

15c Fourier Optics Lab

(Exercises to be Submitted are listed at the End)

1. Review of geometric optics

- a. Missions:
 - i. Image the ceiling fluorescent lights onto the floor using a lens
 - ii. You have a flashlight with the image of an arrow located at the front of the flashlight. Turn the flashlight on and image the arrow using only an aperture.
 - iii. Draw ray optics explanations of what you did in the 2 exercises
- b. Possible resources **NOT** required
 - i. http://phet.colorado.edu/sims/geometric-optics/geometric-optics_en.html
 - ii. <http://spie.org/Documents/Publications/00%20STEP%20Module%2003.pdf>
 - iii. <http://astrowww.phys.uvic.ca/~tatum/goptics/geomop2.pdf>

2. Wave Optics Introduction

- a. Missions
 - i. Draw the wave fronts and k vectors corresponding to a plane wave propagating along the z direction
 - ii. Draw the wave fronts and k vectors corresponding to a diverging spherical wave
 - iii. Draw the wave fronts and k vectors corresponding to a converging spherical wave
 - iv. Write the mathematical expression for all of the waves above given that they propagate with velocity c , so the period $T=\lambda/c$, since the wave travels one wavelength during one period. By definition $T=2\pi/\omega$ and $k=2\pi/\lambda$
 - v. **Huygen's wavelet theory states that the forward propagation of a wave can be replicated by point sources if the point sources are placed along the positions occupied by a wavefront from the original wave (surface of constant phase)**
 - vi. Go to <http://www.falstad.com/ripple/> and use it to do the following
 1. Create a propagating spherical wave from a point source
 - a. Explain how the image relates to the wave fronts and k vectors in ii
 2. Combine 2 point source of the same frequency, change the separation between the sources and explain what you are seeing
 3. Combine many sources to create a plane wave
 4. Combine many sources to create a converging spherical wave
 5. Create a source that mimics a single very narrow slit and explain results
 6. Create a source that mimics a single wide slit, or explain which previous exercise already achieved this mission.

7. Create a source that mimics two narrow slits and explain results or explain which previous exercise already achieved this mission.

b. Possible resources **NOT** required

- i. http://en.wikipedia.org/wiki/Huygens%E2%80%93Fresnel_principle
- ii. <http://farside.ph.utexas.edu/teaching/3021/lectures/node150.html>
- iii. <https://www.boundless.com/physics/wave-optics/diffraction/huygens-principle/>
- iv. Very math intense
<http://mathpages.com/home/kmath242/kmath242.htm>

3. Lenses and focusing

a. Missions

- i. Given a spherical diverging point source at $z = -R$, calculate the phase shift as a function of (x, y) in the $z = 0$ plane that would convert the diverging spherical wave into a plane wave propagating along the z direction

b. Possible resources NOT required

- i. <http://www.owl.net/~dodds/Files332/fourier.pdf>
- ii. http://en.wikipedia.org/wiki/Fourier_optics
- iii. <http://www.optics.unm.edu/sbahae/Optics%20Lab/Fourier%20Optics.pdf>

4. Real diffraction patterns

a. Missions

- i. Send a laser pointer through a diffraction grating slide and a cloth “diffraction gratings” etc, if you wish. Explain what you see

5. Fourier Transform Optics of Slits

- a. **Note a light source at position $z = 0$ that passes through a lens at $z = f$ ($f = \text{focal length}$) will produce an image that is the Fourier transform of the object at position $z = 2f$. Adding another identical lens at $z = 3f$ will reproduce both the phase and the amplitude of the original source at position $z = 4f$. Ask instructor for a detailed derivation if you are interested.**

b. Review Fourier series if needed:

