

1. Single Lens

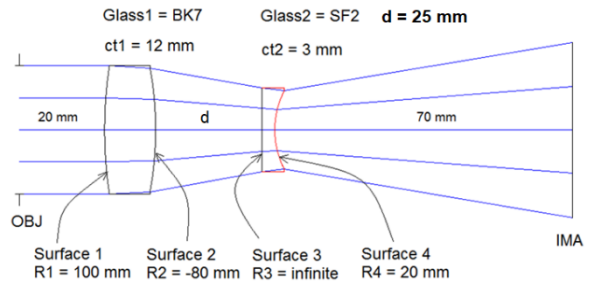
Consider a bi-concave lens whose center thickness is 5 mm, aperture is 35 mm, and glass is N-BK7. The object is at infinity, wavelength $\lambda = 0.6 \mu\text{m}$, and radii $|R_1| = 100 \text{ mm}$ and $|R_2| = 120 \text{ mm}$.

- (a) What is the effective focal length of the lens?
- (b) What is the back focal length of the lens?
- (c) What is the front focal length of the lens?
- (d) What is the mass of the lens?
- (e) What is the edge thickness of the lens?

2. Two Lenses

Let $\lambda = 650 \text{ nm}$ and ENP = 25.4 mm.

- (a) Implement the following system in Zemax LDE.
- (b) What is the effective focal length of the system?
- (c) What is the back focal length of the system?
- (d) What is the front focal length of the system?
- (e) What is the spot radius on the image plane?
- (f) For which value of distance d the system is afocal?



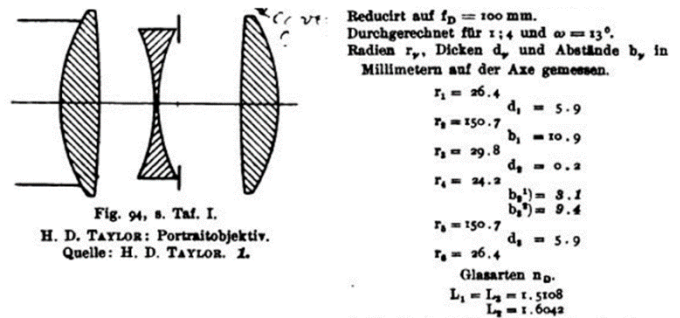
3. Cooke Triplet

The Cooke triplet is a photographic lens designed and patented (patent number GB 22,607) in 1893 by Dennis Taylor.

See also:

https://en.wikipedia.org/wiki/Cooke_triplet

Implement the lens data given right in Zemax.



4. A plano-convex lens

ct = 5 mm

ENPD = 25 mm

f/# = 4

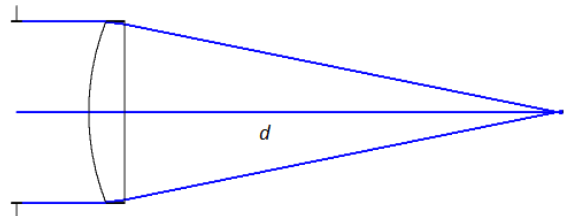
Glass = N-BK7

Wavelength = $0.55 \mu\text{m}$

$R_2 = \text{inf}$

$R_1 = ?$ (radius of curvature of 1st surface)

$d = ?$ (distance between 2nd surface and image plane where we have smallest spot size)



5. Thermal Infrared Lens

Glass = Germanium

ENPD = 25 mm

f/# = 2

$R_1 = 49.030 \text{ cx}$ (cx means convex)

$R_2 = 69.460 \text{ cc}$ (cc means concave)

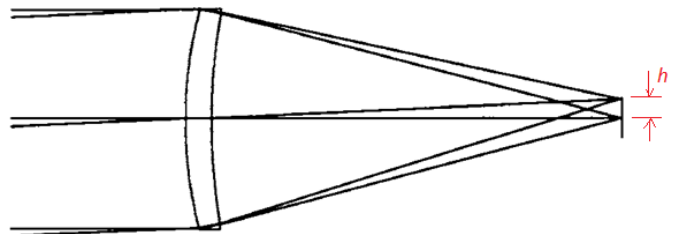
ct = 3 mm

Wavelength = $10 \mu\text{m}$

Full FOV = 5°

(a) Find the back focal length of the lens. (Hint use quick focus)

(b) Find the image height h .



