Lab 06. Wave Properties of Microwaves

1. Objectives

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

2. Theory : Electromagnetic waves

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

$$c = 1/f, \tag{1}$$

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 Figure 1.

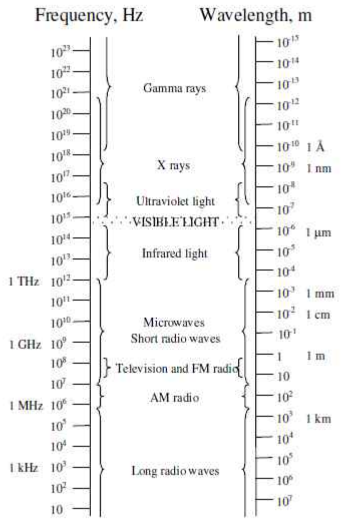

Figure 1

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 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 (430 - 750 THz). These wavelengths (and hence, frequencies) differ by nearly five orders of magnitude, and yet we shall find that both waves exhibit the effects of **polarization**.

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. When the electric field of a wave is oriented in a particular direction, that is to say, not in random directions, we say the wave is **polarized**.

In this workshop, we will investigate the polarization of two types of electromagnetic waves that have somewhat different wavelengths and frequencies: microwaves and visible light. We will both produce and analyze polarized waves.

Figure 2 shows a periodic electromagnetic wave traveling in the z-direction and polarized in the x-direction. **E** is the vector of the electric field and **B** is the vector of the magnetic field. Study this figure carefully. We will refer to it often. 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. 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. Even though the electric field vector is constrained to be perpendicular to the direction of propagation, there are still infinitely many orientations possible (illustrated in Figure 3). Electromagnetic waves from ordinary sources (the sun, a light bulb, a candle, etc.), in addition to having a continuous spectrum, are a mixture of waves with all these possible directions of polarization and, therefore, don't exhibit polarization effects.

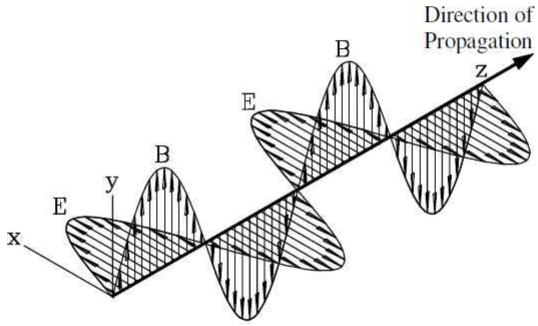

Figure 2

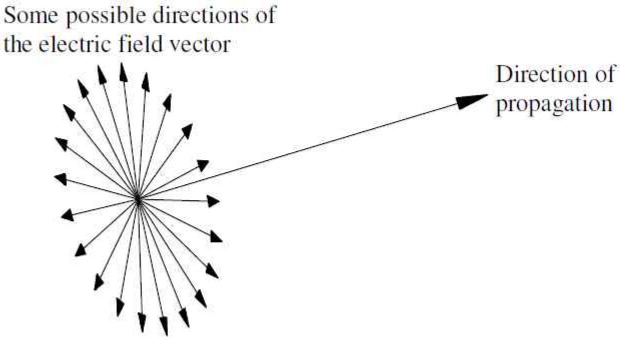

Figure 3

It is, however, possible to produce **linearly polarized electromagnetic waves**. In other words, waves whose electric field vector *only* oscillates in one direction. Look again at Figure 2. It schematically shows a linearly polarized electromagnetic wave polarized in the x-direction.

