Microwaves in Waveguides

Introduction

Microwaves are commonly used in various aspects of everyday life. In your kitchen you most likely have a microwave oven. A close look at many towers and rooftops around the city will reveal microwave antennas used for telecommunication. You may even have a satellite antenna for TV reception. If you have been caught speeding in an automobile you may have been the "victim" of microwave technology.

Microwaves are a part of the electromagnetic spectrum situated between radio frequencies (RF) and infrared light (IR). Thus more than one method of transmission is available to microwaves. For lower frequencies, coaxial cables can be used. For all frequencies freely propagating waves are also used, especially for communications. Another technology specific to microwaves consists of waveguides. These are hollow metal tubes which are used to confine the microwave radiation just as coaxial cables are used for RF frequencies. Various waveguide components exist to manipulate the microwaves just as lumped components are used for audio and RF frequencies.

In this experiment you will become familiar with generators of microwave radiation, various waveguide components as well as the propagation of EM radiation in waveguides.

Waveguide Propagation

The waveguide you will use here is a rectangular tube of metal (good conductor). The dimensions are chosen to propagate frequencies in a particular range: 8.2 - 12.4 GHz, called X-band by convention. As this EM radiation is confined in space it will propagate in a variety of modes. You will learn of the details of waveguide propagation in one of your third year EM courses.

Waveguide technology is built around the $TE_{1,0}$ mode which is illustrated in Fig. 1. The boundary conditions for EM radiation at a perfect conductor requires that **E** be perpendicular to the metal surface and that **H** be parallel. The **T**ransverse **E**lectric mode satisfies this condition as illustrated in Fig. 1.

You will note that this mode is about 1/2 of a wavelength wide. Thus you might expect that for frequencies low enough propagation will become impossible.

Indeed this is the case.

The cutoff frequency

Each mode also has a critical frequency, the cutoff frequency, below which energy cannot propagate along the guide. The largest wavelength that can propagate in the $TE_{1,0}$ mode ($TE_{m,n}$ when m=1; n=0) in a waveguide of dimensions a, b is given by:

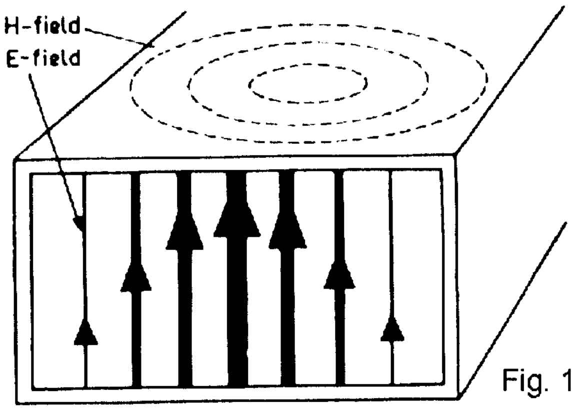


Fig. 1

$$\lambda_c = \frac{2}{\sqrt{(m/a)^2 + (n/b)^2}} = \frac{2}{\sqrt{(1/a)^2 + (0/b)^2}} = 2a \qquad (1)$$

Equation (1) defines the cutoff wavelength λ_C. The wavelength propagating in the waveguide is not the free space wavelength λ_0 but the waveguide wavelength λ_g which is given by:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1-(\lambda_0/\lambda_c)^2}} = \frac{\lambda_0}{\sqrt{1-(\lambda_0/2a)^2}} \qquad (2)$$

λ_g is longer than the free space wavelength. When the waveguide frequency approaches the cutoff frequency the waveguide wavelength diverges and no energy propagates.

The frequency is given by $f = c/\lambda_0$ which can also be expressed in terms of the waveguide wavelength: $f = c\sqrt{(1/\lambda_g)^2 + (1/2a)^2}$ (3)

Both the frequency and wavelength can be measured in this experiment whereby you can verify the above expressions.

Attenuation

Another concept you should become familiar with, if you are not already, is that of expressing attenuation in terms of decibels (dB). The attenuation of a signal from one point to another is given by:

$$A_{dB} = 10\log_{10}\frac{P_1}{P_2} \qquad (4)$$

where P_1 and P_2 are the power levels at points 1 and 2 respectively.

You will note that the attenuators in this experiment are calibrated in terms of dB. Power is also expressed in terms of dB relative to a particular power level. The unit most convenient for this experiment is the dBm, the power relative to 1mW.

Using equation (4) with P_1 = P and P_2 = 1 mW we obtain:

$$P = 1(mW)\times 10^{\frac{A_{dB}}{10}} \qquad (5)$$

For example 2 mW is equal to +3 dBm and 0.25 mW is equal to -6 dBm.

Microwave Generators

There are many different types of microwave signal generators. Two that you can study in this experiment are the reflex klystron and the Gunn diode oscillator. These devices operate on the principle of positive feedback of EM energy to accelerated electrons thereby causing oscillations to occur. Follow the instructions to set up the oscillator and measure the operating mode for the klystron or voltage-current characteristic of the Gunn oscillator.

In the following sections the figures have a klystron for the microwave signal generator. You may use either the scope or the SWR meter to measure microwave signals in these experiments. If you us the SWR meter you must use 1HKz modulation. This is sometimes convenient when using the oscilloscope as well.

Exercises and Experiments

Exercise 1: Operating the reflex klystron

Setup the equipment as in Fig. 2 to measure both the frequency and wavelength of the propagating microwaves.

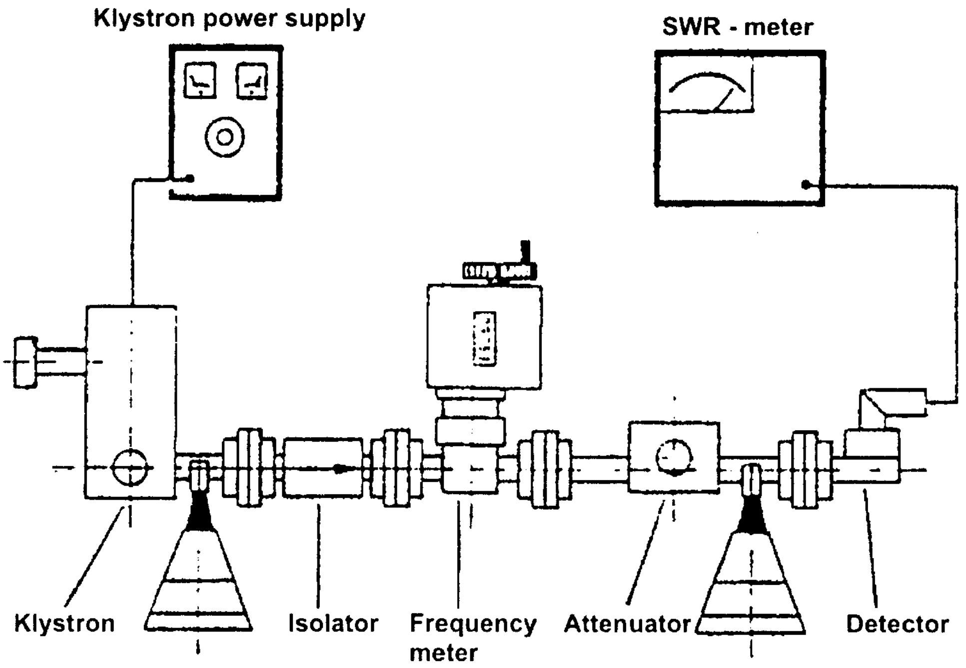


Figure 2: Set up for square wave operation of the klystron

Energizing the klystron. Square wave operation

1.1 Set the Waveguide Attenuator at 40 dB. Select 30dB, 100Hz -1kHz bandwidth, gain control in center on the SWR meter. Switch on the instrument.

1.2 On the klystron power supply, the "Res/refl.on" button has to be out. Switch on the power supply. Only 6.3 V heater voltage is now supplied to the klystron.

1.3 Select the 1KHz square wave and set the reflector voltage knob in center position (~ 100V). Wait at least 1 min and then press the "Res/refl.on" button. The klystron is supplied now with 300V on the resonator and ~ 100V modulated with 40V square wave on the reflector.

1.4 Set the reflector voltage to a value that gives a maximum SWR – meter deflection (~200V). Resonator current meter should read 10-30 mA. (If no deflection is obtained, select 40dB on the SWR meter and repeat step 4).

1.5 Disconnect the BNC cable from the detector and connect it to the frequency meter. Select 50dB on the SWR meter and tune the frequency meter until the maximum deflection on the SWR meter is achieved. The frequency meter setting at maximal deflection is *the klystron output frequency.*

The klystron frequency increases when the tuning know is tuned counter clockwise.

Given this method of operation explain the physical principle behind the operation of the wave meter. The cavity and detector can be setup in two possible configurations leading to either a maximum or minimum of power on resonance. Take this into account in your explanation.

Note: when you have finished with the wave meter you should move it well off resonance so that it will not affect your other measurements!

Note: To get stable operation it is advisable to let the klystron warm up 10 minutes before performing the steps 1.4, 1.5.

Exercise 2: Mode studies on oscilloscope

Set up the equipment as in Fig. 3

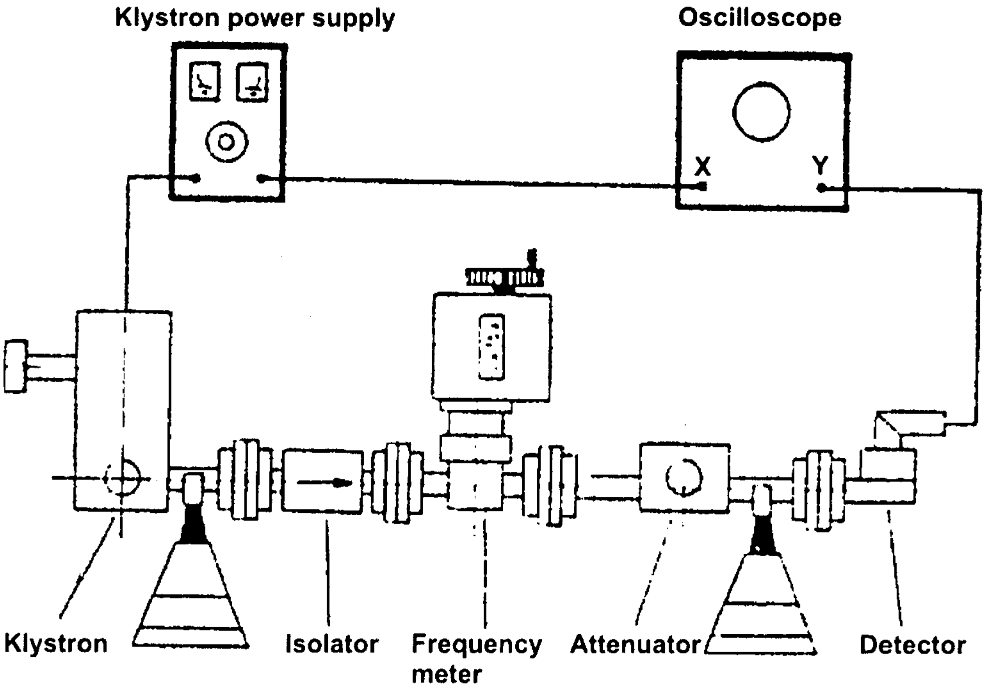


Figure 3: Set up for oscilloscope studies of the klystron

2.1 Set the variable attenuator at 20 dB.
2.2 The oscilloscope should be used in the X-Y mode. The X EXT input should be connected to the "0-30V, 50Hz" output of the klystron power supply. The detector is connected to the oscilloscope input A on 1V/div DC.
2.3 The klystron has to be set up as follows: power supply on 50Hz~; the "Res./refl on" button is out and the reflector voltage control is in center position. Switch on the power supply.
2.4 The horizontal line now visible on the oscilloscope can be adjusted to be symmetrical around the vertical centerline by using the potentiometer knob at the rear of the klystron power supply and also with the X POSITION knob on the oscilloscope.
2.5 Press the "Res./refl on" button and adjust the reflector voltage to approx. 200V.
You should see a pattern similar to Fig. 4. If the pattern is double, adjust the phase of the horizontal input voltage with the potentiometer knob on the back of the power supply. Adjust the vertical sensitivity or the wave guide attenuation to get full vertical deflection.
The pattern on the oscilloscope shows one of the klystron modes. The horizontal axis is *the reflector voltage axis* and the vertical is *the power axis*.

