First order optics

Paraxial lens parameters

How to measure them

Background

- Usually knowing efl is enough
  - Find using nodal bench for exact measurement
  - Other tests can give approximate value
    - See Wyant lab #2 notes for other tests
- Sometimes need to know exactly
  - Radii, index and center thickness
  - This lab shows how

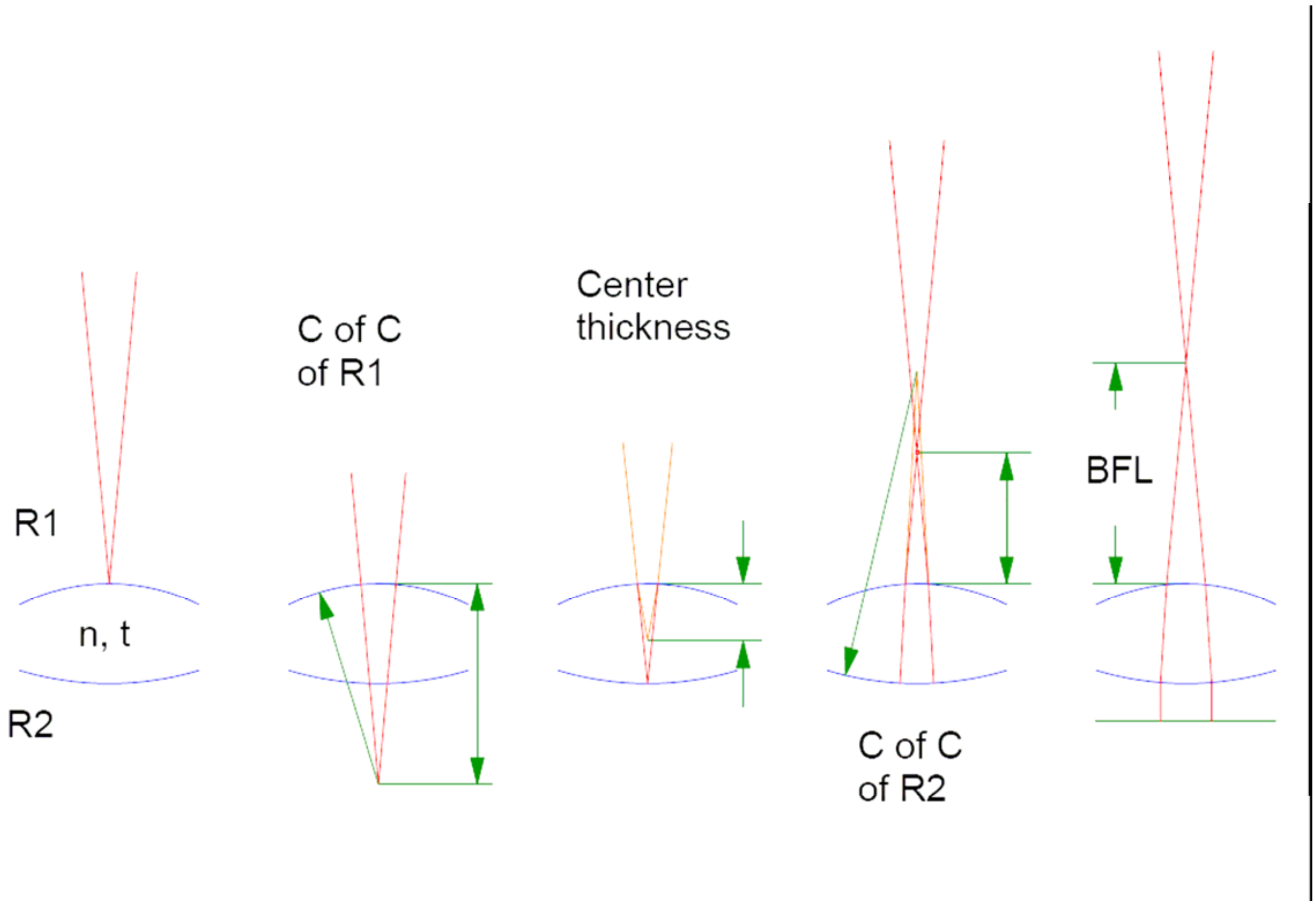
What you will learn

- How to reverse engineer a lens
- Difference between real and paraxial quantities
- Use of Excel Solver
  - Means of solving non-linear simultaneous equations
  - Finding solutions for non-closed for equations
- Zemax multi-configuration editor
  - The IGNR operator

