OPTI 340, Spring 2009
Design Project 10

Due: May 4, 2009

<u>Design Project 10</u>: Diffractive Optical Elements – DOE's

In the late 1980's a novel type of optical element promised to revolutionize the optical world. Instead of using refraction and reflection for imaging, researches at MIT found that by using plotolithographic techniques to produced very fine diffractive structures, imaging could be achieved. In this Design Project you will be introduced to the tools available in CODE V to that describe Diffractive Optical Elements or DOE's. We will be using DOE's for chromatic aberration correction of a singlet.

- EFL: 80 mm
- F/number: f/4
- Wavelength: d, F, C
- FOV: ± 1˚ FOV (H = 0, 0.7, and 1.0)
- Center thickness: 5 mm
- Aperture stop on first lens surface

Part A: Refractive Lens

Define 80 mm focal length, f/4 plano-convex singlet using Schott N-BK7 glass with a center thickness of 5 mm. Use the visible d spectrum and cover a 1° semi-field of view. Document the optical performance of your singlet as you will be comparing its performance with subsequent designs.

Provide the following;
Layout
Lens prescription
Third-order analysis
Ray fan diagram
Spot diagram

What are the limiting aberrations of this lens? What would be your next step to improve the chromatic and aberration performance of this lens?

Hopefully your answer to the preceding question was to make the singlet a cemented achromat with a flint glass as we have done earlier this semester. Insert a 2mm thick Schott F2 negative lens in contact with the rear surface of your singlet and re-optimize for minimum RMS spot size.

Provide the following;
Layout
Lens prescription
Third-order analysis
Ray fan diagram
Spot diagram

What are the limiting aberrations of this lens?

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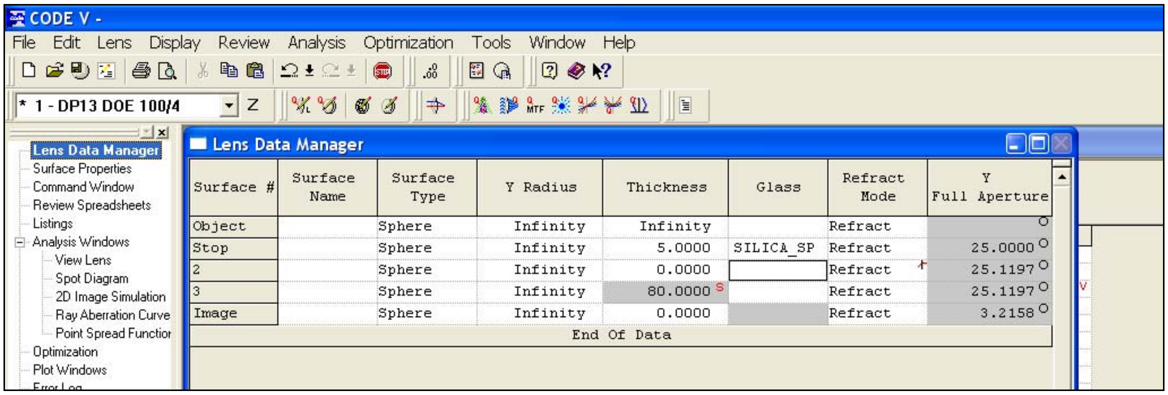
PART B: DOE LENS

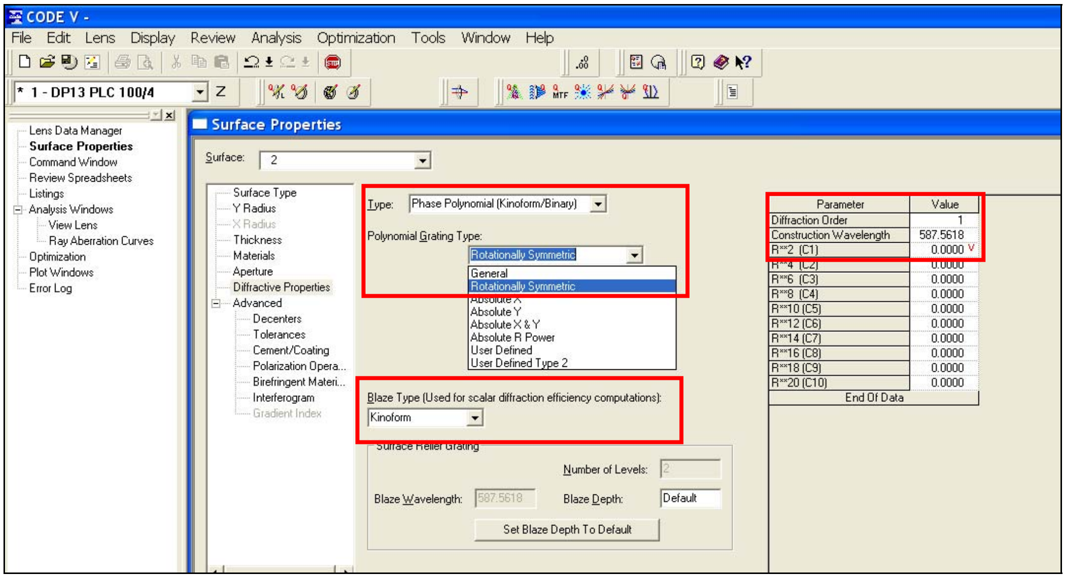
Defined a singlet lens as in Part A, but instead of using refraction to focus light, use a diffractive structure. Use a 5mm thick fused silica substrate and make both surfaces of the lens plano and define a diffractive surface on the rear surface of your lens:



Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Full Aperture
Object		Sphere	Infinity	Infinity		Refract	O
Stop		Sphere	Infinity	5.0000	SILICA_SP	Refract	25.0000 O
2		Sphere	Infinity	0.0000		Refract	25.1197 O
3		Sphere	Infinity	80.0000 S		Refract	25.1197 O
Image		Sphere	Infinity	0.0000		Refract	3.2158 O
End Of Data							

Plane parallel plate 5 mm thick

Several types of diffractive structures can be in CODE V, but for our purposes we'll restrict our example to exploring the ***Rotationally Symmetric* Phase Polynomial** (kinoform/binary). A kinoform is a diffractive structure that uses a 2π phase change to affect the optical wavefront as it interacts with the diffractive surface. Allow only the R^2 coefficient (C1) to vary during optimization and make the focal length of the DOE lens 80 mm. Set the Blaze Type to 'Kinoform' and use the default Blaze depth.



Surface: 2

Type: Phase Polynomial (Kinoform/Binary)

Polynomial Grating Type: Rotationally Symmetric

Blaze Type (Used for scalar diffraction efficiency computations): Kinoform

Number of Levels: 2

Blaze Wavelength: 587.5618

Blaze Depth: Default

Parameter	Value
Diffraction Order	1
Construction Wavelength	587.5618
R**2 (C1)	0.0000 V
R**4 (C2)	0.0000
R**6 (C3)	0.0000
R**8 (C4)	0.0000
R**10 (C5)	0.0000
R**12 (C6)	0.0000
R**14 (C7)	0.0000
R**16 (C8)	0.0000
R**18 (C9)	0.0000
R**20 (C10)	0.0000
End Of Data	

Surface Properties→Diffractive Properties

By designating a *Rotationally Symmetric* grating type the grating type we're restricting our design space to consider only phase polynomials that are symmetric about the optical axis. Also, by only varying the R^2 phase term, we be restricting the wavefront correction of the DOE to only affect optical power.

The right column of the Surface Properties box lists the coefficients that describe the phase polynomial. Use the first diffractive order for your DOE. This tells CODE V to generate a kinoform using the **m=1** diffraction order. The construction wavelength defines the wavelength used to define **ideal blaze depth** of the phase profile for this kinoform.

Now optimize your DOE to make the focal length 80 mm.

Provide the following;

- Layout
- Lens prescription
- Third-order analysis
- Ray fan diagram
- Spot diagram

Congratulations, you've designed a diffractive optical element. Now the question is can it be made and how good will it be?

a. What is the limiting aberration of the DOE?
b. Calculate the focal length of the DOE at C, d, and F and provide a table summarizing your calculations.
c. Calculate the difference in power between F and C.
d. Calculate the effective Abbe number of the DOE used in this spectral band.
e. Calculate the effective Partial Dispersion of the DOE used in this spectral band.
f. Determine the maximum spatial frequency of the DOE
g. Determine the diffraction efficiency of the DOE at F, C, and d wavelengths
h. Compare the optical performance of the DOE to the conventional plano-convex singlet. Which lens has better optical performance?
i. What type of application do you think is appropriate for a DOE? Comment on spectral band width, f/number, FOV, etc.
j. Show via a lens layout where light from the following orders fall:
    1. m = 0
    2. m = -1
    3. m = +2

