

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Physics

8.02

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Experiment 9: Interference and Diffraction

OBJECTIVES

1. To explore the diffraction of light through a variety of apertures
2. To learn how interference can be used to measure small distances very accurately. By example we will measure the wavelength of the laser, the spacing between tracks on a CD and the thickness of human hair

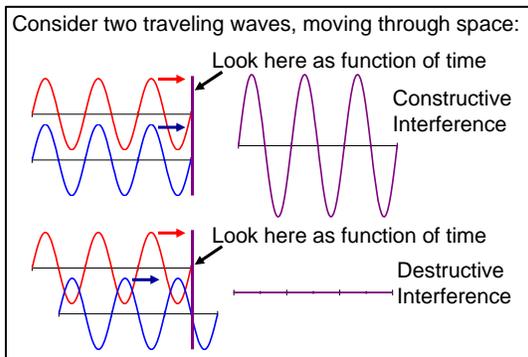
WARNING! The beam of laser pointers is so concentrated that it can cause *real* damage to your retina if you look into the beam either directly or by reflection from a shiny object. Do NOT shine them at others or yourself.

PRE-LAB READING

INTRODUCTION

Electromagnetic radiation propagates as a wave, and as such can exhibit interference and diffraction. This is most strikingly seen with laser light, where light shining on a piece of paper looks speckled (with light and dark spots) rather than evenly illuminated, and where light shining through a small hole makes a pattern of bright and dark spots rather than the single spot you might expect from your everyday experiences with light. In this lab we will use laser light to investigate the phenomena of interference and diffraction and will see how we can use these phenomena to make accurate measurements of very small objects like the spacing between tracks on a CD and the thickness of human hair.

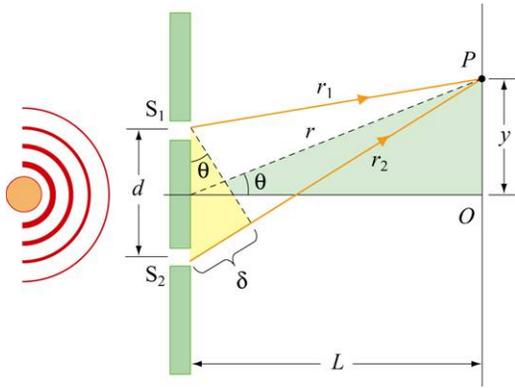
The Details: Interference



The picture at left forms the basis of all the phenomena you will observe in the lab. Two different waves arrive at a single position in space (at the screen). If they are in phase then they add constructively and you see a bright spot. If they are out of phase then they add destructively and you see nothing (dark spot).

The key to creating interference is creating phase shift between two waves that are then brought together at a single position. A common way to do that is to add extra path length to one of the waves relative to the other. In this lab the distance traveled from source to screen, and hence the relative phase of incoming waves, changes as a function of lateral position on the screen, creating a visual interference pattern.

Two Slit Interference



The first phenomenon we consider is two slit interference. Light from the laser hits two very narrow slits, which then act like in-phase point sources of light. In traveling from the slits to the screen, however, the light from the two slits travel different distances. In the picture at left light hitting point P from the bottom slit travels further than the light from the top slit. This extra path length introduces a phase shift between the two waves and leads to a position dependent interference pattern on the screen.

Here the extra path length is $\delta = d \sin(\theta)$, leading to a phase shift ϕ given by $\frac{\delta}{\lambda} = \frac{\phi}{2\pi}$.

Realizing that phase shifts that are multiples of 2π give us constructive interference while odd multiples of π lead to destructive interference leads to the following conditions:

Maxima: $d \sin(\theta) = m\lambda$; Minima: $d \sin(\theta) = (m + \frac{1}{2}) \lambda$

Multiple Slit Interference

If instead of two identical slits separated by a distance d there are multiple identical slits, each separated by a distance d , the same effect happens. For example, at all angles θ satisfying

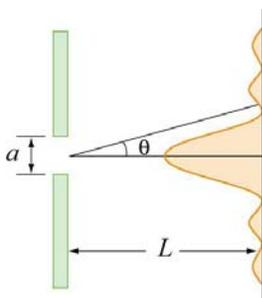
$d \sin(\theta) = m\lambda$ we find constructive interference,

now from all of the holes. The difference in the resulting interference pattern lies in those regions

that are neither maxima or minima but rather in between. Here, because more incoming waves are available to interfere, the interference becomes more destructive, making the minima appear broader and the maxima sharper. This explains the appearance of a brilliant array of colors that change as a function of angle when looking at a CD. A CD has a large number of small grooves, each reflecting light and becoming a new source like a small slit. For a given angle, a distinct set of wavelengths will form constructive maxima when the reflected light reaches your eyes.



