Lab 6: Microwaves

1 Introduction

Refer to Appendix D for photos of the apparatus

This lab allows you to test the laws of reflection, refraction and diffraction using microwaves. The wavelength of the microwaves used is on the order of a few centimeters. In contrast, visible light is a few hundred nm. As you probably know, the wave nature of light becomes obvious when the instruments you are using are on the scale of the wavelength of the light. The purpose of this lab is to further emphasize the wave nature of electromagnetic radiation by working with microwaves.

The source of the microwaves in this lab is a Klystron, or microwave generator. For a more detailed description of the Klystron please refer to the appendix at the end of this lab.

EXERCISE 8 PERTAINS TO THE BACKGROUND CONCEPTS AND EXERCISES 1-7 AND 9-26 PERTAIN TO THE EXPERIMENTAL SECTIONS.

2 List of experiments

Below is a list of this lab's experiments,

1. Reflectors: Observe the similarities and differences between microwaves and light.
2. Law of Reflection: Investigate the law of reflection using microwaves.
3. Law of Refraction: Investigate the law of refraction using microwaves.
4. Evanescent waves: Study the exponential decay of radiation.
5. Measuring the wavelength of microwaves.
6. Diffraction of microwaves.
7. Michelson interferometer using microwaves.

3 Suggested Reading

Refer to the relevant chapters,

R. Wolfson and J.M. Pasachoff, **Physics with Modern Physics** (3rd Edition, Addison Wesley, 1999).

4 Apparatus

- Transmitter
- Detector
- Probe
- Oscilloscope
- Table size compass
- Meter stick
- Solid wax semi-cylinder
- Plexiglass sheet
- Wax prism
- Wire mesh
- Wood sheet
- Glass sheet
- Wood frame wrapped with Aluminum foil
- Metal grids of various spacing
- Solid Copper plate
- Solid Aluminum plate

5 Experiment I: Reflectors

The purpose of this experiment is to observe the similarities and differences between microwaves and light. First we will observe the differences. Using different materials we will observe which materials reflect and which ones transmit microwaves.

Place the transmitter and the detector at opposite ends of the round wooden board such that they face each other. Turn on the transmitter and detector. Adjust the "intensity" and "variable sensitivity knobs" until the detector is reading the maximum signal.

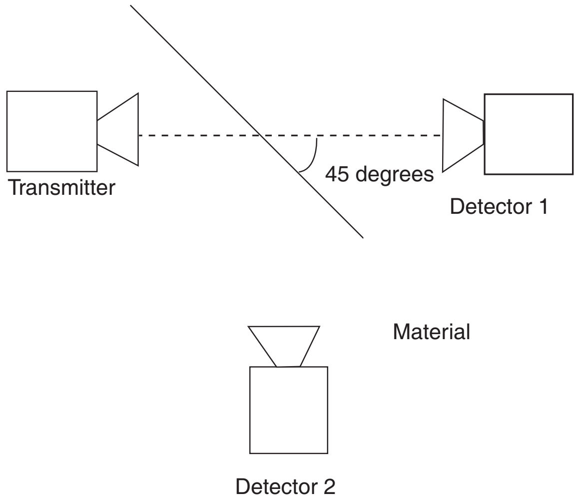

Figure 1: Reflector setup.

Table 1: Table template for exercise 1. D stands for detector position.

Material	**D 1**	**D 2**	**Comments**
Nothing			
Wooden frame			
Solid Al plate			
Plexiglass			
Solid Cu plate			
Wire mesh (size)			

Since different detectors have different sensitivities, use the detector labeled #1. Now place different items in between the transmitter and detector as shown in figure 1. Instead of using two detectors, move the same detector between positions 1 and 2 in figure 1 to ensure the same sensitivity throughout the experiment.

Exercise 1: Make a table, similar to table 1, of the different values read on the detector and materials used.

Use as many different materials as are available, including the different sizes of wire mesh. In the comments column mention whether the material is a reflector, transmitter, partial reflector or possibly an absorber.

Exercise 2: What are some possible reasons for these observations?

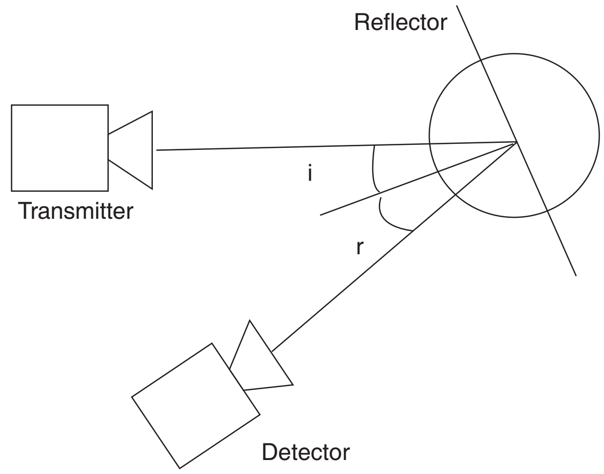

Figure 2: Law of reflection setup.

