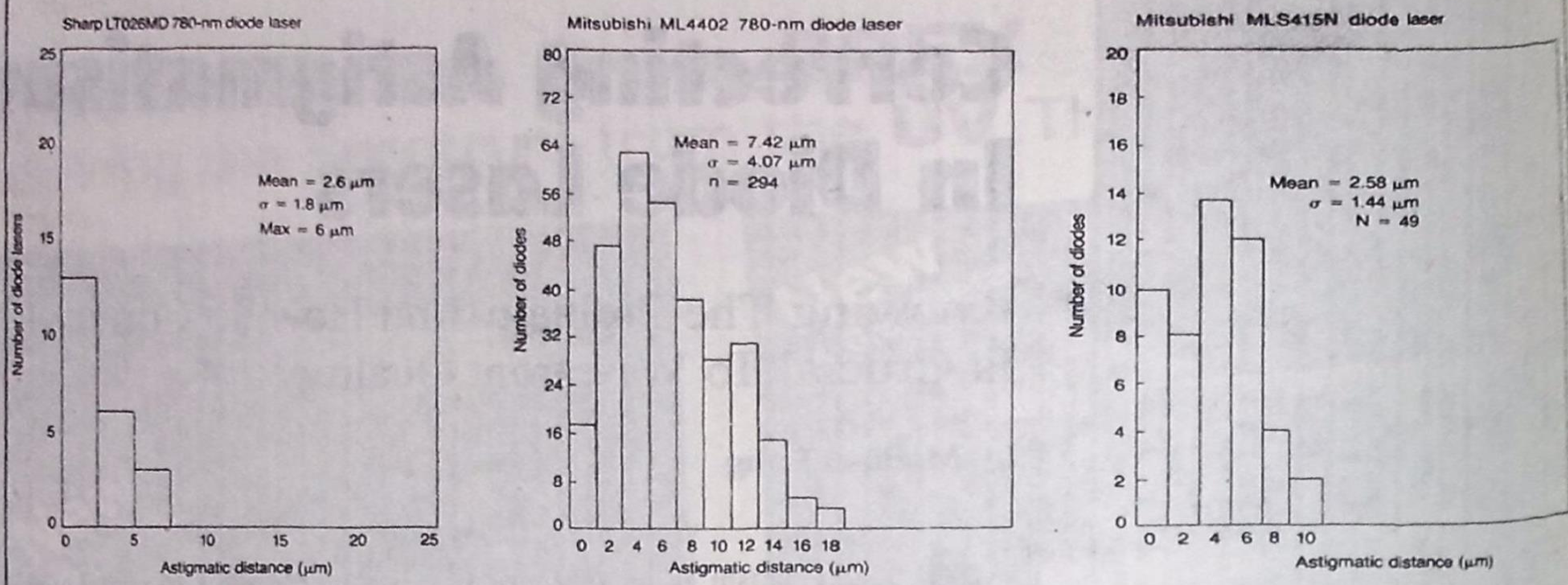

Figure 2. Histograms of astigmatism for three different diode lasers.

nism both parallel and perpendicular to the junction plane. In these lasers, the phase front of the optical wave is planar in both directions, and the wavefront emitted from the laser will have its waists, both perpendicular and parallel to the junction, located at the output facet of the waveguide.

In gain-guided diode lasers, gain-guiding is the guiding mechanism in the junction plane, and index-guiding is the guiding mechanism perpendicular to the junction plane. In this type of laser, the wavefront exiting from the diode laser is cylindrical. The beam waist perpendicular to the junction plane is still located at the output facet of the diode laser, but the waist parallel to the junction plane is displaced a distance, D, behind the facet (Figure 1). This distance is the longitudinal astigmatism inherent in the diode laser and must be considered when designing optical systems incorporating these lasers.

Variations In Astigmatism

Index-guided diode lasers typically exhibit a small amount of astigmatism (between 2 and 8 micrometers). Gain-guided diode lasers usually have between 30 and 60 μm of astigmatism. The new gain-guided visible diode lasers (670-680 nanometers) from all manufacturers have about 40 μm of axial astigmatism.