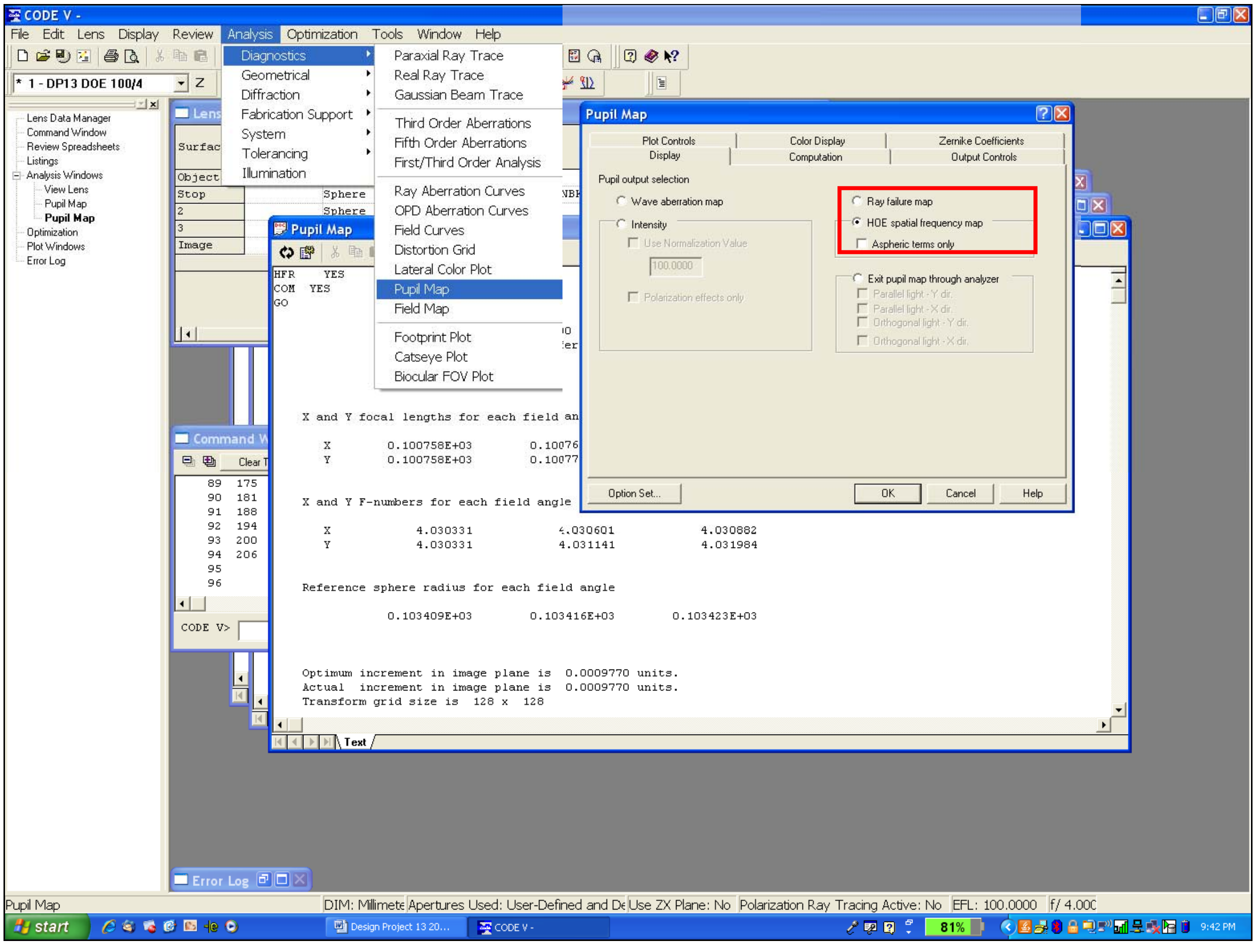
The maximum spatial frequency of the DOE often determines if a diffractive pattern can be etched into a substrate. Higher spatial frequency patterns are more difficult and expensive to fabricate and require exotic technologies to produce. Currently electron beam direct write pattern generators can write 5 micron patterns or 200 l/mm patterns. E-beam DW pattern generators are expensive and slow and thus expensive to use. Laser beam direct write pattern generators are faster and less expensive to operate and can write up to 10 micron patterns or 100 l/mm patterns. Lower frequency patterns, > 10 l/mm can sometimes be directly diamond turned onto a substrate or replicated from a diamond turned master.

