University of Rochester

Laboratory XIII
Wave Properties of the Electromagnetic Spectrum

DEPARTMENT OF PHYSICS & ASTRONOMY

PHYSICS 123 - 183
WAVES AND MODERN PHYSICS

Name: ______________________________ **Date:** ______________________

Collaborators: ____________________________ **Lab Section:** ____________

PRELAB EXERCISES (2 points)

This prelab must be completed and handed in to the lab TA at the start of the lab.

Question 1 **1 point**

Using the equation $\lambda = d \sin\theta$, derive an expression for $(\Delta\lambda/\lambda)^2$ using the method of error propagation described in *Appendix B: Error Analysis* on the Physics Labs website.

Question 2 **1 point**

How can you determine the slit separation by observing the interference pattern in this experiment? Explain your reasoning.

Objective

Observe double-slit and single-slit interference and diffraction patterns using both a helium-neon laser and a microwave source. Measure the fringe spacings to calculate the wavelengths of each source and confirm that wave optics applies across a wide range of the electromagnetic spectrum.

Theory

Since the 17th Century, the prevailing view of the nature of light has changed several times. Isaac Newton described light as a stream of particles (or "corpuscles"), partly because of its property of straight-line travel. Contemporaries of Newton, such as Christiaan Huygens, argued that light could be explained geometrically as a wave-like phenomenon. In the 19th century, the experimental work of Thomas Young led to the broad acceptance that light consists of waves. And in the 20th century, it was shown that light, or more generally any part of the electromagnetic spectrum, behaves with both particle-like and wave-like properties.

One method of observing the wavelike nature of light is through the interference and diffraction of electromagnetic radiation, as these are fundamentally wavelike behaviors. You will observe interference in laser light and microwaves using a double-slit experiment, and measure diffraction from a single slit.

Double-Slit Interference

If light is incident on a screen with two narrow slits separated by a distance d, the slits act as point sources of electromagnetic waves. When the light from the slits is projected onto a screen at a distance $L \gg d$, the light from the slits constructively and destructively interferes at the screen, producing a "fringe" pattern of light and dark spots.

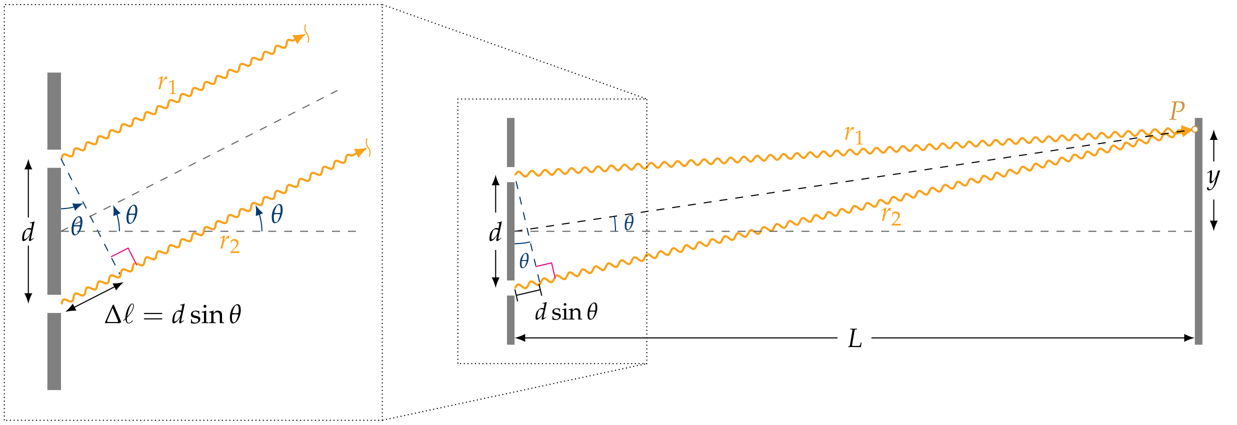

Figure 1: *Plane electromagnetic waves incident on two slits of width a and separation d produce an interference pattern on a screen located a distance L from the slits. The inset (left) shows that when $L \gg d$, the rays from the two slits can be treated as parallel.*

