Lab 3

Interference and Diffraction

In this lab you will quantitatively study diffraction of light and gain experience in making precision optical measurements.

3.1 Spectral Lines

In lab 1, we studied *ray optics* where light is considered to follow straight geometric paths. This works well for the large overall features of light. In contrast, on a smaller scale, we must consider light as a wave, which spreads out after passing through a narrow slit, bends around a corner, or overlaps on itself. In this case, we must treat light using *wave optics*.

The principle of *wave superposition* states that when two light waves pass through the same region of space, the resulting *amplitude* is the sum of the amplitudes of the two individual waves. When the waves add together in phase to produce a larger amplitude, we speak of *constructive interference*. When they add together out of phase to cancel each other out (either partially or completely), we speak of *destructive interference*. When many waves are superimposed to produce a single resultant wave, the interference is called *diffraction*.

It is easiest to 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). It is more difficult to see wave interference effects from ordinary light sources (e.g. sunlight, incandescent and fluorescent bulbs, LEDs, etc.), which are generally *polychromatic* (i.e. a mixture of many colors) and *incoherent* (a mixture of many wave phases).

3.2 Double-slit Interference

The simplest manifestation of the wave nature of light is double-slit interference, as depicted in Fig. 3.1. When a coherent light wave impinges on the two slits from the left, the wavelets exiting from each slit are in phase. However, as each wavelet travels a different distance \( L_1 \) and \( L_2 \) to a point on a distant screen, their

![Figure 3.1 Young's double slit diffraction.](image-url)
phases become different. This phase difference is \( \delta = 2\pi (L_1 - L_2)/\lambda \), which leads to a superposed amplitude proportional to \( A \propto \cos \delta \). The intensity of the light (which our eyes detect) varies as the square of the amplitude: \( I = A^2 \propto \cos^2 \delta \). The interference maxima (i.e. constructive interference) occur when the path difference is a whole number of wavelengths:

\[
L_2 - L_1 \equiv d \sin \theta = m\lambda \quad \text{(maximum)} \quad (3.1)
\]

where \( m \) is any integer. The minima (destructive interference) occur in between the maxima at angles that obey

\[
L_2 - L_1 \equiv d \sin \theta = (m + 1/2)\lambda \quad \text{(minimum)} \quad (3.2)
\]

For small angles \( \sin \theta \equiv y/L \), where \( y \) is the vertical position on the screen (see Fig. 3.1) and \( L \) is the distance from the slits to the screen.

### 3.3 Diffraction gratings

When a double-slit arrangement is replaced by a diffraction grating consisting of many equally-spaced slits, Eq. (3.1) still governs the interference maxima, although the peaks become very sharp. A diffraction grating has three key parameters, 1) slit spacing, 2) slit width and 3) slit number. For example, a narrower slit width yields a broader diffraction envelope, within which one can observe many interference peaks, but doesn't change the width or spacing of the peaks. A smaller slit spacing yields a larger separation between two adjacent interference peaks, but doesn't change the width of the peaks or the size of the envelope. A larger number of slits yields sharper interference peaks, but doesn't change the peak spacing or the size of the envelope.

You can browse an introductory physics textbook or the Hyperphysics sections on Interference and Diffraction for more detailed information. Good resolution refers to the ability to distinguish between peaks arising from different wavelengths (when the grating is illuminated with more than one wavelength). A grating has much higher resolution than a double-slit arrangement.

### 3.4 Diffuse Light Source

One can use a grating to measure the wavelength of a monochromatic source, so long as the slit spacing is not wider than the spatial-coherence of the light. This is a piece of cake if you illuminate the grating with a laser; all of the slits get the same phase. However, in research one often desires to characterize the spectrum of a non-laser or diffuse light source. This presents a challenge because the wavefronts from such a source are typically incoherent, meaning the phases of the light across a region of space are jumbled. Without taking special measures, the each grating slit would be somewhat random phase and ruin the grating diffraction pattern.
In this lab, you will study the spectrum from a mercury vapor discharge lamp, which like any diffuse source has poor spatial coherence. We will get around this problem with the setup illustrated in Fig. 3.3. First, the light from the lamp is concentrated onto a single narrow slit using an auxiliary lens. A lens (E-1) placed after the narrow slit is used to collimate the light. This creates nice spatially coherent wavefronts to illuminate the lens.

