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Review Article

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Lens designs with extreme image quality features

Abstract: In order to best assess the importance of new technologies to optical design, it is useful to consider what the limits are to what can be done with 'old' technologies. That may show where something new is needed to overcome the limitations of existing optical designs. This article will give a survey of some remarkable high-performance designs, some of which are extremely simple, and most of which only use technology that has already been around for decades. Each of these designs has some limitation that would be nice to overcome. One new technology that will probably revolutionize optical design will be curved surfaces on image chips.

Keywords: aberrations; aspherics; optical design.

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1 Introduction

A survey of some unusual designs, which have extremely high performance under certain conditions, such as a single wavelength or a curved image surface, can show what can be done with existing technologies. These designs can then indicate what areas of technology need to be developed to further extend the limits of what is possible. There are very few designs that are perfect or nearly perfect, and that is a good place to start this short survey. Here, 'perfect' means just that – it is an optical system, like a flat mirror, which has no optical aberrations at all. A flat mirror, however, makes a perfect virtual image of a real object, and that is an example of the kind of limitation that we would like to overcome. It is much more desirable to have a perfect real image of a real object.

2 Perfect and nearly perfect designs

Figure 1 shows the Luneburg lens from 1944 [1], a gradient index ball with a radially symmetric index gradient. It forms a perfect monochromatic image of collimated light on the back surface of the ball. The light rays are curved inside the ball, and the perfect focus occurs for any field angle incident on the ball. The index of refraction is 1.414 (square root of 2) at the center and 1.0 at the rim of the ball. This is not physically realizable but can be approximated with structures in the microwave region. Figure 2 shows a related design, the Maxwell fisheye lens from 1854 [2]. It is also a perfect system, monochromatically, and focuses any point on the surface of the spherical ball onto the opposite side of the ball at unit magnification. The ray curves inside the ball are arcs of circles. The refractive index in the center is 3.0, and at the rim of the ball, it is 1.5.

It is hard to imagine that there could be a simple two-element design that is nearly perfect and with no index gradient, but Figure 3 shows just such a design [3].

It is a monocentric catadioptric system, and all four surfaces, one of them reflecting, have the same center of curvature. There are only four design variables: two-element thicknesses and an airspace on either side of the common center of curvature. With these four variables, it is possible to correct for the focal length and third-, fifth-, and seventh-order spherical aberration. Higher orders beyond that are extremely small. The glass can be any typical optical glass.

If the aperture stop is at the common center of curvature of this monocentric design, then, there are no field aberrations. The image is curved and also has the same center of curvature as all the surfaces. Now, here is a remarkable feature of this design. The higher-order spherical aberration is so small that this design works very well at 0.99 NA. When optimized for the wavefront, a 0.99-NA design with a 20-mm focal length has an r.m.s. OPD of 0.0035 wave at 0.55 μ, assuming a glass index of about 1.6. The performance goes to about 0.006 waves r.m.s. When the design is reoptimized for the lower glass index of n=1.5. If the NA is extended to 0.999 NA, the wavefront hardly changes. Because of that, this design has the very

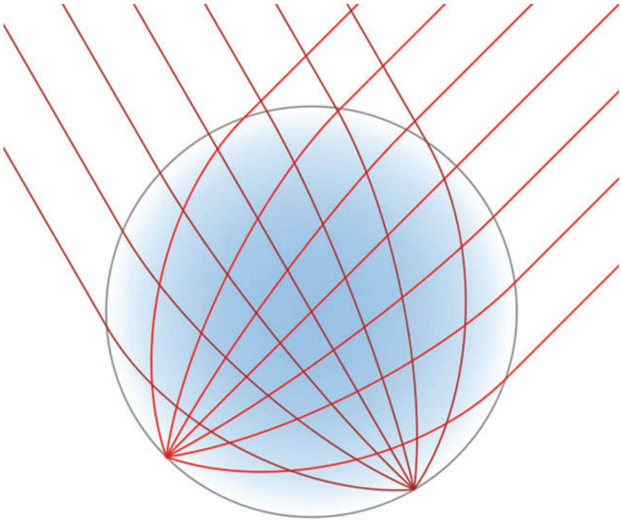

Figure 1 Luneburg gradient index lens.

unusual feature of not needing an aperture stop. Total internal reflection at the second surface as the design NA approaches 1.0 will effectively define an aperture stop, and reflection losses will apodize the pupil near its rim so that there is very little energy beyond 0.99 NA.

The Figure 3 picture shows the design with a 20° field. The obscuration due to the image surface is very small, about 15% diameter for a 20° full field 0.99 NA design. The performance is the same for any field angle. This is a monochromatic design, but it could be achromatized by adding two 'buried surfaces' to the design. The main practical limitations of this remarkable system are that its size is large compared to the pupil diameter and its curved image surface. The variation of the orders of spherical aberration with these very few monocentric design parameters is extremely nonlinear, and it is quite difficult to fully optimize this design.

