C-10

Microwaves

An introduction to the properties of microwaves and microwave apparatus. Microwave demonstrations of optical phenomena.

Measure the transmission of microwaves in a wave guide, dielectric rod, hollow cylinder beyond cut-off (and then filled with a dielectric), in free space, and in the region behind a surface at which total deflection is taking place. Measure the free space wavelength by impedance variation of a movable reflector and by the Michelson interferometer arid compare: with that in the wave guide. Study the reflection and transmission of a polarized wave. Measure a terminating impedance with the VSWR detector. Study and observe the behavior of a directional coupler, a magic-tee, a phase shifter, an attenuator, and a slug tuner. Observe reflection, refraction, and diffraction by a "crystal" from as many planes as possible.
Observe thin film interference arid thus determine wavelength, the absorption of a wet and dry sponge, elliptical or circular polarization, the Guoy phase advance, the variation of electric field across the guide, the relative positions of maximum electric and maximum magnetic field in a standing wave, etc. Understand the reflex klystron and its mode of square wave.

References

Microwave Theory

1) Slater, "Microwave Transmission"

2) Ramo & Whinnery, "Fields and Waves in Modern Radio"

3) Bronwell & Beam, "Theory and Applications of Microwaves"

4) Southwell, "Wave Guide Transmission"

5) Muchmore, "Microwave Essentials"

6) Montgomery, Dicke, and Purcell, "Principles of Microwave Circuits"

Microwave Demonstrations of Optical Phenomena

1) Strong, "Concepts of Classical Optics", Appendix J by Hull, pp.507-524

2) Carpenter, Am. J. Phys. 27, 98-100 (1959)

3) Andrews, "Optics of the Electromagnetic Spectrum"

Checklist of Excercises for Experiment C-I0

1. frequency measurement.
2. wavelength in a waveguide.
3. transmission in different waveguides.
4. free space transmission.
5. wave guide cutoff study with lucite insert.
6. transmission and reflection through polarizer, Brewster angle.
7. paraffin prism total internal reflection.
8. index of refraction of paraffin prism.
9. free space wavelength by impedance, Michelson, and Fabry-Perot methods.
10. thin film interference.
11. diffraction of microwaves by "cubic lattice".
12. elliptically polarized radiation.
13. Guoy phase shift.
14. probing E field using phase shifter and attenuator.
15. probing E and B fields directly with antenna probes.
16. terminal impedance of unterminated end of wave guide.
17. directional coupler .
18. magic T .
19. double slug tuner.
20. phase shifter .
21. isolator .
22. read about standard reflex type Klystron.

INTRODUCTION

Microwaves are electromagnetic radiation with frequency between roughly 109 Hz and 1011 Hz. An interesting property of microwaves is that their wavelengths are on the order of centimeters, so that wave phenomena familiar in optics can be observed on "every- day" length scales with relatively simple apparatus. Because of the high frequency of microwaves, wires appropriate at audio frequencies must be replaced with waveguides in microwave circuits. Wave properties of EM radiation are crucial in microwave circuits, and there are many devices which exploit them.

The exercises in this experiment can be divided into three categories. Exercises of the first category demonstrate phenomena familiar in optics, such as polarization, Michelson inter- ferometry, and Brewster's angle, using microwaves. The second category investigates the properties of microwaves propagating in free space, in various materials, and in waveguides. The final category involves study of the properties of microwave circuit elements such as the magic T and the directional coupler. Most of these exercises are straight forward, but there are many of them, so budget your time accordingly.

STARTUP

The apparatus used in this lab are very simple; the hard part is to find them. Begin by locating and identifying the various components which are needed. Everything you need is located on or in the two work benches. When doing the exercises, try to be organized and keep the work bench clean. Components can usually be connected together using only two screws at opposite corners; there is no need to use four. N ote that most of the joints put a flat surface flange against another with two grooves: a quarter-wavelength deep groove circling the waveguide opening, and a groove for a rubber O-ring for pressurizing in high-altitude radar use. What is the purpose of the quarter-wavelength deep groove?

