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Solution of Exercises
Lecture Optical design with Zemax– Part 4

4 Aberrations

4.1 Strehl ratio and geometrical vs diffraction Psf spot size

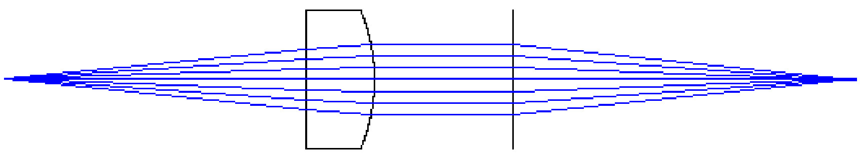
A single plano-convex lens made of K5 with focal length f = 25 mm and thickness d = 5 mm is illuminated by a diverging beam with numerical aperture NA = 0.1 and wavelength λ = 546.07 nm. After the lens the light should be collimated. If the collimated beam is refocussed without further aberrations, the 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 NA, for which the relative error is smaller then 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:

Lens Data Editor

	Surf:Type	Comment	Radius		Thickness		Glass		Semi-Diameter		Conic	Par 0(unused)		Par 1(unused)
OBJ	Standard		Infinity		21.8800000				0.0000000		0.0000000			
*	Standard		Infinity		5.0000000		K5		5.0000000	U	0.0000000			
2*	Standard		-13.1145757	X	10.0000000				5.0000000	U	0.0000000			
3	Paraxial				25.0000000				5.0000000	U				25.0000000
*	Standard		Infinity		-				0.0430952		0.0000000			



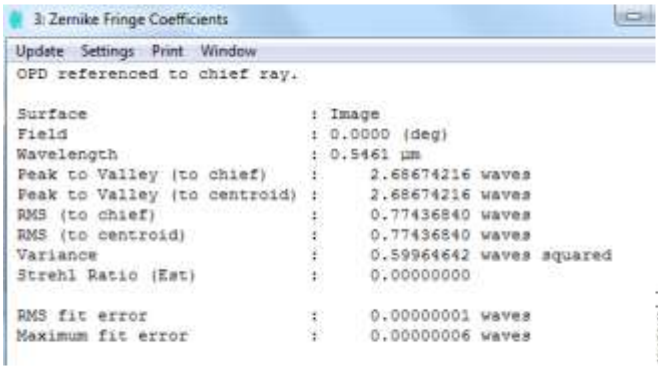
b) If the numerical aperture is changed, the following steps are performed:

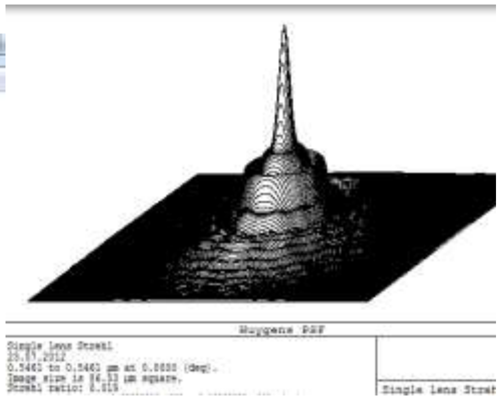
1. Reduce NA
2. Determine the Airy diameter out of the spot diagram window
3. Set the apertur in the image plane exactly to the Airy value
4. Calculate the estimated Strehl ratio from the Zernike window
5. Calculate the accurate Strehl ratio from the Huygens PSF window with appropriate sampling
6. Calculate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

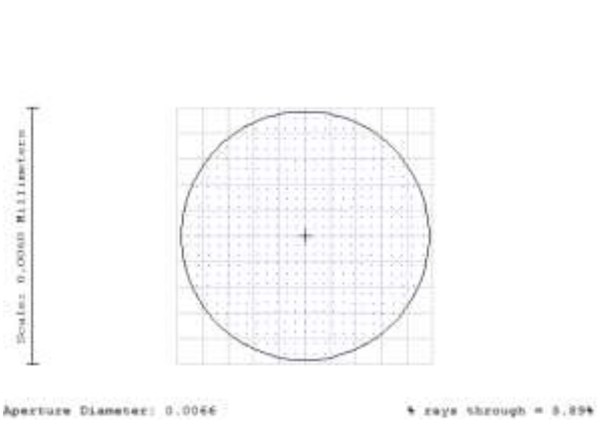
Then the following table is obtained:

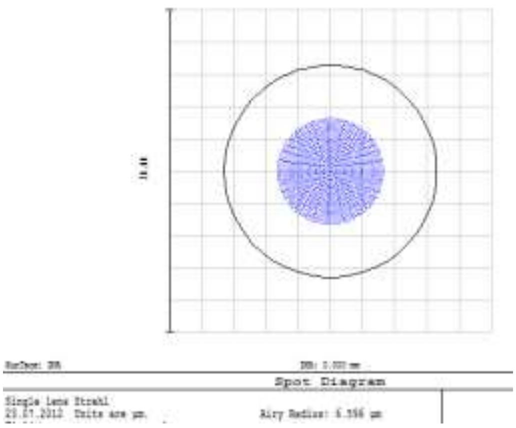
NA	Strehl exact	Strehl estimated	relative error	Airy radius	geometrical EE inside Airy	diffraction EE inside Airy
0.1	0.019	0	0	0.003299	0.0389	0.0394
0.08	0.058	0	0	0.004123	0.0889	0.0889
0.07	0.053	0	0	0.004712	0.1449	0.1443
0.06	0.172	0.2158	0.255	0.005497	0.2514	0.3403
0.055	0.342	0.3662	0.0661	0.005996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