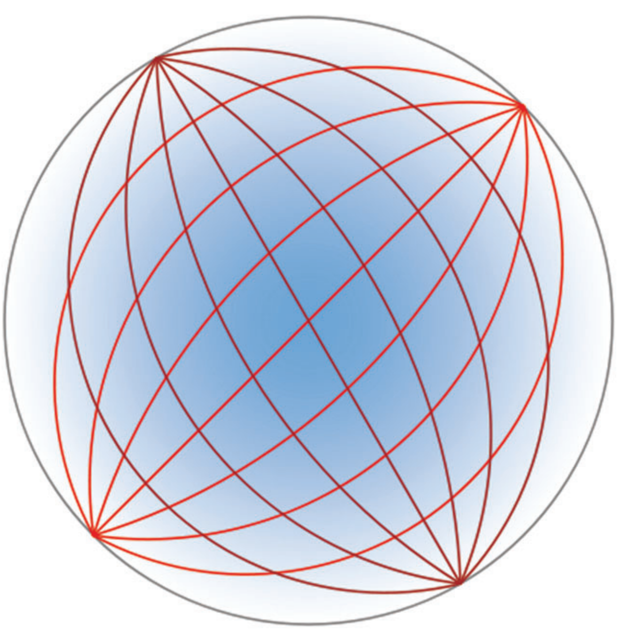

Figure 2 Maxwell Fisheye gradient index lens.

There is a new perfect optical design [4], which is the ultimate in simplicity – a single optical element – and also the ultimate in image quality, with no monochromatic aberrations. It is shown in Figure 4, and it has perfect image quality at NA=1.0, in air, and at NA=3.0 with an immersion focal surface. This design is simply a gradient index Maxwell's fisheye lens that has been cut in half and then given a reflective outer surface. By means of a very simple geometrical construction, it is possible to prove that this new design, just ½ of Maxwell's design and with a reflective outer surface, is a perfect design with no geometrical aberrations of any order. It images perfectly, to a point, any point on the flat surface to another point on that same surface. The radial gradient index goes from 3.0 at the center to 1.5 at the outer surface.

Prior to this new design, there were only four known perfect optical systems. The Luneburg gradient index lens and the Maxwell fisheye lens both form real images on a curved surface. Another perfect system is the single surface aplanatic surface, a spherical surface between two different index of refraction materials, with an object and image conjugate ratio that is the same as the ratio of the refractive index on opposite sides of the aplanatic surface. This gives perfect imagery, but both the object and image are curved, and one conjugate is virtual. The last of the well-known perfect optical systems is a flat mirror. This is the only one where both object and image can be flat, with perfect imagery, but one has to be virtual.

This new design here is the first new perfect optical system in many decades and has both the object and image flat and real, with no virtual conjugate. Of course, there is no practical way right now to make this large change in the index gradient, but the design shows that gradient index is a very powerful design tool, and more complicated designs may not require such large index differences. The design is only perfect monochromatically, but there is a partial equivalent to this system in the Wynne-Dyson design [5], which does have color correction and does not use gradient index.

Figure 5 shows how two of these elements can be joined so that the input and output are in opposite directions.

3 Curved image designs

Allowing a design's image to be curved can greatly simplify the design complexity required to meet various

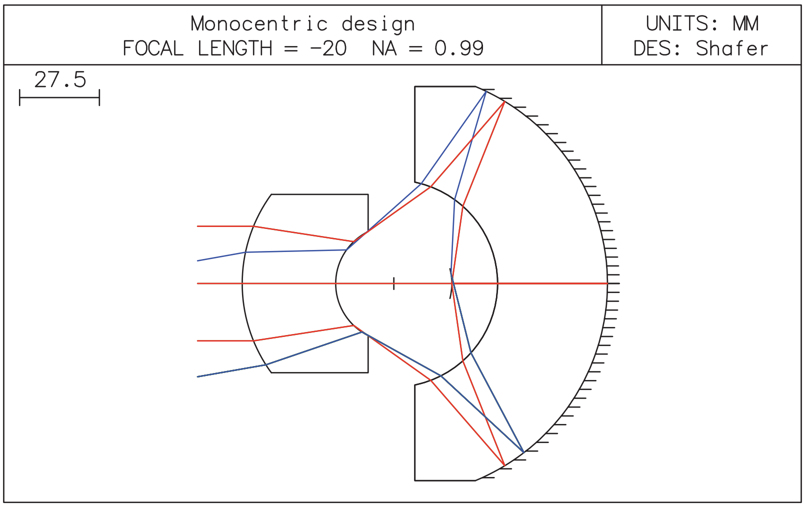

Figure 3 A nearly perfect 0.99-NA monocentric design.

performance goals. Figure 6 shows a design that is f/1.0 with a 20° field on a curved image surface [6]. The spot size is 1.0 arc second over the whole 20° field with no vignetting, so the design is diffraction-limited for a 150-mm focal length at 0.55 μ. The best performance happens when the last lens surface is right up against the curved image, but this design here is still good with a 2.0-mm working distance.