Now turn on the amplifier, the power supply, and the SWR meter. Connect the output from the crystal detector attached to the waveguide to the input of the SWR meter. DO NOT CHANGE THE FREQUENCY of the klystron by deforming the cavity through the bow strut; all the exercises can be performed using a single frequency. The amplifier is no longer tunable, so just leave it at minimum volume. Set the klystron to "DIRECT" and do not adjust the setting of "AMP-ZERO ADJUST". The only klystron adjustment is the repeller voltage. Increase it until the output attains its first maximum.

The most complicated apparatus you will use in this lab is the standing wave ratio (SWR) meter, but it is quite simple to use, too. You can ignore most of the 415E operating manual, but turn to page 3-2 now and look at figure 3-1. Leave both the frequency(5) and bandwidth(6) alone, and set input biased low(4). The meter has four scales: DB expand, SWR expand (both red), SWR, and DB. The only scales you will be using are the SWR and DB scales, so leave EXPAND at NORM. By definition, SWR is the ra- tio of the maximum amplitude to the minimum amplitude in a standing wave pattern, or SWR = $(A + B)/(A - B)$ where the standing wave pattern is formed by a incident wave $Einc = Aei(wt-kz)z$ travelling toward positive x direction, and a reflected wave $Eref = Bei(wt+kz+q.)z$. When there is no reflected wave, the SWR is unity. To mea- sure the SWR for a standing wave, set up a standing wave in the waveguide by putting a metallic plate at the end of the guide, and glide the detector along the waveguide until you get the maximum reading. Now use the RANGE, GAIN, and VERNIER knobs until the reading is at SWR = 1 (you can also use the attenuator flap at the other end of the waveguide to change the amplitude of the waves; this will not change the SWR). Then move the detector until you hit the minimum reading. The scale is then properly calibrated to give the SWR. If the reading overflows below 3.2, switch to the next range and read the 3.2-10 range. If the meter still underflows, switch to the next range and read the 1-4.0 scale again, but multiply the reading by 10, and so on. If you find this passage confusing, please consult the 415 E operating manual p. 3-5.

EXERCISE 1: FREQUENCY MEASUREMENT Slowly turn the micrometer, which drives a piston down the critical cavity, until you observe a minimum in reading. Read the micrometer and use the calibration chart to obtain the frequency. This can also give you the free-space wavelength by using c = v'\. How does this method work? After you've finished this exercise DON'T FORGET to change the micrometer back to its original position so that you have maximum signal.

EXERCISE 2: MICROWAVE WAVELENGTH IN WAVEGUIDE

Set up a standing wave in the waveguide by terminating the end of the waveguide using a metal plate (which acts as a short). Glide the detector along the waveguide and find the minima (the minima are sharper than the maxima, so they give a more accurate measurement). What is the wavelength in the guide?

EXERCISE 3: TRANSMISSION OF MICROWAVES IN WAVEGUIDES Attach the small horn to the end of the waveguide and connect the SWR meter to the other horn/crystal detector. With the horns oriented at an angle of 45 degrees or so as indicated in figure l(a) (to minimize direct transmission from the source horn to the receiving horn), insert the following between the two horns and measure the amplitude of the received signal: 1" aluminum tube.
1" red dielectric rod lightly held with fingers.
Same dielectric, but now grasped in a tight fist. %" brass tube with a cylinder of lucite inserted. Same brass tube, but without the lucite. Rectangular piece of waveguide. E-bend waveguide. H-bend waveguide.

EXERCISE 4: FREE SPACE TRANSMISSION

With the receiving horn in line with the source horn (see figure I(b)), measure the change in the received signal when:

the distance between the horns is increased.
when your hand is inserted between source and receiver . when a dry sponge is inserted. when a wet sponge is inserted.
same as I, but mount the large horns over the small ones.

EXERCISE 5: WAVEGUIDE CUT-OFF Study the change in the waveguide cut-off with the gadget shown in figure 2. As you have observed in a previous exercise, the cut-off frequency is lowered by the presence of lucite in the waveguide. Without the lucite, the waveguide is beyond cut-off, so as you move the two pieces apart, the signal transmitted to the detector will falloff (presumably exponentially.) Note that the outside ends of the lucite pieces are tapered to reduce reflection from there.

