Electromagnetic Waves: Interference

Goals and Introduction

A planar *wave front* of an electromagnetic wave is a line of points along which the magnitude of the electric field is the same everywhere (because of properties of electromagnetic waves, this would also be true for the magnetic field). We can think of a wave front as if it is a "row of crests" of the traveling wave, moving forward together in unison. As a wave front travels further and further away from an isotropic source of waves, this model of the wave front becomes more valid. Each wave front will be separated from the one behind it by one wavelength of the wave. After all, the wavelength of the wave can be thought of as the distance between crests. To aid in understanding this picture, imagine looking down on a pond of still water and tapping the edge with a regular frequency. Wave fronts will be created that travel away from your finger with a speed that depends on the speed of mechanical waves in the water. The distance between each wave front (wavelength) depends on how quickly you are tapping, or the frequency of the source. This is the familiar relationship stated again, here, in Eq. 1.

$$v = f\lambda \qquad \text{(Eq. 1)}$$

When a planar wave front strikes an obstacle or opening in a boundary, such as window on the wall of a house, most of the wave will just pass straight through. For example, if you shine a light down a long hallway towards an exterior window on the far end of the hall, an observer outside would expect to see a single bright area on the wall of the next building. This story changes however if the size of the opening becomes comparable to the wavelength of the light. When this occurs, we are actually able to observe a phenomenon where the wave *interferes* with itself! The result of this interference is that other bright regions may appear on the exterior wall of the next building, separated by distinct dark locations, and away from the direct path out of the window. This phenomenon is called *diffraction*.

It is more likely that you have experienced diffraction of sound waves in your daily life. Imagine you are outside by that exterior wall of the next building and someone shines the light away from that far away window, but also shouts loudly. While it is very unlikely you will see any evidence of the light (barring some strong reflection), you will likely hear the sound. This is because the wavelength of the sound waves in air is comparable to the size of the window. There are "bright regions" of the sound away from the direct path out of the window. It is sometimes said that diffraction is the "bending" of a wave.

The full description and model of how the wave diffracts is a bit beyond the scope of the lab introduction, but we can describe a few of the main features when a screen is held up some distance away from an opening, or slit, through which light is passing. For one, we expect to see a central bright spot, or broad bright region in the center of the screen. This is because it is still true that most of the light should just pass straight through the opening and hit the screen. On either side of the central bright spot, we have two distinct locations where there appears to be no light intensity. One of the dark locations is designated as the $m = 1$ location and the other as the $m = -1$ location, where m is always an integer (which side is called negative is arbitrary – it is just a way of distinguishing one side from the other for indexing purposes). These are locations of *destructive interference*. In other words, the waves arriving at this location are adding in a regular way, such that they cancel each other out, causing no light to actually be seen at this location. If our eyes are good enough, we would be able to find a second location of destructive interference on both sides of the central bright spot ($m = 2$ and -2), where successive dark regions are separated by other broad bright regions of *constructive interference*. These other bright regions area always less intense than the central bright spot however because the waves interfering a these locations have traveled farther from the opening to get there (as opposed to traveling straight forward and hitting the screen. For reference, you may recall learning about constructive and destructive interference of mechanical waves. Those same principles are at work here for the addition of the wave fronts where they strike the screen.

If you would like to play with the idea of diffraction and work with an interactive simulation, go to https://phet.colorado.edu/en/simulation/legacy/wave-interference and click on the light tab at the top once you launch the simulation. Then, click on "one slit" on the far-right menu. Note that you can use this interactive simulation to test out some of the other ideas in this lab activity, as well!