Figure 7 shows an f/1.0, 20° field design with one extra lens, much less glass path, correction for axial and lateral color, and the same monochromatic correction as before. Designs like this have worked in the past with fiber-optic field flatteners and image tubes, for night vision applications. This design, however, has a very much higher correction level than prior designs and would be a great match to a curved surface detector array like that recently discussed by Dumas et al. [7].

4 Extremely large NA and field angle combinations

The closest design to a perfect system that does not use a gradient index and which does not require a curved object or image is probably one of the examples given by Brian Caldwell [8] that combines high NA and a large field angle and yet has excellent aberration correction. Figure 8 shows one example, and as Caldwell points out, this is only possible because of having an intermediate image in the design. His remarkable designs achieve this great combination of high NA and field angle at the expense of a very, very large system size compared to the system

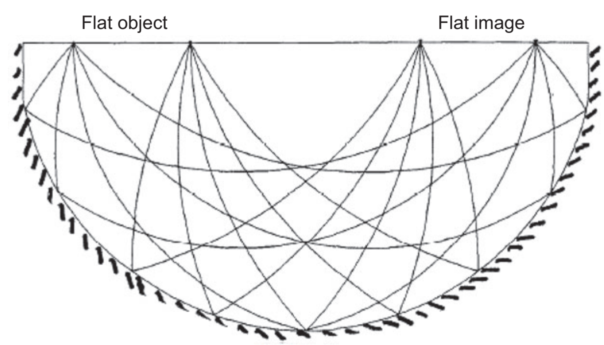

Figure 4 Perfect 1.0X gradient index catadioptric design.

focal length. The example shown is f/1.0 and a 140° field with no vignetting and nearly uniform illumination. There are some very aspheric elements. The use of designs with an intermediate image is a growing trend and led to some remarkable designs, like a 300 to 1 zoom ratio system, among others.

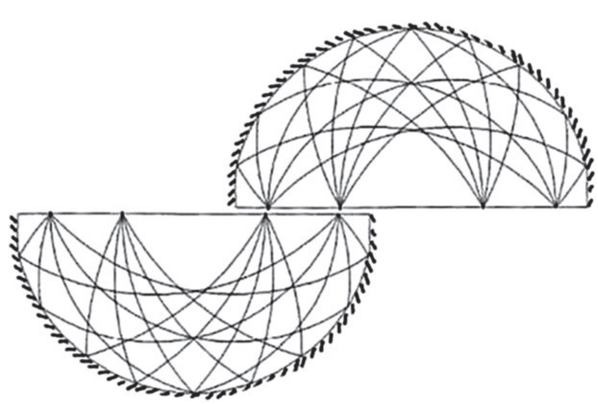

Figure 5 Opposite input and output directions.

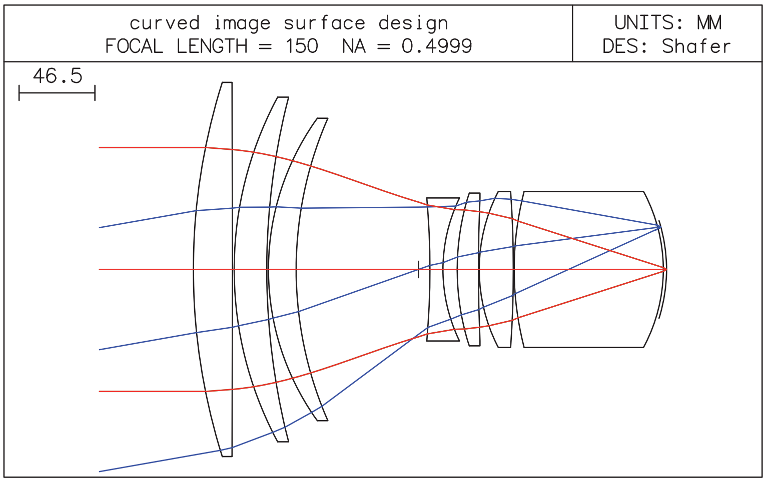

Figure 6 A f/1.0, 20° field curved image design.