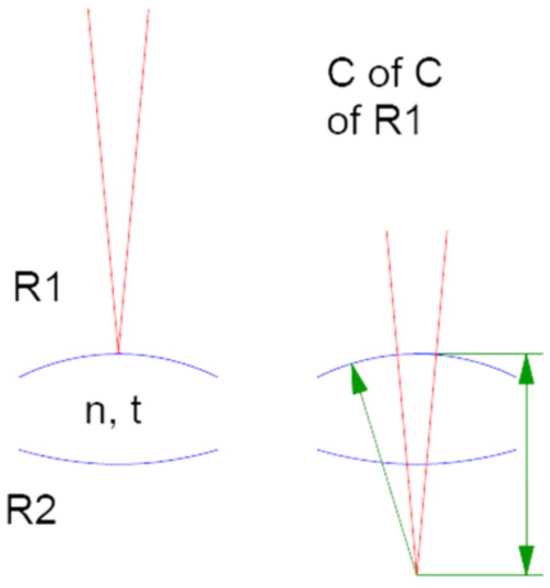
Paraxial lens properties

- Two radii, the two surfaces
- Index of refraction
- Center thickness, a physical thickness
- In all, four unknowns
- Need at least four measurements
- There are some practical issues
  - Are conjugates accessible?

A set of four measurements



Setting zero and front radius



On left, use PSM to get a Cat's eye reflection from the front surface

(How is Cat's different from a conjugate reflection?)

Call z-axis stage reading zero

If there is working distance, move PSM toward lens until a reflection well focused from R1. Distance moved is R1. This is a direct measurement of R1.

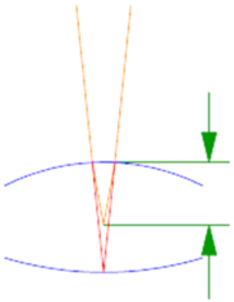
What happens to the return spot if PSM is moved laterally? Is this different behavior from the Cat's eye?

Center thickness

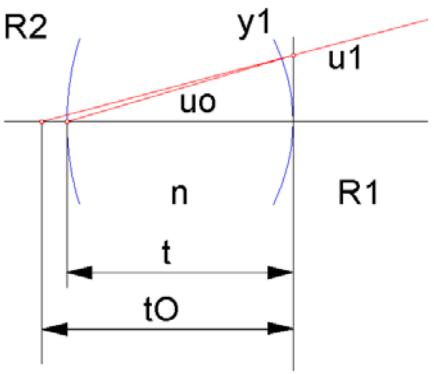
Move PSM toward lens to pick up Cat's eye from rear vertex. Distance moved from front surface Cat's eye is the optical center thickness.