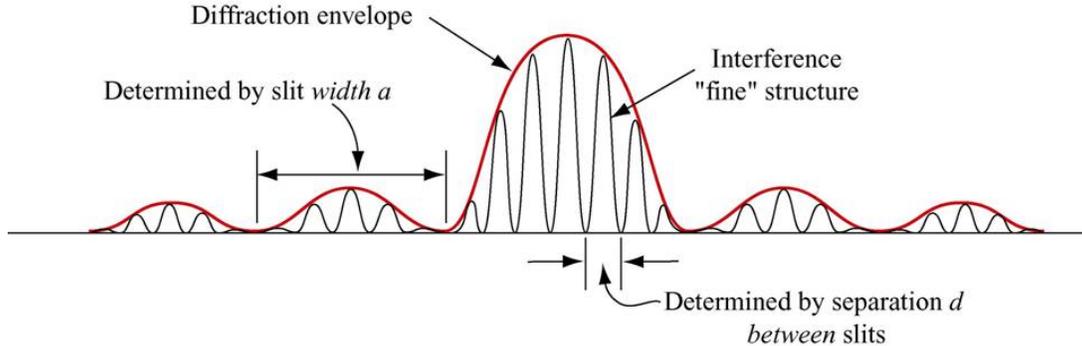
Diffraction



The next kind of interference we consider is light going through a single slit, interfering with itself. This is called diffraction, and arises from the finite width of the slit (a in the picture at left). The resultant effect is not nearly as easy to derive as that from two-slit interference (which, as you can see from above, is straight-forward). The result for the angular locations of the minima is $a \sin(\theta) = m\lambda$.

Putting it Together

If you have two wide slits, that is, slits that exhibit both diffraction and interference, the pattern observed on a distant screen is as follows:

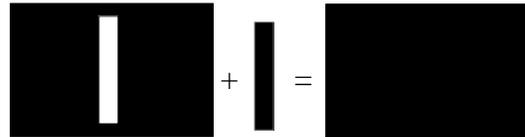


Here the amplitude modulation (the red envelope) is set by the diffraction (the width of the slits), while the “individual wiggles” are due to the interference between the light coming from the two different slits. You know that this must be the case because d must be larger than a , and hence the minima locations, which go like $1/d$, are closer together for the two slit pattern than for the single slit pattern.

The Opposite of a Slit: Babinet’s Principle

So far we have discussed sending light through very narrow slits or reflecting it off of small grooves, in each case creating a series of point-like “new sources” of light that can then go on and interfere. Rather amazingly, light hitting a small solid object, like a piece of hair, creates the same interference pattern as if the object were replaced with a hole of the same dimensions. This idea is Babinet’s Principle, and the reason behind it is summed up by the pictorial equation at right.

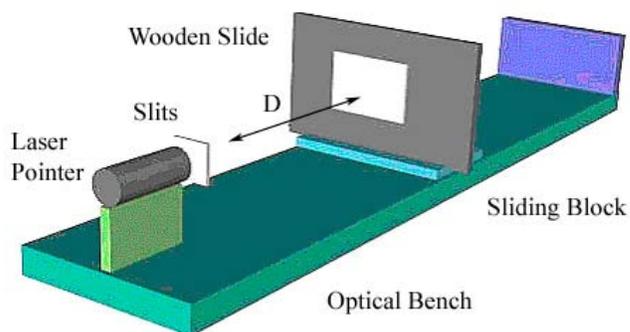
If you add an object to a hole of the same size, you get a filled hole. EM waves hitting those objects must add in the same fashion, that is, the electric fields produced when light hits the hole,



when added to the electric fields produced by the small object, must add to the electric fields produced when light hits the filled hole. Since no light can get through the filled hole, $E_{\text{hole}} + E_{\text{object}} = 0$. Thus we find that the electric fields coming out of the hole are equal and opposite to the electric fields diffracting off of the small object. Since the observed interference pattern depends on intensity, the square of the electric field, the hole and the object will generate identical diffraction patterns. By measuring properties of the diffraction pattern we can thus measure the width of the small object. In this lab the small object will be a piece of your hair.

APPARATUS

1. Optical bench



The optical bench consists of a holder for a laser pointer, a mount for slides (which contain the slits you will shine light through), and a sliding block to which you will attach pieces of paper to mark your observed interference patterns. Note that a small ring can be slid over the button of the laser pointer in order to keep it on while you make your measurements.

2. Slit Slides

You will be given two slides, each containing four sets of slits labeled a through d. One slide contains single slits with widths from $20\ \mu\text{m}$ to $160\ \mu\text{m}$. The other slide contains double slits with widths of $40\ \mu\text{m}$ or $80\ \mu\text{m}$, separated by distances of $250\ \mu\text{m}$ or $500\ \mu\text{m}$.

