

## Understanding the Universe: Physics Through the Ages

### Laboratory 2

### Thomas Young and the Wave-Nature of Light

#### A. Introduction

Isaac Newton was famous, not only for formulating the laws of motion but also for pioneering in the study of optics. As discussed in class, he used a prism to show that sunlight was a mixture of the colors that make up the rainbow. In his *Opticks* (1704), Newton argued that light was made up of tiny particles. Slightly earlier, the Dutch physicist Christiaan Huygens wrote a *Treatise on light*, in which he proposed that light was a wave. It was only in 1789 that Thomas Young proposed a simple experiment that appeared to resolve the controversy by showing that light indeed behaves as a wave (according to 20th-century quantum mechanics, however, even Young's wave description is incomplete). Young, a leading British natural philosopher, also formulated an influential theory of color vision and was the first to decode the Egyptian hieroglyphics being brought to Europe by Napoleon's troops.

Although Newton and others had observed alternating patterns of bright and dark bands of light under certain circumstances, Young would be the first to explain these patterns with the wave theory and the principle of **interference**. The alternating bright and dark bands occur when two or more waves pass through each other. Interference can be illustrated by the following figures:

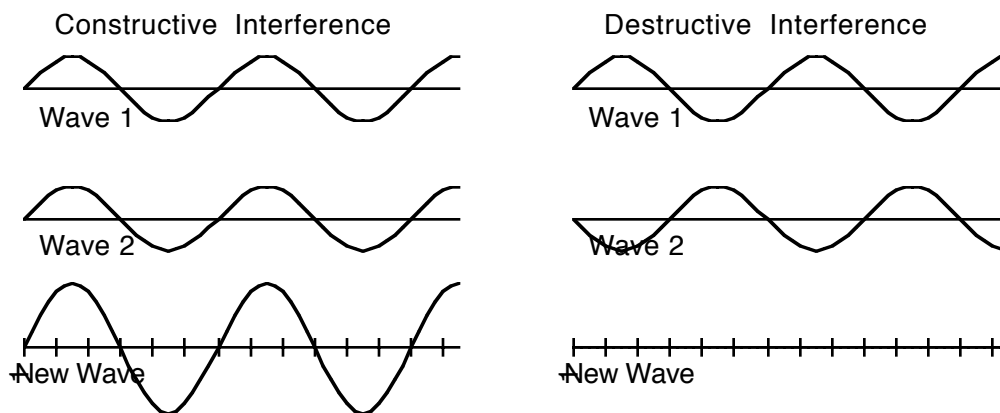


Fig. 1: Interference Patterns

Note that waves 1 and 2 have the same amplitude and wavelength in both cases. In the first case, the maxima coincide, and the resulting wave has the same wavelength but twice the amplitude of the individual waves. This is called **constructive interference**. In the second case, the maxima of wave 1 coincide with the minima of wave 2 and the two waves annihilate each other. This is called **destructive interference**. The phenomena in both cases result from the **principle of superposition**, which asserts that overlapping waves form a new wave with amplitude given by the sum of the amplitudes of the combined waves at each point.

Young observed and measured the alternating bands with very simple equipment--a card with a rectangular hole across which he stretched a single human hair. Holding the card close to his eye, he viewed a distant candle and saw in the blurred edge of his field of vision

alternating bright and dark bands across the hair (see Fig. 2 below). Young described the experiment as follows, in “An account of some cases of the production of colors not hitherto described” [1802], in Henry Crew, ed., *The wave theory of light* (New York, 1900), 63-64:

“I therefore made a rectangular hole in a card, and bent its ends so as to support a hair parallel to the sides of the hole; then, upon applying the eye near the hole, the hair, of course, appeared dilated by indistinct vision into a surface, of which the breadth was determined by the distance of the hair and the magnitude of the hole, independently of the temporary aperture of the pupil. When the hair approached so near to the direction of the margin of a candle that the inflected light was sufficiently copious to produce a sensible effect, the fringes [alternating bands] began to appear; and it was easy to estimate the proportion of their breadth to the apparent breadth of the hair across the image of which they extended. I found that six of the brightest red fringes, nearly at equal distance, occupied the whole of that image. The breadth of the aperture was  $66/1000$  [of an inch], and its distance from the hair  $8/10$  of an inch; the diameter of the hair was ...  $1/600$  [of an inch]. Hence, we have  $11/1000$  for the deviation of the first red fringe at the distance of  $8/10$ ; and as  $8/10 / 11/1000 = 1/600 / 11/480000$ , or  $1/43636$  [of an inch] for the difference of the routes of the red light where it was most intense.”

