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APPLICATION NOTES:
Using Precision Molded Aspheres

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Using Aspheric Lenses: Part I – The Basics

Aspheric lenses – A brief history

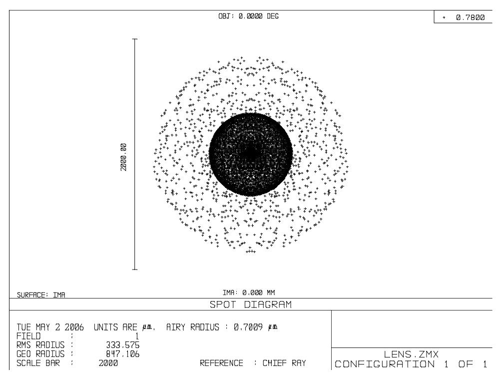
The power of using aspheric lenses has been known for several centuries, starting with the formulas invented by Renee Descartes in the early 1600s. Although it was known that aspheric lenses had major advantages over their spherical counterparts, the cost and complexity of manufacturing them has limited their use in commercial and scientific applications.

In the last fifty years, new manufacturing methods have been developed that allow high volume, cost effective production of precision aspheric surfaces. Some examples of these methods include diamond turned aspheric optics and compression molded glass aspheric lenses. While diamond turning can produce very good quality aspheric lenses in small quantities, molding is the only true method for low priced glass aspherics for high volume applications.

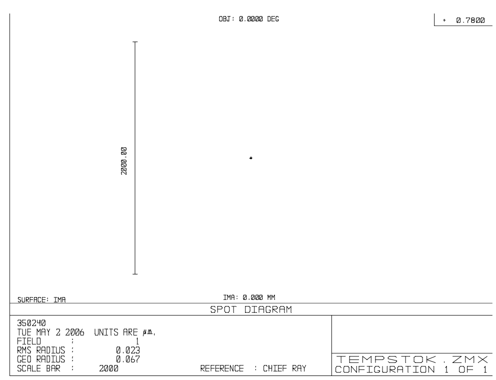
Advantages of Aspheres

Traditional spherical lenses have a simple shape that can be described as an arc of a circle and can be specified using only a radius of curvature. Although these lenses are simple to manufacture and inexpensive to use, they suffer in performance due to a phenomenon called spherical aberration. This inherent defect is due to the fact that a spherical shape is not the ideal shape for a focusing or collimating lens to be. The ideal case is a more complex shape that is typically defined using a radius of curvature, a parabolic term (conic), and several high order coefficients.

Figure 1:
Comparison of spot size between conventional spherical optic and aspheric optic. (8mm input beam, 8mm EFL, 780nm)



Spherical Lens: 667µm RMS spot size



Aspheric lens: Diffraction Limited spot

The complex shape of aspheric lenses allows for correction of spherical aberration. This provides better quality collimated beams for collimating applications, a smaller spot size for focusing applications, and better image quality for imaging applications. In fact, in many cases just a single aspheric lens can take the place of several conventional spherical lenses, leading to a lighter, more compact, less expensive, and better performing optical system. Aspheres are now a viable design option for many applications.

LightPath Technologies has over 10 years of experience in molding high precision glass aspheric lenses for the industrial, scientific, communications, medical, and defense markets. The LightPath catalog contains over 35 standard molded aspheric lens types. Customization and design of new lenses is also available if the off-the-shelf lenses do not fit your needs.

Design Wavelengths

All of the aspheric lenses in LightPath's catalog are designed for a specific design wavelength. It is at the design wavelength that all the other specifications for the lens are given. The lenses can be used at wavelengths other than the design wavelength, so it is best to think of the design wavelength more as a reference than a requirement. If you use a lens at a wavelength other than the design wavelength, there will be three changes to the lens – the effective focal length (EFL) will change, the back focal length (BFL) will change, and the wavefront error (RMS WFE) will change.

