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Solution of Exercises
Lecture Optical design with Zemax– Part 5

5 Aberrations

5.1 Multi configuration, universal plot and slider

Load a classical achromate with a focal length of f = 100 mm, no field and numerical aperture NA = 0.1 from one of the vendor catalogs. Fix the wavelength to λ = 546.07 nm.
a) Add a thin mensicus shaped lens behind the system with an arteficial refractive index of n = 2 to enlarge the numerical aperture in the image space by a factor of 2 without introducing spherical aberration. To achieve this, the surfaces must be aplanatic and concentric.
b) Now reduce the initial 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°, -47.5°, -45°, -42.5° and -40°. The second coordinate break should be defined by a pick up with a resulting bending angle of the system axis of -90°.
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 correponding universal plot.
e) Show the variation of the spot in the image plane by using the slider.

Solution:

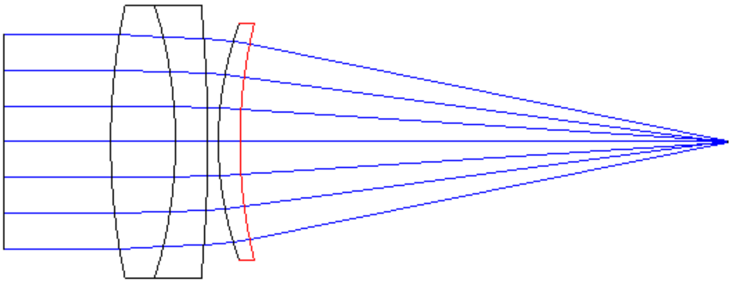
As a first step, the achromate AAP-100.0-25.4 from the CVI Melles Griot catalog is loaded. The field is set to zero, the aperture has a diameter of D = 20 and the wavelength is set to 546 nm.

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 menue.

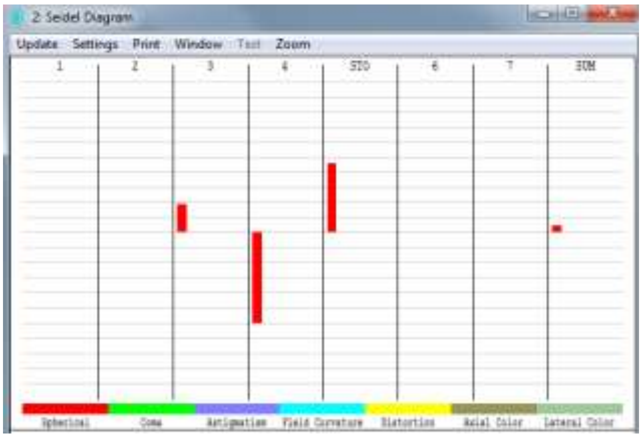
Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.0000000	
1	Standard		Infinity		0.0000000				10.0000000	
2	Standard		Infinity		10.0000000				10.0000000	
3*	Standard	AAP-100.0-25.4	62.0050000		6.0000000		N-BK7		12.7000000	U
4*	Standard		-42.3790000		3.0000000		SF2		12.7000000	U
*	Standard		-133.284000		1.0000000				12.7000000	U
6*	Standard		31.5626243	A	2.0000000		2.00,0.0		11.0000000	U
7*	Standard		45.3244720	M	45.3552881				11.0000000	U
IMA	Standard		Infinity		-				5.0000E-003	U



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 mensiscus lens are frozen to be constant. Then the first distance is set to 0 and the cardinal points are calculated.

2: Cardinal Point Data

Update Settings Print Window

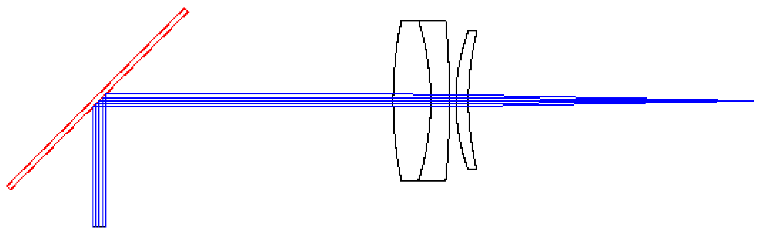
```
Cardinal Point Data Summary

File : C:\Gross\Lectures - Gross\Optical design with Zemax\Zemax example
Title: Even Asphere Lens:  See System, General, Title/Notes
Date : 20.09.2012


Starting surface   : 1
Ending surface     : 8
Wavelength         : 0.546074
Orientation        : Y-Z
Lens units         : Millimeters

Object space positions are measured with respect to surface 1.
Image space positions are measured with respect to surface 8.
The index in both the object space and image space is considered.

                              Object Space         Image Space
Focal Length          :       -50.000000           50.000000
Focal Planes          :       -46.796886            0.008129
Principal Planes      :         3.203114          -49.991871
Anti-Principal Planes :       -96.796886           50.008129
Nodal Planes          :         3.203114          -49.991871
Anti-Nodal Planes     :       -96.796886           50.008129
```

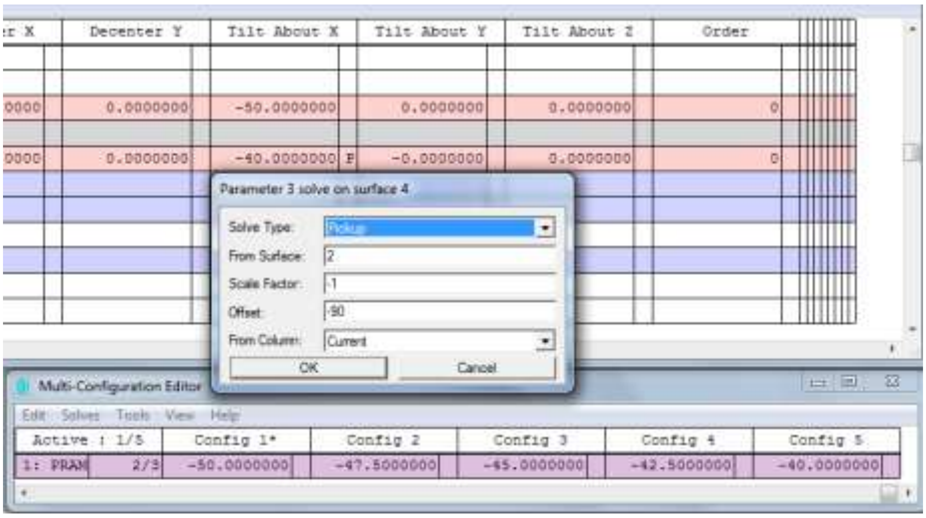
It is seen, that the front focal plane lies 46.8 mm in front of the system. The bending mirror is introduced in a corresponding distance.

Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter		Par 1(unused)	Par 2(unused)	Par 3(unused)	
OBJ	Standard		Infinity	Infinity		0.0000000					
1	Standard		Infinity	20.0000000		1.0000000					
2	Coordinat..			0.0000000	-	0.0000000		0.0000000	0.0000000	-45.0000000	
3*	Standard		Infinity	0.0000000	MIRROR	20.0000000	U				
4	Coordinat..			-46.7968800	-	0.0000000		0.0000000	0.0000000	-45.0000000	P
5*	Standard	AAP-100.0-25.4	-62.0050000	-6.0000000	N-BK7	12.7000000	U				
6*	Standard		42.3790000	-3.0000000	SF2	12.7000000	U				
*	Standard		133.2840000	-1.0000000		12.7000000	U				
8*	Standard		-31.5626243	-2.0000000	2.00,0.0	11.0000000	U				
9*	Standard		-45.3244720	-45.3552881		11.0000000	U				
IMA	Standard		Infinity	-		1.5720E-004					



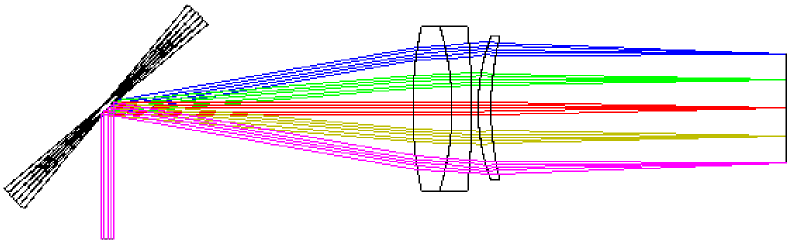


c) The multi-configuration is established as follows:

Multi-Configuration Editor

Edit Solves Tools View Help

Active : 1/5		Config 1*	Config 2	Config 3	Config 4	Config 5
1: PRAM	2/3	-50.0000000	-47.5000000	-45.0000000	-42.5000000	-40.0000000

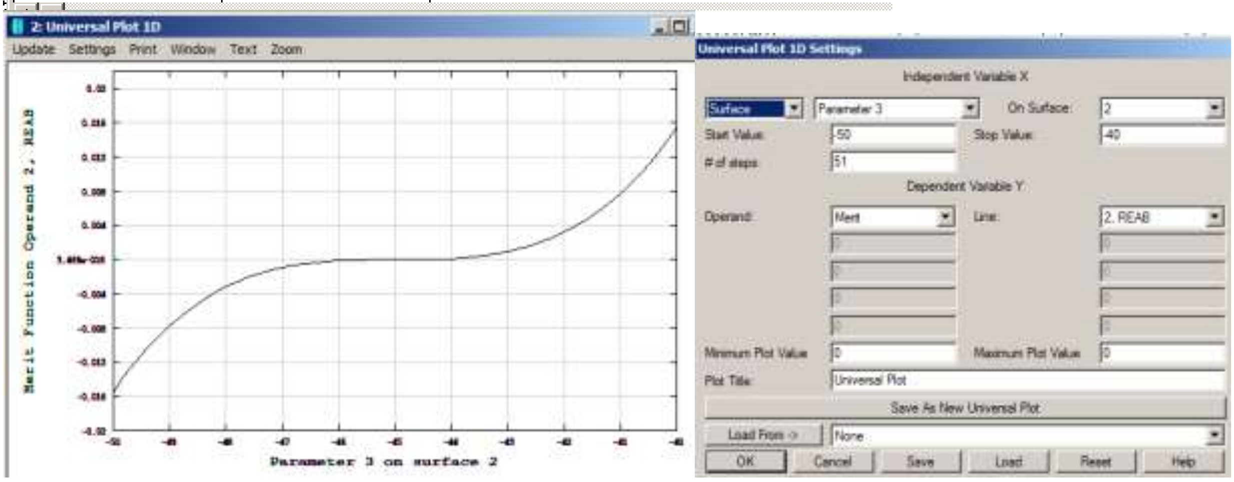


d) The universal plot is generated with a REAB-operand in the merit function for the 1st configuration.