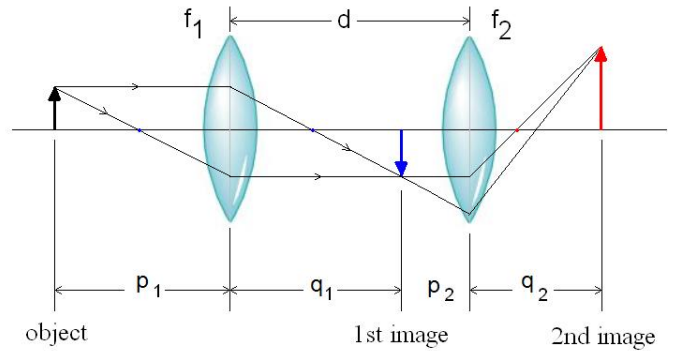
6. Two Thin Lenses

Consider the system given right.
 Show that back, front and effective focal length of the system are respectively given by:

$$BFL = \frac{f_2(d - f_1)}{d - (f_1 + f_2)}$$

$$FFL = \frac{f_1(d - f_2)}{d - (f_1 + f_2)}$$

$$EFL = \left[\frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2} \right]^{-1}$$



7. For the system given in Ex1, find EFL, BFL and FFL of the system if $f_1 = -30$ mm, $f_2 = +20$ mm and $d = 10$ mm. Implement your solution in Zemax and compare your results.

8. For the system given in Ex1, find the final image position and its magnification for an object placed at $p_1 = 30$ cm if $f_1 = +100$ mm and $f_2 = +200$ mm and $d = 200$ mm.

9. For the system given in Ex1, what focal lengths are necessary in this two-element lens system if one requires a 200 mm (effective) focal length, a 100 mm back focus, and a 50 mm air space?

10. Pupils

A lens of +50 mm focal length is mounted in another lens lens but of -70 mm focal length. The distance between lenses is 60 mm. When a stop 5 mm in diameter is placed halfway between the two lenses,
 (a) what is the location and diameter of the entrance pupil? and
 (b) what is the location and diameter of the exit pupil?
 Use Zemax to verify the results.

11. Cooke Triplet

Three thin lenses are arranged in the following order: a positive lens ($f = 60$ mm, $d = 8$ mm) separated 13 mm from a negative lens ($f = -40$ mm, $d = 6.4$ mm) and followed by another positive lens ($f = 50$ mm, $d = 7.2$ mm) with a separation of 13 mm from the negative lens. Assume that second lens is the aperture stop.

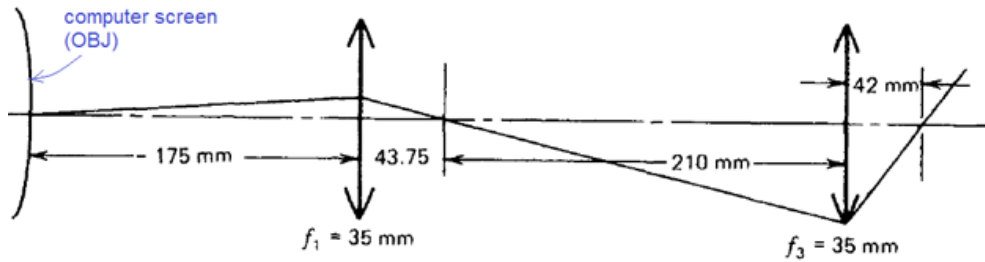
- (a) What is the effective focal length of the system?
- (b) Where are pupils for an object at infinity?
- (c) If an object is 300 mm from the first lens, where are the image and pupils for the system?

12. Find the image distance for an object positioned 200 mm from the vertex of a double concave lens having radii 100 mm and 200 mm, a thickness 5 mm, and index of $n = n_L = 1.5$.

13. Using Fermat's principle, show that parallel rays falling on a concave mirror can only be focused on a single point if it is a paraboloid.

14. An application of y-u trace

Consider a simple optical system in Figure below. Starting with $(y_0, u_0) = (0, 0.1)$, find the final height and slope angle of this ray.