MICROWAVE WAVE PROPERTIES AND "OPTICS"

EXERCISE 6: POLARIZATION OF MICROWAVES Unlike ordinary light, the microwaves produced in this lab are polarized. Three observations can be made:

1. Transmission: the setup is shown in figure 8(a). Rotate the "polarizer" grid and observe how the transmitted signal is modified. Note the relation between the orientation of the metal strips and the E-field direction for maximum and minimum transmission. Explain.

2. Reflection: put the receiver at 90° to the source and observe the reflected signal as the "polarizer" is rotated.

3. Brewster's angle: Use the 45°-45°-90° paraffin prism as the reflecting surface for this experiment. Mount the 90° twist section to rotate the electric field. (Why?) Mount the receiver on the analyzer as shown in figure 8(b) and rotate it 90°. Adjust the angle of incidence, while keeping the receiver at the correct angle of reflection, until a minimum is observed.

EXERCISE 1: TOTAL INTERNAL REFLECTION Use the 45°-45°-90° paraffin prisms for this experiment. Mount the large horn on the source and use the small horn for detection. Irradiate one of the prisms as shown in figure l(c). Study the frustrated wave by observing the change in the transmitted signal as you move the detector away from the surface. Another way to study this effect is to put the two 45° prisms together, as shown in figure l(d), and observe the change in the transmitted and reflected signals as the separation d is increased. Use the large horns for both the source and the detector. Since there is not enough space on the bench, mount the detector to a floor support as shown in figure 9 when you want to observe the reflected waves.

EXERCISE 8: INDEX OF REFRACTION

Use the 600-300-90° paraffin prism as shown in figure 19 and measure the index of re- fraction using Snell's law. Is the answer consistent with the Brewster's angle measured before?

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EXERCISE 9: FREE SPACE WAVELENGTH MEASUREMENTS .. There are several way to measure the free space wavelength:

1. The impedance method: put a large horn on the source and put an aluminum reflector some distance away from it to set up a standing wave. Put the detector with the small horn between them. Now move the reflector until you see a maximum or a minimum. The distance between the maxima or the minima will give you the wavelength. To ensure that the reflector stays aligned properly when it is movedt tape down a ruler on the bench along the direction of propagation and glide the aluminum reflector long it (there are two reflectors; use the one with the groove at its base). Take readings for a large number of maxima or minima.

2. Michelson Interferometer: this is a better method for measuring the wavelength. The familiar Michelson setup is shown in figure 4. The two aluminum reflectors are used as mirrors and the wire grid serves as the beam splitter. Use the large horns on both the source and the detector, and as before, tape the ruler down to the table to ensure that the reflector is moving along the direction of the incident beam. It is important that both the reflectors and the beam splitter are at the correct angles. Again, there is not enough space on the work bench, so you should mount the detector on the floor support. Take readings for a large number of wavelengths.

3. Fabry-Perot interferometer: the setup is shown in figure 5. The detector is mounted on one of the irises. Move the detector along with the iris and a periodic change in the signal should be observed. How planar is the wave through the first iris?

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EXERCISE 10: THIN FILM INTERFERENCE

The setup is shown in figure 7. Add the glass slides one by one, and when the stack is a quarter wavelength thick, the transmitted signal should be a minimum. As more slides are added, the signal goes up again until reaching a maximum at a half wavelength. This way one can measure the wavelength in glass, and from the wavelength in free space measured earlier one can calculate the index of refraction for the glass at this particular microwave frequency.

EXERCISE 11: DIFFRACTION BY CUBIC LATTICE OF SCATTERERS

The "crystal" is just a 5 by 5 array of aluminum balls, but a distinct increase in signal can be observed at the appropriate angles. The setup is shown in figure 16. Use the large horns for both the receiver and the source, and aim them at the center of the crystal. Instead of mounting the receiver on the table as shown in the diagram, it is easier to mount it on the floor stand, so that you. can rotate the crystal easily. Place the receiver at 10° intervals and rotate the crystal to find the peaks. Ignore the small peaks. You should at least see reflections from the [1,0}, [1,1}, and [1,2} planes.
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EXERCISE 12: ELLIPTICAL POLARIZATION The setup is shown in figure 15. The transition guide should ensure a smooth change from the rectangular guide to the circular guide. In the circular guide, there is symmetry so that it can support two polarization modes and the polarization can be in any direction. This symmetry can be broken by the insertion of a polystyrene plate. With the plate inside the circular guide, there are only two possible polarizations, one parallel and one perpendicular to the plate. Polystyrene is a material which can shift the phase of the microwave, so the component of the wave polarized parallel to the plate suffers a shift is phase. With the '\/4 plate provided (these two thin plates have the words "'\/4, do not alter" scratched on them), the shift is 90° so that we have a circularly polarized wave. Unfortunately these plates are made for a slightly different frequency, so the wave is r~ally elliptical. If the two plates are stacked together, the shift will be doubled. If the plates are placed at an angle {) to the original polarization plane, the wave coming out of the horn should be polarized at 2{). You can check the polarization using the analyser shown in figure 8(b).

