Solution of Exercises
Lecture Optical design with Zemax– Part 4

4 Aberrations

4.1 Strehl ratio and geometrical vs Psf spot size

A single plano-convex lens made of K5 with focal length \( f = 25 \) mm and thickness \( d = 5 \) mm is illuminated by a diverging beam with numerical aperture \( \text{NA} = 0.1 \) and wavelength \( \lambda = 546.07 \) nm. After the lens the light should be collimated. If the collimated beam is refocused without further aberrations, the point spread function is not diffraction limited.

a) Calculate the accurate Strehl ratio, the estimated Strehl ratio and the geometrical and diffraction encircled energy inside the ideal Airy diameter.

b) If now the numerical aperture is reduced, the Marechal estimation becomes better. Calculate the largest \( \text{NA} \), for which the relative error is smaller than 2%. What amount of the beam power for geometrical and diffraction encircled energy is inside the Airy diameter obtained here?

Solution:

a) System data and layout:
b) If the numerical aperture is changed, the following steps are performed:

1. Reduce NA
2. Determine the Airy diameter out of the spot diagram window
3. Set the aperture in the image plane exactly to the Airy value
4. Calculate the estimated Strehl ratio from the Zernike window
5. Calculate the accurate Strehl ratio from the Huygens PSF window with appropriate sampling
6. Calculate the geometrical encircled energy by the footprint diagram (with option: delete vignette)
7. Calculate the diffraction encircled energy by the text output of the EE window.

Then the following table is obtained:

<table>
<thead>
<tr>
<th>NA</th>
<th>Strehl exact</th>
<th>Strehl estimated</th>
<th>relative error</th>
<th>Airy radius</th>
<th>geometrical EE inside Airy</th>
<th>diffraction EE inside Airy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.019</td>
<td>0</td>
<td>0</td>
<td>0.003299</td>
<td>0.0389</td>
<td>0.0394</td>
</tr>
<tr>
<td>0.08</td>
<td>0.058</td>
<td>0</td>
<td>0</td>
<td>0.004123</td>
<td>0.0889</td>
<td>0.0889</td>
</tr>
<tr>
<td>0.07</td>
<td>0.053</td>
<td>0</td>
<td>0</td>
<td>0.004712</td>
<td>0.1449</td>
<td>0.1443</td>
</tr>
<tr>
<td>0.06</td>
<td>0.172</td>
<td>0.2158</td>
<td>0.255</td>
<td>0.005497</td>
<td>0.2514</td>
<td>0.3403</td>
</tr>
<tr>
<td>0.055</td>
<td>0.342</td>
<td>0.3662</td>
<td>0.0661</td>
<td>0.005996</td>
<td>0.3414</td>
<td>0.4611</td>
</tr>
<tr>
<td>0.051</td>
<td>0.486</td>
<td>0.4958</td>
<td>0.0198</td>
<td>0.006466</td>
<td>0.4467</td>
<td>0.5534</td>
</tr>
<tr>
<td>0.05</td>
<td>0.520</td>
<td>0.5277</td>
<td>0.0146</td>
<td>0.006600</td>
<td>0.4780</td>
<td>0.5650</td>
</tr>
<tr>
<td>0.045</td>
<td>0.676</td>
<td>0.6753</td>
<td>0.00104</td>
<td>0.007328</td>
<td>0.6887</td>
<td>0.6607</td>
</tr>
<tr>
<td>0.04</td>
<td>0.798</td>
<td>0.7940</td>
<td>0.00501</td>
<td>0.008244</td>
<td>1.0</td>
<td>0.7281</td>
</tr>
</tbody>
</table>

The relative error of the estimated Strehl ratio is smaller than 2% for NA < 0.051. Here the geometrical encircled energy is 45%, the diffraction calculated encircled energy 55%.
4.2 Aberrations and Performance of an Diode Collimator

Load the lens GLC-6.5-8.0-830 DIODE LASER COLLIMATING LENS from the catalog of CVI Melles Griot.
a) What is the numerical aperture of the lens in the image? Determine the Strehl ratio and compare the estimated and the exact value.
b) What are the two surfaces with the largest contribution to the spherical aberration? The first lens groups looks like an achromate. Corresponds the correction of this part of the system to an achromate?
c) Show, that all intersection points of the spot diagram are inside the Airy diameter. If the spot is analysed it is seen, that there is a bright kernel with a surrounding halo. What is the relative power content of the inner kernel region? What is the diameter of this inner part?
d) What is the image contrast of a grating object with 100 line pairs per millimeter of this system? Determine the MTF of the lens for defocussing. What is the depth of focus intervall, where inside the contrast is larger than 50%? Explain the asymmetry of the curve.

Solution:

a) The system looks as follows.

<table>
<thead>
<tr>
<th>Surf</th>
<th>Type</th>
<th>Comment</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Semi-Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBJ</td>
<td>Standard</td>
<td>Infinity</td>
<td>Infinity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Standard</td>
<td>Infinity</td>
<td>5.000000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>Standard</td>
<td>GLC-6.5-8.0-830</td>
<td>0.0179467</td>
<td>4.6120000</td>
<td>N-BAP2</td>
<td>5.0000000</td>
</tr>
<tr>
<td>3</td>
<td>Standard</td>
<td>-6.9484977</td>
<td>1.2699900</td>
<td>N-SF10</td>
<td>5.0000000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Standard</td>
<td>-18.009167</td>
<td>0.1280600</td>
<td></td>
<td>5.0000000</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Standard</td>
<td>10.0000494</td>
<td>3.6600000</td>
<td>N-SF11</td>
<td>5.0000000</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Standard</td>
<td>23.9251621</td>
<td>0.9790000</td>
<td></td>
<td>5.0000000</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Standard</td>
<td>5.6561086</td>
<td>1.1320000</td>
<td>N-SF11</td>
<td>4.0000000</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Standard</td>
<td>Infinity</td>
<td>1.2124999</td>
<td>M</td>
<td>4.0000000</td>
<td></td>
</tr>
<tr>
<td>IMA</td>
<td>Standard</td>
<td>Infinity</td>
<td>-</td>
<td></td>
<td>5.509E-007</td>
<td></td>
</tr>
</tbody>
</table>