The electric field of a plane wave of wavelength λ, propagating in the z-direction and polarized in the x-direction, can be described by:

$$\boldsymbol{E}_x = \boldsymbol{i} E_x \sin\left(\frac{2\pi}{\lambda}(z - ct)\right), \tag{2}$$

where **E**x is the vector of the electric field, *Ex* its amplitude, and **i** the unit vector in the x-direction. A wave of the same wavelength, polarized in the y -direction, is described by:

$$\boldsymbol{E}_y = \boldsymbol{j} E_y \sin\left(\frac{2\pi}{\lambda}(z - ct) + \phi\right). \tag{3}$$

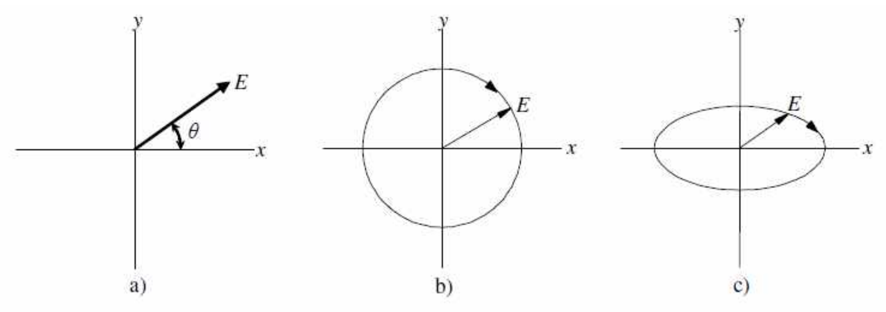

Figure 4

Here, **j** is the unit vector in the *y*-direction and f is a constant that accounts for the possibility that the two waves might not have the same phase. From two such waves, one can construct all plane waves of wavelength l traveling in the *z*-direction. If both *x*- and *y*-components are present and their phase difference is zero (or 180°), the wave will be linearly polarized in a direction somewhere between the *x* -direction and the *y*-direction, depending on the relative magnitudes of $\mathbf{E}_x$ and $\mathbf{E}_y$ (see Figure 4a). Mathematically such a wave is described by:

$$\boldsymbol{E} = \boldsymbol{E}_x + \boldsymbol{E}_y = (\boldsymbol{i}E_x \pm \boldsymbol{j}E_y)\sin\left(\frac{2\pi}{\lambda}(z-ct)\right), \tag{4}$$

where the plus sign refers to a phase difference of zero and the minus sign to one of 180° (π radians). The angle q between this polarization direction and the x -direction is given by

$$\tan\theta = \frac{E_y}{E_x} \tag{5}$$

If the phase shift is not zero (or 180°), the wave will not be linearly polarized. While we will only be investigating linear polarization in this lab, it is useful to know something about other types of polarization. Consider the case where the magnitudes are equal, but the phase shift is ±90° (± π/2 radians). In other words:

$$E_x = E_y \text{ and } \phi = \pm\frac{\pi}{2} \tag{6}$$

The resulting wave, called a *circularly polarized* wave, can be written:

$$\boldsymbol{E} = \boldsymbol{E}_x + \boldsymbol{E}_y = E\left[\boldsymbol{i}sin\left(\frac{2\pi}{\lambda}(z-ct)\right) \pm \boldsymbol{j}cos\left(\frac{2\pi}{\lambda}(z-ct)\right)\right] \tag{7}$$

by making use of the fact that $\sin(\alpha+\pi/2) = \pm\cos\alpha$. With the plus sign, this equation describes a wave whose electric field vector, **E**, rotates clockwise in the *x-y* plane if the wave is coming toward the observer. Such a wave, illustrated by Figure 4b, is called a *right circularly polarized* wave. With the minus sign, the equation describes a *left circularly polarized* wave. With the phase shift still ±90°, but with different magnitudes

$$E_x \neq E_y \text{ and } \phi = \pm\frac{\pi}{2} \tag{8}$$

the **E** vector will still rotate clockwise or counterclockwise but will trace out an ellipse as shown Figure 4c. With thermal sources, there is a random mix of different E_x, E_y, and f values. The resulting wave will be unpolarized.

Polarized electromagnetic waves can be obtained in two ways:

1. by using sources, such as certain lasers, that produce only waves with one plane of polarization, or
2. by polarizing unpolarized waves by passing them through a **polarizer**, a device that will let only waves of one particular plane of polarization pass through.

Some sources of electromagnetic waves generate linearly polarized waves. Examples include the microwave generator we'll use today as well as some types of lasers. Other sources generate unpolarized waves. Examples include thermal sources such as the sun and incandescent lamps.

