Introduction Modern Physics
Physics Lab 188, Spring 2002
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Microwave Optics

Experiment 1 : Introduction to the System

This experiment gives a systematic introduction to the Microwave Optics System. It is not a necessary prerequisite to the experiments that follow, but it may prove helpful in learning to use the equipment effectively and in understanding the significance of measurements made with this equipment.

- <u>Procedure</u>

1. Arrange the Transmitter and Receiver on the Goniometer as shown in figure 1, with the Transmitter on the fixed arm. Be sure the Transmitter and Receiver are adjusted to the same polarity (the horns should have the same orientation, as shown in the figure.

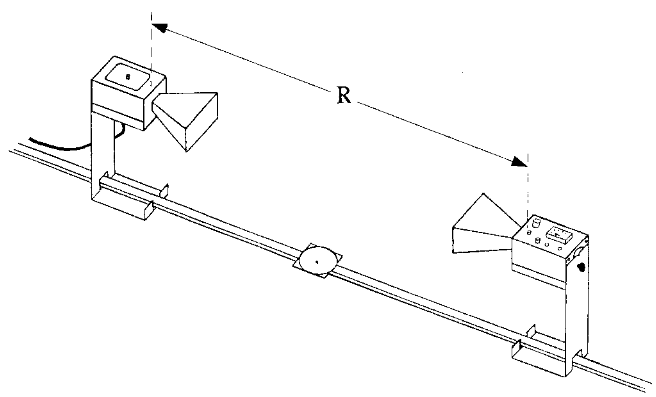

Figure 1: Equipment Setup

2. Plug in the Transmitter and turn the INTENSITY selection switch on the Receiver from OFF to 30X. (The LEDs should light up on both units.)
3. Adjust the Transmitter and Receiver so the distance between the source diode in the Transmitter and the detector diode in the Receiver (the distance labeled R in Fig. 1 is 40 cm). Adjust the INTENSITY and VARIABLE SENSITIVITY dials on the Receiver so that the meter reads 1.0 (full scale).

   Set the distance R to each of the values shown in Table 1. For each value of R, record the meter reading. (Do not adjust the Receiver controls between measurements.) After making the measurements, perform the calculations.

Table 1:

R (cm)	M Meter Reading	M × R (cm)	M × R^2 (cm^2)
40	1.0	40	1600
50			
60			
70			
80			
90			
100			

4. Set R to some value between 30 and 50 cm. While watching the meter, slowly decrease the distance between the Transmitter and Receiver. Does the meter deflection increase steadily as the distance decrease ?
5. Move a Reflector, with the plane of the Reflector parallel to the axis of the microwave beam, toward and away from the beam axis. Observe the meter readings. Can you explain your observations in steps 5 and 6 ? Be aware of the following:

IMPORTANT: *Reflections from nearby objects, including the table top, can affect the results of your microwave experiments. To reduce the effects of extraneous reflections, keep your experiment table clear of all objects, especially metal objects, than those components that are required for the current experiment.*

6. Loosen the hand of the screw on the back of the receiver and rotate the Receiver. This varies the polarity of maximum detection. (Look into the Receiver horn and notice the alignment of the detector diode.) Observe the meter readings through a full 360 degree rotation of the horn. At what polarity is no signal detected by the Receiver ?
   Try rotating the Transmitter horn as well. When finished, reset the Transmitter and Receiver so their polarities match (e.g.; both horns are horizontal or both horns are vertical).
7. Position the Transmitter so the output surface of the horn is directly over the Degree Plate of the Goniometer arm. With the Receiver directly facing the Transmitter and as far back on the Goniometer arm as possible, adjust the Receiver controls for a meter reading of 1.0. Then rotate the rotatable arm of the Goniometer. Set the angle of rotation (measured from 180-degree point on the degree scale) to each of the values shown in Table 2, and record the meter reading at each setting.

- <u>Questions</u>

1. The electric field of an electromagnetic wave is inversely proportional to the distance from the source of the wave (i.e. $E = 1/R$). Use your data from step 4 of the experiment to determine if the meter reading of the Receiver is directly proportional to the electric field of the wave ?
2. The intensity of an electromagnetic wave is inversely proportional to the square of the distance from the source of the wave (i.e. $I = 1/R^2$). Use your data from step 4 of the experiment to

Table 2:

Angle	Meter Reading	Angle	Meter Reading
0°	1.0	50°	
10°		60°	
20°		70°	
30°		80°	
40°		90°	

determine if the meter reading of the Receiver is directly proportional to the intensity of the wave ?

3. Considering your results in step 7, to what extent can the output of the Transmitter be considered a spherical wave ? A plane wave ?