EXERCISE 13: GUOY PHASE SHIFT Read the article by R. Carpenter before you do this exercise. The setup is shown in figure 18. Use the antenna probe crystal detector (see figure 11) for this experiment. Make sure that the tip of the probe is travelling along the path connecting the vertex of the horn to the vertex of the elliptical mirror. To move the probe manually along the track, put the gear box in between settings to disengage it. The best speed of the motor is one for which the probe runs from the farthest position to the vertex in 3 to 5 minutes. The recorder is already set up, so all you have to do it to turn it on and set the correct range on the SWR meter. Since the signal level is very large when the probe is near the focus of the reflector, you have to make two runs. In one run you use a more sensitive range to see the minima outside the focused region and just let it overflow near the focus, and in the other run use another range to see the minima around the focused region. You can superimpose the two graphs together

PROPERTIES OF MICROWAVES IN A WAVEGUIDE

EXERCISE 14: PROBING THE E FIELD USING A PHASE SHIFTER AND ATTENUATOR

The attenuator is a pointed strip made of a non transparent, absorbent material which supposedly diminishes the amplitude without shifting the phase. It is taped to a rectan- gular polysterene strip, which is then clamped to a aluminum stand (see figure 6). The attenuator will absorb the most energy when placed where the field is strongest, so one can use it to investigate qualitatively the variation in amplitude of E field inside the waveguide by moving the strip laterally across the guide.

The phase shifter is just a pointed strip of polystyrene. This material supposedly shifts the phase (moves the position of the minima) of the wave without diminishing its amplitude and the shift is proportional to the amplitude of the wave. With this gadget one can also look at the change in amplitude of the wave inside the waveguide. The setup is similar to the exercise using the attenuator, but instead of using the horn detector, a standing wave is set up by short circuiting the waveguide using a metallic strip and use the sliding detector to see the change in position of the minima.

EXERCISE 15: PROBING THE E AND B FIELDS DIRECTLY

With the probe antenna shown in figure 11 one can probe the E field near the open end of the waveguide directly. It is not easy to maintain a fixed geometry between the probe and the guide, but a rough check can be made. The B field is more difficult to look at because the two probes provided do not work very well. From EM theory we know that in a standing wave the E and B fields are 90° out of phase, that is, *Emax* should exist at *Bmin* and vice versa. This can be checked by using the detector (it has its own crystal) which fits the SW machine as shown in figure 10(a). You will see that the measurements agree reasonably well with the predictions, but not exactly. The discrepancy can be attributed to the fact the the loop antenna in the detector has non zero impedance and it will probably be affected by the E field as well. The other detector (it needs an external crystal), shown in figure 10(b) can also be used to look at the B field. The the B probe is inserted in the center hole and the E field probe is inserted in the laarger hole beside it. The reflector will set up a standing wave between it and the source (remember to put on the small horn). According to theory the E field should be zero at the reflector and the B field should be a maximum, and one quarter of a wavelength away from the reflector the reverse should occur. The two probes can be pushed in and out of the reflector to check these predictions. Remember to turn the magnetic probe so that there is a maximum signal.

afterward to get the whole picture.

EXERCISE 16: TERMINATING IMPEDANCE OF FREE SPACE

The impedance of a waveguide termination is defined as the ratio of the electric to magnetic fields at the termination. In general, to measure the ratio of a load impedance Z, at one end of a transmission line to the characteristic impedance *Zo* of the line, one only needs to measure the VSWR and the distance of the first minimum from the load. The necessary information is contained in Chapter 3 of *Electromagnetic Energy Transmission and Radi- ation* by Adler, Chu and Fano. The formulas are contained in section 3.4. Determine the impedance of free space.

