Aberration Balancing

To improve system performance, optical designers make sure that the total aberration contribution from all surfaces taken together sums to nearly zero. Normally, such a process requires computerized analysis and optimization. However, there are some simple guidelines that can be used to achieve this with lenses available in this catalog. This approach can yield systems that operate at a much lower f-number than can usually be achieved with simple lenses.

Specifically, we will examine how to null the spherical aberration from two or more lenses in collimated, monochromatic light. This technique will thus be most useful for laser beam focusing and expanding.

Figure 1.31 shows the third-order longitudinal spherical aberration coefficients for six of the most common positive and negative lens shapes when used with parallel, monochromatic incident light. The plano-convex and plano-concave lenses both show minimum spherical aberration when oriented with their curved surface facing the incident parallel beam. All other configurations exhibit larger amounts of spherical aberration. With these lens types, it is now possible to show how various systems can be corrected for spherical aberration.

A two-element laser beam expander is a good starting example. In this case, two lenses are separated by a distance that is the sum of their focal lengths, so that the overall system focal length is infinite. This system will not focus incoming collimated light, but it will change the beam diameter. By definition, each of the lenses is operating at the same f-number.

The equation for longitudinal spherical aberration shows that, for two lenses with the same f-number, aberration varies directly with the focal lengths of the lenses. The sign of the aberration is the same as focal length. Thus, it should be possible to correct the spherical aberration of this Galilean-type beam expander, which consists of a positive focal length objective and a negative diverging lens.

If a plano-convex lens of focal length f_1 oriented in the normal direction is combined with a plano-concave lens of focal length f_2 oriented in its reverse direction, the total spherical aberration of the system is

$$\mathrm{LSA} = \frac{0.272\, f_1}{\mathrm{f}/\#^2} + \frac{1.069\, f_2}{\mathrm{f}/\#^2}.$$

After setting this equation to zero, we obtain

$$\frac{f_1}{f_2} = -\frac{1.069}{0.272} = -3.93.$$

To make the magnitude of aberration contributions of the two elements equal so they will cancel out, and thus correct the system, select the focal length of the positive element to be 3.93 times that of the negative element.

Figure 1.32(a) shows a beam-expander system made up of catalog elements, in which the focal length ratio is 4:1. This simple system is corrected to about 1/6 wavelength at 632.8 nm, even though the objective is operating at f/4 with a 20-mm aperture diameter. This is remarkably good wavefront correction for such a simple system; one would normally assume that a doublet objective would be needed and a complex diverging lens as well. This analysis does not take into account manufacturing tolerances.

A beam expander of lower magnification can also be derived from this information. If a symmetric-convex objective is used together] with a reversed plano-concave diverging lens, the aberration coefficients are in the ratio of 1.069/0.403 = 2.65. Figure 1.32(b) shows a system of catalog lenses that provides a magnification of 2.7 (the closest possible given the available focal lengths). The maximum wavefront error in this case is only a quarter-wave, even though the objective is working at f/3.3.