Experiment 2 : Reflection

- Procedure

1. Arrange the equipment as shown in figure 2, with the Transmitter on the fixed arm of the Goniometer. Be sure the Transmitter and Receiver are adjusted to the same polarity (the horns should have the same orientation, as shown in the figure.

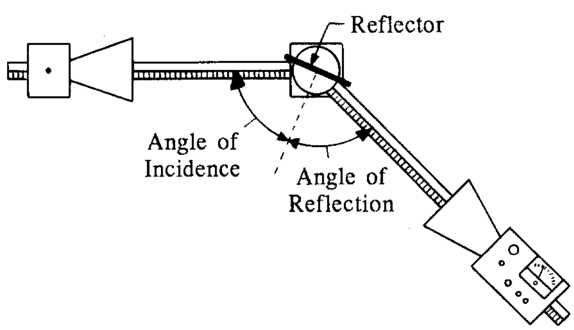

Figure 2: Angles of Incidence and Reflection

2. Plug in the Transmitter and turn the Receiver INTENSITY selection switch to 30X.
3. The angle between the incident wave from the Transmitter and a line normal to the plane of the Reflector is called **Angle of Incidence**. Adjust the rotating Component Holder so that the Angle of Incidence equals 45-degrees.
4. Without moving the Transmitter or the Reflector, rotate the movable arm of the Goniometer until the meter reading is a maximum. The angle between the axis of the Receiver horn and a line normal to the plane of the Reflector is called the **Angle of Reflection**.

5. Measure and record the angle of reflection for each of the angles of incidence shown in Table 3. (NOTE: At some angles the Receiver will detect not only the wave that is reflected, but also the wave coming directly from the Transmitter, giving misleading results. Determine the angles for which this is true, and mark the data collected at these angles with an asterisk '*'.)

Table 3:

Angle of incidence	Angle of reflection
10°	
20°	
30°	
40°	
50°	
60°	
70°	
80°	
90°	

- Questions

1. What relationship holds between the angle of incidence and the angle of reflection ? Does this relationship hold for all angles of incidence ?
2. In measuring the angle of reflection, you measured the angle at which a maximum meter reading was found. Can you explain why some of the wave was reflected into different angles ? How does this affect your answer to question 1 ?
3. Ideally this experiment would be performed with a perfect plane wave, so that all the radiation from the Transmitter would strike the Reflector at the angle of incidence. Is the microwave from the Transmitter a perfect plane wave (see Experiment 1, step 7) ? Would you expect different results if it were a perfect plane wave ? Explain.

Experiment 3 : Refraction through a Prism

- Introduction

An electromagnetic wave usually travels in a straight line. However, when it crosses a boundary between two different media, the direction of propagation of the wave is changed. This change in direction is called **Refraction**, and it is summarized by a mathematical relationship known as the Law of Refraction (otherwise known as Snell's Law):

$$n_i.sin\theta_i \ = \ n_r.sin\theta_r$$

where θ_i is the angle between the direction of propagation of the incident wave and the normal to the boundary between the two media, and θ_r is the corresponding angle for the refracted wave (see figure 3). The quantities n_i and n_r are parameters that depend on the materials between which the wave is passing; n is called the **index of refraction** for the material

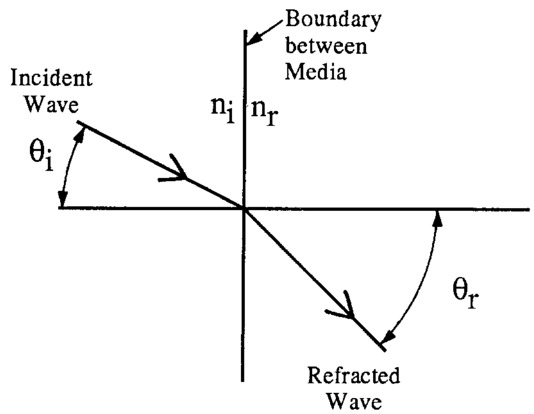

Figure 3: Angles of Incidence and Refraction

In this experiment, you will use the law of refraction to measure the index of refraction for styrene pellets.

- Procedure

1. Arrange the equipment as shown in figure 4. Rotate the empty prism mold and see how it effects the incident wave. Does it reflect, refract, or absorb the wave ?