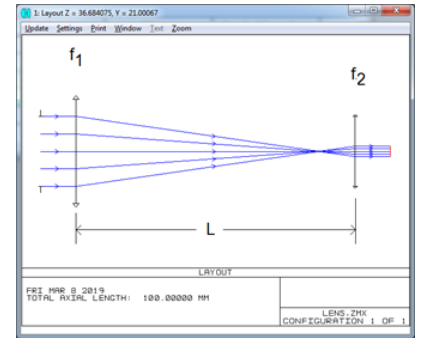
15. Paraxial Lenses

The focal lengths of four thin lenses are $f_1 = 100$ mm, $f_2 = -50$ mm, $f_3 = 80$ mm, and $f_4 = -280$ mm. Separations between the lenses are $t_1 = 20$ mm, $t_2 = 40$ mm, and $t_3 = 30$ mm. Using Zemax, find the image location if the object is 400 mm from the first lens. Check your results using y-u trace.

16. Keplerian Telescope

Figure shows a Keplerian (or Astronomical) Telescope consisting of two positive thin lenses. Use y-u trace.

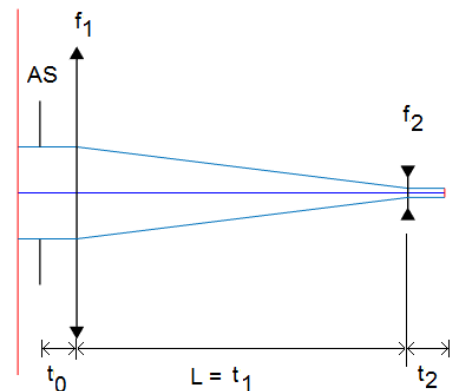
- (a) Show that the entrance and exit rays are parallel to the optical axis when $L = f_1 + f_2$.
- (b) What is the magnification of the system when $L = f_1 + f_2$?
- (c) What is the back focal length of the system when $L = (f_1 + f_2)/2$?



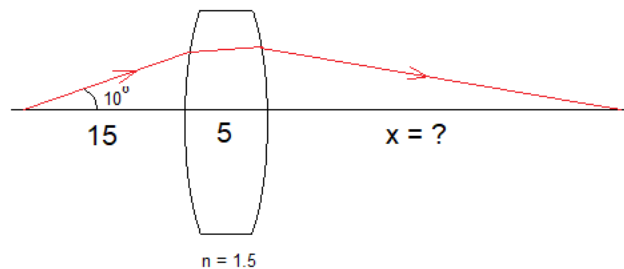
17. Galilean Telescope

Figure shows a simple Galilean Telescope consisting of two thin lenses. Let $f_1 = 100$ mm, $f_2 < 0$, $t_0 = t_2 = 10$ mm and diameter of AS is 20 mm. We want to design an afocal system. Use y-u trace.

- (a) Show that the distance between lenses must be $L = f_1 + f_2$.
- (b) Show that magnification of the system is given by $m = -f_1/f_2 = D_{EnP} / D_{Exp}$ where D_{EnP} and D_{Exp} are diameters of the entrance and exit pupils respectively.
- (c) For which value of f_2 and L , the system's exit pupil diameter is 4 mm?
- (d) For the values of L and f_2 in part (c), determine the location and diameter of EnP and Exp?



18. Perform paraxial and real ray tracing for a given ray in figure. Determine value of x for each case and compare your results. Assume that radius of curvature of first lens is $R_1 = 100$ mm and of second surface is $R_2 = -100$ mm.

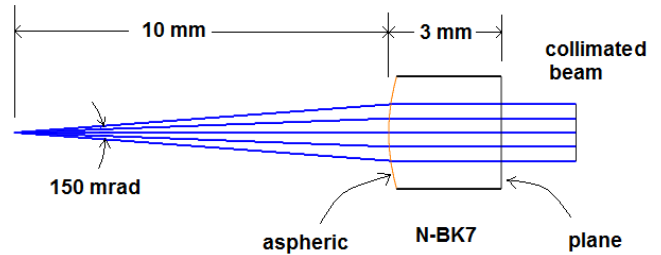


19. Design and optimize an $f/5$ singlet lens made of N-SF10 glass. The final design solution should meet the specifications and constraints given in the table.

