Name _____ Date _____ Partners_____

MICROWAVE AND LIGHT INTERFERENCE

OBJECTIVES

- To better understand the wave nature of light

- To study interference effects with electromagnetic waves in microwave and visible wavelengths

OVERVIEW

Electromagnetic waves are time varying electric and magnetic fields that are coupled to each other and that travel through empty space or through insulating materials. The spectrum of electromagnetic waves spans an immense range of frequencies, from near zero to more than 10^{30} Hz. For periodic electromagnetic waves the frequency and the wavelength are related through

$$c = \lambda f \qquad (1)$$

where λ is the wavelength of the wave, f is its frequency, and c is the velocity of light. A section of the electromagnetic spectrum is shown in Fig. 1.

In Investigation 1, we will use waves having a frequency of 1.05×10^{10} Hz (10.5 GHz), corresponding to a wavelength of 2.85 cm. This relegates them to the so-called **microwave** part of the spectrum. In
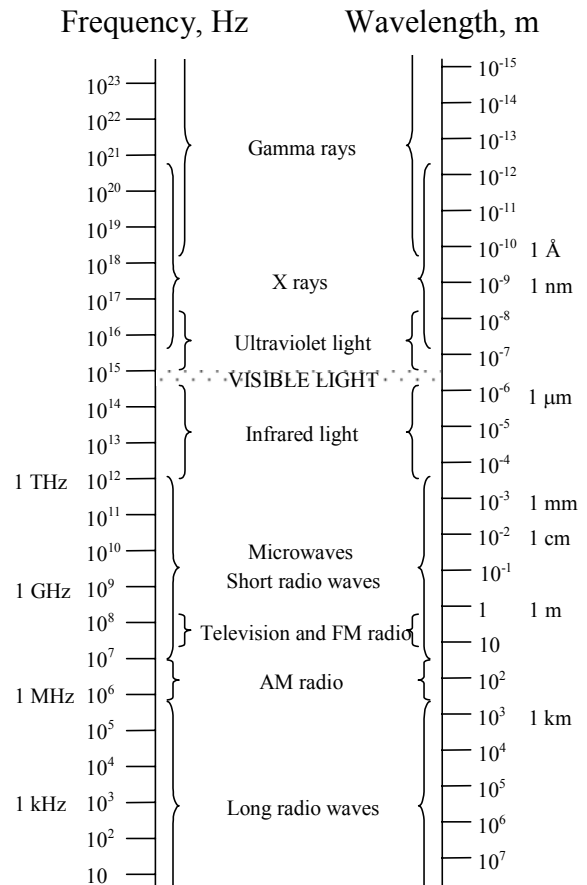

Fig. 1. Section of the electromagnetic spectrum.

Investigation 2, we will be using visible light, which has wavelengths of 400 –
700 nm (1 nm = 10^{-9} m), corresponding to frequencies on the order of
4.3×10^{14}-7.5×10^{14} Hz. These wavelengths (and hence, frequencies) differ
by nearly five orders of magnitude, and yet we shall find that both waves
exhibit the effects of **interference**.

Electromagnetic waves are **transverse**. In other words, the directions of
their electric and magnetic fields are perpendicular to the direction in which
the wave travels. In addition, the electric and magnetic fields are
perpendicular to each other. Fig. 2 shows a periodic electromagnetic wave
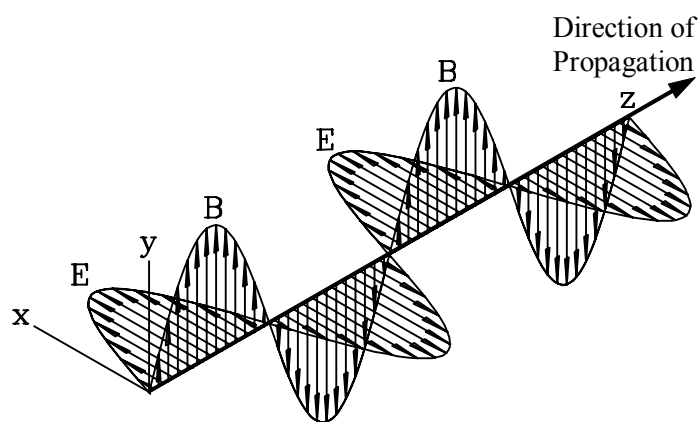traveling in the *z*-direction. Study this figure carefully. We will refer to it
often.

Fig. 2. Periodic electromagnetic wave, **E** = vector of the electric field,
B = vector of the magnetic field.

Electromagnetic waves are produced whenever electric charges are
accelerated. This makes it possible to produce electromagnetic waves by
letting an alternating current flow through a wire, an **antenna**. The frequency
of the waves created in this way equals the frequency of the alternating
current. The light emitted by an incandescent light bulb is caused by thermal
motion that accelerates the electrons in the hot filament sufficiently to produce
visible light. Such thermal electromagnetic wave sources emit a continuum of
wavelengths. The sources that we will use today (a microwave generator and a
laser), however, are designed to emit a single wavelength. Another essential
characteristic of these two sources is that they emit radiation of definite phase.
That is to say, they are *coherent*.

The inverse effect also happens: if an electromagnetic wave strikes a
conductor, its oscillating electric field induces an oscillating electric current of
the same frequency in the conductor. This is how the *receiving* antennas of a
radios or television sets work. The associated oscillating magnetic field will
also induce currents, but, at the frequencies we will be exploring, this effect is
swamped by that of the electric field and so we can safely neglect it.

Electromagnetic waves carry energy. The energy density at any point is proportional to the square of the *net* electric field. The *intensity* (what we can observe) is the time average of the energy density. **Important Note: To find the intensity of the electromagnetic waves at any point, we must first add up (as vectors, of course), all of the electric fields to find the *net* electric field. We cannot simply add intensities.** It is this property of electromagnetic waves[1] that lead to interference effects.

In this workshop you will be studying how electromagnetic waves interfere. We will, once again, be using two small regions of the electromagnetic spectrum: microwaves and visible light. Look at Fig. 1 to understand the relative position of microwaves and visible light. The microwaves that you will be using in this experiment have a frequency of 1.05×10^{10} Hz, corresponding to a wavelength of 2.85 cm. The name *microwave* is to be understood historically: In the early days of radio the wavelengths in use were of the order of hundreds, even thousands, of meters. Compared with these waves, those in the centimeter region, which were first used in radar equipment during W.W. II, were indeed '*micro*' waves.