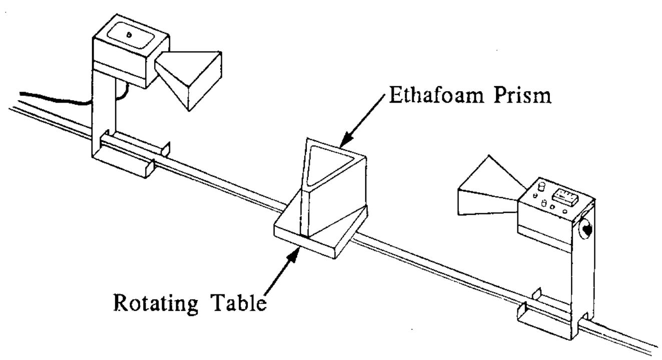

Figure 4: Equipment Setup

2. Fill the prism mold with the styrene pellets. To simplify the calculations, align the face of the prism that is nearest to the Transmitter perpendicular to the incident microwave beam.
3. Rotate the movable arm of the Goniometer and locate the angle θ at which the refracted signal is a maximum. (NOTE: θ is just the angle that you read directly from the Degree Scale of the Goniometer.) Write the value of θ.
4. Using the diagram shown in figure 5, determine θ_i and use your value of θ to determine θ_r. (You will need to use a protractor to measure the Prism angles.)
5. Plug these values into the Law of Refraction to determine the value of n_r/n_i.

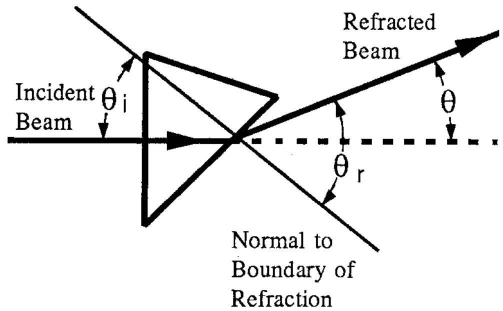

Figure 5: Geometry of Prism Refraction

6. The index of refraction for air is equal to 1.00. Use this fact to determine n_r, the index of refraction for the styrene pellets.

- Questions

1. In the diagram of the figure 5, the assumption is made that the wave is unrefracted when it strikes the first side of the prism (at an angle of incidence of 0°). Is this a valid assumption ?
2. Using this apparatus, how might you verify that the index of refraction for air is equal to one ?
3. Would you expect the index of refraction of the styrene pellets in the prism mold to be the same as for a solid styrene prism ?

Experiment 4 : Polarization

- Introduction

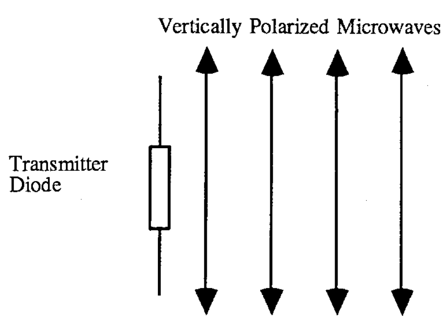

Figure 6: Vertical Polarization

The microwave radiation from the Transmitter is **linearly Polarized** along the axis of the Transmitter diode; that is, as the radiation propagates through space, its electric field remains aligned with the axis of the diode. If the Transmitter diode were aligned vertically, the electric field of the transmitted wave would be vertically polarized, as shown in figure 6. If the detector diode were at an angle θ to the Transmitter diode, as shown in figure 7, it would only detect the component of the incident electric field that was aligned along its axis. In this experiment you will investigate the phenomenon of polarization and discover how a polarizer can be used to alter the polarization of microwave radiation.

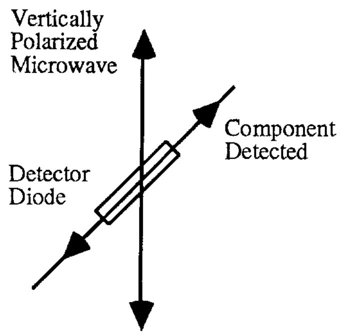

Figure 7: Detecting Polarized Radiation

- Procedure

1. Arrange the equipment as shown in figure 8 but without the polarizer and adjust the Receiver controls for nearly full-scale meter deflection.

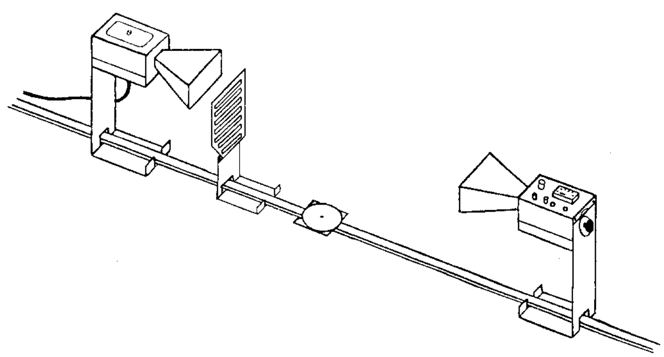

Figure 8: Equipment Setup

2. Loosen the hand screw on the back of the Receiver and rotate the Receiver in increments of ten degrees. At each rotational position, record the meter reading in Table 4.

