Lens Selection

Having discussed the most important factors that affect the performance of a lens or a lens system, we will now address the practical matter of selecting the optimum catalog components for a particular task. The following useful relationships are important to keep in mind throughout the selection process:

- Diffraction-limited spot size = 2.44 λ f/#
- Approximate on-axis spot size of a plano-convex lens at the infinite conjugate resulting from spherical aberration = $\dfrac{0.067\,f}{\mathrm{f}/\#^3}$
- Optical invariant = $m = \dfrac{\mathrm{NA}}{\mathrm{NA}''}$.

Example 1: Collimating an Incandescent Source

Produce a collimated beam from a quartz halogen bulb having a 1-mm-square filament. Collect the maximum amount of light possible and produce a beam with the lowest possible divergence angle.

This problem, illustrated in figure 1.29, involves the typical tradeoff between light-collection efficiency and resolution (where a beam is being collimated rather than focused, resolution is defined by beam divergence). To collect more light, it is necessary to work at a low f-number, but because of aberrations, higher resolution (lower divergence angle) will be achieved by working at a higher f-number.

In terms of resolution, the first thing to realize is that the minimum divergence angle (in radians) that can be achieved using any lens system is the source size divided by system focal length. An off-axis ray (from the edge of the source) entering the first principal point of the system exits the second principal point at the same angle. Therefore, increasing the system focal length improves this limiting divergence because the source appears smaller.

An optic that can produce a spot size of 1 mm when focusing a perfectly collimated beam is therefore required. Since source size is inherently limited, it is pointless to strive for better resolution. This level of resolution can be achieved easily with a plano-convex lens.

While angular divergence decreases with increasing focal length, spherical aberration of a plano-convex lens increases with increasing focal length. To determine the appropriate focal length, set the spherical aberration formula for a plano-convex lens equal to the source (spot) size:

$$\frac{0.067\,f}{\mathrm{f}/\#^3} = 1\ \mathrm{mm}.$$

This ensures a lens that meets the minimum performance needed. To select a focal length, make an arbitrary f-number choice. As can be seen from the relationship, as we lower the f-number (increase collection efficiency), we decrease the focal length, which will worsen the resultant divergence angle (minimum divergence = 1 mm/f).

In this example, we will accept f/2 collection efficiency, which gives us a focal length of about 120 mm. For f/2 operation we would need a minimum diameter of 60 mm. The LPX-60.0-62.2-C fits this specification exactly. Beam divergence would be about 8 mrad.

Finally, we need to verify that we are not operating below the theoretical diffraction limit. In this example, the numbers (1-mm spot size) indicate that we are not, since

diffraction-limited spot size = 2.44 × 0.5 μm × 2 = 2.44 μm.

Example 2: Coupling an Incandescent Source into a Fiber

In *Imaging Properties of Lens Systems* we considered a system in which the output of an incandescent bulb with a filament of 1 mm in diameter was to be coupled into an optical fiber with a core diameter of 100 µm and a numerical aperture of 0.25. From the optical invariant and other constraints given in the problem, we determined that $f = 9.1$ mm, CA = 5 mm, $s = 100$ mm, $s'' = 10$ mm, NA″ = 0.25, and NA = 0.025 (or f/2 and f/20). The singlet lenses that match these specifications are the plano-convex LPX-5.0-5.2-C or biconvex lenses LDX-6.0-7.7-C and LDX-5.0-9.9-C. The closest achromat would be the LAO-10.0-6.0.

