# *Characteristics of Efficient Diode Laser Collimators*


## ABSTRACT

A series of lenses for focusing and collimating the output of semiconductor lasers is described. The description of an anamorphic prism pair to convert the beam cross-section from elliptical to circular is also given. Designs which perform to diffraction limitation yet lend themselves to low cost manufacturing are specifically considered. Correction for the aberrative effects of diode windows, a situation commonly encountered, is analyzed in detail.


## INTRODUCTION

Single-mode diode lasers are currently finding expanding application in fields such as video recording, fiber-optics communication, alignment devices, and many other areas in which helium neon lasers are presently used. In nearly all of these applications the diode laser has to be used in conjunction with a collimating or re-focusing lens system. These associated optics are required because of the inherently wide angle radiation pattern of the diode, which arises from its very small source dimensions (of the order of the wavelength of the radiation). The radiation pattern can be as large as 90º in one dimension, which means that for efficient collection of the laser energy the optics must have a large numerical aperture. In addition, the highly coherent nature of the single-mode radiation dictates that the optics used with the laser must be diffraction limited if its full potential in terms of producing highly collimated beams or sharply focused spots is to be realized. Thus, these optics must be designed and manufactured to stringent quality standards, and yet at the same time they must be capable of being produced at low cost and in large volume.

In terms of optical design, meeting these somewhat conflicting goals translates into devising systems having a minimum number of component elements made of readily worked glass types and having low sensitivity to alignment errors. The number of elements in the systems described here was minimized by choosing the simplest lens form that could allow correction of the aberrations that are significant in this application. Thus, these systems were corrected for spherical aberration, coma, astigmatism, and sphero-chromatism, while chromatic aberration and field curvature were not controlled. These last two aberrations will not affect performance in most diode laser applications, since the radiation is essentially monochromatic and the source dimensions are extremely small. Correction of sphero-chromatism (chromatic variation of spherical aberration) is important because it means that the lenses can be made to perform well over a wide range of wavelengths by simply adjusting the back focal distance appropriately. Correction of the off-axis aberrations allows for a small amount of misalignment between the diode and the lens without significant loss of performance.

The selection of a specific set of lenses to be offered was based on an assessment of potential needs in this rapidly expanding field. Thus, a group of objective lenses of various numerical apertures was designed with the same clear aperture, so that they could be used together in pairs to focus the laser energy to sharp spots of various diameters at different distances from the laser. It was presumed that the shorter focal length, high numerical aperture objectives would most often be used alone as beam collimators, while the longer focal length, lower numerical aperture lenses would be most useful for refocusing the beam. A large diameter, moderate numerical aperture lens was also included for producing a larger collimated beam for long distance applications. A beam-expanding telescope that could be used in conjunction with one of the high numerical aperture collimating objectives was also included for long distance situations in which higher throughput is needed. The set of lenses also contains two moderate resolution objectives intended for use as energy collecting optics for focusing laser energy onto small detectors in long range communications or tracking system applications.

The diode laser has certain properties peculiar to itself, among which is an asymmetric radiation pattern. This pattern results from the fact that the diode cavity has a rectangular cross-section which produces a wide angle output from the narrow cavity dimension and a smaller angular output from the broader cavity dimension. When a lens is used to collimate this asymmetric pattern, a beam with an elliptical cross-section results. For many applications this elliptical beam is acceptable, however, where minimum beam spread is needed in both directions, it becomes necessary to reshape the beam into circular form. Reshaping the beam requires some kind of anamorphic optical system. A beam-expanding telescope employing cylindrical lenses could in principle be used for this reshaping, however, such a system is difficult and expensive to produce to the necessary diffract limited quality. A much simpler approach was taken for the present lens set — an anamorphic prism pair. This system, which is described in detail later, is relatively easy to manufacture and is fairly insensitive to alignment errors. An associated characteristic of the diode laser beam asymmetry is an astigmatic effect that could result in poorer collimation in one plane of the radiation pattern. This effect, if present, can easily be compensated by introducing a weak cylindrical lens of appropriate power into the collimated beam. There are indications, however, that the trend in diode development is towards devices that are free of astigmatism, so that in the near future this correction may not be necessary. In fact, the present set of lenses does not correct for this.