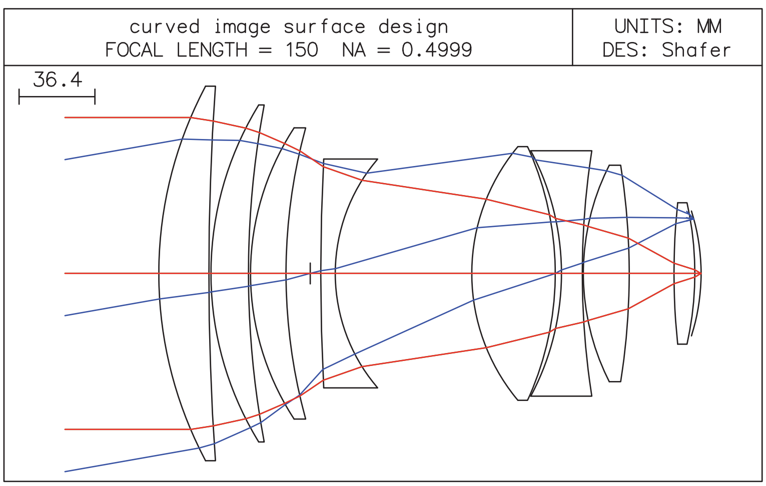

Figure 7 Color-corrected curved image design.

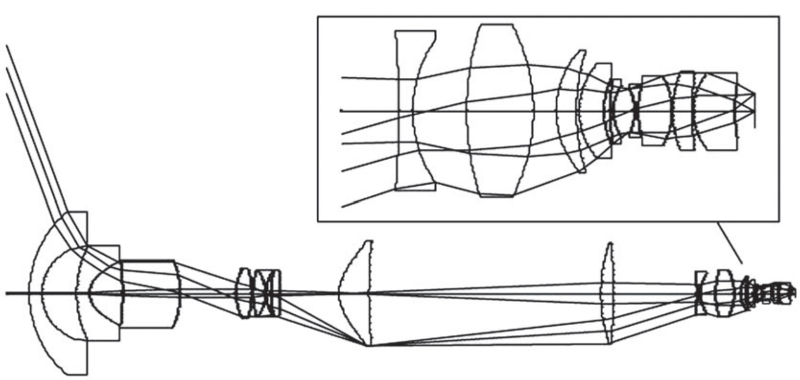

Figure 8 A f/1.0, 140° field intermediate image design.

5 Very compact designs

It is possible to get some very compact designs that combine high NA and a large field size, with very few elements, by the use of aspherics and diffractive surfaces. This type of design is the opposite extreme from the Caldwell designs, and Figure 9 shows a very compact example [9]. It is f/0.9 with a 70° unvignetted field and a

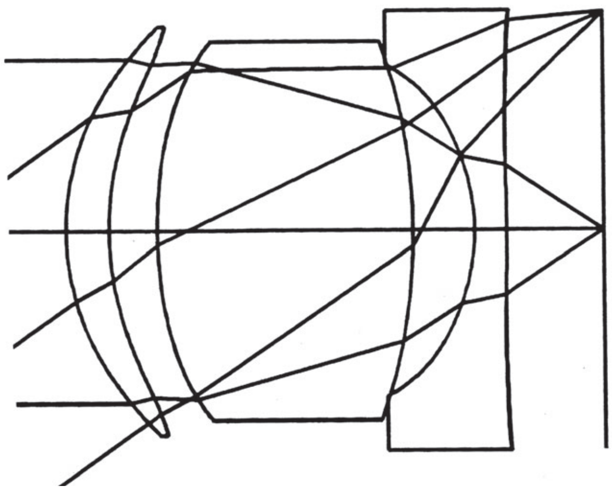

Figure 9 A f/.9 70° field diffractive/refractive design.

flat image. The design is diffraction-limited over the field for a focal length of 10 mm at 0.55 μ. The reason that this design can be so good is that it uses diffractive power to allow the system to be corrected for Petzval and have a flat image while only using positive power lenses. The last lens is externally a negative lens but has positive net power because of strong diffractive power on its surface. That use of strong diffractive power reduces the incidence angles a lot, and several high-order aspherics also give key variables that make this design possible. Because of the large amount of diffractive power, the useful spectral bandwidth is very limited.

6 Extreme index difference designs

Another way to reduce incidence angles and correct for Petzval without using a diffractive surface is to use a large index difference in the design. Figure 10 shows a design [10] that uses three highly aspheric cemented doublets of low-index BK7 glass and high-index SF58 glass. It is diffraction-limited at 0.6328 μ at f/1.0 over a 60° unvignetted field for a 25-mm focal length.

Figure 11 shows one more example of this [10]. We start with this two-element design that has a diffractive surface on the second surface, with considerable diffractive power. You can see by the ray paths that the purely refractive part of the first lens has negative power, and yet, the element has net (refractive+diffractive) positive power because of the diffractive surface. This f/2.0, 50-mm focal length design is diffraction-limited monochromatically over an unvignetted, 45° field and has a 25-mm back focus.