3. What happens to the meter readings if you continue to rotate the Receiver beyond 180-degrees?
4. Setup the equipment as shown in figure 8, and reset the angle of rotation of the Receiver for vertical polarization (the horn shoul be oriented as shown in the figure).
5. With the slits of the polarizer aligned horizontally, at what angle of polarization does the Receiver show a minimum meter deflection ? Repeat this measurement with slits aligned at 22.5, 45, 67.5 and 90-degrees with respect to the horizontal.

Table 4:

Angle of Receiver	Meter Reading	Angle of Receiver	Meter Reading	Angle of Receiver	Meter Reading
0°		70°		140°	
10°		80°		150°	
20°		90°		160°	
30°		100°		170°	
40°		110°		180°	
50°		120°			
60°		130°			

Table 5:

Angle of Slits	Angle of Rec. for Min. Meter Reading
0° (Horiz.)	
22.5°	
45°	
67.5°	
90° (Vert.)	

6. Remove the Polarizer. Rotate the Receiver so its polarization is at right angles to that of the Transmitter. Record the meter reading. Then replace the Polarizer and record the meter readings with the Polarizer slits horizontal, vertical, and at 45-degrees.

Table 6:

Angle of Slits	Meter Readings
Horizontal	
Vertical	
45°	

- Questions

1. If the meter reading of the Receiver (M) were directly proportional to the component of the electric field (E) along its axis, then the meter reading would be given by the relationship $M = M_0 \cos\theta$, where θ is the angle between the detector and Transmitter diodes and M_0 is the meter reading when $\theta = 0$ (see figure 7). Graph your data from step 3 of the experiment. On the same graph, plot the relationship $M_0 \cos\theta$. Compare the two graphs.

2. The intensity of a linearly polarized electromagnetic wave is directly proportional to the square of the electric field (e.g.; $I = kE^2$). If the meter reading of the Receiver was directly proportional to the intensity of the incident microwave, then the meter reading would be given by the relationship $M = M_0 \cos^2\theta$. Plot this relationship on your graph from question 1. Based on your graphs,

discuss the relationship between the meter reading of the Receiver and the polarization and magnitude of the incident microwave.

3. On the basis of your data from step 5, how does the Polarizer affect the incident microwave ?

Experiment 5 : Double-Slit Interference

- Introduction

The wave is broken into two waves which superpose in the space beyond the apertures. Just as in the standing wave pattern, there are points in space where maxima are formed and others where minima are formed.

With a double slit aperture, the intensity of the wave beyond the aperture will vary depending on the angle of detection. For two thin slits separated by a distance d, maxima will be found at angles such that d.sinθ = nλ; where θ is the angle of detection, λ is the wavelength of the incident radiation, and n is any integer (see figure 9). Before beginning this experiment, read through your textbook (be sure you understand the nature of the double-slit diffraction pattern.

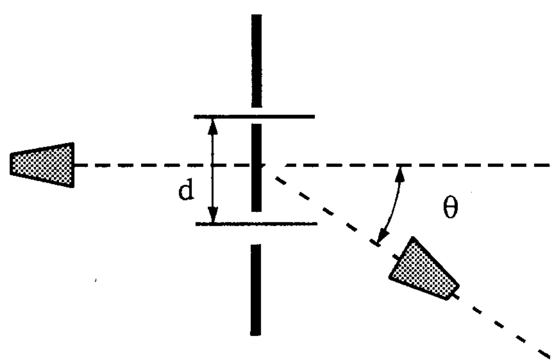

Figure 9: Double-Slit Interference

- Procedure

1. Arrange the equipment as shown in figure 10. Use the Slit Extender Arm, two Reflectors, and the Narrow Slit Spacer to construct the double slit. (We recommended a slit width of about 1.5 cm.) Be precise with the alignment of the slit and make the setup as symmetrical as possible.
2. Adjust the Transmitter and Receiver for vertical polarization (0°) and adjust the Receiver controls to give a full scale reading at the lowest possible amplification.
3. Rotate the rotatable Goniometer arm (on which the Receiver is mounted) slowly about its axis. Observe the meter readings.
4. Reset the Goniometer arm so the Receiver directly faces the Transmitter. Adjust the Receiver controls to obtain a meter reading of 1.0. Now set the angle θ to each of the values shown in the Table 7. At each setting record the meter reading in the table. (In places where the meter

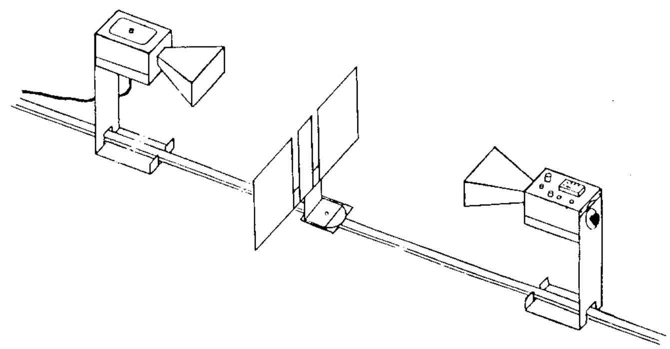

Figure 10: Equipment Setup

reading changes significantly between angle settings, you may find it useful to investigate the signal level at intermediate angles.)