In the following section, the impact of diode laser properties on the design of lens systems is discussed. After that, the characteristics, features and performance of the several optical systems in the set is covered in some detail. The paper concludes with a discussion of various considerations that affect the application and manufacturing of these lenses.

## DIODE LASER PROPERTIES AFFECTING LENS DESIGN

The chief diode laser properties that affect the design of the associated optics are the wavelength, beam divergence, and beam ellipticity. If there is a window on the diode, window thickness, material, and separation from the diode surface must also be taken into consideration.

Currently available diode lasers have approximately the following operating wavelengths: 780, 820, 830, 850, 930, 1220, 1330, and 1550 nanometers. The beam divergence angles of these lasers are typically: l0 × 35, l0 × 50, 13 × 30, 13 × 40, 18 × 36, 20 × 40, and 30 × 40º FWHM (full-width at half maximum). For an ideal Gaussian output beam shape, the $l/e^2$ irradiance contour angular dimensions would be about 1.70 times larger, and for optimum energy collection this is the value most often wanted. The highest numerical aperture objective in the set, 0.62, collects energy within a cone of 77º angular diameter, and is thus compatible with lasers of a FWHM up to 45º, close to the largest laser divergence listed previously. The aspect ratio of the divergence angles in the two orthogonal planes of the radiation pattern ranges from 2:1 to 5:1. The anamorphic prism pair expander was designed to handle ratios from 2:1 to 6:1, with the capability of adjusting to any ratio in between.

Most diode lasers have a protective window hermetically sealed to the housing. Depending on the numerical aperture of the collimating objective lens, the thickness of this window and the material from which it is made can affect the performance of the optics very drastically. The aberration introduced by the window thickness can be compensated by modifying the lens in a relatively simple manner, as will be discussed later. Another important consideration associated with the window is its spacing from the diode laser surface. This spacing, together with the window thickness, determines the minimum working distance that a collimating objective must have. When used as a videodisc objective, the disc thickness has the same effect as a window on the diode. The higher numerical aperture objectives were specifically designed with flat rear surfaces to allow easy modification to suit a given disc or window thickness. Typical window thicknesses range from 0.17 to 0.30 mm, with a few instances of thicknesses as high as 1.0 mm. The spacing of the window from the diode surface varies from 0.7 to 1.0 mm, with one case of a spacing as large as 3.0 mm being noted. Typical videodisc thickness is 1.2 mm. The working distances of the objectives described here are compatible with the window spacing dimensions of most commonly available diode lasers, as is shown later.

## DESCRIPTION AND PERFORMANCE OF THE LENS SYSTEMS

The following describes the construction, performance and special features of the objective lenses and other optical systems that were designed. **Figure 1** shows the optical components of the six diffraction limited objectives.

The first five of these lenses were designed with a clear aperture of 8.0 mm. This particular aperture was chosen as being the smallest diameter such that the shortest length (highest numerical aperture) lens would still have a reasonably large working distance. As mentioned earlier, the five lenses have common clear apertures so that they can be used in pairs to refocus the laser output into a small diffraction limited spot. The basic parameters of these lenses together with their wavefront performance over a range of laser wavelengths is shown in **Table 1**.

The 6.5 mm focal length, 0.62 NA objective is designed with four elements consisting of a cemented doublet and two singlets. This particular lens form was chosen to allow as large a working distance as possible for an objective of this high a numerical aperture. As indicated earlier, the last element was purposely designed with a flat rear surface to allow for easy modification for the aberrative effects of a window or recording disc. This element, which is 5.2 mm thick, could easily accommodate a 2.0 mm thick disc. Videodisc applications usually call for an objective which operates at a finite conjugate ratio. This lens can also be corrected for use at finite conjugate ratios by adjusting the last element's thickness. **Table 1** shows that the lens has very low wavefront distortion over a wide spectral range. In fact, this objective has a peak wavefront error of only 0.14 wavelengths even at the helium neon wavelength of 632.8 nm, which allows it to be tested with a visual range type of interferometer.

