Wave Optics: Diffraction and Interference

(A short report is required for this experiment)

Light as a Wave

In previous experiments, we studied reflection, refraction, and the formation of images by thin lenses. To interpret these observations, it was sufficient to consider light as composed of rays, which travel in straight lines, and which are bent at the interface between different materials.

However, there are many observations that can be explained only by considering the wave nature of light. The intensity of a wave is proportional to the square of the wave amplitude. All waves (including light waves) are combined according to the superposition principle. This states that waves are combined by adding their amplitudes, not their intensities. Where two identical waves are in phase with each other, the total amplitude is twice the amplitude of a single wave. The intensity is proportional to the square of the amplitude, hence four times the intensity of a single wave. Where they are out of phase with each other the amplitude and intensity are both zero.

In this experiment you will observe the diffraction pattern created by light passing through a narrow slit, and the interference pattern formed by light passing through two or more closely spaced slits. Other apertures and a diffraction grating will also be used. The theory is covered in your text, and is not reproduced here. The patterns will be observed visually on a screen, and measured with a ruler.

The Laser

The light source in these experiments is a helium-neon (He-Ne) laser. The laser is used because the light (a) is intense, (b) is in a narrow beam of nearly parallel light, (c) has a single wavelength of 632.8 nm, and (d) is coherent, i.e., the light waves have a fixed phase over many a large number of periods. We can regard any beam of light as a large number of wave trains traveling in the same direction. For a laser beam, these trains are very long, more than a million times the wavelength. The coherence length can be more than 1 m, even as long as 100 m.

Do NOT look directly into the laser beam! Although the lasers we use are relatively low power, they can cause discomfort, and perhaps damage, if you look directly into the laser beam.

A. Diffraction by a Single Slit

When a water wave is blocked by a barrier, it can go around it according to Huygen’s principle: every point on the unblocked wavefront is a new source of wavelet, and these wavelets can reach behind the barrier. Similarly, when light passes through a slit, some light reaches the region expected to be in the shadow of the aperture. This is because new wavelets are created by the wavefront at the aperture. The light intensity behind the slit is determined by how these wavelets interfere with each other, i.e., added up according to the principle of superposition. The result
is a series of light and dark bands, due to constructive and destructive interference, both extending into the expected shadow region. This phenomenon is known as diffraction. It results from the interference of infinite number of wavelets.

Place the holder with four single slits (0.16 mm, 0.08 mm, 0.04 mm, 0.02 mm widths) in front of the laser beam. Adjust the holder location so the light is incident on the 0.16 mm wide slit (D), and observe the diffraction pattern on the wall. The height of the laser beam may be adjusted with the small adjustment screws on the laser. Make sure that the beam is perpendicular to the slit and the screen. The geometry is show in the figure below

Measure the width \( w \) of the central bright band by locating the intensity minima on both sides. Record the slit width \( a \) and distance \( L \) between the slit and the screen. How many bright bands can you see on each side? Measure the distance \( y_i \) between each minimum and the central maximum. Determine the width of each minima using the same method, i.e., from the difference \( y_{i+1} - y_i \). Repeat the same measurements with the other three slits.

The theory of single slit diffraction predicts that, for wavelength \( \lambda \), the condition for dark bands to occur is

\[
a \sin \theta = m\lambda \quad m = \pm 1, \pm 2, \pm 3, \ldots
\]

where \( m \) is an integer index for each minimum. Since for small angles, \( \sin \theta \approx \tan \theta = y / L \), where \( y \) is the position on the screen, we expect the minima to occur at

\[
y_m = \pm mL\lambda / a.
\]

As a result, the central band width is

\[
w = 2L\lambda / a
\]

and it is twice the width of any side bands.