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

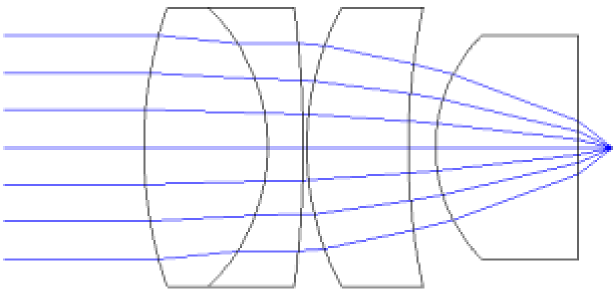
Load the lens GLC-6.5-8.0-830 DIODE LASER COLLIMATING LENS from the catalog of CVI Melles Griot.
a) What is the numerical aperture of the lens in the image? Determine the Strehl ratio and compare the estimated and the exact value.
b) What are the two surfaces with the largest contribution to the spherical 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:

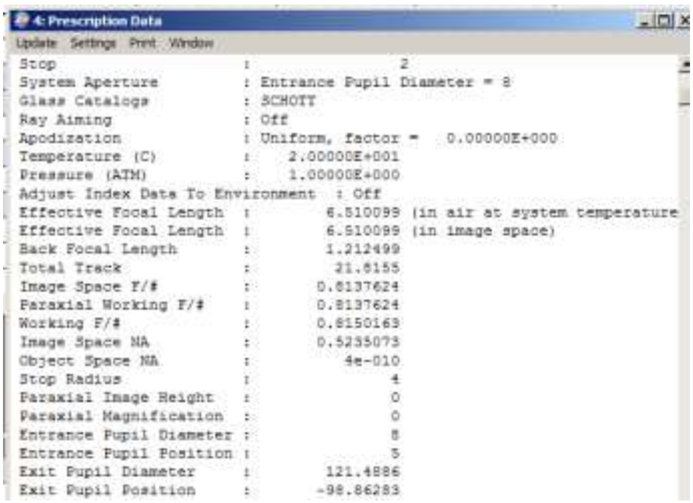
a) The system looks as follows.

Lens Data Editor
Edit Solves View Help

Surf	:Type	Comment	Radius	Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity	Infinity				0.0000000	
1	Standard		Infinity	5.0000000				4.0000000	
*	Standard	GLC-6.5-8.0-..	15.0179464	4.4410000		N-BAK2		5.0000000	U
3*	Standard		-6.9484977	1.2830000		N-SF4		5.0000000	U
4*	Standard		-39.009167	0.1280000				5.0000000	U
5*	Standard		10.5089484	3.6400000		N-SF11		5.0000000	U
6*	Standard		23.9251621	0.9790000				5.0000000	U
7*	Standard		5.6561086	5.1320000		N-SF11		4.0000000	U
8*	Standard		Infinity	1.2124989	M			4.0000000	U
IMA	Standard		Infinity	-				5.509E-004	



The numerical aperture is NA = 0.524 in the image space.

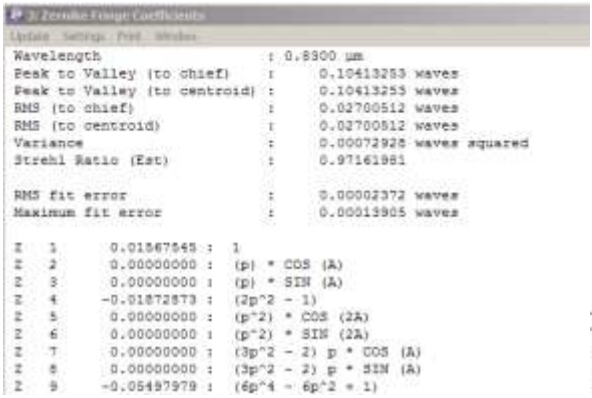


4: Prescription Data

Update Settings Print Window

Stop	: 2
System Aperture	: Entrance Pupil Diameter = 8
Glass Catalogs	: SCHOTT
Ray Aiming	: Off
Apodization	: Uniform, factor = 0.00000E+000
Temperature (C)	: 2.00000E+001
Pressure (ATM)	: 1.00000E+000
Adjust Index Data To Environment	: Off
Effective Focal Length	: 6.510099 (in air at system temperature
Effective Focal Length	: 6.510099 (in image space)
Back Focal Length	: 1.212499
Total Track	: 21.8155
Image Space F/#	: 0.8137624
Paraxial Working F/#	: 0.8137624
Working F/#	: 0.8150169
Image Space NA	: 0.5235073
Object Space NA	: 4e-010
Stop Radius	: 4
Paraxial Image Height	: 0
Paraxial Magnification	: 0
Entrance Pupil Diameter	: 8
Entrance Pupil Position	: 5
Exit Pupil Diameter	: 121.4886
Exit Pupil Position	: -98.86283

The Strehl ratio in Marechal approximation is D = 0.972, the exact value is D = 0.975.

