Introduction

Equipment: In Part I you use a machinist rule, a laser, and a lab clamp on a stand to hold the laser at a grazing angle to the bench top. In Part II you use the laser, the lab clamp with stand, and a CD, DVD, and a Blu-ray.

Objective: In the lab you measure the wavelength of light from a red and blue laser using a simple machinist rule. Finally using the laser you measure the spacing between the rows of reflecting pits on an audio CD, DVD, and Blu-ray.
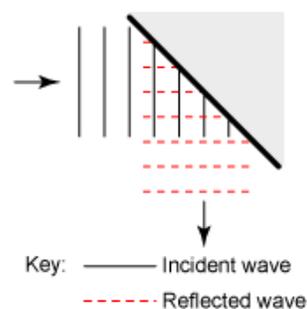
Part I: Measuring the Wavelength of Light

What happened to the law of reflection?

In this experiment we will use a steel ruler to measure the wavelength of light emitted by a laser. The laser produces a narrow intense beam of monochromatic (i.e., single wavelength) light. The ruler has a shiny, metallic finish. Consequently, if you reflect the laser light off the surface of the ruler, it behaves like a mirror with the angle of reflection equal to the angle of incidence.

Key: ———— Incident wave
      - - - - - Reflected wave

Reflection of Plane Wave

(Angle of incident = Angle of reflection)

However, if you shine the laser beam onto the part of the ruler where the black division marks are, a surprising thing happens: not only does the light reflect at the expected angle, but one observes that there are many *additional* reflections. One might wonder why the law of reflection suddenly seems to be violated just because there are some non-reflective marks on the ruler.
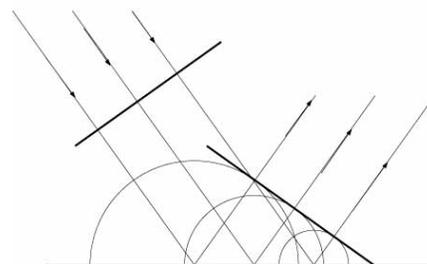
One way to think about this question is to use Huygens' wavelet picture in which all reflections are possible. That is to say, every point of the ruler bathed by the incoming laser light will be the source of new wavelets radiating out in all directions. There occurs a wholesale cancellation, *destructive interference*, for all these possible paths (of reflection) except for those paths whose length do not deviate much (less than λ) from the minimum path length. The minimum path is that for which the reflected angle equals the incident angle.

However, the non-reflective division marks on the ruler eliminate some of the possible reflections, thereby preventing this wholesale cancellation of paths. In other words, the additional bright spots one sees on the wall are due to reflections that are only possible because we are preventing them from being canceled by destructive interference. We secure *more* reflections by arranging for *fewer* possibilities of reflection!! Continuing with this line of reasoning thus suggests that the bright spots are due to *constructive interference*.
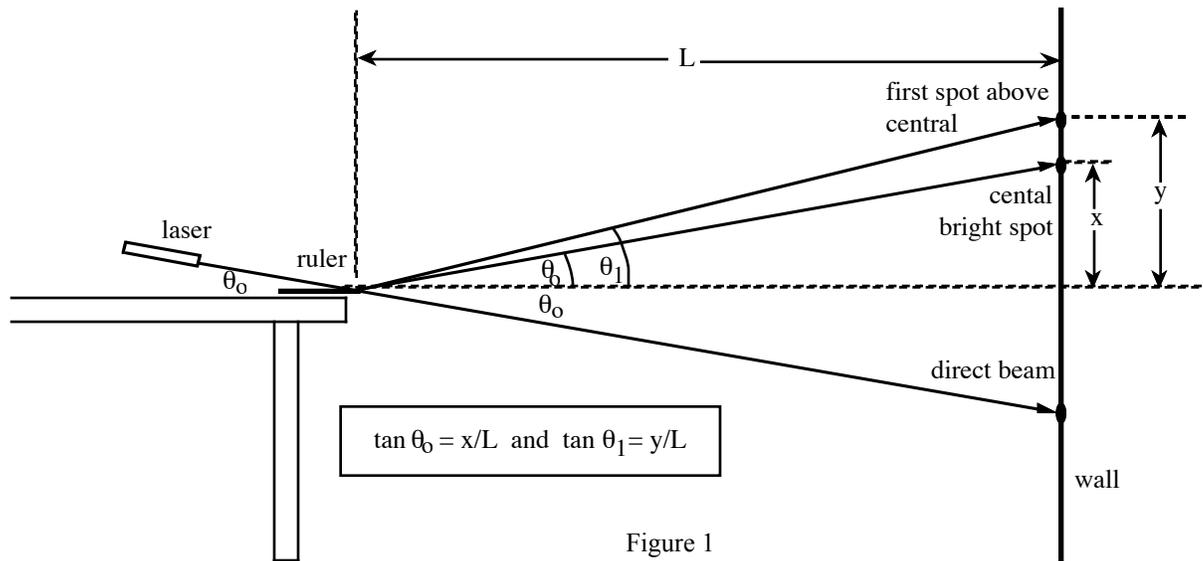
→ Note: The condition for constructive interference is that adjacent paths between wavefronts must differ in length by an *integral* number of wavelengths.