Figure 1 shows a ray diagram of two-slit interference for a monochromatic light source. Light from slit 1 travels a distance r_1 to the screen, while light from slit 2 travels a distance r_2. The interference conditions at the screen are related to the difference in path lengths $\Delta\ell = r_2 - r_1 = d\sin\theta$:

$$d\sin\theta = m\lambda, \qquad \text{constructive interference,} \tag{1}$$

$$d\sin\theta = \left(m + \frac{1}{2}\right)\lambda, \qquad \text{destructive interference,} \tag{2}$$

where $m = 0, \pm1, \pm2, \ldots$ Consider interference at a point P on the screen, at vertical distance y from the midpoint of the two slits. In the limit where $L \gg d$,

$$\sin\theta \approx \tan\theta = \frac{y}{L}. \tag{3}$$

Combining eqs. (1) and (3) gives the vertical position of any interference maximum on the screen:

$$\boxed{y_{\text{max}} = m\frac{\lambda L}{d}} \tag{4}$$

$$\text{where } m = 0, \pm 1, \pm 2, \ldots$$

The intensity pattern on the screen, described by

$$I(\theta) = I_{\text{max}} \cos^2\left(\frac{\pi}{\lambda} d \sin\theta\right), \tag{5}$$

is shown in Fig. 2. In actuality, eq. (5) does not fully describe the fringe pattern, which (as you will observe) includes the effect of single-slit diffraction.

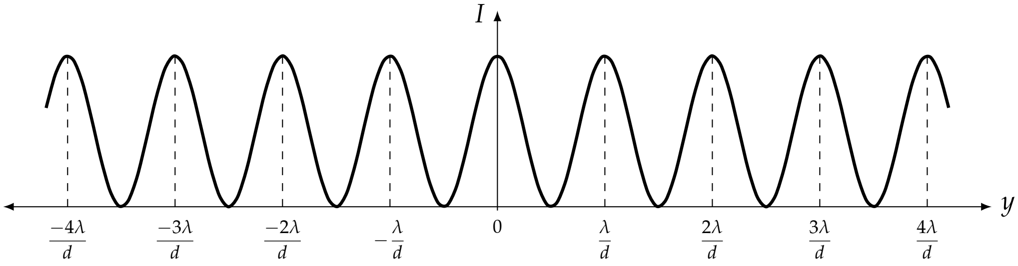

Figure 2: *The two-slit fringe pattern on a screen at a distance L from two slits separated by distance d, from eq. (5).*

Single-Slit Diffraction

The wavelike nature of light also causes it to deviate from straight-line motion when it passes around or through an obstacle, such as the single slit of width a shown in Fig. 3. The bending and spreading of the waves at the single slit is called diffraction, which produces a characteristic interference pattern distinct from the two-slit fringes discussed above.

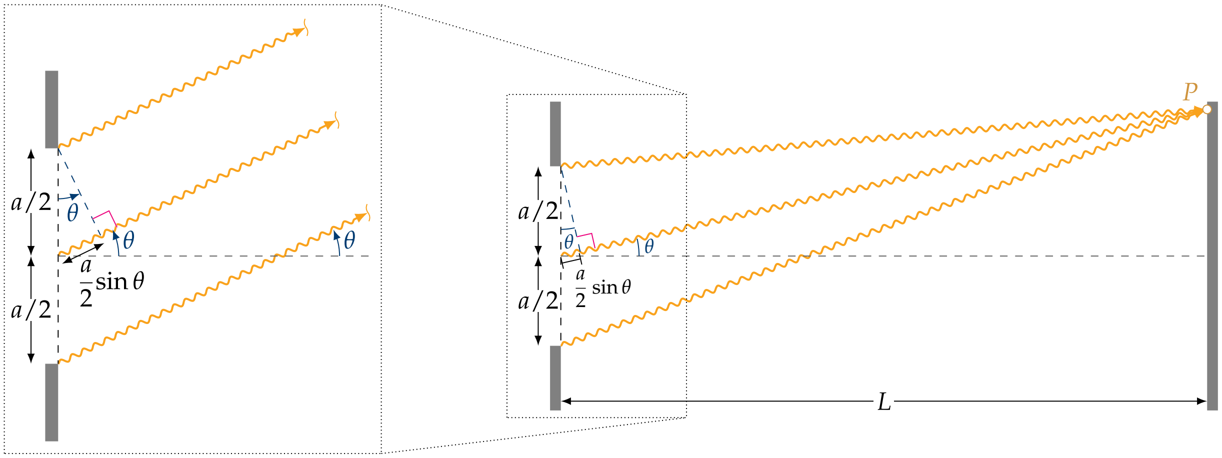

Figure 3: *Plane electromagnetic waves incident on a single slit of width a located a distance L from a screen. The inset shows that when $L \gg a$, the rays from every point inside the slit can be treated as parallel.*

