Chapter 5

Achromats

5.1 Introduction

The progression of an achromat from the basic conventional form to a diamond-turned aspheric hybrid for the infrared spectrum will be demonstrated in this Chapter. We start with a cemented doublet for the visible spectrum, then change to the mid-wave and long-wave infrared regions, and proceed with the rest of the improvements relating to aberration reductions in the long-wavelength spectral band. For this exercise, we elect a 100-mm focal length with an *f*/4 relative aperture and add a field of ±2 deg.

5.2 Thin Achromat for the VIS Spectrum, On-Axis Performance

A conventional achromat consist of two elements. One has positive power and a low relative dispersion (high Abbe number), the other has negative power and a high relative dispersion (low Abbe number). The elements' powers, required for chromatic aberration correction, are

$$\phi_a = \frac{V_a}{\left(V_a - V_b\right)}\phi \text{ for the front element,} \tag{5.1}$$

and

$$\phi_b = \frac{V_b}{\left(V_b - V_a\right)}\phi \text{ for the rear element.} \tag{5.2}$$

V_a and V_b are the mentioned Abbe numbers for the two elements.

With $\phi_a = \left(n_a - 1\right)c_a$ and $\phi_b = \left(n_b - 1\right)c_b$, Eqs. (5.1) and (5.2) change to

$$\left(n_a - 1\right)c_a = \frac{V_a}{\left(V_a - V_b\right)}\phi \text{ and } \left(n_b - 1\right)c_b = \frac{V_b}{\left(V_b - V_a\right)}\phi,$$

from which we can extract the net curvature for the front element *a*:

$$c_a = \frac{V_a}{(V_a - V_b)(n_a - 1)}\phi . \tag{5.3}$$

The net curvature of the rear element *b* is

$$c_b = \frac{V_b}{(V_b - V_a)(n_b - 1)}\phi . \tag{5.4}$$

Since the shapes of the elements in an achromat do not influence the chromatic aberration, we make the first element equi-convex, i.e., $c_{a1} = -c_{a2} = 0.5c_a$. Further, we give the first surface of element *b* the same curvature as the second surface of element *a*, i.e., $c_{b1} = c_{a2}$. With that,

$$c_{a1} = \frac{V_a}{2(V_a - V_b)(n_a - 1)}\phi = -c_{a2} \ . \tag{5.5}$$

Furthermore, since $c_{b1} = c_{a2}$ and

$$c_b = \frac{V_b}{(V_b - V_a)(n_b - 1)}\phi ,$$

$$c_{b2} = c_{a2} - c_b = -c_{a1} - \frac{V_b\phi}{(V_b - V_a)(n_b - 1)} \ . \tag{5.6}$$

For the front element *a* (crown) we take glass BK7 with $n_a = 1.517$ and $V_a = 64.17$. The rear element *b* (flint) is made from glass F2 with $n_b = 1.620$ and $V_b = 36.37$. With that we get

$$c_{a1} = \frac{64.17}{2(64.17 - 36.37)(1.517 - 1)} \times 0.01 = 0.022324 ,$$

or $R_{a1} = 1/c_{a1} = 44.795387$ mm and $R_{a2} = -44.795387$ mm.

With $c_{b1} = c_{a2} = -0.022324$,

$$c_{b2} = -0.022324 - \frac{36.37 \times 0.01}{(36.37 - 64.17)(1.62 - 1)} = -0.001223 ,$$

and $R_{b2} = 1/c_{b2} = -817.966784$ mm.