<http://mathworld.wolfram.com/FourierSeries.html>

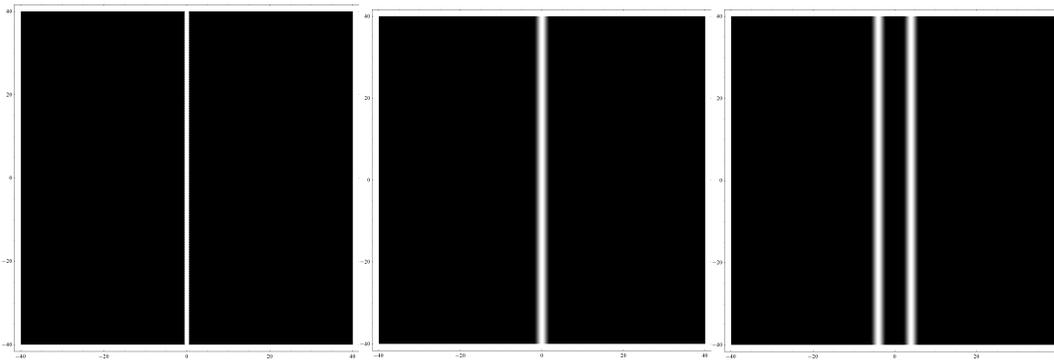
c. Review Fourier transforms if needed:

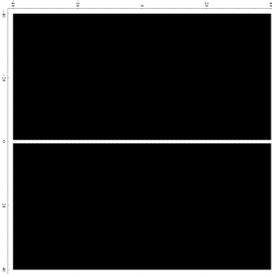
http://en.wikipedia.org/wiki/Fourier_transform

d. 15b flashback

- i. Low pass filter on a square wave gave a sine wave
- ii. High pass filter highlights edges, corresponding to the derivative
- iii. Marilyn Monroe and Albert Einstein
- iv. Go to <http://www.falstad.com/fourier/> look at square wave with 1 odd order, 2 odd orders, 3 odd orders. Go to all orders

- e. **Mission Overview** using the 4F setup to look at the x and y components of the k vectors that are generated by diffraction by $g(x,y)$, the amplitude variation created by the LCD make. Explore how filtering the x and y components changes the image by blocking part of the light in the Fourier transform plane. If you close down the aperture, you block k vectors with large components in the x and y direction. If you use the needle, you block the small k vectors with small components in the x and y directions. The original plane wave only has a k vector in the z direction, so it will appear as a single spot at the origin since it corresponds to $k_x=k_y=0$.
- f. **Missions**
1. Look at diffraction due to a single vertical slit with square edges. Note: you can use the zoom control on the image to continuously tune the effective size of the slit
 - a. Close the aperture in the Fourier transform plane and look at the image of the grating. How does it change. Explain
 - b. Open the aperture, but place the needles so that it blocks the central spot in the Fourier transform plane and look at the image of the grating. How does it change. Explain
 - c. Optional: look at the diffraction due to a single horizontal slit with square edges
 2. Look at diffraction due to a single slit with smooth edges
 - a. Close the aperture in the Fourier transform plane and look at the image of the grating. How does it change. Explain
 - b. Open the aperture, but place the needles so that it blocks the central spot in the Fourier transform plane and look at the image of the grating. How does it change. Explain
 3. Double slit with smooth edges. How does this result compare with what you got in part 7 of the previous section where you used the applet to create two slit interference?