The ray diagram of single-slit diffraction in Fig. 3 allows us to geometrically derive the diffraction pattern, using an argument first developed by Huygens and refined by French physicist Augustin-Jean Fresnel in the 19th Century. By treating each spatial point in the plane of the slit as a point source of spherical waves, we can construct the condition for interference at the screen. Here we consider the location of the intensity *minima* in the diffraction pattern, which obey the condition

$$a \sin\theta = m\lambda, \qquad m = \pm 1, \pm 2, \ldots \qquad \text{(destructive interference)}. \tag{6}$$

By considering the interference of $n \to \infty$ point sources of spherical waves in the plane of the slit[1], the intensity on the screen as a function of angle can be derived:

$$I(\theta) = I(0)\left(\frac{\sin\beta}{\beta}\right)^2, \qquad \beta = \frac{\pi a}{\lambda}\sin\theta, \tag{7}$$

where the intensity minima occur at $\beta = m\pi$, with $m = \pm 1, \pm 2, \ldots$ The single-slit diffraction pattern is shown in Fig. 4.

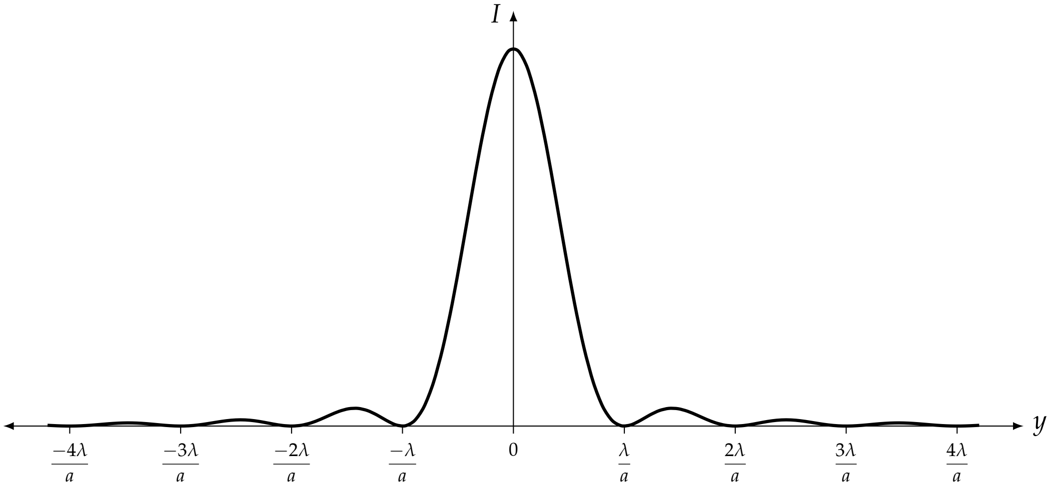

Figure 4: *The diffraction pattern from a single slit of width a.*

The actual interference pattern from the double slit will be a combination of the fringe pattern and the diffraction from each slit. The combined pattern is described by eq. (8) and plotted in Fig. 5.

$$I(\theta) = I(0)\left(\frac{\sin\beta}{\beta}\right)^2 \cos^2(\delta), \qquad \beta = \frac{\pi a}{\lambda}\sin\theta, \qquad \delta = \frac{\pi d}{\lambda}\sin\theta. \tag{8}$$

Experiment

For the optical measurements in this lab, you will be using a 632.8 nm He-Ne laser. You will mount the slit(s) and the screen on an optical bench to obtain a precise spacing L. The setup is shown in Fig. 6.

CAUTION: Never look directly into the laser beam or allow it to fall on your eyes. Direct exposure to the beam can cause permanent eye damage. When the laser is turned on, but you are not using it for a measurement, keep the aperture covered with a sheet of paper.

Double Slit Interference

1. Using a microscope, carefully determine the separation of the two slits, d, on the slide. Determine the uncertainty in the measured separation. If necessary, convert your result to centimeters and record

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[1] A detailed treatment can be found in E. Hecht, *Optics* (Pearson: 2015), Ch. 10.