6 Experiment II: Law of Reflection

The law of reflection states that the angle of reflection is equal to the angle of incidence where both angles are measured from the normal to the reflecting surface. Use a material that was a good reflector in part 1 to confirm that this law holds true for microwaves (see figure 2).

Exercise 3: Does the law of reflection hold for microwaves?

7 Experiment III: Law of refraction

The law of refraction states that the sine of the angle of incidence times the index of refraction of the first medium is equal to the sine of the angle of refraction times the index of refraction of the second medium,

$$n_1 \sin(i) = n_2 \sin(r) \tag{1}$$

Here i is the angle of incidence and r is the angle of refraction as shown in figure 3.

Exercise 4: Using the semi-cylinder of wax measure the angle of refraction for several different angles of incidence. From these measurements show that the law of refraction holds true for microwaves and determine the index of refraction of wax.

Exercise 5: Why is a semi-cylinder of wax used instead of another shape?

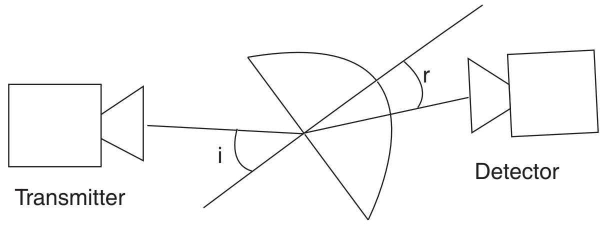

Figure 3: Law of refraction setup.

8 Experiment IV: Evanescent waves

When total internal reflection occurs there is radiation that extends into the medium with the lower index of refraction. This radiation does not propagate indefinitely but instead decays exponentially. It can be proven that since it decays exponentially it does not carry any energy. If there is a second material with a high enough index of refraction, in this case a second wax prism, the decaying wave can propagate in the new medium.

Microwaves that radiate from the first prism decay exponentially, so the microwaves that propagate in the second prism will only have the intensity of the decaying waves as they hit the second prism. This means that the microwaves detected at detector 1 in figure 4 will vary exponentially with the separation of the prisms.

Exercise 6: Record the signal strength at detector 1 for various distances of separation of the two wax prisms. Plot a graph of signal strength versus distance of separation.

Exercise 7: What is the distance between the plates at which the signal in detector 1 goes to zero? How does this distance compare to the wavelength of the microwaves? Discuss the difficulties in doing this experiment using visible light.

9 Experiment V: Measuring the wavelength of microwaves

There are various ways of measuring the wavelength of microwaves. Here are two suggested experiments.

Method 1: Standing waves

In the first method, we will use one of the reflectors

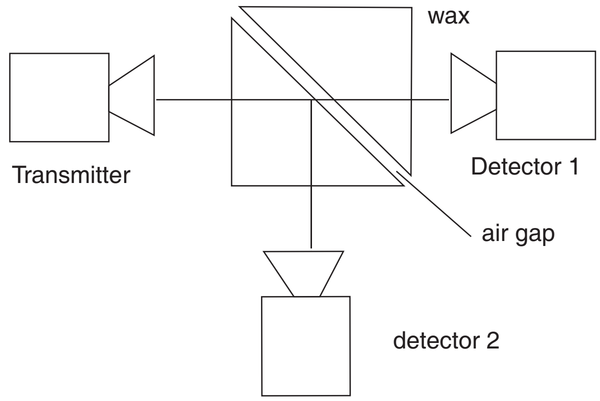

Figure 4: Evanescent wave setup.

you used in experiment 1 to retro-reflect microwaves. The two travelling microwaves will interfere to produce standing waves.

Exercise 8: How is the wavelength of the standing wave related to the wavelength of the travelling waves?

Using an antenna as a probe, we can measure the intensity of the microwaves at any point in space. We can use an oscilloscope to measure the output of the probe. An amplifier can be introduced between the probe and the oscilloscope to get a stronger signal. By moving the probe back and forth we can see that the signal has peaks corresponding to the anti-nodes of the standing waves. Set-up the transmitter and probe as shown in figure 5.