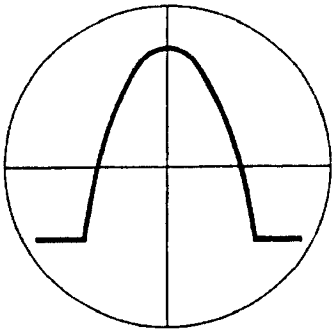


Figure 4: A mode pattern

2.6 Tune the frequency meter until a dip appears on the top of the mode pattern (Fig.5a). The meter setting is *the mode-top frequency*. Note and record the reflector voltage V_o, the mode-amplitude A_o and the frequency of the mode-top f_o.
2.7 Change the reflector voltage to get the mode positioned as in Fig.5b. Note and record the reflector voltage V_1 (the upper oscillation start voltage). Repeat this step to get the lower oscillation start voltage.

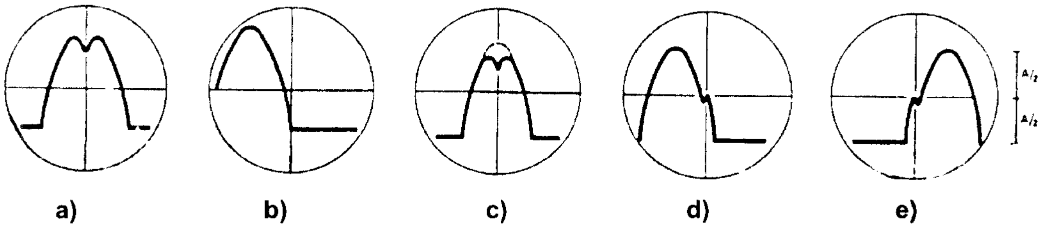


Figure 5: Mode patterns

2.8 Repeat step 2.7 for two more modes. Use the results to draw a mode diagram similar to that in Fig. 6, upper part.

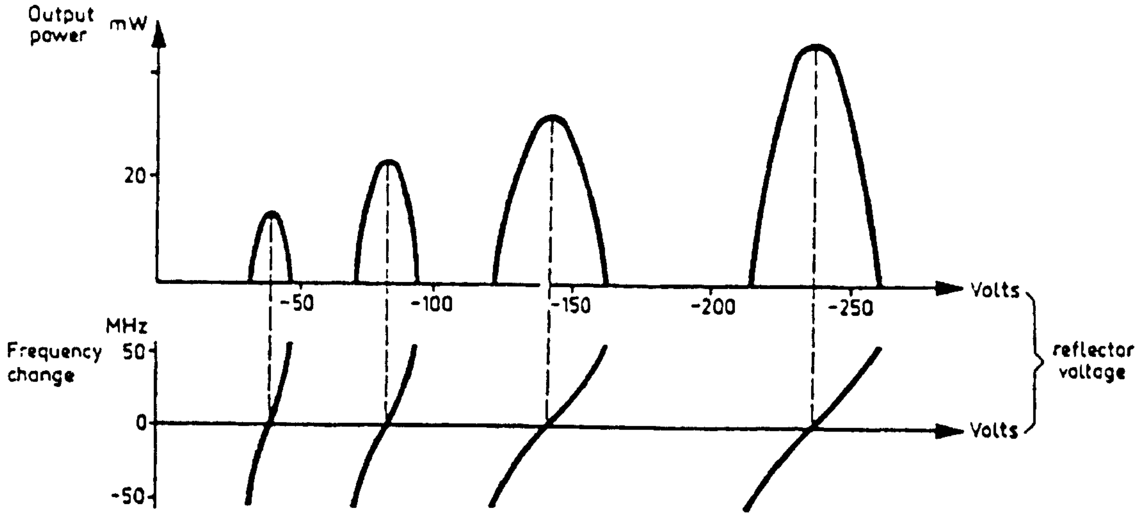


Figure 6: Relationship between output power, oscillation frequency and reflector voltage for a klystron 2K25

Exercise 3: Electronic tuning

3.1 Adjust the reflector voltage to get the highest mode on the oscilloscope. Select a frequency of ~9000 MHz.

3.2 Determine the half-power points as follows: adjust the reflector voltage and the frequency meter to get the patterns from Fig. 5c,d,e. Note and record the reflector voltages and the frequencies. Calculate the electronic bandwidth f'-f" and the tuning sensitivity: $\frac{f'-f''}{V'-V''}$ of the klystron used in this experiment.

Questions:

a) When maximizing the SWR meter deflection with the 1 kHz knob, what are you actually doing?

b) Why is it recommended to have large bandwidth (100Hz) on the SWR meter when looking for the signal?

c) Why does the klystron oscillate only within certain intervals of the reflector voltage?

d) Which one of the modes observed by you corresponds to the longest electron transit time?

Experiment 1: Frequency, wavelength and attenuation measurements

In Exercise 1 we have used the frequency meter to determine the oscillation frequency of the klystron. In this experiment we will calculate the frequency from the wavelength.

- Set up the equipment as shown in Fig. 7.
- Set the variable attenuator at 20 db and adjust the probe depth of the standing wave detector to the red mark on the scale.
- Select 40dB; 100Hz -1KHz bandwidth and gain control in center position on the SWR-meter.
- Energize the klystron (use the mode at ~200V reflector voltage, modulate with 1 kHz square wave). Adjust to maximum deflection on the SWR meter

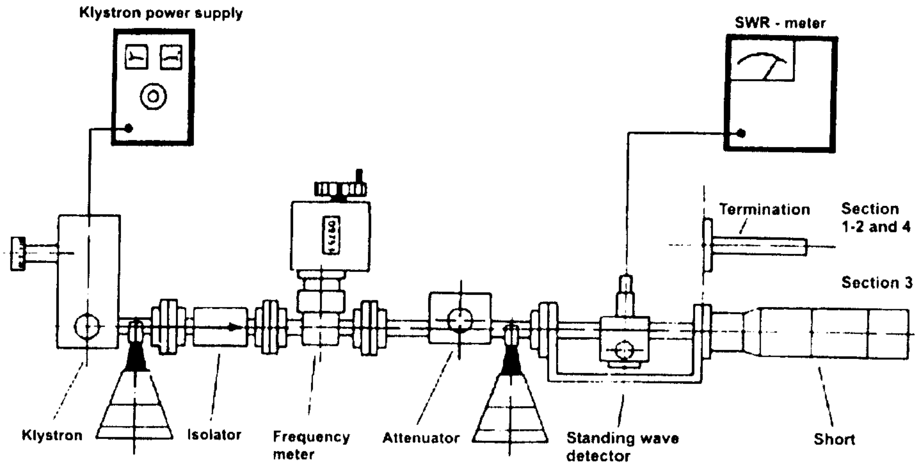


Figure 7: Setup for Experiment 1

Frequency measurement: tune the frequency meter until a "dip" is observed in the SWR-meter deflection. Tune the frequency meter to obtain minimum deflection. Note the frequency meter setting

Wavelength measurement: replace the termination with the variable short. Detune the frequency meter!

- Move the probe along the line, observe the SWR-meter (the deflection will vary strongly). Move the probe to a minimum deflection point. To get an accurate reading it is necessary to increase the SWR-meter gain when close to a minimum. Record the probe position.
- Move the probe to the next minimum and record the probe position. Calculate the waveguide wavelength λ_g as twice the distance between the minima.
- Measure the waveguide inner dimension a (the broad dimension).

We defined before (Equations 1-5) the waveguide wavelength λ_g and the cutoff wavelength λ_c Verify the relation between frequency f and λ_g. The knob on the frequency meter adjusts a cavity that is weakly coupled to the waveguide.

Attenuation measurement: replace the variable short with the termination. Tune the klystron to 9000MHz.

- Adjust the SWR-meter gain to obtain full-scale deflection on the 30dB scale. If necessary change the variable waveguide attenuator setting. Note the micrometer reading on the attenuator. Do not touch the knobs of the SWR-meter anymore!
- Increase the waveguide attenuation in 2 dB-steps up to 10dB by turning the micrometer clockwise. Record the corresponding micrometer settings.
- Draw a curve over the change in attenuation as a function of the micrometer reading. Compare with the curve attached to the attenuator.

Experiment 2: SWR measurements

The **SWR**, standing wave ratio, is the conventional way of measuring the relative amount of traveling waves vs. standing waves. As you may recall properly matched transmission lines propagate EM radiation without reflection whereby all the radiation would be in the form of a traveling wave. If impedance mismatches are introduced, reflections will occur, leading to some standing (stationary) waves. As standing waves are not very useful for the transmission of radiation, the SWR of a waveguide component can be considered a figure of merit. The SWR is defined as the ratio of the maximum electric field amplitude to the minimum electric field amplitude in the waveguide.

Thus if all the radiation was propagating there would be a sinusoidal oscillating signal, i.e. $E(r,t) = E_0 \sin(\omega t - kr)$ and the SWR would equal one. Fig. 8 illustrates some examples of standing wave patterns.

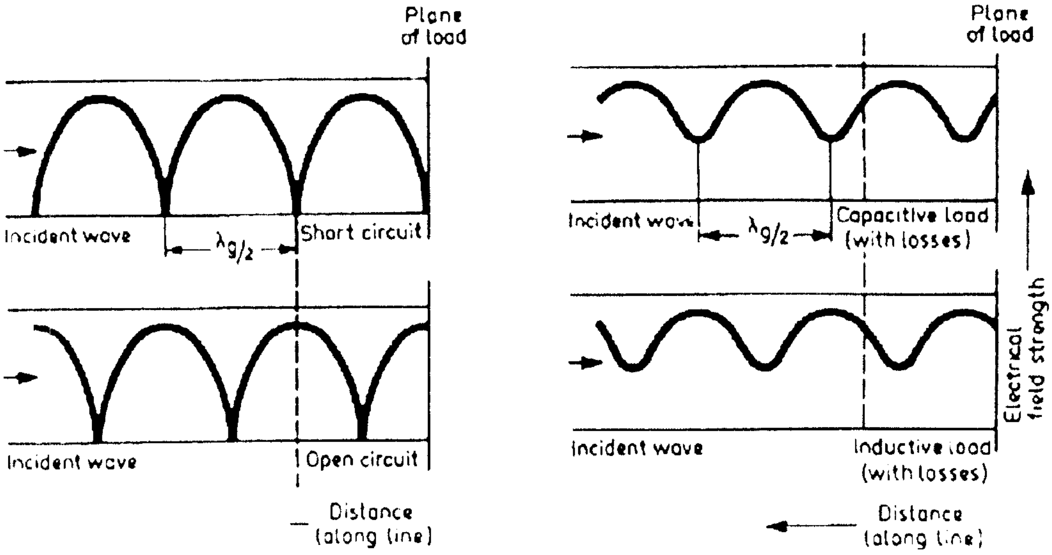


Figure 8: Standing wave patterns

Waveguide technology provides a simple way to directly measure the SWR. A sliding crystal detector can measure the microwave power as a function of position along the waveguide. A sliding screw-tuner can be used to insert a metal stub into the waveguide in a controlled fashion. This allows one to adjust the amount and position of impedance mismatch in the waveguide and thus vary the SWR due to the stub. Imagine trying to design a sliding detector into a coaxial cable!

- Setup the apparatus as in Fig. 9. Set the variable attenuator to 20dB. Completely unscrew the probe on the slide screw-tuner (0 on the scale). Adjust the probe depth on the standing wave detector to the red mark on the scale.
- Energize the klystron for maximum output at 9.0 GHz. Modulate the reflector with 1000Hz square wave. With the SWR-meter on 40dB and 20Hz, obtain a medium deflection.
- Move the probe along the standing wave detector. You'll observe that deflection changes very little, i.e. transmission line is well matched

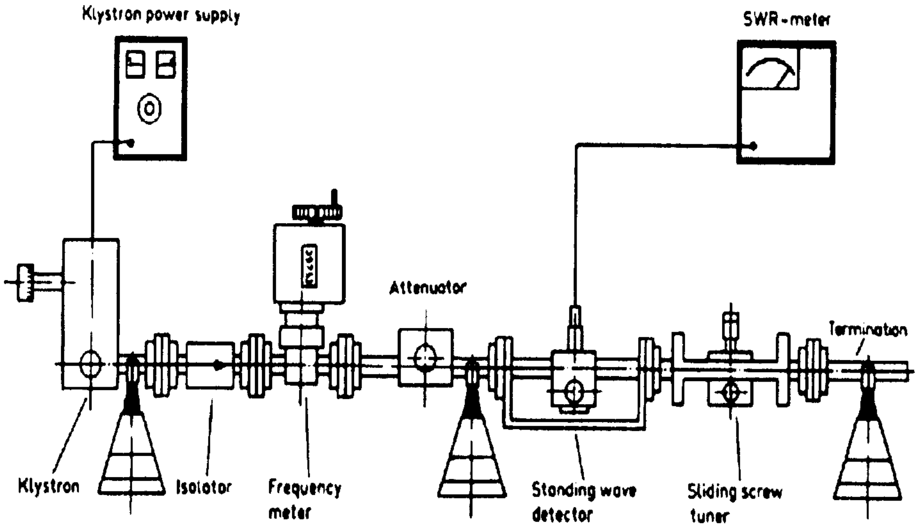


Figure 9: Set up for Experiment 2

Measurement of low and medium SWR:

- Increase the probe depth of the slide screw tuner to 5 mm and move the probe along the standard wave detector to a maximum.
- Adjust the SWR-meter gain until the meter indicates 1.0 on the upper scale, move the probe to a minimum and do not change anything else
- Measure the SWR of the stub in the sliding screw tuner. Measure the SWR for stub depths of 0, 3.7 and 9 mm. What is the SWR in the limit of ever increasing impedance mismatch?