The 8.0 mm focal length, 0.50 numerical aperture objective consists of three singlets, one of which is a thick flat plate. This particularly simple lens form was chosen for its combination of high performance and potentiality for economic manufacture in large quantity. The flat plate element, which corrects the spherical aberration in the system, is relatively easy to manufacture, and is obviously insensitive to decentration in mounting. Allowing the plate to be in contact with the adjacent meniscus element obviates any aberrative effects due to tilting of the plate in its mounting. As in the preceding objective, the thickness of the rear flat plate element can be modified to compensate for window or disc thickness, and use at finite conjugates. The plate has a nominal thickness of 4.0 mm, which is ample to permit adjustment for a 2.0 mm disc thickness. The middle element is an aplanatic meniscus; this lens form has reduced sensitivity to misalignment in mounting. The nominal wavefront performance for this objective is 0.05 wavelengths at the design wavelength of 830 nm. At longer wavelengths, the values of wavefront error shown in **Table 1** can be reduced to 0.04 wavelengths simply by increasing the plate thickness slightly. This plate thickness modification could also be combined with that required to correct for the diode laser window thickness. As with the preceding objective, this lens also performs well at helium neon (632.8 nm) wavelength (0.16 wavelength peak wavefront error) which would allow testing in the visible region.

The 14.5 mm focal length, 0.275 NA objective also contains three elements, but in this case the first two form a cemented doublet. The third element is an aplanatic meniscus lens, which, since it introduces neither spherical aberration nor coma, can be removed to produce a

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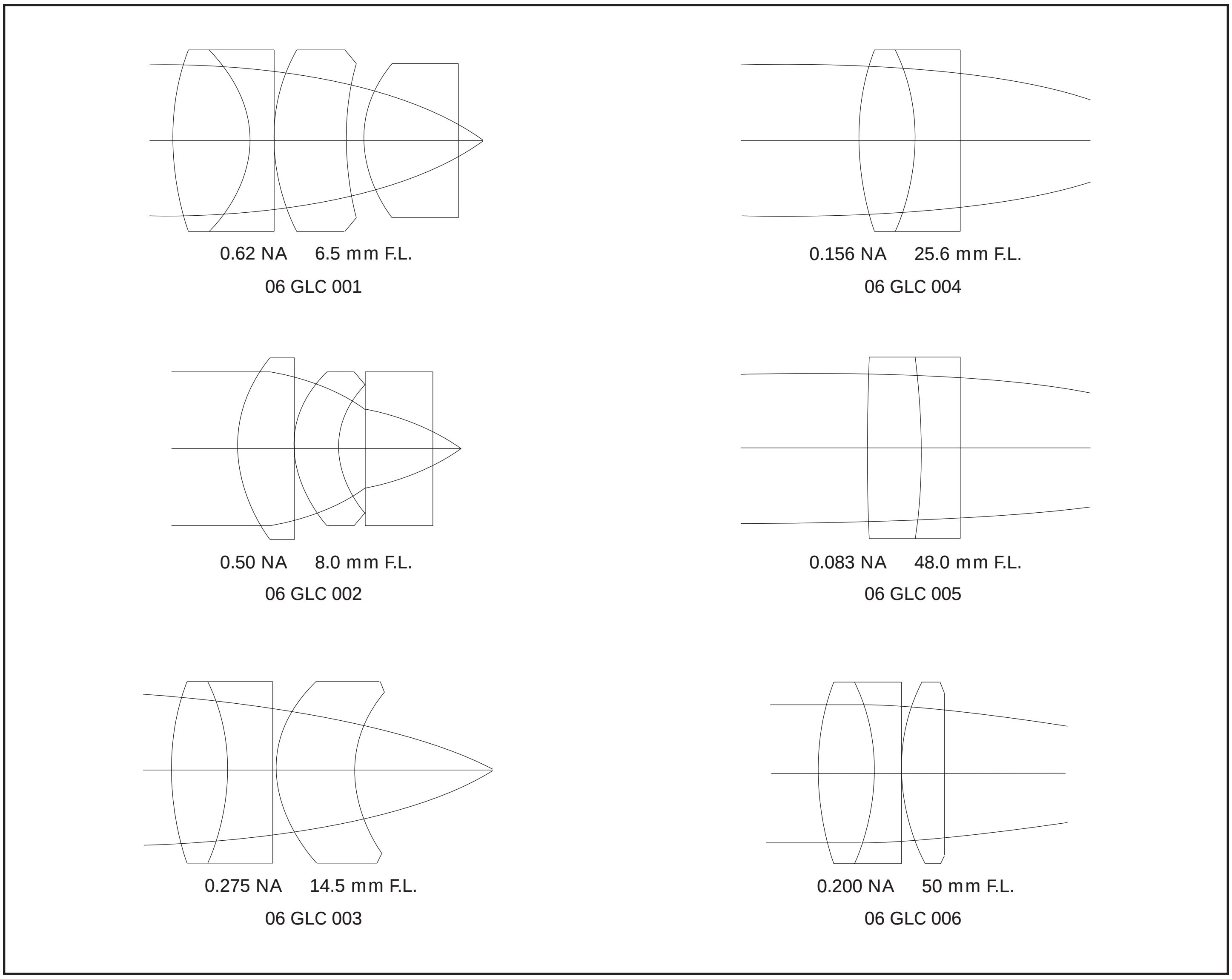