to depends on R1, n and t, the physical thickness

Center thickness

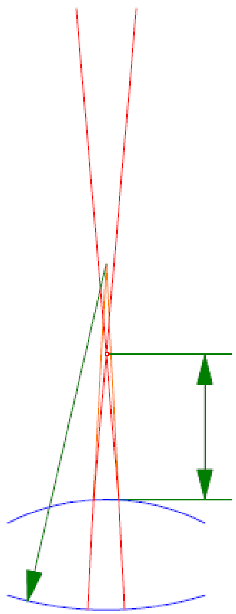


$$t_O = {y_1}/{u_1} = \frac{-tR_1}{nR_1 + t(n-1)}$$

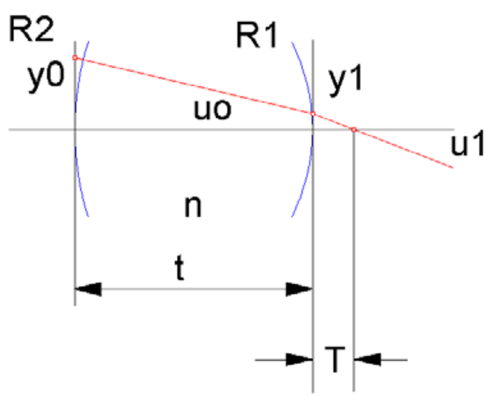


Measurement of R2

Move the PSM away from the Cat's eye from the front surface vertex until the focus is conjugate with the apparent center of curvature of R2.



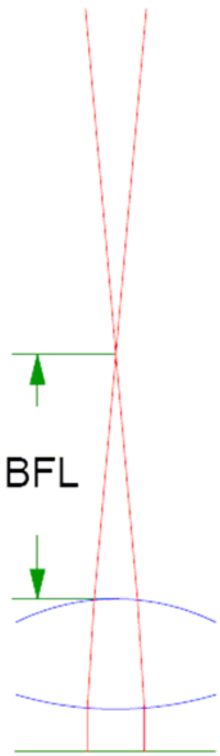
C of C
of R2



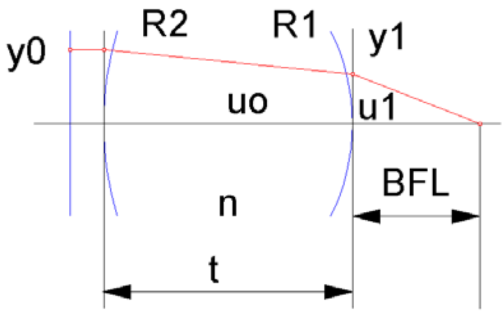
$$T = {y_1}/{u_1} = \frac{\left(1 - {t}/{R_2}\right)}{\frac{n}{R_2} - \left[\frac{(n-1)\left(1-\left({t}/{R_2}\right)\right)}{R_1}\right]}$$

Here T depends on all four paraxial parameters

Measurement of the BFL



Place a plane mirror behind the lens and measure the BFL, or distance from the R1 vertex to the focus



$$BFL = \frac{y_1}{u_1} = \frac{\left[1 - \frac{t(n-1)}{nR_2}\right]}{(n-1)\left[\frac{1}{R_2} - \frac{1}{R_1} + \frac{t(n-1)}{nR_1R_2}\right]}$$

Again, the BFL depends on all four paraxial quantities

Now have three measurements to use to solve for R2, n and t.

If there is not sufficient working distance to measure R1, what could be done at this point?

Solving the three equations with Excel

	A	B	C	D	E
1	Lens parameter	value			
3	n, known or best estimate	1.5			
5	t, known or best estimate	3			
7	r1, known if shorter than working distance	2.237			
9	r2, known or best estimate	-5			
11	c1 = 1/R1, used in the calculation	0.447027269			
13	a, optical center thickness based on	3.616814875			
14	known or estimated parameters				
15	b, R2 center of curvature based on	-1.02720698			
16	known or estimated parameters				
17	d, BFL based on	-2.8693282			
18	known or estimated parameters				
19	a, b and d are all relative to vertex of R1				
21		calculated	measured	difference	difference squared
23	C of C R1	2.237	2.237	0	0
25	Vertex R1 or CT	3.616814875	2.99	-0.626814875	0.392896887
27	C of C R2	-1.02720698	-0.5	0.52720698	0.277947199
29	BFL	-2.8693282	-2.5	0.369328203	0.136403321
31			sum of squared differences		0.807247408
32					

Recipe for solution

In B3, B5, B7 and B9 enter reasonable estimates for n, t, R1 and R2

B13, B15 and B17 are calculated based on the estimates above

Cells B23, 25 27 and 29 are simply copied from B7, B13, B15 and B17

C23, C25, C27 and C29 are measured values using the PSM

D23, D25, D27 and D29 are the differences between the B and C cells

E23, E25, E27 and E29 are the squares of the differences

E31 is the sum of the squares

Under Tools, click on Solver. If not installed, click on Add-ins and install

Target cell is the sum of the squares, or E31; Equal to Value of zero

By changing B3, B5 and B9. (Remember R1 is already known)