GENERALIZED PROCEDURE

In this lab you will shine the light through slits, across hairs or off of CDs and make measurements of the resulting interference pattern.

Part 1: Laser Wavelength

In this part you will measure the wavelength of the laser using the two narrow double slits, and making the measurements that you determine are necessary in pre-lab #1.

Part 2: Diffraction from a CD

Finally, you will measure the width of tracks on a CD by reflecting laser light off of it and measuring the resulting diffraction pattern.

Part 3: Thickness of Human Hair

Next you will discover the ability to measure the size of small objects using diffraction, by measuring the width of a human hair.

END OF PRE-LAB READING

Experiment 9: Interference and Diffraction

Answer these questions on a separate sheet of paper and turn them in before the lab

1. Measuring the Wavelength of Laser Light

In the first part of this experiment you will shine a red laser through a pair of narrow slits ($a = 40 \mu\text{m}$) separated by a known distance (you will use both $d = 250 \mu\text{m}$ and $500 \mu\text{m}$) and allow the resulting interference pattern to fall on a screen a distance L away ($L \sim 40 \text{ cm}$). This set up is as pictured in Fig. 2 (in the “Two Slit Interference” section above).

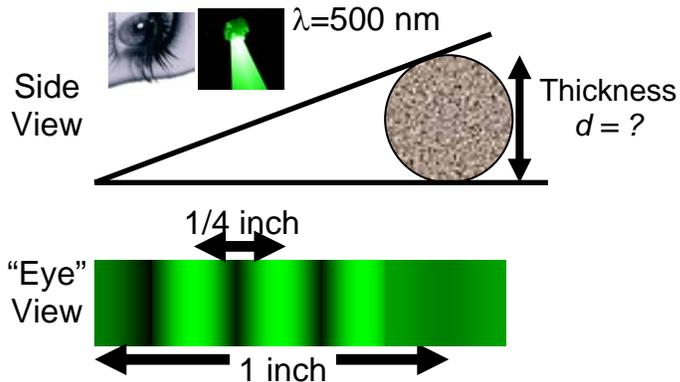
- (a) Will the center of the pattern (directly between the two holes) be an interference minimum or maximum?
- (b) You should be able to easily mark and then measure the locations of the interference maxima. For the sizes given above, will these maxima be roughly equally spaced, or will they spread out away from the central peak? If you find that they are equally spaced, note that you can use this to your advantage by measuring the distance between distance maxima and dividing by the number of intermediate maxima to get an average spacing. If they spread out, which spacing should you use in your measurement to get the most accurate results, one close to the center or one farther away?
- (c) Approximately how many interference maxima will you see on one side of the pattern before their intensity is significantly reduced by diffraction due to the finite width a of the slit?
- (d) Derive an equation for calculating the wavelength λ of the laser light from your measurement of the distance Δy between interference maxima. Make sure that you keep a copy of this equation in your notes! You will need it for the lab.
- (e) In order to most accurately measure the distance between maxima Δy , it helps to have them as far apart as possible. (Why?) Assuming that the slit parameters and light wavelength are fixed, what can we do in order to make Δy bigger? What are some reasons that can we not do this ad infinitum?

2. Single Slit Interference

Now that you have measured the wavelength λ of the light you are using, you will want to measure the width of some slits from their diffraction pattern. When measuring diffraction patterns (as opposed to the interference patterns of problem 1) it is typically easiest to measure between diffraction minima.

- (a) Derive an equation for calculating the width a of a slit from your measurement of the distance Δy between diffraction minima. Make sure that you keep a copy of this equation in your notes! You will need it for the lab. Note that this same equation will be used for measuring the thickness of your hair.
- (b) What is the width of the central maximum (the distance on the screen between the $m=-1$ and $m=1$ minima)? How does this compare to the distance Δy between other adjacent minima?

3. Another Way to Measure Hair



In addition to using hair as a thin object for diffraction, you can also measure its thickness using an interferometer. In fact, you can use this to measure even smaller objects. Its use on a small fiber is pictured at left. The fiber is placed between two glass slides, lifting one at an angle relative to the other. The slides are illuminated with green light from above, and when the set-up is viewed from above, an interference pattern, pictured in the "Eye View", appears.

What is the thickness d of the fiber?

4. CD

In the last part of this lab you will reflect light off of a CD and measure the resulting interference pattern on a screen a distance $L \sim 5 \text{ cm}$ away.

- A CD has a number of tracks, each of width d (this is what you are going to measure). Each track contains a number of bits, of length $l \sim d/3$. Approximately how many bits are there on a CD? In case you didn't know, CDs sample two channels (left and right) at a rate of 44100 samples/second, with a resolution of 16 bits/sample. In addition to the actual data bits, there are error correction and packing bits that roughly double the number of bits on the CD.
- What, approximately, must the track width be in order to accommodate this number of bits on a CD? In case you don't have a ruler, a CD has an inner diameter of 40 mm and an outer diameter of 120 mm.
- Derive an equation for calculating the width d of the tracks from your measurement of the distance Δy between interference maxima. Make sure that you keep a copy of this equation in your notes! You will need it for the lab.
- Using the previous results, what approximately will the distance between interference maxima Δy be on the screen?