You will recall that conductors cannot sustain a *net* electric field. Any externally applied electric field will give rise to a force on the free electrons that will cause them to move until they create a field that precisely cancels the external field (thereby eliminating the force on the electrons). If an electromagnetic wave strikes a conductor, the component of its oscillating electric field that is parallel to the wire will induce an oscillating electric current of the same frequency in the conductor. This oscillating current is simply the free electrons in the wire redistributing themselves. Now you will also recall that an oscillating electric current will produce electromagnetic waves. An important thing to note about these induced waves is that their electric fields will be equal in magnitude and opposite in direction to the incident wave *at the surface (and inside) of the conductor*.

Consider now a plane electromagnetic wave incident upon a wire. Fig. 3 schematically shows a top view of such a case. Only one incident wave front and the resultant induced wave front are shown. The incident wave front is shown as having passed the wire and is traveling from the top of the figure to the bottom. The induced wave will be of the form of an expanding cylinder centered on the wire and, since the induced wave travels at the same speed as does the incident wave, the cylinder's radius is equal to the distance that the incident wave front has traveled since it struck the wire. At the point where the induced wave and the incident wave touch, they add destructively as the induced wave is 180° out of phase with respect to the incident wave.

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[1] This is a general property of waves, not just for electromagnetic waves.
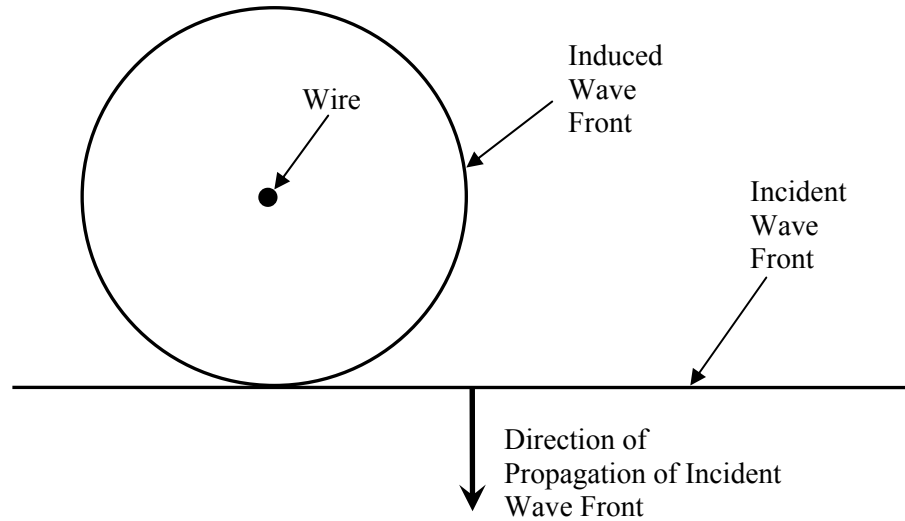
Fig. 3. An electromagnetic wave incident upon a wire

Fig. 4 shows the same situation, but with a number of wires all oriented in the same direction. We can see that the induced wave fronts all line up in phase at the incident wave front. However, since the induced waves are 180° out of phase with the incident wave, the resulting wave front is reduced in amplitude. We indicate this by showing the incident wave front as a dashed line. With enough such wires, the amplitude *for the forward direction* can be reduced to a negligible level. The energy of the incident wave is not lost; it is simply re-radiated in other directions.
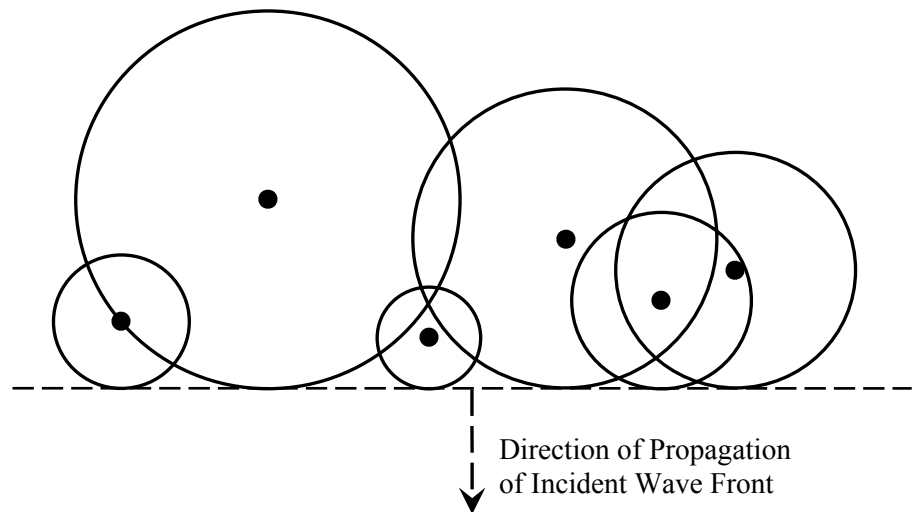

Fig. 4. An electromagnetic wave incident upon an assembly of wires

Fig. 5 is similar to Fig. 4, with a few notable differences. Most significantly, the wires are now arranged in a linear array. We also now have the incident wave come in at an angle (from the top left).
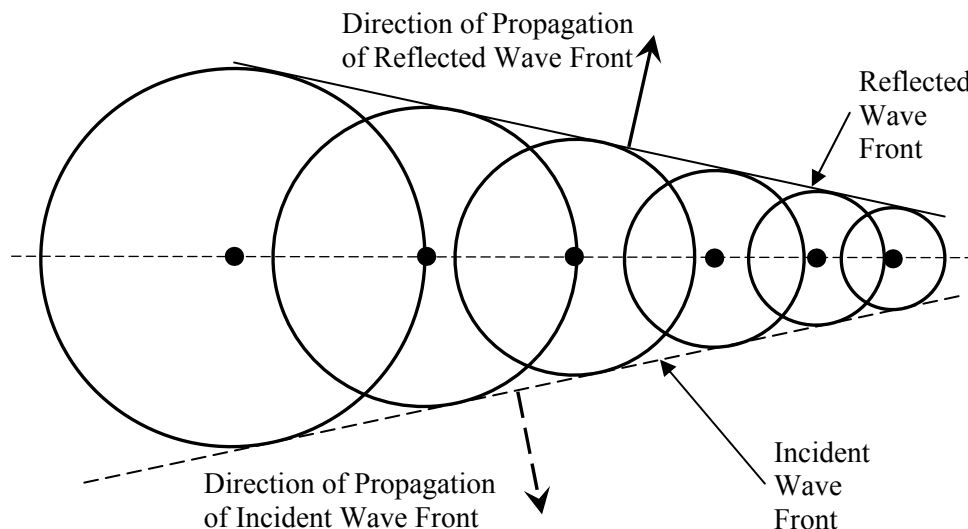
Fig. 5. An electromagnetic wave incident upon a linear array of wires

We recognize this arrangement as the "wire grid polarizer" from an earlier lab. In the earlier lab, we investigated the polarization properties of *transmitted* electromagnetic waves. We now consider the properties of the *scattered* or *reflected* waves. In Fig. 5, we see that not only do the induced waves line up with each other in the plane of the incident wave, now they also line up with each other in another plane. This alignment of wave fronts gives rise to constructive interference, meaning that the resulting wave front's amplitude is enhanced in this direction. With enough wires, essentially all of the incident wave's energy will be radiated in this direction.