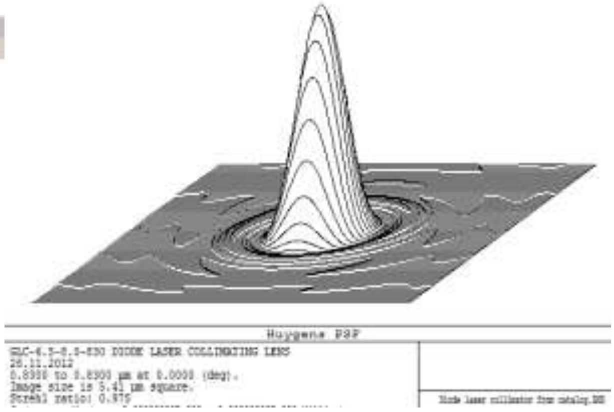


3: Zernike Fringe Coefficients

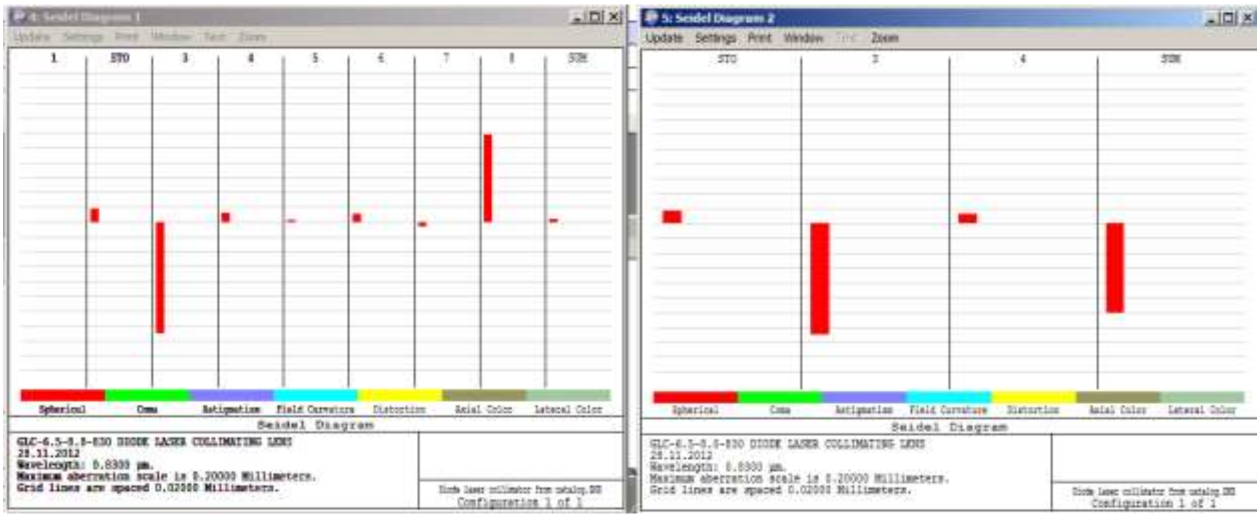
Update Settings Print Window

Wavelength	: 0.8300 µm
Peak to Valley (to chief)	: 0.10413253 waves
Peak to Valley (to centroid)	: 0.10413253 waves
RMS (to chief)	: 0.02700512 waves
RMS (to centroid)	: 0.02700512 waves
Variance	: 0.00072928 waves squared
Strehl Ratio (Est)	: 0.97161981
RMS fit error	: 0.00002372 waves
Maximum fit error	: 0.00013905 waves

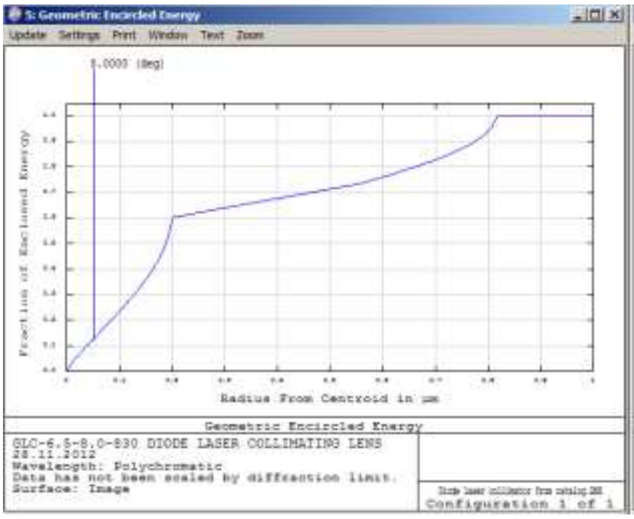
Z	1	0.01567545 :	1
Z	2	0.00000000 :	(p) * COS (A)
Z	3	0.00000000 :	(p) * SIN (A)
Z	4	-0.01872873 :	(2p^2 - 1)
Z	5	0.00000000 :	(p^2) * COS (2A)
Z	6	0.00000000 :	(p^2) * SIN (2A)
Z	7	0.00000000 :	(3p^2 - 2) p * COS (A)
Z	8	0.00000000 :	(3p^2 - 2) p * SIN (A)
Z	9	-0.05497979 :	(6p^4 - 6p^2 + 1)