**FIGURE 1. Optical design of six objectives.**

**TABLE 1. Objective Lens Wavefront Performance**

| Numerical Aperture | Focal Length (mm) | Aperture Diameter (mm) | Peak Wavefront Distortion (wavelength units) | | |
|---|---|---|---|---|---|
| | | | 830 nm | 1300 nm | 1550 nm |
| 0.602 | 6.5 | 8.0 | 0.04 | 0.05 | 0.06 |
| 0.500 | 8.0 | 8.0 | 0.05 | 0.13* | 0.14* |
| 0.275 | 14.5 | 8.0 | 0.06 | 0.02 | 0.02 |
| 0.156 | 25.6 | 8.0 | 0.06 | 0.04 | 0.03 |
| 0.083 | 48.0 | 8.0 | 0.05 | 0.04 | 0.03 |
| 0.200 | 50.0 | 20.0 | 0.07 | 0.05 | 0.05 |

**The wavefront distortion of this lens can be reduced to 0.04 for these wavelengths by increasing the thickness of the flat plate element slightly.*

well corrected objective of longer focal length. Thus the doublet was designed as a fully corrected element by itself, and in fact forms the next objective (25.6 mm focal length) in this set. The convertible characteristic of this design was chosen to permit economy in tooling and inventory without compromising performance. **Table 1** shows that the lens performs well over the range from 830 to 1550 nm. This lens can also be tested in the visible region, because the peak wavefront error at 632.8 nm is only 0.13 waves. At the numerical aperture for which the lens was designed, 0.275 NA, the aberration effect of even a rather thick window is not great, as will be shown later.

As indicated before, the 25.6 mm focal length, 0.156 NA objective is identical with the front doublet of the previous lens. Since the aplanatic meniscus third element of that lens introduces no spherical aberration or coma, the wavefront performance of the doublet will be the same as for the triplet.

The 48.0 mm focal length 0.083 numerical aperture objective is a cemented doublet adapted from a visible range design. It performs well over the interval from 830 to 1550 nm, and is also well corrected at 632.8 nm, permitting testing at that wavelength.

The 50 mm focal length, 0.20 NA objective also has a triplet form with the front two elements being a cemented doublet. This objective has a 20 mm clear aperture, and when used as a collimator, would produce a much larger diameter beam than the preceding objectives (all of which have an 8.0 mm diameter). Because of the greater amount of spherical aberration that had to be corrected at this larger diameter, the meniscus element is no longer of the aplanatic form, and therefore the lens is not convertible in focal length as in the preceding case. Because of the larger diameter, the wavefront distortion of this lens is not quite as low as for the other objectives; nevertheless, this objective is still very good over the entire diode laser spectral range, and can also be tested in the visible.