Under Options increase precision, tolerance and convergence

Click OK. If no good solution, click Quadratic, Central and Conjugate under options

Excel solution

	A	B	C	D	E
1	Lens parameter	value			
3	n, known or best estimate	1.484975531			
5	t, known or best estimate	2.69404503			
7	r1, known if shorter than working distance	2.237			
9	r2, known or best estimate	-3.52756646			
11	c1 = 1/R1, used in the calculation	0.447027269			
13	a, optical center thickness based on	2.990346911			
14	known or estimated parameters				
15	b, R2 center of curvature based on	-0.50040889			
16	known or estimated parameters				
17	d, BFL based on	-2.50022313			
18	known or estimated parameters				
19	a, b and d are all relative to vertex of R1				
21		calculated	measured	difference	difference squared
23	C of C R1	2.237	2.237	0	0
25	Vertex R1 or CT	2.990346911	2.99	-0.000346911	1.20347E-07
27	C of C R2	-0.50040889	-0.5	0.000408887	1.67188E-07
29	BFL	-2.50022313	-2.5	0.000223132	4.97877E-08
31			sum of squared differences		3.37323E-07
32					

Sum of squares minimized, solutions in B3, B5 and B9

Lens design example

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.000000	
1	Paraxial				100.000000				12.700000	U
2	Standard	variable distance	Infinity		99.561047	V			0.000000	
STO*	Standard	R1	60.020000		4.000000		BK7		12.700000	U
4	Standard	R2 config 2 & 3	-353.300000		-4.000000	P	MIRROR		0.000000	
5*	Standard	R2 config 1	-353.300000		10.000000				12.700000	U
6*	Standard	mirror	Infinity		-10.000000	P	MIRROR		12.700000	U
7*	Standard	R2	-353.300000	P	-4.000000	P	BK7	P	12.700000	U
8*	Standard	R1	60.020000	P	-99.561047	P			12.700000	U
9*	Standard	R1 rev	353.300000	P	4.000000	P	BK7	P	12.700000	U
10*	Standard	R2 rev config 2,3	-60.020000	P	-4.000000	P	MIRROR	P	12.700000	U
11*	Standard	R2 rev config 1	-60.020000	P	10.000000				12.700000	U
12*	Standard	mirror	Infinity		-10.000000	P	MIRROR	P	12.700000	U
13*	Standard	R2 rev	-60.020000	P	-4.000000	P	BK7	P	12.700000	U
14*	Standard	R1 rev	353.300000	P	2.650440	P			12.700000	U
15	Standard		Infinity		-100.000000	P			12.700000	U
16	Paraxial	paraxial			0.000000				12.700000	U
17	Paraxial				-100.000000				12.700000	U
IMA	Standard		Infinity		-				0.083519	