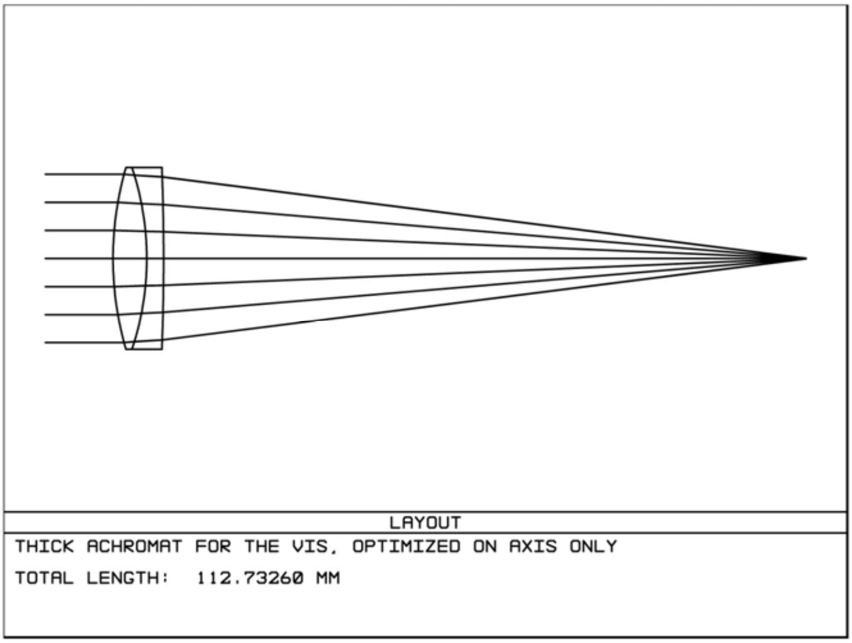

Figure 5.1 Cemented achromat for the VIS spectrum (corrected for on-axis only) after adding thicknesses and optimizing.

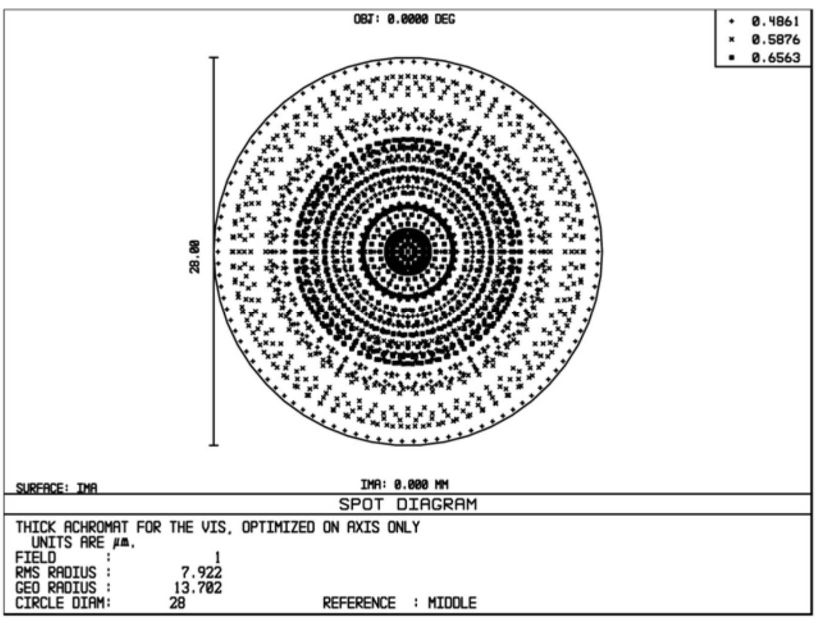

Figure 5.2 Blur-spot size of the optimized achromat for the visible spectrum.

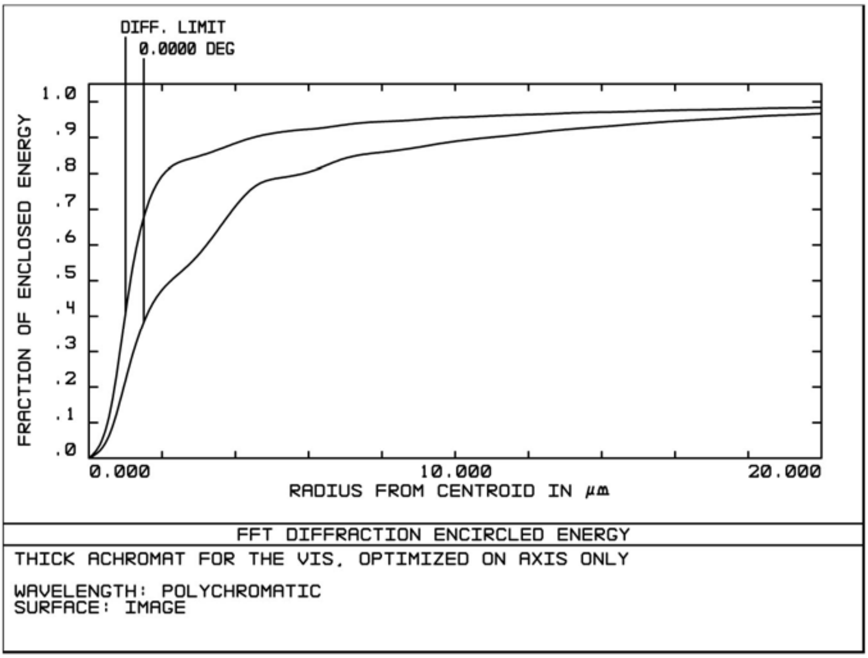

Figure 5.3 The encircled energy with reference to the diffraction limit.