Measurement of high SWR. The double minimum method:

- Set the probe depth on the slide screw tuner to 9 mm. Move the probe along the standing wave detector until a minimum is indicated. Adjust the SWR-meter gain to obtain a reading of ~3 dB on the lower scale.
- Move the probe on the standing wave detector to the left until full scale deflection is obtained (0 dB on lower scale) Note the probe position (d_1).
- Repeat the step above but this time move the probe to the right. Note the probe position (d_2).
- Replace the sliding screw-tuner and matched load with the movable short. Move the short and determine the distance between successive maxima. How is this distance related to λ_g ?
- Calculate the SWR as: $$S = \sqrt{1 + \frac{1}{\sin^2 \frac{\pi(d_1 - d_2)}{\lambda_g}}} \approx \frac{\lambda_g}{\pi(d_1 - d_2)} \qquad (6)$$

The Isolator

Now that you have been introduced to the concept of SWR you should realize that for many microwave components the manufacturer attempts to minimize the SWR at each waveguide port. Take a look into the isolator ports. What do you see that looks, perhaps, out of place? Why did the manufacturer put these things into the waveguide?

With the arrow pointing *towards* the microwave generator and the variable attenuator at zero measure the microwave power level. Rotate the isolator so that now its arrow points *away* from the generator. Adjust the attenuator to bring the power level down to the previous setting. Now you can calculate the "insertion loss" of the isolator in the backward direction assuming 0 dB insertion loss in the forward direction.

The isolator is a fascinating device which relies on the non-time reversal symmetry of Maxwell's equations to allow transmission in one direction but not the reverse. See appendix B for a brief description of a Faraday-rotation isolator. Isolators are commonly used to protect devices from strong reflections, as we do in this experiment. Microwave oscillators often will not function properly if a large amplitude wave is incident upon them.

Experiment 3: Antenna Measurements

The open waveguide acts as an antenna. In the case of a rectangular waveguide this antenna presents a mismatch of about 2:1 (SWR = 2) and radiates in many directions. The match will be improved if the open waveguide has a "horn" shape.
The radiation pattern of an antenna is a diagram of the field strength or power intensity as a function of the aspect angle at a constant distance from the radiating antenna. It consists of several lobes (see Fig. 10). The major power is concentrated in the main lobe and it is normally desirable to keep the power in the side and back lobes as low as possible.

Definitions:

- Gain (G): the power intensity at the maximum of the main lobe compared to the power intensity achieved from an imaginary antenna radiating equally in all directions and being fed with the same power.
- 3 dB-beamwidth θ: the angle between the two points on a main lobe where the power intensity is half the maximum power intensity

When measuring an antenna pattern it is interesting to plot the "far field pattern", which is achieved at a minimum distance of: $R_{\min} = \dfrac{2D^2}{\lambda_o}$ where D is the size of the broad side of the rectangular horn antenna and λ_0 is the free space wavelength.
It is also important to avoid disturbing reflections. Do not stand too close to the set up; move slowly and keep an eye on the SWR-meter!

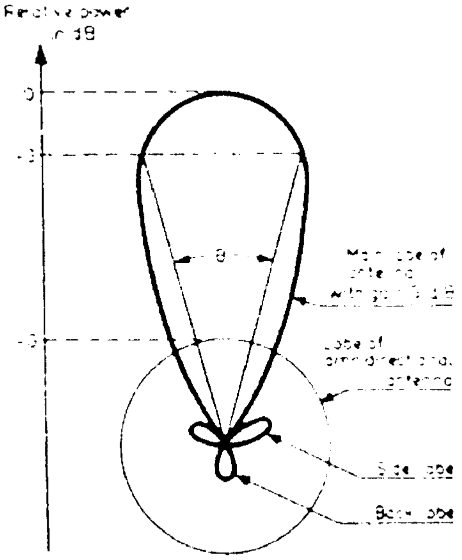


Figure 10: Antenna pattern

Antenna measurements are mostly made with the unknown antenna as receiver. There are several methods to measure the gain of an antenna. One method is to compare the unknown with a "standard gain" antenna. Another method is to use two identical antennas, one as transmitter (power P_t) and the other as receiver (power P_r). The following relation between P_r and P_t can be proved:

$$\frac{P_r}{P_t} = G^2 \frac{\lambda_0^2}{(4\pi R)^2} \tag{7}$$

The gain G is therefore given by: $G = \dfrac{4\pi R}{\lambda_0}\sqrt{\dfrac{P_r}{P_t}}$ (8)

The two powers (or the ratio only!) and the distance R are measured and G can be calculated.

Procedure for antenna diagram plotting: Set up the equipment as in Fig. 11.
When horns are in-line, the scale on the rotary joint should indicate 90°.
Energize the klystron for maximum output at 9.0 GHz, 1 kHz square wave modulation. Set the variable attenuator at ~ 20 dB. Obtain full scale deflection on the SWR-meter.
Take measurements by turning the receiving horn in 10° alternating left-right steps.
Repeat at 9.5 GHz. Draw a diagram on polar graph paper.

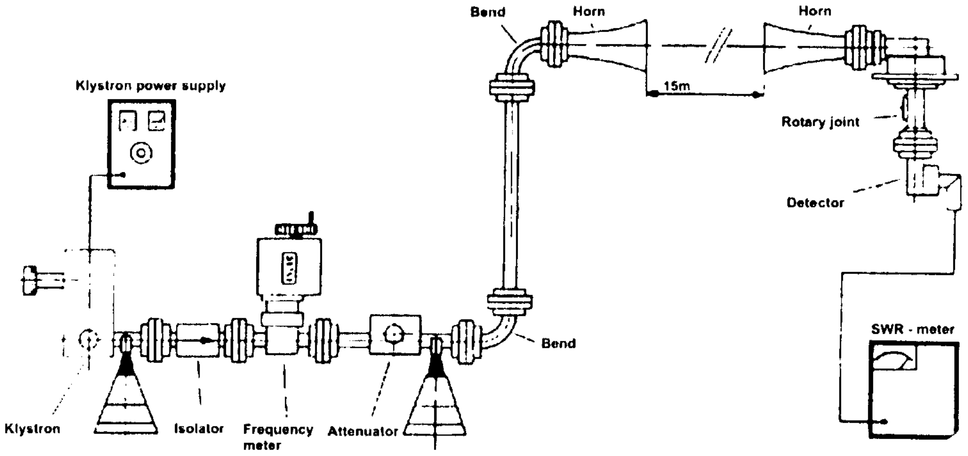
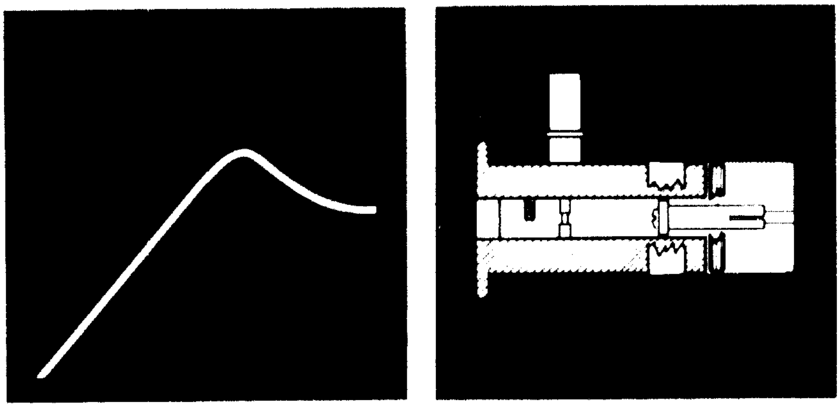


Figure 11: Set up for Experiment 3

Procedure for gain measurement: Set the variable attenuator at ~40 dB.
Obtain full scale deflection on the SWR-meter when the horns are in-line.
Remove the crystal detector and let it replace the transmitting horn. Readjust the SWR meter to get the deflection on scale (do not touch the gain control knob). Record the gain range and the deflection (incident power).
Measure the incident power on the receiving antenna as a function of angle and plot this on polar graph paper. Determine the 3 dB width, in degrees, of the main lobe of the antenna pattern.
Why do we elevate the antenna?

Appendix A
The Gunn Oscillator



1. Voltage current characteristic of a Gunn diode

2. Gunn oscillator PM 7015X

Figure 12: The Gunn oscillator

The Gunn diode oscillator is named after J.B. Gunn who in 1960 was studying high field phenomena in Gallium Arsenide (GaAs). When the applied electrical field was about 2000 V/cm, he discovered oscillations of microwave frequencies. In his own words:
... *when I pushed the electric field up to the neighbourhood of 1000 to 2000 V/cm something entirely unexpected happened. Instead of a simple variation of current with voltage, all hell broke loose - the current started to jump up and down in a completely irregular way that very much*

resembled electrical noise mechanism I knew. The current variations were in the order of amperes rather than the nanoamperes you ordinarily see.
Averaging over the microwave oscillations the voltage current behavior was as in Fig. 12. Above the voltage V_0 the GaAs diode IV curve develops a negative resistance.

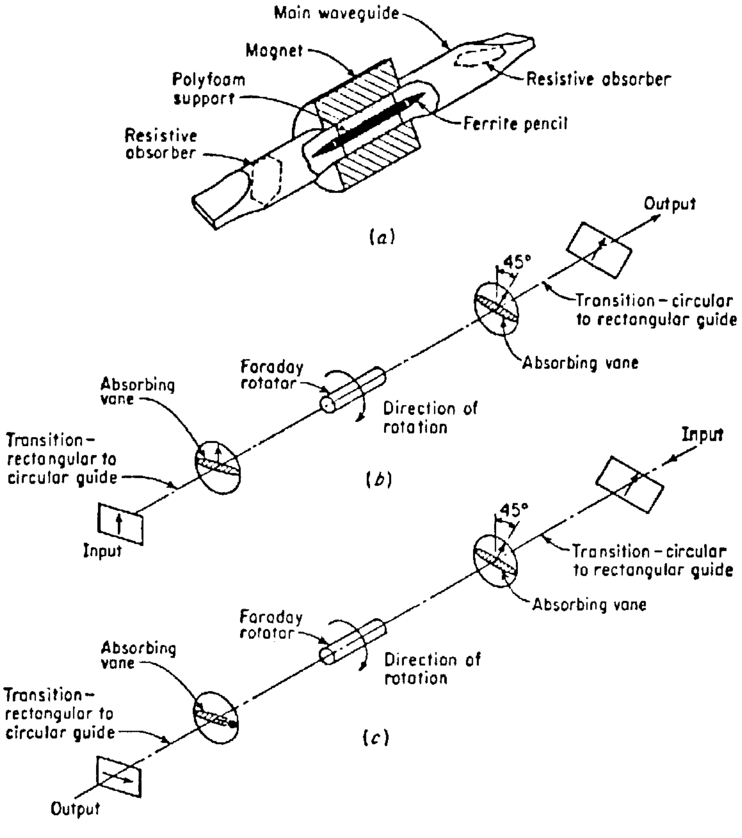
Cavity-controlled oscillator

In a Gunn oscillator the diode is placed in a resonant cavity. In this case the oscillation frequency is determined by the cavity more than by the diode itself. Biasing in the negative resistance region causes the diode to oscillate at the cavity resonance frequency. Today (1982) the Gunn oscillators dominate the low power local oscillator and the low-power transmitter market above 6 GHz. The oscillation frequency range extends up to 100 GHz. The Gunn oscillators are reliable and low-noise, and produce CW power from a few milliwatts up to a few watts.
In this oscillator the cavity consists of a waveguide section with a movable short-circuit section. It can be continuously moved by turning the tuning knob and thus change the oscillation frequency. The Gunn diode is post mounted across the waveguide and the iris serves as an impedance match to the mating waveguide.