The maximum spatial frequency of the DOE can be determined using the Pupil Map Analysis. In Command mode:

```
CODE V> PMA;HFR Y;COM Y;GO
```

Pupil map analysis; plot holographic spatial frequencies; compact output;go

From the GUI:



Pupil output selection
○ Wave aberration map
○ Intensity
☐ Use Normalization Value 100.0000
☐ Polarization effects only
○ Ray failure map
● HOE spatial frequency map
☐ Aspheric terms only
○ Exit pupil map through analyzer
☐ Parallel light - Y dir.
☐ Parallel light - X dir.
☐ Orthogonal light - Y dir.
☐ Orthogonal light - X dir.

```
HFR    YES
COM  YES
GO

   X and Y focal lengths for each field an

      X        0.100758E+03        0.10076
      Y        0.100758E+03        0.10077

   X and Y F-numbers for each field angle

      X           4.030331            4.030601            4.030882
      Y           4.030331            4.031141            4.031984

   Reference sphere radius for each field angle

               0.103409E+03        0.103416E+03        0.103423E+03

   Optimum increment in image plane is  0.0009770 units.
   Actual  increment in image plane is  0.0009770 units.
   Transform grid size is  128 x  128
```

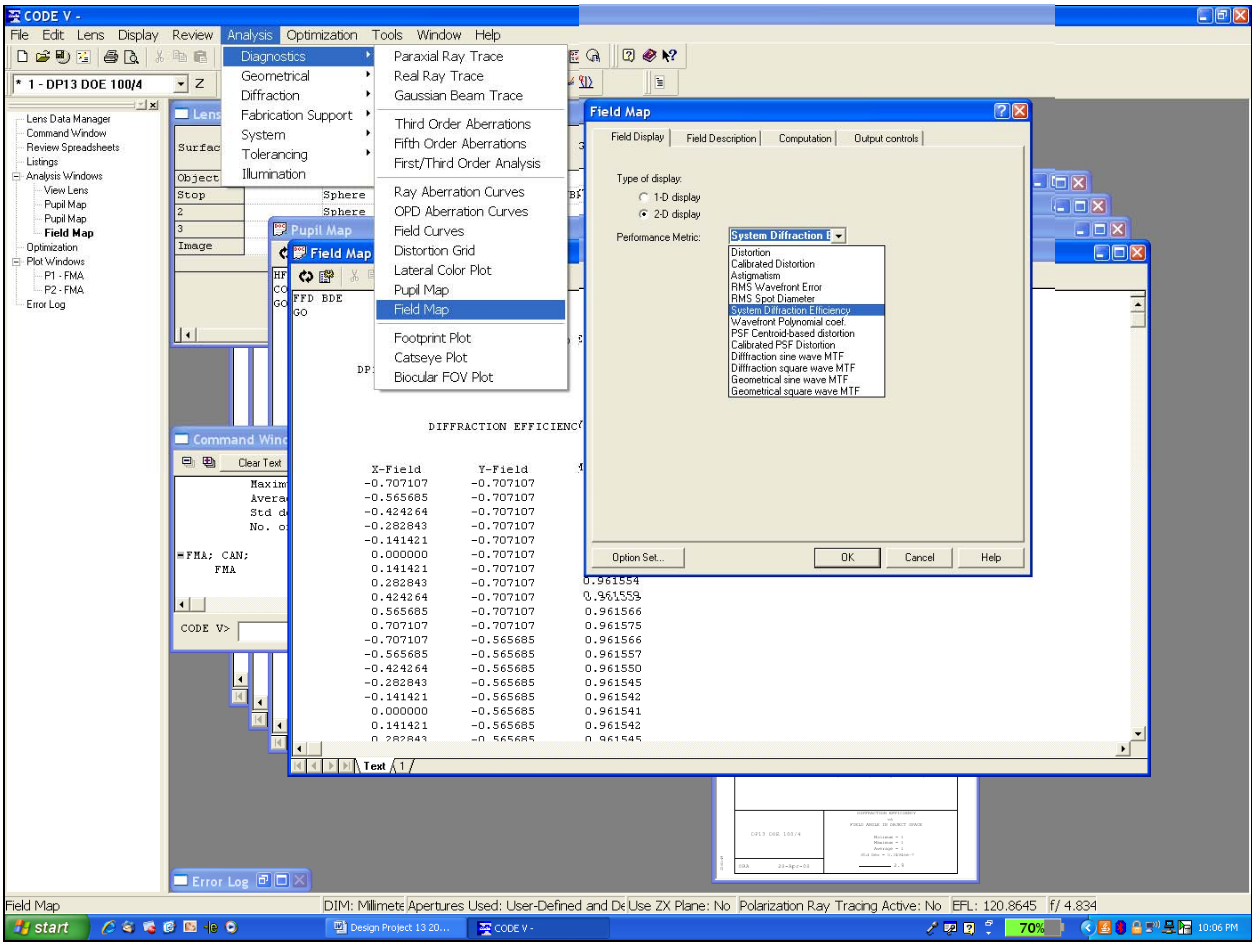
The output will list the spatial frequency of the DOE as a function of spatial position in the pupil at each wavelength and field position. To determine where the pupil falls on the diffractive surface, use FOOtprint analysis.