Young has thus measured the wavelength of candle light to be  $1/43,636$  of an inch, or about 5821 Angstroms [**1 Angstrom =  $10^{-8}$  cm**; present measurements give red light a wavelength of about 6300 Angstroms]. Young provided no diagrams, did not discuss the geometry upon which his computations rested, and simply stated his conclusion [ibid., 62]:

... wherever two portions of the same light arrive at the eye by different routes, either exactly or very nearly in the same direction, the light becomes more intense when the difference of the routes is any multiple of a certain length, and least intense in the intermediate state of the interfering portions; and this length is different for light of different colors.... [that is, different colored lights have different wavelengths]

Young’s card with the human hair was created what would become known as the **double-slit experiment**. Rather than making 2 slits, he allowed the light to pass around both edges of the hair. In Fig. 3, imagine a taut length of hair passing perpendicular through the page at  $d$  (the diameter of the hair);  $L$  shows the distance between the hair and the aperture of the pupil in Young’s eye;  $x$  is the distance between the innermost bands of light Young observed, a distance he estimated by dividing the apparent diameter of the hair as it fell on his retina by the number of bands he observed across the diameter of the hair.

## B. Some Theory

Why do the waves passing around Young’s hair or through the double slits interfere? Suppose you are lying on the beach (a straight, long beach) and you observe a plane wave passing between two large rocks not far from the shore. If you get up to look behind the rocks (sacrificing a few minutes of your sunbathing for science), you will notice that as a wave passes through the aperture between the rocks, it propagates as a spherical wave (a spherical wave is what you get when you toss a rock into a pool). Thus, if you have three fairly wide rocks making two apertures, you will see a spherical wave originating from each aperture as the long wave hits the rocks. These will propagate as in Fig. 2 below and will interfere. The fact that points of the wavefront can serve as originators of spherical waves (as the wave passes through the apertures) is called **Huygens’ principle**.

Before you can start the experiment, you must obtain an expression that will allow you to compute the wavelength of light (a very small quantity) in terms of things you can measure.

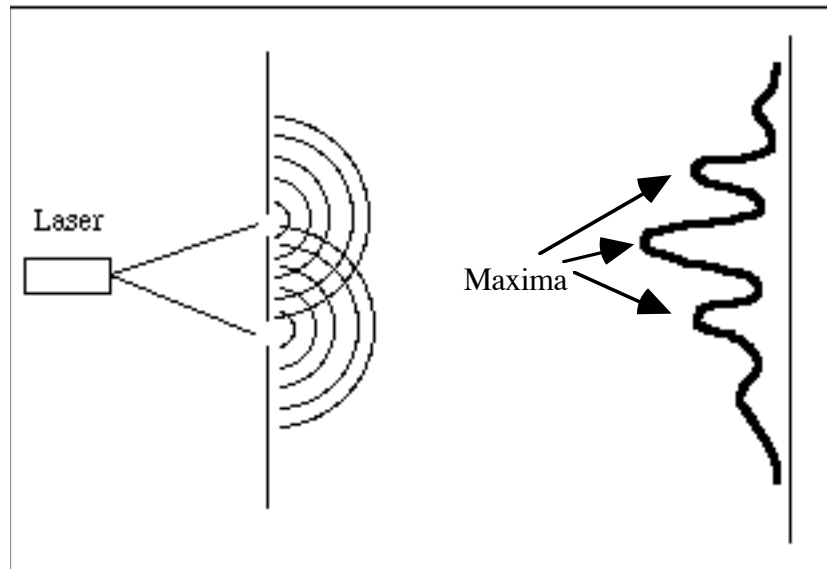


Fig. 2: Double-slit interference pattern

Consider Fig. 2, where light from the laser passes through a double slit and hits a distant screen. The badly drawn bold line at the right marks the intensity of the light falling on the screen, i.e., the pattern of alternating bright and dark spots which result from the interference of the spherical waves generated by the two slits.