Figure 2:
Example of changes in the 350140 lens when used at different wavelengths:

350140 used at 780nm (design wavelength)
Effective Focal Length: 1.452mm
Back Focal Length: 0.876mm
RMS WFE: < 0.070λ (Diffraction limited)

350140 used at 532nm
Effective Focal Length: 1.424mm
Back Focal Length: 0.851mm
RMS WFE: < 0.110λ

350140 used at 1550nm
Effective Focal Length: 1.479mm
Back Focal Length: 0.901mm
RMS WFE: < 0.080λ

As a rule of thumb, if you use a LightPath aspheres at a shorter wavelength than the design wavelength, both the EFL and BFL will decrease from the value given in the catalog. Conversely, if you use the lens at a longer wavelength than the design wavelength, the EFL and BFL will increase. The change in wavefront error is possible to quantify with some analysis in Zemax, Oslo or other popular optical simulation programs. In general, the wavefront error of a lens is more sensitive to deviations from the design wavelength when used at short visible wavelengths rather than longer infrared wavelengths.

Laser Windows

Many of the lenses in LightPath's catalog include a coverglass window in the design. These windows are denoted by a small rectangle in the optical path shown on the drawings. The laser window are there to show that these lenses were designed to compensate for the spherical aberration introduced by the coverglass window that is used in commercial "TO-can" type lasers and photodiodes. When a lens is compensated for a laser window, the thickness and index of the window will be denoted on the lens diagram.

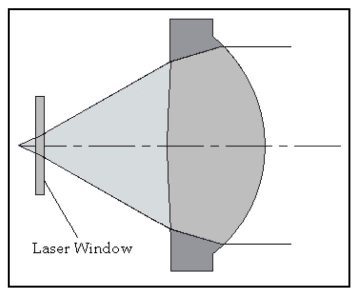


Figure 3: Example of an asphere with a laser window.

If a lens is picked that is compensated for a laser window and the application does not have a window physically present, the wavefront error will increase and the back focal length will decrease. The BFL and wavefront change can be simulated in Zemax or other popular optical simulation programs. In general, though, the degree of performance degradation depends on the speed of the lens – slower lenses will not be impacted as much as fast lenses are.

Figure 4:
Example of changes in the 350150 lens when used with and without laser window:

350150 used with laser window
Back Focal Length: 1.09mm
RMS WFE: < 0.070λ (Diffraction limited)

350150 used without laser window
Back Focal Length: 0.99mm
RMS WFE: < 0.150λ

Ellipticity and Ways to get Around it

Most commercially available laser diodes project an elliptical beam due to the diode junction having a rectangular shape. This elliptical beam can create difficulties for many applications and lowers the efficiency of fiber coupling. A number of techniques exist to “circularize” laser diodes, such as LightPath’s CircuLight anamorphic lenses, anamorphic prism pairs, micro-optics (i.e.: BlueSky® CircuLaser), and beam truncation. Each has their advantages and disadvantages as outlined below.

CircuLight
LightPath’s CircuLight™ lens technology creates a simple solution to circularize and collimate many of the available laser diodes. The first surface of the lens collimates the fast axis of the laser while letting the slow axis continue to diverge. The second surface of the lens collimates the slow axis of the laser while passing the already collimated fast axis through. By collimating the fast axis of the diode before the slow axis, it allows the slow axis light to “catch up” to the beam diameter of the fast axis, resulting in a collimated and circular beam in a very elegant and compact package. Diode to single-mode fiber coupling can be increased to over 90% in some cases. An alignment tab is built-in to aid in adjusting the rotational orientation.

Anamorphic Prism Pair
Anamorphic prism pairs are the most frequently used method for achieving good beam quality and circularization of laser diodes. Although this method achieves approximately 50% energy throughput, it is often difficult to align the prisms, the prisms are expensive, and the exit beam is not collinear with the laser diode - all of which make packaging difficult. An additional collimating optics is needed as well, adding to the cost and complexity.

Beam Truncation
Beam truncation is the least efficient method, and is accomplished by simply “clipping” the beam with an aperture or lens. It produces a circular beam, but only 10%-30% of the beam is transmitted.