Furthermore, we can see from Fig. 5 that the angle that this *reflected* wave front makes with the plane of the wires is the same as that of the incident wave front. In other words, "angle of incidence equals angle of reflection". We will find that, for microwaves, the "wire grid polarizer" makes a fine mirror (but only for waves with their electric fields aligned with the wires!).

What about Polaroid glasses and filters? Why do they not act like mirrors? The answer is that Polaroid filters and glasses are thick relative to the wavelength of visible light. The conductive molecules are randomly distributed throughout the filter and, hence, are arranged more like the wires shown in Fig. 4 than in Fig. 5.

INVESTIGATION 1: INTERFERENCE EFFECTS WITH MICROWAVES

Activity 1-1: Polarization of Microwaves Reflected From A Wire Grid

For this activity, you will need the following:

- Gunn diode microwave transmitter
- Microwave receiver

- Goniometer

- Wire Grid

It is imperative that you NOT peg the meter as doing so can damage it! If you find the meter pegged, immediately turn down the sensitivity and/or move the receiver away from the microwave generator!
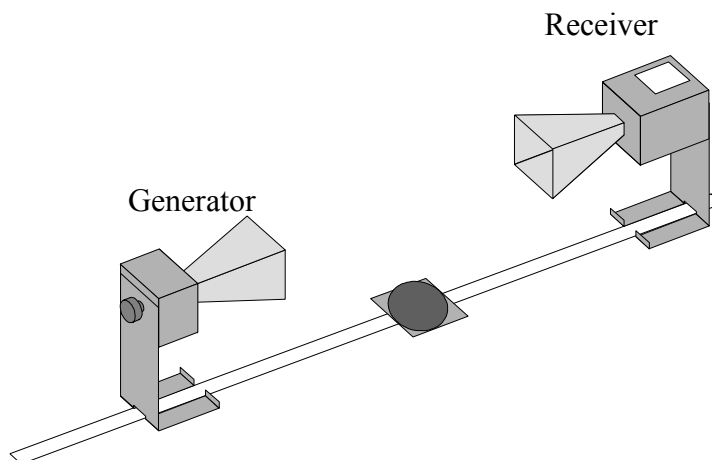

Fig. 6. Microwave generator and receiver arrangement.

1. Refer to Fig. 6. Place the generator on the main arm of the goniometer such that entrance to the "horn" is between 30-40 from the goniometer's hinge (at the center of the circle). Place the receiver on the goniometer's shorter arm so that its horn is about the same distance from the hinge.

2. Set the angle between the two arms the goniometer at 180° (so that the receiver is "looking" directly at the transmitter). Set both the receiver and the transmitter at 0° (so that the electric field of the emitted and detected waves is oriented vertically). Turn on the generator by plugging the AC adapter wire into the generator and then plug the adapter into an AC outlet. Adjust the sensitivity on the receiver to obtain a signal that is 75% of full scale on the meter. **Again, do not let the meter peg!** Leave the sensitivity at this setting for the remainder of this Investigation.

3. Place the wire grid so that the center pin of the goniometer hinge fits into the recess in the bottom of the grid frame (see Fig. 7). Align the grid so that it is at 40° on the goniometer scale.

Question 1-1: What is the angle (labeled "Angle of Incidence" in Fig. 7) between the incident microwave beam and the normal to the plane formed by the wire grid array?
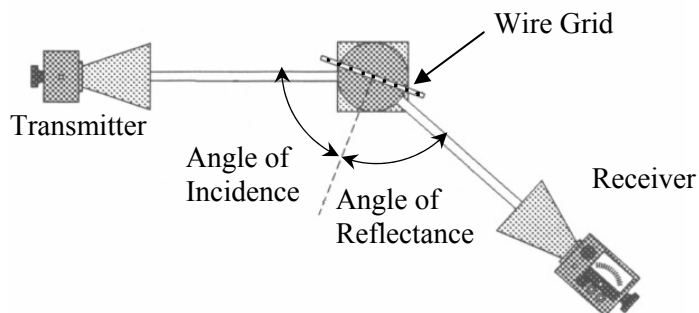
Angle of Incidence _____

Fig. 7. Microwave receiver, transmitter and wire grid arrangement

Prediction 1-1: At what angle between the goniometer arms do we expect to find a maximum detected signal? Explain.

Goniometer Angle _____

4. Record the detected signal strength with grid in place and the receiver still at 180°.

Meter Reading _____

5. Slide the receiver (still attached to the short goniometer arm) until you find the angle where the detected signal is at a maximum. [Note: You may find it easier to slide the receiver if you put a bit of paper under the receiver to reduce sliding friction.]. Record the angle between the two goniometer arms and the detected signal strength.

Goniometer Angle _____

Meter Reading _____

Question 1-2: Does the wire grid array behave like a mirror? Explain.

___

Activity 1-2: Two Slit Interference Pattern

To further observe interference with microwaves, you will need the following:

- Gunn diode microwave transmitter

- Microwave receiver

- Goniometer

- Double slit hood

- Meter stick or tape measure, plastic ruler

> **CAUTION:**
> **DO NOT ALLOW THE RECEIVER'S METER TO PEG AT ANY TIME!**

1. Set the angle between the two arms the goniometer back to 180°. Set the knob on the back of the generator and receiver to 0º. Starting with the meter multiplier on 30, adjust the sensitivity to obtain a signal near 0.5 on the meter. If you cannot achieve this with a sensitivity of 10 or 3, move the receiver closer to the generator.
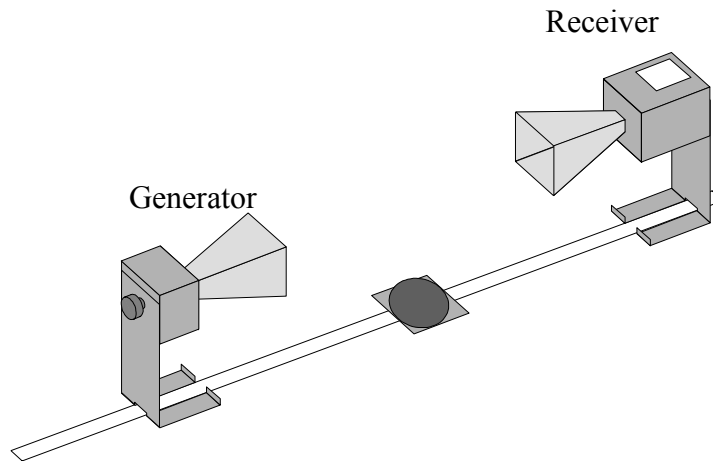

Fig. 8. Microwave generator and receiver arrangement.