Alternatively, the spatial frequency at a specific location can be determined through the **HFR** (holographic frequency) command:

HFR Ri Sk Fm Zn , where Ri, Reference ray number
Sk, Surface number of DOE
Fm, Field number
Zn, Zoom position

In our DOE, R^2 is the upper marginal ray (top of pupil) and F3 is the upper field. Use the **HFR** command to determine the spatial frequency at the top edge of the DOE. (**Note:** Negative values of frequency may occur as a numeric artifact of providing continuous derivatives. The physical grating frequency is always the absolute value.

The diffraction efficiency will vary with wavelength and can be determined using the **Field Map** Analysis option in CODE V. The **FMA** option will calculate the **System Diffraction Efficiency** at the *reference* wavelength:



Type of display:
○ 1-D display
● 2-D display

Performance Metric: System Diffraction E

```
Surfac
Object
Stop                 Sphere
2                    Sphere
3
Image
```

```
Maxim
Avera
Std d
No. o

FMA; CAN;
    FMA

CODE V>
```

```
FFD BDE
GO

DP

                    DIFFRACTION EFFICIENC

     X-Field      Y-Field
    -0.707107    -0.707107
    -0.565685    -0.707107
    -0.424264    -0.707107
    -0.282843    -0.707107
    -0.141421    -0.707107
     0.000000    -0.707107
     0.141421    -0.707107
     0.282843    -0.707107    0.961554
     0.424264    -0.707107    0.961559
     0.565685    -0.707107    0.961566
     0.707107    -0.707107    0.961575
    -0.707107    -0.565685    0.961566
    -0.565685    -0.565685    0.961557
    -0.424264    -0.565685    0.961550
    -0.282843    -0.565685    0.961545
    -0.141421    -0.565685    0.961542
     0.000000    -0.565685    0.961541
     0.141421    -0.565685    0.961542
     0.282843    -0.565685    0.961545
```

DIM: Millimete Apertures Used: User-Defined and De Use ZX Plane: No Polarization Ray Tracing Active: No EFL: 120.8645 f/ 4.834

Change the reference wavelength to calculate the diffraction efficiency at each wavelength. For example to calculate diffraction efficiency at C (W1 = 656nm), change the reference wavelength to 1 (CODE V>REF 1).

PART C: Hybrid Refractive-Diffractive Achromat

Restore the plano-convex singlet from PART A and define a DOE on the plano surface as in Part B. Again restrict the diffractive structure to a Rotationally Symmetric Phase Profile but now vary the C1 (R^2) and C2 (R^4) coefficients. Optimize the achromat to meet the design specifications.

Provide the following:

- Layout
- Lens prescription
- Third-order analysis
- Ray fan diagram
- Spot diagram

a. What is the limiting aberration of the hybrid achromat?
b. What aberration does the C1 coefficient play in optical correction?
c. What aberration does the C2 coefficient play in optical correction?
d. Calculate the focal length of the DOE at C, d, and F and provide a table summarizing your calculations.
e. Determine the maximum spatial frequency of the DOE
f. Determine the diffraction efficiency of the DOE at F, C, and d wavelengths
g. Compare the optical performance of the hybrid achromat to the conventional achromat. Which lens has better optical performance?
h. What are the benefits of using a hybrid lens verses a conventional achromat?

The tools introduced in this Design Project outline the basic analyses required to evaluate the productibility and operation of a diffractive surface. However, more extensive and detailed analyses are often required to determine if a diffractive solution is appropriate for a given application. For example, surface scatter introduced by the diffractive surface can add unwanted background noise to the image plane. Similarly, higher order diffraction and diffraction efficiency variation with actual blaze depth will introduce unwanted background noise into the image plane; effects such as these must be evaluated to determine if their effects will compromise the performance expectations of the optical system.