Exercise 9: How far apart are the anti-nodes of the standing waves in terms of the wavelength of the microwaves?

Exercise 10: Using a ruler find the distance between two adjacent anti-nodes and from that determine the wavelength of the microwaves. Use the distance between many widely spaced anti-nodes for better accuracy.

Method 2: Multiple reflections

In the second method we use a reflector and a partial reflector to get two beams to interfere at the detector (see figure 6). The first beam is reflected off the partial reflector into the detector. The second beam goes through the partial reflector and reflects off the mirror back to the detector. These two beams interfere to give the signal observed by the detector.

Exercise 11: When the mirror is moved the differ-

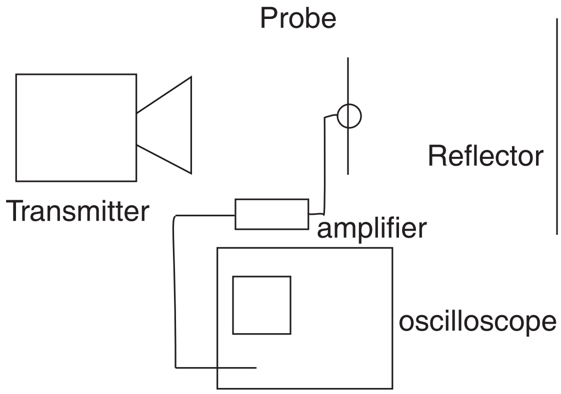

Figure 5: Probe setup.

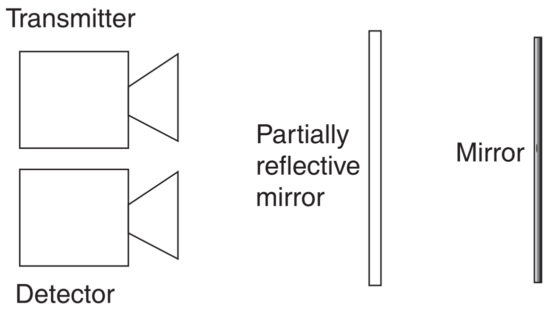

Figure 6: Method 2 setup.

ence in path length between the two beams changes. As a result the signal at the detector will increase and decrease in a cyclical manner. What is the change in path difference between the beams that will bring the signal back to its initial value?

Exercise 12: How much should the mirror move in order to produce this change in path length?

Exercise 13: Measure the displacement of the mirror needed to move through several cycles of constructive interference, and from this measurement, determine the wavelength of the microwaves.

10 Experiment VI: Diffraction

Straight edge diffraction: When a metal plate is placed in the beam path the beam will diffract around the edge of the plate. By Huygen's principle every point on a wave front is a point source of light and these sources interfere to produce the new wave front a moment later. If a part of the wave front is blocked some of these point sources are no longer there so the whole wave front is effected. We will show that the blocked wave front contributes to the whole wave. To show this, we will use a metal plate to block a part

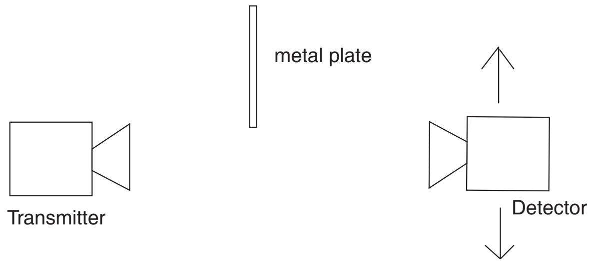

Figure 7: Straight edge diffraction.

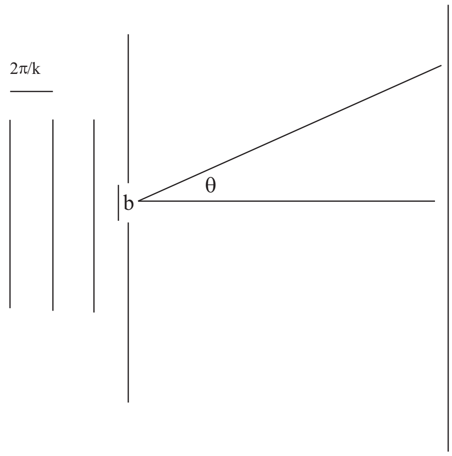

Figure 8: Single slit diffraction.

of the wave and look at the remaining wave for any changes.

Exercise 14: Using the setup in figure 7, move the detector and measure the intensity of the signal. Draw a sketch of the intensity pattern.

Exercise 15: Is any signal measured when the detector is in the shadow of the plate?

Exercise 16: Are there any interference fringes, if so where do they occur?