The numerical aperture is \( NA = 0.524 \) in the image space.
The Strehl ratio in Marechal approximation is $D = 0.972$, the exact value is $D = 0.975$.

b) The Seidel surface contributions show, that the 2nd and the 7th surface (without the first help surface) of the system have the largest contributions to the residual aberrations. If the Seidel diagram is calculated only for the 3 surfaces of the first cemented group it is seen, that the spherical aberration is not corrected. Therefore, this part does not correspond to a conventional achromate.
c) The spot diagram has a geometrical radius of 0.825 µm, the Airy radius is 0.8253 µm and therefore all spot points are inside. The diameter of this inner part is \(D = 0.2 \mu m\).

If the geometrical encircled energy function is considered (without 'multiply by diffraction limit') and with 256x256 sampling points, it is seen, that inside this region we have approximately 60% of the beam power.

d) The calculation of MTF versus focus gives in the nominal image plane a contrast of 80%. From the text version of this plot we get the limiting values of \(-0.01\) mm and \(+0.01\) mm for 50% contrast, Therefore the corresponding depth of focus is \(\Delta z = 20 \mu m\).

The asymmetric behavior is a result of the residual spherical aberration of the system.
4.3 Anamorphotic Diode collimator

A semiconductor diode with wavelength 650 nm and the divergence / aperture values 0.4 / 0.1 in the fast and slow axis respectively should be collimated in a circular beam with a diameter of approximately 8 mm. The collimated beam is now focused into a fiber with numerical aperture of NA = 0.1.

\[
\begin{align*}
\text{diode} & \quad \text{NA}_y = 0.4 \\
\lambda & = 650 \text{ nm} \\
\text{L1} & \quad \text{aspherical collimator} \\
\text{L2} & \quad \text{cylindrical lens} \\
\text{L3} & \quad \text{cylindrical lens} \\
\text{L4} & \quad \text{focussing lens} \\
\text{circular beam} & \quad D = 8 \text{ mm} \\
\text{fiber} & \quad \text{NA} = 0.1
\end{align*}
\]

Find a solution for this problem with only available catalog lenses. Is the setup diffraction limited? Explain the shape of the residual spot pattern. What are the reasons for the residual aberrations in the system? What can be done to further improve the result? Discuss possible steps to get a shorter system. What are the consequences of a compact layout?

Solution

If the desired beam diameter after the collimation of the fast axis is 8 mm, the focal length of the first lens is

\[
f = D / 2 \cdot \text{NA}_y = 10 \text{ mm}
\]

Since the numerical aperture of the fast axis is high, it is recommended to use an aspherical collimator lens, which is corrected for spherical aberration on axis. If such a lens is found in the lens catalogs, it must be considered:
1. the lens should be used without cover glass plate
2. if a working wavelength near to the 650 nm is found, it is an advantage

Possible solution:
Catalog Asphericon, lens with the No A12-10HPX

Necessary steps to process this lens:
1. load the lens
2. turn around
3. set NA to 0.4 and vignetting factors in field menu to VCX = 0.75

4. change wavelength to 650 nm
5. optimize first distance to collimate this wavelength (default merit function, with criterion: direction cosines)

A footprint diagram shows the elliptical beam cross section behind the lens.

In the next step, a Galilean telescope with factor $\Gamma = 4$ must be found to enlarge the diameter of the x-section to the same value as in the y-section. First a negative cylindrical lens with a rather short focal length must be found.

Possible solution: Lens with 1 inch negative focal length in the catalog of Melles Griot: RCC-25.4-12.7-12.7-C
The lens is inserted behind the collimating asphere and rotated around the x-axis by 90° to work in the x-section.

The distance to the collimator is not very relevant and is fixed to be 5 mm.

For a Galilean telescope with factor 4, the second lens must have a focal length of 4x25.1 mm = 100.4 mm. In the same lens catalog one can found the following lens: RCX-40.0-20.0-50.9-C
The lens is inserted, turned around to get a better performance and also tilted by 90° in the azimuth. A first guess gives a distance of $100 - 25 = 75$ mm between the telescope lenses to get a collimated x-section. But from the spot diagram with direction cosine option it is seen, that the angle distribution is not equal in both sections. Due to the finite positions of the principal planes of the lenses, the distance must be optimized with an angle criterion default merit function.

Spot diagram before and after this focusing operation with the same scale:

The footprint diagram now shows a rather circular cross section. The residual error can be neglected and comes from the fact, that for this wavelengths, the catalog focal lengths are not exact.

The data are now the following:
To focus the beam into a fiber with numerical aperture 0.1, the focal length must be not smaller than $f = \frac{4.32\, \text{mm}}{0.1} = 43.2\, \text{mm}$. A lens of approximately this size can be found in the catalog of Melles Griot as an achromate. This helps in getting a better correction:

LAO-44.0-14.0

This lens is inserted to complete the system. Finally the last distance is optimized to get a minimal spot size.

It is seen, that the spot is nearly diffraction limited.