Appendix B

Microwave Isolator

Perhaps one of the most important applications of ferrites in microwave circuits is the microwave isolator. A typical microwave isolator is shown in Appendix B - Fig. 1. It consists of a circular waveguide carrying the TE_{11} mode with transitions for converting the circular mode to rectangular waveguide modes at both ends. In the central region a pencil-shaped ferrite material is introduced. To minimize reflections, the ferrite pencil is tapered gradually at both ends. A permanent magnet is placed outside of the waveguide to provide a longitudinal static magnetic field through the ferrite pencil. The ferrite causes the plane of polarization of the TE_{11} mode to rotate by an amount determined by the size of the ferrite pencil, its length, and the strength of the magnetic field. The direction of rotation of the plane of polarization is determined by the direction of the static magnetic field.



Appendix B Fig. 1

FIG. 1 Faraday-rotation isolator. (*a*) Schematic arrangement of the elements; (*b*) transmission in the forward direction; (*c*) transmission in the reverse direction.

The principle of operation of this device can be explained with the help of Appendix B -Fig. 1(b) and (c). The electromagnetic waves at the rectangular TE_{10} mode enter from the left side and are transformed into the circular TE_{11} mode by a gradual transition. The plane of polarization of this circular mode is the same as that of the rectangular TE_{10} mode. In passing through the ferrite, the plane of polarization is rotated clockwise by 45°. The circular mode with the rotated plane of polarization is then converted back into the rectangular mode. The rectangular waveguide at the right is physically oriented in such a way that the plane of polarization of the incoming waves from the left coincides with that of the usual TE_{10} mode in this guide. Thus the electromagnetic waves propagate through this device from left to right and suffer only a small attenuation in the ferrite material.

The propagation of waves in the reverse direction, however, is prevented by the device. Consider, for instance, electromagnetic waves at the rectangular TE_{10} mode entering the system from the right. After coming through the transition, the mode is converted to the circular TE_{11} mode when the plane of polarization remains the same as that of the incoming TE_{10} mode. The ferrite rotates the plane of polarization by 45°, as before, in the clockwise direction. After rotation, the plane of polarization becomes such that the wave can no longer propagate into the rectangular waveguide at the left. A resistive attenuation card can now be placed parallel to the wide dimension of the waveguide at the left to absorb the energy of the waves coming from the right to the left. Thus, under ideal conditions, no propagation from the right to left is possible.

Isolators can be used to improve the frequency stability of microwave generators, such as klystrons and magnetrons, where the reflection from the load affects the generating frequency. In such cases the isolator is placed between the microwave generator and the load so that the energy is transmitted from the generator to the load with a very small attenuation. On the other hand, the energy of the reflected waves resulting from the load mismatch is highly absorbed by the isolator. This prevents the frequency instability of the generator.

References

Sivers-Lab-Philips: Microwaves: basic experiments (reprint available from the Resource Centre)

D. M. Pozar: Microwave engineering, J. Wiley 2005

This guide sheet has been re-written in 2006 by R.M. Serbanescu. Previous versions: B.W.Statt 2001

Wellington Institute of Technology
Te Whare Wananga o te Awakairangi

IONAL PROPERTIES OF MICROWAVE AERIALS

(a) To investigate the beam forming properties of various microwave aerials and to compare their relative gain.

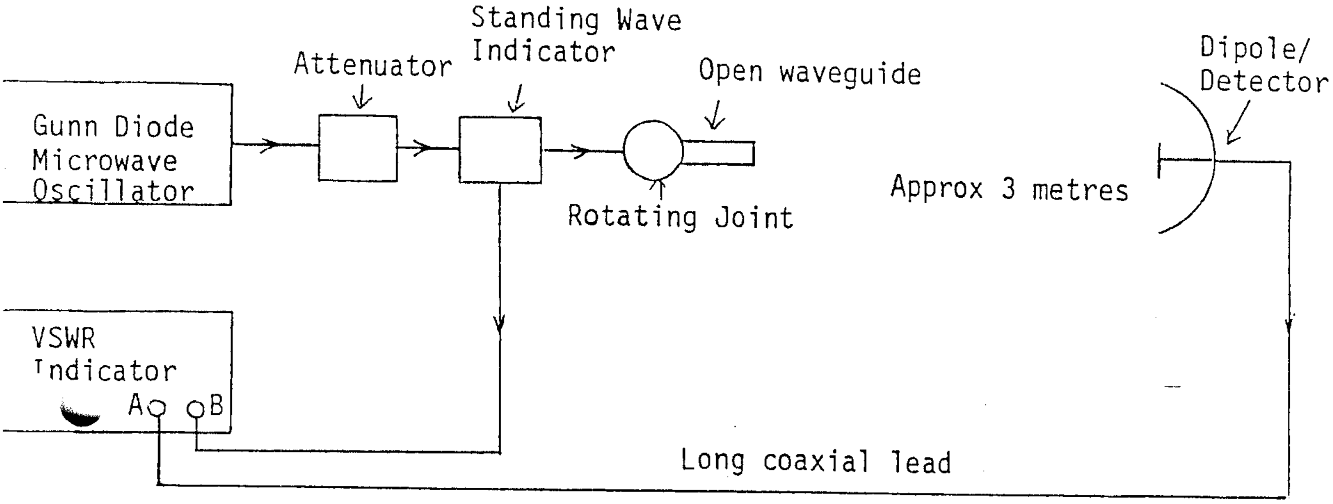
(b) To observe beam slewing effects with slotted aerial arrays.

: Refer to class notes.

TUS :

1. Microwave test bench
2. Rotating joint
3. H plane horn
4. Pyramidal horns
5. Waveguide twist section
6. 180° waveguide bend
7. Receiving paraboloid with dipole/detector
8. Series slot array
9. Shunt inclined slot array
10. Sivers Lab. multi-element array SL19703

URE : Part A



1. Set up the bench as shown with the S.W.I. used to monitor the bench output at a frequency of about 9.1 GHz. For the antenna use an open circuit termination.

2. Place the receiving paraboloid on top of a small table about 3 metres from the microwave source. Elevate the paraboloid so that the receiving dipole is the same height as the source's waveguide, by the use of a plastic box. Carefully align the source and paraboloid for a maximum received signal, as shown by the indicator.
   Note : the polarisation of the receiving dipole can be changed by rotation of the dipole. At this stage the dipole should be vertically polarised.

3. Set the adjustable pointer to an indicated 90°.

4. (a) Adjust the received level to give a reading of 0 dB on the indicator.
   (b) Rotate the joint to the left until the level on the indicator falls by 3 dB. Note the deviation in degrees.
   (c) Similarly rotate to the right to determine the deviation.
   (d) Determine the SWR of the antenna under test.
   (e) Record your results in the prepared table.

5. Para. 4 is to be repeated for several different waveguide horn antennas. Also the relative gain of each antenna is to be determined with respect to the open circuited termination as follows :

   (a) Realign the open circuit termination for a maximum.
   (b) the gain of each antenna will progressively increase by a factor of about 5 dB max, set the output level to read -5 dB. on VSWR meter
   (c) Fit the H plane sectoral horn which has an aperture of approximately 7.5 x 1 cms.
   (d) Note the increase in output power in dB. (This is the relative gain
   (e) Repeat para. 4 to determine the beamwidth and SWR.

6. Repeat para. 4 and 5 to test also the pyramidal horns :

   (a) Small Horn, approx. 7.5 x 2.5 cms
   (b) Large horn, approx. 7.5 x 7.5 cms

   Note : it is easier to compare the gain of each successive horn with its predecessor. Then calculate the gain wrt the open circuit termination.

7. Calculate and record the theoretical gains of each antenna from :

$$\text{Gain} = 10 \operatorname{Log}_{10} \left(4.5 \frac{ab}{\lambda^2}\right)$$

where a = final broad dimension
b = final narrow dimension

8. To the output of the rotating joint add the 90° twist section. Refit the open circuited termination and realign the dipole/detector to the correct polarisation.

9. Determine the half power beamwidth.

10. Repeat 9 for the remaining horn antennas.

11. (a) Align the square pyramidal horn for a maximum signal and adjust to read 0 dB.

    (b) Now rotate the dipole/detector for the opposite polarisation and determine the isolation.

Part B

1. To the output of the rotating joint attach the 180° waveguide bend and the alternately inclined slot array terminated at the load end with a matched load.

2. Carefully align the slot array with the receiving paraboloid which has to be raised still further to offset the height of the 180° bend.

3. Determine the half-power beamwidth, the SWR of the load and the relative gain wrt the open end termination.

4. Fit the sivers lab. array and determine its gain wrt the open ended termination, beamwidth in both planes, and SWR at a frequency of 9.1 GHz.

   Adjust the frequency of the gunn diode to maximise the gain of the antenna. Record the gain, beamwidth and SWR.

SULTS : Part A

Horn Antennas - Vertically Polarised

erial Type	VSWR	Aerial Gain dB		Beamwidth - Degrees		
		Relative	Theoretical	Left	Right	Total
pen waveguide		0				
Plane Horn						
mall Horn						
arge Horn						

Horizontally Polarised

Aerial Type	Beamwidth - Degrees		
	Left	Right	Total
Open Waveguide			
H Plane Horn			
Small Horn			
Large Horn			

Polarisation Discrimination

Measured discrimination = ____________________ dB

Part B

Aerial Arrays at 9.1 GHz Matched

Array Type	Beamwidth Degrees			Polarisation V/H	SWR	Relative Gain dB
	Left	Right	Total			
Shunt (inclined slot)						
Sivers				H		
Sivers				V		

Sivers Array

Frequency for maximum gain = ______________ GHz

Beamwidth Degrees			SWR	Relative Gain dB
Left	Right	Total		

[illegible]NS :

1. Comment on the beam forming properties of the horns tested.
2. Comment on the matching properties of the horns.
3. Explain why the SWR measured for the large pyramidal horn is lower than that for the H plane sectoral horn.
4. Why is the SWR of the H plane sectoral horn larger than that for the open-circuit termination?
5. Compare the gain of the horns tested
   (a) by measurement
   (b) by calculation

HUTT VALLEY POLYTECHNIC

Te Whare Wananga o te Awakairangi

26 x 20cm x 1cm in 2mm

CENTRAL INSTITUTE OF TECHNOLOGY

ELECTRONIC ENGINEERING DEPARTMENT

PROPAGATION LABORATORY

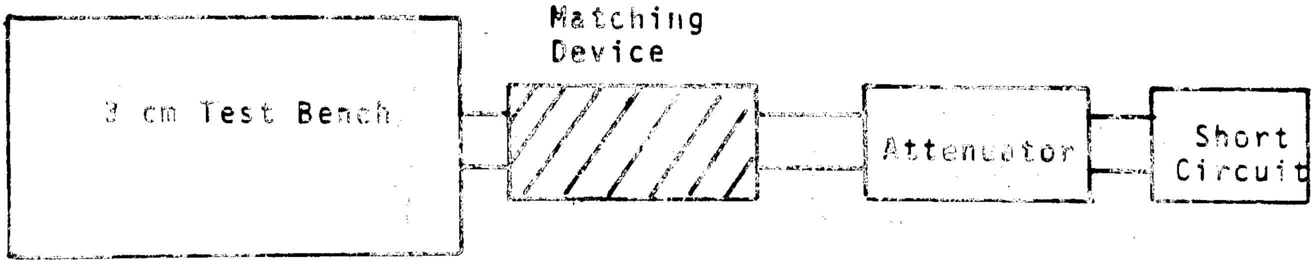
LOAD MATCHING IN WAVEGUIDES : Part 2

AIM : To investigate three methods of matching a load to a waveguide.

THEORY : A complex load may be matched to a waveguide using :

(i) A triple screw tuner
(ii) A double stub tuner
(iii) A single stub and phase shifter.