g. Possible resources **NOT** required

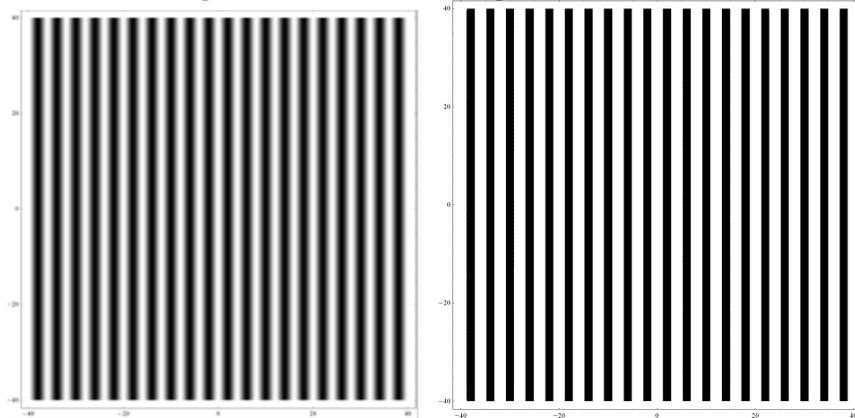
- i. <http://scienceworld.wolfram.com/physics/FraunhoferDiffraction.html>
- ii. http://en.wikipedia.org/wiki/Fraunhofer_diffraction
- iii. http://en.wikipedia.org/wiki/Kirchhoff's_diffraction_formula
- iv. <http://optics.hanyang.ac.kr/~shsong/13-Fresnel%20diffraction.pdf>
- v. <http://www2.ph.ed.ac.uk/~wjh/teaching/mo/slides/scalar/scalar.pdf>
- vi. <http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/fraunhofcon.html>
- vii. <http://lpc1.clpccd.cc.ca.us/lpc/molander/pdfs/diffraction.pdf>
- viii.

6. Fourier transform optics beyond slits. The first 3 missions are mandatory

a. Missions

i. Periodic Gratings

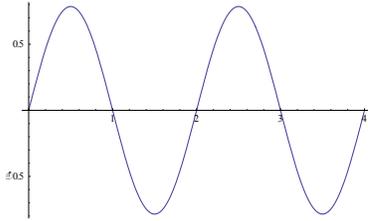
1. Below are diffraction gratings with smooth edges and square edges. Note you can change the effective period by zooming in and out on the image



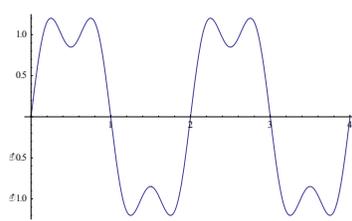
Note a square wave can be Fourier decomposed into sine waves
<http://mathworld.wolfram.com/FourierSeriesSquareWave.html>

$$f(x) = \frac{4}{\pi} \sum_{n=1,3,5,\dots}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi x}{L}\right).$$

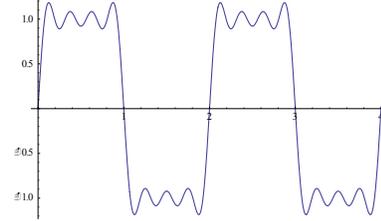
First order only



Two orders only



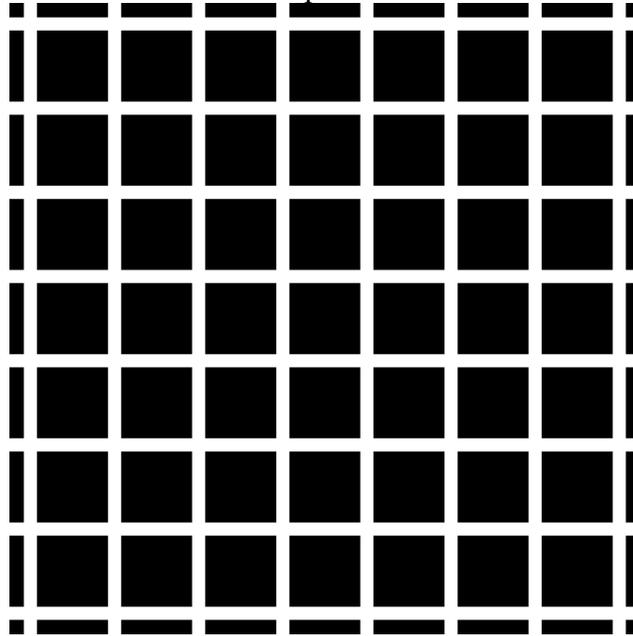
Three orders only



2. Use the needle or the aperture to double the period of the square wave diffraction grating. Explain
3. Convert a square wave to a sine wave without changing the grating by using the needle or the aperture. Explain

ii. A grating of squares

Look at the diffraction pattern due to



http://www.michaelbach.de/ot/lum_herGrid/hermannGrid.gif

1. Now use two pieces of tape to create a slit in the Fourier plane, allowing only one direction of the diffraction pattern to pass. Predict the image you see and test your prediction
- iii. **Introduction to holograms:** Calculate the optical transmission mask required to convert an plane wave into a spherical wave. Which ones matches your calculation?