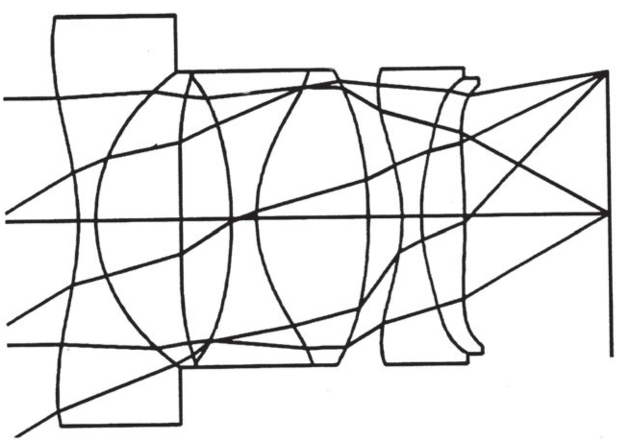

Figure 10 A f/1.0, 60° field, high/low index doublets.

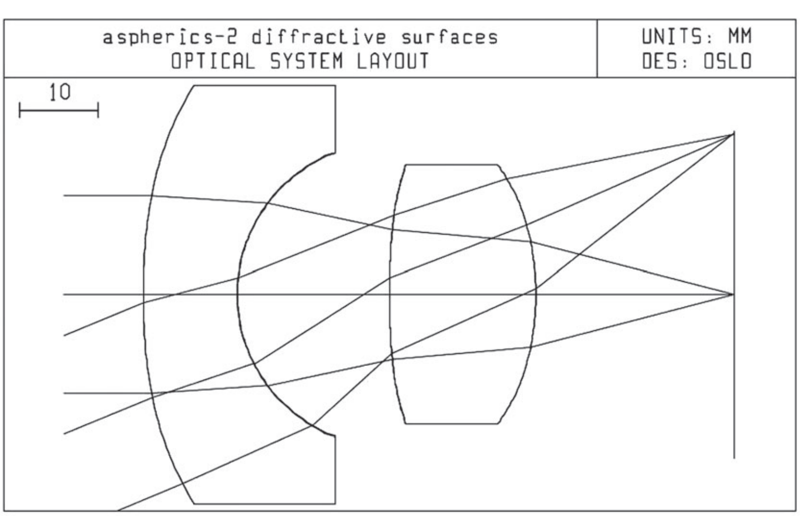

Figure 11 Diffractive/refractive lens, f/2.0 45° field.

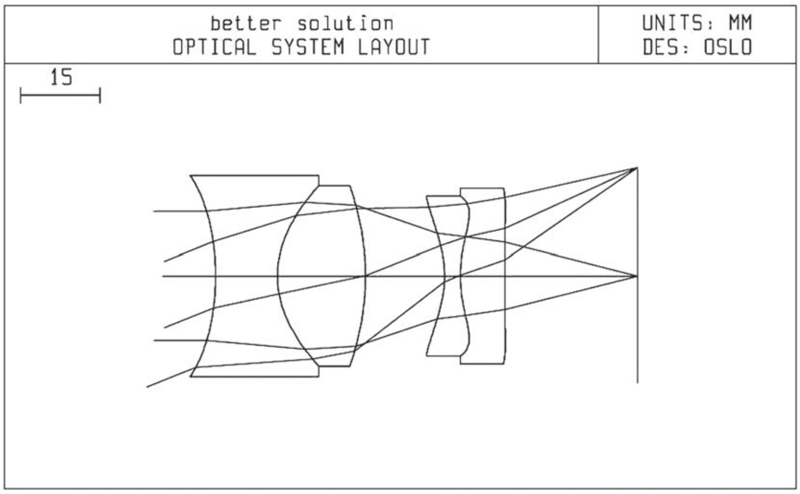

Figure 12 High/low index doublets, no diffractive surfaces.

Next, we remove the diffractive surface and use very high- and very low-index glass pairs to get the same type of effect on the Petzval correction. Here, I used silica and LASFN21. All surfaces in this Figure 12 design [10] are aspheric, and the design is diffraction-limited over the whole unvignetted field. By choosing the glasses appropriately, it is possible to get a color-corrected design that could be used as a SLR camera lens design. To get the needed dispersion difference in the glasses, it is necessary to substantially reduce the index difference, and that makes the monochromatic correction decline a lot, but it still gives a high-resolution color-corrected camera lens design comparable to a multielement double-Gauss design in performance.

7 Extreme correction for aberrations

Figure 13 shows an example of a lithographic stepper lens design [11] from the year 2000. This very complicated design has many elements as well as a small number of aspherics. This typical design has a field diameter of about 26 mm, 0.70 NA, a distortion correction to 1.0 nm, and a wavefront correction to a few thousandths of a wave r.m.s. at 0.193 μ. More recent designs [12] like Figure 14 have many fewer lenses with very many more aspherics, typically 9 or 10. There are also refractive designs that are about 0.93 NA with a 26-mm field diameter as well as catadioptric immersion designs at 1.35 NA, all using very many high-order aspherics.

