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Exercises
Lecture Optical design with Zemax– Part 7

7 Correction

7.1 Fourier filtering and Imaging

Set up a telecentric 4f-system with a magnification of m = 4. The system should be arranged by two appropriate achromates from conventional vendor catalogs with the focal lengths f_1 = 25 mm and f_2 = 100 mm. The wavelength of the application is the e-line, the object size is 3 mm and the numerical aperture should be NA = 0.1.

a) Set up the system with telecentric behavior in the object and the image space. In particular adjust the system and a rectangular stop with approporiate size in the intermediate focal plane. The adjustment should be performed on axis only.

b) Check the magnification of the realized lens.Calculate the performance of the system in the center and the edge of the field size. Is the system diffraction limited ? What are the dominant aberrations in the field ?

c) Show, that the resolution of the system in the field is anisotropic due to the elongated shape of the spot by inspecting the MTF of the system.

d) Calculate a diffraction based imaging of the complete object field. Take a rectangular grid as an object. Can the anisotropic resolution be seen ?
Now calculate a geometrical imaging model of the same grid. What is the difference between the results of both models ?

e) To demonstrate the Fourier filtering in the pupil plane, removechange the rectangular pupil stop by a slit with dimensions D_x = 5 mm , D_y = 0.15 mm. What changes with the diffraction limited image ? What is the consequence for the geometrical image ?

f) Calculate the Airy diameter of the system and constitute an object with size 10 times the Airy diameter. Put this small object in the center and at the edge of the field. Discuss the results and compare them. Is the grid resolved ?

Solution:

a) Corresponding achromates are found for example in the catalog of Melles&Griot as:
First lens with f = 25 mm: LAO – 25.0 – 12.5

Second lens with f = 100 mm: LAO – 25.0 – 12.5

The first achromate must be reversed. The distances must be adjusted in a way to guarantee a collimated ray bundle between the lenses and to let the chief ray cross the optical axis in the back focal plane of the first lens. The system stop has to be fixed at the intermediate focal point. Correspondingly the distance between the stop and the second lens must be arranged to get telecentricity in the image space, the final image distance must be adjusted to get a sharp image.

1st step: find t1, merit function angular radius
2nd step: find t2, not telecentric, initial distance infinity, entrance pupil at lens with diameter D = 3 mm
3rd step: after adding the second lens:
4th step: adjusting the distance behind the stop: chief ray parallel to axis, merit function with REAB = 0
5th step: focusing image plane on axis; merit function with spot criterion

The result is (for this choice of lenses):

Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	
OBJ	Standard		Infinity	0.0000000		1.0000000	
1	Standard		Infinity	22.0215000		1.0000000	
2*	Standard		41.5210000	1.0000000	N-SF10	6.2500000	U
3*	Standard		12.4190000	4.5000000	N-BAK4	6.2500000	U
4*	Standard	LAO-25.0-12.5	-15.7960000	24.2535000		6.2500000	U
STO	Standard		Infinity	97.4617441		2.4986142	
6*	Standard	LAO-100.1-50.0	65.7860000	14.0000000	N-BAK4	25.0000000	U
7*	Standard		-50.0570000	3.5000000	N-SF10	25.0000000	U
8*	Standard		-155.170000	90.5770317 V		25.0000000	U
9	Standard		Infinity	0.0000000		4.0586688	
IMA	Standard		Infinity	–		4.0586688	
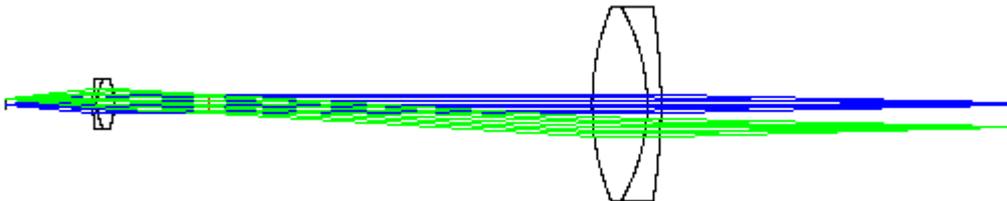
In the intermediate focal plane, a rectangular diaphragm with half widths 2.5 is placed.
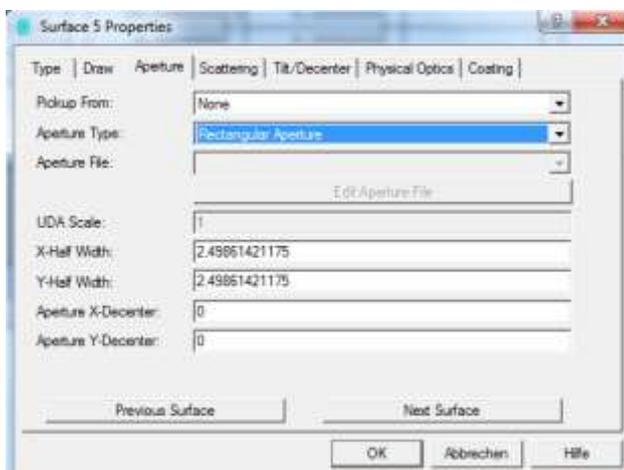
b) The performance of the system can be estimated by a spot diagram as follows.
From this diagram or the Prescription data –menu we get a magnification of m = -4.004.
In the center, the system is nearly diffraction limited, for the field of y = 1.5 mm, it is worse.