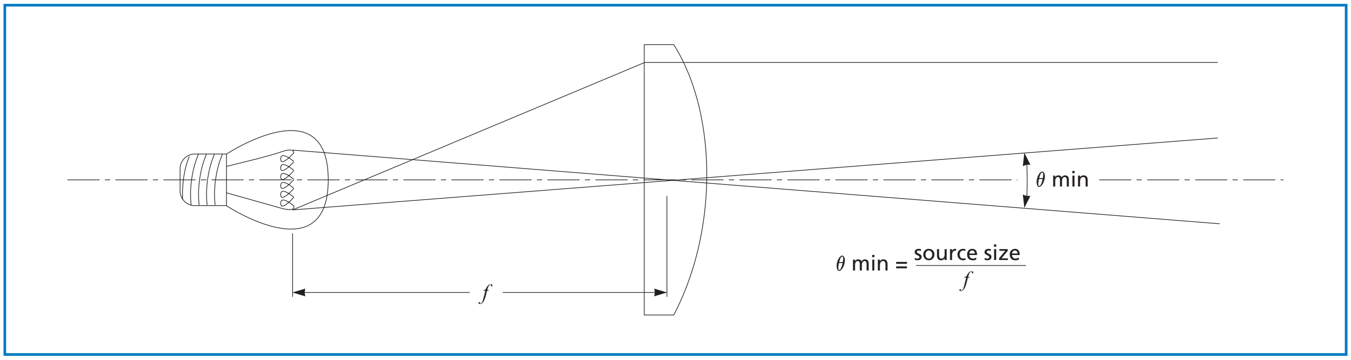


Figure 1.29 **Collimating an incandescent source**

We can immediately reject the biconvex lenses because of spherical aberration. We can estimate the performance of the LPX-5.0-5.2-C on the focusing side by using our spherical aberration formula:

$$\text{spot size} = \frac{0.067\ (10)}{2^3} = 84\ \mu\text{m}.$$

We will ignore, for the moment, that we are not working at the infinite conjugate.

This is slightly smaller than the 100-µm spot size we are trying to achieve. However, since we are not working at infinite conjugate, the spot size will be larger than that given by our simple calculation. This lens is therefore likely to be marginal in this situation, especially if we consider chromatic aberration. A better choice is the achromat. Although a computer ray trace would be required to determine its exact performance, it is virtually certain to provide adequate performance.

Example 3: Symmetric Fiber-to-Fiber Coupling

Couple an optical fiber with an 8-µm core and a 0.15 numerical aperture into another fiber with the same characteristics. Assume a wavelength of 0.5 µm.

This problem, illustrated in figure 1.30, is essentially a 1:1 imaging situation. We want to collect and focus at a numerical aperture of 0.15 or f/3.3, and we need a lens with an 8-µm spot size at this f-number. Based on the lens combination discussion in *Lens Combination Formulas*, our most likely setup is either a pair of identical plano-convex lenses or achromats, faced front to front. To determine the necessary focal length for a plano-convex lens, we again use the spherical aberration estimate formula:

$$\frac{0.067\ f}{3.3^3} = 0.008\ \text{mm}.$$

This formula yields a focal length of 4.3 mm and a minimum diameter of 1.3 mm. The LPX-4.2-2.3-BAK1 meets these criteria. The biggest problem with utilizing these tiny, short focal length lenses is the practical considerations of handling, mounting, and positioning them. Because using a pair of longer focal length singlets would result in unacceptable performance, the next step might be to use a pair of the slightly longer focal length, larger achromats, such as the LAO-10.0-6.0. The performance data, given in *Spot Size*, show that this combination does provide the required 8-μm spot diameter.

Because fairly small spot sizes are being considered here, it is important to make sure that the system is not being asked to work below the diffraction limit:

$$2.44 \times 0.5\ \mu\text{m} \times 3.3 = 4\ \ \mu\text{m}\,.$$

Since this is half the spot size caused by aberrations, it can be safely assumed that diffraction will not play a significant role here.

An entirely different approach to a fiber-coupling task such as this would be to use a pair of spherical ball lenses (LMS-LSFN series) or one of the gradient-index lenses (LGT series).