Index-guided diode lasers vary in their amount of astigmatism from manufacturer to manufacturer, from diode to diode, and even between two diodes of the same type. Diode types with smaller amounts of astigmatism show smaller unit-to-unit variations. Figure 2 shows the variation in astigmatism for three different types of commercial diode lasers. The amount of variation in astigmatism can be as much as 4 μm at the one-sigma point.

Astigmatism in an individual diode laser is also dependent upon the output power. Figure 3 shows that there can be as much as 1.2 μm change over the output power range of a diode laser, and that the direction and magnitude of the change is unpredictable.

Measuring Astigmatism

The longitudinal astigmatism of 10 visible-wavelength diode lasers from Toshiba and NEC was measured in the test setup depicted in Figure 4. Each diode laser was placed in front of a microscope objective seated on a translation stage controlled by a piezoelectric micropositioning system (the Melles Griot Nanomover™). With a CCD camera positioned in the image plane of the objective, we could display the focused image of the diode laser on a CRT. We moved the microscope objective in 1-μm steps until one focus (the thinnest ellipse achievable) could be observed on the CRT. We continued to move the objective in 1-μm steps until the thinnest ellipse in the perpendicular direction appeared on the CRT display. The distance between the orthogonal foci is the longitudinal astigmatism. The results of these measurements indicate that the amount of axial astigmatism present in visible diode lasers varies between 38 and 40 μm.

Effect On Wavefront Quality

In many diode laser applications, it is important to have as little wavefront distortion as possible in the final collimated or focused beam. The amount of astigmatic wavefront distortion, W, caused by the axial astigmatism of the diode laser depends on the wavelength and the numerical aperture of the diode. It can be expressed as:

$$W \approx \{NA^2 \times z\}/2\lambda,$$

where NA is the numerical aperture and z is the diode astigmatism. The divergence can be expressed as a function of the wavefront or the axial astigmatism:

$$Div \approx 8W/\varphi,$$

where φ is the diameter of the clear aperture and W is expressed in the same units as φ.

Correcting In Collimators

Cylinder Lens. The simplest way to correct astigmatism in a diode laser collimator is to place a plano-concave cylinder lens in front of the collimator. If the collimating lens is focused on the front facet of the diode, the cylinder should have negative refracting power with the power oriented parallel to the junction. If the collimating lens is focused on the waist behind the exit facet of the diode laser, then the cylinder lens should have positive power and be oriented perpendicular to the plane of the junction.

If the cylinder lens is placed *before* the collimating lens, the cylinder radius is given[1] (approximately) by:

$$R = \frac{\varphi^2}{8n\,D\,(1 - \cos u)}$$

where φ is the clear aperture of the lens, n is the refractive index of the lens, and u is the smaller of the half acceptance angle of the collimator or the divergence of the laser.

If the cylinder is placed *after* the collimating lens, and we make the assumption that the two lenses are thin, then we can treat the astigmatism as defocus, and calculate the necessary focal lengths using:

$$\frac{1}{F_{cyl}} = \frac{1}{F_{coll}} - \frac{1}{F_{ast}}$$

where f_{ast} is the focal length of the collimator plus the amount of astigmatism present.

Rotating Double Cylinders. Since longitudinal astigmatism varies from diode to diode, a technique that would allow varying the amount of astigmatic correction may be desirable. If a small amount of astigmatism (less than 10 μm) is present, it can be corrected by placing two plano-concave cylinders together, rotating them with respect to each other and then rotating them with respect to the diode laser. All rotation is about the optical axis. This is equivalent to rotating a cylinder or variable power. Unfortunately, this method introduces distortions in the wavefront, which limits its use to weak cylinders and hence diode lasers with relatively small amounts of astigmatism.

Anamorphic Beam Expanders. A beam expander constructed from cylindrical lenses can simultaneously correct astigmatism and circularize the asymmetric beam emitted by the diode laser. Different amounts of astigmatism can be corrected with the same expander by varying the spacing between the elements. This approach keeps the beam coaxial to the diode laser. However, because it requires several cylindrical elements, this method can be cost-prohibitive.