OBJ: 0.0000, 0.0000 mm   OBJ: 0.0000, 1.5000 mm

IMA: 0.000, 0.000 mm   IMA: 0.000, -6.008 mm
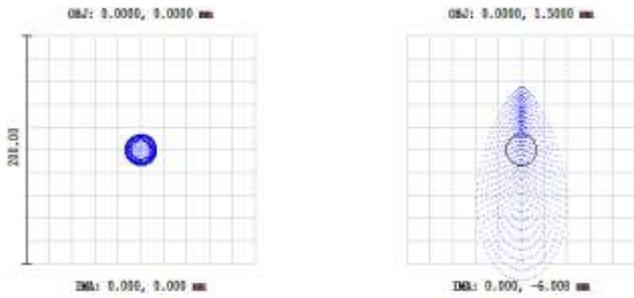
Spot Diagram

its are μm.   Airy Radius: 13.46 μm
      1   2
  11.499   47.290
 13.650   114.839   Telecentric 4f sys

If the spoit diagram is considered, mainly coma, and defocus seems to be the reasons for the decrease of the performance. The defocus can be astigmatism or field curvature. To decide about this question, the Seidel diagram is considered. It is seen, that both aberration types are there but the astigmatism dominates by a factor of 2.

c) The MTF shows a large separation of the tangential and sagittal contrast curves. This describes the anisotropic resolution of the coma/elliptical spot shape.
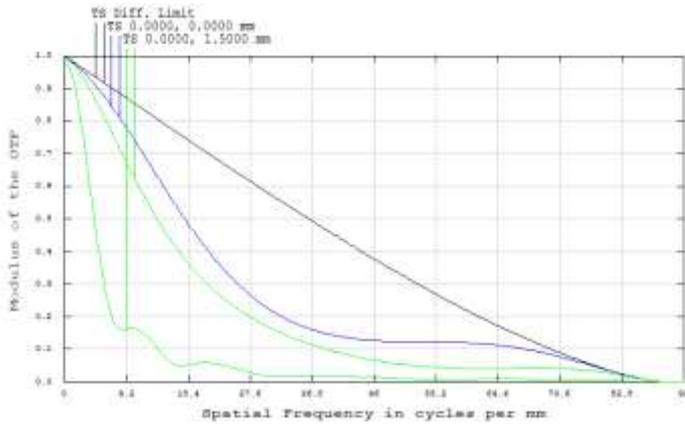
d) The result look like this picture, the settings are documented on the right. The difference in the resolution can not be recognized in this coarse representation.
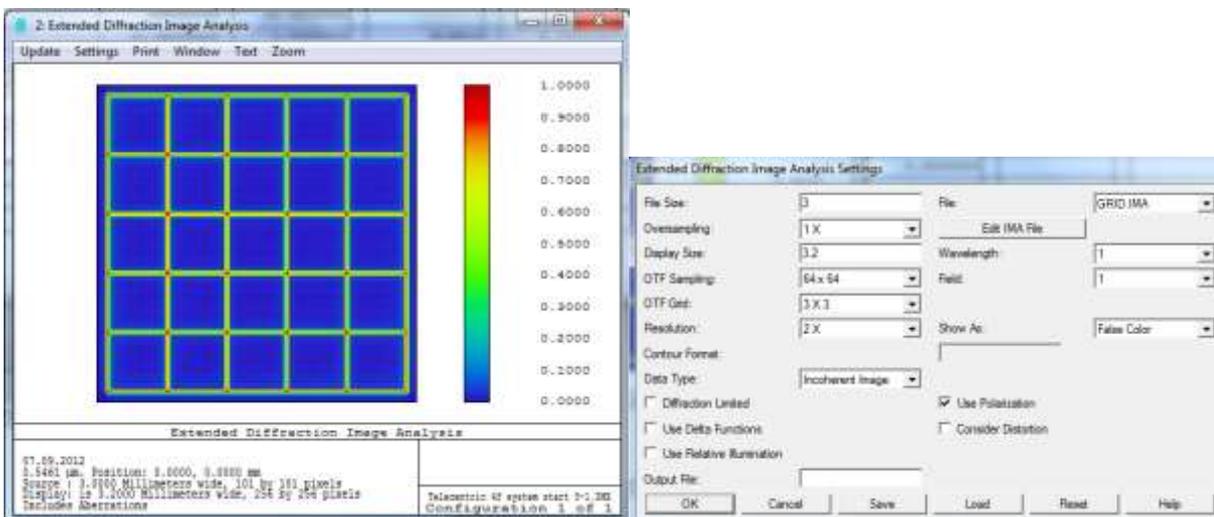