2. Slide the double slit hood over the *generator's* horn, creating two coherent microwave sources as shown schematically in Fig. 9.
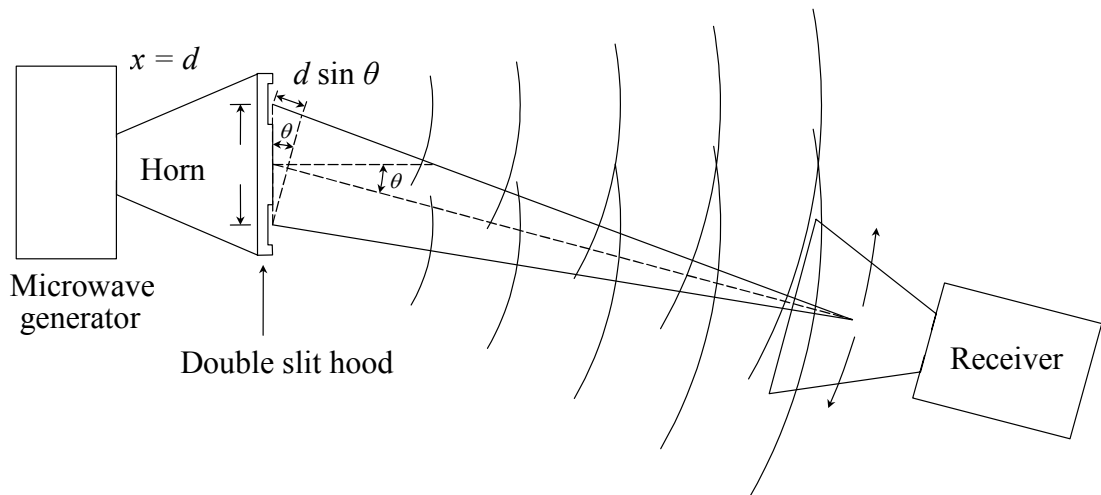

Fig. 9 Interference from the two slit hood.

3. Place the generator on the main arm of the goniometer such that the hood lies directly over the goniometer's hinge. Place the receiver on the goniometer's shorter arm so that the horns are about 25 cm apart. The signal amplitude that the receiver will detect depends on the phase of the microwaves when they reach the receiver probe. To a good approximation, if $x = d \sin \theta$ is equal to an integral number of wavelengths $n\lambda$, then the microwaves from the two slits will interfere constructively and you will see a maximum register on the meter. Likewise, if $d \sin \theta$ is equal to a half-integral number of wavelengths $(n - \frac{1}{2}) \lambda$, the meter will register a minimum.

constructive interference: $\quad n\lambda = d \sin \theta$

destructive interference: $\quad (n - 1/2)\lambda = d \sin \theta$

d = distance between centers of slits (double slit hood): _____

4. Start with the receiver is at 0°. Adjust the horn around 0° to obtain a maxima signal. Then move the horn receiver to greater angles and note further maxima and minima. You will need to increase the sensitivity to find the minima accurately. However, **reduce the sensitivity as you move away from the minima so that you do not peg the meter!** You should be able to locate two minima and one other maximum on each side of the central maximum, but just look on one side of the central maximum (0°). (Hint: It is easier to slide the receiver if you place a sheet of paper under its feet.)

Angles of maxima: _____ _____

Angles of minima: _____ _____

5. Use your data for the first non-central maxima to find the wavelength. Show your calculations below.

Wavelength value: _____

6. Use your data for the first minima to find the wavelength. Show your calculations below.

Wavelength value: _____

Question 1-3: How do your values compare with the microwave wavelength? Discuss any errors/uncertainties.

7. Turn off the receiver and set it aside.

Activity 1-3: Standing Waves

When waves moving in a given medium have the same frequency, it is possible for the waves to interfere and form a stationary pattern called a **standing wave**. Standing waves, though they are not found in all waves, do occur in a variety of situations, most familiarly perhaps in waves on a string, like in a guitar or violin. The incident and reflected waves combine according to the superposition principle and can produce a standing wave.

We have seen how a grid of wires acts like a mirror for microwaves. A metal plate can be thought of as the limit as the spacing between the wires vanishes. Microwaves reflected from a metal plate have the same frequency and wavelength as the incident microwaves. At certain distances along the path, the electric fields of the two waves will constructively interfere and produce a maximum signal in the detector probe, while at other locations they will destructively interfere and produce a minimum signal. This will occur, for example, between the detector and reflector in Fig. 10, which we will next investigate. The incoming field from the generator will be reflected from the metal plate and subsequently interfere with the incident wave. Certain positions of the reflector will therefore cause maximum and minimum voltages in the detector probe. We can use the positions of these maxima and minima to determine the wavelength of the electromagnetic field.

For this activity, you will need the following materials:

- Gunn diode microwave transmitter

- Microwave modulator

- Microwave probe

- Amplifier-power supply

- Six-range DC meter

- Metal reflector plate

- Goniometer

- Component holders

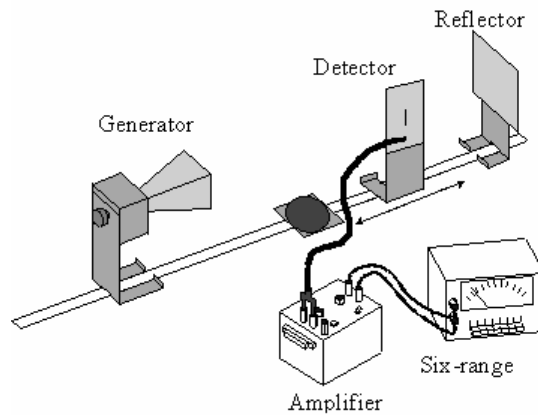- Meter stick or tape measure, plastic ruler

Fig. 10. Reflector placed by microwave detector probe.