Tilted Plate. A tilted plate placed between the negative and positive elements of a beam expander will add longitudinal astigmatism. The amount of astigmatism added depends on the angle of tilt and the thickness of the plate. The added astigmatism can be calculated

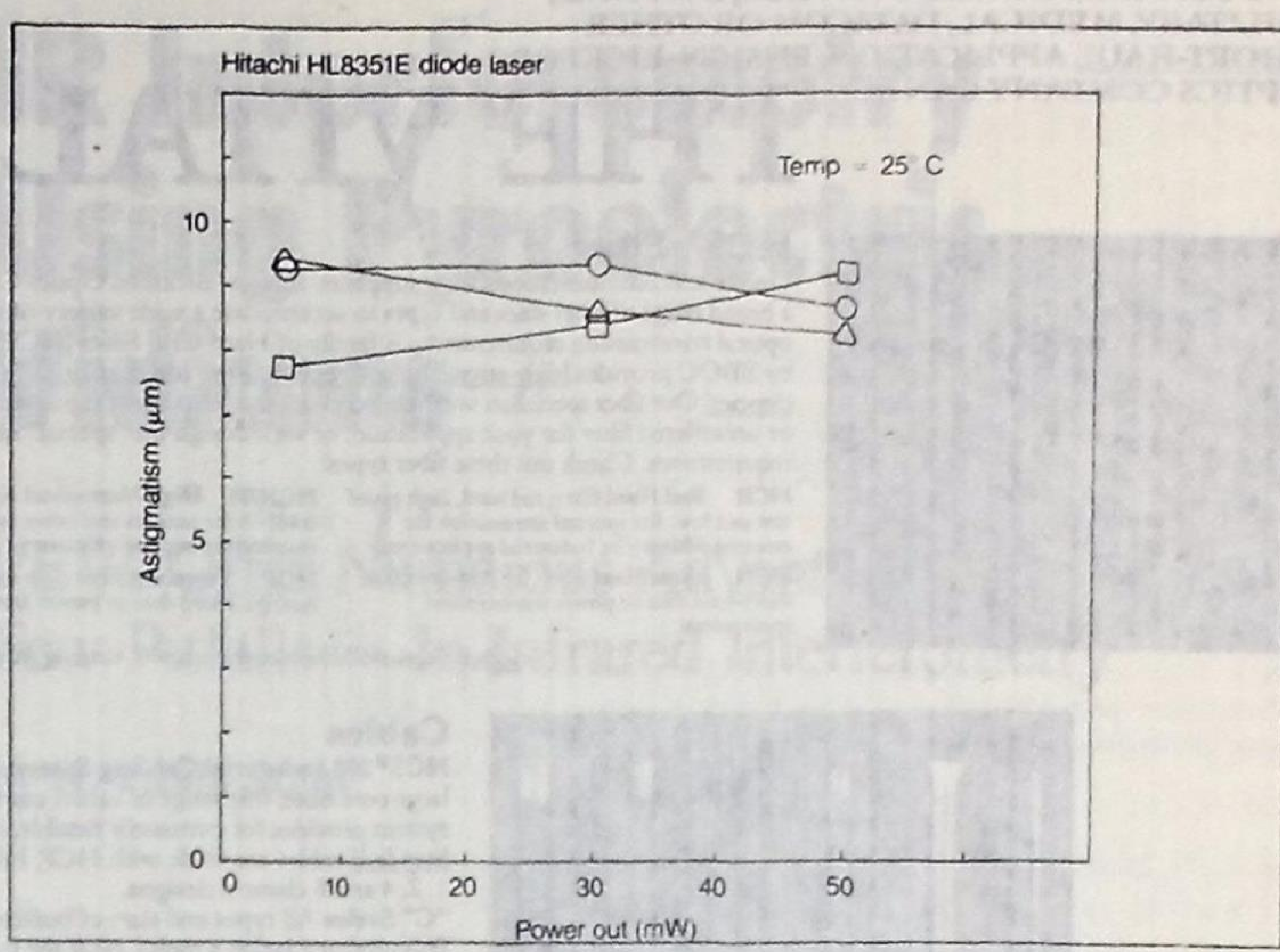

Figure 3. Changes in output power will change the amount of astigmatism present in the output of a diode laser.