Specification	Constraint
Focal Length	70 mm
Semi-Field of View (SFOV)	5 degrees
Wavelength	532 nm
Center Thickness of singlet	Between 2 mm and 12 mm
Edge Thickness of singlet	Larger than 2 mm
Optimization criteria	RMS Spot Size averaged over FOV
Object location	At infinity

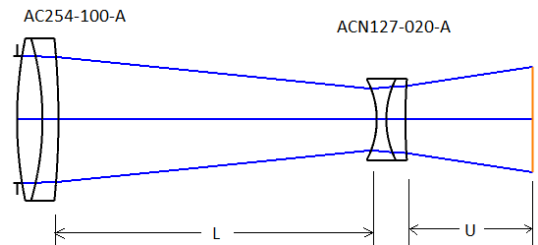
20. Figure below shows a plano-hyperbolic collimator made from N-BK7 glass. It is used to collimate a laser diode whose beam divergence is 150 mrad and wavelength is 633 nm.

- (a) Determine the proper diameter of the collimating lens.
- (b) Find the radius of curvature and the conic constant of the aspherical surface to collimate the light properly. (Hint: the system is afocal)



21. Figure shows an optical system with two lenses selected from Vendor "Thorlabs" Lens Catalog (AC254-100-A and ACN127-020-A). System aperture is ENPD = 20 mm, FOV = $1^\circ (\pm 0.5^\circ)$, wavelength is $\lambda = 600$ nm and the object is at infinity.

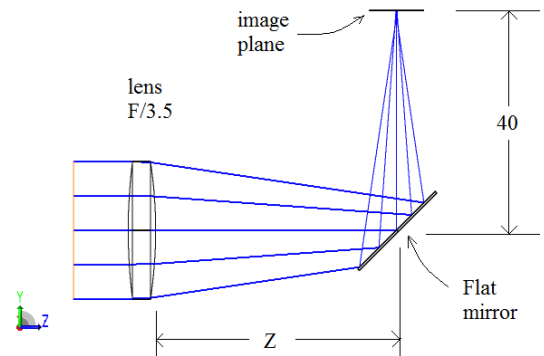
- (a) For $U = 10$ mm, determine the value of L such that the system is afocal.
- (b) For $U = 10$ mm, determine the value of L such that the system has minimum spot size at image plane.



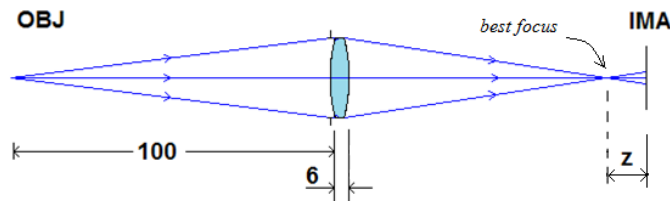
22. Design the following optical system containing a lens and a flat mirror System:

- * ENPD = 25 mm, $\lambda = 405$ nm, Object is at infinity
- Lens
 - * 1st surface radius $R_1 = 100$ mm, $ct = 5$ mm
 - * Glass = K5, $F/\# = 3.5$
- Plane Mirror
 - * Diameter = 20 mm

- (a) Determine the radius of curvature of 2nd surface of the lens.
- (b) Find the optimum distance (Z) between 2nd surface of the lens and mirror such that the spot size on the image plane is minimum. Use default merit function.

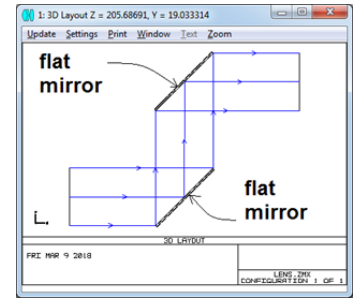


23. Figure shows an equi-convex lens ($|R_1| = |R_2| = 50$ mm, $t = 6$ mm) made from N-BK7. Entrance pupil of the system is 25 mm. Initially the image plane is placed at the paraxial focus. The distance between STOP and first surface of the lens is zero. Using Zemax, determine the position z (with respect to initial image plane location) corresponding to minimum spot radius for Fraunhofer C line.



24. Basic Periscope with two mirrors

Fulfill the fold mirror simulation as shown in Figure in Zemax.