1. Locate the microwave detector probe, a rectangular piece of circuit board (and attached cord) to which a detector *diode* (an electrical device that conducts current in only one direction) is soldered. Notice the solder line that extends beyond the ends of the diode and acts as an antenna.

The antenna is designed to be equal to the length of two wavelengths, i.e. 5.7 cm. When the electric field of the microwave strikes it, an ac voltage at a frequency 10.5 GHz is *induced* across the diode.

The amplitude of the DC signal from the detector diode is generally quite weak, so it must be amplified. Locate the amplifier and the six-range DC meter (voltmeter). **DO NOT plug the probe into the amplifier yet!** Set the amplifier to DC, its gain to a high value (near 100), and its DC OFFSET to zero (12 o'clock position). Turn on the amplifier. Select the 10 V range on the DC meter. Plug the OUT of the amplifier into the six-range meter (red to red, black to black). Adjust the DC OFFSET so that the meter reads slightly above zero. At lower scales, the meter becomes increasingly sensitive to the DC OFFSET of the amplifier. **It is imperative that you NOT peg the meter as doing so can damage it!** The meter is extremely sensitive to the DC OFFSET of the amplifier, so be extremely careful!

CAUTION:
DO NOT ALLOW THE SIX-RANGE METER TO PEG AT ANY TIME! IF YOU FIND THE METER PEGGED, IMMEDIATELY SELECT A LARGER (LOWER SENSITIVITY SCALE!

Start measurements with the six-range meter set to the 10 V scale. Decrease as necessary.

2. Using a BNC-to-banana adapter, plug the probe into the IN of the amplifier. One of the arms of the BNC-to-banana adapter has a tab, which indicates it should be plugged into the ground (black) terminal. Position the diode at about 50 cm from the front of the microwave generator's horn and oriented vertically, as shown in Fig. 10. Make sure the orientation of the generator is 0º.

3. Adjust the distance of the probe from the generator until the meter registers a voltage about 3/4 of full scale (10 V scale). **Keep the probe *at least* 15 cm away from the generator to keep the diode from burning out**. (The stand holding the detector probe is easier to slide if you put a piece of paper under its feet. Also, remember to keep your hand out of the way since any conductor in the vicinity, e.g. a piece of metal, even your hand, will reflect waves and may give you spurious results.)

Note: The meter *may* register a voltage when there are no microwaves incident upon the detector, due to the DC OFFSET of the amplifier. We could subtract this offset from our measurements, but, for purposes here, we need only be able to identify maxima and minima.

Prediction 1-2: If we place a reflector behind the detector probe, the microwave should be reflected back towards the generator. What do you think will happen to the original wave and the reflected wave? What are the conditions to produce a maximum constructive standing wave? What are the conditions to produce a minimum?

4. Place a reflector (solid flat piece of metal) behind the detector probe, as shown in Fig. 10. This will produce a standing wave between the generator and the reflector. Making sure to keep the probe at least 15 cm from the generator, slide the probe along the leg of the goniometer, and notice there are positions of maxima and minima signal strength. Slide the detector probe along the goniometer, no more than a cm or two, until you determine a maximum signal. Then slide the reflector, again no more than a centimeter or two, until you obtain another signal strength maximum. Continue making slight adjustments to the detector probe and reflector until the meter reading is as high as possible, but not pegging on the 10 V scale. If this occurs, move the generator back further away.

5. Now find a node (minimum) of the standing wave pattern by slightly moving the probe until the meter reading is a minimum. We want to determine the wavelength of the standing wave, so only relative distances between maxima and/or minima are relevant. In this case, it is easiest to

use the goniometer scale and measure the distance using the probe base and goniometer scale. Record the position of the probe below:

Initial probe position at minimum: _____

6. While watching the meter, slide the probe along the goniometer until the probe has passed through at least ten antinodes (maxima) and returned to a node. Be sure to count the number of antinodes that were traversed. Record the number of antinodes traversed and the new probe position.

Antinodes traversed: _____

Final probe position at minimum: _____

Question 1-4: What are the analogies with the nodes and antinodes found here and for the standing waves found from an oscillating string fixed at both ends (guitar)? Sketch a picture.

Question 1-5: What is the distance in terms of the wavelength between adjacent antinodes (maxima)?

Question 1-6: What is the wavelength you deduce from your data?

Wavelength of standing wave: _____

Question 1-7: Using this experimental wavelength value, determine the frequency of the wave. Is this consistent with your apparatus? If not, please explain.

Wave frequency: _____

7. Unplug the generator's power supply from the receptacle and turn off the amplifier before proceeding.

INVESTIGATION 2:   INTERFERENCE EFFECTS WITH VISIBLE LASER LIGHT

Please read *Appendix J: Lasers* before you come to lab.

OVERVIEW

In an earlier experiment you studied various interference phenomena with electromagnetic waves whose wavelength λ was approximately 3 cm (microwaves). In this experiment you will study similar phenomena with electromagnetic waves in the visible part of the spectrum. For brevity, we will simply use the common term "light". Light waves have a much shorter wavelength ($\lambda \approx 4 - 7 \times 10^{-5}$ cm) than do microwaves.
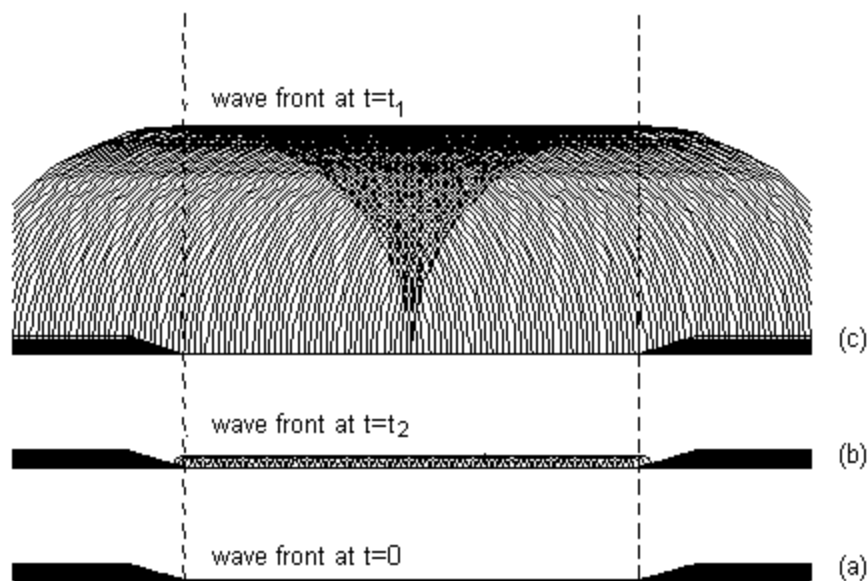

Fig. 11. The propagation of a wave front through a hole.