The following figure shows the result of the geometrical calculation for 10^6 rays.
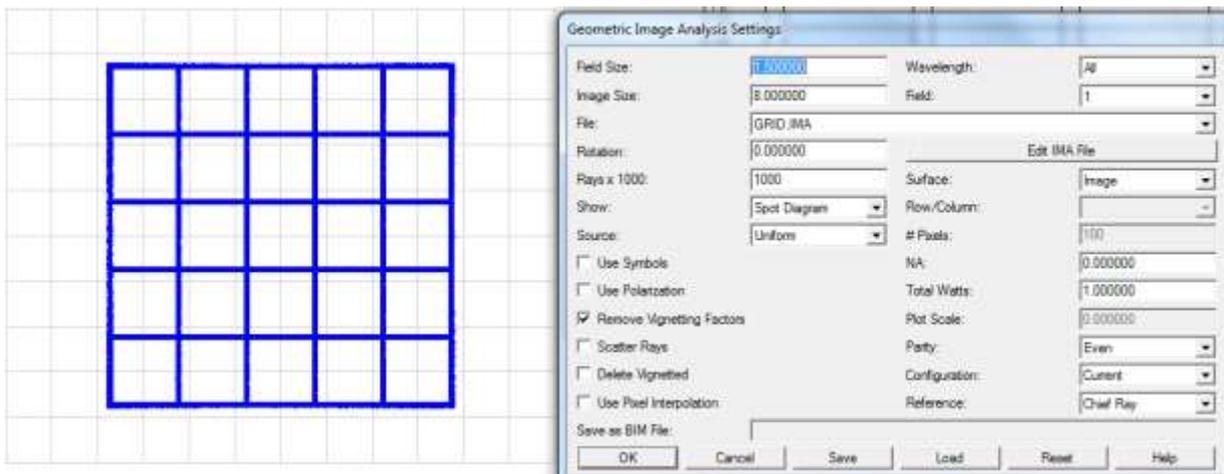
Both models shows a comparable sharp imaging of the grid. In the diffraction model, the special effects of diffraction are seen at the crossing points, where a higher intensity is calculated. Furthermore, in the diffraction calculation we have a stronger profile across a bar cross section. This can be seen in a zoom representation of a single crossing point at higher resolution.
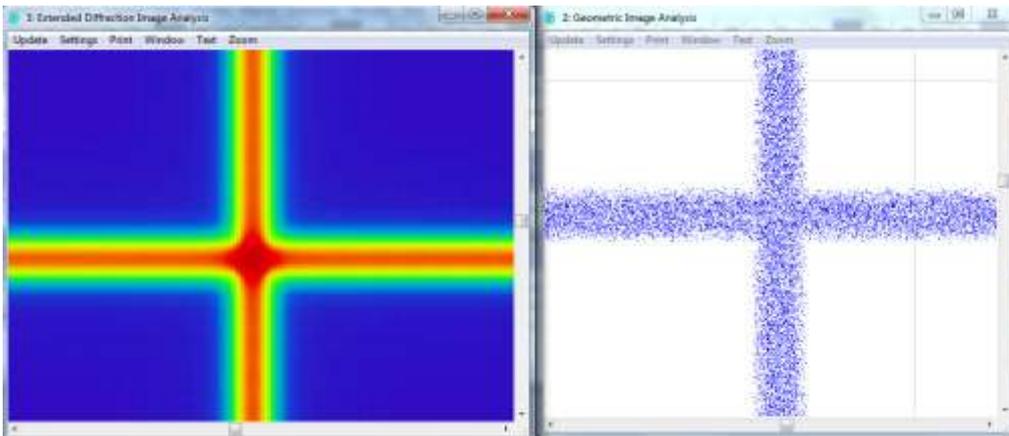
e) If a rectangular slit stop is established in the system, we get the following results:
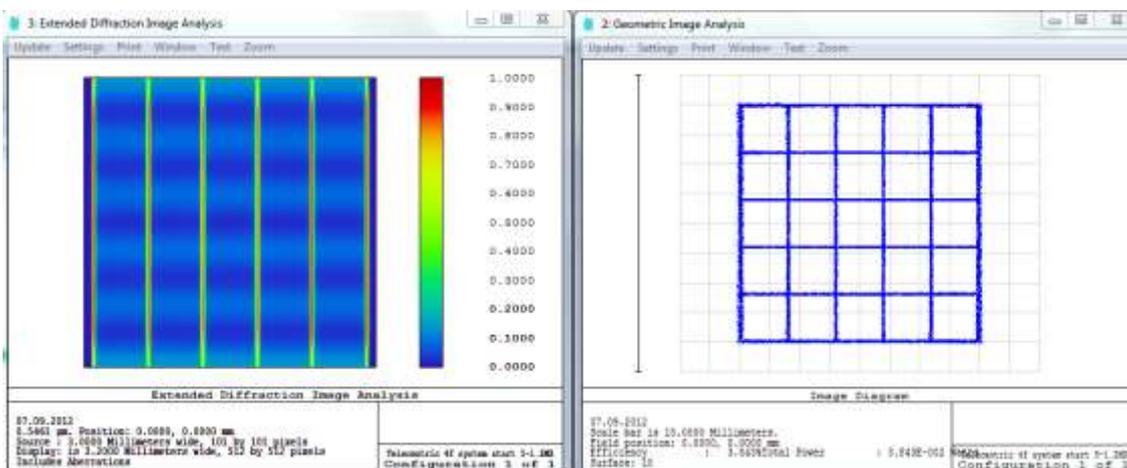