Single slit diffraction: For single slit diffraction the intensity distribution, I, varies as,

$$I = I_0 \frac{\sin^2 \beta}{\beta^2} \tag{2}$$

where, I_0 is the maximum intensity and β is related to the phase difference between adjacent points on the slit and is given by,

$$\beta = \frac{1}{2}(kb \sin \theta) \tag{3}$$

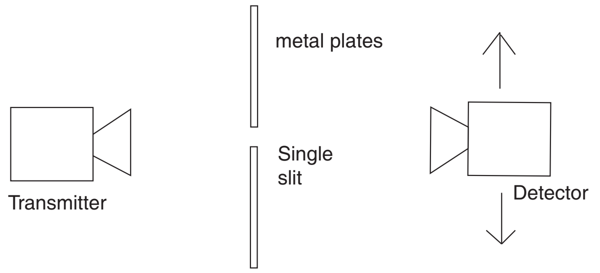

Figure 9: Single slit diffraction setup.

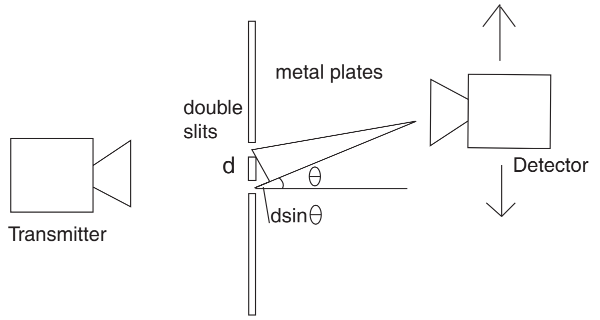

Figure 10: Double slit interference setup.

Here k is the wave number, b is the width of the slit and θ is the angle to the incident beam direction (see figure 8).

Exercise 17: Using the set-up in figure 9, move the detector to find the peaks in the signal and make a qualitative sketch of the diffraction pattern.

Exercise 18: How does the diffraction pattern compare with the prediction of equation 2?

Double slit interference: When two slits are placed in front of the incident beam, the microwaves interfere to produce an interference pattern with the position of the interference peaks given by,

$$d \sin \theta = m\lambda \tag{4}$$

Here d is the slit spacing, λ is the wavelength of the microwaves, m is the order of the peak and θ is the angle to the normal of the slits (see figure 10).

Exercise 19: Find the position of the peaks of the interference pattern and make a qualitative sketch of the signal.

Exercise 20: Measure the slit spacing, and from the position of the peaks, determine the wavelength of the microwaves.

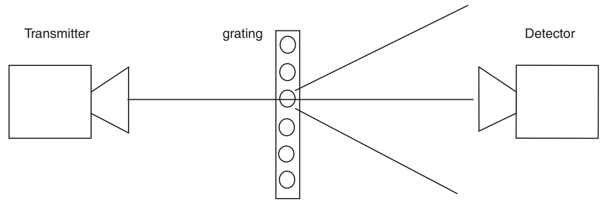

Figure 11: Diffraction grating.

Exercise 21: How does your answer for the wavelength compare with your results from the previous experiments?

Diffraction grating: Many evenly spaced slits.

Exercise 22: Find the position of the peaks in the interference pattern and make a sketch of the signal.

Exercise 23: How does the diffraction pattern compare to the double slit interference pattern?

11 Experiment VII: Michelson interferometer

The Michelson interferometer is a widely used device. It is used for making precise measurements and is based on the interference of light. The device uses a beam splitter to split the incident beam along two different paths, and then recombine them. The two beams recombine to produce an interference pattern. If the optical path length changes along either of the two arms then the interference pattern changes. Constructive interference occurs when the path difference is an integral number of wavelengths.

Exercise 24: Construct the Michelson interferometer shown in figure 12. Move one of the mirrors to observe the change in the interference pattern. Measure the distance you must move the mirror to observe several peaks in the interference pattern.

Exercise 25: Find the wavelength of the microwaves using the distance of mirror movement between peaks in the interference signal. (Hint: this is very similar to experiment 5)

Exercise 26: Tabulate all measurements of the wavelength of microwaves that were obtained in this lab.