EXERCISE 17: DIRECTIONAL COUPLER The directional coupler is a clever device and is shown in figure 12. The device has the wrong opening size so a quarter wave matching section has to be used between it and the source. Look inside the directional coupler and you will see that there are irises on both sides which allow the microwaves to leak from the central waveguide to the two sides A and B. Mount the coupler and use a matching load (see figure 13(a)) on the unterminated side of the coupler. The matching load (just a waveguide with a card made of microwave-absorbing material in the middle) should provide unity SWR, i.e., it will not produce a reflected wave. The irises on sides A and B are separated by *,\14* which make the leaked wave interfere in such a way that the leaked wave will propagate in the same direction as the original wave. In chamber B, there is a matched load at the end of the side opposite the source (see figure 12) so the leaked wave will be absorbed, hence there will be little signal there. Now replace the matched load bya reflecting metal plate to create a large reflected wave. Chamber A also has a matched load on one side, but it is opposite to the reflected wave, so the signal at A should stay at the same level because the reflected wave will get absorbed while the incoming wave is the same as before. On the other hand, there is a signal at B now because there is no absorption of the reflected wave. The reading at A and B should be about the same because the reflected wave should have the same amplitude as the incoming wave. Since the signal at A is proportional to the incoming wave and the signal at B is proportional to the reflected wave, one can thus get a measure of the VWSR from the directional coupler.

EXERCISE 18: MAGIC T

From figure 13(c) we can see that there is even symmetry between sides A and B of the magic T if the two sides have the same matching load. The incident wave has even symmetry so the power is divided evenly between A and B, but no power is diverted into the 4th arm because no mode with even symmetry can propagate in that arm. Once the symmetry is broken by a unmatched load, however, the wave is no longer in a even mode and can propagate in the 4th arm. You can check these properties by: putting matched loads at A and B (e.g., the small horns). putting your hand in one of the sides.

putting your hands on both side.

EXERCISE 19: DOUBLE SLUG TUNER

The double slug tuner is shown in figure 14. It contains two metallic slugs each about '\/4 long. The separation between them can be adjusted, and they can also be moved along together. The separation between the slugs will determine the size of the reflected wave. For example, when the separation is zero, they form a single slug half a wavelength long. The reflection from the first end and the reflection from the second end will be 90° out of phase and result in complete cancellation. The phase of the reflected wave can be controlled by the position of their center of mass. So the double slug tuner has a variable load impedance (both magnitude and phase). An interesting exercise to tryout is the following:

Mount the magic T .
Put a matched load with impedance *Zo* (figure 13(a)) on side A.
Put the slug tuner on side B, and adjust it to get minimum signal (unity SWR) from the 4th arm. Now the slug tuner has the same load impedance *Zo* as the matched load. Remove the matched load and the signal should increase. Record this signal. This signal results because of the impedance mismatch between *Zl* at A and *Zo* at B. This signal should also be a maximum, which one can check by changing the center of mass position. Adjust the tuner again until unity SWR is reached. Now side B also has impedance *Zl.* Put the matched load *Zo* back on. We have now *Zo* on A and the signal should go up again. This signal is produced due to the impedance mismatch between *Zl* at B and *Zo* at A, but since A and B just switched roles, it should be the same as the signal recorded previously.

EXERCISE 20: PHASE SHIFTER The phase shifter, which is just a waveguide with a movable slab of polystyrene, is shown in figure 13(b). The slab can be moved laterally across half of the waveguide. Mount the phase shifter on the source and terminate its end with a reflecting metallic plate. One can then study the change in phase (i.e., the change in position of the minima) as you move the slab across the waveguide.

EXERCISE 21: ISOLATOR

The isolator is shown in figure 17(a). This device allows microwaves to pass through it in only one direction. If the wave comes in from the other direction it will be refracted by magnetic material into an absorber on one side. Mount the isolator to the source both ways and check the magnitude of the transmitted wav.

EXERCISE 22: KLYSTRON

The klystron used in this lab is a standard reflex type, so you should look it up in books and understand its operation.