Figure 1, which is not to scale, shows the experimental arrangement. The ruler is placed on a table about 2 m (distance L) from the wall, and the laser is positioned so that the beam just strikes near the end of the ruler at a grazing angle. Part of the laser beam misses the ruler completely and continues undeviated to the wall ("direct beam"). Many reflections will appear on the wall, but, to keep the drawing simple, only two are shown in the figure. The brightest reflected spot, the central bright spot, corresponds to the reflection whose angle is equal to the angle, θ_O. Many more reflection spots, above and below θ_O, will be present.

$$\tan\theta_O = x/L \quad \text{and} \quad \tan\theta_1 = y/L$$
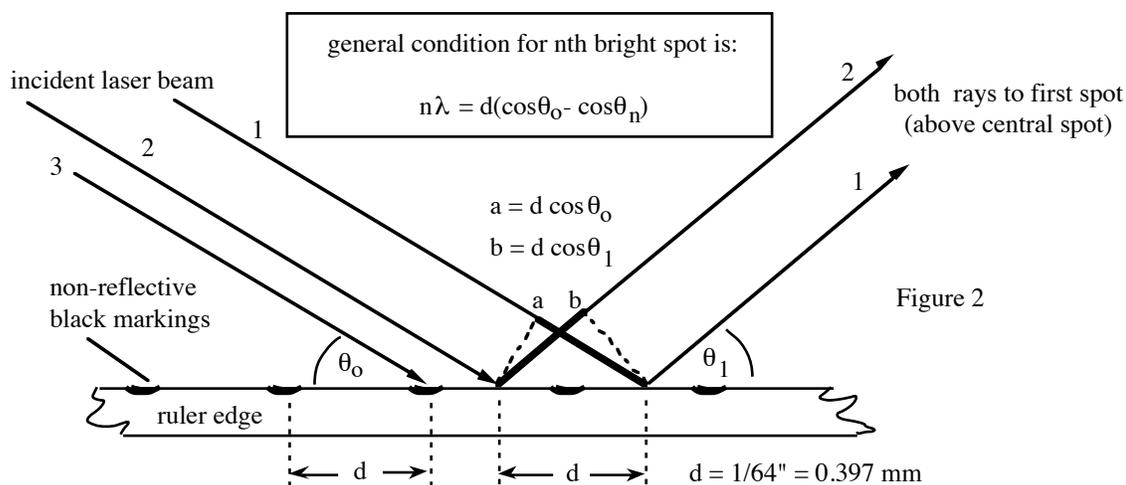
Figure 1

Let us now apply the condition for constructive interference to our specific geometry. A more detailed illustration is presented in figure 2; again, only a few paths are shown to keep the diagram simple. Incident laser beam rays, labeled 1 and 2, strike adjacent reflective surfaces on the ruler. Ray 3 happens to strike a black marking and we assume there is little or no reflection. The incident laser beam is actually broad enough to be incident across several reflective and non-reflective areas of the ruler, but that does not change our analysis of where on the wall we can expect to have constructive interference.

As shown in figure 2, ray 1 travels an additional distance (indicated by a heavy line and labeled "a") compared to ray 2 before it reaches the ruler. After the reflection, ray 2 travels an additional distance (also indicated by a heavy line, labeled "b") compared to ray 1 before it reaches the wall. The rays are *very* close together and the wall is *far* away so, for all practical purposes, the rays are considered to be parallel. We can now write the general condition for constructive interference for this particular geometry: the *difference* between paths 1 and 2 must be equal to an integral number of wavelengths.

$$n\lambda = a - b = d\,(\cos\theta_O - \cos\theta_n) \tag{1}$$

Here n is any integer and d is the spacing of the lines on the ruler.

→ Note that for n = 0, we simply have the condition that there is no difference in path lengths, which is the condition that the angles of incidence and reflection are equal and we have specular reflection.