The remaining lenses in the series derive from components of a special beam expander that was designed for this spectral region. The parameters of the telescope are listed in **Table 2**.

The telescope contains five elements, a triplet objective consisting of a cemented doublet and a meniscus singlet, together with two identical negative singlets at the input end. The telescope and the two detector lenses derived from it are shown in **Figure 2**.

A triplet objective of small f-number was used in order to keep the telescope short, without compromising performance. Two identical plano-concave negative lenses were used at the input end so that their overall aberration contribution would be minimal, and the triplet objective would therefore be reasonably well corrected by itself. Another advantage of using two input lenses is that moving one of them allows finer focus control than moving both together. In the design of the telescope, the meniscus element was maintained as an aplanat, and the cemented doublet was optimized to correct for the aberration of the two negative input lenses. The residual wavefront distortion of the resulting telescope design is 0.05 wavelengths at 830 nm, 0.06 wavelengths at 1300 nm, and 0.06 wavelengths at 1550 nm (after refocusing for the chromatic variation in focal length of the objective and input lenses).

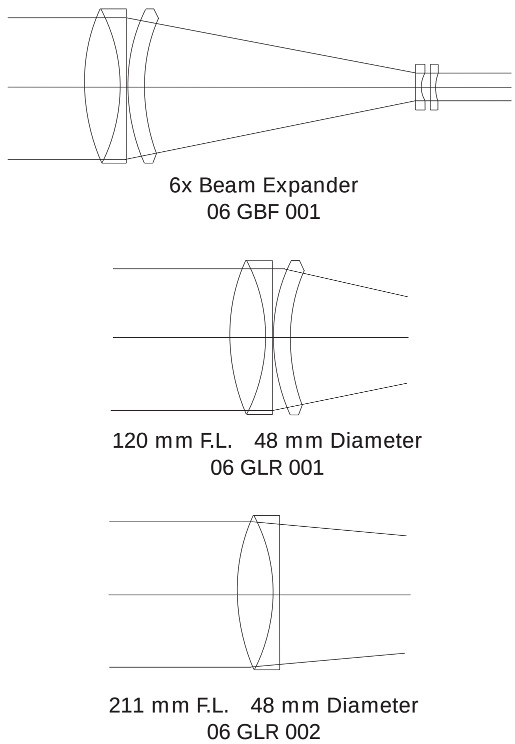


**FIGURE 2. 6× telescope and receiver lenses.**

**TABLE 2. Beam Expander Telescope Parameters**

| | |
|---|---|
| Magnification | 6.0 |
| Input Aperture Diameter | 8.0 mm |
| Output Aperture Diameter | 48.0 mm |
| Overall Length (vertex to vertex) | 122.1 mm |

The triplet objective of the telescope has a focal length of 120 mm and a clear aperture 48 mm, and thus operates a f/2.5. The aberration blur for this objective has a diameter of about 25 microns, which corresponds to an angular resolution of 0.2 milliradians. The useful field of the lens is about 2.0º in diameter.

Removing the aplanatic meniscus from the triplet objective results in a doublet objective with a focal length of 211 mm. This objective has an f-number of 4.4 when used at its full aperture of 48 mm. Since the meniscus element of the triplet introduces no aberration, the doublet has the same angular resolution of 0.2 milliradians, or a blur diameter of about 45 microns.

The spot size of each of these objectives is compatible with the dimensions of typical detectors that would be used in diode laser applications.