IN-LAB ACTIVITIES

EXPERIMENTAL SETUP

1. Download the LabView file from the web and save the file to your desktop. Start LabView by double clicking on this file.

MEASUREMENTS

Part 1: Laser Wavelength

In this part you will measure the wavelength λ of the laser light you are using

1. Set up the optical bench as pictured in the apparatus diagram.
 - a. Clip paper onto the wooden slide, and place roughly 40 cm away from the slide holder
 - b. Place the double slit slide in the slide holder and align so that light from the laser goes through slit pattern *a*.
 - c. Turn the laser on (lock it with the clip that slides around the on button)
 - d. Adjust the location of the wooden slide so that the pattern is visible but as large as possible
2. Mark the locations of the intensity maxima. If they are too close to measure individually, mark of a set of them and determine the average spacing.

Question 1:

What distance between the slide and the screen did you use? What was the average distance Δy between maxima?

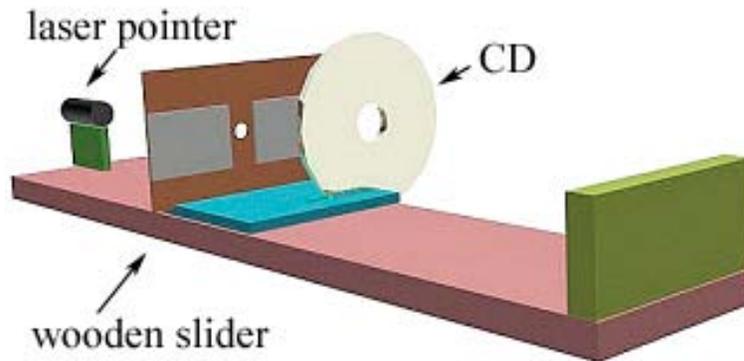
Question 2:

Using $\lambda = \frac{d\Delta y}{L}$, what do you calculate to be the wavelength of the laser light? Does this make sense?

Part 2: Diffraction from a CD

In this part you will determine the track width on a CD by measuring the distance between interference maxima generated by light reflected from it.

1. Remove the slide from in front of the laser pointer
2. Clip a card with a hole in it to the back of the wooden slide.
3. Place a CD in the groove in the back of the wooden slider. Light will pass through the hole in the slider and card, reflect off the CD, and land on the card.
4. Turn on the laser and measure the distance between interference maxima.



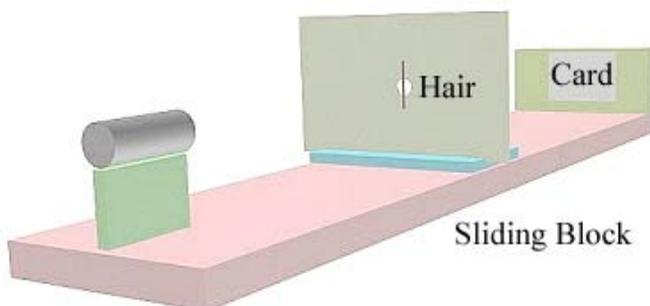
Question 3:

Using $d = \frac{\lambda L}{\Delta y}$, what is the width of the tracks? Does this make sense? Why are they that size?

Part 3: Thickness of Human Hair

Now you will measure the thickness of a human hair using diffraction.

1. Remove the CD and card from the wooden slide, and tape some hair across the hole (the hair should run vertically as pictured below).
2. Clip a card to the block at the end of the apparatus.
3. Shine the laser on the hair, and adjust the distance between the hair and the card so that you obtain a useable diffraction pattern.



Question 4:

What is the thickness of the hair that you measure? Does this seem reasonable?

Further Questions (for experiment, thought, future exam questions...)

- Instead of measuring the wavelength of light from the two slit patterns, you could have instead used single slits. Would that have been more or less accurate? Why?
- Why did you use two slit patterns to measure the light wavelength rather than pattern d.
- Where does most of the measurement error come from? How would you improve this in future labs?
- If we redid these experiments with a blue laser instead of red, what changes would you have needed to make? Would it have affected the accuracy of the measurements?
- Does the track width change as a function of location on the CD? If so, is it larger or smaller near the outside?
- What is the ratio of the track size to the wavelength of the light that you used (which is very similar to the wavelength of light used in commercial players)?
- What would happen to the diffraction pattern if the track width was smaller?
- Why are people anxious to move to blue lasers in commercial CD and DVD players?