Questions:

- For each slit, plot \( y_m \) versus \( m \). Do the data fall on a straight line through the origin? Does the slope agree with the prediction of Eq. (2)?
- Plot \( w \) versus \( 1/a \) for the 4 slits. Do the data fall on a straight line? Does the slope agree with Eq. (3)?
- Are all the bright side bands of equal width? Are they half as wide as the central bright band? Are they of equal brightness?
B. Double Slit Interference

Measurements

The incident light is in phase at the two narrow slits. Ideally, we may consider each slit to have zero width and each acts as a point source of one secondary wavelet. With these assumptions, the intensity pattern on the wall may be derived from superposing only 2 waves that originate from the two slits. They arrive at an arbitrary point on the wall with a phase difference that depend on the difference in path lengths, as shown in the figure below. Locations where light from the two slits arrives out of phase will be dark, and locations where light from the two slits arrives in phase will be bright, i.e., constructive and destructive interference occur at different points on the screen.

Bright and dark "fringes" alternate, with the center of the pattern being bright. For slit spacing \( d \), the position of the \( m^{th} \) bright fringe (intensity maximum) is given by the condition

\[
d \sin \theta = m \lambda, \text{ where } m = 0, \pm 1, \pm 2, \pm 3, \ldots
\]  

Despite the similarity between this equation and Eq. (1), note that one equation applies to intensity maxima and the other to intensity minima. Small angle approximation of Eq. (4) leads to

\[
y_i = \pm mL\lambda / d.
\]

for the positions of the maxima on the wall.

Replace the single slit holder with the double slit holder, and position it such that the light is incident on pattern A (0.04 mm slits separated by 0.250 mm). Record the value of \( L \). Observe the pattern carefully. You should see the single slit diffraction pattern of a 0.04 mm slit and a smaller pattern of bright and dark fringes. This is because in reality each slit has a finite width that always results in a single slit diffraction pattern and the experiment observes the interference between two such diffracted waves. The result is to have narrow interference stripes within each bright diffraction band.

Measure \( y \) for several bright fringes. Record your data in a table that includes columns for the values of the angle \( \theta \), and for calculated values of \( d \). Calculate \( \theta \) for each bright fringe measured, and calculate the corresponding slit spacing \( d \). Finally, calculate the average value of the slit separation \( d \), and compare this with the given slit spacing.
Additional observations
Position each of the other three double slits in the beam, and observe the interference pattern. Compare the features of the interference pattern with the single slit diffraction patterns observed earlier, and with the first double slit interference pattern. Describe clearly what aspect of the interference pattern is governed by the slit width, and what is governed by the slit separation.

C. Multiple Slits
One of the holders has patterns of 2, 3, 4, and 5 slits. In each case the slit width is 0.04 mm, and the slit separation is 0.125 mm. Start with the double slits (A) in the laser beam. Observe the interference pattern and make any desired measurements. Move each of the other slit patterns into the beam and observe the changes. Summarize your observations.

D. Diffraction Grating
A diffraction grating effectively consists of a large number of evenly spaced slits. Place the grating in the laser beam and measure the distance between the central bright spot and several bright spots on each side. As for the double slits, the maxima are at angles such that
\[ m \lambda = d \sin \theta, \]
where \( d \) is the spacing between slits. Calculate the grating spacing for each measured maximum, and calculate the average. Compare this with the grating spacing given by the manufacturer.
(The number of slits per mm is stamped on the grating or the holder.)

E. Additional Observations

Fine wire or Strand of Hair
A narrow opaque object will create a diffraction pattern that may be used to measure the width of the object. The diffraction pattern is like that of a narrow slit, with the width of the object replacing the slit width. Try this with a fine wire or strand of (your) hair.

Opaque Disk
An opaque disk also forms a diffraction pattern. A bright spot appears in the center of the diffraction pattern of an opaque disk. To observe this, you will have to spread out the laser beam using the small lens mounted on a holder. Compare with the diffraction pattern of a circular aperture.

Hologram
To make a hologram, a laser beam is split by a partially reflecting mirror. Some of the light is incident on photographic film. Some of the light is reflected from an object onto the film. These two portions of the laser beam form an interference pattern on the photographic film, which carries information about the three dimensional shape of the object. When the developed film is properly illuminated, a three dimensional image is formed.

Please use caution when observing the hologram, and do not look directly into the laser beam! Observe the hologram; reach behind it to touch the phone. Pay attention to the magnifier and move your head about to see the key pad from different angles.