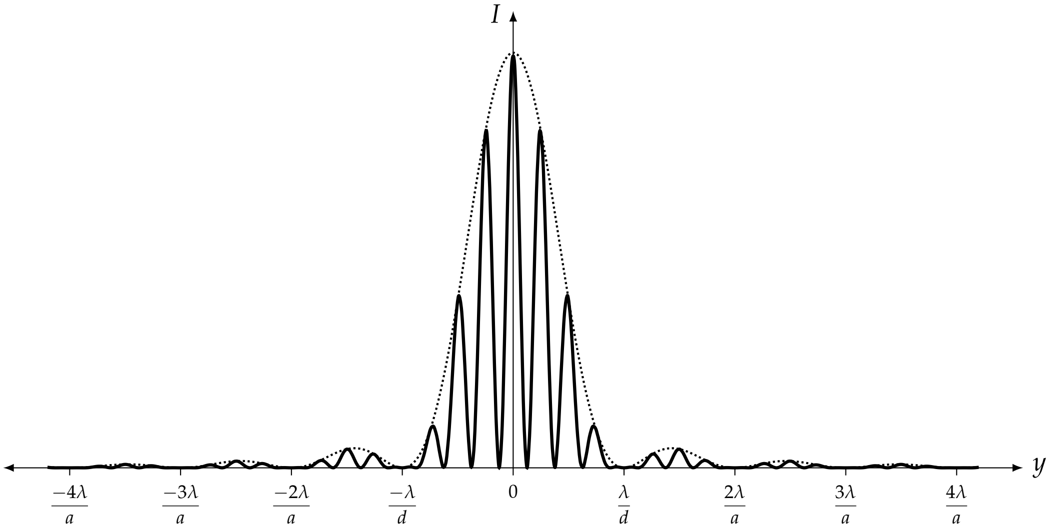

Figure 5: *The observed intensity pattern in a two-slit experiment with slit width a and slit spacing $d = 4a$.*

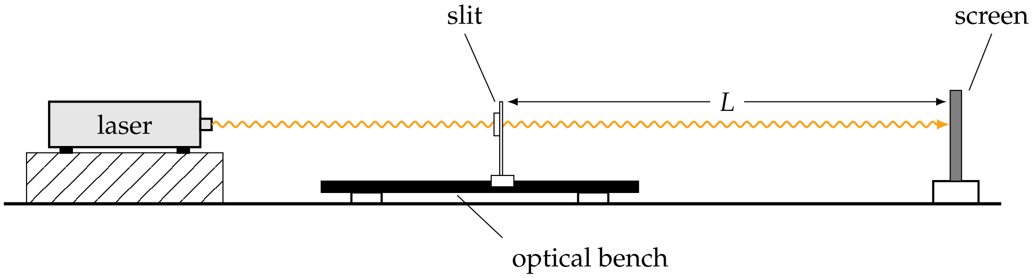

Figure 6: *The optical bench setup for interference and diffraction measurements.*

your result in Data Table 1 in the Postlab exercises. Turn the screw in only one direction to avoid mechanical "backlash" errors. Your lab assistant will help you. (This measurement does not need to be made first; since there is only one microscope, you may want to wait a while to avoid the queue.)

2. Set up the apparatus as shown in Fig. 6. Install the slide in the holder and place it in front of the laser. Aim the laser at the double slit portion of your slide (note the number of slits indicated on the grating) and send the back-reflection from the grating back into the laser cavity. This helps to ensure that the d you measured for the slit separation is the d used in the experiment.

3. Place the screen at the other end of the table from the laser, maximizing L. When the laser is turned on, a series of faint parallel vertical fringes will be seen on the screen. The spacing of the fringe maxima, y, depends on the screen-slit length L and the wavelength λ; see eq. (4).

4. Sketch the fringes in Graph 1 in the Postlab exercises. Use shaded bars or lines to indicate the bright fringes. The brightest fringe (or maximum) on the screen is called the zero-order fringe, F_0 (see also Fig. 5). F_0 is where the path length from the two slits is equal ($\Delta\ell = 0$). The two adjacent bright fringes on each side are the first-order maxima, with a path length difference of one wavelength ($\Delta\ell = \lambda$). The next fringes are the second-order maxima, with a path length difference of two wavelengths ($\Delta\ell = 2\lambda$), and so on for higher orders.

5. Measure the separation y on the screen between neighboring fringes. Be sure to measure the center-to-center distance rather than the edge-to-edge distance. While you could measure two adjacent fringes, a more accurate method is to measure the separation spanning six to eight fringes and divide by the number of fringe spacings, yielding the average separation between two adjacent fringes. Because the

fringes are not sharp lines, you may want to make several measurements. Record your measurements in Data Table 1 in the Postlab exercises.

6. Measure the distance L from the slits to the screen. Use L, d, and y in eq. (4) to calculate the wavelength of the laser light, λ. Compare your experimental value to the known 632.8 nm wavelength of the He-Ne laser. Record your result in the Postlab exercises.