Configuration 1 shown for calculation of bfl

Grayed out lines are ignored

Lens design example con’t 1

Edit Solves Tools View Help

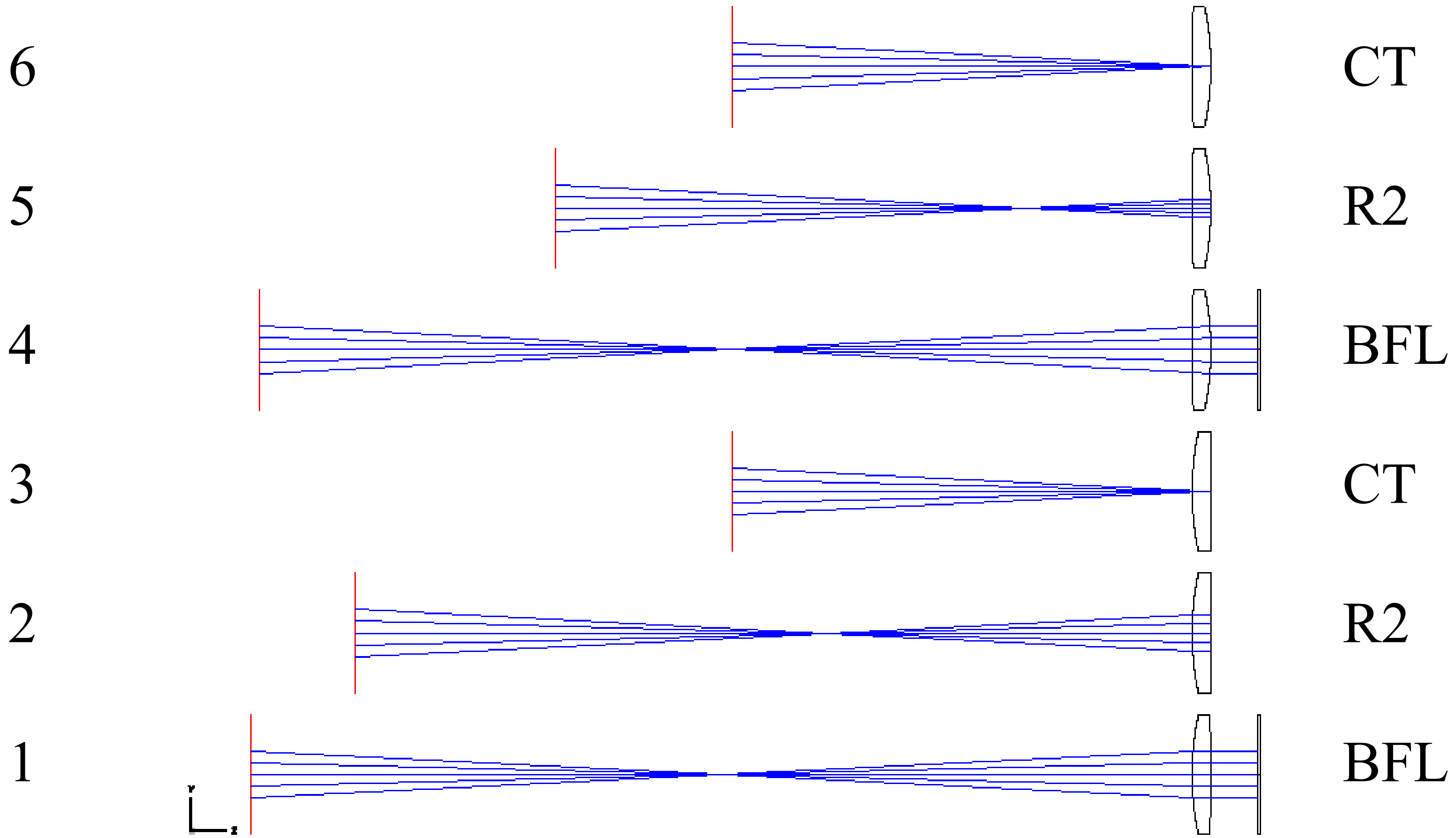
Active : 1/6		Config 1*	Config 2	Config 3	Config 4	Config 5	Config 6
1: MOFF	0	BFL	R2	CT	BFL	R2	CT
2: THIC	2	99.561047 V	77.411271 V	-2.701440 V	97.681577 V	35.085383 V	-2.650440 V
3: IGNR	3	0	0	0	1	1	1
4: IGNR	4	1	0	0	1	1	1
5: IGNR	5	0	1	1	1	1	1
6: IGNR	6	0	1	1	1	1	1
7: IGNR	7	0	1	1	1	1	1
8: IGNR	8	0	0	0	1	1	1
9: IGNR	9	1	1	1	0	0	0
10: IGNR	10	1	1	1	1	0	0
11: IGNR	11	1	1	1	0	1	1
12: IGNR	12	1	1	1	0	1	1

Configurations 1, 2 and 3 are looking thru short radius first

Configurations 4,5 and 6 are looking thru long radius first

Line 2 shows what the measurements should be knowing the index, thickness and two radii