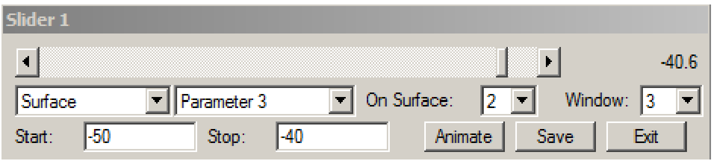
Merit Function Editor: 0.000000E+000

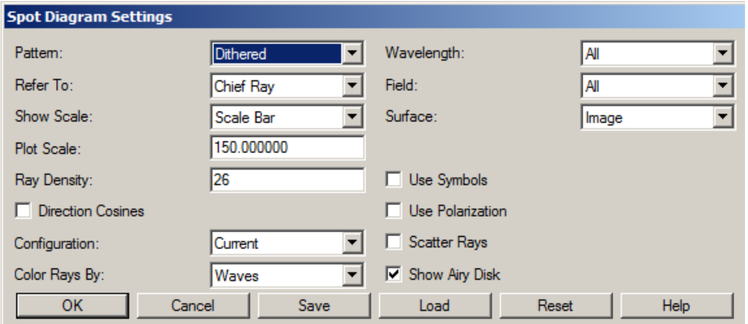
Edit Tools View Help

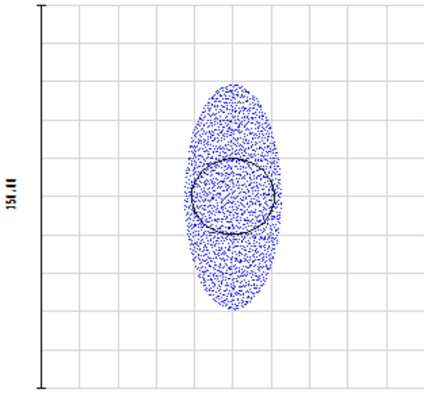
Oper #	Type	Cfg#	
1: CONF	CONF	1	
2: REAB	REAB	10	1



e) The spot diagram is used with dithered ray sampling and a fixed scale. The slider is configured as follows:







5.2 Singlet optimization

Optimize a single lens with the data λ = 546.07 nm, object in the distance 100 mm from the lens on axis only, focal length f = 45 mm and numerical aperture NA = 0.07 in the object space. The lens should be made of the Schott glass N-K5 and has a thickness of 5 mm.

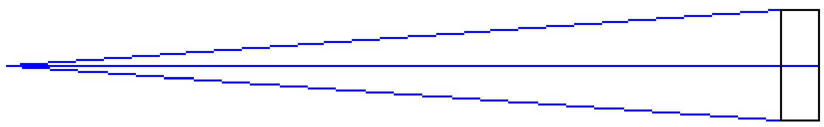
a) Try to start from a plane plate approach to find the best lens bending solution.
b) Now start the optimization with a lens and an image distance, which is near to the solution. Is the optimized lens diffraction limited in its performance ?
c) One possibility to improve the result is to use an aspherical lens. The first approach is to use the rear surface with a conic constant to allow the program a conic section as solution. Is this sufficient to get a diffraction limited solution ?
d) Now enlarge the numerical aperture by a factor of two. Re-optimize the system. What about the diffraction limited performance ? Use an aspherical coefficnet of 4th order to improve the system. What is the result ?
e) Now introduce a finite object size of diameter 10 mm. What is the dominant aberration for the off-axis field points ? Can the system by made diffraction limited by re-optimization, for example with more aspherical constants ? What can be done to get a better performance ?

Solution

a) Starting setup:
The two radii and the image distance is chosen as variable.

Lens Data Editor
Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		100.00000				0.0000000	
1	Standard		Infinity	V	5.0000000		N-K5		7.0172133	
STO	Standard		Infinity	V	0.0000000	V			7.2470266	
IMA	Standard		Infinity		-				7.2470266	



Merit function: the default spot diameter and the focal length (EFFL) is required.

Merit Function Editor: 4.9137787E+009

Edit Tools View Help

Oper #	Type						Target	Weight
1: DMFS	DMFS							
2: BLNK	BLNK	Default merit function: RMS spot radius centroid GQ 3 rings 6 arms						
3: EFFL	EFFL	1					45.0000000	1.0000000
4: BLNK	BLNK	No default glass thickness boundary constraints.						
5: BLNK	BLNK	Operands for field 1.						
6: TRAC	TRAC	1	0.0000000	0.0000000	0.3357107	0.0000000	0.0000000	0.8726646
7: TRAC	TRAC	1	0.0000000	0.0000000	0.7071068	0.0000000	0.0000000	1.3962634
8: TRAC	TRAC	1	0.0000000	0.0000000	0.9419651	0.0000000	0.0000000	0.8726646

If the optimization is started, no useful result is obtained:

b) If a starting system for example with the following data are used:

Lens Data Editor

Edit Solves View Help

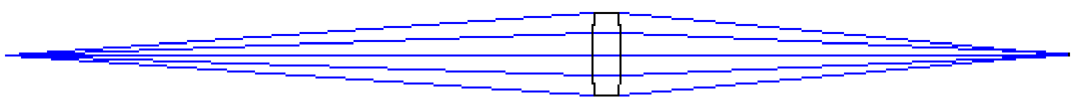
Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		100.00000				0.0000000	
1	Standard		50.000000	V	5.0000000		N-K5		7.0522886	
STO	Standard		-50.00000	V	100.00000	V			7.0389381	
IMA	Standard		Infinity		-				1.0404210	

we get the correct solution:

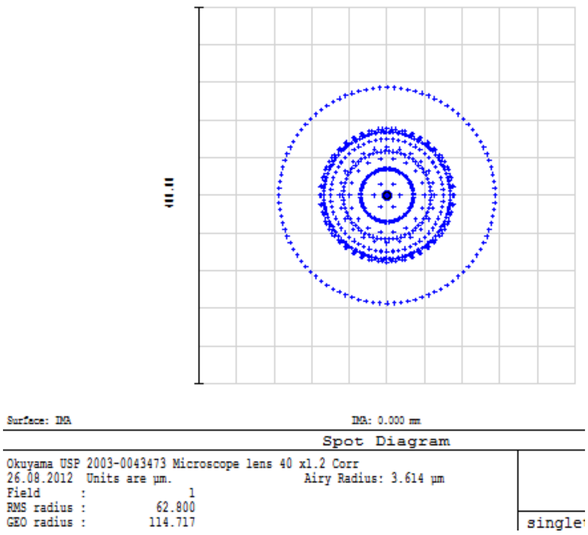
Lens Data Editor

Edit Solves View Help

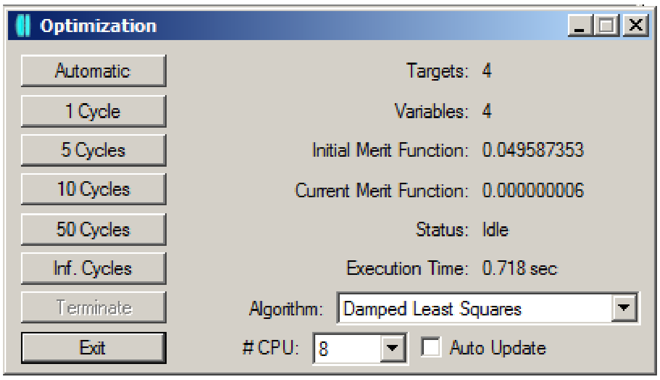
Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		100.00000				0.0000000	
1	Standard		42.073190	V	5.0000000		N-K5		7.0590650	
STO	Standard		-51.58353	V	76.464653	V			7.0084010	
IMA	Standard		Infinity		-				0.1147172	

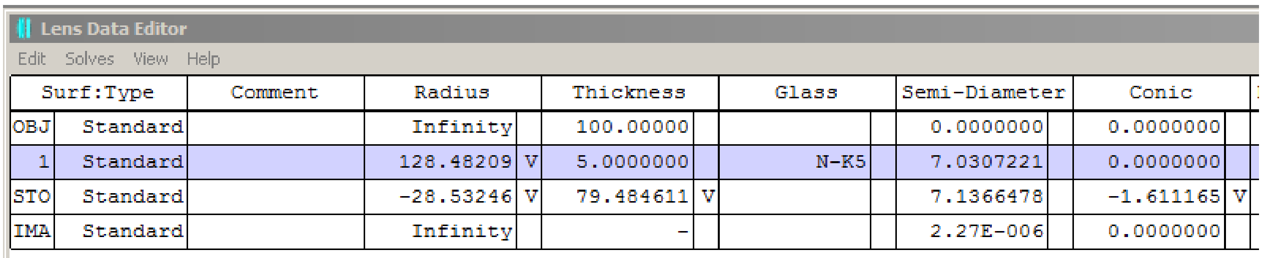


The spot diagram shows, that the singlet lens is not diffraction limited:

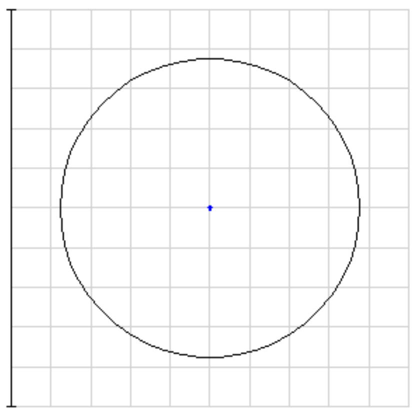


c) Now the conic constant of the back surface is chosen as variable and the optimization is run again. The solution is found after several iterations, the merit function is near to zero. Therefore the system must be diffraction limited





Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter		Conic	
OBJ	Standard		Infinity		100.00000				0.0000000		0.0000000	
1	Standard		128.48209	V	5.0000000		N-K5		7.0307221		0.0000000	
STO	Standard		-28.53246	V	79.484611	V			7.1366478		-1.611165	V
IMA	Standard		Infinity		-				2.27E-006		0.0000000	

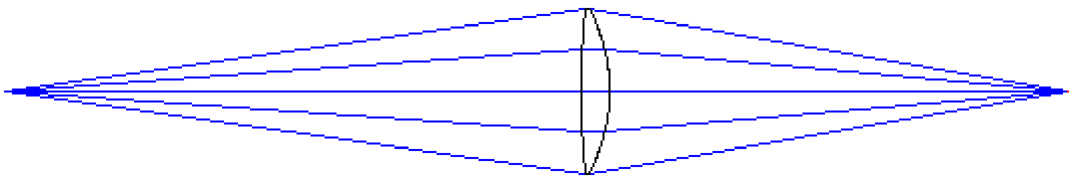


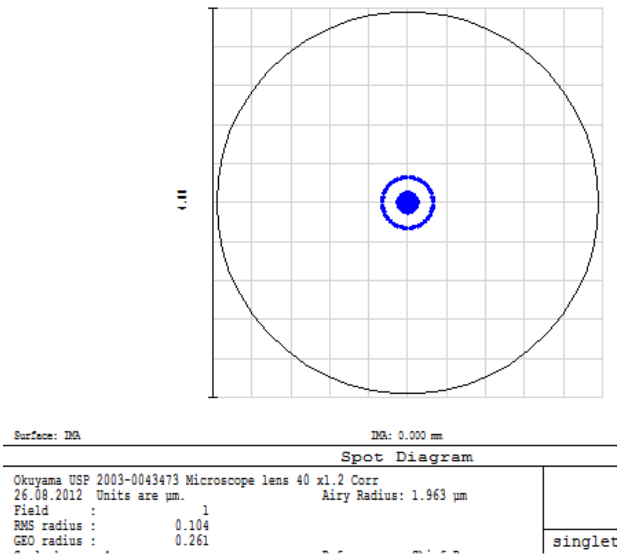
d) The numerical aperture is changed to NA = 0.14 and the optimization is run again. The system is still diffraction limited, but a little bit worse in comparison to the lower aperture. The exact result depends on the number of rings in the pupil for the spot optimization.

Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter		Conic	
OBJ	Standard		Infinity		100.00000				0.0000000		0.0000000	
1	Standard		134.58731	V	5.0000000		N-K5		14.246158		0.0000000	
STO	Standard		-28.26146	V	79.494556	V			14.287696		-1.587773	V
IMA	Standard		Infinity		-				2.61E-004		0.0000000	



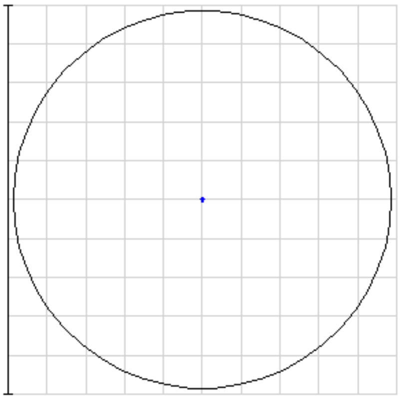


If now an aspherical coefficient of the 4th order is included, the result is as good as in c).

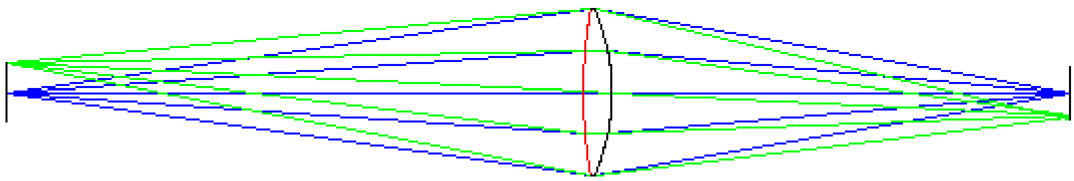
Lens Data Editor

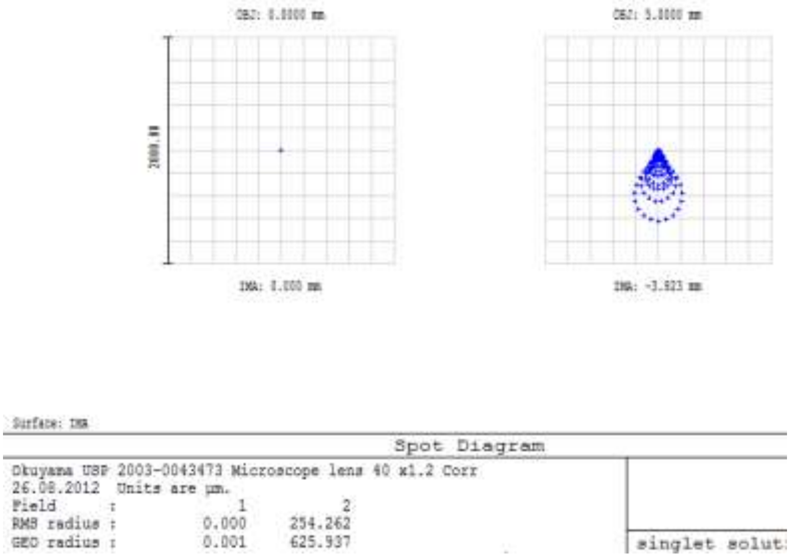
Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter		Conic		Par 0(unused)		2nd Order T..		4th Order T..	
OBJ	Standard		Infinity		100.00000				0.0000000		0.0000000							
1	Even Asp..		79.577400	V	5.0000000		N-K5		14.319090		0.0000000				0.0000000		-6.4E-007	V
STO	Standard		-32.83674	V	79.331877	V			14.340888		-1.865597	V						
IMA	Standard		Infinity		-				7.74E-007		0.0000000							

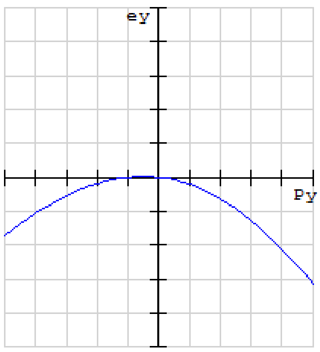


e) If a finite field size of diameter 10 mm is introduced (y = 5 mm), we get the following spot diagram. The shape of the field spot is dominated by a coma contribution.





Correspondingly the ray fan plot shows a strong quadratic contribution

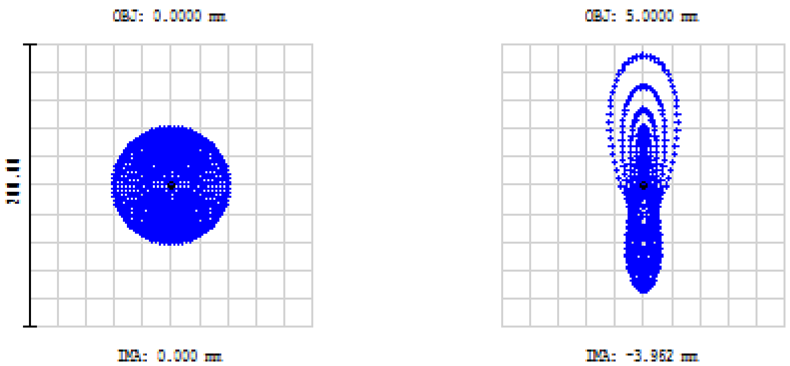


The Zernike coefficients show, that there is a considerable contribution of astigmatism (term no 5) too:

```
Z   1      6.45600165 :  1
Z   2      0.00000000 :  (p) * COS (A)
Z   3     33.79714491 :  (p) * SIN (A)
Z   4      6.39171319 :  (2p^2 - 1)
Z   5     -4.83179215 :  (p^2) * COS (2A)
Z   6      0.00000000 :  (p^2) * SIN (2A)
Z   7      0.00000000 :  (3p^2 - 2) p * COS (A)
Z   8     15.95549081 :  (3p^2 - 2) p * SIN (A)
Z   9     -0.07019705 :  (6p^4 - 6p^2 + 1)
Z  10      0.00000000 :  (p^3) * COS (3A)
Z  11      0.01367457 :  (p^3) * SIN (3A)
Z  12      0.03030820 :  (4p^2-3) p^2 * COS (2A)
Z  13      0.00000000 :  (4p^2-3) p^2 * SIN (2A)
Z  14      0.00000000 :  (10p^4 - 12p^2 + 3) p * COS (A)
Z  15     -0.59967622 :  (10p^4 - 12p^2 + 3) p * SIN (A)
Z  16     -0.00541962 :  (20p^6 - 30p^4 + 12p^2 - 1)
```