All the phenomena that you will observe can be described quite accurately with a simple theoretical model dating back to Christian Huygens (1629 - 1695). This model applies to wave phenomena in general and does not make any reference to the electromagnetic nature of light.

Huygens' Principle states that every point of a wave front can be thought of as the origin of spherical waves. This seems to be contradicted by experience: How can a laser emit a pencil beam? Would the light not spread out immediately?

We investigate this question with a **gedanken (thought) experiment**: Let a **plane wave** be incident on a screen that has a hole cut into it. Imagine that at the time $t = 0$ the wave front, coming from below, has just reached the hole as shown in Fig. 11a. An instant later, at $t = t_1$, the spherical **wavelets** that were, *according to Huygens' Principal*, created at every point of this wave front have begun to spread, as in Fig. 11b. Later yet at $t = t_2$, shown in Fig. 11c, we find that the wavelets have spread considerably; but, in a central region as wide as the slit, they have formed a new wave front propagating in the same direction as the old one. This reasoning can be repeated point by point in space and time as needed.
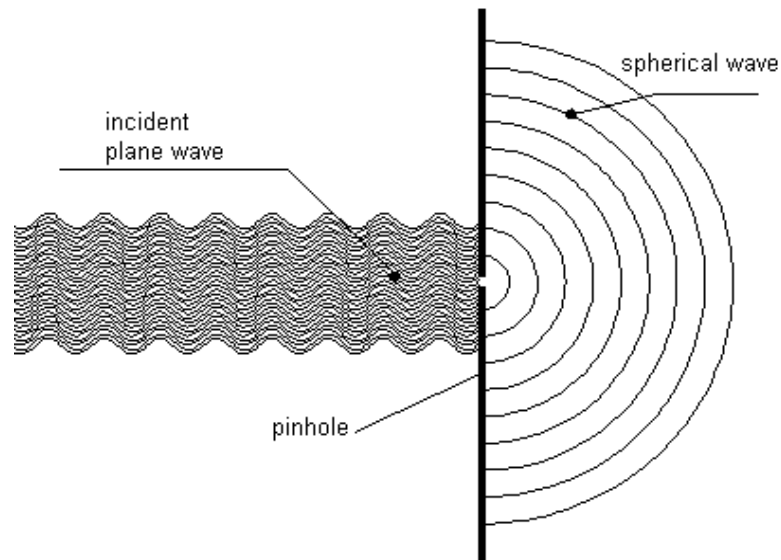

Fig. 12 A wave front hitting a small pinhole.

As a result, one will see by and large what one would have expected: a ray of light of the width of the slit, propagating in the original direction. Only on very close observation will one see that a small amount of light has *leaked around the corner* to regions where according to a *ray model* it should not be. The larger the hole, the smaller will be the *fraction* of the light that leaks around the corner, a process called **diffraction**. Largeness is a relative term - large with respect to what? The only measure of length that is appropriate for this problem is the wavelength of the incident light: When the size of the hole is large compared to the wavelength only a small part of all the light will find its way around the edge, most of it will be in the central beam. Only if the size of the hole is small compared to the wavelength will one find that the light spreads out spherically, as shown in Fig. 12. Clearly this is only a hand waving argument. A mathematically

rigorous explanation of diffraction, based on Huygens' Principle, is credited to J. A. Fresnel, (1788-1827).

For this investigation, you will need the following:

- Laser

- Lab jack

- Small Support stand

- Clamp for stand

- Slide with single slits of varying widths

- Slide with multiple slits

- Diffraction grating slide

- Board placed on table to observe patterns

- 3-m tape
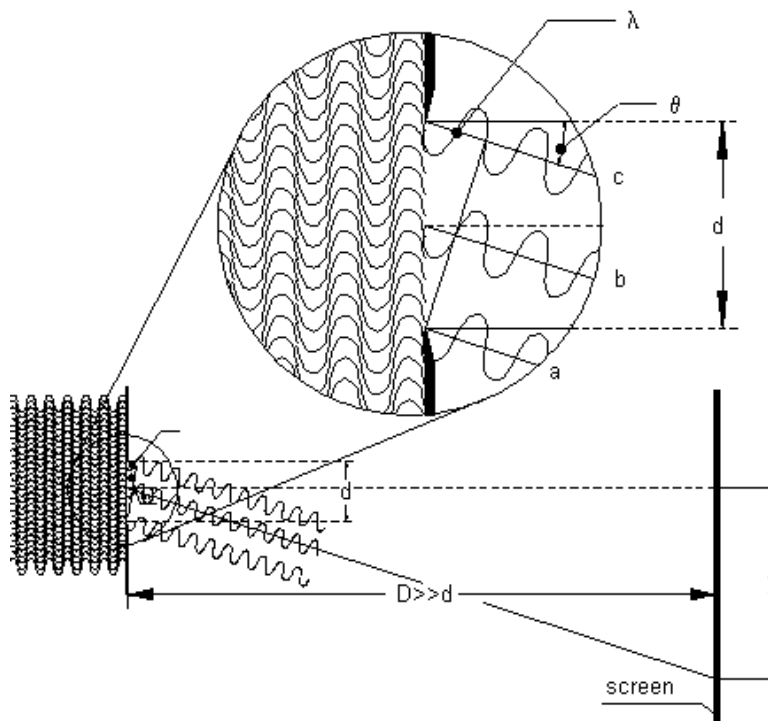
- White paper

THE SINGLE SLIT

Fig. 13 Diffraction by a single slit.