25. Fulfill the fold mirror and lens simulation as shown in Figure in Zemax.

Surf	Type	Comment	Radius	Thickness	Glass
OBJ	Standard		Infinity	Infinity	
STO	Standard		Infinity	50.000	
2	Coordinat..			0.000	
3	Standard		Infinity	0.000	MIRROR
4	Coordinat..			-70.000	
5	Standard		-80.000	-5.000	BR7
6	Standard		40.000	-60.000	
IMA	Standard		Infinity		

26. For two spherical mirrors, derive Cassegrain Telescope Design Equations via paraxial ray tracing equations.

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2} \quad \text{and} \quad d + b = \left(1 - \frac{d}{f_1}\right) f$$

27. Design a Cassegrain Telescope whose focal length is 1.2 m, aperture 0.2 m and distance between mirrors is 0.4 m. Determine radius of curvatures and conic constants for each mirror.

28. 5X Beam Expander, Galilean system.

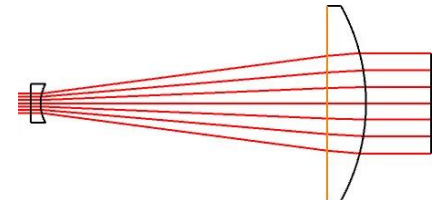
Select two lenses from Edmund Optics Stock.

#45-008: A 6mm diameter plano-concave lens with a -12mm focal length

#45-127: A 25mm diameter plano-convex lens with a 60mm focal length.

Optimize for 3 mm input beam and the output beam will be 15 mm.

Assumed the laser Helium Neon (HeNe) is used in the design.



29. Using stock lenses

(a) Design an Astronomical telescope whose total length is 60 cm and magnifying power M = 10x.

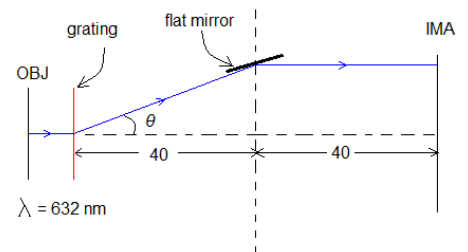
(b) Design a Galilean telescope whose total length is 60 cm and magnifying power M = 10x.

30. A mirror and a Grating

A monochromatic laser beam ($\lambda = 632.8 \text{ nm}$) is falling on a grating with 600 lines/mm. Diffracted first order beam ($m = 1$) falls on a plane mirror and it is reflected as shown.

(a) Find diffraction angle, θ .

(b) Using Zemax, design the optical system such that the reflected ray from mirror is parallel to the optical axis.

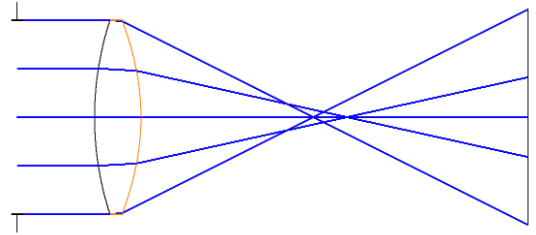


31. Eye Models in Zemax

- <https://support.zemax.com/hc/en-us/articles/1500005575002-How-to-model-the-human-eye-in-OpticStudio>
- <https://support.zemax.com/hc/en-us/articles/7772225130259-Realistic-modeling-of-relief-type-diffractive-intraocular-lenses-using-User-Defined-Surface-DLLs>

32. Singlets with best shape

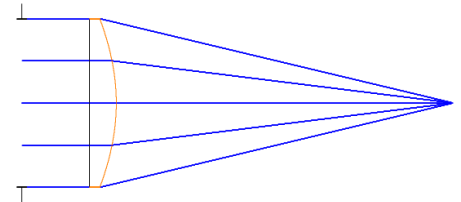
Consider a singlet.
 ENPD = 20 mm,
 EFFL = 80 mm (f/4)
 ct = 3 mm
 λ = d-line
 FOV = 0



For an object at infinity, find the radii of curvatures of singlet resulting in minimum spherical aberration for index of refraction $n = 1.5, 2.0, 3.0, 4.0$. For each of them, investigate aberration plots, Seidel diagrams, RMS spot radius, ray fan, etc.