Look at the diffraction pattern due to the images below. Move the images around on the screen and look at the resulting motion of the diffraction pattern. Explain differences in the results for the 4 images

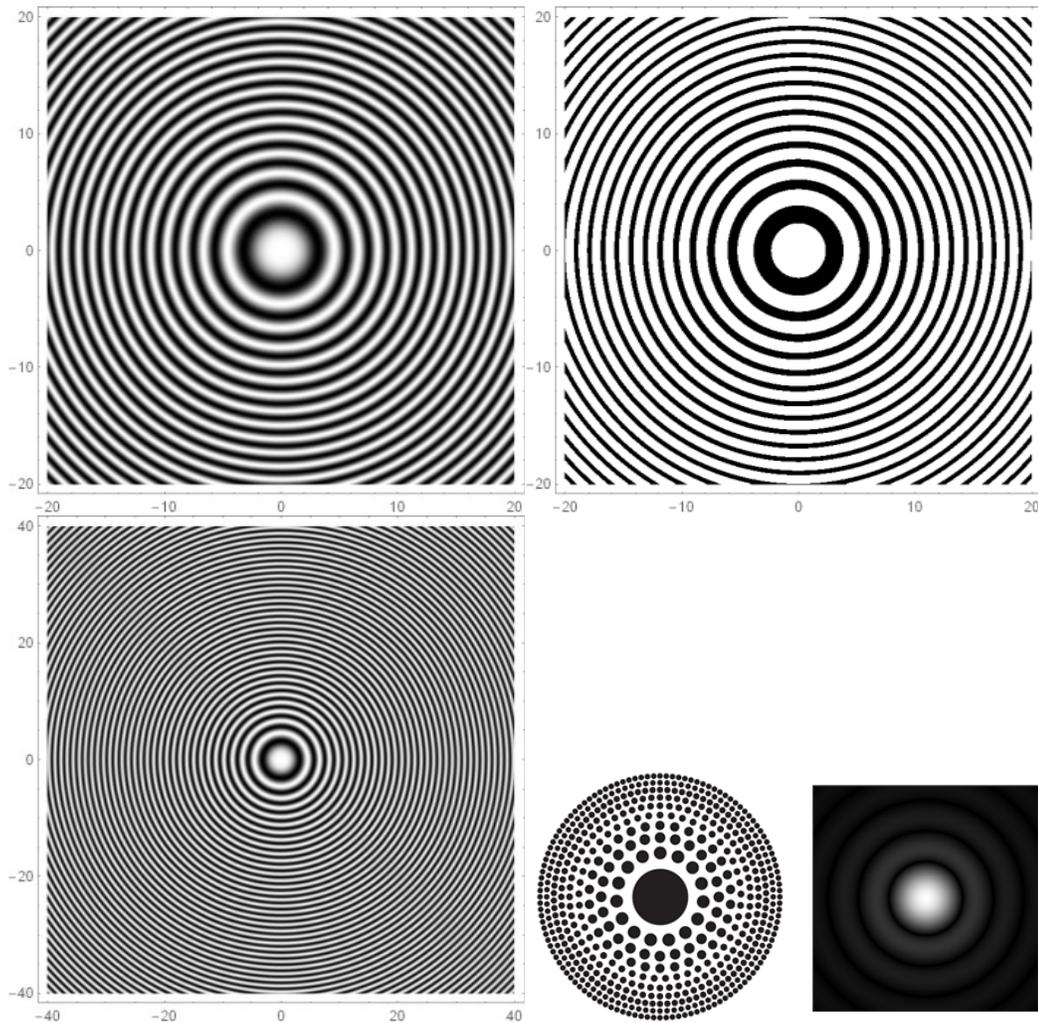
https://upload.wikimedia.org/wikipedia/commons/thumb/9/97/Zone_plate.svg/2000px-Zone_plate.svg.png