Diffraction patterns can be observed with a single slit. Fig. 13 shows three representative wavelets emerging from a single slit. The angle has been chosen so that the path difference between the wavelets a) and c) is equal to

the wavelength λ. For a single slit such a condition will result in **darkness**: For each wavelet emerging from the lower half of the slit there will be one from the upper half that is out of phase by half a wavelength that will extinguish it. In the case of the **single slit** the condition for darkness is thus

$$y_n^{dark} = \frac{n\lambda D}{d} \qquad (2)$$

where n is any whole integer greater than 0 ($n = 1,2,3…$).
A more detailed derivation gives the intensity, I, as a function of angle, θ:

$$I(\theta) = I_0 \frac{\sin^2\left(\dfrac{\pi d}{\lambda}\sin\theta\right)}{\left(\dfrac{\pi d}{\lambda}\sin\theta\right)^2}. \qquad (3)$$

$I(\theta)$ is shown in Fig. 14a. Dark bands appear when the intensity drops to zero. It is easy to see that y_n^{dark} correspond to such minima (since $\sin(\theta) = y/D$). Bright bands appear at the maxima of the intensity distribution. By inspection, we can see that the intensity goes to I_0 as θ goes to zero (use $\sin(x) \approx x$ for very small x). The rest of these maxima are best found through numerical methods.
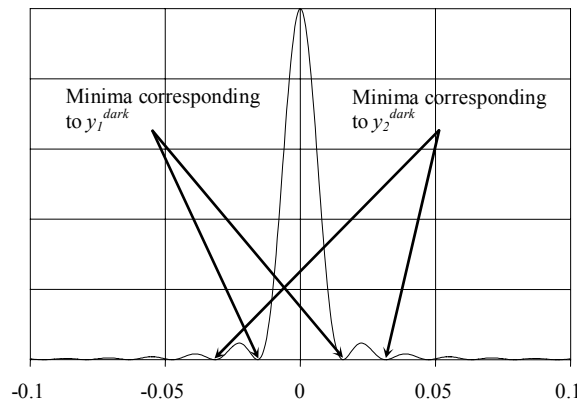

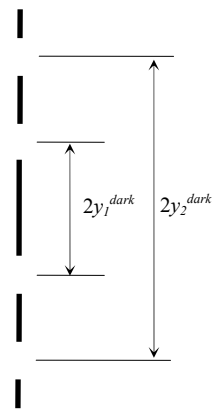Fig. 14a. Intensity distribution $I(\theta)$ for a single slit.   Fig. 14b Interference pattern

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Activity 2-1: Single Slit Interference

CAUTION: THE LASER BEAM IS VERY INTENSE. DO NOT LOOK DIRECTLY INTO IT! DO NOT LOOK AT A REFLECTION OF THE BEAM FROM A METALLIC SURFACE.

1. Aim the laser at white paper placed on the board approximately 1 m away, and turn it on. Note the brightness of the spot on the screen. The parallel beam of light is only a few millimeters in diameter.

2. Clamp the slide holder containing the single slit slide in the support stand so that the slits are horizontal. Place the slit close to the laser.

3. Use the lab jack to adjust the height of the laser so that the beam passes through the next-to-narrowest single slit ($d = 0.04$ mm).

4. Observe the diffraction pattern on the screen for the smallest slit. You should observe something like shown in Fig. 14b. The black "bars" represent the bright bands while the gaps represent the dark bands.

Question 2-1: What do you observe? Approximately how wide are the light bands? Can you explain this in terms of Fig. 14?

5. Measure the distance D from the slit slide to the screen.

   D _____

6. Move the laser so it is incident on the next widest single slit ($d = 0.04$ mm). Measure the diffraction pattern for this slit. To do this, measure from the dark band on one side of the center to the dark band on the other side of the center light band (see Fig. 14). This will give you $2y_n^{dark}$. Measure for three different bands and record in **Table 2-1**.

Table 2-1

d	n	$2y_n^{dark}$	y_n^{dark}	λ
	1			
0.04 mm	2			
	3			

7. Use the values found for $2y_n^{dark}$ to determine y_n^{dark} and record them in **Table 2-1**.

Question 2-2: Use the bands and the measurements you found to find the wavelength of the laser using Eq. (2). Record the values in **Table 2-1**. Find the average and record below.

   λ _____

8. Move the laser so that it is incident on the wider slits of 0.08 mm, and then on 0.16 mm. Look at the intensity pattern for each.

Question 2-3: What can you qualitatively say about how the diffraction pattern changes as the slit width goes from smaller to larger?

Question 2-4: Why do you think that the bands would get larger or smaller (depending on your answer to Question 2-3)? Why would the bands get closer together or further apart (also depending on your previous answer)?

THE DOUBLE SLIT

We consider now the case of two very narrow parallel slits making the following assumptions:

1. The distance d between the slits is large compared to their widths.

2. Both slits are illuminated by a plane wave e.g. light from a distant source or from a laser.

3. The incident light has a well-defined wavelength. Such light is called monochromatic, i.e. light of one color.

4. The individual slits are narrow, no more than a few hundred wavelengths wide.

Each of the two slits is the source of wavelets. Since the slits are very narrow, each is the source of just one series of concentric cylindrical wavelets, as shown in Fig. 15. Both slits are illuminated by the same plane wave, the wavelets from one slit must, therefore, be **in phase** with those from the other. Let the black rings in Fig. 15 indicate the positions of positive ½ waves (maxima) at a certain moment in time. In certain directions one sees black "rays" emanating from a point half way between the slits. In these directions the waves from the two slits will overlap and add (constructive interference). In the directions in between the black "rays" positive half waves (black) will coincide with negative half waves

(white) and the waves from the two slits will extinguish each other (destructive interference).
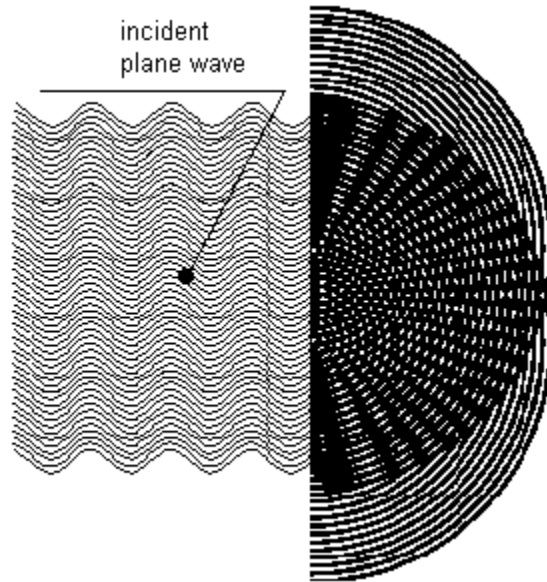

Fig. 15. Diffraction by a double slit, schematic.

