Diffraction and the Wavelength of Light

Goal: To use a diffraction grating to measure the wavelength of light from various sources and to determine the track spacing on a compact disc.

Lab Preparation

Light is an electromagnetic wave, like a radio wave, but very high frequency and very short wavelength. Different colors of light have different wavelengths. The eye can detect wavelengths ranging from about 400 nm (violet) to 700 nm (red).

The distribution of wavelengths of light given off by a particular source is called the spectrum of that source. An incandescent lamp gives off a continuous spectrum containing all wavelengths in the visible part of it, from red to violet. A laser emits light of a single wavelength. A spectral lamp that contains the excited vapor of a particular element emits a spectrum that contains a few discrete wavelengths that are characteristic of that atom. The object of this experiment is to measure some of these wavelengths, and then to use observations of diffraction from a compact disc to infer spacing of information stored on the CD.

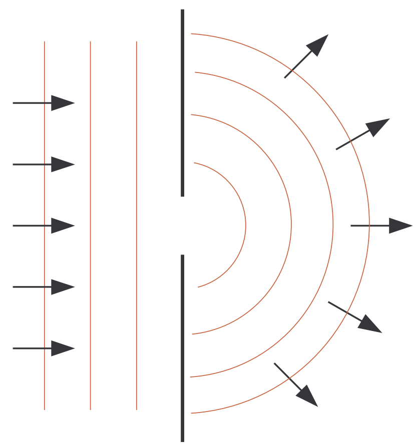

Figure 1

The word "diffraction" refers to the spreading out of waves after passing through a small opening (Figure 1). Diffraction effects are important when the size of the opening is comparable to or less than the wavelength.

To measure wavelengths, we need a device that can split a beam of light up into different wavelengths. Such a device is a <u>diffraction grating</u>. A transmission diffraction grating consists of a very large number of equally spaced parallel lines scratched on a transparent surface. The diffraction gratings used in this experiment are plastic replicas of a master grating, made by pressing the plastic against the master grating, which acts as a mold. A diffraction grating behaves as if it were a series of slits in an opaque screen.

Consider a diffraction grating consisting of a very large number of slits. When all the waves spreading out from all the slits are added up, they cancel out everywhere except in certain directions along which all the crests of all the waves exactly coincide and add up constructively. These particular directions are determined by the wavelength of the light, λ, and the distance d, between centers of adjacent slits in the grating, known as the grating spacing. An example of the constructive interference that arises for just two slits is shown in Figure 2.

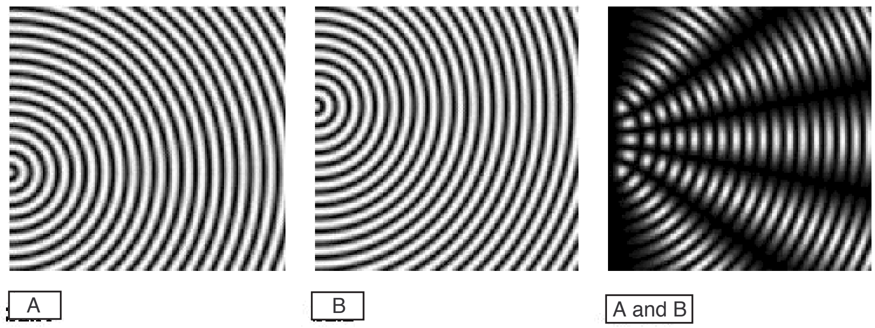

Figure 2

The patterns that arise for more than two slits sharpen the directions of the brightest regions. For a diffraction grating, the directions of maximum intensity can be specified by a series of angles. Consider Figure 3 below. The angles are measured relative to the line $\overline{OP}$, which is parallel to the light falling on the diffraction grating initially.

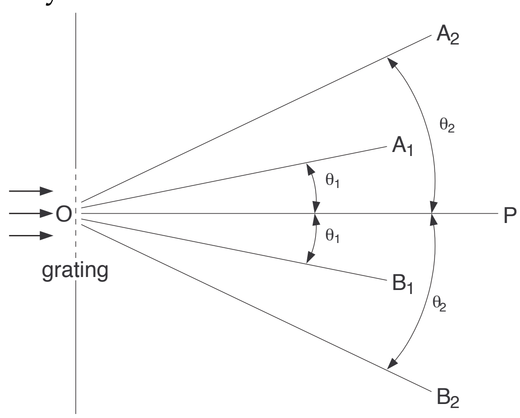

Figure 3

On either side of $\overline{OP}$ are two directions of maximum intensity (lines $\overline{OA_1}$ and $\overline{OB_1}$) known as the "first order" maxima, at angle θ_1 given by