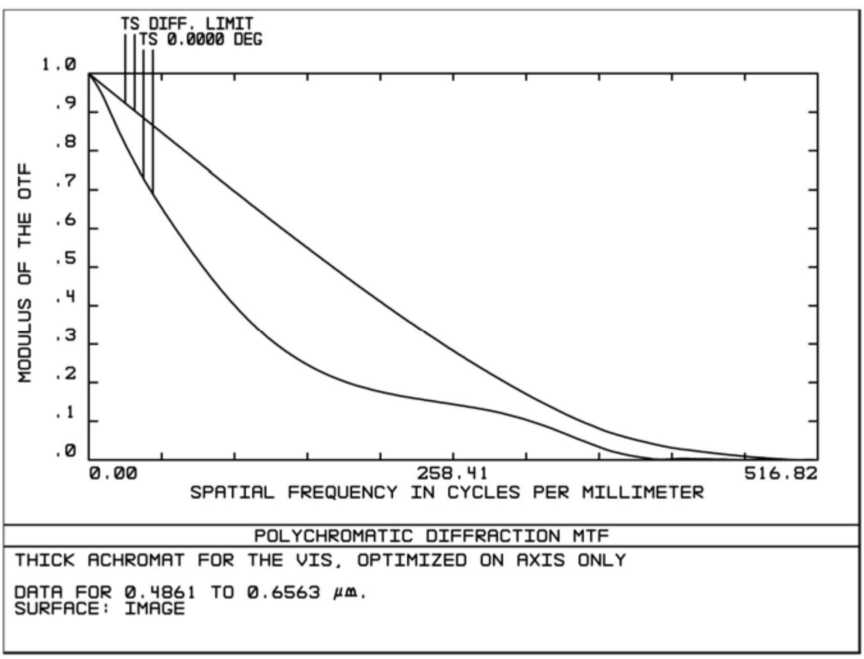

Figure 5.4 Modulation transfer function of the achromat.

This choice of curvatures results in a respectable small spherical aberration of

$$\sum_{1}^{4} TSC = -0.0225 \text{ mm} .$$

We add reasonable thicknesses of 5 mm and 2.5 mm and optimize. The chromatic aberration remains corrected and the transverse spherical aberration reduces to –0.0156 mm.

We summarize our findings for the expected performance with a 4-plot report shown in Figs. 5.1, 5.2, 5.3, and 5.4. These selected plots are from the ZEMAX lens design program, which was used for the optimization of the achromat.

5.2.1 Adding a field to the on-axis corrected achromat

Adding a ±2-deg field of view to the on-axis corrected lens shows that there is a relatively large amount of coma present. This is indicated in Fig. 5.5. To also correct for coma, the shapes of the elements need to be changed. We perform this task first by an optimization process with the computer, and then show for comparison Smith's analytical method.[1] This is done to provide more insight into the method of aberration correction.