In diffraction calculation, a filtering and blocking of the higher diffraction orders has nearly completly removed the horizonthal grid lines. Therefore the image is no longer similar to the object. In the geometrical picture, a first sight seem to have an unchanged image. A close look shows, that the width of the horizonthal and vertical bars is now different. This comes from the fact, that the slit diaphragm truncates those parts of the pupil, where large aberration are present.
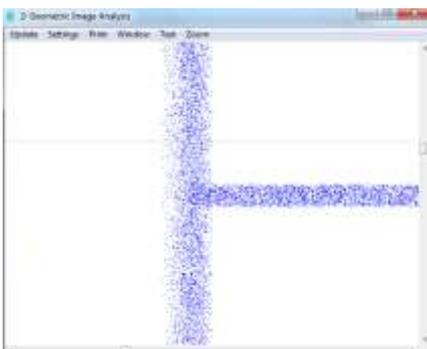
The large number of blocked rays can also be recognized at thereduces computational time.

f) The Airy diameter is D = 13.4 μm. Therefore the field size in the image calculation is chosen to be 0.134 mm. The results of the imaging calculations in the center and at the edge are as follow:
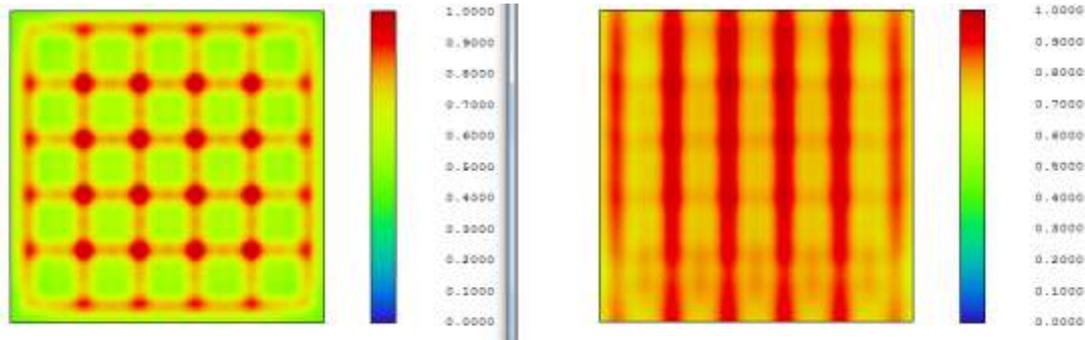
Its is seen, that the gridbars are resolved on axis, but the degradation is seen clearly. In the field, the resolution of the grid bars is only given in the sagittal direction. Therefore, the cossed grid degenerates to a line grid.