Single Slit Diffraction

In this measurement, you will replace the double-slit slide with a single slit and observe the diffraction pattern independently of the interference fringes.

1. Aim the laser at the single slit portion of the slide. When the laser is aimed properly, an intensity pattern similar to that shown in Fig. 4 will be visible.

2. Sketch to scale the appearance of the pattern in Graph 1 in the Postlab exercises. Use shaded bars or lines to indicate the bright fringes. Identify the zero-order fringe in your sketch. Draw the scale of the pattern on your sketch so that you can compare it to the fringes from the double slit.

Multiple Slit Interference

Use the multiple-slit portion of the grating slide to observe how the interference pattern changes as the number of slits increases beyond two.

1. Aim the laser at the four-slit portion of the slide. When the laser is aimed properly, an interference pattern will be visible on the screen.

2. Sketch to scale the appearance of the pattern in Graph 2 in the Postlab exercises. Use shaded bars or lines to indicate the bright fringes. Identify the zero-order fringe in your sketch. Draw the scale of the pattern on your sketch so that you can compare it to the single and double slit patterns.

3. Repeat for the six-slit grating, sketching the fringe pattern to scale in Graph 2.

Interference by a Wire Screen

Here, we replace the grating slide with a wire mesh, which is just a section from a screen window.

1. Place the wire mesh in the holder. Aim the laser so that it passes through the mesh.

2. Sketch to scale the appearance of the pattern from the mesh in Figure 3. Explain your observation.

3. When you are finished using the mesh, please return it to its appropriate location.

Double-Slit Interference with a Microwave Source

In this part of the experiment, you will explore the wave-like nature of a different part of the electromagnetic spectrum, using a microwave transmitter and receiver to determine the wavelength of microwave radiation. Interference maxima and minima will be produced by the double slit, but in contrast to the optical measurement, the separation of the maxima will be measured as an angle rather than as a displacement on a screen. The receiver, shown in Figure 7, includes a meter to measure the intensity of the radiation received.

1. Use calipers to measure the center-to-center separation of the double slit, d. Note that d is the distance between the centers of the two slits, not the slit width. The double slit is formed by three metal plates; measure the width of the center plate and add the slit width (1.5 cm) to obtain d. Record this value in Data Table 2 in the Postlab exercises.

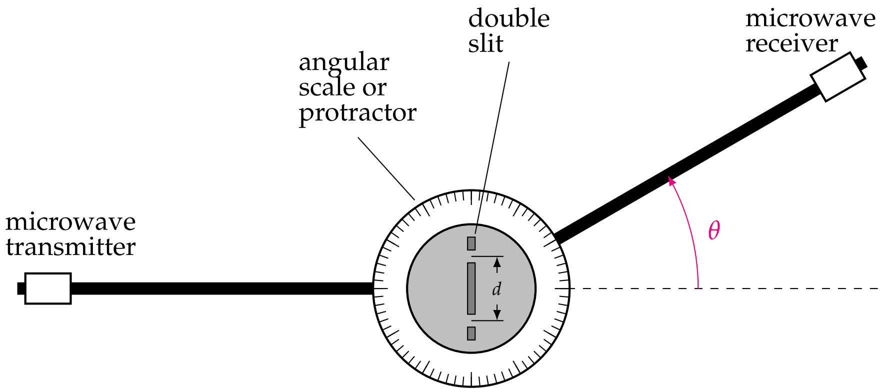

Figure 7: *Top view of the setup to measure double-slit interference with a microwave transmitter and receiver.*

2. Install the double slit on the turntable at the center between the transmitter and receiver horns. Place the receiver at the movable end and the transmitter at the fixed end, so that the double slit does not rotate with the receiver.
3. Align the double slit so that it is normal (perpendicular) to the transmitter horn and centered on the transmitter/receiver axis.
4. Reset the protractor scale so that its 180° mark is at the indicator for the transmitter horn.
5. Position the receiver so that it is directly opposite the transmitter along the central axis. Record this starting angle and the receiver meter reading in Data Table 2.
6. Move the receiver 5° in one direction and record both the angle and the receiver meter reading in Data Table 2.
7. When you find a maximum or a minimum, record both the angle and the receiver meter reading in Data Table 2.
8. Continue moving the receiver in 5° increments in the same direction until you have passed through two maxima. Record both the angle and the receiver meter reading at every position in Data Table 2.
9. Repeat the measurements to the other side of the 0° mark.