https://upload.wikimedia.org/wikipedia/commons/6/66/Zonenplatte_Cosinus.png

<http://www.nature.com/nature/journal/v414/n6860/abs/414184a0.html>

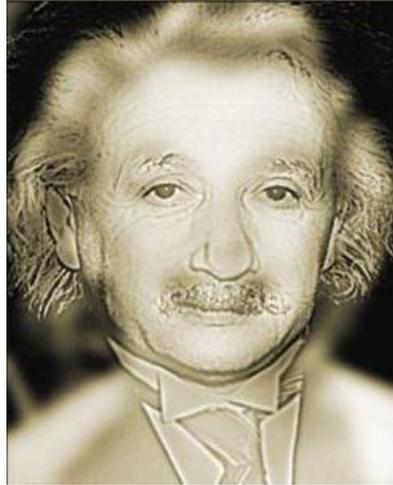
<http://pinhole.stanford.edu/zoneplatemath.htm>

<https://upload.wikimedia.org/wikipedia/commons/thumb/1/14/Airy-pattern.svg/2000px-Airy-pattern.svg.png>



iv. Optional possibilities

- v. Make a diffraction pattern with $\text{Exp}[-\alpha x^2]$ and explain the diffraction pattern for various α
- vi. Look at the diffraction pattern for a point source
- vii. Convert Marilyn Monroe into Albert Einstein
<http://www.123opticalillusions.com/pages/albert-einstein-marilyn-monroe.php>



- viii.
- ix. Try anything you want (try highpassing the Boston skyline)



Appendix on Controlling the LCD Display and Data Analysis Software

LCD Control

The liquid crystal display should automatically match the computer display pixel-by-pixel.

Matlab program to create bars is 'image_bars01.m'.

N=number of bars

W=width in pixels

Spacing = period in pixels.

Run program.

View file '15c.jpg'. One way to do this is to control-click in the matlab file list, and choose "open outside of matlab". It will open in Preview.

Data Analysis Control

Matlab program to integrate camera output is 'photobooth_vert_integrate.m'. Take a picture in Photobooth, run the Matlab program, and click the button on the GUI to load the most recent. It is possible to choose a limited vertical region for the integration by entering a pixel range into the GUI. Note that larger numbers correspond to lower position in the image.

Exercises to be Submitted

1. Draw ray optics explanations of imaging due to a lens and imaging due to a pinhole camera. what you did in the 2 exercises
2. Draw the wave fronts and k vectors corresponding to a plane wave propagating along the z direction
3. Draw the wave fronts and k vectors corresponding to a diverging spherical wave
4. Draw the wave fronts and k vectors corresponding to a converging spherical wave
5. Write the mathematical expression for all of the waves above given that they propagate with velocity c.
6. Given a spherical diverging point source at $z = -R$, calculate the phase shift as a function of (x,y) in the $z=0$ plane that would convert the diverging spherical wave into a plane wave propagating along the z direction
7. For the exercise where you looked at diffraction due to a single vertical slit with square edges explain the changes you observed in the image of the slit when you closed the aperture and when you inserted the needle to block the central spot in the fourier transform plane. Compare the diffraction pattern for the square slit with the diffraction pattern for the smooth slit and explain any differences
8. How does this diffraction pattern for the double slit compare with what you got in part 7 of the previous section where you used the applet to create two slit interference?
9. For the square wave diffraction grating how did you double the period you saw in the $4f$ plane and how did you produce a sine wave grating in the $4f$ plane?
- 10.
11. When you looked at the diffraction pattern due to the squares, what happened when you used tape to create a slit in the Fourier transform plane? Explain your results.
12. Provide an equation for the optical transmission mask required to convert an plane wave into a spherical wave. **Note you have created a simple hologram. Next week's lab will look at more complex homolograms.**