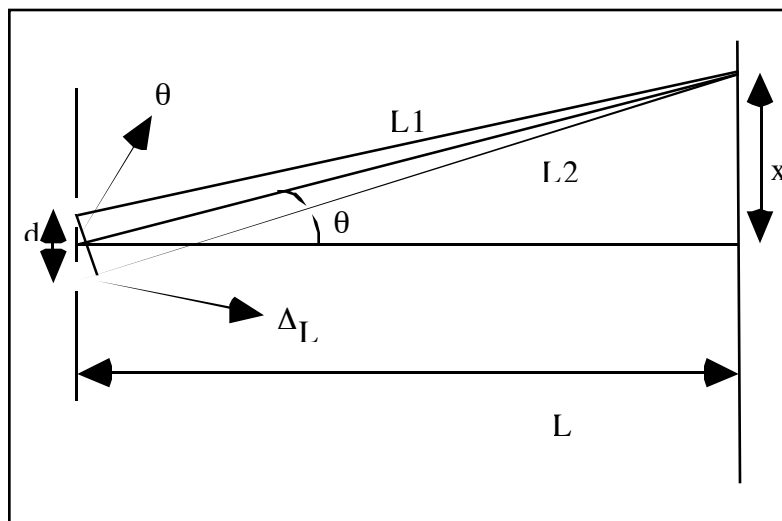


Fig. 3: The double-slit geometry

Fig. 3 abstracts from the Fig. 2 to illustrate only the first bright fringe. Let  $L$  be the distance between the slit and the screen,  $d$  the separation between the two slits, and  $x$  the distance on the screen from the central maximum to the first bright fringe. Let  $L_1$  and  $L_2$  be the respective path lengths for light traveling from slit 1 and slit 2, as indicated in Fig. 3.  $\Delta L$  is the path difference:

$$\Delta L = L_2 - L_1 \quad [1]$$

In order for the distance  $x$  to correspond to a maximum brightness in the interference pattern, the difference in path lengths  $\Delta L$  must be an integral number of wavelengths of light. **Do you see why (hint: see Fig. 1 above)?** That is:

$$\Delta L = n\lambda, \text{ where } n = 1, 2, 3 \dots, \text{ and} \quad [2]$$

$\lambda = \text{the wavelength of light}$

Some geometry will now let us determine  $\Delta L$  in terms of distances we can measure. If  $L \gg d$ , then  $L_1$  and  $L_2$  are approximately equal, and make an angle  $\theta$  with the horizontal line. In this case, the two triangles containing the angle  $\theta$  are essentially similar, and we can write:

$$x/L = \Delta L/d, \text{ or } \Delta L = xd/L \quad [3]$$

Combining Eq. [2] and Eq. [3] allows us to obtain an expression for the wavelength of light:

$$\lambda = xd/nL \quad [4]$$

For  $n = 1$ , we have the first maximum away from the center, for  $n = 2$ , the second, etc. From the discussion above, we should expect that all the maxima will have the same amplitude. However, a glance at your experimental setup will convince you that the amplitude decreases as we move away from the central maximum.

The fact that the interference pattern decreases in amplitude is due to a phenomenon known as **diffraction**. In our discussion above, we implicitly assumed that the slits have infinitesimal width. In practice, of course, that is not the case. The width of the slits produces the decrease in amplitude. Recall that Huygens principle states that each point of the propagating front can be treated as a source of spherical waves. When we obtained the interference pattern above, we assumed that each slit behaves as a point, creating the two spherical waves (Fig. 2). A slit of finite width, however, offers many points that work as sources of spherical waves. As light goes through a narrow, finite-width slit, it interferes with itself even before it meets with the waves coming from the other slit. This effect produces the modulation of the interference pattern. To study it, we can make the light pass through single slits of different widths. The narrower the slit, the wider the diffraction pattern, i.e., the wider the width of the central maximum.

### C. Your Experimental Procedures

You will reproduce Young's procedure, replacing his candle and hair with a He-Ne laser and a double slit scratched on a plate of glass. From other measurements, we know that the wavelength of light from the laser is **6328 Angstroms** (1 Angstrom =  $10^{-8}$  cm). In your experiment, you can thus check the validity of Eq. [4]. Note also that in your experiment,  $L$  is the total distance from slit-to-mirror-to-image.