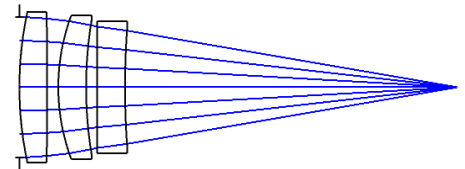
33. Aspherical singlet lens

Design a plano-convex aspheric lens whose focal length is 50 mm, index $n = 1.6$ and $f/\# = 2$.
 Optimize the lens such that it has minimum S.A.
 (a) Use only conic constant (Radius and Conic are variable)
 (b) Use only Even Asphere (Radius and A2 and A4 are variable)
 (c) Use both (Radius, Conic and A2 and A4 are variable)



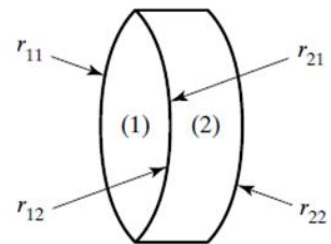
34. Triplet Design

Design a triplet lens system whose focal length is 75 mm (for d-line) and aperture 25 mm such that it has minimum spherical aberration. For all lenses, material is N-BK7, $ct = 5$ mm and distance (thickness) between any two of them is 2 mm.



35. Achromatic Doublet Design

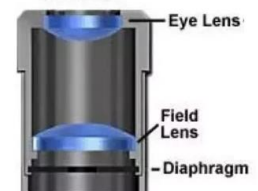
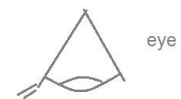
Consider two glasses which are cemented together to be used in designing an achromatic lens,
 EFFL = 125 mm (d-line)
 ENPD = 30 mm
 GLAS = SCHOTT
 WAVE = F, d, C visible
 SFOV = 1° .
 ct_1 and $ct_2 = 3-8$ mm



(a) Determine the radius of curvatures and optical materials via optimization tool of Zemax.
 (b) Repeat the same procedure for spaced doublet design (Let the distance between lenses be in the range $[0, 2]$ mm)

36. Ramsden Eyepiece

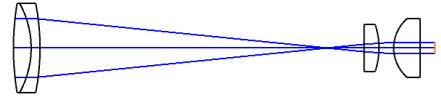
Design a Ramsden Eyepiece (a spaced doublet made from same glasses) whose specifications are as follows:
 EFFL = 25 mm (d-line)
 ENPD = 6 mm
 GLAS = SCHOTT
 WAVE = F, d, C
 SFOV = 10°
 ct_1 and $ct_2 = 3-8$ mm
 ER = 10 mm
 $60 < TOTR < 75$ mm



You may use the following Zemax operands in the optimization.
 EFFL, AXCL, LACL, TOTR, OPLT, OPGT

37. Keplerian Telescope

Combine two systems in exercise 35 and 36 to make a 5X Keplerian Telescope.



38. Eyepiece with eye

Using Zemax eye model and eyepiece in 36.

39. Consider an optical system used in the near infrared (NIR) range. Use two lenses made from same material.

- Material : F2
- Wavelength : 1064 nm
- We need to resolve : 0.1 NATO mil* in object space
- ct1 and ct2 : 3-8 mm
- Full FOV : 3.6°.
- Detector : CCD with 10 μm pixel size (pitch)
- TOTR : [100 mm, 200 mm]
- Max Distortion : 1 %

- (a) Determine focal length, f/#, clear aperture, depth of focus of the system and Nyquist frequency of sensor.
- (b) Using Zemax, determine radii of curvatures of lenses such that the system has the best performance.
- (c) For the optimized system, determine the values of max OPD and MTF at Nyquist frequency?

* 1 NATO mil (also known as artillery mil) is an angle defined by 1 / 6400 of a circle.
 1 circle = 2π rad = 360 deg = 6400 NATO mil = 400 grad
 Hence, 1 NATO mil ≈ 1 mrad ≈ 0.057 deg.
 In Turkish Army, we use the term Milyem instead of NATO mil.