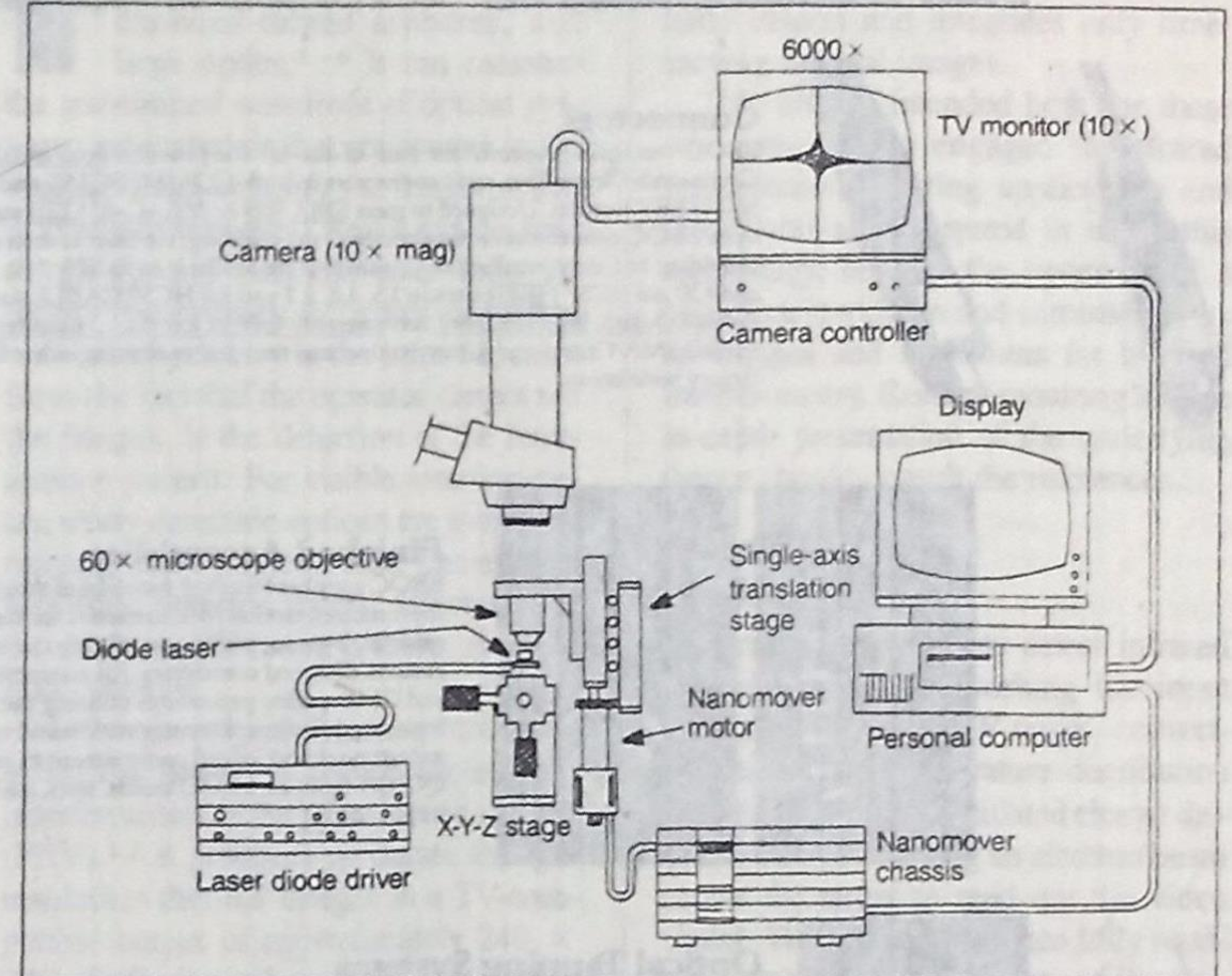

Figure 4. Schematic diagram of the measurement apparatus for determining the amount of astigmatism in a diode laser.

using the following expression:

$$D = \frac{t}{\sqrt{n^2 - \sin^2(U_p)}} \cdot \left[\frac{n^2\cos^2(U_p)}{(n^2 - \sin^2 U_p)} - 1\right]$$

where t is the thickness of the plate, u_p is the tilt angle, and n is the index of refraction of the tilt plate.

References

1. Kuttner. "Laser Beam Scanning," *Optical Engineering, Volume 8*, p352, Marcel Dekker, New York, 1985.
2. W. Smith, *Modern Optical Engineering*, pp 83-84, McGraw-Hill, New York, 1966.