**CAUTION:** Do not look into the laser beam or even at a directly reflected beam. Laser light is very intense and can damage your eyes more than you think. Handle optical devices in such a way that your fingers do not touch the optical surfaces.

Your experimental setup will include the He-Ne laser, a glass plate with various slit patterns (see the final page of this description for the slit dimensions), paper, a ruler, a meter stick, and a photoresistor-xy recorder. This latter apparatus can record the light coming out of the slits and plot its intensity, reproducing the interference pattern on a sheet of paper.

Step 1) Set HP power supply to 5 volts. Adjust the height of the laser and slit plate so that the laser light falls on the xy recorder at the height of the photoresistor. This will guarantee that the resistor will perform optimally by receiving as much light as possible. The room should be as dark as possible.

Step 2) Choose a double-slit pattern and place it in the laser beam. Make sure the beam falls right on the middle of the slit. Turn the y-scale range to 100 mV/in. Adjust the y-zero control so that if no light is falling on the photoresistor (the “eye”) the pen is practically as low as it gets. Using the x-zero button, place the photoresistor in the central maximum of the interference pattern. Turn the y-scale to lower settings as needed to avoid having the pen hit the photoresistor.

Step 3) Return the photoresistor to the far left of the xy recorder. Place a clean sheet of paper onto the xy recorder, turn the CHART switch to “hold” (so that the paper is held fixed) and the PEN switch to “down.” Using the x-scale zero control, slowly sweep across the x-scale of the recorder. When you get to the right side of the recorder, lift the pen and remove the paper. You have your first interference pattern!

Step 4) Repeat for at least one other double slit.

Step 5) For all interference patterns you draw, compute the wavelength of the He-Ne laser light and compare it to the known value. For each pattern, also use  $n = 2$  (or higher) to compute the wavelength. Do whatever else you feel is important to test the theory discussed above. Explore different possibilities offered by the several multiple slits.

#### D. Your Lab Report

Be sure to include the following:

A concise description of your experimental problem and objectives.

Copies of all the interference patterns you used to compute the wavelength, labeled with the appropriate slit dimensions and types.

All data generated from your measurements.

A summary of the final results, with comments about how well your measured wavelengths agree with the accepted value, and what possible sources of error might have entered your measurements.

**Extra credit:** Use a human hair, attached tautly to a card across a rectangular hole about 1 x 0.5 cm in size, and a candle to reproduce Young’s original apparatus and measurement. Hold the card close to your eye with the hair running vertically, place the lighted candle about 4-5 inches from your eye, and look toward a distant, dark background about 10-20° left or right of the candle. The exact distances between your eye, card and candle for best seeing the interference bands will depend on the optical system of your eye (whether you are near- or far-sighted). You may need to remove your glasses or contact lenses.

Count the number of bands you see with fuzzy vision across the surface of the hair, and have a friend estimate the distance between the surface of your eye and the card. Calculate the wavelength of the candlelight, assuming that the diameter of human hair ( $1/600$  of an inch) has not changed since Young's time. The distance you measure between your eye and the card yields  $L$  in Eq. [4]. To determine  $x$  for Eq. [4], hold a ruler directly behind the card, and estimate the width of the hair when viewed with fuzzy vision. Dividing this measured width by the number of bands you observe will give you a value for  $x$ . The diameter of the hair is  $d$ ; and  $n$  in this case will be 1.

# Slit Plate Dimensions

Element	A	B	C	D	E	F(i)	F(ii)	F(iii)
Number of Slits	1	1	1	1	1	1	1	2
Slit Width	88	176	351	703	1406	88	703	88
Slit Spacing	---	---	---	---	---	---	---	264
Element	F(iv)	G	H	I	J	K	L	M
Number of Slits	1	20	40	80	30	15	10	4
Slit Width	44	44	22	11	44	44	44	44
Slit Spacing	---	88	44	22	44	132	88	88
Element	N	O	P	Q	R	S	T	U
Number of Slits	3	2	1	2	2	2	2	1
Slit Width	44	44	44	88	88	88	88	88
Slit Spacing	88	88	---	1318	615	264	88	---

\* All dimensions are in microns (1000 microns = 1 mm) \*