Fig. 16 gives an example of destructive interference: At the angle θ shown in the figure, the waves from the two slits are out of step by a half wavelength.   Clearly, destructive interference will also result in all those directions for which the waves from the two slits are out of step by an **odd** number of half wavelengths.   In those directions in which the distances traveled by the two waves differs by an **even** number of half wavelengths the interference will be constructive.
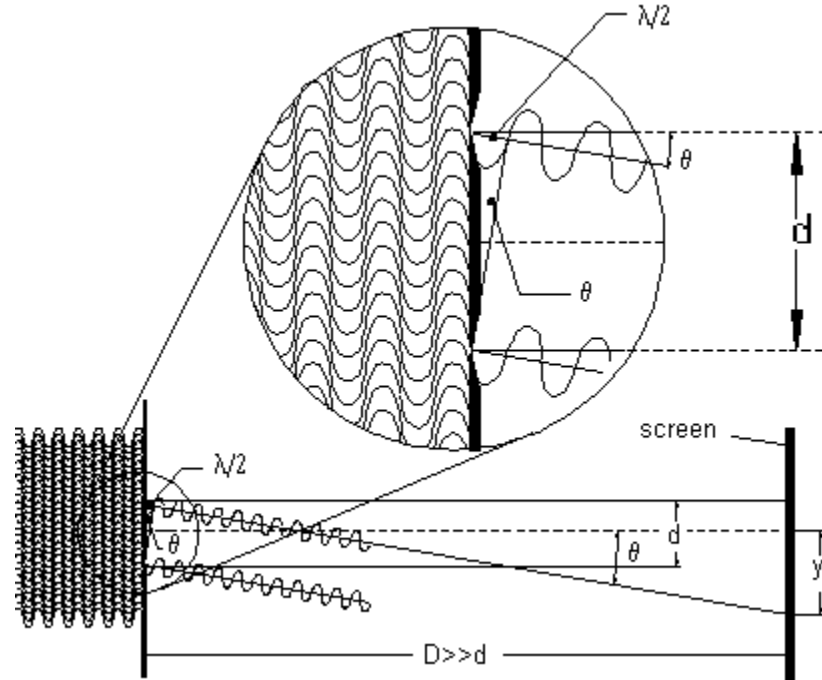
Fig. 16. Diffraction by a double slit, with details.

On a screen intercepting the light, one will therefore see alternating light and dark bands. From the positions of these bands it is easy to determine the **wavelength** of the light. From Fig. 16 we find

$$\sin\theta = \frac{\lambda}{2d} \tag{4}$$

where d is the distance between the slits and λ is the wavelength. We can also note that

$$\tan\theta = \frac{y_1^{dark}}{D} \tag{5}$$

where y_1^{dark} is the distance of the **first** dark band from the center line and D is the distance from the slit to the screen. From this we can obtain (for small angles $\tan(\theta) \approx \sin(\theta)$) the wavelength:

$$\lambda \approx \frac{2y_1^{dark} d}{D} \tag{6}$$

Convince yourself that this can be generalized to

$$\lambda \approx \frac{2y_n^{dark} d}{(2n-1)D}, \quad n = 1,2,3,... \tag{7}$$

where y_1^{dark}, y_2^{dark}, y_3^{dark}, etc. are the distances to the first, second, third, etc. dark band from the centerline.

Activity 2-2: Multiple Slit Interference

1. Replace the single slit slide with the multiple slit slide.

2. Make the laser light incident upon the double slit with the slide close to the laser.

Question 2-5: How is this pattern different from the single slit pattern?

3. With a pencil or pen, mark a line slightly off to the side the position of the central ray. Then mark a point right on the first four dark spots above and below the central ray position. It may be easiest to take the white paper off the board to measure the positions between the dark spots above and below the critical rays. Mark on your diagram where the distances $2y_1^{dark}$, $2y_2^{dark}$, and $2y_3^{dark}$ actually are. Measure them and write them down below.

   $2y_1^{dark}$ _____

   $2y_2^{dark}$ _____

   $2y_3^{dark}$ _____

4. Use the measurements in step 4 to calculate the wavelength. Perhaps calculate λ using all three experimental values and compare them.

   λ _____

Question 2-7: How well does this value agree with the single slit determination?

THE DIFFRACTION GRATING

Adding more slits of the same widths and with the same slit to slit distances will not change the positions of the light and dark bands but will make the light bands narrower and brighter. In **diffraction gratings** this is carried to extremes: many thousands of lines are scratched into a piece of glass or a mirror surface, giving the same effect as many thousands of slits. The "slit" to "slit" distance d is usually made very small so that for a given wavelength λ the distances y_n^{bright} from the bright bands to the center become very large. At the same time, the thicknesses of the bands of monochromatic light become narrow lines. This enables one to measure the distances y_n^{bright} (and hence the wavelengths) very accurately with such gratings. The order m specifies the *order* of the principal maxima, and $m = 0$ for the central beam at a scattering angle $\theta = 0$. The first bright spot on either side of the central maxima would be $m = 1$ scattered at angle θ_1; the next spot would be $m = 2$ scattered at angle θ_2 and so forth.

It is therefore quite easy to calculate the wavelength of light using a diffraction grating. The wavelength is given by the equation

$$m\lambda = d \sin \theta_m \qquad (8)$$

D is the distance from the diffraction grating to the screen, and the first maximum ($m = 1$) is observed at an angle θ_1 from the central ray. Then y_m^{bright} is the distance on the screen from the central ray to the maxima corresponding to order m. Then

$$\tan \theta_m = \frac{y_m^{bright}}{D} \qquad (9)$$

By using the two previous equations we can calculate the wavelength. Eq. (9) can be used to find θ_m, and then that value plugged into Eq. (8).

Activity 2-3: The Diffraction Grating

In this activity, you will use the diffraction grating to calculate the wavelength of the light.

1. Find the slide that contains the diffraction grating. Printed on the slide should be the number of lines per millimeter (N). Record this value and then determine the distance d between adjacent slits $1/N$.

   N _____ d _____

> **NOTE:** The grating surface is about six millimeters in from the face of the housing.

2. Measure the distance D between the diffraction grating and the screen very precisely. It should be about 15-20 cm, to allow for the band separations to be as large as possible while still being on the screen.

D _____

3. Shine the light from the laser through the diffraction grating and ensure that you can measure the maxima. You probably will have to look at the first order, because the others will be off the screen. It may help to turn the grating and screen horizontal to make these measurements. Measure and record the distance from the center of one maximum to the same maxima on the other side of the central ray. Write down the order you used and the distance measured.

Order m _____

Distance between bright spots on either side of central spot _____

4. Note that the measurement you just recorded is $2y_m^{bright}$.

5. Use your data to calculate the wavelength of the laser light.

λ _____

Question 2-8: How well does this value for the laser wavelength agree with your previous values? Which method (single slit, double slit, or grating) appears to be the best? Explain and discuss possible sources of error for each method.