Lab 14

Interference of Light

Continuing Objectives

1. Be able to identify sources of experimental uncertainty in a measurement.

3. Be able to write an experimental result (including correct number of significant digits, uncertainty, units).

4. Be able to make careful measurements to ensure reproducible results.

5. Know how to keep a clear and organized record, including an introduction (with purpose of lab and appropriate laws or equations), apparatus sketch, table of raw data and calculated quantities, and a good conclusion or summary.

Introduction

Waves are distinguished by the fact that they *diffract* (spread out) when they pass obstacles or through apertures (slits) and that they display *interference* behavior when two or more waves come together at a point. In the 18th and 19th centuries, experiments similar to those in this lab demonstrated diffraction and interference behavior for visible light. The conclusions drawn from these experiments were profound: visible light is a wave of some sort. In the mid-1800s, it was shown convincingly by Maxwell that light (as well as many other forms of radiation) is an *electromagnetic* wave.

Interference phenomena are not just a curious side-show in our discussion of waves. Rather, they are prevalent and important in numerous situations involving waves, such as concert halls, microwave ovens, anti-reflective coatings, and any sort of wireless communications. Interference is extremely useful, enabling the most precise measurements of wavelengths of light and distances. The former opens the way to a detailed understanding of atomic structure (as you will see in the lab on Emission

Spectra) and eventually the composition of stars and our universe. Understanding interference will also help you appreciate the colorful reflections of a compact disk or a soap bubble. Furthermore, interference is critical for understanding many of the implications of quantum mechanics.

This lab offers a qualitative exposure to interference phenomena that you will study elsewhere in the course. You will explore the surprising patterns that light makes after it passes through a single slit and multiple slits of varying width and slit spacing. You will also see the patterns that light makes in reflections off thin films; you will look at the interference pattern caused by the air gap between two pieces of glass along with the pattern caused by the reflections of light from the front and back surface of a soap film. *There are not very many calculations in this lab. The goal for you today is to see, explore, and play with these interference phenomena and to make accurate records of your observations in your lab notebook.*

NOTE: Parts I and II of this lab use the equipment available at your lab bench. Part III of this lab uses equipment available in the back of the room. Part III can be done without having completed Parts I and II; since we only have limited equipment for Part III, your instructor or TA will have you do Part III whenever the equipment is available.

Part I: Single-slit Diffraction

When a wave passes through a small opening (a "slit"), it spreads out. This effect (referred to as *diffraction*) is apparent for sound waves (you can hear someone talking to you from the next room, even if you are not in the direct line-of-sight). Diffraction is not as noticeable for light passing through an opening, due to the *much* smaller wavelength for visible light (red light has a wavelength of 600 nm, as opposed to a wavelength of 1 m for typical sound waves). In the lecture part of the course, you will learn more about the quantitative relations that describe this effect. Here, you will learn about the phenomena by experimentation.

WARNING: In this and future labs, you will be working with lasers. Never look directly into the laser or look directly into any reflections of the beams off shiny metal or glass surfaces. For safety, you should ensure that your eye-level is *always* above the laser level.

1. Examine the wheel mounted on a post and labeled DIFFRACTION SLITS. Notice that there are different sets: SINGLE SLITS, DOUBLE SLITS, MULTIPLE SLITS, and PATTERNS. We will work in part I with the SINGLE SLITS set. Rotate the wheel and look through the various openings, slits, and obstructions. Notice the variation in slit width (denoted a) when looking through the four individual *single slits* of width $a = 0.02\,\text{mm}$, $a = 0.04\,\text{mm}$, $a = 0.08\,\text{mm}$, and $a = 0.16\,\text{mm}$.

2. PREDICT what will happen when laser light passes through an individual slit. Write your prediction in your lab notebook.

STOP Discuss your prediction with your instructor or TA

3. Mount the laser on the optical bench so that it points toward the wall. Place the white screen upright on the table close to the wall, so that the laser strikes it somewhere near its center. Mount the DIFFRACTION SLITS wheel on the optical bench between the laser and the screen with the labeled side of the wheel facing the laser. Make sure to place the slit wheel at least 0.5 m away from the screen.