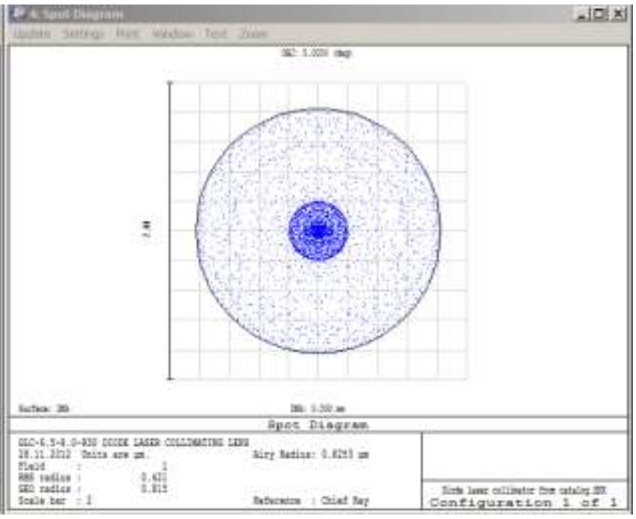


b) The Seidel surface contributions show, that the 2nd and the 7th surface (without the first help surface) of the system have the largest contributions to the residual aberrations.
If the Seidel diagram is calculated only for the 3 surfaces of the first cemented group it is seen, that the spherical aberration is not corrected. Therefore, this part does not correspond to a conventional achromate.

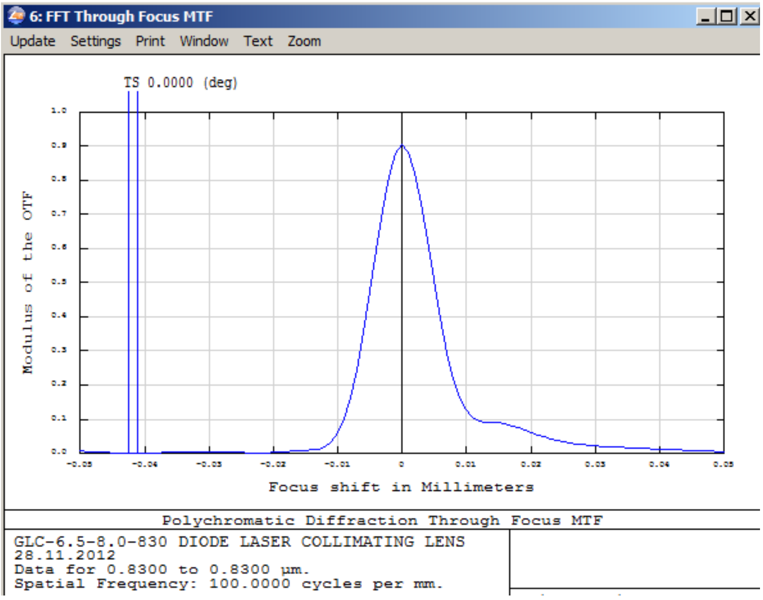


c) The spot diagram has a geometrical radius of 0.825 µm, the Airy radius is 0.8253 µm and therefore all spot points are inside. The diameter of this inner part is D = 0.2 µm.
If the geometrical encircled energy function is considered (without 'multiply by diffraction limit) and with 256x256 sampling 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 µmm for 50% contrast, Therefore the corresponding depth of focus is Δz = 20 µm.
The asymmetric behavior is a result of the residual spherical aberration of the system.



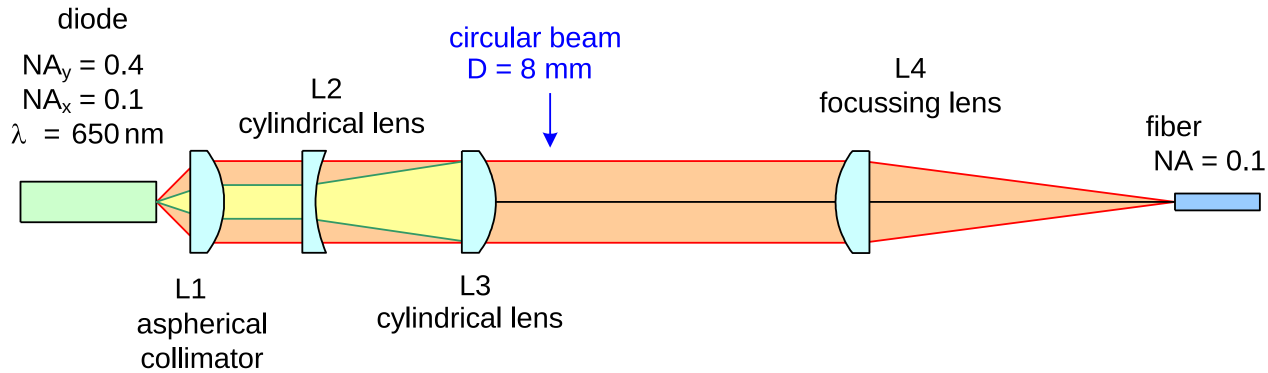
T Through Focus MTF 2

Settings Print Window

-0.019000	0.016689	0.016689
-0.018000	0.047819	0.047819
-0.017000	0.083070	0.083070
-0.016000	0.125590	0.125590
-0.015000	0.174072	0.174072
-0.014000	0.228309	0.228309
-0.013000	0.287493	0.287493
-0.012000	0.350733	0.350733
-0.011000	0.416931	0.416931
-0.010000	0.484849	0.484849
-0.009000	0.553126	0.553126
-0.008000	0.620324	0.620324
-0.007000	0.684963	0.684963
-0.006000	0.745571	0.745571
-0.005000	0.800721	0.800721
-0.004000	0.849080	0.849080
-0.003000	0.889451	0.889451
-0.002000	0.920807	0.920807
-0.001000	0.942330	0.942330
0.000000	0.953431	0.953431
0.001000	0.953778	0.953778
0.002000	0.943298	0.943298
0.003000	0.922189	0.922189
0.004000	0.890912	0.890912
0.005000	0.850173	0.850173
0.006000	0.800909	0.800909
0.007000	0.744254	0.744254
0.008000	0.681506	0.681506
0.009000	0.614087	0.614087
0.010000	0.543501	0.543501
0.011000	0.471287	0.471287
0.012000	0.398973	0.398973
0.013000	0.328045	0.328045

4.3 Anamorphotic Diode collimator

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



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 improved the result ?
Discuss possible steps to get a shorter system. What are the consequences of a compact layout ?