7.2 Ring illumination with axicon

Establish an illumination system with a ring shaped profile with the help of an axicon.
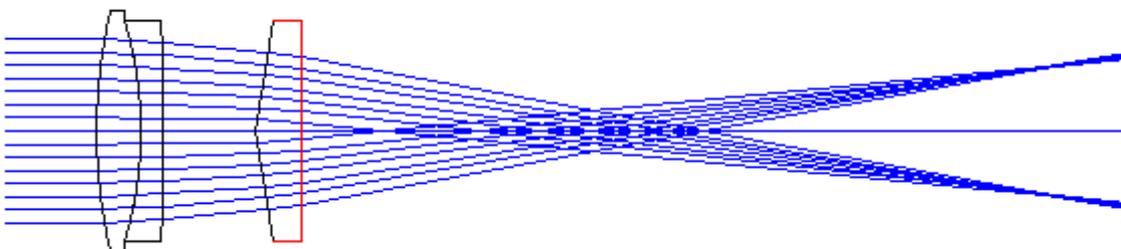First load an achromatic lens with focal alength f = 100 mm out of a vendor catalog und create a collimated monochromatic beam with diameter D = 20 mm and the wavelength 632.8 nm of HeNe as a laser source. The axicon consists of a plane an a conic surface. The conic surface can be approximated by a classical hyperbolic conic section with an extremme small radius of curvature. The conic constant must have a large negative value.
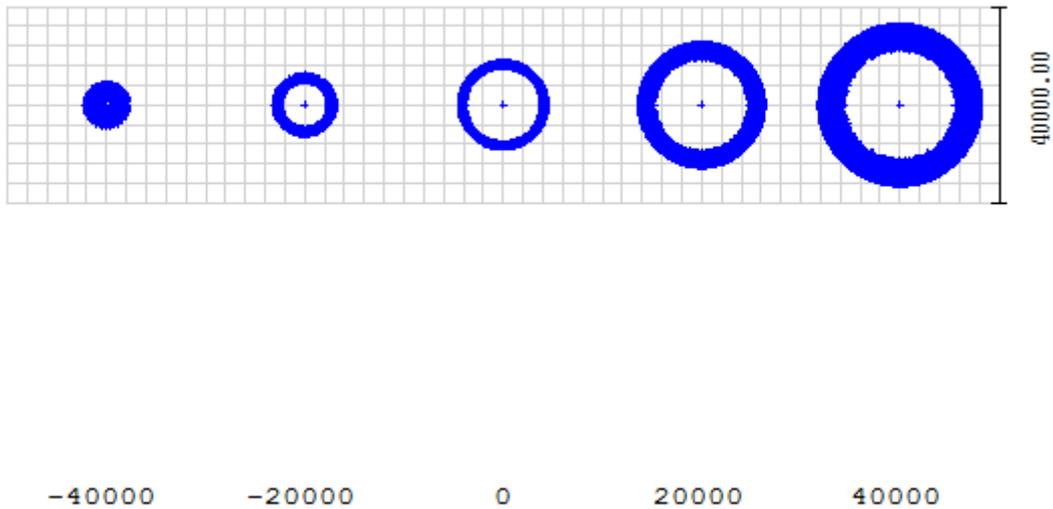What happens, if the 'Quick focus' option is used ?
Now insert between the lens and the axicon a 'negative axicon', which diverges the light. What happens, if negative axicon is moved along the optical axis ?

Solution:

Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter		Conic
OBJ	Standard		Infinity	Infinity		0.0000000		0.0000000
1	Standard		Infinity	10.000000		10.000000		0.0000000
*	Standard	LAO123	59.239232	4.8000000	SK11	13.250000	U	0.0000000
3*	Standard		-41.75855	2.5000000	SF12	12.000000	U	0.0000000
4*	Standard		-255.0301	10.000000		12.000000	U	0.0000000
5*	Standard		1.00E-005	5.0000000	N-K5	12.000000	U	-40.00000
6*	Standard		Infinity	90.000000		12.000000	U	0.0000000
IMA	Standard		Infinity	–		8.6305076		0.0000000

		Comment	Radius	Thickness	Glass	Semi-Diameter		Conic
OBJ	Standard		Infinity	Infinity		0.0000000		0.0000000
1	Standard		Infinity	10.000000		10.000000		0.0000000
*	Standard	LAO123	59.239232	4.8000000	SK11	13.250000	U	0.0000000
3*	Standard		-41.75855	2.5000000	SF12	12.000000	U	0.0000000
4*	Standard		-255.0301	10.000000		12.000000	U	0.0000000
5*	Standard		Infinity	3.0000000	N-K5	12.000000	U	0.0000000
6*	Standard		1.00E-005	39.000000 P		12.000000	U	-40.00000
7*	Standard		1.00E-005	5.0000000	N-K5	12.000000	U	-40.00000
8*	Standard		Infinity	40.000000		12.000000	U	0.0000000
9	Standard		Infinity	0.0000000		3.4226403		0.0000000
IMA	Standard		Infinity	–		3.4226403		0.0000000

