Computer exercise 5 – a lens without coma and astigmatism

Now we will try to construct a lens which has zero coma and astigmatism. For this reason, it will be good for wide-angle applications such as scanning. We will use the simplest possible solution: a singlet lens and a stop. Unlike the singlet lenses we have constructed before, though, this lens will have its stop removed from the lens. First we do thin lens analysis to find out approximately what the lens should look like, and then we try to optimize a thick lens to fulfill the requirements.

From 12.76, we know that the structural aberration coefficients of a thin lens with a remote stop are

$$\begin{aligned} \sigma'_I &= \sigma_I \\ \sigma'_{II} &= \sigma_{II} + \chi\sigma_I \\ \sigma'_{III} &= 1 + 2\chi\sigma_{II} + \chi^2\sigma_I \\ \sigma'_{IV} &= 1/n \\ \sigma'_V &= \chi(\sigma_{IV} + 3\sigma_{III}) + 3\chi^2\sigma_{II} + \chi^3\sigma_I \end{aligned} \tag{1}$$

where χ is the stop shift variable, which for objects at infinity (Y=-1) is

$$\chi = \begin{cases} -\dfrac{Ks}{2}, & s < 0 \\ \dfrac{Ks}{2Ks - 2}, & s > 0 \end{cases} \tag{2}$$

where s is the physical shift of the stop. From the equations it follows that a stop shift can be used to minimize the coma and the astigmatism. The stop shift will not affect the spherical aberration or the field curvature, while it will actually introduce distortion.

First we demand that the coma is zero. This happens if

$$\chi = -\frac{\sigma_{II}}{\sigma_I} \tag{3}$$

i.e., it's enough to adjust the stop shift. This can be done for a lens of any shape. Second, we demand that the astigmatism is zero. Using equations 1 and 3, we find that this happens if

$$\sigma_{II}^2 = \sigma_I\ . \tag{4}$$

This condition means the bending factor of the lens must be adjusted to produce the right amount of aberrations. For Y=-1, the equation becomes

$$AX^2 - BX + C + D = (EX - F)^2, \tag{5}$$

and using 12.64 it is possible to solve for X and find the two solutions

$$X = -(1 - n^2) \pm n^2. \tag{6}$$

Inserting equation 6 along with 12.64 into 12.63, it can be found that

$$\begin{aligned} \sigma_I &= n^2\left(1 \pm \frac{n+1}{n-1}\right)^2 \\ \sigma_{II} &= n\left(1 \pm \frac{n+1}{n-1}\right) \end{aligned} \tag{7}$$

and consequently the stop shift parameter is

$$\chi = -\left[n\left(1 \pm \frac{n+1}{n-1}\right)\right]^{-1}. \tag{8}$$

Then we can write down all the monochromatic aberrations after the stop shift:

$$\begin{aligned} \sigma'_I &= n^2\left(1 \pm \frac{n+1}{n-1}\right)^2 \\ \sigma'_{II} &= 0 \\ \sigma'_{III} &= 0 \\ \sigma'_{IV} &= 1/n \\ \sigma_V &= \frac{(n-1)(n+1)}{2n^2} \end{aligned} \quad . \tag{9}$$

So now we know how to construct a thin lens with a shifted stop that has no aberration or coma.

Task

A. Theoretical

Using a refractive index of 1.5, find the bending factors, the physical stop shifts, and the structural aberration coefficients for the two possible solutions. Draw approximate layouts of the two systems. Include your calculations and the layouts in your report. Hand written is OK.

Pick the one with the smallest amount of spherical aberration. If you have performed the calculations correctly, the lens should be a standard, off-the-shelf lens. This is quite practical – you can easily buy the lens and then, simply by inserting a stop at the right position, you can improve its performance for wide-angle applications.

B. With synopsys

Construct the lens in synopsys, and optimize it for zero coma and astigmatism. The object should be at infinity, and the object angle 30°. The lens should have a real thickness. Adjust the aperture size to give an F-number of 12.5. Use monochromatic light of wavelength 632.8 nm (a HeNe laser).

Optimizing for zero astigmatism in synopsys is rather difficult – the program doesn't have separate parameters for field curvature and astigmatism. Instead it uses the two parameters tangential astigmatism and sagittal astigmatism. Using our definition, we would say that the astigmatism is zero when (according to Synopsys) the tangential astigmatism and the sagittal astigmatism are the same. They are then equal to the field curvature. This condition can be fulfilled quite well without optimization, if you just give the lens the correct bending and adjust the stop position.

If you write MRR in the command window, a dialog opens. Here you can pick the alternative FCV, which produces a plot. The graph shows where the tangential and the sagittal image planes are. If the image planes coincide or nearly coincide, the astigmatism is zero. If the image fields are still curved, the system has field curvature. However, field curvature can always be compensated by e.g. a curved image screen, so in this exercise we disregard it.

Analyze the performance of your lens. Include the lens layout, the system specifications, the aberrations, ray fans, MTF for the middle and the edge of the image field, and an FCV graph in your report.