4. Adjust the positions of the wheel and the laser so that the laser beam falls squarely on the 0.04 mm wide slit (the second to narrowest slit) of the SINGLE SLITS set. When viewed (at an angle!) from the side of the slit from which the light emerges, the slit should be uniformly illuminated. With the room lights off, observe the light falling on the screen. If the slit formed a sharp shadow, you might expect to see a thin rectangular spot of light on the wall with clearly defined left and right edges. You will actually see something different: a *diffraction pattern*.

5. Describe and **draw a careful sketch** of the pattern you observe on the screen. Your sketch should illustrate **accurately** the numbers and relative sizes of the bright and dark spots in the diffraction pattern. Compare the observed pattern with your prediction.

6. You should observe *several* bright spots on the screen. The *central maximum* is the widest and brightest of these spots. Determine the width, Δx_c, of this spot by measuring the distance between the centers of the two dark spots on either side of the central spot. Note that you have a meter stick, a ruler, and a set of calipers on your desk. Which should you use to measure these distances?

7. Repeat this measurement with the $a = 0.16\,\text{mm}$, $a = 0.08\,\text{mm}$, and $a = 0.02\,\text{mm}$ single slits, keeping the distance from the slit to the screen fixed. Open Excel and make a table with your results for the slit width a in one column and the corresponding width on the screen Δx_c in the other. Does the central spot become wider or narrower as the slit width is increased? Are the other spots more spread out or more closely spaced when the slit width is increased?

   TASK: **Qualitatively** summarize your observations and conclusions thus far.

8. Now determine a **quantitative** relationship between the width of the slit a and the width of the central maximum, Δx_c. Is this relationship:

   (a) linear, i.e., $\Delta x_c \propto a$,

   (b) quadratic, i.e., $\Delta x_c \propto a^2$,

   (c) inverse-linear, i.e., $\Delta x_c \propto 1/a$, or

   (d) inverse-squared, i.e., $\Delta x_c \propto 1/a^2$?

   Hint: A quick way to find relationships in data is to determine ratios. When several data points are available, another way to find the relationship is to plot one variable versus the other and examine the resulting graph.

9. Again, shine the laser through the 0.04 mm single slit. **Record the relative positions of the laser, the wheel, and the screen.** Move the laser closer to the slit (but keep the slit and the screen in the same position). Does the spacing of the diffraction pattern change when you adjust the laser-slit distance? Return the laser to its original position, and move the screen closer to the slit. Does the spacing of the diffraction pattern change when you adjust the screen-slit distance? **Return the screen, wheel, and laser to their original positions.**

   TASK: Summarize your observations.

10. A small obstruction surrounded by air can also produce diffraction, similar to that arising from the passage of light through a small slit. Look for a slide with a thin piece of hair taped across the center of the opening. Orient the hair vertically and use the provided mount to place it in the path of the laser (remove the wheel from the beam path, but make sure you've recorded its position). **Sketch** the pattern that you observe and **compare** it to what you observed with a single slit. Make an estimate for the width of this hair. (If you are curious about your hair width, you might also use a piece of your hair and tape it to the empty slide.)

11. Repeat this with the hair oriented horizontally. **Contrast** your observations with those when the hair was oriented vertically.

12. You have now seen that, depending on the size of a slit or obstruction, the resulting diffraction pattern can be very diffuse (large Δx_c) or very sharp (small Δx_c). Given this, why would diffraction limit how small of an object you can observe in a light microscope? (Hint: how would you be able to distinguish something from its environment? Or, if you had two patterns next to each other, would bigger or smaller sized obstructions make them easier to tell apart?)

STOP

Discuss your results on single-slit diffraction with your instructor or TA.