Given an opening with a certain lateral width, w, and incident light with a wavelength, λ, it is possible to predict at what angles away from the opening we will find these distinct regions of destructive interference (Eq. 2). Note that we usually just choose to work with the positive values of m. Again, the first distinct dark region on either side of the central bright spot is $m = 1$.

$$w \sin\theta = m\lambda \qquad \text{(Eq. 2)}$$

While the explanation of how the interference occurs in the case of diffraction is a bit complicated, we can get a window on how this happens by introducing a second opening, adjacent to the first but separated by a distance, d. When the wave front strikes both of these openings, it would be akin to, in our earlier example, having your friend tap the surface of the pond in unison with you and at the same frequency. Both openings act as a source of waves that spread outward (Figure 1). In the figure, we see a row of wave fronts arriving at a barrier with two openings. The red wave fronts are from the source leaking through the bottom opening in the barrier and the blue wave fronts are from the source leaking through the top opening. We can see that these fronts will always overlap along the line between the two openings. This will form a central bright spot. However, there will be other distinct locations where the two waves will constructively interfere! Two of these directions are shown in Figure 1, where we see that along these directions, it appears that the two waves will always overlap if the lines from each wave front are extended. This experiment was first performed, and is named after, Thomas Young – The Young's double-slit experiment.

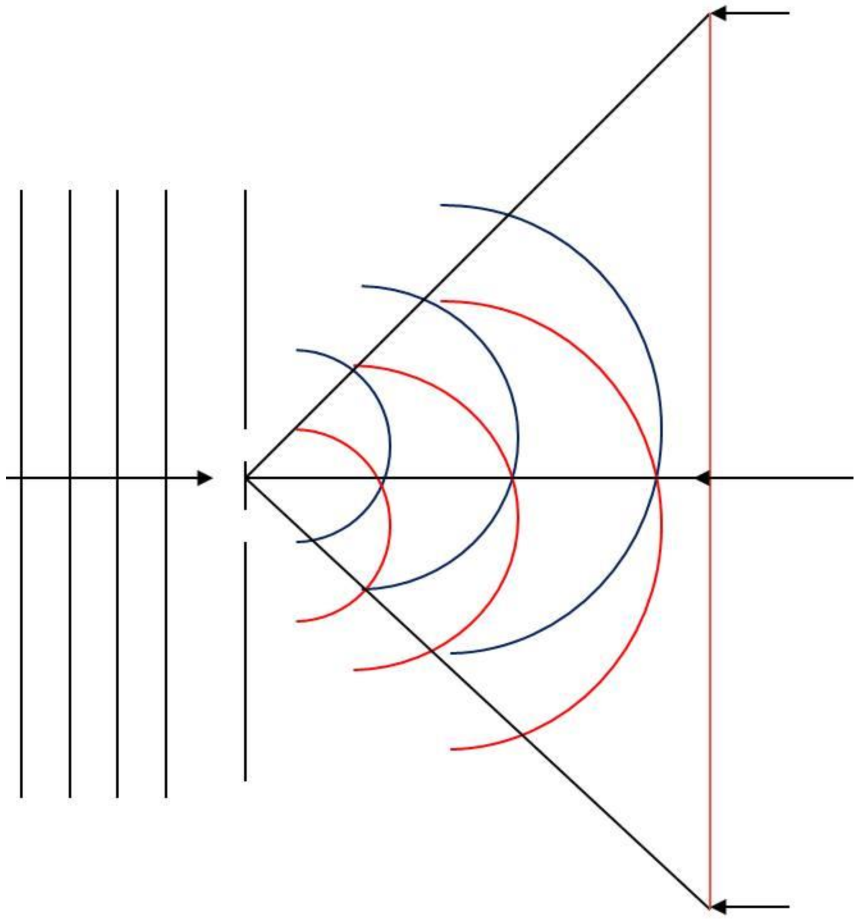

Figure 1

The primary features of the double-slit experiment are the distinct regions of constructive interference. Note that this is different than diffraction, where the distinct regions were due to destructive interference. This occurs when the extra distance one wave front must travel compared to the other to reach the screen is an integer number of wavelengths. In Figure 2, we can imagine that if constructive interference is occurring at the location indicated on the right side, this is because the difference between r_2 and r_1 is some integer number of wavelengths. In this figure, d is the distance between the slits, D is the distance from the slits to the screen or measurement region, and y is the distance from the central bright spot ($m = 0$) to another bright region, indexed with an integer m. The value of m depends on how many bright regions away the location is from the central bright spot. In this experiment, because of the equipment being used, you will see so many bright regions that it will not be necessarily possible to locate the central bright spot. However, you will notice that each of the regions seem to be equidistant. Thus, you can treat $m = 1$ and just measure the distance between adjacent bright spots to find y.