2

general condition for nth bright spot is:

$$n\lambda = d(\cos\theta_o - \cos\theta_n)$$

incident laser beam

2 — both rays to first spot (above central spot)

$a = d \cos\theta_o$

$b = d \cos\theta_1$

non-reflective black markings

Figure 2

θ_o a   b θ_1

ruler edge

← d →   ← d →   d = 1/64" = 0.397 mm

When $\lambda \ll d$, as it is in this experiment, $(\cos\theta_o - \cos\theta_n)$ must be extremely small for equation (1) to be true if n is an integer ≈ 1. However, due to the way in which cosine varies with the angle for small angles, θ_o and θ_n can be large enough for easy measurement while $(\cos\theta_o - \cos\theta_n)$ remains very small. This is the secret why the *grazing* method will measure wavelengths that are very short compared to the relatively large spacing on the ruler. Note the grazing angle is the complement of the angle of incidence, and that all angles in the diagram are shown *greatly* exaggerated.

Measurement procedure

Allow the ruler to slightly overhang the edge of the table then adjust the angle of the laser beam. Place the laser about 35 cm above the table, and the ruler must be flat on the table.

Reflect the laser from a part of the rule where there are NO black divisions. Record the direct beam and the reflected beam directly on the paper on the wall.

Now reflect the beam from the part of the rule with black divisions. Notice that on your ruler there are a series of marks with different spacing and lengths interspersed.

→ **Make sure you are using *only* the 1/64" marks.**

Record as many spots as you can. Verify which set of marks are producing the spots you see on the wall by sliding the ruler to the left and right and see sets of spots appear and disappear.

The angles of incidence and reflection would be difficult to measure directly (with a protractor, for example). The geometry indicated in figure 1 shows you how to determine the angles by distance measurements.

→ Hint: The distance from the central bright spot to the place where the direct beam strikes the wall is 2x (see figure one).

Make several measurements and determine θ_0, θ_1, θ_2, and θ_3 then use equation (1) to determine the wavelength of the laser light.

Q1.) In your lab create a diagram that documents all of the length parameters for your set-up.

Q2.) When the laser hits the center of the ruler with no black markings what do we see and why?

Q3.) Now when the laser is grazing along the 64ths mark why are we getting a diffraction pattern?

Q4.) If you changed the spacing of the ruler from 1/64th to 1/32nd then how would the diffraction pattern change? Explain

Q5.) Include a table with the data taken for the diffraction pattern.

Q6.) From equation 1 figure out how to graph the data to calculate the wavelength of the laser. Show your work and explain your reasoning.

Q7.) Include the graph with all needed labels. Make note of the slope.

Q8.) If you change the wavelength of light used in the ruler experiment from red to blue will the diffraction spacing increase or decrease? Explain and then try it.

Part II: Determining the Amount of Data on a CD

Now that you have measured the wavelength of the laser using a ruler, you can use the laser as a "ruler" to measure the spacing between tracks on a compact disc (CD)! Thus, you may determine the maximum amount of information that can be stored on a CD.

CD diffraction

The bottom of a CD is a highly reflective surface containing a spiral of "pits". If stretched out, this spiral would be about 5 km long! The digital data are defined by the pit length and the distance between pits. The pits are arranged in a fashion similar to that shown in figure 3. The depth of a pit is 0.11 μm and the width is 0.5 μm. Its length varies between 0.83 and 3.56 μm.
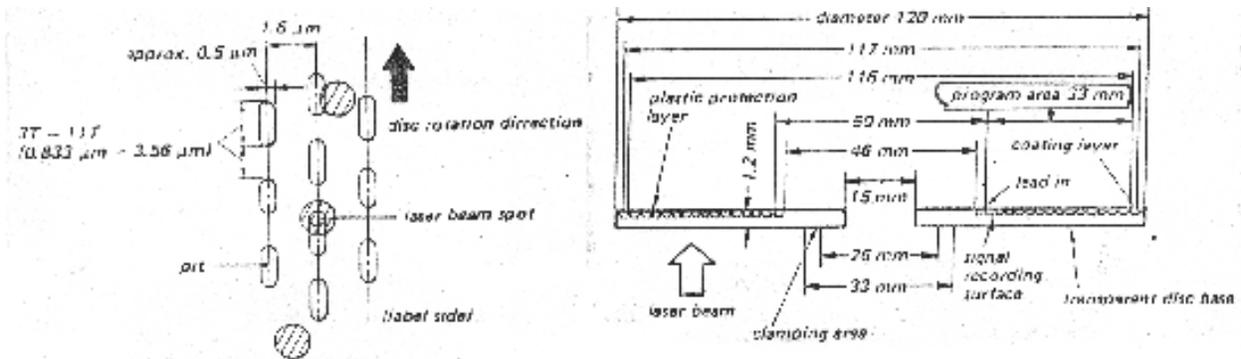

Figure 3

The spiral of pits behaves in much the same way as a reflective diffraction grating. That is why you see beautiful rainbow colors when white light illuminates the CD. When a laser beam is reflected off the disc, a diffraction pattern is formed.[1] If the angle of incidence is close to the normal, the condition for constructive interference is identical to that for a transmission diffraction grating, which is discussed in your textbook:

$$d \sin \theta = n\lambda ,$$ (3)

where n is the diffraction order, d is the slit spacing, and θ is the angular position of the nth maximum. In the present example, the rows of pits behave like reflective slits, and the distance between the rows of pits, d, can be estimated by

$$d = \frac{n\lambda}{\sin \theta} \quad . \tag{4}$$

By measuring θ and using your value of λ from Part I, you can use equation (3) to calculate the distance between rows of pits. The experimental arrangement is illustrated in figure 4.