These designs have their incredible levels of wavefront, distortion, and telecentricity variation correction at the expense of large-size optical elements and expensive aspherics. They are essentially monochromatic designs for use with a laser. Some have partial deep UV laser color correction, using silica and calcium fluoride.

8 Extreme wavelength range

Most of these designs shown have extremely good monochromatic correction but are very limited by the useful

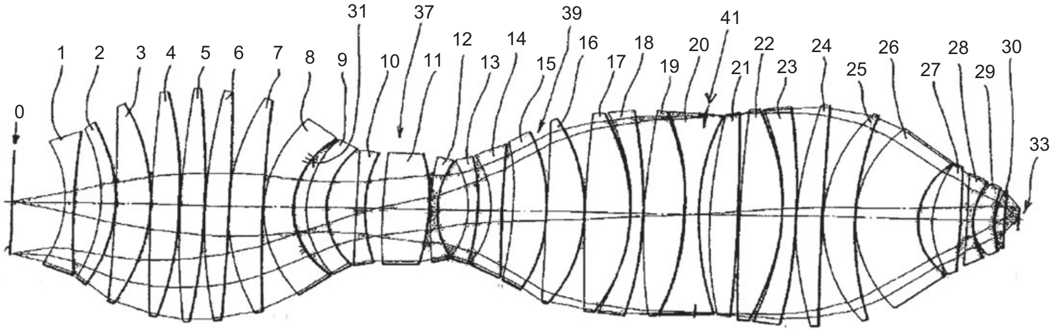

Figure 13 Lithographic stepper lens, 0.70 NA, from year 2000.

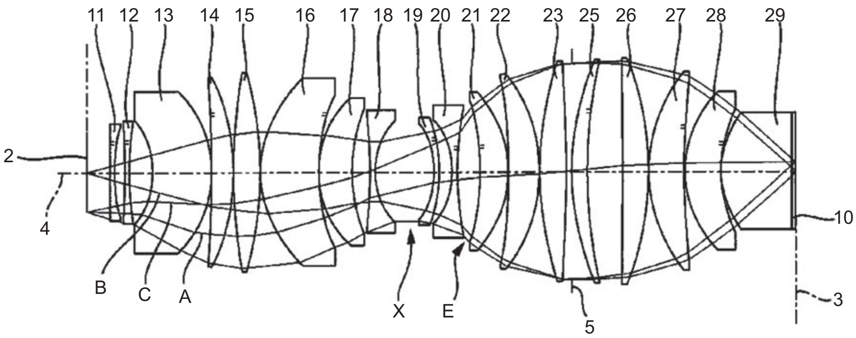

Figure 14 Immersion design with many aspherics, year 2010.

spectral bandwidth with good correction. Even with the use of anomalous dispersion glasses, it is still difficult for most designs to get excellent correction over a broad spectrum.

Figure 15 shows an unusual catadioptric microscope objective [13], which is 0.90 NA and is diffraction-limited over a small field over an enormous spectral range – from the deep UV through the near IR – and, yet, only uses one glass type in the design. The key to this broad spectral correction is the use of an Offner field lens at an intermediate image.

9 Extreme tolerance insensitivity

There are some special situations where the sensitivity of the design parameters to small changes is such that there might be no first derivatives with respect to a particular aberration. The simplest example of this is the Dall-Kirkham telescope design [14], shown in Figure 16. It has a conic primary mirror that is an ellipse and a spherical convex secondary mirror. This design is attractive to amateur telescope makers because it avoids the difficulty of making the conic secondary mirror that a classical

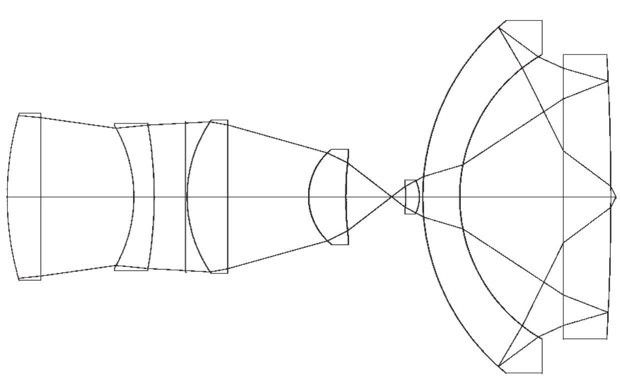

Figure 15 A 0.90-NA all-silica design for 0.266 μ – 0.800 μ.

Cassegrain telescope requires. Spherical aberration is corrected in this design: the elliptical primary mirror has a small amount of undercorrected spherical aberration, and the convex spherical secondary mirror has a small amount of overcorrected spherical aberration. The design has worse coma than the classical Casssegrain design with the same first-order parameters.