Solution

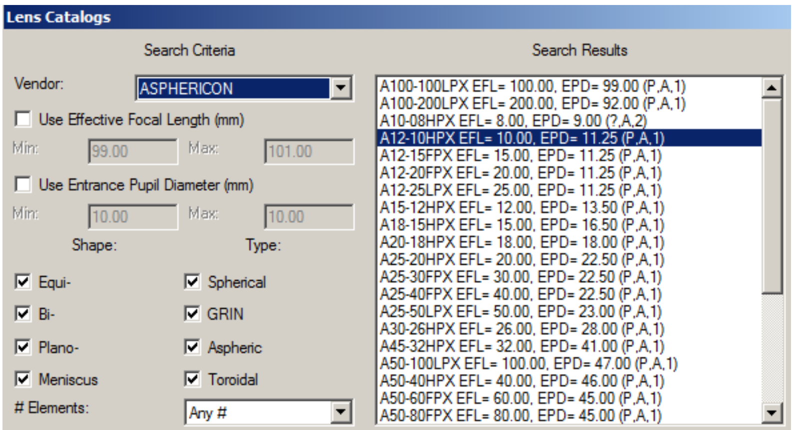
If the desired beam diameter after the collimation of the fast axis is 8 mm, the focal length of the first lens is

$$f = D/2/NA_y = 10mm$$

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:

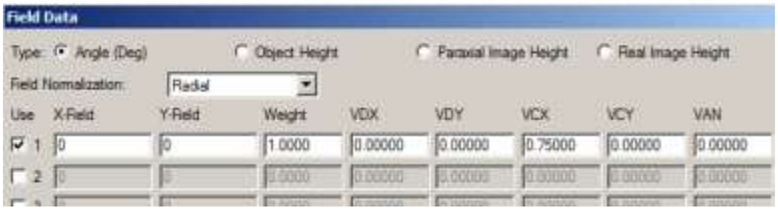
1. the lens should be used without cover glas plate
2. if a working wavelength near to the 650 nm is found, it is an advantage

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



Necessary steps to process this lens:

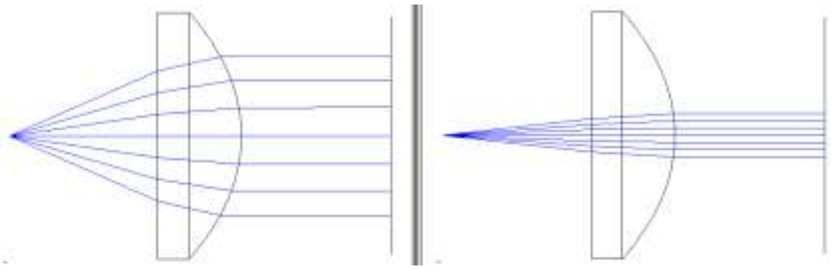
1. load the lens
2. turn around
3. set NA to 0.4 and vignetting factors in field menu to VCX = 0.75



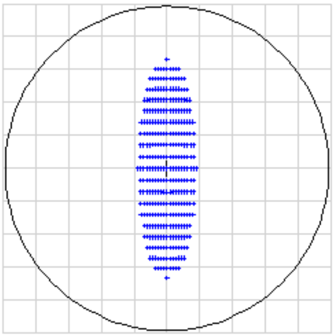
4. change wavelength to 650 nm
5. optimize first distance to collimate this wavelength (default merit function, with criterion: direction cosines)

Lens Data Editor

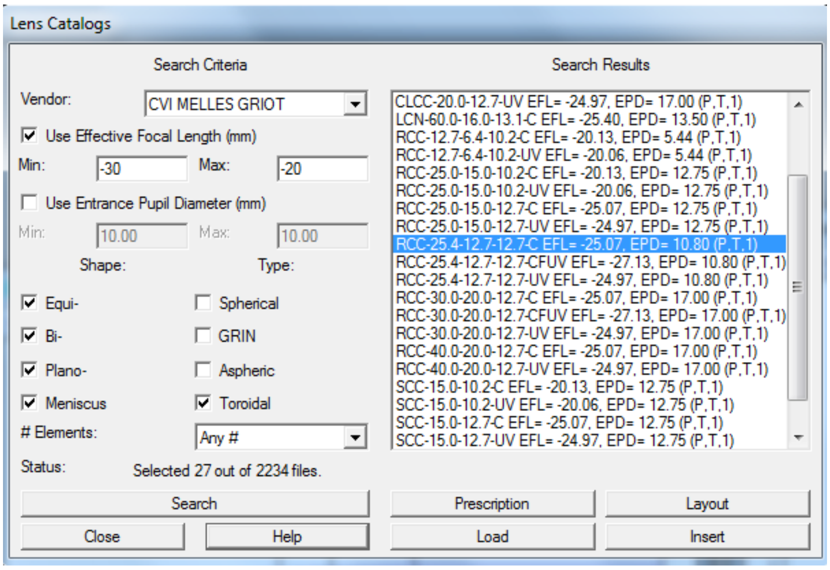
Surf:Type		Comment	Radius	Thickness		Glass	Semi-Diameter		Conic	Par 0(unused)	Par 1(unused)	Par 2(unused
OBJ	Standard		Infinity	0.0000000			0.0000000		0.0000000			
1	Standard		Infinity	7.5326518	V		0.0000000		0.0000000			
*	Standard		Infinity	4.2500000		S-LAM64	3.2875188		0.0000000			
3*	Even Asp..	A12-10HPX	-7.770000	7.6097524			6.2500000	U	-1.000000		-0.000000	-9.8E-005
4	Standard		Infinity	0.0000000			4.0192801		0.0000000			
IMA	Standard		Infinity	-			6.0000000	U	0.0000000			



