8.1 Multi configuration, universal plot and slider

Load a classical achromate with a focal length of \( f = 100 \text{ mm} \), no field and numerical aperture \( \text{NA} = 0.1 \) from one of the vendor catalogs. Fix the wavelength to \( \lambda = 546.07 \text{ nm} \).

a) Add a thin meniscus shaped lens behind the system with an artificial refractive index of \( n = 2 \) to enlarge the numerical aperture by a factor of 2 without introducing spherical aberration. To achieve this, the surfaces must be aplanatic and concentric.

b) Now reduce the numerical aperture to a diameter of 2 mm and set a folding mirror in the front focal plane of the system. The incoming beam should be come from below and is deflected to the right side.

c) Generate a multi-configuration system for a scan system by rotating the mirror. The first coordinate break angle can take the values \(-50^\circ, -47.5^\circ, -45^\circ, -42.5^\circ \) and \(-40^\circ\). The second coordinate break should be defined by a pick up with a resulting bending angle of the system axis of \(-90^\circ\).

d) The chief ray of the scan system is telecentric in the paraxial approximation. Due to the residual aberrations of the system, there is a deviation from the telecentricity in the real system. Show this by a corresponding universal plot.

e) Show the variation of the spot in the image plane by using the slider.

Solution:

As a first step, the achromate AAP-100.0-25.4 from the Mess Griot catalog is loaded. The field is set to zero, the aperture has a diameter of \( D = 20 \) and the wavelength is set to 546 nm.

a) Two surfaces are added, the distances are chosen to be 1 and 2 mm. The first surface radius is taken as a solve to be aplanatic, the second to force the marginal ray angle to be \(-0.2\). This corresponds to an aplanatic-concentric lens. Finally the image distance is optimized with the Quick focus menu.
In the Seidel bar menus it can be verified, that this lens does not introduce any spherical aberration.

b) First the two radii of the meniscus lens are frozen to be constant. Then the first distance is set to 0 and the cardinal points are calculated.
It is seen, that the front focal plane lies 46.8 mm in front of the system. The bending mirror is introduced in a corresponding distance.
c) The multi-configuration is established as follows:

![Multi-Configuration Editor](image)

1: PRDM    2/3  -50.0000000
2: Config 1  -47.5000000
3: Config 2  -45.0000000
4: Config 3  -42.5000000
5: Config 4  -40.0000000

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d) The universal plot is generated with a REAB-operand in the merit function for the 1st configuration.

![Universal Plot](image)
e) The spot diagram is used with dithered ray sampling and a fixed scale. The slider is configured as follows:

![Slider 1](image)

![Spot Diagram Settings](image)

### 8.2 Multiconfiguration Interferometer 1

A Mach-Zehnder interferometer has the following principal geometry

![Interferometer Diagram](image)

a) Set up a Mach-Zehnder interferometer as a multi configuration. The incoming beam should have a wavelength of $\lambda = 632.8$ nm and is collimated with 10 mm diameter. The long sides of the interferometer are 100 mm long and the short ones 50 mm.

b) Introduce a Zernike surface on one side of the sample and make it visible in the interferogram. As an example, a spherical aberration of 5th order (term No. 16 in Fringe nomenclature) with 1 $\lambda$ coefficient should be used.

c) Show the effect on the interferogram, if one mirror is shifted in a direction by 1 mm, which causes a lateral displacement of the test beam. What happens, if the combining mirror is tilted wrong by 0.1°? What happens, if a tilt is set in the interferogram settings?