After the light goes through the grating, we could observe the diffraction pattern on a far-away screen. However, because we lose so much light in our effort to make it spatially coherent, it will be rather hard to see. We can image the pattern that would have appeared on a distant screen to the focus of a second (E-2). This creates a tiny diffraction pattern at the focus of the lens. The angles of the peaks scale with distance. In place of \( \sin \theta \equiv y/L \) for a distant screen, we have \( \sin \theta \equiv y/f \), where \( f \) is the focal length of the lens (E-2). Because the pattern is so small, you will use a microscope to look at it. Tick marks in the microscope will allow you to conveniently measure the inter-maxima spacing and hence the wavelength of the light source.

### 3.5 Equipment

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

Q3.1 While type of light source is both monochromatic and highly coherent?
(a) sunlight
(b) neon lamp
(c) red light-emitting diode
(d) blue laser
(e) common fluorescent bulb

Q3.2 Red $\lambda = 635$ nm light that passing through a $d = 0.1$ mm double-slit aperture illuminates a large white screen 75 cm from the aperture. At the center of the resulting interference pattern, compute the angular separation (in radians) and the distance (in cm) between two adjacent peaks.

Q3.3 Qualitatively describe what happens to a grating diffraction pattern when we increase the number of slits while holding the slit width and slit separation constant. Visit the Hyperphysics website and browse the section on Light and Vision → Diffraction → Multiple Slits.

Q3.4 In Fig. 3.3, the purpose of the “auxiliary lens” (at left) is to
(a) remove unwanted rays of light that are heading in undesirable directions.
(b) concentrate light from the lamp onto a slit-shaped source object.
(c) correct aberrations in the wave front.
(d) collimate the light (i.e. make the beam parallel and the wave fronts flat).
(e) focus the diffraction pattern onto the plane of the scale.
(f) create a focused image of the “experimental slits”.
(g) transfer an image of the diffraction pattern onto the viewer’s retina.

Q3.5 Consider the two diffraction patterns shown in Figs. 3.4 and 3.5. Which one is a double-slit pattern and which is a single-slit pattern?
Exercises

A. Preliminary: Work together as a class to view the double-slit patterns from two lasers, 473 nm (blue) and 633 nm (red), on a distant white wall, as shown in Fig. 3.1. Use the smallest double-slit spacing available on your slide. Measure the fringe spacing, and use the relation \( \frac{\lambda}{d} = \frac{\Delta x}{L} \) to determine the slit separation \( d \). Check the slit separation using the microscope eyepiece with adjustable cross hairs (see part 2 of L3.7).

B. Configuration: Set up the equipment as illustrated in Fig. 3.3 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 (three ports per lamp). If multiple teams are using different ports of the same lamp, this height cannot 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.

L3.1 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!!

L3.2 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 the E-2 lens about 20 cm from the eyepiece. (Note that the focal length of lens E-2 is approximately 20 cm). Place the E-1 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.

L3.3 (a) Carefully slide your optical bench from side to side until the beam is centered on the source slit.
(b) 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.
(c) You must now reposition lens E-1 so that the source slit is precisely at its focal length. To do this, use a flat mirror to 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.

L3.4 Now cover the light source with the diffuser and look into the eyepiece. Adjust the position of 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 find that this is a large adjustment, 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 multicolored diffraction pattern with a bright white line at the center of the eyepiece.

C. Qualitative observations

L3.5 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.

L3.6 Change filters to isolate the red line and try again. Which color has lines that are easier to resolve, red or green? Explain why.

L3.7 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.

L3.8 Finally, insert the grating in place of the double-slits, and compare its resolution to that of the single and double slits.

D. Quantitative wavelength measurements

L3.9 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 each line twice, once using the best double-slit pattern and once using the grating. It will be helpful to note the following:

1. For small angles (expressed in radians) \( \theta \equiv \frac{y}{f} \) where \( y \) 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. 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.