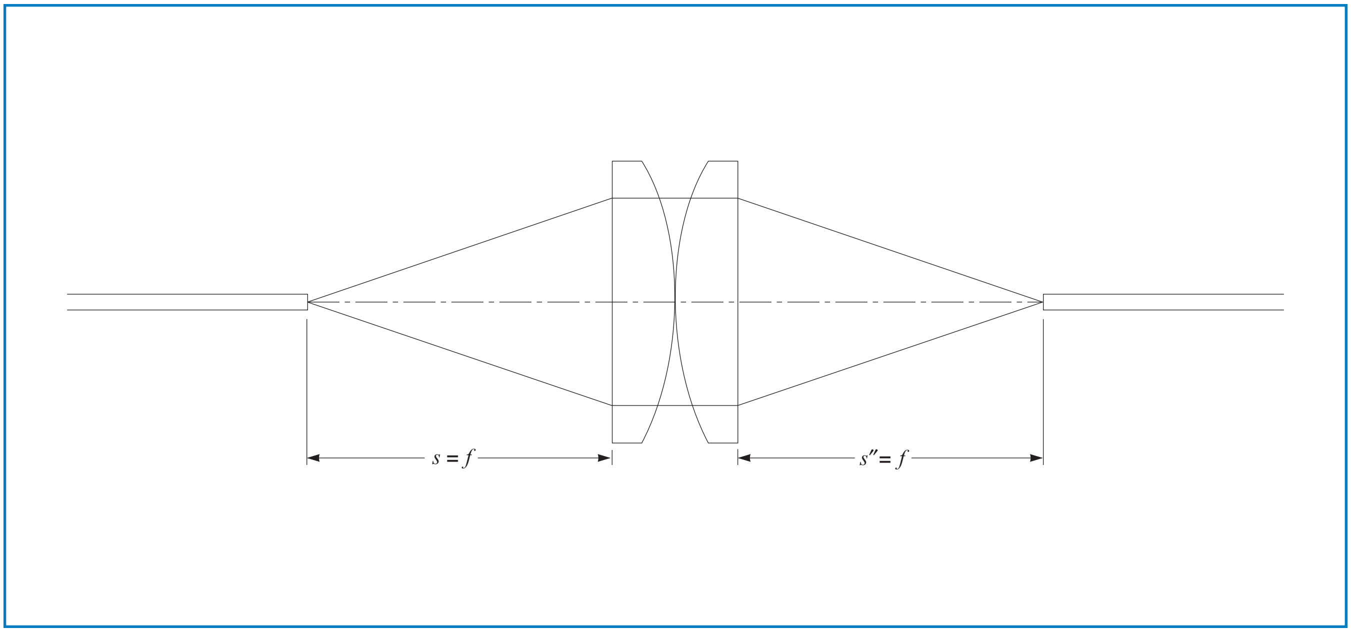


Figure 1.30 **Symmetric fiber-to-fiber coupling**

Example 4: Diffraction-Limited Performance

Determine at what f-number a plano-convex lens being used at an infinite conjugate ratio with 0.5-μm wavelength light becomes diffraction limited (i.e., the effects of diffraction exceed those caused by aberration).

To solve this problem, set the equations for diffraction-limited spot size and third-order spherical aberration equal to each other. The result depends upon focal length, since aberrations scale with focal length, while diffraction is solely dependent upon f-number. By substituting some common focal lengths into this formula, we get f/8.6 at $f = 100$ mm, f/7.2 at $f = 50$ mm, and f/4.8 at $f = 10$ mm.

$$2.44 \times 0.5\ \mu\text{m} \times \text{f}/\# = \frac{0.067 \times f}{\text{f}/\#^3}$$

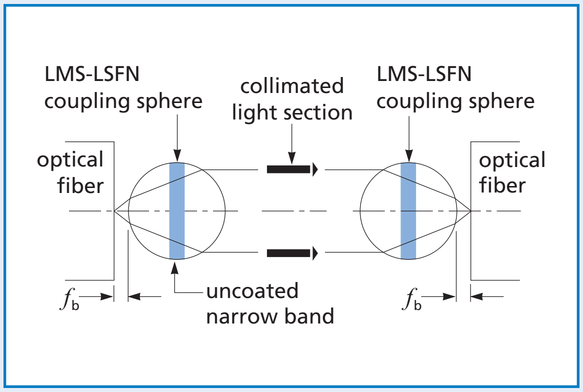
or

$$\text{f}/\# = (54.9 \times f)^{1/4}.$$

When working with these focal lengths (and under the conditions previously stated), we can assume essentially diffraction-limited performance above these f-numbers. Keep in mind, however, that this treatment does not take into account manufacturing tolerances or chromatic aberration, which will be present in polychromatic applications.

APPLICATION NOTE

Spherical Ball Lenses for Fiber Coupling



Spheres are arranged so that the fiber end is located at the focal point. The output from the first sphere is then collimated. If two spheres are aligned axially to each other, the beam will be transferred from one focal point to the other. Translational alignment sensitivity can be reduced by enlarging the beam. Slight negative defocusing of the ball can reduce the spherical aberration third-order contribution common to all coupling systems. Additional information can be found in “Lens Coupling in Fiber Optic Devices: Efficiency Limits,” by A. Nicia, *Applied Optics*, vol. 20, no. 18, pp 3136–45, 1981. Off-axis aberrations are absent since the fiber diameters are so much smaller than the coupler focal length.