**Solution:**

a) Setup of the interferometer:
b) On the front surface of the sample, a Zernike-Fringe type is introduced. In the reference arm, this surface is an air-to-air surface and therefore has no impact on the beam. The data of the surface can be viewed in the Extra Data Editor. A 16-term setup with normalization radius 5 mm is established, the coefficient is scaled in mm and therefore set to 0.0006328 mm.
To view the Interferogram, the following settings are realized. It has to be noticed, that the reference wave is plane. Therefore in the General menue, the option 'Afocal Image Space' must be activated.

c) A lateral shift between the two arms can be e.g. simulated by changing the vertical distance of the reference arm from 50 mm to 51 mm. Since the reference wave is plane, the interferogram is not changed. The lack of overlapping diameters, which occurs in practice, is not seen in Zemax. The same happens, if the beam combining mirror is tilted. It seems to be an error in the software, that a difference in beam position or orientation is not detected from the data.

If a tilt is set in the wavefront / interferogram menue, the interferogram is changed dramatically due to a tilt overlay.
8.3 Universal plot for 4f-System Telecentricity

Establish a generalized 4-f-optical system with the achromatic lens LAL 50.0 - 20.0 from the catalog of CVI Melles and Griot with focal length \( f_1 = 50 \) mm as front lens and LAL 200.0 - 50.0 with \( f_2 = 200 \) mm as a rear group. The wavelength should be 632 nm and the initial numerical aperture \( NA = 0.1 \).

a) What is the numerical aperture in the image space?

b) If the stop is located in the intermediate focal point, the system is both sided telecentric. If the object sided telecentricity is forced explicitly in Zemax, determine the residual telecentricity error in the image space as a function of the object field height between \( y = 0 \) and 4 mm as a universal plot.

c) Generate a two dimensional universal plot, which shows the spot rms-diameter in the image on axis as a function of the object distance and the image distance. The distances should be varied in a range of 10 mm in the object space and 20 mm in the image space.

d) If the lens groups are turned around, the performance of the image is worse. Compare the two spot diameters of both configurations. What happens to the telecentricity criterion of b)?

Solution

The lens is loaded and reversed in orientation. The wavelength is set to 632 nm and the numerical aperture \( NA = 0.1 \). The cardinal point options gives the principal plane to be located 3.729 mm inside the lens on the object side and -1.219 mm on the image side. The focal length is exactly \( f = 50.031 \) mm. Therefore in paraxial approximation, the first distance is chosen to be \( 50.031 - 3.729 = 46.302 \) mm and the distance to the back focal point 48.812 mm. These distances can be checked by simple raytraces of the marginal and the chief ray.

Second, the lens with 200 mm focal length is inserted from the catalog. The the first principal plane is located 2.082 mm inside the lens, the exact focal length is 200.132 mm. Therefore the distance from the stop to the lens is 198.050 mm. The second principal plane is located at \(-6.040 \) mm, therefore the image distance is 194.092 mm.

Other possibilities to find the optimal distances can be:
1. Optimize by looking on the corresponding paraxial or real ray angle
2. Solve the chief ray intersection to be zero for the pupil location. In this case, Zemax needs one additional artificial surface.
a) The magnification of the system is \( m = 4.00 \), the numerical aperture in the image space is \( 0.1/4 = 0.025 \).

b) The telecentricity is forced in Zemax in the general menue. The universal plot is configured as follows:

The result of this calculation shows a residual telecentricity error of 1.8 mrad at the fullfield, the error grows approximately quadratic.
c) To get a 2D universal plot with the diameter, we first must build the function of the diameter out of the radius operand RSCH by multiplying it by a factor of 2. For this, we construct the following merit function

\[
\text{merit function}
\]

Then the 2D universal plot is configured as follows

The result is seen here. The interpretation of the figure is:

We see a nearly linear quadratic variation of the spot size for a defocussing of the object or the image. Due to the magnification of 0.25, the depth of focus in the object and the image space differs by a factor of 1/16. Therefore the defocussing sensitivity for the image space defocus along t7 is much smaller than the object defocussing dependence.
d) The spot diameter on axis is in the optimal configuration 25 μm, in the reverted setup the diameter grows by a factor of 10 to 285 μm.

The telecentricity error is reduced to 0.1 mrad.