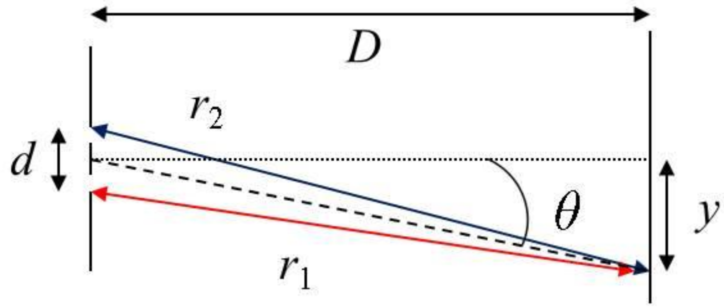

Figure 2

The Young's double-slit experiment is modeled using Eq. 3 and Eq. 4. Note that Eq. 4 could also be used for the locations of destructive interference in the diffraction experiment.

$$d \sin\theta = m\lambda \qquad \text{(Eq. 3)}$$

$$\tan\theta = \frac{y}{D} \qquad \text{(Eq. 4)}$$

The effect of the Young's double-slit experiment can be enhanced by including more slits. This makes the bright regions brighter and more distinct because the falloff in intensity as you move away from the location of constructive interference will be more steep, causing a higher resolution. Very often, diffraction gratings will report a number of slits (sometimes called *rulings*) per unit length, g. We can find d, the distance between each of the slits, by taking the inverse of the g (Eq. 5). Once this is done, we are then able to use Eq. 3 and Eq. 4 to model the diffraction grating.

$$d = \frac{1}{g} \qquad \text{(Eq. 5)}$$

In today's lab, you will make measurements to determine the distance between the slits of a diffraction grating and a double slit arrangement, and compare to the expected values. You will also perform measurements to determine the lateral width of a slit in a diffraction experiment and compare to the expected value.

<u>Goals</u>: (1) Observe the constructive interference of light through a diffraction grating and through a double-slit opening

(2) Perform measurements to determine the spacing between the slits of a diffraction grating and the slits in a double-slit opening

(3) Observe the destructive interference of light through a single slit opening
(4) Perform measurements to determine the lateral width of a single slit using diffraction

Procedure

Equipment – mini-optics bench, light source, diode laser, slit mask aperture, two component carriers, diffraction scale ruler, diffraction grating, diffraction plate, circular ray table base, viewing screen

WARNING: Be careful to not look directly into the laser light during the experiment.

NOTE: The room lights should be turned down during the rest of the experiment.

1) Lay out the lab optics bench from the kit box. Note that the rulers on the sides are in units of mm. You can place components of this lab on this bench during the experiment. Some are magnetic and will be held in place when you place them on the bench.

2) Place the light source from the kit box onto the optics bench at the far end. Be sure to turn the knob on the top of the light source so that the bulb is aligned with its reflector to project light forward. The dot on the knob should be facing forward, in the direction the light will travel from the bulb along the bench. Also, attach the diffraction scale ruler to the front of the circular ray table base, and place it at the opposite end of the optics bench.

3) Place the slit mask on one side of a component carrier and the diffraction grating on the other. Then, put the carrier onto the optics bench so that the slit mask is on the same side as the light source.

4) **Record** the value of g on the diffraction grating, the lines per unit length. Pay attention to the units given!

5) Move the component carrier so that it is about 200 mm from the location of the diffraction scale ruler. Your setup should look similar to Figure 3.

Figure 3

6) **Record** the distance between the diffraction grating and the diffraction scale ruler, *D*.