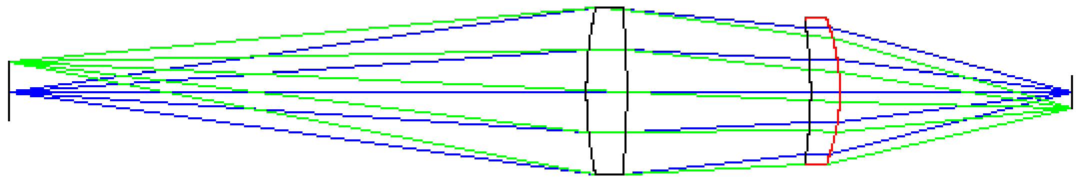
Now we reoptimize the system and allows step by step more constants for the aspherical surface. The performance is improved a little bit, but a diffraction limited system is not obtained.

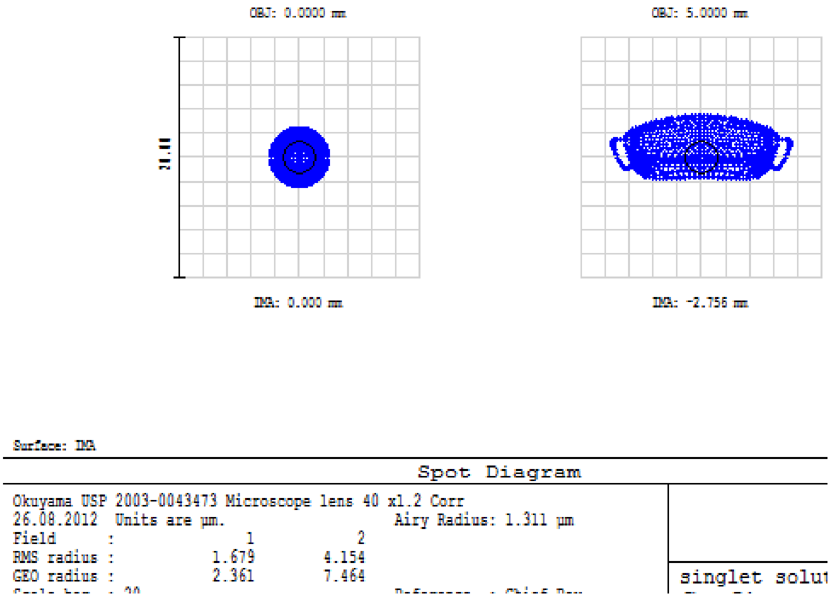
Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter		Conic		Par 0 (unused)		Par 1 (unused)		Par 2 (unused)		Par 3 (unused)		Par 4 (unused)	
OBJ	Standard		Infinity		100.00000				5.0000000		0.0000000											
1	Standard		46.851817	V	6.0000000		N-SF		16.529166		0.0000000											
STO	Even Asp..		-47.92363	V	78.792587	V			16.495173		-2.512347	V			0.0000000		3.01E-006	V	-1.2E-010	V	-7.5E-015	V
IMA	Standard		Infinity		-				4.0173870		0.0000000											



As an alternative solution, an additional aspherical lens is introduced behind the aspherical singlet and the system is reoptimized. The distance between the two lenses is allowed to change. The system is better, but a diffraction limited performace is not obtained. Especially the field correction is still worse.

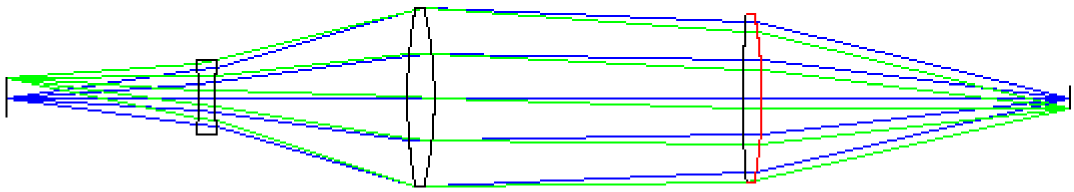
Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter		Conic		Par 0 (unused)		Par 1 (unused)		Par 2 (unused)	
OBJ	Standard		Infinity		100.00000				5.0000000		0.0000000							
1	Standard		66.334604	V	7.0000000		SF6		14.483417		0.0000000							
STO	Even Asp..		-136.7346	V	31.866324	V			14.249774		0.0000000				0.0000000		2.77E-006	V
3	Standard		-76.83583	V	5.0000000		SF6		12.498937		0.0000000							
4	Even Asp..		-33.38862	V	40.227626	V			12.659323		0.0000000				0.0000000		5.50E-006	V
IMA	Standard		Infinity		-				2.7549139		0.0000000							

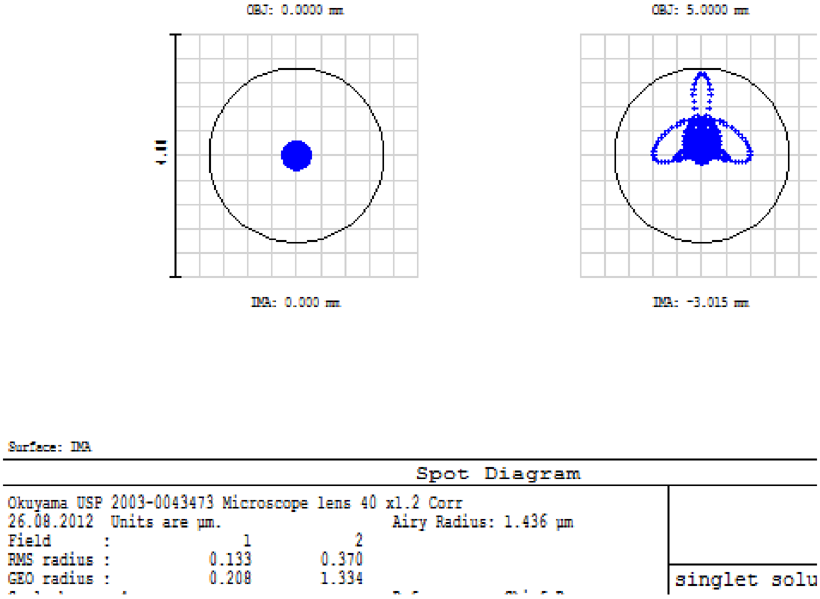




If a third lens (spherical) is placed in a fixed distance before the aspherical singlet, we get a nearly perfect solution. Thgis first lens becomes negative