Table 7:

θ	Meter Readings	θ	Meter Readings
0°		45°	
5°		50°	
10°		55°	
15°		60°	
20°		65°	
25°		70°	
30°		75°	
35°		80°	
40°		85°	

5. Keep the slit widths the same, but change the distance between the slits by using the Wide Slit Spacer instead of the Narrow Slit Spacer. Move the Transmitter farther back so that the slits are evenly illuminated. Repeat the measurements of step 2. (You may want to try other slit spacings as well.)

- Questions

1. From your data, plot a graph of meter reading versus θ. Identify the angles at which the maxima and minima of the interference pattern occur.
2. Calculate the angles at which you would expect the maxima and minima to occur in a standard Fraunhoffer two-slit diffraction pattern; maxima occur wherever $\mathrm{d.sin}\theta = \mathrm{n}\lambda$, minima occur wherever $\mathrm{d.sin}\theta = (n + \frac{1}{2})\lambda/2$. How does this compare with the locations of your observed maxima and minima ? Can you explain any discrepancies ? (What assumptions are made in the derivations of the formulas and to what extent are they met in this experiment ?)
3. Can you explain the relative drop in intensity for higher order maxima (You may want wait until you have completed Experiment 6: Single Slit Diffraction to answer this question. Then

consider the single-slit diffraction pattern created by each slit. How do these single slit patterns affect the overall interference pattern ?)

Experiment 6 : Single-Slit Interference

- <u>Introduction</u>

  When a wave passes through an aperture whose dimensions are near that of the wavelength of the wave, a diffraction pattern is formed. If the aperture is a single slit, the intensity of the diffracted wave will vary depending on the angle of detection: minima will be found at angles such that $a.\sin\theta = n\lambda$; where a is the slit width, θ is the angle of detection, λ is the wavelength of the incident radiation, and n is any integer (see figure 11).

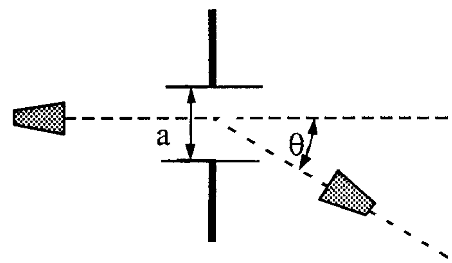

Figure 11: Single-Slit Diffraction

- <u>Procedure</u>

  1. Arrange the equipment as shown in figure 12. Use the Slit Extender Arm and both Reflectors to construct the vertical slit. Set the slit width to 7.0 cm and align the slit as symmetrically as possible.

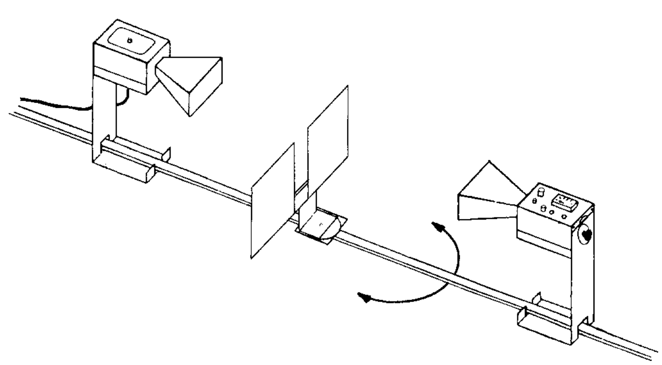

Figure 12: Equipment Setup

2. Set the rotational scale on the back of both the Transmitter and receiver for vertical polarization (0°). Adjust the Receiver controls to give a full scale reading at the lowest possible INTENSITY setting.

3. Rotate the rotatable Goniometer arm (on which the Receiver is mounted) slowly about its axis. Observe the meter readings.

4. Reset the Goniometer arm so the Receiver directly faces the Transmitter. Adjust the Receiver controls to obtain a meter reading of 1.0. Now set the angle of the Goniometer arm to each of the values shown in Table 8. At each setting record the meter reading in the table. You may need to increase the INTENSITY setting to clearly see all the maxima and minima. If so, be sure you multiply all your data by the appropriate value (i.e. 30, 10, 5, or 1) so your results are truly proportional to the signal intensity. (In places where the meter reading changes significantly between angle settings, you may find it useful to investigate the signal level at intermediate angles.)