Name: ______________________ **Date:** ______________________

Collaborators: ______________________ **Lab Section:** ______________

POSTLAB EXERCISES (20 points)

Submit the postlab to the TA at the end of the lab.

Double-Slit Interference and Single-Slit Diffraction (8 points)

Question 3 **2 points**

Sketch the observed fringes for double slit interference and single slit diffraction in Graph 1.

Graph 1: *Double-slit and single-slit interference patterns.*

Question 4 **1 point**

Record the double slit separation d, the screen-slit distance L, and the average separation between adjacent fringes y. Be sure to use the same units for all values.

Data table 1: *Double-slit measurements.*

Quantity		Measurement		Uncertainty
Double slit separation	$d =$		$\Delta d =$	
Screen-slit distance	$L =$		$\Delta L =$	
Average fringe separation	$y =$		$\Delta y =$	

Question 5 **1 point**

Calculate the wavelength λ of the He-Ne laser using the observed double slit pattern and eq. (4).

Question 6 **1 point**

Determine the uncertainty $\Delta\lambda$ associated with your experimentally determined wavelength using your estimated uncertainty on L, d, and y. Show your final answer as $\lambda \pm \Delta\lambda$, and compare the result to $\lambda_{\text{He-Ne}} = 632.8\,\text{nm}$. Use the expression

$$\left(\frac{\Delta\lambda}{\lambda}\right) = \sqrt{\left(\frac{\Delta y}{y}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta d}{d}\right)^2} \tag{9}$$

Question 7 **1 point**

Which parameter of L, d, and y has the greatest influence on $\Delta\lambda$? Explain your answer.

Question 8 **2 points**

Compare the single slit and the double slit fringe patterns. What similarities and differences do you observe between them?

Multiple Slit Interference (4 points)

Question 9 **2 points**

Sketch the 4-slit and 6-slit interference patterns in Graph 2.

Graph 2: *Multiple slit interference patterns.*

Question 10 **1 point**

What happened to the interference pattern as the number of slits increased? Address issues such as brightness, separation, and sharpness.

Question 11 **1 point**

Without measuring with a microscope, do all the sets of slits on the slide have equal separation? How can you tell from theory and your observations?

Interference by a Wire Mesh (2 points)

Question 12 **1 point**

Sketch the interference patterns for the wire mesh in Graph 3.

Graph 3: *Interference pattern for the wire mesh.*

Question 13 **1 point**

How can you create an interference pattern similar to the wire screen interference pattern? Explain your reasoning. If necessary, demonstrate or draw a picture showing how to recreate the wire screen interference pattern.

Microwave Double Slit Measurement (6 points)

Question 14 **1 point**

Record the angle and receiver meter reading at 5° increments for as many points as you can obtain. Also record the angles and readings at any maxima and minima you observe.

Data table 2: *Microwave Double Slit Measurements*

Double slit separation: $d =$ ____________ cm

θ [°]	Amplitude	θ [°]	Amplitude	Minima (angle in °)	Reading (ampl.)	Maxima (angle in °)	Reading (ampl.)
5		-5					
10		-10					
15		-15					
20		-20					
25		-25					
30		-30					
35		-35					
40		-40					
45		-45					
50		-50					
55		-55					
60		-60					
65		-65					
70		-70					
75		-75					
80		-80					
85		-85					
90		-90					

Question 15 **2 points**

Plot the amplitude vs. θ on the graph in Graph 4. Include units and labels.

Graph 4: *Microwave double-slit interference pattern.*

Question 16 **1 point**

Using your plot in Graph 4, find the angle between adjacent maxima, θ. You may wish to compute an average value for θ using the distance between several maxima.

Question 17 **1 point**

Using your measurement of d, your estimated distance between adjacent maxima θ , and eq. (1), calculate the wavelength λ of the microwave radiation. Record your uncertainties in Data Table 3.

Data table 3: *Double-slit microwave measurements.*

Double slit separation	$d =$		$\Delta d =$	
Angle between maxima	$\theta =$		$\Delta\theta =$	
Calculated wavelength	$\lambda =$			

Question 18 **1 point**

Determine the uncertainty $\Delta\lambda$ associated with your experimentally determined μ-wave wavelength using your estimated uncertainty on d and θ. Show your final answer as $\lambda \pm \Delta\lambda$. Use the expression

$$\left(\frac{\Delta\lambda}{\lambda}\right) = \sqrt{\left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta\theta}{\tan\theta}\right)^2}, \tag{10}$$

expressing the uncertainty $\Delta\theta$ in radians. Note that microwaves are typically around a few centimeters in wavelength.