APPARATUS : Set up the apparatus as shown below but without the matching section :



In addition you will require :

1. Triple screw tuner
2. Waveguide Junction
3. Phase shifter
4. Double stub tuner
5. Precision Short circuit.

METHOD :

1. Adjust the load attenuator for an S.W.R. of about 4:1.

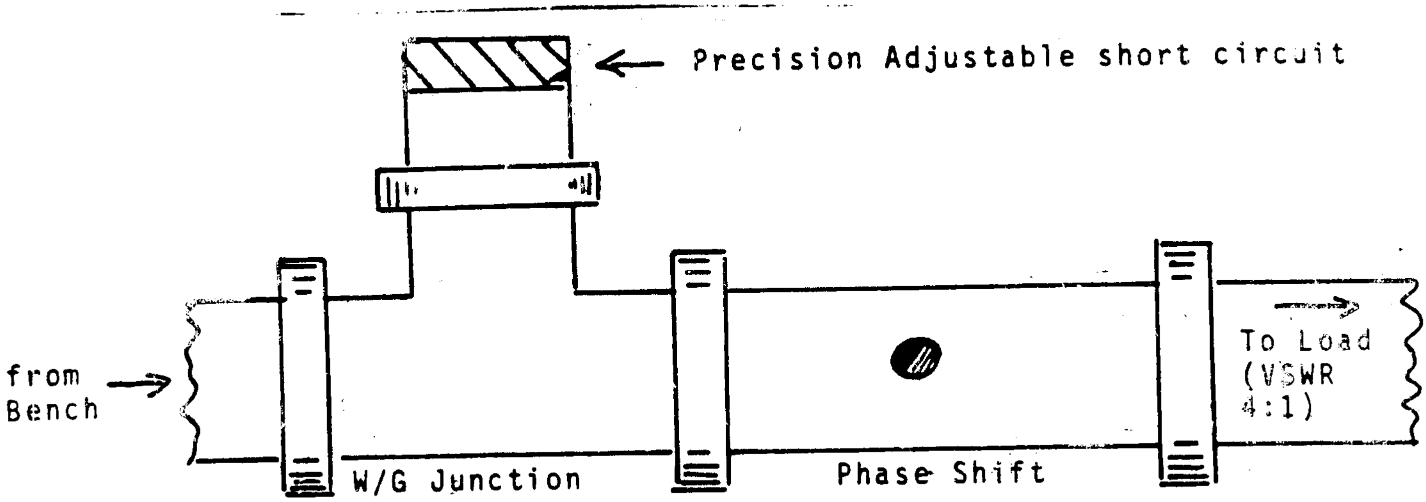
2. Insert triple screw tuner and adjust for best V.S.W.R.

   V.S.W.R. ______________________

3. Replace triple screw tuner with double stub tuner and repeat.

   V.S.W.R. ______________________

4. Replace with the phase shifter and precision short as shown over page and repeat.



RESULTS : Part 1.

Comment on best S.W.R., ease of adjustment, and relative advantages of each method.

CENTRAL INSTITUTE OF TECHNOLOGY

ELECTRONIC ENGINEERING DEPARTMENT

PROPAGATION LABORATORY

MEASUREMENT OF MICROWAVE COMPONENTS

THEORY : Determining the operating characteristics of microwave components involves the measurement of :

(i) The effects of inserting the device into a microwave system.
(ii) The performance of the device itself.

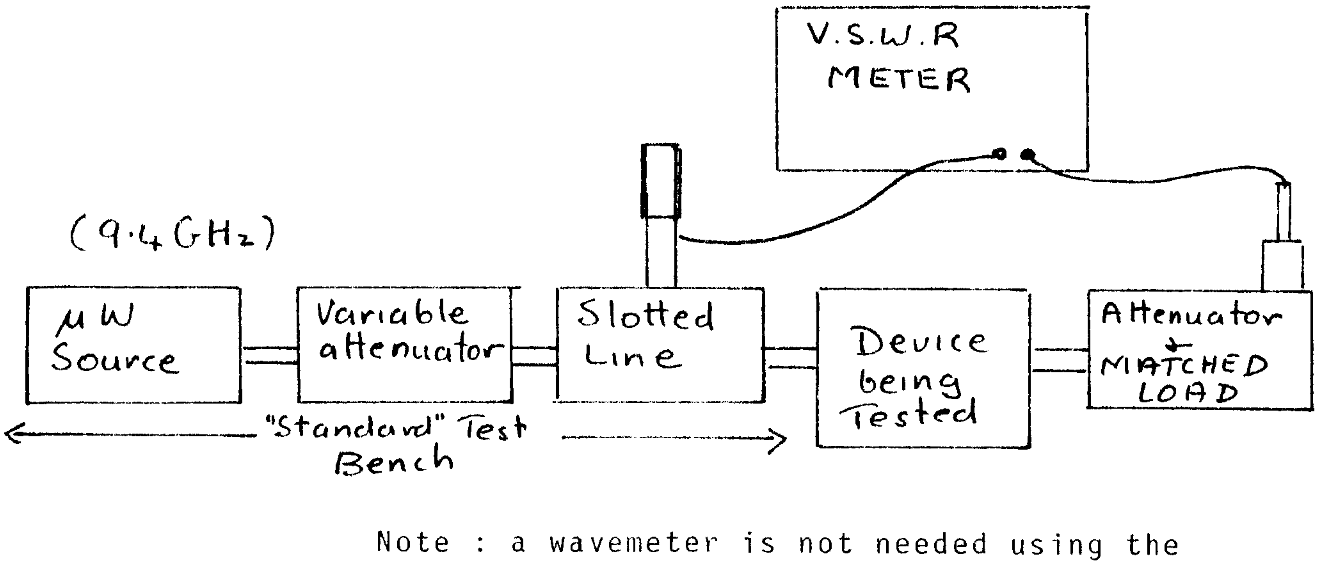
The following may be measured :

(a) Insertion loss : The drop in output power in dB when the device is inserted between a microwave bench and a matched detector. Note : the Insertion loss caused by the device is when it is operated in its minimum loss mode.

(b) V.S.W.R. : The effect on the V.S.W.R. seen by the generator when the device is set up as for (a) above.

(c) Component Measurements : Examination of the operation of the device itself using a matched detector to determine the levels involved.

APPARATUS : Standard Test bench set at f = 9.4 GHz unless otherwise specified.
Matched detector consisting of :
(a) Wideband coaxial detector
(b) Wideband coaxial/waveguide transformer
(c) Calibrated attenuator.



Note : a wavemeter is not needed using the Marconi solid state source.

PROCEDURE :

Microwave Devices

The following devices are available for measurement :

1. Ferrite Isolator
2. Ferrite Circulator
3. Magic Tee
4. Bethe Coupler (Cross coupler)
5. P.i.N. diode switch
6. Waveguide Switch

At least four of these devices should be measured.

1. Ferrite Isolator (Rank)

Insert the device between the bench and the matched load. Determine :

(a) Insertion loss __________ dB) Device
VSWR __________) connected
) for maximum
) forward
) power

(b) Remove the matched load and replace it with a short circuit and re-measure V.S.W.R.

V.S.W.R. __________

(c) Reverse the isolator, terminate with matched load and measure.

V.S.W.R. __________

Loss __________ dB

(d) From the Return Loss (sum of the two losses above) determine the theoretical V.S.W.R. (use the radial scale of a Smith Chart).

Theoretical VSWR __________

Compare this to the measured VSWR in (a).

2. Ferrite Circulator

Set up with input to port 1, matched detector at port 2. Port 3 open.

(a) V.S.W.R. __________

(b) Terminate port 3 in matched load.

V.S.W.R. __________

Insertion loss of circulator __________ dB

(c) Reverse the positions of the matched detector and the load and determine the isolation between Port 1 and Port 3.

Isolation __________ dB.

3. Magic Tee

(a) Connect the "Magic Tee" to the source via a twin stub tuner. Terminate both side arms with matched loads and adjust the twin stub tuner till V.S.W.R. is better than 1.1:1.

(b) Replace one matched load by the matched detector and determine the loss from the source to the side arm.

Loss ____________ dB.

(c) Note level from the detector, replace the matched load on the side arm and measure the level in the unused input arm.

Isolation ____________ dB.

(d) Isolation between input arms

____________ dB.

4. Bethe (45°) coupler

(a) Set up with matched detector terminating the main arm and matched loads at both side arms.

(b) Set the output for "0" dB on the meter with atleast 40 dB of attenuation held in the meter amplifier and the load attenuator.

(c) Reverse the matched detector and the load on the forward power sampling arm and determine the Coupling Factor.

Coupling Factor _____________ dB.

(d) Reset levels for at least 30 dB of held attenuation and reverse load and detector on the coupled arm to determine the reverse power level.

Reverse power loss ____________ dB.

(e) Directivity factor is now the sum of (c) and (d).

Directivity factor _________ dB.

5. P.i.N. Diode switch

(a) Insert pin diode assembly.

(b) Set Forward bias to 20V d.c.
Check that diode current is flowing.

(c) Measure Insertion loss and V.S.W.R.

Insertion loss ____________ dB.

V.S.W.R. ________________

(d) Reverse bias and repeat measurements.

Loss ____________ dB

VSWR _____________

(e) Measure and plot loss (dB) against bias current from 0 to 10 mA.

6. Waveguide Switch

(a) Set frequency to 9.080 GHz.

(b) Insert switch, put matched detector on one arm and matched load on the other.

(c) Measure V.S.W.R. __________________

Insertion loss ________________ dB.

(d) Determine isolation for reverse position of switch.

Isolation _______________ dB.

(e) Measure performance at frequencies of 9.580 GHz and 8.580 GHz.

	9.580	8.580
VSWR	________	________
Isolation	________ dB	________ dB

CONCLUSIONS : Compare the operation and use of :

(a) Ferrite devices.

(b) Ferrite Circulate and Magic Tee.

(c) PiN diode and Waveguide Switches.

VMS
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ECE 584
Microwave Engineering Laboratory Notebook

D. M. Pozar
E. J. Knapp
2004

Electrical and Computer Engineering

University of Massachusetts at Amherst

Contents

I. Introduction

1. General Comments

Lab Organization:
There are a total of six laboratory experiments described in this manual. The first three involve basic microwave measurement techniques for power, frequency, wavelength, standing wave ratio, impedance, and S parameters. The last three experiments deal with the characterization of some basic microwave components, extending the techniques learned in the first group of experiments. Each group of students will have two weeks in which to complete each of the six experiments. The first three experiments will be set up during the first six weeks of the semester, and the last three experiments will be set up during the following six weeks. Every two weeks each group will rotate to a new experiment station.

Be sure to completely read the description of each experiment before beginning the experiment. This will help you to see the overall plan of action, and should decrease the likelihood that you will do the procedure incorrectly, or forget to do part of the procedure.

Some of the laboratory experiments will involve material that is out of sequence with the classroom lecture, and you will be covering topics that have not yet been discussed in class. You will need to read some text material (*Microwave Engineering*, 3rd edition, by D. M. Pozar) ahead of the lecture schedule so that you have a better understanding of the experiments you are performing. Prior to going to your first lab, you should read over the description of the first three experiments in the lab handbook. Also, make sure you read pages 3-10 of the lab handbook, since they contain general information that you need to know.

You will be performing Labs 1, 2, and 3 through the first half of the semester, and Labs 4, 5 and 6 will be completed during the second half of the semester. Each Lab Section will have six lab groups, with two students in each group (some groups may consist of three students in special situations). Each lab group will take two consecutive Lab periods to complete each of the six lab experiments.

There will be two bench setups for each of three experiments on any given lab day, so two lab groups will start with Lab 1, and the other two groups will start with either Lab 2 or Lab 3. For this reason, it is very important that you read over the first three experiments (slotted line, vector network analyzer, Gunn diode) prior to coming to your first lab. You also need to study ahead in the text material, as required for these labs.

Lab Reports:
Lab reports are required of individual students, and are due two weeks after the corresponding experiment has been completed. Students are encouraged to keep a lab notebook to record original data, equipment layout, and notes about the experiment. Reports should be neat and clearly organized, and should include original data sheets. Graphs should be neatly drawn, either using a computer graphics package, or by hand with a straightedge and French curve. Each graph axis of a graph must include a title and units. Organization of the lab report is left to the student, but a suggested report outline follows:

1.	Introduction	(purpose of experiment)
2.	Procedure	(equipment used, configuration, unexpected problems)
3.	Results	(measured data, relevant calculations)
4.	Discussion	(interpretation of results)
5.	Conclusions	(what was learned, recommendations)

In some of the experiments topics for optional work are suggested - you should consider these options, if time permits. Students are also encouraged to try out their own "what if. . . " ideas. period. You are encouraged to keep a lab notebook, with careful notes about the experiment setup, measurements, expected (or unexpected) results, problems encountered, etc. Completed lab reports are required of each student, and are due two weeks after each experiment is completed. The Teaching Assistant will collect lab reports at the beginning of the lab period.

Care of Equipment:
Please be very careful with the microwave test equipment, as it is very delicate, and expensive to repair or replace. (Microwave network analyzers cost approximately $70,000 each; microwave connectors and adapters range in cost from $35 to $90 each.) If you suspect something is not operating correctly, report it to the lab technician or Teaching Assistant. Be especially careful when using connectors to avoid breaking pins and cross-threading. If at any time you are uncertain about lab safety, please ask the Teaching Assistant before proceeding.

Lab Support:
There will be a Teaching Assistant assigned to each of the Lab Sections to help with questions about experiment setup and measurements. In addition, our Research Engineer (Mr. Eric Knapp) will be available to maintain the microwave lab equipment. Any problems with basic measurement equipment (e.g. network analyzer, signal sources, VSWR meters, etc.) should be reported to Mr. Knapp at 545-4699 or at knapp@mirsl.ecs.umass.edu.