Micro-Optics
Some micro-optics approaches utilize a small cylinder lens mounted internally, which slows down the diverging fast axis beam. This lens is incorporated into an existing laser diode unit. This method does not produce a collimated beam and an external collimating lens is still needed. The value-added benefit of this approach is its compact size, low cost and high-energy throughputs of approximately 75-80%. This integrated approach limits the variety of laser diode options.

RoHS Compliance
New European regulations now restrict the amount of certain hazardous substances that can be included in electrical components, including optics that may be present within those components. The RoHS standard calls out strict limitations to the amount of materials like Lead, Mercury, Chromium, and Cadmium that can be present. This can present a problem for optics manufactures and customers since many of the most commonly used glasses are high in lead content.

In response to the RoHS requirements (and the similar JGPSSI requirement in Japan), LightPath has introduced a new line of molded aspheric lenses made from a lead-free “green” glass called ECO550. This glass completely meets the requirements of both RoHS and JGPSSI. Many of LightPath’s legacy aspheric lenses have already been redesigned for this new glass type, and the remainder will be transferred over 2006 – 2007.

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Using Aspheric Lenses: Part II – Choosing the Right Lens for Diode Collimation

One of the most common uses for aspheric lenses is in the collimation of edge emitting diode lasers. With over 35 standard lenses in LightPath's catalog to choose from, however, this can sometimes be a confusing task. The guide below will hopefully clear up some of the questions around choosing the best lens to use with a specific laser for a particular application.

Due to the way that the laser cavity is constructed in edge emitting diode lasers, light is emitted in a diverging, elliptical geometry - so the divergence is typically specified in both the x and y axes separately. The axis with the larger divergence is called the "fast axis" and the axis with the smaller divergence is called the "slow axis".

When selecting a lens to collimate the laser, first consider the NA of the lens. If the application requires a high amount of the laser light to be coupled though the system, a lens with a high enough NA must be chosen. The NA of a lens is a measure of the maximum amount of divergence that the lens can capture from the laser. Ideally, a lens should be used that has an NA higher than the NA of the laser's fast axis. If not, the laser will "clip" the lens causing some of the light to be wasted. To convert the laser NA to the divergence angle (and vice-versa), use the following formula:

$$NA = n \cdot \sin(\phi)$$

In most cases, n= 1 since the NA of the laser is defined in air. Therefore, solving for ϕ the equation is simplified to:

$$\phi = \sin^{-1}(NA)$$

It is important to note that ϕ is the *half* angle of the divergence cone and is given at the *marginal ray* (not $1/e^2$ or half angle half max).

After the minimum NA necessary for the lens is determined, next consider what beam diameter is preferred. Although ray-tracing is necessary to precisely determine the beam diameter for a given NA source with a particular lens, it can be approximated with the following formula:

$$BeamDiameter \cong 2 \cdot EFL \cdot NA$$

where EFL is the effective focal length of the lens and NA is the numerical aperture of the source (not the NA of the lens).

Important Note:
Some laser manufacturers give the NA of the source in different terms, such as half max (50% point) or $1/e^2$ (87% point). Whatever type of number is entered into the formula for the NA of the source will be the same type of number given for the beam diameter. For example, if the half max NA for a laser is used with the above formula, you will get the half max beam diameter. There is no simple way to convert from a half max number or a $1/e^2$ beam diameter to a full beam diameter for a specific source

because it depends on the intensity profile of the source itself. A reasonable approximation, though, for most edge emitting diode lasers is to assume a gaussian beam profile. Using this beam profile, you can convert the beam diameters as follows:

1. To convert a half max beam diameter to a full beam diameter, multiply the diameter by 2.576.
2. To convert a $1/e^2$ beam diameter to a full beam diameter, multiply the diameter by 1.517.

Remember that most edge emitting diodes are elliptical, so the beam diameter will be different in the x-axis versus the y-axis. Use the formula above to calculate the beam diameter in both axes to determine the shape of the collimated, elliptical beam.

Example: A Mitsubishi ML101J8 laser is to be used with an aspheric lens to produce a 0.75mm (full width half max) collimated beam in the fast axis. What lens should be chosen?