One way of producing linearly polarized electromagnetic waves from unpolarized sources is to make use of a process that directs waves of a given polarization in a different direction than waves polarized in the perpendicular direction. Earlier we noted that the electric field of an electromagnetic wave incident upon a wire induces an oscillating current in the wire. Some energy will be lost through resistive heating, but most will be re-radiated (scattered).

Only the component of the oscillating electric field that is parallel to the wire will induce a current and be scattered. The electric field component perpendicular to the wires, on the other hand, will be essentially unaffected by the wires (assuming a negligible wire diameter). Hence, both the scattered and unscattered electromagnetic waves are linearly polarized. For microwaves, we can (and will) use an array of actual wires. For visible light, we use a **Polaroid** filter. **Polaroid** filters are made by absorbing iodine (a conductive material) into stretched sheets of polyvinyl alcohol (a plastic material), creating, in effect, an oriented assembly of microscopic "wires". In a Polaroid filter the component polarized parallel to the direction of stretching is absorbed over 100 times more strongly than the perpendicular component. The light emerging from such a filter is better than 99% linearly polarized.

A polarizer will only pass the components of an electromagnetic wave that are parallel to its polarizing axis. Figure 5 shows polarized electromagnetic waves incident on a polarizing filter, P (shown as a wire array). The electric field of the incident wave ($\mathbf{E}_i$) is oriented at an angle Θ relative to the polarization axes of P. Let **p** be a unit vector along the polarization axis of the polarizer. The effect of the polarizer, then, is to "project out" the component of $\mathbf{E}_i$ that is along **p**: $\mathbf{E}e = \mathbf{p}\,(\mathbf{p}\cdot\mathbf{E}_i) = E_i \cos\,\Theta\,\mathbf{p}$. Because the intensity of an electromagnetic wave is proportional to the square of its electric field amplitude, it follows that the intensity of the electromagnetic waves exiting the analyzer is given by:

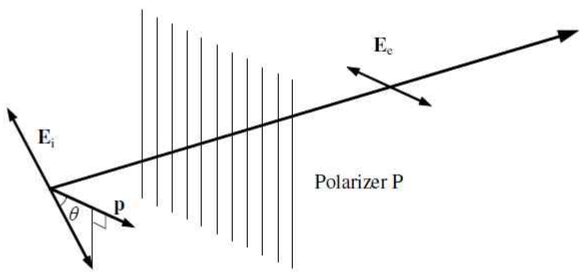

Figure 5

$$I_e = I_i \cos^2\theta. \tag{9}$$

This is known as Malus' Law, after the French physicist who discovered the polarizability of light. Initially unpolarized electromagnetic waves can be thought of as a mixture of all possible polarizations. Each possible polarization will be attenuated according to Malus' law, and so the total intensity will be the initial intensity times the average of cos2q (which is 1/2). In other words, the intensity is reduced to one half of the incident intensity.

Except in the case where θ is zero (or 180°), $\mathbf{E}_e$ (the electric field of the electromagnetic waves exiting the polarizer) will have a component that is perpendicular to $\mathbf{E}_i$. If we place yet another polarizer after P (call it P′) with its polarization axis right angles to incident wave's polarization axis, we will get electromagnetic waves out whose polarization is orthogonal to the incident waves' polarization. We have effectively rotated the polarization of the incident waves (with some loss of intensity). Applying Malus' Law, we get:

$$I' = I_i \cos^2\theta \cos^2\theta' \tag{10}$$

where Θ is the angle between the initial polarization and the first polarizer, P, and Θ' is the angle between P and the second polarizer, P′. But P′ is at right angles to the initial wave's polarization, so $\theta + \theta' = 90°$. Hence, $\cos^2\theta' = \sin^2\theta$. Using another trigonometric identity ($\sin 2\Theta = 2 \sin\Theta \cos\Theta$), we finally get $I' = 0.25 I_i \sin^2 2\theta$. We can see we get the maximum transmission when θ = 45° (sin 2×45° = 1) and that it is one quarter of the intensity of the incident polarized waves (I_i).