2. Microwave Radiation Hazards

Excessive exposure to electromagnetic fields, including microwave radiation, can be harmful. Although the power levels used in our Microwave Instructional Lab are very low and should not present a health risk, it is still prudent to,

- be aware of the recommended safe power limits
- be aware of the power densities with which you will be working
- use good work habits to minimize exposure to radiated fields

The question of what is a "safe" radiation level is controversial; like highway speed limits, all we can say with total certainty is that less is safer. Microwave radiation is nonionizing, so the main biological effect is induced heating, which may occur relatively deep inside the body to affect sensitive organs. Health risks increase according to the power density and the duration of the exposure. The eye is the most sensitive organ, and studies have shown that cataracts can develop from exposures as short as 1.5 hours to power densities of 150 mW/cm^2. Thus, using a safety factor of more than 10, the current US safety standard, C95.1-1991, recommends a maximum exposure power density of 10 m W/cm^2, at frequencies above 10 GHz, with lower levels at lower frequencies. By comparison, the power density from the sun on a clear day is about 100 mW/cm^2, but most of this power is beyond the microwave spectrum, and so does not enter deeply into the body.

The sources used in the Microwave Instructional Laboratory, such as sweep generators and Gunn diodes, have power outputs in the 10 - 15 m W range. In most cases, there is little danger of being exposed to radiation at these power levels because our experiments use coaxial lines or waveguide, which provide a high degree of shielding. It is possible, however, to encounter power densities near the US recommended limit at the end of an open-ended coaxial cable or waveguide. Such power densities exist only right at the open end of the coax line or waveguide, due to the $1/r^2$ decrease of radiated power with distance. For example, at a distance of 10 cm from a waveguide flange with an input power of 20 mW, the Friis formula gives the power density as,

$$S = \frac{PG}{4\pi R^2} = \frac{(20)(2.5)}{4\pi(10)^2} = 0.04 \text{ mW/cm}^2$$

which is seen to be far below the recommend safety limits.

Even though there should be little danger from microwave radiation hazards in the lab, the following work habits are recommended whenever working with RF or microwave equipment:

- ***Never look into the open end of a waveguide or transmission line that is connected to other equipment.***

- ***Do not place any part of your body against the open end of a waveguide or transmission line.***

- ***Turn off the microwave power source when assembling or disassembling components***

3. Overview of Microwave Test Equipment

A key part of the microwave laboratory experience is to learn how to use microwave test equipment to make measurements of power, frequency, S parameters, SWR, return loss, and insertion loss. We are fortunate to have a very well-equipped microwave laboratory, but most of the equipment is probably not familiar to students. Here we briefly describe the most important pieces of test equipment that will be used in the laboratory experiments. More detail on the operation of this equipment can be found in the Operation Manuals in the Microwave Instructional Lab. The Appendix of this manual contains a list of the major pieces of equipment in the Microwave Instructional Lab.

Sweep Generator:
The source of microwave power for most of our experiments will be supplied by a microwave sweep generator. We have several sweep generator models, including the HP8620 mainframe and the HP8350 mainframe, each of which uses plug-in modules to cover specific frequency bands. These generators can be used as a single-frequency source (CW), or as a swept source, where the frequency is varied from a specified start and stop frequency. The HP8620 model uses manually adjustable knobs and buttons to specify the frequency, while the newer HP8350 units use electronically adjustable frequency ranges. The HP8350 also includes digital readouts for frequency and output power. Both sweep generators have a switch on the plug-in unit to turn the RF power on and off. To obtain the best frequency stability it is recommended that the AC power for the sweep generator be left on during the lab period, and the RF power switched off at the plug-in module when re-arranging components.

Power Meter:
We can measure microwave power with the HP436A power meter. This meter uses a sensor head that converts RF power to a lower frequency signal measured by a calibrated amplifier. Before using, the HP436A should first be zeroed by pressing the *zero* button, then calibrated by connected the sensor head to the calibration connector on the front panel. A calibration dial on the front panel should be set to the value indicated on the calibration data listed on the sensor head. The HP436A can be set to display power in mW or dBm.

Frequency Counter:
We have several microwave frequency counters, including the HP5342A, the HP5350B, and the HP5351A. These give precise measurement of frequency using a heterodyning technique, followed by a high-speed digital counter.

Spectrum Analyzer:
The spectrum analyzer gives a frequency domain display of an input signal, and allows measurement of power of individual frequency components. This is especially useful when a signal contains components at several frequencies, as in the case of a Gunn diode, or the output of a mixer. We have two HP8559A microwave spectrum analyzers.

Vector Network Analyzer:
The vector network analyzer is one of the most useful measurement systems in microwave engineering, as it can be used to measure both magnitude and phase of a signal. It is usually arranged to measure the S parameters of a one- or two-port network, but this data can easily be converted to SWR, return loss, insertion loss, and phase. We will primarily use the HP8753 vector

network analyzer in our work. This is a state-of-the-art analyzer, with an internal microprocessor for error correction and instrument control, and data display. See the Appendix for details on the calibration procedure for the HP8753.

Scalar Network Analyzer:
The scalar network analyzer, the HP8757, is similar to the vector analyzer, but measures only the magnitude of a reflection or transmission.

SWR Meter:
The standing wave ratio is measured using the HP415 SWR meter in conjunction with a slotted waveguide line and detector carriage. The RF input to the line is modulated at 1 kHz by the microwave sweeper source. The amplitude of the electric field in the slotted line is sampled by a small adjustable probe, which drives a detector diode. The output of the detector is a low-level 1 kHz signal, which is amplified, filtered, and displayed by the HP415 SWR meter. The scale on the SWR meter is calibrated to read SWR directly.

4. Resources

Here we list some of the many resources that can help you with your work in the microwave laboratory:

- Manuals for laboratory equipment - kept on the shelves in the Microwave Instructional Laboratory

- Serenade Manuals - a copy is available in the Microwave Instructional Laboratory

- Your textbook - describes *S*-parameters, operation of network and spectrum analyzers, microwave couplers and resonators, and more

- The library - many good references on microwave measurements and microwave theory

- Lab Teaching Assistant - for help with procedures, faulty equipment, etc

II. The Experiments
1. The Slotted Line

Introduction:
In this experiment we will use a waveguide slotted line to study the basic behavior of standing waves, and to measure SWR, guide wavelength, and complex impedance. Slotted lines can be made with any type of transmission line (waveguide, coax, microstrip, etc.), but in all cases the electric field magnitude is measured along the line with a small probe antenna and diode detector. The diode operates in the square-law region, so its output voltage is proportional to power on the line. This signal is measured with the HP415 SWR meter. To obtain good sensitivity, the RF signal is modulated with a 1 kHz square wave; the SWR meter contains a narrowband amplifier tuned to this frequency. The HP415 has scales calibrated in SWR, and relative power in dB. This experiment also introduces the student to common waveguide components such as waveguide-to-coax adapters, isolators, wavemeters, slide-screw tuners, detectors, and attenuators.

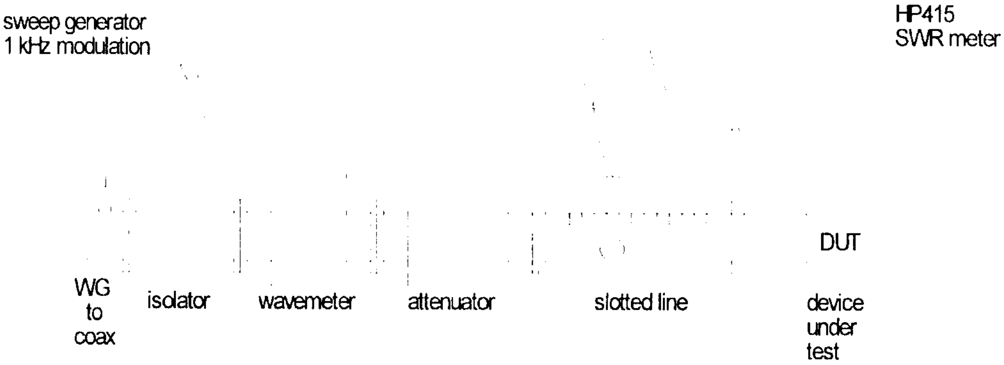
While the slotted line is cumbersome to use and gives less accurate results when compared with the automated vector network analyzer, the slotted line is still the best way to learn about standing waves and impedance mismatches. Before doing the experiment, read pages 69-72 of the textbook for a general description of the slotted line. Make sure that you understand the difference between "guide wavelength" and "wavelength". There is a discussion on pages 101, 109, and 113 on this topic. There is a manual in the lab describing the operation of the SWR meter; it is often non-intuitive. The detector diode must operate in the square law region for good behavior and accurate results. If the power level is too high, the small signal condition will not apply and the output will be saturated, while for very low power, the signal will be lost in the noise floor. Attenuation and impedance are discussed on pages 109-115, and there is also a very useful example there to help with your calculations later.

Equipment Needed:

HP8620 or HP8530 sweep oscillator and X-band plug-in
coax-to-waveguide adapter
waveguide isolator
cavity wavemeter
precision attenuator
slotted line and detector
HP415 SWR meter
waveguide matched load
frequency counter (optional)
waveguide section (1m long)
fixed waveguide attenuator (3 to 10 dB)
slide-screw tuner
blank waveguide flange
waveguide iris

Procedure:

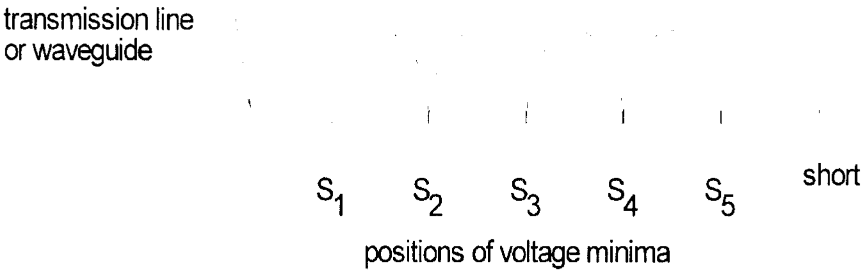
1. Setup:
Set up the equipment as shown below. We are using X-band waveguide, with a=0.9", and a recommended operating range of 8.20 - 12.40 GHz for dominant mode operation.



2. Measurement of Guide Wavelength:
Set the source to a CW frequency in the above range, and measure the frequency with the frequency counter or wavemeter. Do not rely on the scale reading on the sweep generator, as this may not be accurate.

The wavemeter is a tunable resonant cavity, and is used by tuning it until a dip is registered on the SWR meter; the frequency is then read from the scale of the wavemeter. Be sure to detune the wavemeter after frequency measurement to avoid amplitude fluctuations that may occur when the wavemeter is set to the operating frequency.

Place the blank flange on the load end of the slotted line; use two or more screws to get good contact. Set the attenuator near zero dB. Adjust the SWR sensitivity for a reading near midscale, then adjust the carriage position to locate several minima, and record these positions from the scale on the slotted line. Note that voltage minima are more sharply defined than voltage maxima, so the minima positions lead to more accurate results. See the sketch below.



Since the voltage minima are known to occur at spacings of $\lambda_g/2$, the guide wavelength can be determined. Do this for several frequencies.

3. Measurement of SWR:

Measure the SWR of the following components at two frequencies, at least 2 GHz apart:

a) a fixed attenuator with a short at one end
b) a matched load
c) an open-ended waveguide
d) a blank flange (short circuit)

After measuring the operating frequency, connect one of the above loads to the end of the slotted line. Adjust the probe carriage for a maximum reading on the SWR meter, then adjust the gain and sensitivity of the meter to obtain exactly a full-scale reading. Now move the probe carriage to a voltage minimum, and read the SWR directly from the scale. If the SWR is greater than about 1.2, increase the gain of the meter by 10 dB, and read the SWR on the SWR=1 to 3 scale.

To obtain accurate results with the slotted line, it is critical that the signal level be low enough so the diode is operating in the square-law region. This can easily be checked by decreasing the power level with the attenuator and verifying that the power reading (in dB) indicated on the SWR meter drops by the same amount. If it does not, reduce the received power level by reducing the penetration depth of the probe. Alternatively, the power level can be reduced at the sweeper, but it is usually best to work with a minimum probe depth, and maximum source power to maintain a good signal to noise ratio.

If the probe is extended too far into the waveguide the field lines can be distorted, causing errors. This can be checked by re-measuring the SWR with a smaller probe depth; if the same SWR is obtained, the probe depth is ok. Otherwise, the process should be repeated with progressively shallower probe depths, until a suitable depth is found. This is generally a more serious issue when low SWRs are being measured.