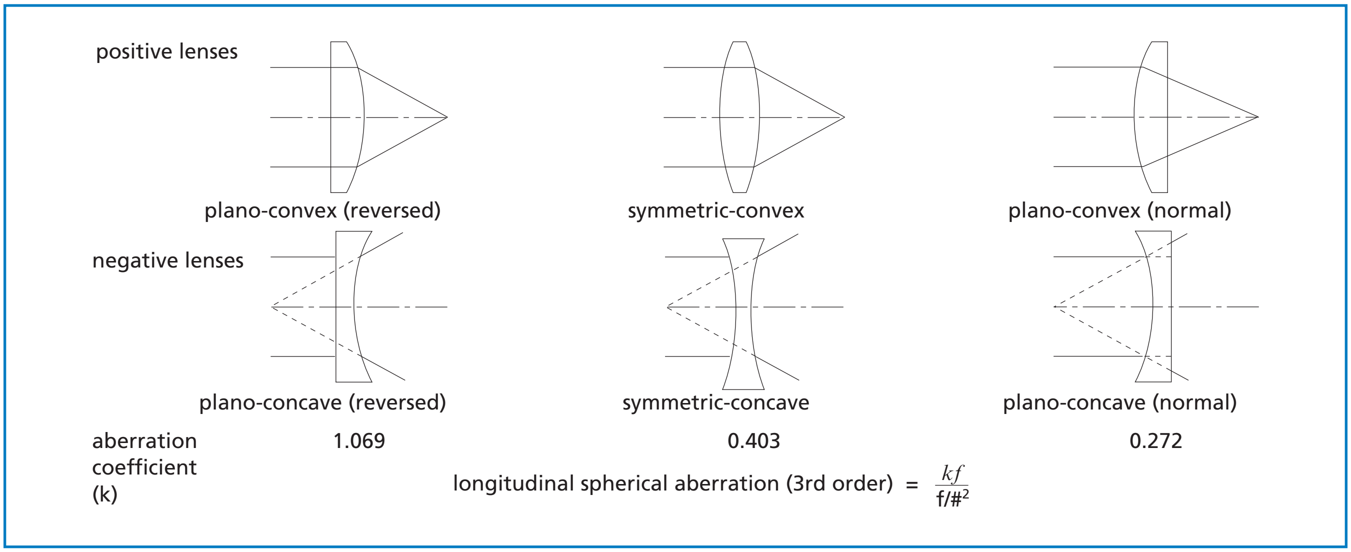
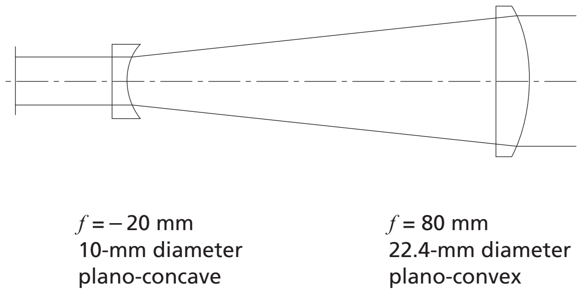
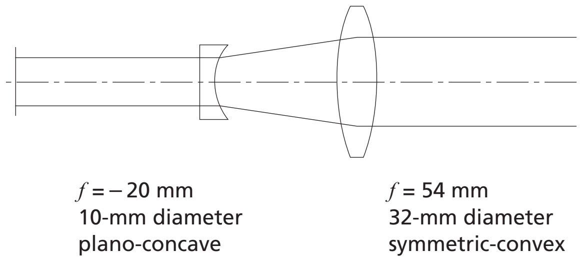


Figure 1.31 **Third-order longitudinal spherical aberration of typical lens shapes**

a) CORRECTED 4 × BEAM EXPANDER



b) CORRECTED 2.7 × BEAM EXPANDER



c) SPHERICALLY CORRECTED 25-mm EFL f/2.0 OBJECTIVE

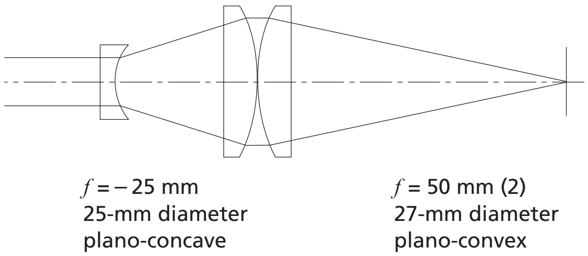


Figure 1.32 **Combining catalog lenses for aberration balancing**

The relatively low *f* numbers of these objectives is a great advantage in minimizing the length of these beam expanders. They would be particularly useful with Nd:YAG and argon-ion lasers, which tend to have large output beam diameters.

These same principles can be utilized to create high numerical aperture objectives that might be used as laser focusing lenses. Figure 1.32(c) shows an objective consisting of an initial negative element, followed by two identical plano-convex positive elements. Again, all of the elements operate at the same f-number, so that their aberration contributions are proportional to their focal lengths. To obtain zero total spherical aberration from this configuration, we must satisfy

$$1.069\, f_1 + 0.272\, f_2 + 0.272\, f_2 = 0$$

or

$$\frac{f_1}{f_2} = -0.51.$$

Therefore, a corrected system should result if the focal length of the negative element is just about half that of each of the positive lenses. In this case, $f_1 = 425$ mm and $f_2 = 50$ mm yield a total system focal length of about 25 mm and an f-number of approximately f/2. This objective, corrected to 1/6 wave, has the additional advantage of a very long working distance.