Table 8:

θ	Meter Readings	θ	Meter Readings
0°		45°	
5°		50°	
10°		55°	
15°		60°	
20°		65°	
25°		70°	
30°		75°	
35°		80°	
40°		85°	

5. Change the slit width to 13.0 cm. Move the Transmitter further from the slit to provide a more uniform illumination of the slit. Repeat the measurements of step 4. You may want to try other slit widths. If so, experiment with Transmitter and Receiver distances and with Receiver sensitivity to get optimum results.

- Questions

1. From your data, plot a graph of meter reading versus angle. Identify the angles at which minima and maxima occur. Are the angles in agreement with those you would expect in a Fraunhoffer single-slit diffraction pattern ?

2. The standard Fraunhoffer formula for single-slit diffraction depends on several assumptions. What are these assumptions and to what extent are they met in this experiment ?

Experiment 7 : Fabry-Perot Interferometer

- Introduction

When an electromagnetic wave encounters a partial reflector, part of the wave is reflected and part of the wave is transmitted through the partial reflector. A Fabry-Perot Interferometer consists of two parallel partial reflectors positioned between a wave source and a detector (see figure 13).

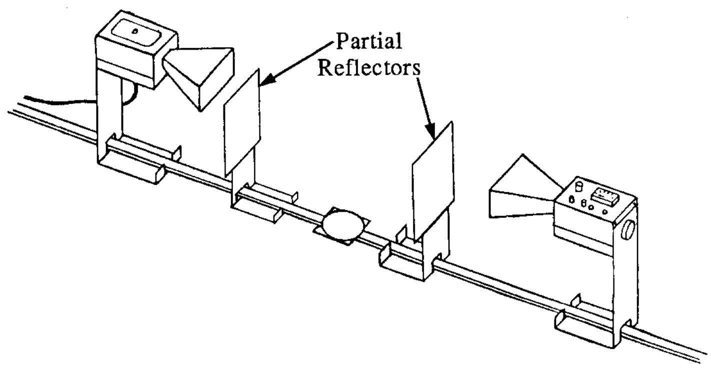

Figure 13: Fabry-Perot Interferometer

The wave from the source is reflected back and fourth between the two partial reflectors. However, with each pass, some of the radiation passes through to the detector. If the distance between the partial reflectors is equal to $n\lambda/2$, where λ is the wavelength of the radiation and n is an integer, then all the waves passing through to the detector at any instant will be in phase. In this case, a maximum signal will be detected by the Receiver. If the distance between the partial reflectors is not a multiple of $\lambda/2$, then some degree of destructive interference will occur, and the signal will not be a maximum.

- Procedure

  1. Arrange the equipment as shown in figure 13. Plug in the Transmitter and adjust the Receiver Controls for an easy readable signal.
  2. Adjust the distance between the partial reflectors and observe the relative minima and maxima.
  3. Adjust the distance between the partial reflectors to obtain a maximum meter reading. Record, d_1, the distance between the reflectors.
  4. While watching the meter, slowly move one reflector away from the other. Move the reflector until the meter reading has passed through at least 10 minima and returned to a maximum. Record the number of minima that were traversed. Also record d_2, the new distance between the reflectors.
  5. Use your data to calculate λ, the wavelength of the microwave radiation.
  6. Repeat your measurements, beginning with a different distance between the partial reflectors.

- Questions

  1. What spacing between the two partial reflectors should cause a minimum signal to be delivered to the Receiver ?

2. In an optical Fabry-Perot Interferometer the interference pattern is usually seen as a series of concentric rings. Do you expect such a pattern to occur here ? Why ? Check to see if there is one.

Experiment 8 : Michelson Interferometer

- Introduction

  Like the Fabry-Perot interferometer, the Michelson interferometer splits a single wave, then brings the constituent waves back together so that they superpose, forming an interference pattern. Figure 14 shows the setup for the Michelson interferometer. A et B are reflectors and C is a partial reflector. Microwaves travel from the Transmitter to the Receiver over two different paths. In one path, the wave passes directly through C, is reflected back to C from A, and then is reflected from C into the Receiver. In the other path, the wave is reflected from C into B, and then back through C into the Receiver.