$$\lambda = d sin\theta_1$$

Two other directions are lines $\overline{OA_2}$ and $\overline{OB_2}$ (the "second order" maximum) at angle θ_2 given by

$$2\lambda = d sin\theta_2$$

Higher order maxima may be observed at angles given by the general formula

$$m\lambda = d sin\theta_n \text{ with } m = 1, 2, 3, \ldots$$

The diffraction gratings used in this lab have 600 lines per mm. So the spacing d between lines is simply

$$d = \frac{1.00\ mm}{600} = 1.67 \times 10^{-3} \text{ mm} = 1670 \text{ nm}.$$

***Be extremely careful with the laser. Do not look directly in the laser beam and never aim it at another person.**

<u>Procedure</u>

I. <u>Measuring the wavelength of a laser</u>

A. Set up Figure 4 using the laser, diffraction grating, and meter stick. The distance L should be about 50 cm and the diffraction grating used here contains 600 lines per mm. Take special care to ensure the incident laser beam is perpendicular to the meter stick and the grating. The accuracy of your measurements here will influence later measurements in the lab. Make adjustments until you are able to view 1st and 2nd order spots on the meter stick.

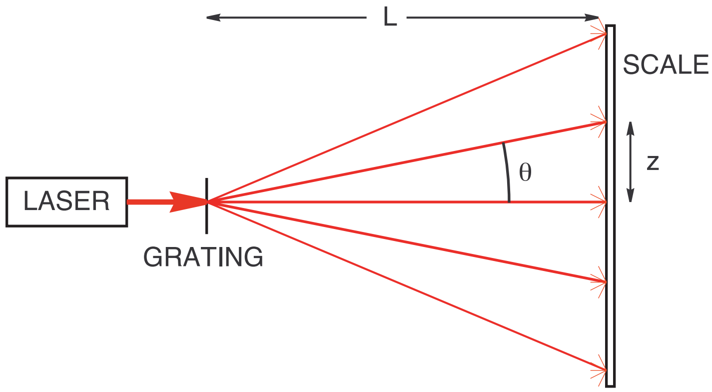

Figure 4

B. Measure and record the location of the first order spots on either side of the central spot (z and z') in a table similar to the one below. Compute the average z and use it to find θ (note: $\tan\theta = \frac{z}{L}$ as shown in Figure 4). Use θ to find λ.

m	z	z'	z_{av}	θ	λ
1					
2					

C. Repeat the measurements and calculations for the second order spots.

II. <u>Measuring discrete wavelengths in an atomic spectrum</u>

A. Position the gas discharge lamp directly behind the screen with the single slit and place the meter stick in the holder as shown in Figure 5.

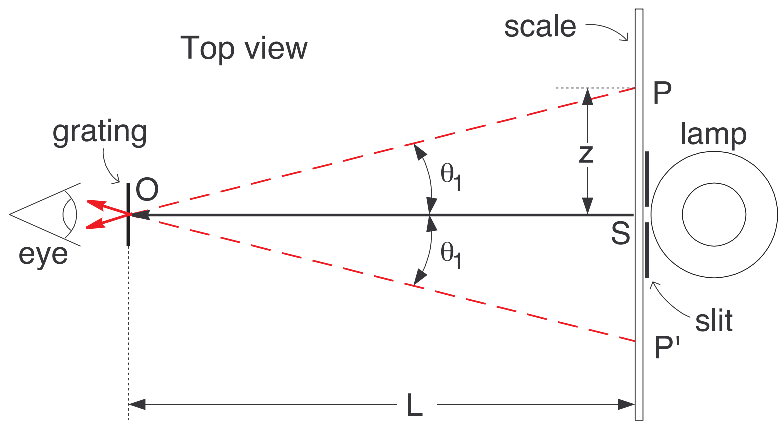

Figure 5

The diffraction grating is mounted at O, at a distance L (30 - 50 cm) from the meter stick so the line from the center of the diffraction grating to the slit (line $\overline{OS}$) is perpendicular to the scale on the meter stick.

Light from the slit S travels along the line $\overline{OS}$ to the grating and is then split up into different orders by the grating before entering the eye. The first order colors are the ones you observe closest to the slit. Higher orders are further away from the slit.

Consider the first order: light enters the eye at an angle θ_1 to the line $\overline{OS}$; it will appear to the eye that this light is coming from point P on the scale at a distance z from the slit S. In fact, for every wavelength coming from the source, there will be a different "image" of the slit at a different point P. The same thing is happening at P' on the other side of the slit to produce another image.

B. Place your eye as close as you can to the diffracting grating and look through it at the scale. You should be able to observe different colors when looking to the left (point P) and then observe the same colors looking to the right (point P'). If you look further to the left and right you should be able to see the 2nd order lines.

