Solution of Exercises
Lecture Optical design with Zemax for PhD – Part 1

1.1 Stair-mirror-setup

1.2 Symmetrical 4f-system

1.3 System layout with ideal lenses

1.1 Conic surface

1.1 Stair-mirror-setup

Setup a system with a stair mirror pair, which deceters an incoming collimated ray bundle with 10 mm diameter by 40 mm in the -y direction. The wavelength of the beam is \( \lambda = 632.8 \) nm. After this pair of mirrors a decentered main objectiv lens with focal length \( f = 200 \) mm made of BK7 is located 25 mm below the optical axis and focusses the beam.

a) setup the system
b) generate layout drawings in 2D and in 3D
c) calculate the beam cross section on the second mirror, what is the size of the pattern?
d) determine the optimal final sensor plane location. Calculate the spot of the focussed beam. Discuss the shape of this pattern.
e) now extend the separation between the two mirrors to 200mm. The system now should be modified to have an intermediate focal point in the midpoint between the mirrors. Calculate the radii of the mirrors to recollimate the beam before the refractive lens. Determine again the best image plane. If the spot diagram is considered, what is the reason for the drastic change?

Solution:

<table>
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<tr>
<th>Surf Type</th>
<th>Comment</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Semi-Berm.</th>
<th>Conic</th>
<th>Par O(zm...)</th>
<th>Decenter X</th>
<th>Decenter Y</th>
<th>Tilt Abou.</th>
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<tr>
<td>2 Coord.:</td>
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<td>0.00000</td>
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<td></td>
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<tr>
<td>3 Standard</td>
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<td>4 Coord.:</td>
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<tr>
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Footprint: the size of the beam in the local system is $D_x = 20$ mm, $D_y = 28.3$ mm

The final image location is determined by the quick focus option. The spot has a typical coma-shaped structure due to the off-axis usage of the lens.

The modified data are now with the radii -282 mm and +282 mm (due to the change of sign by the first mirror) respectively.
The layout and the spot diagram looks as follows:

Since the spherical mirrors induce a large astigmatism, the focusing only looks fine in the y-z-plane. The elliptical shape near the circle of least confusion dominates over the coma.
1.2 Symmetrical 4f-system

Setup a telecentric 4f-imaging system with two identical plano-convex lenses made of BK7 with thickness $d = 10$ mm and approximate focal lengths $f = 100$ mm. The wavelength of the system is $\lambda = 546.07$ nm and the numerical aperture in the object space is $NA = 0.2$. The object has a diameter of 10 mm.

a) Determine the layout and the spot diagram of the system, if the setup is perfectly symmetrical.
b) Optimize the image location. Why is the spot size improved?
c) If the starting aperture is decreased, the system becomes more and more diffraction limited. What is the value of the NA to get a diffraction limited system on axis? Take in mind here, that the lowered spherical aberrations needs a re-focussing, which depends on the aperture.

Solution:

The radius of curvature is approximately 50 mm. A more exact value can be obtained by setting a solve with component power $F = 1/f = 0.01$ mm$^{-1}$ at the second lens surface. To find the first distance, the easiest solution without optimization is to reverse the lens, start with collimated light of 21 mm diameter and find the optimal distance behind the lens with quick focus. This value is inserted in the system, where the best orientation is to have the plane surface towards the object. It has to be noticed, that due to the finite residual aberrations of the single lens, a perfect collimation can not be obtained for all rays in the aperture cone.

The distance between the lens and the stop plane can be found by forcing the system to be telecentric (GENERAL menu) and to let the chief ray axis intersection point to be in the stop plane.
The best image location is approximately 1 mm nearer to the system with a considerably smaller size due to the spherical aberration of the system.

If the numerical aperture is reduced to a value of $\text{NA} = 0.05$, the system approximately is diffraction limited, as can be seen on the spot diagram on axis and the corresponding Airy diameter.
1.3 System layout with ideal lenses

A collimated laser beam with wavelength $\lambda = 1.064 \, \mu m$ and diameter $D = 2 \, mm$ should be expanded by a Kepler-type afocal telescope made of ideal lenses with a first focal length $f_1 = 50 \, mm$ and a factor of 5. The enlarged collimated beam is then focussed down by a cylindrical lens with focal length $f = 100 \, mm$ to get a line focus.

a) Setup the system described above by ideal lenses
b) Show the line focus graphically

Solution:

a) The ideal lens can also be modelled as an ABCD-system.

b) Spot diagram, more points, scale fixed, bad resolution. A footprint is an alternative option.

The ideal lens can also be modelled as an ABCD-system.

It has to be noted, that the footprint only gives the line pattern, if the diameter of the final image plane is fixed to the corresponding finite value, e.g. 10 mm. Due to the perfect system property, otherwise the diameter in the image plane are near to zero.
1.4 Conic surface

A system with an ellipsoidal mirror should be installed. For this task, the following steps should be performed:

a) A source with wavelength $\lambda = 1.064 \, \mu\text{m}$ and numerical aperture NA = 0.1 is imaged by a spherical mirror in a 1:1 setup with a mirror radius of 20 mm.

b) The image distance is enlarged to 40 mm. The radius of the mirror and the conical constant is optimized for this geometry.

c) The coordinate system is rotated by 60° directly after the object. For a proper layout, the subaperture of the mirror which is used should be explicitly defined. Make a shaded model layout with this setup.

What is the bending angle of the central ray at the mirror? Determine the shape and the approximate x/y-aspect ratio of the illuminated area on the mirror.

**Solution:**

a) spherical mirror with radius 20 mm

b) Image distance doubled and a simple merit function (default) is used to optimize the radius $r$ and conic constant
c) An additional surface is introduced after the object and a coordinate break is defined with 60° tilt around the x-axis.

A raytrace shows, that in the y-z-plane the y-values of the aperture cone are 16.3...19.8...22.9 mm. Therefore a rectangular aperture with y-shift 20 mm and half diameters of 4 and 5 mm are defined.

If the ray trace is calculated for the central ray, we get the incidence angle 13.90°. Therefore the bending of the central ray is 27.8°.

A footprint on the mirror looks nearly elliptical with an aspect ratio of 0.712