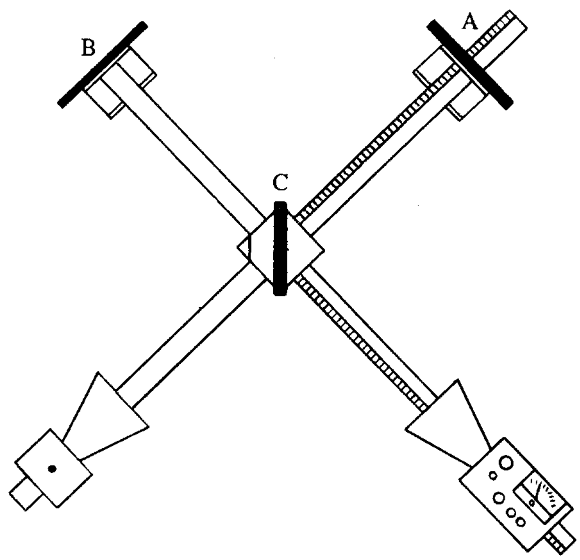

Figure 14: Michelson Interferometer

If the two waves are in phase when they reach the Receiver, a maximum signal is detected. By moving one of the reflectors, the path length of one wave is changed, thereby changing its phase at the Receiver so a maximum is no longer detected. Since each wave passes twice between a reflector and the partial reflector, moving a reflector a distance $\lambda/2$ will cause a complete 360-degree change in the phase of one wave at the Receiver, causing the meter reading to pass through a minimum and to a maximum.

- Procedure

1. Arrange the equipment as shown in figure 14. Plug in the Transmitter and adjust the Receiver for an easily readable signal.

2. Slide reflector A along the Goniometer arm and observe the relative maxima and minima of the meter deflections.
3. Set reflector A to a position which produces a maximum meter reading. Record, x_1, the position of the reflector on the Goniometer arm.
4. While watching the meter, slowly move reflector A away from the partial reflector. Move the reflector until the meter reading has passed through at least 10 minima and returned to a maximum. Record the number of minima that were traversed. Also record x_2, the new position of the reflector A on the Goniometer arm.
5. Use your data to calculate λ, the wavelength of the microwave radiation.
6. Repeat your measurements, beginning with a different position for reflector A.

- Question

  You have used the interferometer to measure the wavelength of the microwave radiation. If you already knew the wavelength, you could use the interferometer to measure the distance over which the reflector was moved. Why would an optical interferometer (an interferometer using visible light rather than microwaves) provide better resolution when measuring distance than a microwave interferometer?

Experiment 9 : Brewster's Angle

- Introduction

  When electromagnetic radiation passes from one media into another, some of the radiation is usually reflected from the surface of the new medium. In this experiment, you will find that the magnitude of the reflected signal depends on the polarization of the radiation. In fact, at a certain angle of incident, known as Brewster's Angle, there is an angle of polarization for which no radiation will be neglected.

- Procedure

1. Arrange the equipment as shown in figure 15, setting both the Transmitter and the Receiver for horizontal polarization (90°).
2. Adjust the Panel so the angle of incidence of the microwave from the Transmitter is equal to 20-degrees. Rotate the Goniometer arm until the Receiver is positioned where it can detect the signal reflected from the Panel. Adjust the Receiver controls for a mid-scale reading, and record the meter reading in Table 9.
3. Without changing the angles between the transmitted beam, the Polyethylene Panel, and the Receiver, rotate both the Transmitter and the Receiver horns so they are set for vertical polarization (0°). Record the new meter reading in the table.
4. Set the angle of incidence to each of the values shown in Table 9. At each point set the Transmitter and Receiver for horizontal polarization and record the meter reading; then set them for vertical polarization and record that reading as well.
5. Plot a graph of Meter Reading versus Angle of Incidence. Plot both the vertical and horizontal polarizations on the same graph. Label Brewster's Angle (the angle at which the horizontally polarized light is not reflected). (To locate Brewster's Angle more accurately, you may want to investigate the signal levels at additional angles of incidence.)

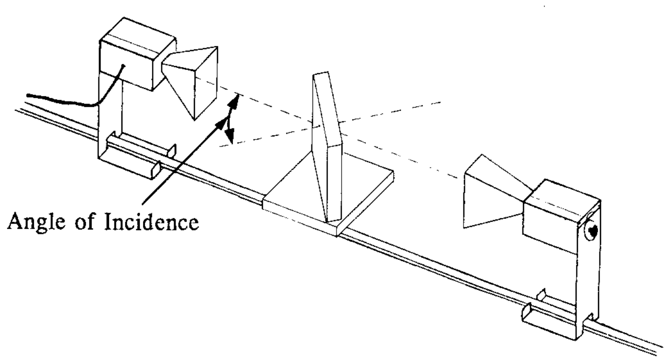

Figure 15: Equipment Setup

Table 9:

Angle of Incidence	Meter Readings (Horizontal Polarization)	Meter Readings (Vertical Polarization)
20°		
25°		
30°		
35°		
40°		
45°		
50°		
55°		
60°		
65°		
70°		
75°		

- Questions

  1. Could you use the microwave apparatus to locate Brewster's Angle by examining the transmitted wave rather than the reflected wave ? How ?
  2. Check in your textbook for the theorical basis of Brewster's Angle. Using your measurement of Brewster's Angle, determine the index of refraction of the Polyethylene Panel.