If the SWR is greater than about 3 to 5, accuracy can be improved by measuring the SWR with the precision attenuator. First, move the probe carriage to a voltage minimum, and record the attenuator setting and meter reading. Then move the probe to a maximum, and increase the attenuator to obtain the same meter reading. The difference in attenuator settings is the SWR in dB.

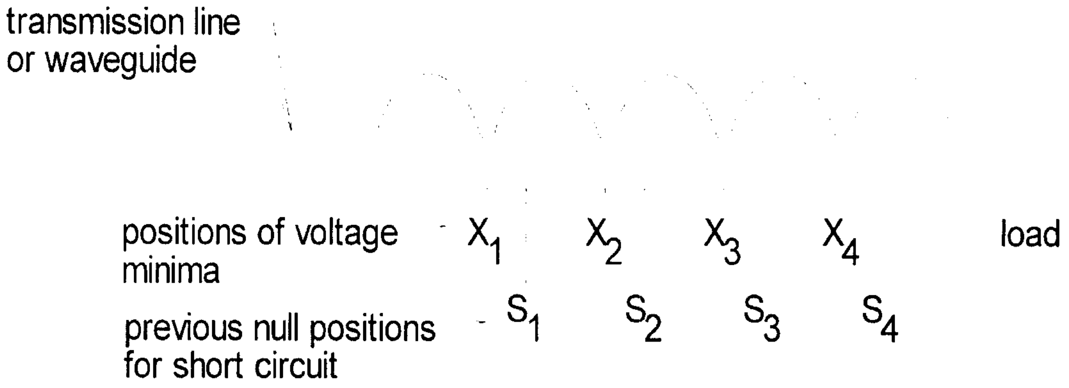
4. Measurement of Attenuation:

The above technique can also be used to measure attenuation. Attach the (two-port) device to be tested before the slotted line, with a matched load after the slotted line. Adjust the probe carriage for a maximum reading, and record this value and the attenuator setting. Now remove the device under test. Adjust the probe carriage for a maximum, and increase the attenuator setting to obtain the previous reading on the SWR
meter. The difference in attenuator settings is the attenuation of the component. This is called the comparison method of attenuation measurement.

Use this technique to measure the attenuation of the fixed attenuator, and a 1m length of waveguide, at several frequencies.

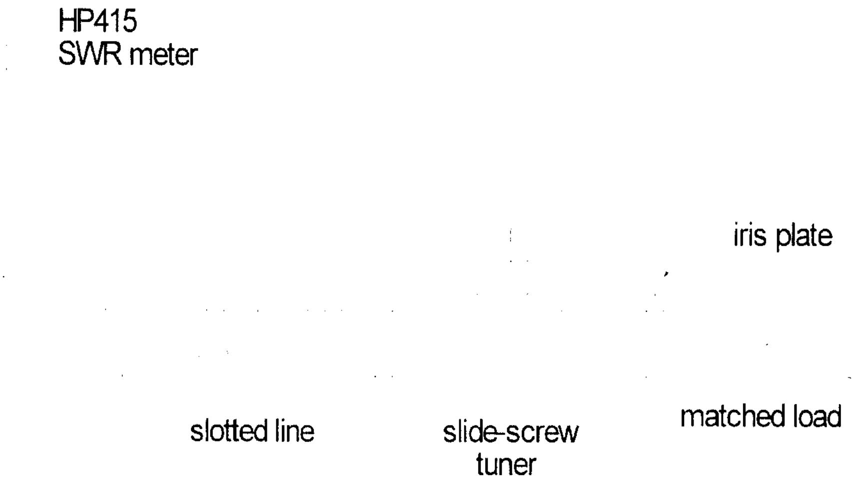
5. Measurement of Impedance:
The previous measurements involved only the magnitude of reflected or transmitted waves, but we can also measure phase with the slotted line.

First terminate the slotted line with the blank flange, and accurately measure the positions of the voltage minima. Next, place the component to be measured on the slotted line, and measure the SWR and the new positions of the minima. The SWR determines the magnitude of the reflection coefficient, while the shift in the position of the minima can be used to find the phase. Then the normalized (to the waveguide characteristic impedance) load impedance can be found. This can be done with a Smith chart, or by direct calculation.



Measure the impedance of the iris (the flat plate with a round hole), backed with a matched load at several frequencies using the above procedure.

6. Tuning a Mismatched Load (optional):
Use the iris backed with a matched load as a mismatched impedance, and place the slidescrew tuner between the slotted line and this impedance, as shown in the figure below. Measure the SWR. Now adjust either the depth or position of the slide-screw tuner, and re-measure the SWR. Keep iterating until you obtain an SWR<1.1, indicating a reasonably good impedance match. Leave the tuner at this setting, and measure the SWR versus frequency. (Remember how tedious this procedure is when you do Experiment 4 on the network analyzer!)



Write-up:

Measurement of Guide Wavelength:
Compare the frequencies read on the sweep generator, the wavemeter, and the frequency counter (if available). Determine the guide wavelength from the measured minima positions; average your results for different adjacent pairs of minima. Using the measured frequency, calculate the guide wavelength and compare with the above results. Discuss reasons for discrepancies.

Measurement of SWR:
Tabulate the measured SWR for each component, versus frequency. Indicate which measurement technique was used. Discuss the results of checking for the square-law region of the detector, and the effect of probe depth.

Measurement of Attenuation:
Compare the measured attenuation for the fixed attenuator with its specified value. Compare the measured attenuation for the 1 m long waveguide section with the calculated value. Discuss reasons for differences.

Measurement of Impedance:
Calculate the normalized impedance of the iris-load from the slotted line data, and plot on a Smith chart versus frequency.

Tuning a Mismatched Load:
Plot the measured SWR versus your tuning iterations. Plot the resulting SWR versus frequency.

2. The Vector Network Analyzer

Introduction:

In this experiment we will learn to use the HP8753 Vector Network Analyzer to measure the magnitude and phase of reflection and transmission coefficients (S parameters) of one and two-port networks. Such measurements are of critical importance in the design and testing of microwave circuits.

A discussion of the scattering matrix is presented in Section 4.3 of the text. Make sure you understand this material, because the experiment is based on measurements of S parameters. In Part 4 you will measure the reflection and transmission coefficients of a circulator. The text has a general discussion about circulators on pp. 308-311. Reflection and transmission coefficients are discussed on pp. 58-63. For Part 5 of this experiment you need to review Smith charts and understand their use. See text pp. 64-69, and the supplemental notes on the Smith chart handed out in class.

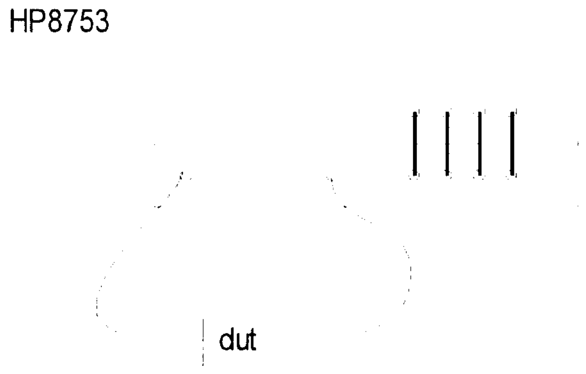
Equipment Needed:

HP8753 Network Analyzer
HP85047A test set
plotter with HP-IB input
coaxial low-pass filter, $f_c = 2.2$ GHz
coaxial circulator
coaxial matched loads and shorts
coaxial attenuator
coaxial connector with "50 Ω" resistor
"black boxes" with unknown networks

Procedure:

1. Setup:

Connect the device under test to the network analyzer. A one-port network may be connected to either port.



2. Calibration:
Set the frequency sweep to cover 1.5 to 5.5 GHz. Perform a full two-port calibration as described in the discussion in the Appendix. You may omit the isolation test. Measure the return loss of a matched load, and verify that the return loss is at least 20 dB over the band. Connect a 10 dB or 20 dB coaxial attenuator between the two ports and verify that $|S_{12}|$ drops by the proper amount.

3. Measure the low-pass coaxial filter:
Connect the filter between the measurement ports, measure $|S_{11}|$ and $|S_{12}|$ from 1.5 to 5.5 GHz, and plot your results. Also take a look at $|S_{21}|$ and $|S_{22}|$. Redo the $|S_{11}|$ measurement with a matched load connected to the output filter port, and compare with the first result. Be sure to use scales ranges (dB/div) to get meaningful results. Note that the HP8753 has the capability of displaying Γ, SWR, Z, and Y in various formats. Try some of these options.

4. Measure the coaxial circulator:
Using the same procedure as above, measure $|S_{21}|$, $|S_{32}|$, and $|S_{13}|$, and then the reverse paths $|S_{12}|$, $|S_{23}|$, and $|S_{31}|$, for the circulator. Use appropriate scales, and always terminate the unused of the three ports with a matched load. Check $|S_{11}|$, $|S_{22}|$, and $|S_{33}|$. Remove the matched load and re-measure $|S_{11}|$, $|S_{12}|$, and $|S_{21}|$. Use a scale of 0.5 or 1 dB per division to get accurate results for the insertion loss measurements.

5. Measure the input impedance of the "50 Ω" resistor:
Connect the coaxial connector with the 50 Ω carbon resistor to the input port, and measure the impedance from 1.5 to 5.5 GHz. Plot the result on a Smith chart format. Move your hand near the resistor and see if there is any effect.

6. Determination of "Black Box" networks:
Several "black box" microwave networks having two or three ports are available in our lab. Measure the S parameters of one of these networks at a frequency range within the range that is indicated, and try to determine the type of circuit or component that is inside the box. Is the network reciprocal? Lossless? Matched? Are any of the ports isolated? Do this for one or two boxes, as time permits.

7. Optional work:
There are lots of other possible measurements you can make, such as:

- Measure the input impedance of the filter using the Smith chart display
- Measure the attenuation vs. frequency of a piece of coaxial cable
- Measure the S-parameters of other components in the lab
- Measure the group delay of the filter

Write-up:

Return loss of matched load:

What were the best and worst return losses measured over the sweep range? List the frequencies where these occurred, and the corresponding SWRs. Complete the following table to convert between return loss, reflection coefficient magnitude, and SWR:

Return Loss	$\|\Gamma\|$	SWR
0 dB		
1 dB		
2 dB		
3 dB		
5 dB		
10 dB		
20 dB		

Low-pass filter:

What is the measured 3 dB cutoff frequency for the filter? What is the roll-off of the attenuation of this filter in the stop-band (dB/octave)? What is the frequency range for which $|S_{12}|<20$ dB? What is the frequency range for which the input SWR is less than 2.0? Is there any difference in $|S_{11}|$ when the output is terminated with a matched load versus having port 2 connected to the network analyzer? What causes this difference?

Circulator:

Over what frequency range is the insertion loss less than 0.5 dB? Over what frequency range is the return loss greater than 20 dB? What is the minimum isolation over this latter range? What is the effect on the above quantities when the matched load is removed? Why does this happen?

"50 Ω" resistor:

The size of the short-circuit calibration "ball", or locus, gives an estimate of the uncertainty in the reflection coefficient measurement. Estimate this uncertainty for your measurements of the 50 Ω resistor. Explain why this impedance does not look like an ideal 50 Ω load.

Black boxes:

Discuss your measurements, and how you arrived at your idea of what is inside the box. Draw a circuit diagram of the network.

Optional work:

Present and discuss your results for any additional measurements you may have made. If you measured the attenuation of a coaxial cable, you may want to compare it to a calculated value, or data from the manufacturer. The Appendix of our text also has a table of data for commonly used cables.

3. The Gunn Diode

Introduction:

Here we will study the characteristics of a Gunn diode oscillator, and make power and frequency measurements. We will measure the *V-I* characteristics of the diode, and its output power using a power meter and a spectrum analyzer. We will use standard X-band waveguide components, a microwave power meter, and a microwave spectrum analyzer (for frequency and power measurement). Then we will use the Gunn diode as an RF source to study the basic operation of a microwave mixer.

The Gunn diode is a very useful source because it is simple, rugged, and compact. With a DC bias supply, the Gunn diode can generate 100 mW of power. From the DC V-I characteristics, we will see that the Gunn diode has a negative differential resistance region. The Gunn diode is described in the text on pp. 521, 609-611. It is a very common microwave source and is widely used. There is a discussion about mixers on pp. 510, 615-630 of the text. Read this material before doing the experiment so that you will understand the basic operation of a mixer.

Note: Be very careful with the polarity of the bias voltage applied to the Gunn diode, as reversing the bias voltage will destroy it. Positive voltage should be connected to the pin terminal of the diode, and negative to the case.