Surf:Type		Comment	Radius		Thickness		Glass	Semi-Diameter	Conic	Par 0 (unused)	Par 1 (unused)	Par 2 (unused)	
OBJ	Standard		Infinity		50.000000			5.0000000	0.0000000				
1	Standard		-49.04023	V	4.0000000		BK7	8.8053783	0.0000000				
2	Standard		62.528372	V	50.000000			9.4283979	0.0000000				
3	Standard		131.57961	V	7.0000000		SF6	22.851156	0.0000000				
STO	Even Asp..		-96.66908	V	80.073404	V		23.018065	0.0000000		0.0000000	6.22E-007	V
5	Standard		271.25718	V	5.0000000		SF6	21.818560	0.0000000				
6	Even Asp..		-110.7407	V	79.734329	V		21.724941	0.0000000		0.0000000	6.97E-007	V
IMA	Standard		Infinity		-			3.0145988	0.0000000				





5.3 Achromate

a) Calculate a classical achromate with the basic data:
- object at infinity
- focal length f = 10 mm
- image side numerical aperture NA' = 0.05
- glass materials BK7 and SF6
- wavelength used: d, F, C
- Performance:
  1. spherical correction at the aperture boundary zero
  2. achromatic correction with identical image position for F and C

Is the system diffraction limited on axis ?
b) Describe the performance for a finite field angle of 2°.
c) If the glass SF6 is used instead of SF12, can a system with equivalent quality be obtained ?

Solution

a) Starting data, approximated

Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.0000000	
1	Standard		Infinity		1.0000000				0.5000000	
*	Standard	LAO123	7.0000000	V	0.5000000		BK7		1.3250000	U
3*	Standard		-7.000000	V	0.2500000		SF12		1.3250000	U
4*	Standard		-20.00000	V	10.000000	V			1.3250000	U
IMA	Standard		Infinity		-				0.0497767	

Merit function:
The longitudinal aberration for the main wavelength is decomposed explicitely by single ray results for the marginal and a quasi-paraxial ray.

Merit Function Editor: 1.863343E-001

Edit Tools View Help

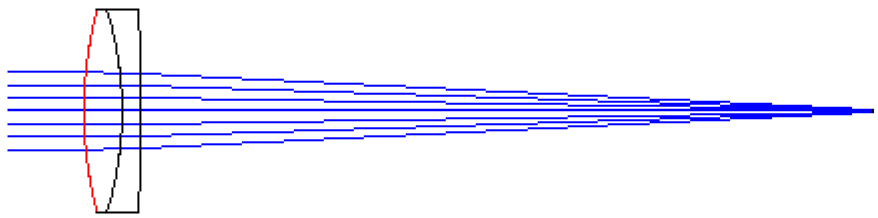
Oper #	Type							Target	Weight	Value	% Contrib
1: BLNK	BLNK										
2: EFFL	EFFL		2					10.0000000	1.0000000	11.5137857	64.0775454
3: AXCL	AXCL	1	3	0.0000000				0.0000000	1.0000000	0.0690721	0.1334083
4: BLNK	BLNK										
5: REAY	REAY	5	2	0.0000000	0.0000000	0.0000000	1.0000000	0.0000000	0.0000000	0.0488159	0.0000000
6: REAB	REAB	5	2	0.0000000	0.0000000	0.0000000	1.0000000	0.0000000	0.0000000	-0.0434778	0.0000000
7: DIVI	DIVI	5	6					0.0000000	1.0000000	-1.1227789	35.2505206
8: REAY	REAY	5	2	0.0000000	0.0000000	0.0000000	1.0000E-002	0.0000000	0.0000000	4.9361E-004	0.0000000
9: REAB	REAB	5	2	0.0000000	0.0000000	0.0000000	1.0000E-002	0.0000000	0.0000000	-4.343E-004	0.0000000
10: DIVI	DIVI	8	9					0.0000000	0.0000000	-1.1366568	0.0000000
11: BLNK	BLNK										
12: DIFF	DIFF	7	10					0.0000000	100.0000000	0.0138776	0.5385256

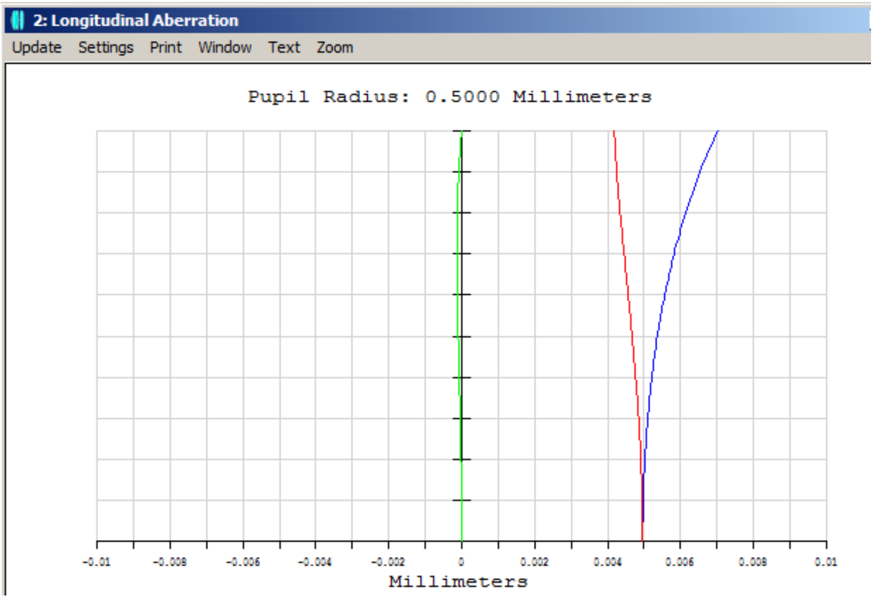
Solution after optimization:

Lens Data Editor

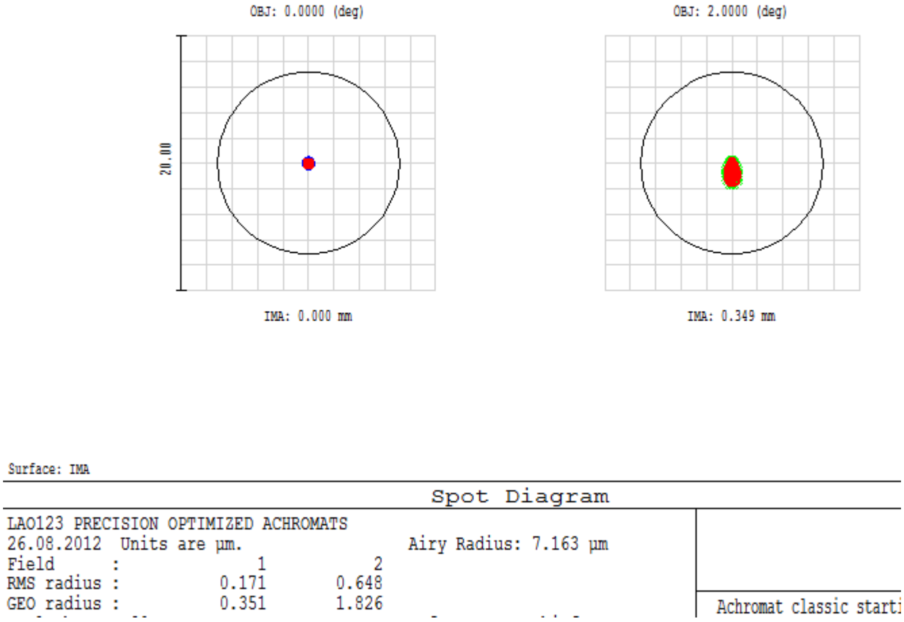
Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.0000000	
1	Standard		Infinity		1.0000000				0.5000000	
*	Standard	LAO123	5.1041421	V	0.5000000		BK7		1.3250000	U
3*	Standard		-4.476792	V	0.2500000		SF12		1.3250000	U
4*	Standard		-22.82270	V	9.5557339	V			1.3250000	U
IMA	Standard		Infinity		-				3.51E-004	





b) For a finite field of 2° the spot diagram is seen here. The performance is diffraction limited in both cases, although the correction in the field shows considerable coma.



This can also be seen by analyzing the Zernike coefficients, the c_5 has the largest value.

```
3: Zernike Fringe Coefficients
Update  Settings  Print  Window
Strehl Ratio (Est)              :      0.99479413

RMS fit error                   :      0.00000000 waves
Maximum fit error               :      0.00000000 waves

Z   1      0.01742544 :  1
Z   2      0.00000000 :  (p) * COS (A)
Z   3      0.01338094 :  (p) * SIN (A)
Z   4      0.01746392 :  (2p^2 - 1)
Z   5     -0.01264260 :  (p^2) * COS (2A)
Z   6      0.00000000 :  (p^2) * SIN (2A)
Z   7      0.00000000 :  (3p^2 - 2) p * COS (A)
Z   8      0.00675226 :  (3p^2 - 2) p * SIN (A)
Z   9      0.00002000 :  (6p^4 - 6p^2 + 1)
Z  10      0.00000000 :  (p^3) * COS (3A)
Z  11     -0.00001025 :  (p^3) * SIN (3A)
Z  12     -0.00001247 :  (4p^2-3) p^2 * COS (2A)
Z  13      0.00000000 :  (4p^2-3) p^2 * SIN (2A)
Z  14      0.00000000 :  (10p^4 - 12p^2 + 3) p * COS (A)
Z  15      0.00004138 :  (10p^4 - 12p^2 + 3) p * SIN (A)
Z  16     -0.00001860 :  (20p^6 - 30p^4 + 12p^2 - 1)
Z  17      0.00000002 :  (p^4) * COS (4A)
Z  18      0.00000000 :  (p^4) * SIN (4A)
Z  19      0.00000000 :  (5p^2 - 4) p^3 * COS (3A)
Z  20     -0.00000003 :  (5p^2 - 4) p^3 * SIN (3A)
Z  21     -0.00000006 :  (15p^4 - 20p^2 + 6) p^2 * COS (2A)
Z  22      0.00000000 :  (15p^4 - 20p^2 + 6) p^2 * SIN (2A)
```

c) If SF6 is used, we don't get a comparable good solution. The best solution is shown below. The reason for this is the small numerical aperture and the high index jump: there is really no higher order spherical aberration at the cemented surface, therefore the spherical correction can not be achieved.

Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.0000000	
1	Standard		Infinity		1.0000000				0.5000000	
*	Standard	LA0123	5.9794174		0.3000000		BK7		1.3250000	U
3*	Standard		-6.394142		0.1500000		SF6		1.3250000	U
4*	Standard		-13.62002	M	9.7938962	V			1.3250000	U
IMA	Standard		Infinity		-				6.73E-004