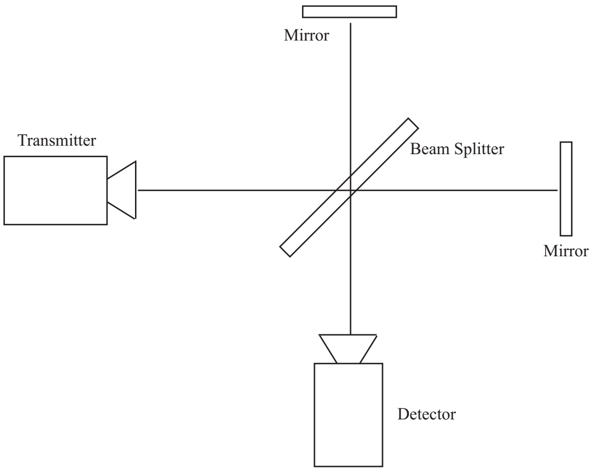

Figure 12: Michelson Interferometer.

Your lab report should include:

Answers to exercises 1-26 with relevant data tables, graphs, figures and qualitative comments.

Refer to Appendix C for Maple worksheets.

12 Appendix

The generator we will be using is called a Klystron. The Klystron is like an amplifier for microwaves. Figure 13 shows a schematic diagram of the Klystron and voltages required. The tube is composed of a cathode, a focusing electrode at cathode potential, a resonator, which also serves as an anode, and a reflector (repeller), which is at a negative potential with respect to the cathode. The cathode is heated so that electrons escape its surface. The focusing electrode, and the anode force the electron beam through the resonator gap and out toward the reflector (repeller). Since the reflector is at a negative potential with respect to the anode, the electrons are turned back toward the anode. Therefore, they pass through the resonator gap a second time. When the Klystron is oscillating, the currents in the cavity walls create standing electromagnetic waves. These electromagnetic waves in the cavity are at a definite frequency determined by the cavity dimensions. This creates an alternating voltage across the gap of the resonator. As electrons pass through the gap, they are either accelerated or decelerated as the voltage across it changes with time. As a result, accelerated electrons leave the gap at an increased velocity and decelerated electrons leave at a reduced velocity. This effect causes the electrons to

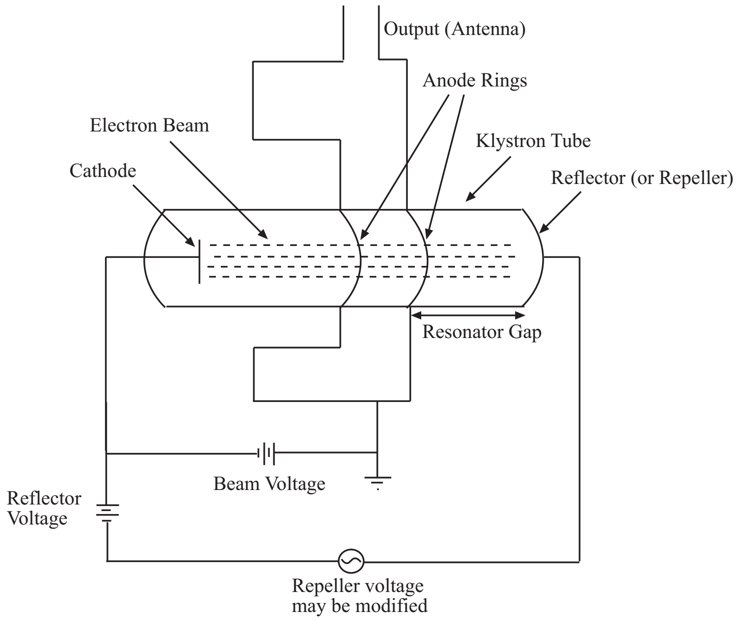

Figure 13: Schematic diagram of a Klystron and required voltages.

group together in bunches, as the faster electrons leave the slower ones behind and catch up to the slower ones ahead of them as they return through the gap. The variation in velocity of the electrons is called **velocity modulation**.

As the bunched electrons pass back through the gap, if the gap voltage is such that the electrons are slowed down, energy is delivered to the resonator and oscillations are continual. If the bunch goes through the resonator when the gap voltage accelerates the electrons, the energy is removed from the resonator and oscillation tends to stop. The strongest oscillations occur when the transit time of the bunch in the gap is n + 3/4 cycles of the resonator frequency ($n = 0, 1, 2, ...$). The frequency of oscillation for a fixed anode voltage is obtained by varying the transit time of the bunch, in the resonator by varying the reflector voltage. The shorter the transit time the more negative the reflector voltage. A small modulation of the repeller voltage produces oscillations powerful enough to create useful microwaves.

Between the cathode and the repeller is the anode, which consists of two rings. When the bunched electrons pass through these rings they induce a charge in the first ring they encounter and then in the second ring. Connected to these rings is an antenna that outputs this alternating voltage as microwaves.