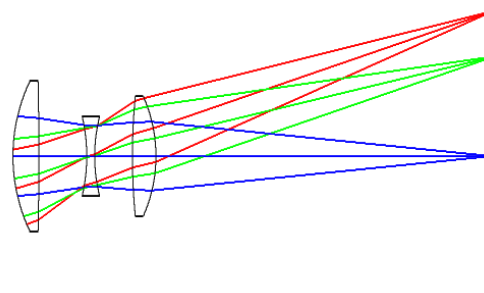
40. Achromatic Doublet Objective Design

Design the following achromatic doublet lens using BK7-SF2 glass pair:

- Entrance pupil diameter 50 mm
- Focal length 250 mm (d-line)
- f/# 5
- SFOV 2 deg
- Spectral range Visual (F, d, C)
- ct(BK7) 5-8 mm (variable)
- ct(SF2) 4-7 mm (variable)
- Object at infinity

- (a) Using thin lens equations given in the lecture determine the radius of curvatures of the lenses.
 - (b) Set all radii of curvatures, center thickness, and distance between last surface & image plane as variable. (totally 6 variables). Optimize the system to obtain minimum RMS spot size averaged over FOV. What are the optimum values of these 6 parameters?
 - (c) Determine the minimum pixel size of the sensor required.
- NOTE: You can use EFFL, AXCL and LACL operands in the merit function.

41. Investigate aberration and MTF plots of the objective named “Cooke 40 degree field.zmx” which can be found under c:\zemax\Samples\Sequential\Objectives.



42. The table shows index of refraction of common optical plastics (polymers). Use any of these two materials to design an achromatic lens whose entrance pupil diameter is 40 mm and focal length is +120 mm for Fraunhofer F,d,C lines and FOV $\pm 2^\circ$.

Wavelength (nm)	PMMA	Poly-styrene	Poly-carb.
365.0	1.5136	1.6431	1.6432
404.7	1.5066	1.6253	1.6224
435.8	1.5026	1.6154	1.6115
480.0	1.4983	1.6052	1.6007
486.1	1.4978	1.6041	1.5994
546.1	1.4938	1.5950	1.5901
587.6	1.4918	1.5905	1.5855
589.3	1.4917	1.5903	1.5853
643.9	1.4896	1.5858	1.5807
656.3	1.4892	1.5849	1.5799
706.5	1.4878	1.5820	1.5768
852.1	1.4850	1.5762	1.5710
1014.0	1.4831	1.5726	1.5672
Abbe number	57.4	30.9	29.9
Density (g/cc)	1.19	1.20	1.06

43. Apochromatic Lens Design

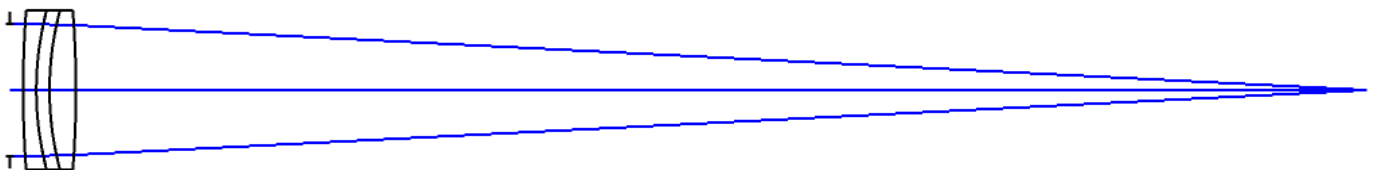
The goal of the apochromatic lens is to reduce the level of chromatic aberration using a triplet lens system.

Design a diffraction limited apochromatic lens to satisfy the following conditions:

All lenses must be cemented together and spherical.

See apochromatic designs under the Zemax Samples folder at C:\<Zemax>\Samples\Sequential\Objectives.

- WAVE : F, d, C (visible)
- FOV : 0°
- EFFL : 120+q mm (for d-line, q is the last digit of your student number)
- ENPD : 25 mm
- GLAS : CDGM catalog
- Object location : Infinity.
- Center thickness of lenses : [3 mm, 7 mm]
- Min. edge thickness of lenses : 2 mm
- Optimization criteria : RMS spot size averaged over FOV



44. Design a Cooke Triplet to perform the following specifications:

F/# : 4
EFL : 60 mm
FOV : 10°
Wavelength : F, d, C (visible).
Glasses : SHOTT
Glass thicknesses : 3-7 mm

After optimization, try to improve optical performance of the design via to Tessar and Heliar forms.