Lens design example con’t 2



Prior to optimizing

Lens Data Editor: Config 1/6

Edit Solves View Help

Surf	Type	Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.000000	
1	Paraxial				100.000000				12.700000	U
2	Standard	variable distance	Infinity		99.560000				0.000000	
STO*	Standard	R1	Infinity	V	10.000000	V	1.52,64.2	V	12.700000	U
4	Standard	R2 config 2 & 3	-353.300000		-4.029609	P	MIRROR		0.000000	
5*	Standard	R2 config 1	Infinity	V	10.000000				12.700000	U
6*	Standard	mirror	Infinity		-10.000000	P	MIRROR		12.700000	U
7*	Standard	R2	Infinity	P	-10.000000	P	1.52,64.2	P	12.700000	U
8*	Standard	R1	Infinity	P	-99.560000	P			12.700000	U
9*	Standard	R1 rev	353.300000	P	4.029609	P	1.52,64.2	P	12.700000	U
10*	Standard	R2 rev config 2,3	-60.042505	P	-4.029609	P	MIRROR	P	12.700000	U
11*	Standard	R2 rev config 1	-60.042505	P	10.000000				12.700000	U
12*	Standard	mirror	Infinity		-10.000000	P	MIRROR	P	12.700000	U
13*	Standard	R2 rev	-60.042505	P	-4.029609	P	1.52,64.2	P	12.700000	U
14*	Standard	R1 rev	353.300000	P	2.650000	P			12.700000	U
15	Standard		Infinity		-100.000000	P			12.700000	U
16	Paraxial	paraxial			0.000000				12.700000	U
17	Paraxial				-100.000000				12.700000	U
IMA	Standard		Infinity		-				11.616117	

Surf 3 is R1, arbitrary center thickness, model index, Surf 5 is R2

These are set as variables and optimized

Lens design example con't 3

Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.000000	
1	Paraxial				100.000000				12.700000	U
2	Standard	variable distance	Infinity		99.561047				0.000000	
STO*	Standard	R1	60.020000	V	4.000000	V	1.52,64.2		12.700000	U
4	Standard	R2 config 2 & 3	-353.300000		-4.000000	P	MIRROR		0.000000	
5*	Standard	R2 config 1	-353.300000	V	10.000000				12.700000	U
6*	Standard	mirror	Infinity		-10.000000	P	MIRROR		12.700000	U
7*	Standard	R2	-353.300000	P	-4.000000	P	1.52,64.2	P	12.700000	U
8*	Standard	R1	60.020000	P	-99.561047	P			12.700000	U
9*	Standard	R1 rev	353.300000	P	4.000000	P	1.00,0.0	P	12.700000	U
10*	Standard	R2 rev config 2,3	-60.020000	P	-4.000000	P	MIRROR	P	12.700000	U
11*	Standard	R2 rev config 1	-60.020000	P	10.000000				12.700000	U
12*	Standard	mirror	Infinity		-10.000000	P	MIRROR	P	12.700000	U
13*	Standard	R2 rev	-60.020000	P	-4.000000	P	1.00,0.0	P	12.700000	U
14*	Standard	R1 rev	353.300000	P	2.650440	P			12.700000	U
15	Standard		Infinity		-100.000000	P			12.700000	U
16	Paraxial	paraxial			0.000000				12.700000	U
17	Paraxial				-100.000000				12.700000	U
IMA	Standard		Infinity		-				0.083542	

Radii, thickness and index are set as variables

Optimized with small entrance pupil for paraxial solution

R1 = 60.2, R2 = -353.3, th = 4, index = 1.5156

Conclusions

- Use all practical conjugate measurements in model
- Works with interferometer or autostigmatic microscope
- Works for doublets as well as singlets
  - Can usually see cement interface
  - Often better reflection than AR coated surfaces
  - Just a more complicated lens design model
- Remember to stop down model before optimization
  - Model must find first order solution
- All in all, pretty easy to do