Measurement procedure

Arrange a disc, laser, and screen in a manner similar to figure 4a. Direct the laser beam such that it strikes the CD approximately half way up, as shown in figure 4b. Adjust the angle between the laser beam and the CD until the specular reflection is just above the laser. Doing this will insure that the incident laser beam is normal to the surface of the CD. This arrangement will give you a horizontal diffraction pattern on the screen with a central bright spot followed by the first-order maximum, etc.

Q7.) Determine the angular position, θ_1, of the first-order maximum, from the geometry of your experiment, then calculate the spacing d with equation (3) Show all work.

Figure 4a

4b
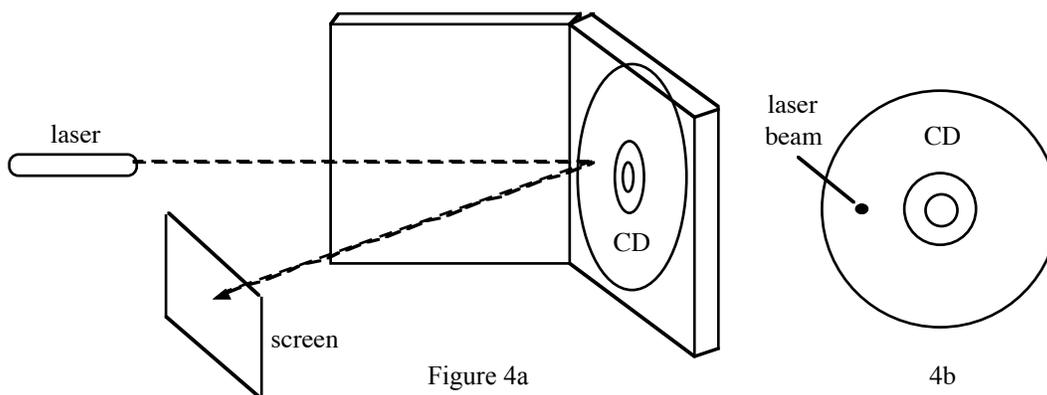
Q8.) Try it for a DVD. How did the interference spacing change? Explain why this makes sense.

Q9.) Try this for a Blu-ray disc. This may require a change of orientation. (Hint: returning to the grazing angle method may give better results.)

You may be interested to know that the table of contents for the whole CD is recorded on the lead-in portion consisting of about 30 tracks (one track equals one trip around the disc). The width of this program area corresponds to the thickness of one human hair. To detect individual pits, the laser beam must be focused down to a spot about 1μm in diameter. This should give you an idea of how remarkably spatially coherent the light is and an appreciation for the technological obstacles that must be overcome to track these bits of information. The CD player is literally operating at the diffraction limit (resolution) of light! And now we have DVD discs! Check the table below for a

comparison between DVD and CD discs.

Specifications	CD	DVD	Blu-ray
Disc Diameter	120 mm	120 mm	120mm
Disc thickness	1.2 mm	1.2 mm	1.2 mm
Disc structure	Single substrate	Two bonded 0.6mm substrates	Two bonded substrates 1.1mm disc and .1 mm protective layer
Laser wavelength	780 nm (infrared)	650 and 635 nm (red)	405 nm (blue)
Numerical aperture	0.45	0.60	0.85
Track pitch	1.6 μm	0.74 μm	0.32 μm
Shortest pit/land length	.83 μm	0.4 μm	.075 μm
Data layers	1	1 or 2	1 or 2
Data capacity	680 megabytes	Single layer 4.7 gigabytes Dual layer 8.5 gigabytes	25 GB single layer 50GB dual layer
Data rate	Data rate 165 kilobytes/sec	Data rate 1,000 kilobytes/sec	36Mbps with room to go much faster

Blu-rayspecs:
http://www.bluraydisc.com/Assets/Downloadablefile/BDROM_physical_format_specifications-18327.pdf

Photograph of pits on a CD. From: *On the Surface of Things* by Felice Frankel and George Whitesides, (Chronicle Books, 1977).