45. Design a Cooke Triplet to perform the following specifications:

F/# : 3.8
EFL : 70 mm
FOV : 15°
Wavelength : SWIR (0.9 μm - 1.7 μm).
Glasses : SCHOTT, CDGM
Glass thicknesses : 3-7 mm

After optimization, try to improve optical performance of the design via to Tessar and Heliar forms.

46. Design a Double Gauss Lens to perform the following specifications:

F/# : 3.3
EFL : 50 mm
EPD : 15 mm
FOV : 40° (Namely SFOV = 0,10,20 deg)
Wavelength : F, d, C (visible)
Glass Catalog : SCHOTT
Glass thicknesses : 3-7 mm

47. Design a Double Gauss Lens to perform the following specifications:

F/# : 3.3
EFL : 50 mm
EPD : 15 mm
FOV : 40° (Namely SFOV = 0,10,20 deg)
Wavelength : F, d, C (visible)
Glass Catalog : CDGM
Glass thicknesses : 3-7 mm

48. Design a Double Gauss Lens to perform the following specifications:

F/# : 3.3
EFL : 50 mm
EPD : 15 mm
FOV : 40° (Namely SFOV = 0,10,20 deg)
Wavelength : SWIR
Glass Catalog : CDGM
Glass thicknesses : 3-7 mm
Detector pixel size : 30 μm

49. Design the following LWIR objective using 1, 2 and 3 lenses. (You will have three different designs)

Spectral range	8-14 μm
Focal length	90 mm
f/#	2.5
SFOV	4°
Materials	Ge–ZnSe–Ge
Glass thicknesses	5-10 mm
Detector Pixel size	25 μm
Total Track Length	< 200 mm
Total Mass	< 200 g

For each of the design, perform optimization to obtain minimum spot radius averaged over FOV.
Compare the performance of designs.

50. Design the following MWIR objective using 1, 2 and 3 lenses. (You will have three different designs)

Spectral range	3-11 μm
Focal length	90 mm
f/#	2.5
SFOV	4°
Materials	Si–Ge–Si
Glass thicknesses	5-20 mm
Detector Pixel size	25 μm
Total Track Length	< 200 mm
Total Mass	< 200 g

For each of the design, perform optimization to obtain minimum spot radius averaged over FOV.
Compare the performance of designs:

51. Design the following SWIR objective using 1, 2 and 3 lenses. (You will have three different designs)

Spectral range	0.9-1.7 μm
Focal length	90 mm
f/#	2.5
SFOV	4°
Materials	SHOTT, CDGM, HOYA
Glass thickness	5-20 mm
Detector Pixel size	20 μm
Total Track Length	< 200 mm
Total Mass	< 200 g

For each of the design, perform optimization to obtain minimum spot radius averaged over FOV.
Compare the performance of designs:

52. Design a varifocal zoom system whose focal length is ranging from 100 mm to 225 mm using $f_1 = 100$ mm and $f_2 = -100$ lenses. Use stock optics.

53. design a zoom (variable) beam expander from $M = 2x$ to $M = 6x$ for ENPD is 8 mm. Use stock optics.

54. Design a Refracting Telescope (or Binocular) with the following specifications:

Magnification	: 4x
FOV	: 6°
Diopter	: ± 2
Maximum total length	: 130 mm
Maximum mechanical diameter	: 40 mm
Eye Relief	: 20 mm
Wavelength	: F, d, C visible

Hint: First start with paraxial lenses. Then, replace objective lens with an achromatic doublet and eye piece with Ramsden, Kelner or RKE. Finally, using LDE and MCE editors, optimize the system to reach the specifications.

55. Design a Hasting Triplet* to satisfy the following requirements:

EFL : 25 mm
WAVE : 400-700 nm
BFL : 20 mm
Diameter : 14 mm
Magnification** : 10x
Optical Aperture Dia. : > 90%
Total Thickness : 12.5 mm
Eye Pupil Diameter : 5 mm

* Hasting Triplet is a kind of magnifier lens consisting of three lenses which are cemented.

** Magnification of a magnifier with focal length f is calculated from $m = 1 + 250 \text{ mm} / f$ or $m = 250 \text{ mm} / f$.
For example, a focal length 50-mm lens will provide a magnification of $M = 250/50 = 5x$

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