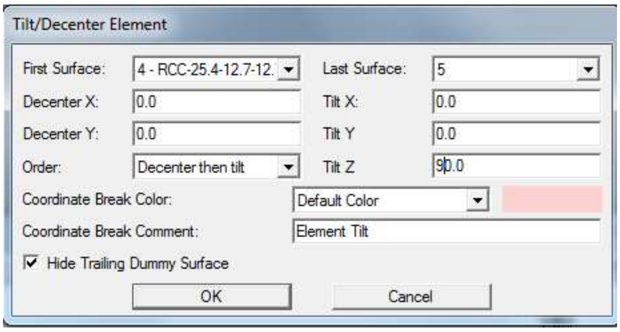
A foorprint diagram shows the elliptical beam cross section behind the lens.



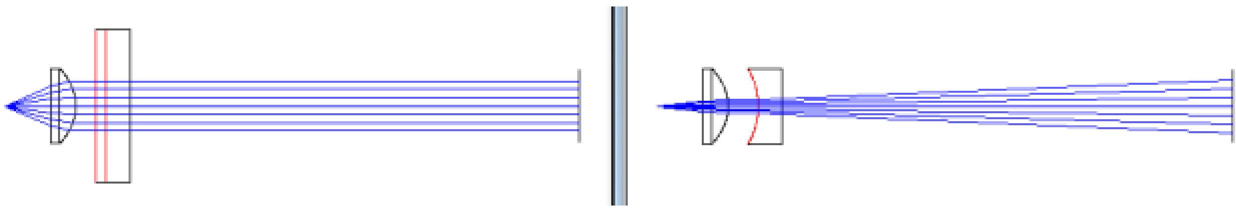
In the next step, a Galilean telescope with factor $\Gamma = 4$ must be found to enlarge the diameter of the x-section to the same value as in the y-section. First a negative cylindrical lens with a rather short focal length must be found.
Possible solution: Lens with 1 inch negative focal length in the catalog of Melles Griot:
RCC-25.4-12.7-12.7-C



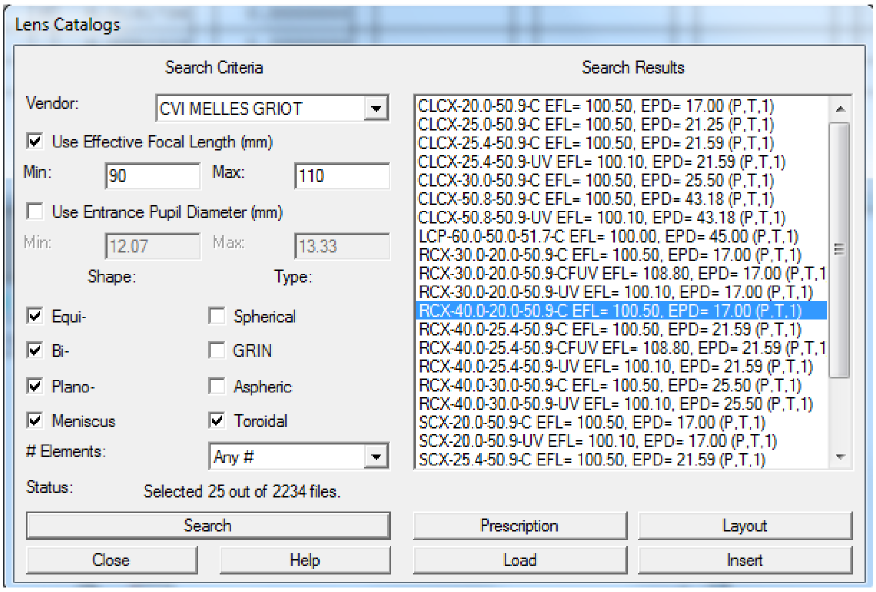
The lens is inserted behind the collimating asphere and rotated around the x-axis by 90° to work in the x-section.