It turns out that once the position of the convex secondary mirror is fixed, the amount of overcorrected spherical aberration it has is extremely insensitive to its radius. Here is why – if the secondary mirror is concentric about the primary mirror focus, or if it is flat, then, it has no spherical aberration. For radii in between those values, the overcorrected spherical aberration rises to a maximum and then declines. At the maximum value (a mathematically stationary point), there is no first derivative of spherical aberration with respect to the radius and that maximum value occurs close to the radius that would normally be chosen from first-order configuration considerations. The position of the final image is quite sensitive to that radius but not the amount of spherical aberration, and there is no first derivative or a very small one for many typical secondary mirror positions and radii. This means that the image stays corrected even for large shifts in the image location, due to a radius change. A ±25% change in the secondary mirror radius causes an enormous shift in the image location but very little change in the amount of overcorrected spherical aberration of the mirror. This lack of a first derivative is dependent on one conjugate of the secondary mirror being virtual. There is, however, a small first derivative of spherical aberration with respect to the axial position of the secondary mirror because that changes the beam diameter on that mirror and, hence, the amount of its spherical aberration.

Another example of this is the Fulcher design [15] shown in Figure 17. This design corrects for spherical aberration with only positive lenses. The front lens has a

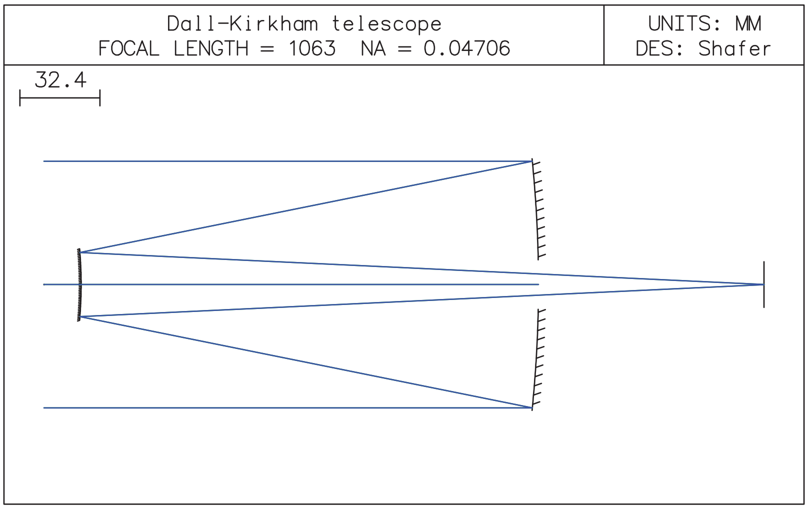

Figure 16 Dall-Kirkham telescope.

shape bending for minimum spherical aberration, which is undercorrected.

Then, the following lenses have surfaces that are chosen according to the following scheme. Figure 18 shows a graph [16] of the overcorrected spherical aberration of a spherical glass surface with a virtual input conjugate. There are three axial points with no spherical aberration: a point B in contact with the surface, a point C at the center of curvature of the surface, and a point A at the aplanatic conjugates. We see that there are two maxima to this curve, one between point A and C and one between B and C. The former bends the rays by much more than the latter, and so, it is chosen for the front surface of each of the three lenses that follow the first lens in the Fulcher design. The rear surface of these three lenses is made concentric about the rays and puts in no spherical aberration. If the glass index is about 1.60 or higher, then, the result is a design where the overcorrected spherical aberration of the last three lenses cancels out the undercorrected spherical aberration from the front lens. Higher-order spherical aberration is extremely small.

The f/2 design of Figure 17 has a 100-mm focal length and an extremely small monochromatic axial wavefront error at 0.55 μ. If the radii of the last three lenses are allowed to depart very slightly from their zero first-order derivative condition (with respect to spherical aberration), then a glass index n=1.6 gives 0.000007 waves r.m.s. wavefront error on-axis that barely changes for higher index values like n=1.8. There is no good solution of this Fulcher type for lower index values, like n=1.55. However,

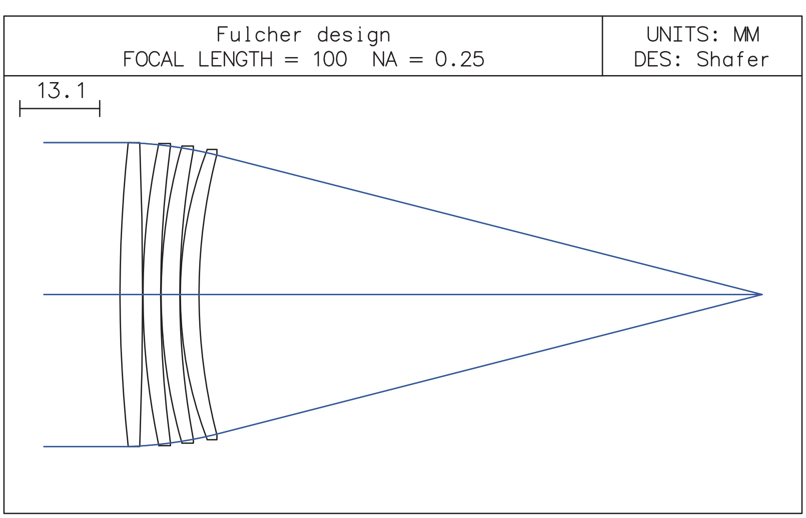

Figure 17 Fulcher design, f/2.0.