Equipments

INCLUDED:

Transmitter (WA-9801) WA-9314B Accessory	1
Goniometer WA-9314B Accessory	1
Receiver (WA-9800) WA-9314B Accessory	1
Component Holder WA-9314B Accessory	2
Meter Stick	1
Patch Cords (Black) SE-9751	2
Patch Cords (Red) SE-9750	2
Digital Multimeter (Digital ammeter) MY68	1
Rotating Table(003-02100) WA-9314B Accessory	1
Fixed Arm Assembly(003-02093) WA-9314B Accessory	1
Polyethylene Panel WA-9316	1
Cubic Lattice WA-9315	1

NOT INCLUDED, BUT REQUIRED:

Science Workshop 750 Interface CI-7650	1
Data Studio Software	1

3. Procedures

Part 1: Introduction to the System

① Arrange the Transmitter and Receiver on the Goniometer as shown in Figure 1.1 with the Transmitter attached to the fixed arm. Be sure to adjust both Transmitter and Receiver to the same polarity - the horns should have the same orientation, as shown.

② Plug in the Transmitter and turn the INTENSITY selection switch on the Receiver from OFF to 10X. (*The LEDs should light up on both units.*)

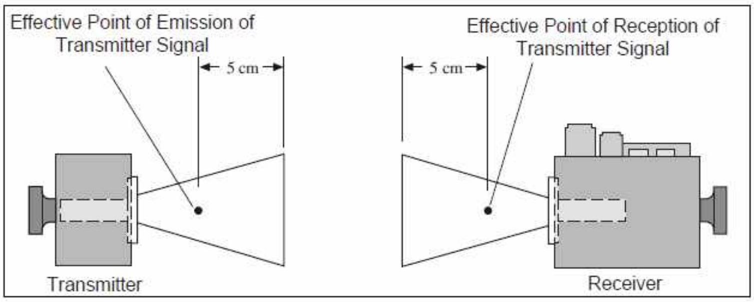

Figure 1.2 Equipment Setup

③ Adjust the Transmitter and Receiver so the distance between the source diode in the Transmitter and the detector diode in the Receiver is 40 cm (*see Figure 1.2 for location of points of transmission and reception*). The diodes are at the locations marked "T" and "R" on the bases. Adjust the INTENSITY and VARIABLE SENSITIVITY dials on the Receiver so that the meter reads 1.0 (*full scale*).

④ Set the distance R to each of the values shown in Table 1.1. For each value of R, record the meter reading. (*Do not adjust the Receiver controls between measurements.*) After making the measurements, perform the calculations shown in the table.

⑤ Set R to some value between 70 and 90 cm. While watching the meter, slowly decrease the distance between the Transmitter and Receiver. Does the meter deflection increase steadily as the distance decreases?

⑥ Set R to between 50 and 90 cm. Move a Reflector, its plane parallel to the axis of the microwave beam, toward and away from the beam axis, as shown in Figure 1.3. Observe the meter readings. Can you explain your observations in steps 5 and 6? Don't worry if you can't; you will have a chance to investigate these phenomena more closely in Experiments 3 and 8, later in this manual. For now just 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, other than those components required for the current experiment.*

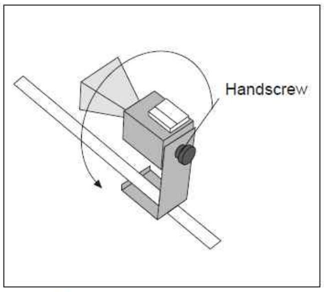

Figure 1.4 Polarization

⑦ Loosen the hand screw on the back of the Receiver and rotate the Receiver as shown in Figure 1.4. 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. A small mirror may be helpful to view the meter reading as the receiver is turned. At what polarity does the Receiver detect no signal?

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*).

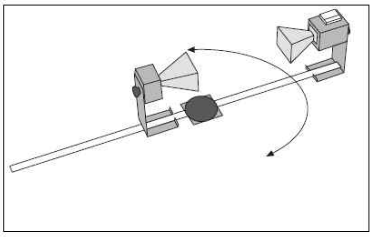

Figure 1.5 Signal Distribution

⑧ Position the Transmitter so the output surface of the horn is centered directly over the center of the Degree Plate of the Goniometer arm (*see Figure 1.5*). 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 as shown in the figure. Set the angle of rotation (*measured relative to the 180-degree point on the degree scale*) to each of the values shown in Table 1.2, and record the meter reading at each setting.