A quick check of the laser specs reveals that the laser has wavelength of 660nm and a full angle half max divergence of 8.5x22 degrees. This 22 degree full angle half max would equate to a 11 degree half angle half max, and the sin(11) would calculates to a half max NA of 0.19. In order to calculate the approximate EFL lens we need, we can use the following formula:

$$BeamDiameter \cong 2 \cdot EFL \cdot NA$$

Plugging in the values for the variables, the formula gets simplified to

$$0.75 \cong 2 \cdot EFL \cdot 0.19$$

Solving for EFL, it is determined that a lens is needed with an EFL of approximately 1.973mm.

The 350150 lens has an EFL of 2.00mm (at 780nm), which is a very close match. The EFL of that lens at 660nm (the laser's emission wavelength) is 1.984. Therefore, using this lens will result in a beam diameter of approximately 0.753mm.

To check the beam diameter in the slow axis, the same formula can be used again.

$$BeamDiameter \cong 2 \cdot EFL \cdot NA$$

The 8.5 degree FAFM slow axis divergence can be converted to half angle by dividing by 2 (4.25 deg). The sin of this angle reveals the slow axis NA to be 0.074.

$$BeamDiameter \cong 2 \cdot 1.984 \cdot 0.074 \cong 0.294 \text{ mm (FWFM)}$$

One last thing to check is if the laser will clip the lens or not. If we assume the laser has a gaussian beam distribution, we can multiply the 0.753mm fast axis beam diameter by 2.576 to get the estimated full beam diameter. The full beam diameter is calculated to be approximately 1.942mm in the fast axis, which is smaller than the lenses 2mm clear aperture. The laser will not clip the lens.

It is important to remember, however, that the equations and calculations above are just approximations. In order to determine the exact optical properties from using a specific laser with a specific lens, a ray-traced optical design is necessary. When this was done for the aforementioned example, it was determined that the approximation was correct within a couple of percent.

Using Aspheric Lenses: Part III – Choosing the Right Lens for Fiber Coupling

Another common use for aspheric lenses is to couple laser light into optical fibers. Choosing the right lens or lenses to do the coupling is important to maintain high efficiency in the optical system. The guide below is intended to show how best to do this while using off-the-shelf components. This guide assumes that the input laser light has already been collimated (not diverging). For help in collimating your diode laser, see part II of this guide.

When selecting a lens to focus light into a fiber, first consider what focal length lens is needed. Lets revisit the formula given in Part II:

$$BeamDiameter \cong 2 \cdot EFL \cdot NA$$

Solving for EFL it becomes

$$EFL \cong \frac{BeamDiameter}{2 \cdot NA}$$ where NA is the numerical aperture of the fiber that is used for the coupling

It is important to note that the EFL value that is calculated above is the *minimum* EFL needed to couple the light completely into the fiber. Longer EFL lenses can be used, but the spot size on the fiber tip will become larger when longer EFL lenses are employed. Therefore, it is best practice to use the shortest EFL lens possible that is larger than the minimum value specified below.

Example: We wish to focus the collimated beam created in Part II of this guide into a 50 micron multimode fiber (Nufern GI50/125S).

The fiber NA given by the manufacturer is approximately 0.20. Fiber NA is normally given at the 99% power point (as opposed to $1/e^2$ or half max), so we should also use the full beam diameter computed in Part II to keep the equation consistent.

$$EFL \cong \frac{BeamDiameter}{2 \cdot NA} \cong \frac{1.942mm}{2 \cdot 0.20} \cong 4.855mm$$

So it is best to look for a lens with an EFL of at least 4.855mm and a clear aperture at least 1.942mm (in order to capture the full collimated beam). One might consider the 350430 lens for its 5mm EFL (at 1550nm), but its 1.5mm clear aperture will not capture the full collimated beam. A better choice might be the 350550 lens. Its 6.10mm EFL at 1550nm becomes 5.94mm at 660nm. The lens also has a large enough clear aperture (2.2mm) to capture the entire input beam.

It is important to remember that the equations and calculations used above are just approximations. In order to determine the exact optical properties from coupling a collimated beam into an optical fiber, a ray-traced optical design is necessary. When this was done for the aforementioned example, it was determined that the approximation was correct within a couple of percent.