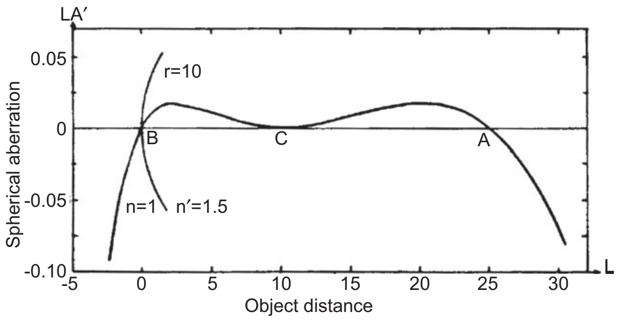

Figure 18 Spherical aberration vs. virtual object distance.

there are many similar-looking good solutions for lower index values where, for example, the front surface of the second lens is working at its aplanatic conjugates. Figure 18 clearly shows that the aplanatic point A has a high sensitivity to radius change, so these other solution types may have very good wavefront correction but will lack the extreme radii tolerance insensitivity that is a feature of the Fulcher design.

Of the eight surfaces in this design, the last six have essentially no first derivative of the spherical aberration with respect to the radius. These surfaces are working at stationary values for their spherical aberration contributions. Although changing the lens thicknesses or airspaces does make a small change in the beam diameter on each element, this is a small effect, and the result is that the design is also very insensitive to changes in those parameters. Although it may seem that these designs are more of a curiosity than anything else, they show the enormous range that can be encountered in design parameter sensitivity. The Figure 3 design has extremely a high-order dependence of correction on the few design parameters, while the Fulcher design is the exact opposite.

10 Conclusion

It is clear from this design survey that there are many designs that use existing technology, which push the limits of what is possible in terms of high performance for high NA values, large field angles, extreme correction levels, broad spectral bandwidth, etc. Some designs are very simple. The conclusion that I draw from this is that what most limits designs are requirements for a flat image and good spectral correction. Future developments in curved detector arrays may address the curved image possibilities for new designs, which would make them simpler with higher performance. The spectral correction problem might benefit from new refractive materials. Liquids have very different anomalous dispersion properties than optical glass, so there is no inherent reason why some nontraditional optical materials might find a place in future designs. Free-form aspheric surfaces will find an increasing role in designs, as well as the use of Forbes type of aspheric formulations. Unusual surface shapes that can be easily specified and optimized will lead to substantial progress in moving toward simpler and higher-performance designs. It looks like there are some relatively near-term future developments that will expand the horizons of what is possible in optical design.

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References

[1] R. K. Luneburg, in 'Mathematical Theory of Optics', (Brown University, Providence, Rhode Island, 1944) pp. 189–213.
[2] Macmillan, Camb. Dublin Math. J. 9, 9–11 (1854).
[3] D. Shafer, Optics News, June, 9–13 (1988).
[4] D. Shafer, SPIE, 2537, 2–12 (1995).
[5] C. Wynne, 'Optical Instruments and Technique' (Oriel Press, London, 1979), pp. 429–434, R. Hershel, US Patent #4,391,494, D. Shafer, US Patent #5,161,062.
[6] D. Shafer, SPIE, 0766, 2–9 (1987).
[7] D. Dumas, M. Fender, N. Baier, J. Primot and E. Coarer, Appl. Opt. 51(22), 5419–5424 (2012).
[8] B. Caldwell, SPIE, 5865, 1–10 (2005).
[9] D. Shafer, IODC, 22 (1994).
[10] D. Shafer, OSA TOPS, 24, 1–6 (1999).
[11] D. Shafer, W. Ulrich, US Patent #6,560,031.
[12] A. Dodoc, W. Ulrich, and H-J Rostalski, US Patent #7, 751,129.
[13] D. Shafer, Yung-Ho Chuang and J. Armstrong, SPIE, 5523, 1–7 (2004).
[14] D. Schroeder, in 'Astronomical Optics' (Academic Press, San Diego, 1999), p. 123.
[15] G. Fulcher, JOSA, 37(1), 47 (1947).
[16] R. Kingslake, in 'Lens Design Fundamentals' (Academic Press, San Diego, CA, 1978).

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