d4 = 10 mm:
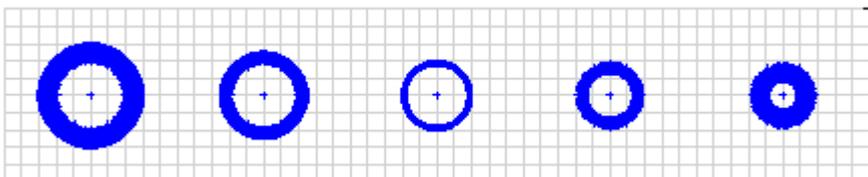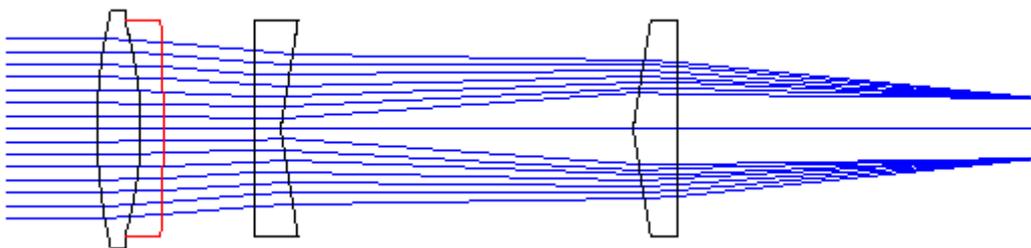
d4 = 30 mm:
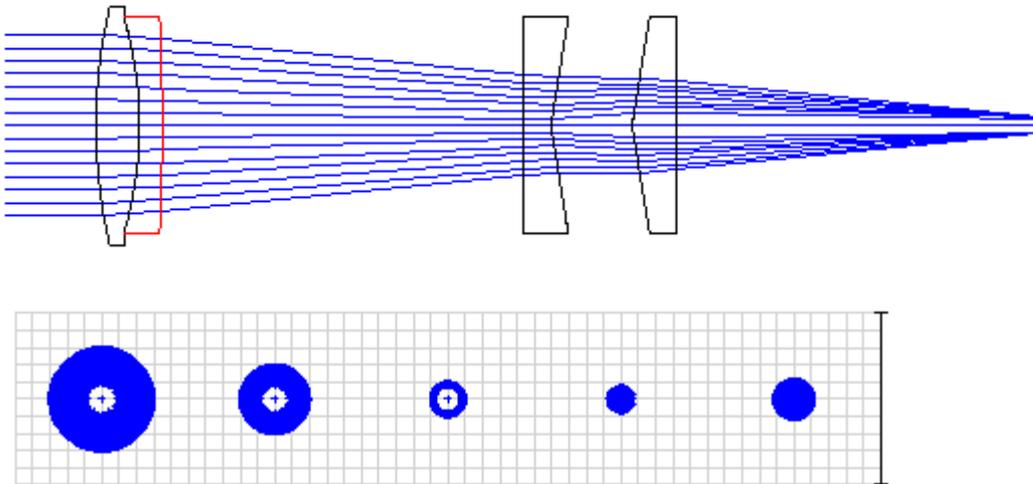
It is seen, that in the plane of the smallest ring width, the diameter of the ring is changed, keeping the width constant.
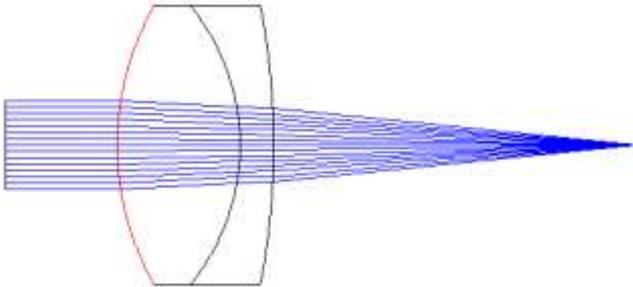
7.3 Fiber coupling and radiation

An initial collimated laser beam of an Ar-Laser at λ = 505 nm and diameter D = 4 mm has to be coupled into a fiber of diameter 4 µm, length L = 20 mm and numerical aperture of NA = 0.1. As a second step, the light should be re-collimated.
a) Extract an appropriate achromate out of a vendors catalog and check, if a good and efficient coupling can be achieved.
b) Estimate the coupling efficiency in the geometrical and the diffraction model.
c) Establish a fiber component with length 20 mm length as a non-sequential component and calculate the radiation profile at the exit surface in the geometrical optical model.
d) Now the emitted light should be collimated again by an achromate with focal length of f = 50 mm.
e) Discuss the homogeneity of the light behind this lens in the spatial domain. Are the rays perfectly collimated ?