Part 2: Polarization

The microwave radiation from the Transmitter is linearly polarized along the Transmitter diode axis (*i.e, 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 5.1. If the detector diode were at an angle to the Transmitter diode, as shown in Figure 5.2, 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.

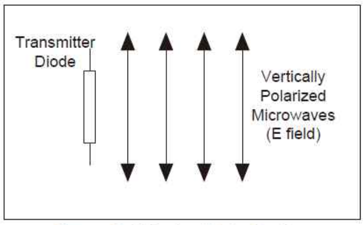

Figure 5.1 Vertical Polarization

① Arrange the equipment as shown in Figure 5.3 and adjust the Receiver controls for nearly full-scale meter deflection.

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 2.1.

③ What happens to the meter readings if you continue to rotate the Receiver beyond 180-degrees?

④ Set up the equipment as shown in Figure 5.4. Reset the angle of receivers to 0-degrees (*the horns should be oriented as shown with the longer side horizontal*).

⑤ Record the meter reading in Table 2.2 when the Polarizer is aligned at 0, 22.5, 45, 67.5 and 90-degrees with respect to the horizontal.

⑥ Remove the Polarizer slits. Rotate the Receiver so the axis of its horn is at right angles (θ_R = 90°). Then place the Polarizer slits.

⑦ Record the meter reading in Table 5.2 when the Polarizer is aligned at 0, 22.5, 45, 67.5 and 90-degrees with respect to the horizontal.

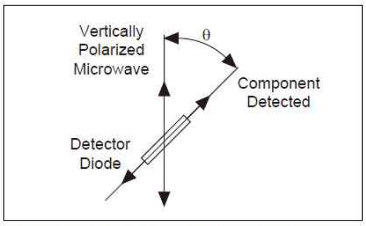

Figure 5.2 Detecting Polarized Radiation

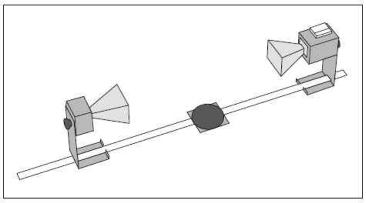
Figure 5.3 Equipment Setup

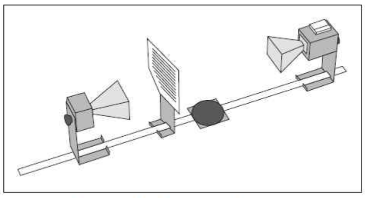
Figure 5.4 Equipment Setup

Part. 3 Double slit interference

In Experiment 3, you saw how two waves moving in opposite directions can superpose to create a standing wave pattern. A somewhat similar phenomenon occurs when an electromagnetic wave passes through a two-slit aperture. The wave diffracts into two waves which superpose in the space beyond the apertures. Similar to 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 sin= n** λ. (Where = the angle of detection, = the wavelength of the incident radiation, and **n** is any integer) (See Figure 6.1). Refer to a textbook for more information about the nature of the double-slit diffraction pattern.

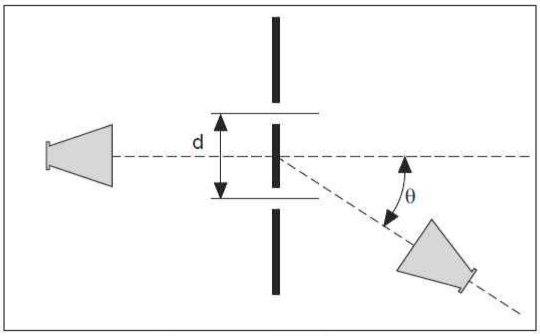

Figure 6.1 Double-Slit Interference

1. Arrange the equipment as shown in Figure 6.2. Use the Slit Extender Arm, two Reflectors, and the Narrow Slit Spacer to construct the double slit. (We recommend 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 rests) slowly about its axis. Observe the meter readings.
4. Reset the Goniometer arm so the Receiver directly faces the Transmitter.
5. Adjust the Receiver controls to obtain a meter reading of 1.0.
6. Now set the angle to each of the values shown in Table 3.1.