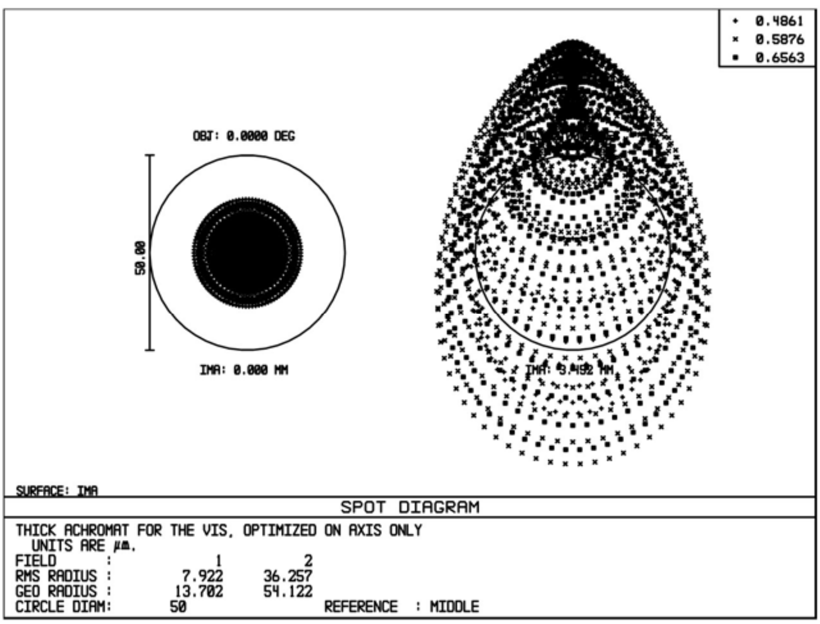

Figure 5.5 The presence of coma indicates the need for further correction. This is also indicated in the modulation transfer function shown in Fig. 5.6.

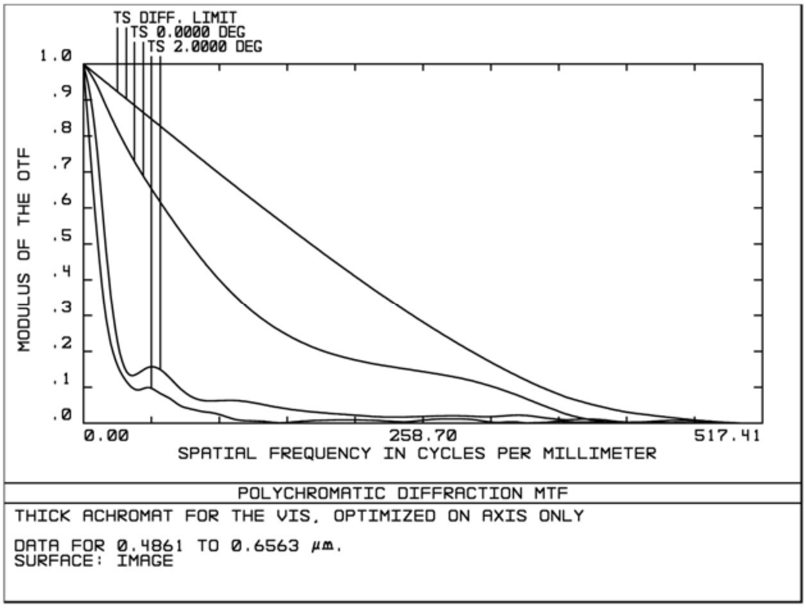

Figure 5.6 The modulation transfer function drops off drastically for the 2-deg off-axis point.

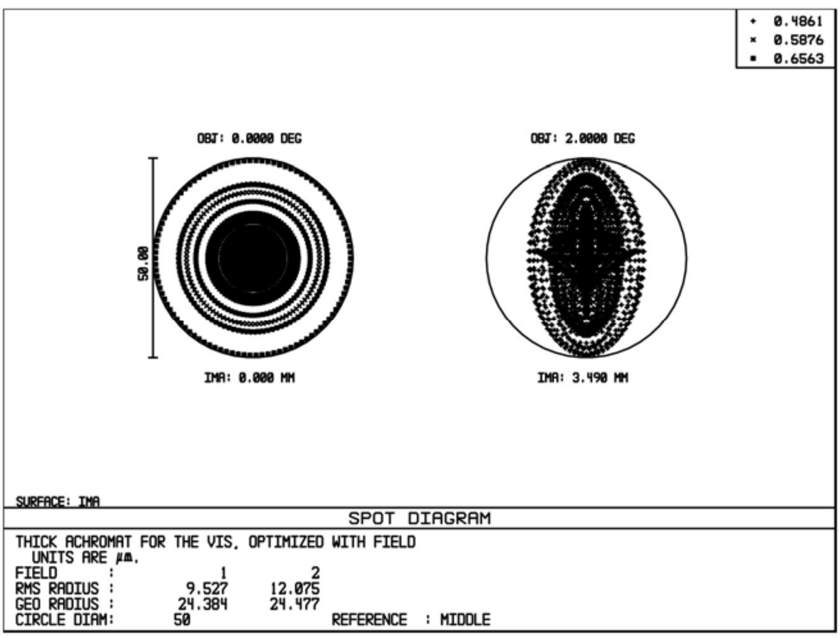

Figure 5.7 Improvement of blur spot after optimization.