Solution:
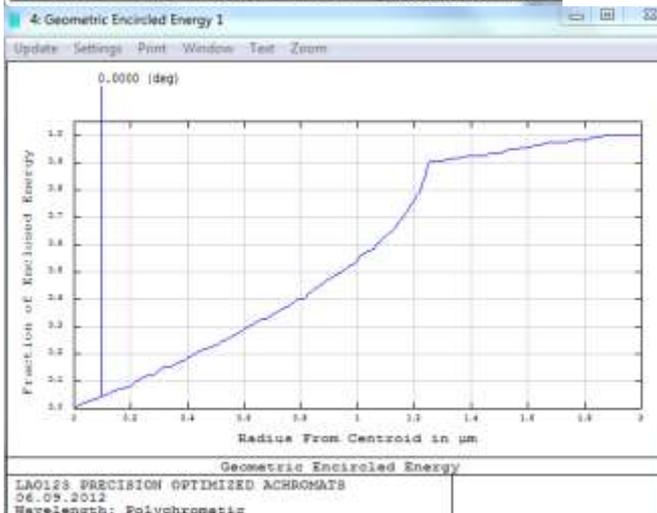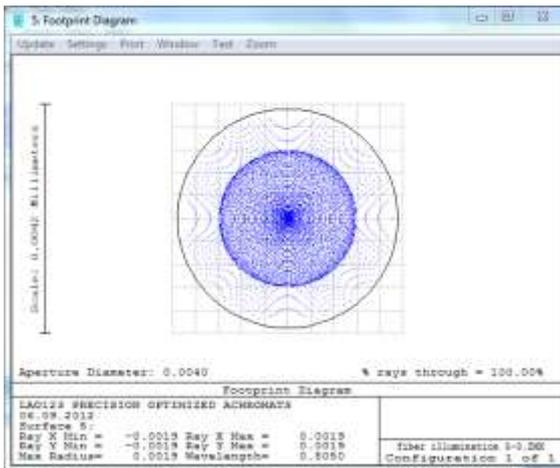
a) The necessary focal lengh of the achromate should be f = D/2/NA = 20 mm.
In the catalog of Melles-Griot, we find a system with f = 20 mm: LAO-20.0-12.5

b) In the geometrical model, we get 100% incoupling efficiency:

5: Footprint Diagram

Update Settings Print Window Test Zoom

Aperture Diameter: 0.0040   % rays through = 100.00%

Footprint Diagram

LAO123 PRECISION OPTIMIZED ACHROMATS
06.09.2012
Surface 5:
Ray X Min =   -0.0019 Ray X Max =   0.0019
Ray Y Min =   -0.0019 Ray Y Max =   0.0019   fiber illumination S-0.DAT
Max Radius=   0.0019 Wavelength=   0.8050   Configuration 1 of 1

4: Geometric Encircled Energy 1

Update Settings Print Window Test Zoom

0.0000 (deg)

Radius From Centroid in µm

Geometric Encircled Energy

LAO123 PRECISION OPTIMIZED ACHROMATS
06.09.2012
Wavelength: Polychromatic

6: Geometric Encircled Energy 2

Update Settings Print Window

1.540	0.948168
1.560	0.949838
1.580	0.954157
1.600	0.954416
1.620	0.959943
1.640	0.964680
1.660	0.969828
1.680	0.974128
1.700	0.974128
1.720	0.974128
1.740	0.976956
1.760	0.981613
1.780	0.981613
1.800	0.981844
1.820	0.989227
1.840	0.991550
1.860	0.996557
1.880	0.998846
1.900	1.000000
1.920	1.000000
1.940	1.000000
1.960	1.000000
1.980	1.000000
2.000	1.000000

In the diffraction model, we get 78% coupling efficiency:

X-Position in µm

7: Diffraction Encircled Energy 1

Update Settings Print Window Text Zoom

Diff. Limit
0.0000 (deg)

Fraction of Enclosed Energy

Radius From Centroid in µm

FFT Diffraction Encircled Energy

8: Diffraction Encircled Energy 2

Update Settings Print Window

Surface: Image
Wavelength: Polychromatic
Reference: Centroid
Reference coordinate units are Milli
Distance units are µm.

Diff. Limit

Reference Coordinates: X =   6.220E-

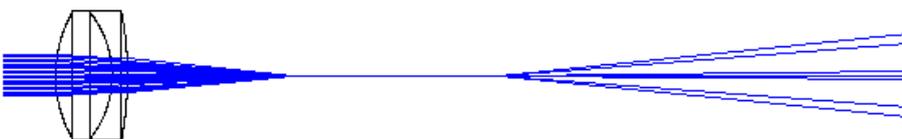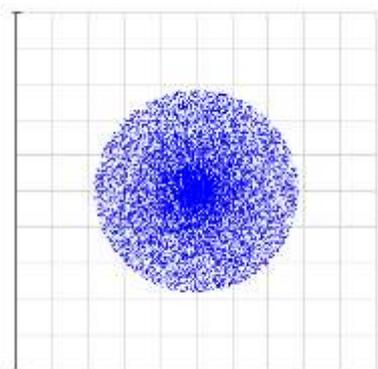| Radial distance	Fraction
0.00000	0.0000
0.20000	0.0189
0.40000	0.0520
0.60000	0.1135
0.80000	0.2141
1.00000	0.3407
1.20000	0.4706
1.40000	0.5820
1.60000	0.6653
1.80000	0.7925
2.00000	0.7776

c) To setup a fiber, the surface type non-sequential and circular light pipe with the parameters:
Exit location z: 20 mm
Material: mirror
Length: 20 mm
Front R: 0.002 mm
Back R: 0.002 mm

Due to the small fiber diameter, for larger angles a high number of reflections take place. Therefore a higher allowed allocation must be set in the general menue to avoid the error message.

