Physics 145: Interference and Diffraction

What's the point?: To quantitatively study the wave properties of light and gain experience in making precision optical measurements

Equipment: Mercury discharge lamp, optical bench with lens holders, optics set (slits, lenses, mirror, grating, micrometer eyepiece)

Introduction:

Like other fundamental quantum-mechanical entities, light exhibits **wave-particle duality**, as manifested by alternative descriptions such as **photon particle** or **electromagnetic wave**. In **ray optics** we consider reflection and refraction in terms of particles or rays of light that follow straight geometric paths. In contrast, when light spreads out after passing through a narrow slit, bends around a corner, or overlaps on itself, we treat it using **wave optics**. In this lab, we will specifically explore the wave properties of light.

The **Principle of Wave Superposition**, an important behavior of light, states that when two waves pass through the same place at the same time, the resulting **amplitude** (i.e. electric field) is the sum of the amplitudes of the two individual waves. Because a wave amplitude can be either positive or negative at a given time and place, such a sum can produce a total amplitude that is either larger or smaller than the individual contributions. When the waves add together to produce a larger amplitude, we speak of **constructive interference**. When they cancel each other out (either partially or completely), we speak of **destructive interference**. When many waves are superimposed to produce a resultant wave, the interference is called **diffraction**.

We don’t typically notice interference effects in everyday life because ordinary light sources are generally **polychromatic** (i.e. a mixture of many colors) and **incoherent** (a mixture of many wave phases). A few common diffraction examples are the "star" pattern surrounding a street lamp when viewed at night through a window screen and the floaters that you see when you look up at a clear sky or a well-lit white screen. It is far easier to directly observe the wave properties of laser light because it is both **monochromatic** (one color) and **coherent** (all of the wavelets emitted from the source are in phase with one another so as to create well-defined crests and troughs).

Double-slit Interference:

The simplest manifestation of the wave nature of light is double-slit interference, as illustrated in Figure 1. When a coherent light wave impinges on the two slits from the left, the rays exiting the slits will be in phase at the instant that they pass through. However, due to the different path lengths L_1 and L_2 traveled by these rays before reaching a common point on the right-hand screen, their phases will differ when they reach that point. In fact, this **phase difference** (δ) will vary across the face of the screen as $\delta = 2\pi(L_1 - L_2)/\lambda$ so that the superposed amplitude varies as $A \propto \cos(\delta)$ and the **intensity** as $I = |A|^2 \propto \cos^2(\delta)$. The intensity is what we observe with our eyes, though there are measurement devices can directly measure amplitude.

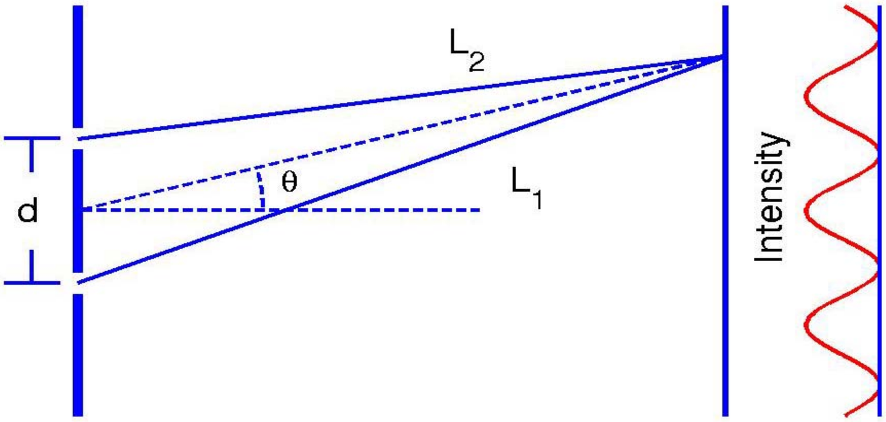

Figure 1: Geometry for the double-slit interference experiment

The net result is that interference maxima (i.e. constructive interference) occurs at angles θ that obey the expression $L_2 - L_1 = m\lambda \cong d\sin\theta$, where m is any integer, while the interference minima (destructive interference) will occur at angles that obey $L_2 - L_1 = (m + 1/2)\lambda \cong d\sin\theta$, where m is any non-zero integer. One can use such a pattern to actually measure the wavelength of a monochromatic source such as a laser or a gas-discharge tube, so long as the slit spacing is not wider than the limited spatial-coherence length of the tube source. Although lasers are much simpler to work with, it will be instructive here to perform the interference experiment using a mercury vapor discharge lamp as illustrated in figure 2. In this configuration, the first slit (towards the left) acts a point source, which the second lens defocuses into a parallel beam. The multiple waves of light passing through experiment slits then create an interference pattern at the right. Using the terminology of ray optics, this pattern is an object that the eyepiece transfers to an image approximately located on the retina of the viewers eye. The scale at the object location allows one to conveniently measure the inter-maxima spacing and hence the wavelength.

Diffraction gratings: When the double slits are replaced by many slits, the same equation which gives the positions of interference maxima still applies, though the interference maxima become brighter and much narrower while the interference minima become darker and broader. You may also be able to observe secondary maxima between the bright spots in the interference pattern. You may wish to browse an introductory physics textbook or the Hyperphysics sections on *Interference* and *Diffraction* to find more detailed information.