7) With your head near the light source, look through the diffraction grating and observe the central bright spot and the first order, ($m = 1$) spectrum that is off to either side.

8) With the aid of your lab partner, slide the diffraction scale ruler alog the surface of the magnetic holder to arrange it such that the center of the central bright spot is at the 0 mark on the ruler. Then, **record** the position, *y*, of the center of the red part of the $m = 1$ spectrum.

9) **Record** the position, *y*, of the center of the blue part of the $m = 1$ spectrum.

10) **Record** the wavelength that is defined on the laser. Then, replace the light source with the laser and be sure that the light passes through the slit mask and grating. Do not look down the beam. You can observe from behind the slit mask whether or not it is hitting the opening or not.

WARNING: Be careful to not look directly into the laser light.

11) Observe the central bright spot on the diffraction scale and the location of either first order bright spot ($m = 1$). **Record** the distance from the center of the central bright spot to the center of the first order, adjacent, bright spot.

12) Remove the slit mask and the diffraction grating and place the diffraction plate on the carrier. Note that each region on the diffraction plate is defined by a letter of the alphabet. Place the carrier on the optics bench near the laser.

13) Without looking directly in to the beam from the laser (look at the plate from the same side as the laser), slide the diffraction plate on the carrier so that the laser light is passing through the

slits that are at location D on the plate. **Record** that the expected value of the distance between these slits is 1.25×10^{-4} m.

14) Place the viewing screen on the other component carrier and then place this carrier on the optics bench so that there is at least 400mm between the diffraction plate and the viewing screen. Slide the viewing screen so the ruler on it is lined up over the interference pattern. **Record** the distance between the centers of two of the regions of constructive interference on the viewing screen.

15) **Record** the distance between the diffraction plate and the viewing screen, *D*.

Question 1: Region E also has two slits, but the slits are separated by a larger distance. How should this affect the location of the first-order region of constructive interference on the screen, if all other parameters are unchanged? Explain why any change will occur.

16) Repeat steps 13 through 15 by having the laser light pass through the region E. **Record** that the expected value of the distance between these slits is 2.50×10^{-4} m, however.

17) Without looking directly in to the beam from the laser (look at the plate from the same side as the laser), slide the diffraction plate on the carrier so that the laser light is passing through the slit that is at location A on the plate. **Record** that the expected value of the lateral width of this slit is 4.0×10^{-5} m.

18) Move the viewing screen so that you can clearly measure the width of the central bright spot. You will likely need to bring the screen closer to the diffraction plate. Once you feel you can measure the lateral width of the bright region well, **record** the width of the central bright region (the distance between the $m = 1$ destructive interference). Also **record** the distance between the diffraction plate and the screen, *D*.

Question 2: Region B also has a single slit, but the width of the slit is larger. How should this affect the location of the first-order region of destructive interference on the screen, if all other parameters are unchanged? Explain why any change will occur. What will happen to the width of the central bright region?

19) Repeat steps 17 and 18 with the light passing through region B. **Record** that the expected value of the lateral width of this slit is 8.0×10^{-5} m, however.

As always, be sure to organize your data records for presentation in your lab report, using tables and labels where appropriate.

Data Analysis

Before beginning, be sure to convert all of your data to SI units. It is assumed you have done this in the following calculations.

Calculate the expected value of the distance between slits, *d*, for the diffraction grating using the value of *g* you recorded in step 4.

Use the values for *D* and *y* that you recorded for the red portion of the first order spectrum, when using the diffraction grating, to determine the angle, θ , at which this constructive interference occurs (Eq. 4).

Look up an appropriate value for the wavelength of the center of the red portion of the spectrum and use it with your data and Eq. 3 to calculate a value for *d*, the spacing between the slits.

Repeat the last two calculations using the data recorded for the blue portion of the first order spectrum.

Calculate a mean value for the distance between slits of the diffraction grating using the results of the red and blue data. This is your experimentally-determined value of *d*.