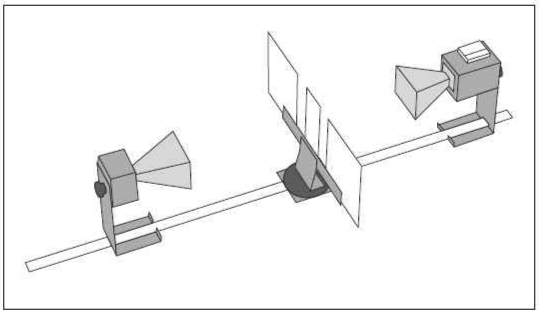

Figure 6.2 Equipment Setup

7. At each setting record the meter reading in the table. (In places where the meter reading changes significantly between angle settings, you may find it useful to investigate the signal level at intermediate angles.)
8. 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.
9. Because the Wide Slit Space is 50% wider than the Narrow Slit Spacer (90 mm vs 60 mm) move the Transmitter back 50% so that the microwave radiation at the slits will have the same relative intensity.
10. Repeat the measurements twice. (You may want to try other slit spacings as well.)

Worksheet 06. Wave Properties of Microwave

요약문 (Abstract)
Fill this area as you done.

실험 분반	(　　) 학년　(　　) 분반	
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제출자		
공동 실험자		

4. Results

Part 1: Introduction to the System

Table 1.1

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

Table 1.2

Angle of Receiver	Meter Reading	Angle of Receiver	Meter Reading	Angle of Receiver	Meter Reading
-90°		-20°		50°	
-80°		-10°		60°	
-70°		0°		70°	
-60°		10°		80°	
-50°		20°		90°	
-40°		30°			
-30°		40°			

Part 2: Polarization

Table 5.1

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°			

Angle of Polarizer	Meter Reading
0° (horizontal)	
22.5°	
45°	
67.5°	
90° (vertical)	

Angle of Slits	Meter Reading
Horizontal	
Vertical	
45°	

Part 3. Double slit interference

Angle (°)	Readings	Angle (°)	Readings
0		0	
5		5	
10		10	
15		15	
20		20	
25		25	
30		30	
35		35	
40		40	
45		45	
50		50	
55		55	
60		60	
65		65	
70		70	
75		75	
80		80	
85		85	
90		90	

Table 6.1

5. Questions

Part 1: Introduction to the System

① The electric field of an electromagnetic wave is inversely proportional to the distance from the wave source (*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 wave source (*i.e*, $\mathbf{I = 1/R^2}$). Use your data from step 4 of the experiment to 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 Transmitter output be considered a spherical wave? - A plane wave?

Part 2: Polarization

① If the Receiver meter reading (M) were directly proportional to the electric field component (E) along its axis, the meter would read 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 θ = 0*). (*See Figure 5.2*). Graph your data from step 2 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 Receiver's meter reading was directly proportional to the incident microwave's intensity, the meter would read 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 Based on your data from step 5, how does the Polarizer affect the incident microwave? Can you explain the results of step 6 of the experiment. How can the insertion of an additional polarizer increase the signal level at the detector? (**HINT:** *Construct a diagram like that shown in Figure 5.2 showing (1) the wave from the Transmitter; (2) the wave after it passes through the Polarizer; and (3) the component detected at the detector diode.*)

Part 3. Double slit interference

① From your data, plot a graph of meter reading versus . 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 two slit diffraction pattern—maxima occur wherever $\mathbf{d\sin\Theta=n\lambda}$, minima occur wherever $\mathbf{d\sin\Theta=n\lambda/2}$. (Check your textbook for the derivation of these equations, and use the wavelength measured in experiment 3.) 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? Consider the single-slit diffraction pattern created by each slit. How do these single slit patterns affect the overall interference pattern?