General

| Aperture | Title/Notes | Units | Glass Catalogs | Environment |
| Files | Non-Sequential | Polarization | Ray Aiming | Miscellaneous |

Maximum Intersections Per Ray: 4000
Maximum Segments Per Ray: 500
Maximum Nested/Touching Objects: 5
Minimum Relative Ray Intensity: 1.0000E-003
Minimum Absolute Ray Intensity: 0.0000E+000
Glue Distance In Lens Units: 1.0000E-006
Missed Ray Draw Distance In Lens Units: 0.0000E+000
Maximum Source File Rays In Memory: 1000000
☐ Simple Ray Splitting
☐ Retrace Source Rays Upon File Open

OK   Abbrechen   Übernehmen   Hilfe

Spot diagramm at the exit surface is not uniform, there is a hot spot in the center.

d) In the Melles Griot catalog, we find the achromate LAO - 50.0 - 25 with focal length f = 50. This lens must be reversed and the correct distance must be found by a small optimization run with the angular spot radius as criterion. We then get the following data:

Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	
OBJ	Standard		Infinity	Infinity		0.0000000	
1	Standard		Infinity	5.0000000		2.0000000	
2*	Standard	LAO-20.0-12.5	12.493000	5.5000000	N-BAK4	6.2500000	U
3*	Standard		-9.911000	1.5000000	N-SF10	6.2500000	U
*	Standard		-32.97500	16.191441		6.2500000	U
5	Non-Sequ..		Infinity	–	QUARTZ	1.89E-003	
6*	Standard		Infinity	44.042494	V	1.13E-003	U
7*	Standard		78.956000	2.5000000	N-SF10	12.500000	U
8*	Standard		24.125000	9.0000000	N-BAK4	12.500000	U
9*	Standard	LAO-50.0-25.0	-31.95400	10.000000		12.500000	U
IMA	Standard		Infinity	–		2.00E-003	U
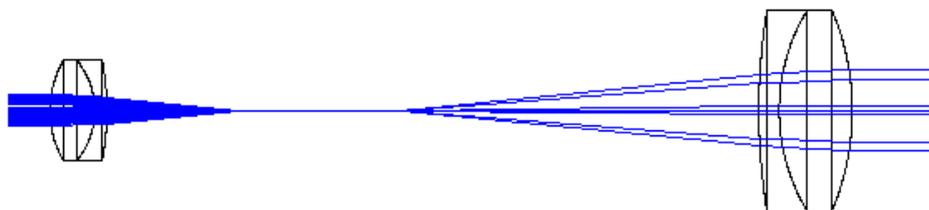
e) The spot diagram behind the collimating lens in the spatial and the angle domain looks as follows.
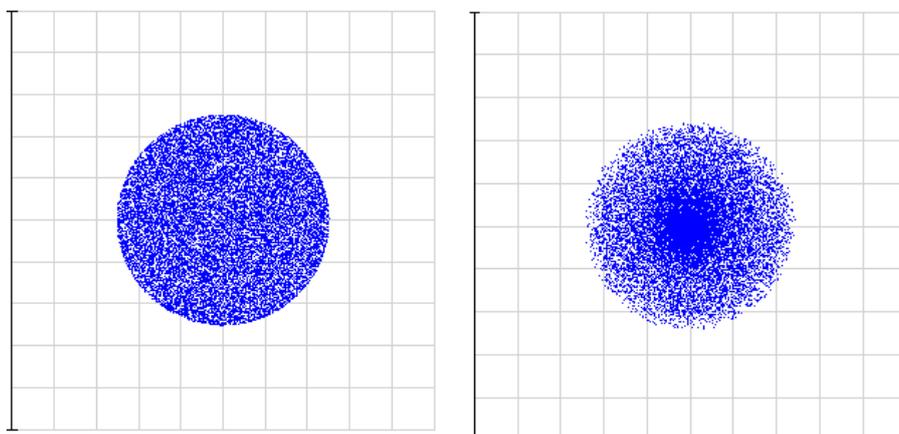
The results is:

The angle distribution is not uniform but collimated well, the spatial distribution is uniform.
The diameter of the collimated beam is D = 10.06 mm corresponding to a numerical aperture of
NA = D/2/f = 0.1 as in on the coupling side