Use the data gathered for the laser light through the diffractions grating in steps 10 and 11 and the expected value of the distance between slits you calculated at the start of this Data Analysis section to calculate a value for the wavelength of the laser light.

Moving on to the double-slit experiments, use the values for *D* and *y* that you recorded for the laser light passing through region D of the diffraction plate in steps 14 and 15 to determine the angle, θ , at which the first-order (m = 1) constructive interference occurs (Eq. 4).

Use the results of the previous calculation and the expected wavelength of the laser light that you recorded during the lab to calculate the spacing between the slits, *d*, in region D.

Repeat the last two calculations for the data from region E in step 16.

Moving on to the single slit experiments, use the width of the central bright region that you recorded for region A to find the distance, *y*, of the first-order destructive interference location from the center of the central bright region (steps 17 and 18) . Accomplish this by dividing the width of the central bright region by 2.

Use this value of *y* and the distance from the diffraction plate to the screen that you recorded in Eq. 4 to find the angle at which the first-order destructive interference occurs.

Then use these results and the expected wavelength of the laser light to calculate, *w*, the lateral width of the slit in region A.

Repeat the previous calculations using the data in step 19 to find, *w*, the lateral width of the slit in region B.

Error Analysis

Calculate the percent error between the mean value you found for *d* for the diffraction grating and the expected value.

$$\%error = \frac{\left| d_{\text{experimental}} - d_{\text{expected}} \right|}{d_{\text{expected}}} \times 100\%$$

Calculate the percent error between the value of the wavelength of the laser light you calculated using the diffraction grating and the expected value from the laser.

Calculate the percent error between the value of *d* you found for region D on the diffraction plate, and the expected value.

Calculate the percent error between the value of *d* you found for region E on the diffraction plate, and the expected value.

Calculate the percent error between the value of *w* you found for region A on the diffraction plate, and the expected value.

Calculate the percent error between the value of *w* you found for region B on the diffraction plate, and the expected value.

Question 3: How well did the values match the expected values in each case? Were there any experiments that were significantly less effective than another? Why might this have occurred? Explain your responses.

Questions and Conclusions

Be sure to address Questions 1 through 3 and describe what has been verified and tested by this experiment. What are the likely sources of error? Where might the physics principles investigated in this lab manifest in everyday life, or in a job setting?

Pre-Lab Questions

Please read through all the instructions for this experiment to acquaint yourself with the experimental setup and procedures, and develop any questions you may want to discuss with your lab partner or TA before you begin. Then answer the following questions and type your answers into the Canvas quiz tool for "Electromagnetic Waves – Interference," and submit it before the start of your lab section on the day this experiment is to be run.

PL-1) Francine records that the diffraction grating has 5000 slits per cm. What is the distance between each of the slits? Express your answer in cm.

PL-2) Olivette is performing a diffraction experiment with a single slit. She measures the width of the central bright region on the screen to be 0.048 m. This is also, therefore, the distance between the first locations of destructive interference. How far is one of the regions of destructive interference from the center of the central bright region?

A) 0.096 m

B) 0.012 m

C) 0.048 m

D) 0.024 m

PL-3) Jack thinks it would be cool to point the laser directly onto his open eye. Jack

A) did not read the warning in this lab document.

B) is a masochist.

C) has endangered his eyes.

D) has made all of the above at least conditionally true.

PL-4) Olivette measures the distance from the single slit to the screen to be 0.200 m. She calculates that the distance from the first-order location of destructive interference to the center of the central bright fringe, y, is 0.002 m. What is the angle at which this location of destructive interference occurs? Express your answer in degrees.

PL-5) Francine helped Olivette with her experiment and reminded her that the wavelength of the laser was 650 nm. Recall, Olivette measured the distance from the single slit to the screen to be 0.200 m. She also calculated that the distance from the first-order location of destructive interference to the center of the central bright fringe, y, is 0.002 m. Find the lateral width of the slit, as predicted by these measurements and given information. While you may find the answer in m, express your final answer in mm.