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

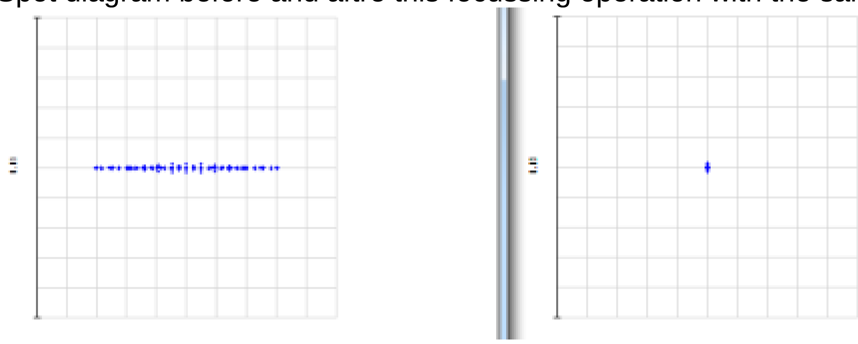


For a Galiean telescope with factor 4, the second lens must have a focal length of 4x25.1 mm = 100.4 mm. In the same lens catalog one can found the following lens:
RCX-40.0-20.0-50.9-C

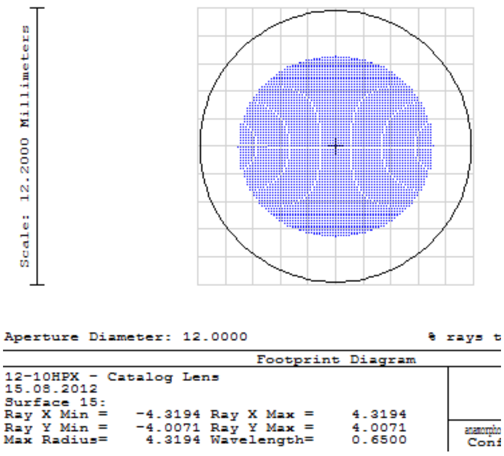


The lens is inserted, turned around to get a better performance and also tilted by 90° in the azimuth. A first guess gives a distance of 100-25=75 mm between the telescoipe lenses to get a collimated x-section. But from the spot diagram with direction cosine option it is seen, that the angle distribution 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 aftre this focussing operation with the same scale:



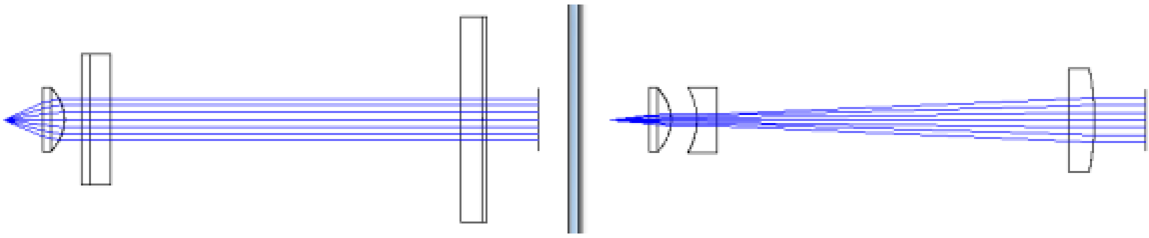
The foorprint diagram now shows a rather curcular cross section. The residual error can be neglected and comes from the fact, that for this wavelengths, the catalog focal lengths are not exact.



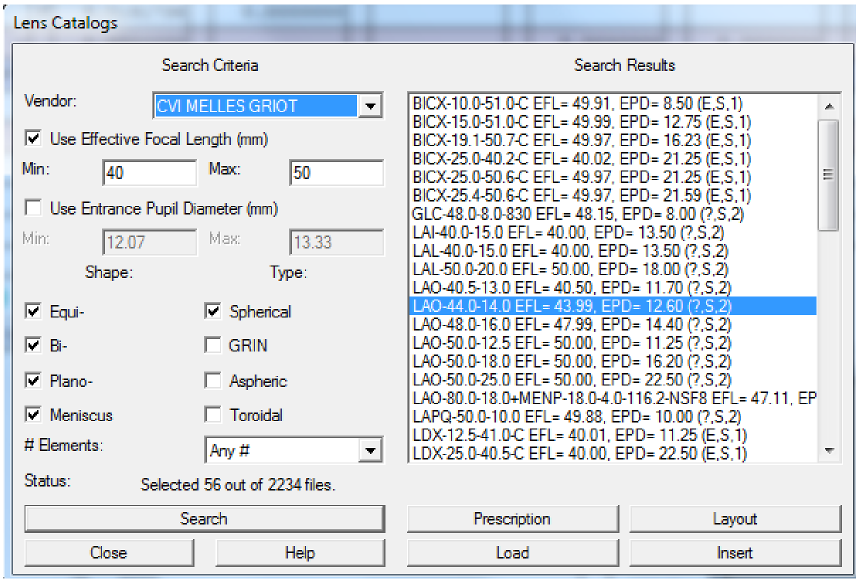
The data are now the following:


Lens Data Editor

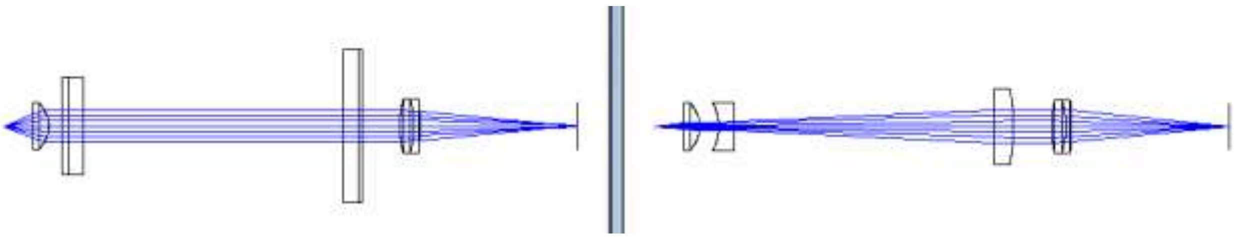
Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0 (unused)	Par 1 (unused)	Par 2 (unused)	Par 3 (unused)	Par 4 (unused)	Par 5 (unused)
OBJ Standard		Infinity	0.0000000		0.0000000	0.0000000						
1 Standard		Infinity	7.5326518		0.0000000	0.0000000						
2* Standard		Infinity	4.2500000	S-LAH64	3.2875188	0.0000000						
3* Even Asp...	A12-10HPX	-7.770000	6.0000000		4.2500000 U	-1.000000		0.0000000	-9.8E-004	4.99E-006	2.39E-008	1.13E-011
4 Coordina...	Element Tilt		0.0000000	-	0.0000000			0.0000000	0.0000000	0.0000000	0.0000000	90.000000
5* Toroidal	RCC-25.4-12...	-12.70000	4.0000000	N-BK7	6.3500000 U	0.0000000	0	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
6* Toroidal		Infinity	-4.000000 T		6.3500000 U	0.0000000	0	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
7 Coordina...	Element Tilt		4.0000000 P	-	0.0000000			0.0000000 P	0.0000000 P	0.0000000 P	0.0000000 P	-90.00000 P
8 Standard	Dummy	Infinity	68.233304 V	P	4.0191736	0.0000000						
9 Coordina...	Element Tilt		0.0000000	-	0.0000000			0.0000000	0.0000000	0.0000000	0.0000000	90.000000
10* Toroidal		Infinity	5.0000000	N-BK7	10.000000 U	0.0000000	0	0.0000000	-0.000000	-0.000000	-0.000000	-0.000000
11* Toroidal	RCX-40.0-20...	-40.00000	-5.000000 T		10.000000 U	0.0000000	0	0.0000000	-0.000000	-0.000000	-0.000000	-0.000000
12 Coordina...	Element Tilt		5.0000000 P	-	0.0000000			0.0000000 P	0.0000000 P	0.0000000 P	0.0000000 P	-90.00000 P
13 Standard	Dummy	Infinity	10.000000	P	4.0082476	0.0000000						
14 Standard		Infinity	0.0000000		4.0070822	0.0000000						
IMA Standard		Infinity	-		6.0000000 U	0.0000000						



To focus the beam into a fiber with numerical aperture 0.1, the focal length must be not smaller than f = 4.32 mm / 0.1 = 43.2 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



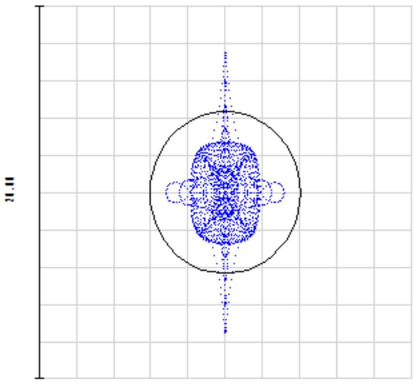
This lens is inserted to complete the system. Finally the last distance is optimized to get a minimal spot size.
It is seen, that the spot is nearly diffraction limited.



Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 2 (unused)	Par 3 (unused)	Par 4 (unused)	Par 5 (unused)
OBJ	Standard		Infinity	0.0000000		0.0000000	0.0000000				
1	Standard		Infinity	7.5826518		0.0000000	0.0000000				
*	Standard		Infinity	4.2600000	S-LAH64	3.2875188	0.0000000				
3*	Even Asp..	A12-10HPX	-7.770000	5.0000000		6.2500000 U	-1.000000	-9.8E-005	6.99E-008	2.39E-009	1.13E-011
4	Coordina..	Element Tilt		0.0000000	-	0.0000000		0.0000000	0.0000000	0.0000000	90.000000
5*	Toroidal	RCC-25.4-12..	-12.70000	4.0000000	N-BK7	6.3500000 U	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
6*	Toroidal		Infinity	-4.000000 T		6.3500000 U	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
7	Coordina..	Element Tilt		4.0000000 P	-	0.0000000		0.0000000 P	0.0000000 P	0.0000000 P	-90.00000 P
8	Standard	Dummy	Infinity	68.233904 V	P	4.0191786	0.0000000				
9	Coordina..	Element Tilt		0.0000000	-	0.0000000		0.0000000	0.0000000	0.0000000	90.000000
10*	Toroidal		Infinity	5.0000000	N-BK7	10.000000 U	0.0000000	-0.000000	-0.000000	-0.000000	-0.000000
11*	Toroidal	RCX-40.0-20..	-50.90000	-5.000000 T		10.000000 U	0.0000000	-0.000000	-0.000000	-0.000000	-0.000000
12	Coordina..	Element Tilt		5.0000000 P	-	0.0000000		0.0000000 P	0.0000000 P	0.0000000 P	-90.00000 P
13	Standard	Dummy	Infinity	10.000000	P	4.0085476	0.0000000				
14*	Standard	LAO-44.0-14.0	28.580000	3.8000000	N-BAK4	7.0000000 U	0.0000000				
15*	Standard		-21.60600	1.4000000	N-SF10	7.0000000 U	0.0000000				
16*	Standard		-69.62400	0.0000000		7.0000000 U	0.0000000				
17	Standard		Infinity	41.407708		3.7859516	0.0000000				
IMA	Standard		Infinity	-		6.0000000 U	0.0000000				



Surface: IMA IMA: 0.000, 0.000 mm

Spot Diagram

12-10HPX - Catalog Lens
15.08.2012 Units are µm. Airy Radius: 4.183 µm
Field : 1
RMS radius : 2.323
GEO radius : 7.544

anamorphotic