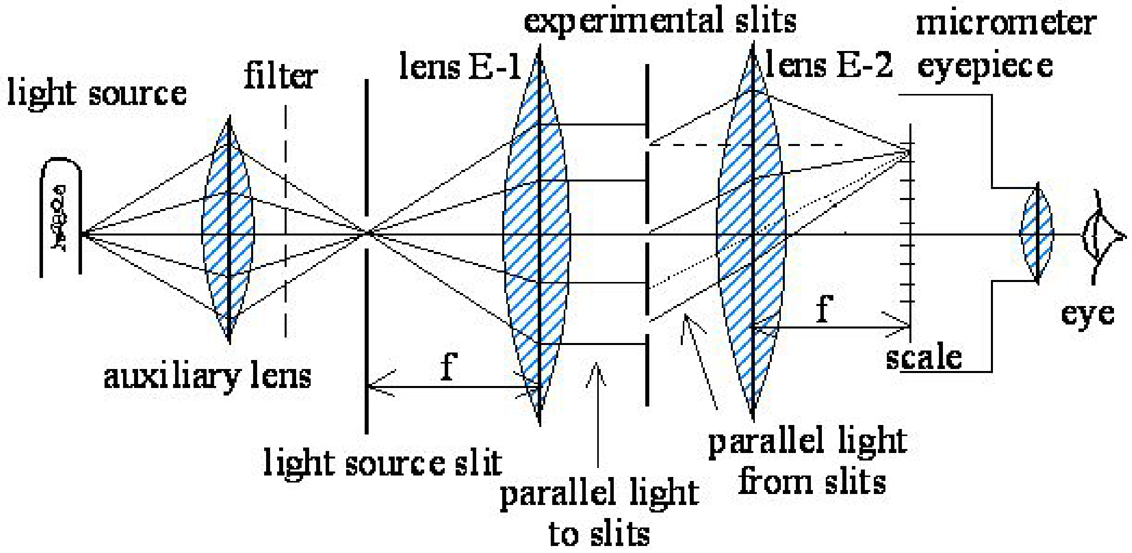

Figure 2. Optical configuration for studying the interference of light

PROCEDURE

A. Configuration: First set up the equipment as illustrated in Figure 2 without any slits in the slit holder. Make sure that the vertical height of the lamp is positioned within its lamp shield so as to optimize the intensity emerging from the output ports. If multiple teams are using different ports of the same lamp, this height can't be adjusted again once the subsequent alignment steps are underway. Each port has a removable white plastic diffuser that allows you to dim the intensity of the light. When the diffuser is not in place, you should avoid looking directly into the port. After this alignment procedure has been completed, you will probably want to remove the diffuser to maximize the intensity of the interference pattern. Now take the following steps to align the optics. You will save a great deal of time by being very careful.

1. Set the center of all three lenses, the source slit, the micrometer eyepiece, and the slit holder at the same vertical height as your light port to within a few millimeters. Be careful to maintain this vertical alignment throughout the lab. Don't bump the lamp after alignment!!!

2. Orient the optical bench so that it is roughly parallel to the direction of the port that you are using. Roughly set the positions of the optical elements on the optics bench. Place the micrometer eyepiece near the far end of the optical bench. Place one lens labeled "E" about 20 cm from the eyepiece. (Note that the focal length of lens E is approximately 20 cm). Place the second E lens about 15 cm from the first. Place the source slit about 20 cm from the second lens. Place the auxiliary lens (which is probably labeled "M") so that the light from the lamp is nicely focused on the source slit. You will need to remove the diffuser for this.

3. Carefully slide your optical bench side to side until the beam is centered on the source slit.

4. By using a sheet of white paper, you should be able to see a bundle of light coming from the source, going through the source slit, passing through each of the lenses, and focusing

somewhere near the center of the eyepiece. If this is not the case, try adjusting the orientation of the optical bench. This will mean repeating steps 2 and 3 again afterwards. If necessary, go back to step 1 and be more careful.

5. You must now place lens E-1 so that the source slit is precisely at its focal length. To do this, place a mirror behind the lens and reflect the light back through the lens to form an image precisely in the plane of the source slit. Use a sheet of paper for a screen.

6. Now cover the light source with the diffuser and look into the eyepiece. Focus lens E-2 until you see a clear image of the source slit. This image should be near the center of your field of view in the eyepiece. If it is not, adjust the position of the source slit slightly sideways. If you move the slit, you may need to go back to step 3 again. Just to be sure that everything is properly aligned, insert the grating into the slit holder. You should clearly see a diffraction pattern with several colors present.

B. Qualitative observations (provide an explanation for each response):

1. Insert the green filter so that only the green mercury line is visible at the eyepiece. Then insert the single-slit slide (containing slits of various widths) between the E-1 and E-2 lenses. Which of the single slits does the best job of resolving the higher-order lines, the widest or the narrowest? Explain why.
2. Change filters to isolate the red line and try again. Which color has lines that are easier to resolve, red or green? Explain why.
3. Now insert the double-slit slide (containing slit pairs with various spacings) between the E-1 and E-2 lenses. Use the aluminum aperture to make sure that only one pair is illuminated. Which slit pair has the best resolving power, large or small spacing? Explain why.
4. Finally, insert the grating in place of the double-slits, and compare its performance to those of the single and double slits.

C. Quantitative wavelength measurements: For each of two different mercury lines (i.e. colors) that you select, identify the filter (or filter combination) that best isolates it. Then measure the wavelength of that line using the best double-slit pattern and using the grating. It will be helpful to note the following:

1. $\tan(\theta) = \frac{x}{f}$, where x is the displacement of a given line relative to the center of the eyepiece scale (one full turn is 0.01 inch), and f is the 20 cm focal length of the E2 lens.
2. Slit-spacings can be accurately measured using the low-power microscope in the lab which has a ruled eyepiece. One full turn on the microscope dial is 0.002 inch.
3. It may be helpful here to remember that for small angles (in radians), $\theta \approx \sin\theta \approx \tan\theta$. A more accurate measurement of the spacing can be obtained by measuring the width of the entire pattern and then dividing the number of maxima in the pattern.