C. To measure a particular wavelength, select one of the brightest lines in the spectrum, focus your eyes on the scale and record the distance z from the slit S to the point P. Record the result and color in a table similar to the one below. Repeat the measurement on the other side (z') at point P'.

Discharge tube gas:				$L =$	
Color	z	z'	z_{av}	θ	λ
. . .					

D. Find the average of z and z', measure L and use these to calculate the angle θ. Use this angle to calculate the wavelength λ (recall that $d = 1670$ nm).

E. Repeat steps C and D for two or three more lines in the spectrum. Choose the brightest lines you observe. Make sure you record what type of discharge tube you used on the top of the table.

III. <u>Measuring wavelength for white light</u>

Replace the discharge lamp with an incandescent lamp so that white light shines through the slit. Once again place your eye close to the diffraction grating and observe. Since the whole spectrum of white light is coming through the slit you should see a continuous spectrum off to each side rather than the discrete lines that appeared in part II.

Measure as closely as you can the upper and lower limits (the z values as in part II) of the continuous spectrum (in other words, find the violet cut-off and the red cut-off of the spectrum). Use these values to determine the wavelength range of the continuous spectrum.

IV. <u>Measuring the track spacing on a compact disk</u>

Light reflected or scattered from an object with a repeating structure can exhibit interference patterns. The constructive interference of reflections from such an array will produce a diffraction pattern that is determined by the wavelength of the light used and the spacing of the repeating structures. Light normally incident on a line of regularly spaced reflectors with a spacing d will add constructively in only those directions for which light from each reflector arrives "in phase" with light from its neighbors. For light reflected or scattered from two adjacent sites in the line, the path length difference must be an integer number of wavelengths, $\Delta L = L_1 - L_2 = n\lambda$. (see Figure 6).

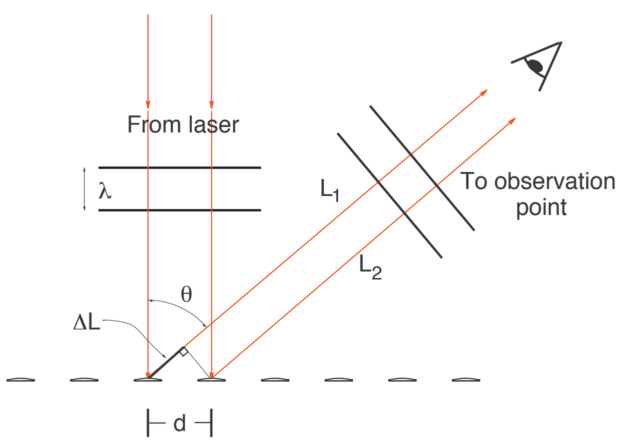

Figure 6

When the observation point is far (many wavelengths) away, the paths of waves reflected or scattered from adjacent sites are practically parallel, and the extra path length ΔL is just $d\sin\theta$. The constructive interference condition is the same as for the diffraction grating used in the preceding parts: $d\sin\theta = m\lambda$. Using laser light of known wavelength, measuring λ allows a determination of d.

Information on compact disks is stored by several techniques. Mass produced music or software CD-ROMs store information by small permanent indentations or pits pressed into a plastic disk with a thin reflective metallic film coating. The presence or absence of indentations causes a change in reflected light from a sharply focused laser. These variations are measured and decoded to reconstruct the data, where each pit (or its absence) represents a single bit of information. Individually produced CDs use other techniques to create variations in the reflective film's properties, which can be permanent (CD-R) or reversible (CD-RW). The data is arranged in concentric tracks. A laser spot that is spread over several square millimeters of the surface will sample many tracks, and the CD's tracks will act like a reflection diffraction grating as in Figure 6.

A. Set up Figure 7 to help measure the *reflection* diffraction pattern from a CD. Be careful setting this up and make sure the laser is reflecting towards the nearest wall and not out where is can hit other people.

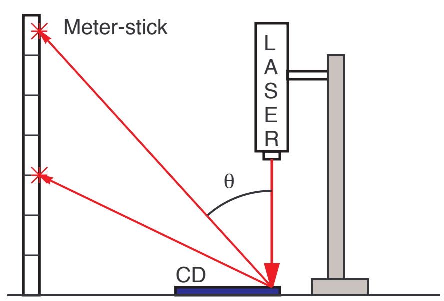

Figure 7

B. How many diffraction spots are observed? Determine (by measuring the necessary distances) the angles, θ_m. What value of m does each spot correspond to? (Hint: where will the $m = 0$ diffraction spot appear?)

C. Based on the observed diffraction pattern and your measured value of λ for the laser light, calculate the spacing, d, between tracks on the CD.

*__When finished with your lab clean up your lab station.__

Homework: For part III compare your values to the known wavelength range for the visible spectrum.