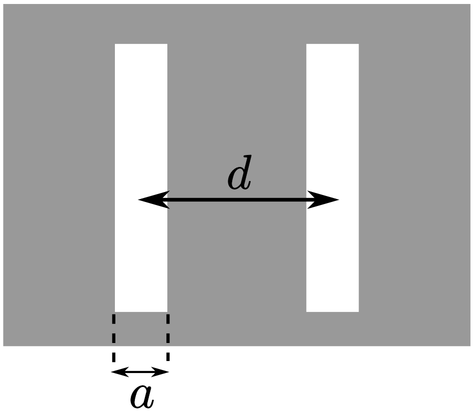

Figure 14.1: Double slit width a and spacing d.

Part II: Multiple-slit Interference

Now consider light (or any wave) passing through two adjacent slits, each with the same width. You may expect that the resulting pattern will consist of two independent overlapping single slit diffraction patterns, similar to those observed in Part I, but offset relative to each other. Although there are remnants of the single slit diffraction pattern, the waves that emerge from one slit will *overlap and interfere* with those emerging from the other slit, vastly changing the resulting pattern. Consider the region which would be occupied by the central maxima of both individual slits. At certain points here, the waves from each slit oscillate in phase (i.e., synchronously) and add (*constructive interference*), resulting in a large net oscillation and a bright spot at that point. At other points, the oscillations are out of phase (one increases while the other decreases) and the waves cancel (*destructive interference*), resulting in zero net oscillation and a dark spot. You will observe such patterns of bright and dark spots in this part of the lab.

1. Put back the Diffraction Slits Wheel. We will work next with the DOUBLE SLITS set. The Double Slits set contains groups of closely spaced slits with different center-to-center separations, d. Mount on the optical bench the laser, wheel and screen in the same positions as before. Shine the laser on the **DOUBLE SLITS** combination with width $a = 0.04\,\text{mm}$ and separation $d = 0.25\,\text{mm}$, ensuring that the beam illuminates both slits. Describe and

sketch accurately the pattern that you observe. You should notice a remnant of the central maximum (henceforth "the central maximum") that just one slit produces. Identify this and compare its width to that of the central maximum for a single slit of width $a = 0.04\,\mathrm{mm}$. **Compare and contrast the pattern within this central maximum to that for a single slit of width size $a = 0.04\,$mm.**

2. Now consider the small stripes within the central maximum. Use the caliper to verify that they are evenly spaced. Measure the distance Δx between adjacent small stripes. Do so by measuring the total distance between as many stripes as possible. Calculate Δx from this. Why is this more accurate than directly measuring the distance between two adjacent stripes?

3. Repeat steps 1 and 2 using the double slits with $a = 0.04\,\mathrm{mm}$ and $d = 0.50\,\mathrm{mm}$ (again make sure both slits are illuminated). Finally, on the MULTIPLE SLITS section of the wheel, use the 2-slit combination, with $a = 0.04\,\mathrm{mm}$ and $d = 0.125\,\mathrm{mm}$. List your results in a table. Consider the relationship between the slit separation d and the distance Δx between the stripes in the central maximum. Is the relation linear, quadratic, inverse-linear, or inverse-squared? Comment in your notebook.

4. Now, observe what happens with more than 2 slits. The MULTIPLE SLITS set has combinations of 3, 4 and 5 slits, all with width $0.04\,\mathrm{mm}$ and separation $0.125\,\mathrm{mm}$. Shine the laser on each, carefully aligning it in order to illuminate all the slits in each combination. Observe the pattern of light on the screen. The distinctive features in these can be very subtle, so look carefully. Describe and **sketch your observations accurately**, commenting specifically on how the pattern and/or the separation between the spots changes as more slits are added.

   You should notice a striking feature which will easily enable you to determine how many slits are present by looking only at the diffraction pattern. What would you expect the pattern to look like if there were many (more than 5) closely spaced slits (with the same width and spacing)?