Experiment 10 : Bragg Diffraction

- Introduction

  Bragg's Law provides a powerful tool for investigating crystal structure by relating the interplanar spacings in the crystal with the scattering angles of incident x-rays. In the experiment, Bragg's Law is demonstrated on a macroscopic scale using a cubic "crystal" consisting of 10-mm metal spheres embedded in an ethafoam cube.

Before performing this experiment, you should understand the theory behind Bragg Diffraction. In particular, you should understand the two criteria that must be met for a wave to be diffracted from a crystal into a particular angle. Namely, there is a plane of atoms in the crystal oriented with respect to the incident wave, such that:
(1) the angle of incidence equals the angle of reflection, and
(2) Brewster's Law, $2d.\sin\theta = n\lambda$, is satisfied; where d is the spacing between the diffracting planes, θ is the grazing angle of the incident wave, n is an integer, and λ is the wavelength of the radiation.

- Procedure

1. Arrange the equipment as shown in figure 16.

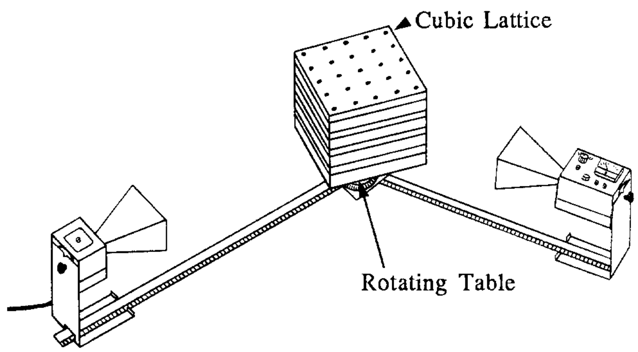

Figure 16: Equipment Setup

2. Notice the three families of planes indicated in figure 17. (The designations (100), (110), and (210) are the Miller indices for these sets of planes.) Adjust the Transmitter and Receiver so that they directly face each other. Align the crystal so that the (100) planes are parallel to the incident microwave beam. Adjust the Receiver controls to provide a readable signal. Record the meter reading.

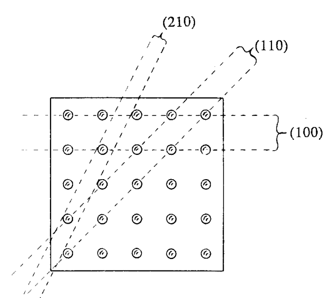

Figure 17: "Atomic" Planes of the Bragg Crystal

3. Rotate the crystal (with the rotating table) one degree clockwise and the rotatable Goniometer arm two degrees clockwise. Record the grazing angle of the incident beam and the meter reading. (The grazing angle is the complement of the angle of incidence, and is measured with respect to the angle under investigation, NOT the face of the cube (see figure 18).)

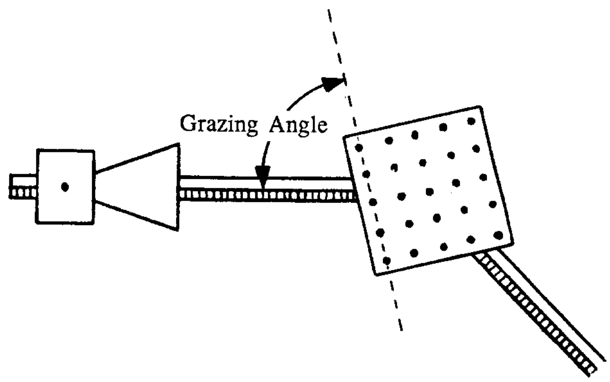

Figure 18: Grazing Angle

4. Continue in this manner, rotating the Goniometer arm two degrees for every one degree rotation of the crystal. Record the angle and meter reading at each position. (If you need to adjust the INTENSITY setting on the Receiver, be sure to indicate that in your data.)
5. Graph the relative intensity of the diffracted signal as a function of the grazing angle of the incident beam. At what angles do definite peaks for the diffracted intensity occur ?
6. Use your data, the known wavelength of the microwave radiation (2.9 cm), and Bragg's Law to determine the spacing between the (100) planes of the Bragg Crystal.
7. Measure the spacing between the planes directly, and compare with your experimental determination.
8. If you have time, repeat the experiment for the (110) and (210) families of planes.

- Questions

1. What other families of planes might you expect to show diffraction in a cubic crystal ? Would you expect the diffraction to be observable with this apparatus ? Why ?
2. Suppose you did not know before hand the orientation of the "inter-atomic planes" in the crystal. How would this affect the complexity of the experiment ? How would you go about locating the planes ?