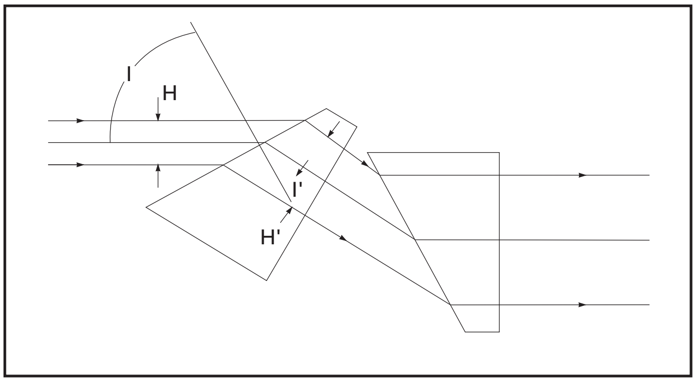


**FIGURE 3. Anamorphic prism pair beam expander.**

## ANAMORPHIC PRISM PAIR BEAM EXPANDER

A simple and economic way of transforming the elliptical laser beam cross-section emerging from a collimating lens into a circle, is to use a pair of identical wedge prisms, as shown in **Figure 3**. This result could also be accomplished with a single prism, however, the prism pair has the advantage of directing the beam back along its original direction, and also allows larger amounts of ellipticity to be corrected.

If the exit face of the wedge prism is made normal to the emerging beam, then the anamorphic magnification, M, of the prism is given by:

$$M = H'/H = \cos I'/\cos I$$

The magnification of a pair of prisms is just the square of this value.

A set of prisms with a given wedge angle can be used to produce a fairly wide range of magnification simply by tilting both or them at appropriate angles. The equation, which applies at either surface of the prism, shows that when the prism is tilted, the major effect on magnification occurs at the side with the higher angle of incidence. Even when tilted, the angles on the exit side of the prism are small, hence, the cosines remain close to unity and there is little magnification at that surface. In the prism set that was designed, tilting each prism through 10º on either side of the nominal orientation results in a magnification change from 2:1 to 6:1. This change in incidence angle is small enough so that in production the same anti-reflection coating can be applied to prisms destined for any of the expanders. To obtain a given magnification in production, a precise jig is used to align the prisms, and they are then cemented into their housing. Magnifications other than the standard ones offered can obviously be produced.

## APPLICATIONS AND MANUFACTURING CONSIDERATIONS

A major consideration for the highest numerical aperture objectives is the aberration introduced by the window of the diode when the objective is used as a collimator. Obviously, this consideration is even more important if the objective is to be used with a thick optical recording disc. **Figure 4** shows the peak wavefront distortion that is introduced into the beam collimated by objectives of various numerical aperture as a function of window thickness and material.

In a diffraction limited system, it is desirable to keep any degrading influences to 0.1 wave or less. It is apparent that the typical diode window thickness of 0.17 to 0.3 mm causes excessive aberration in the 0.62 NA case and marginal degradation in the 0.50 NA case. The window effect is negligible for numerical apertures of 0.275 and lower. The aberrations due to the window can be compensated in a simple way for the two high numerical aperture objectives for which this effect is important. Both the 0.50 and the 0.62 numerical aperture objectives were designed specifically to allow for this correction by making the rear surface (next to the diode) flat. The correction for the window then just amounts to reducing the thickness of the last element of the objective by an appropriate amount. This adjustment is somewhat complicated by the fact that the window probably has a different refractive index from that of the objective lens element. The following equation, which refers to **Figure 5**, predicts the lens thickness adjustment based on third order aberration:

$$T_{L'} = T_L - T_w \frac{N_L^3\left(N_L^2 - 1\right)}{N_w^3\left(N_L^2 - 1\right)}$$

where; $T_{L'}$ = adjusted thickness of objective rear element
$T_L$ = nominal thickness of objective rear element
$N_L$ = refractive index of objective rear element
$N_w$ = refractive index of window
$T_w$ = laser diode window thickness

In a typical case $N_L = 1.76$ and $N_w = 1.51$, so that the factor multiplying the window thickness, $T_w$, becomes 0.966. This shows that even when the window has a refractive index considerably different than that of the objective lens rear element, the change in thickness of this element needed to compensate aberration is essentially equal to the window thickness itself. When this adjustment in the objective lens is made, the clearance between the objective lens housing and the outside of the laser window becomes equal to the nominal objective lens working distance less the spacing between the diode laser surface and the inside of the laser window. Expressed mathematically, this is:

$$S_L = W.D. - S_D$$

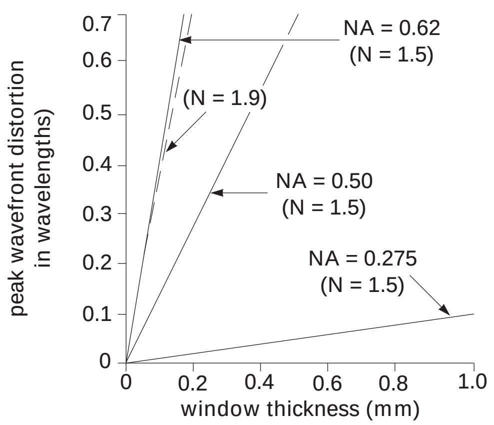


**FIGURE 4. Effect of a window on wavefront distortion (@ 830.0 nm).**

This is also shown in **Figure 5**. In the case of the 0.62 NA objective, which has a working distance of 1.21 mm, a diode laser with a 0.7 mm spacing between the diode surface and the inside surface of the diode window would result in a clearance of 0.51 mm between the outside of the window and the objective housing (using the adjusted rear element thickness).

It is also important that the flatness of the window surfaces and any wedge angle between them be consistent with a wavefront degradation of significantly less than 0.1 wave. The optical homogeneity of the window material must also be of a quality consistent with this requirement. These specifications of course apply only over the actual area of the window traversed by the laser beam. For a 0.62 numerical aperture, the beam cone angular diameter is 77 º, and it encompasses a dimension of 1.6 mm at window distance of 1.0 mm from the diode surface, so that typically only a very small window surface area is actually involved.

Another consideration about mating objective lenses to diodes is that of alignment of the lens axis to the center of the diode. The objectives described here were designed to operate with half field angles of 0.7 to 1.0º without significant degradation in performance. In the case of the shortest focal length objective (the 0.62 NA with focal length 6.5 mm), the useful field of 0.7º means that the center of the diode radiating source area (not its housing, which may be significantly off-center due to tolerances) should be aligned to the lens housing to within plus or minus 0.08 mm to avoid degradation due to off-axis aberrations. The alignment tolerance on the 0.50 NA objective is plus or minus 0.14 mm. Its tolerance is larger than that for the 0.62 NA lens because its focal length of 8.0 mm is larger as is its 1.0º field. (In general, linear field is equal to the angular field, in radians, times the focal length of the lens.) The objectives were designed for modest field coverage consistent with the reasonably careful alignment tolerances to be presumed in precision applications of this

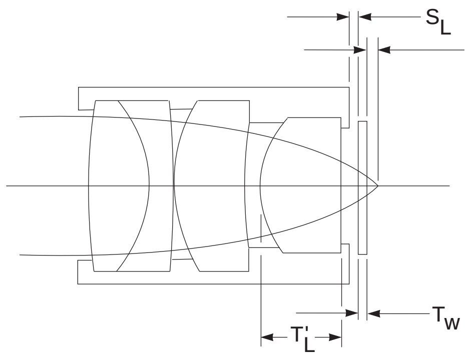


**FIGURE 5. Correcting for window thickness.**

kind. Designing for a larger field would have complicated the designs considerably. In this connection, it should also be realized that in order for the collimated beam produced with a 0.62 NA objective to have a diffraction limited planar wavefront, the axial position of the lens with respect to the diode must be adjustable with a sensitivity of about one micron.

No attempt was made to correct for field curvature in designing these lenses. This allows the components to be assembled without tight centration and spacing tolerances. Further economies were realized by using high index glasses for most of the elements. This makes suppression of aberration during design simpler, produces elements with longer radii and allows for the effective use of single layer antireflection coatings.

It is obvious from the considerations about the interaction between lens characteristics and diode properties that there are important economic trade-offs in lens and laser manufacturing and installation costs. From the point of view of the lens designer and manufacturer, it would be highly desirable that diode laser window thickness and material be standardized. It would also be valuable to standardize the diode surface to window spacing to a minimum dimension consistent with economic manufacture of the lasers. This spacing is important because of its impact on objective lens working distance. Large spacings call for long working distances, which are difficult to achieve in high numerical aperture objectives. A final hope is that mechanical alignment of the diode center within its housing can be held to within tolerances on the order of 0.025 mm, allowing the laser to be incorporated into an optical assembly without the need for later adjustments.

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