5. A diffraction grating is essentially a set of many closely spaced slits. Replace the wheel with the diffraction grating (a clear slide with 500 slits every mm, i.e., slit separation $d = 0.002\,\mathrm{mm}$, which is much smaller than the slit separations you worked with previously) placed on the clip mount. Move the laser and diffraction grating closer to the screen (half the distance). Observe the pattern of dots on the screen. You should definitely see a bright central dot. Based on your previous results of the dependence of Δx on the slit spacing d, it shouldn't surprise you where the neighboring bright spots will be (look off to the sides of the screen). Describe and sketch the pattern in your lab notebook.

6. Using a meter stick, measure the distance Δx between the central spot and one of its nearest neighbors. What does the relationship that you determined in step 3 predict for this spacing? Are the prediction and observation consistent?

7. Remove the diffraction grating from the clip mount so that the laser shines directly on the screen. Look at the spot on the screen *through* the diffraction grating from roughly the same distance the grating was at when in the holder, and describe what you observe (as before, look off to the sides of the screen while looking through the grating). In particular, **compare** what you observe with the interference pattern that you observed in step 5. **Explain** your observations. (**Hint**: think of the spot on the screen as a source of light. Consider what happens to light from this spot that passes through the grating.)

8. Now, look through the diffraction grating at the lights in the lab. What do you notice about the white light after it passes through the grating? Diffraction gratings separate light into its constituent colors and allow for easy and accurate measurement of wavelengths of light. As you will see in lecture, various atoms and molecules emit distinct combinations of colors. Diffraction gratings are widely used in physics, biology, chemistry, and astronomy to separate these colors and determine the elements and molecules present in the system under observation.

STOP

Discuss your results on multiple-slit interference with your instructor or TA.

Part III: Thin Film Interference

Interference phenomena are not only apparent when waves pass through small apertures but are quite evident with reflection off two parallel (or nearly parallel) closely spaced surfaces, such as the neighboring surfaces between two glass plates or the front and back surfaces of a soap film. This forms the basis for a technique that enables you to determine, *very precisely*, variations in distance.

NOTE: The equipment and supplies for this section are located in the back of the room.

1. **Air wedges.** Take two glass plates and clean them, if necessary, with alcohol.
   (a) Hold the plates on top of each other and underneath one of the green lamps. Moving your head around, observe the reflection of the green light from the glass plates and describe or sketch the pattern that you observe.

Press down hard on the top plate in different locations and observe the changes in the pattern.

This fringe pattern results from interference between light reflected off the bottom surface of the top plate and the upper surface of the bottom plate. It effectively maps the changes in thickness of the air gap between the plates. By pressing on the top slide, you are changing the air gap, and hence the fringe pattern.

(b) In part (a), you observed *incredibly small* variations in the plate separation. Each fringe represents a change in separation of $\lambda/2$, where $\lambda = 546.1\,\mathrm{nm}$ is the wavelength of the green light. To illustrate this, place a hair between the plates, near one of the ends. Briefly explain what you see.

If you were manufacturing optical-quality glass plates, how could you use the techniques in this section to determine the flatness of the plates to high precision? These techniques are, in fact, widely used in industry, so this is not just hypothetical.

2. **Soap films.** Dip a wire ring into the dish with soap solution and pull it out to make a film. Hold the ring such that the film is oriented vertically, and observe the reflections of green light off the film. Describe and sketch the patterns that you observe.

   What do the fringes tell you about the thickness of the film? How does the pattern of bands change over time as you hold the ring vertically? Explain your observations.

3. So far we have used light sources which are almost perfectly monochromatic, i.e., emit light of one color or wavelength. To illustrate the dependence of interference effects on wavelength, hold a pair of plates beneath a white light source (the decorative lights at the entrance to Olin 268 work well). Describe and explain the pattern visible in the reflection (most likely you will not see a simple ROYGB pattern of colors).

4. If you repeat the soap film experiment using the same white light source, what color would you expect to see at the top of the bubble? Do the colors appear in ROYGB order from bottom to top or from top to bottom? **Make a prediction.** Hint: red light has a longer wavelength than blue light. Then repeat the soap film experiment with this white light source.

Write a conclusion for this lab.