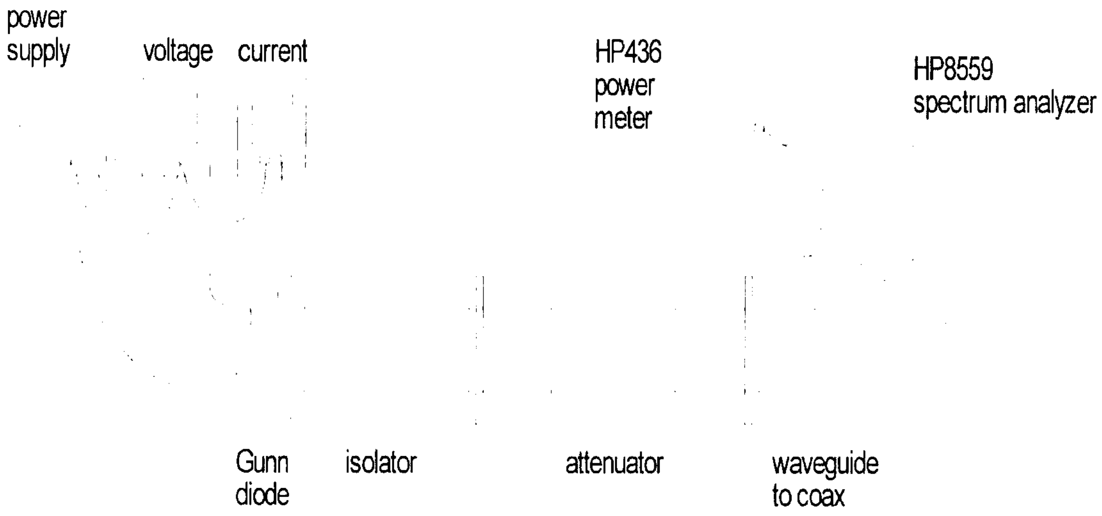
Equipment Needed:

Gunn diode with X-band waveguide flange
waveguide isolator
variable attenuator
waveguide to coax adapter
HP436 power meter
HP8559 spectrum analyzer
DC power supply
DC voltmeter
DC ammeter
microwave mixer
1-10 MHz oscillator

Procedure:

1. Setup:

Arrange the equipment as shown below. The power supply should be set to provide a voltage limit of 8 volts, and/or a current limit of 300 mA. Be careful to use the correct polarity when connecting the power supply to the diode: positive to pin terminal, negative to case. The output of the waveguide-to-coax adapter is connected to the power meter, or spectrum analyzer, as needed.



2. Measure DC V-I characteristics:
Vary the DC voltage to the diode from 0-8 V in 0.5 V steps, and measure the diode current. Use a finer voltage step near the "knee" in the V -I curve.

3. Measure power output:
Use the HP436 power meter to measure the RF power delivered by the Gunn diode (set the attenuator to zero), versus voltage, over its operating range. At a relatively strong operating point, check the calibration of the waveguide attenuator using the power meter, over the range of 0 to 20 dB.

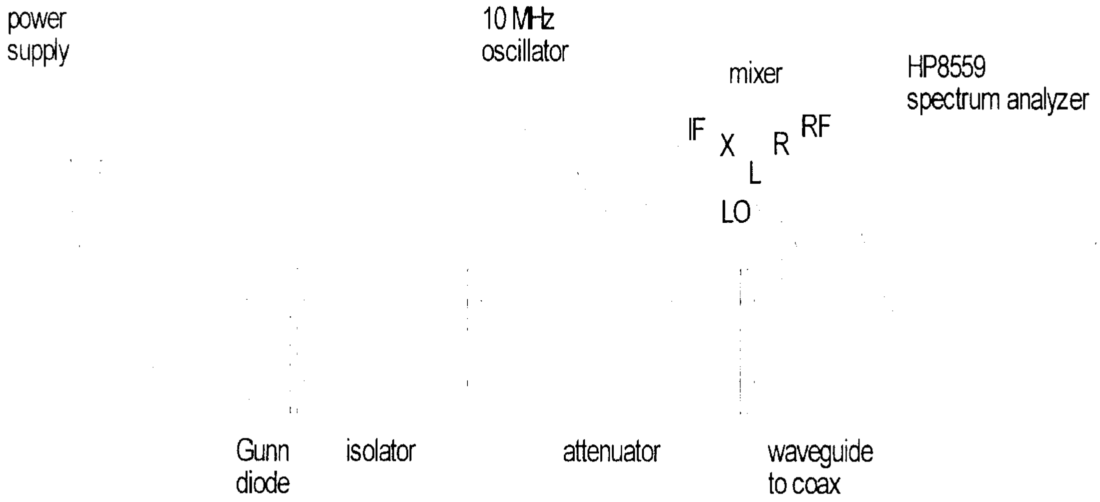
4. Using the spectrum analyzer:
A spectrum analyzer is a sensitive receiver that rapidly tunes its RF operating frequency over a relatively narrow bandwidth (SPAN) to give a display of power vs. frequency. Connect the spectrum analyzer to the waveguide to coax adapter, in place of the power meter. Set the *center frequency* of the spectrum analyzer to 9.5 GHz, and the *frequency span* to about 100 MHz/div. If necessary, adjust the *resolution BW* for a clean, stable display. Measure the power level and frequency versus bias voltage over the operating range of the diode.

5. Tuning the diode:
The small tuning screw on the flange of the Gunn diode can be used to adjust the resonant frequency of the Gunn diode, from about 9 to 10 GHz. For several positions of this screw, adjust the bias voltage, power, and operating frequency, f. (Use care when tuning the diode.) For each case, use the spectrum analyzer to check for a second harmonic at $2f$, and record this power level. Also, check the frequency range near f and $2f$ for other spurious signals. The spectrum analyzer may show spurious signals from its local oscillator; check for this by using the *signal identifier* button.

6. Basic mixer operation:
We will study mixers in more detail later in class, but for now all we need to know is that a mixer forms the sum and difference frequencies of two sinusoidal input signals. Thus, a mixer can be used

for the operations of modulation and demodulation, or frequency upconversion and down-conversion.

In the setup below, the local oscillator (LO) input is supplied by the Gunn diode (operating at about f_{LO} = 10 GHz, with a power level between -5 dBm and 10 dBm). The modulating signal, applied at the X input of the mixer) is supplied by an oscillator operating at about f_{IF} = 10 MHz. The RF output of the mixer will consist of the local oscillator signal and two sidebands at the frequencies $f_{LO} \pm f_{IF}$. This is called a double sideband modulated signal.



Connect the equipment as shown above, but first set the Gunn diode output power between -5 dBm and 10 dBm, using the spectrum analyzer to measure the output power. (The Gunn diode may have to be tuned to a new frequency to obtain enough power.) Then connect the waveguide-to-coax adapter to the mixer, and view the output of the mixer on the spectrum analyzer. Adjust the IF oscillator power level as high as possible, keeping only two sidebands visible. Note the effect of a change in IF frequency. Set the IF oscillator to square wave output and observe the spectrum.

7. Temperature stability (optional):
Set the operating point of the Gunn diode for a strong signal, and monitor the signal with the spectrum analyzer set to a small frequency scan, such as 500 kHz/div. Now heat the diode by holding a soldering iron or heat gun near (but not touching!) the Gunn diode, and observe the shift in frequency.

Write-up:
V-I characteristics: Plot the measured V -I curve. Mark the region of the graph where the diode generates RF output power.

Power output:
Plot the output power measured with the HP436, versus bias voltage. On this same graph, plot the power output as measured with the spectrum analyzer. Use a dBm scale. Explain why there is a difference between these two measurements.

Attenuator calibration:
Plot the measured attenuation of the attenuator versus the actual attenuator setting on a dB - dB scale.

Frequency measurement:
Plot the frequency of the diode output signal versus bias voltage.

Frequency tuning:
Plot the frequency and power level of the diode output versus screw position (using the number of half-turns, for example). Also plot the power level of the second harmonic on this same graph.

Mixer operation:
Discuss the operation of the mixer, and the observed mixer output spectrums. Explain the spectrum that results from square wave modulation.

Temperature stability (optional):
Discuss the results of this test, and suggest a way to avoid such frequency drift versus temperature.

4. Impedance Matching and Tuning

Introduction:

In this experiment we will study two types of matching or tuning techniques: the stub tuner and the quarter-wave transformer. We will first use the network analyzer and a stub tuner to tune a mismatched load at a single frequency, and then over a broad frequency range. Next we will design and fabricate a quarter-wave transformer to match a 500 line to a 250 load, and test this circuit. You should complete Experiment #2, on the Network Analyzer, before doing this experiment.

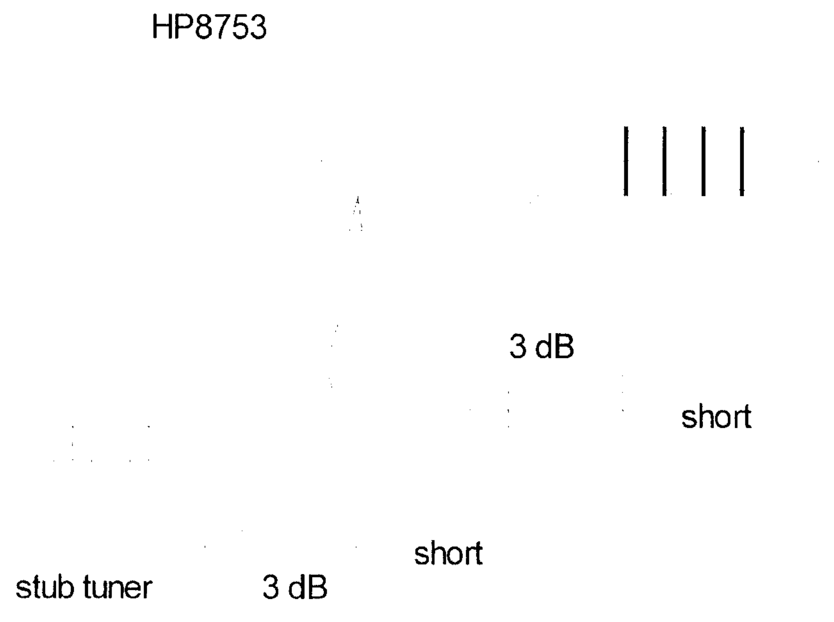
Equipment Needed:

HP8753 Vector Network Analyzer
HP85047A 6 GHz S-parameter test set
plotter with HP-IB input
3 dB coaxial attenuator
coaxial short
microstrip substrate with SMA connector
25 Ω chip resistor (or two 50 Ω resistors)

Procedure:

1. Setup:

Arrange the equipment as shown below. Set the sweep oscillator to sweep from 2-4 GHz, and calibrate the HP8753 Network Analyzer. Since we will only be making reflection measurements in this experiment, it is only necessary to do a one-port calibration. Store the Cal Set in memory.

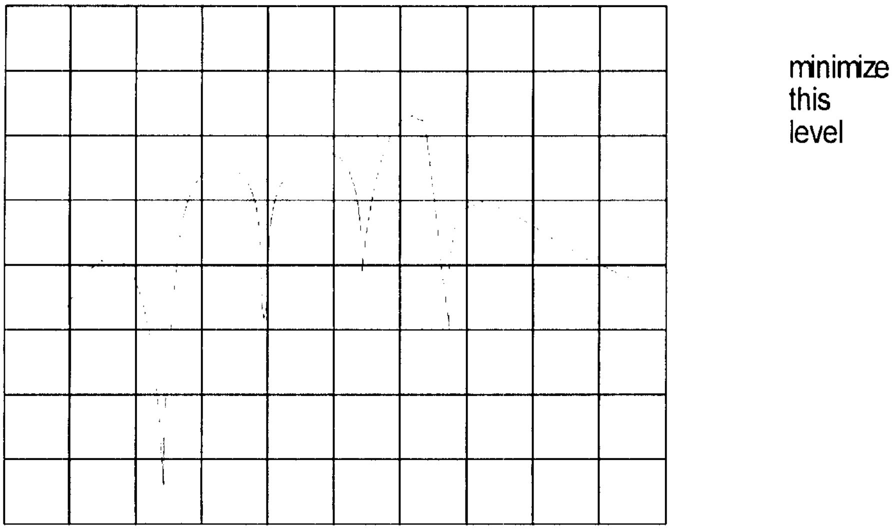


2. Single frequency tuning:

Our mismatched load will consist of a 3 dB coaxial attenuator backed with a short circuit. Connect this load to the analyzer (without the stub tuner), and measure the return loss. Now insert the stub tuner, as shown above, and tune for the best possible return loss at 3 GHz. Record the response, and measure the positions of the stubs (and the stub separation). Repeat this tuning procedure at 2.5 GHz and at 3.5 GHz. It will be helpful to learn how to use the frequency markers on the network analyzer for this work.

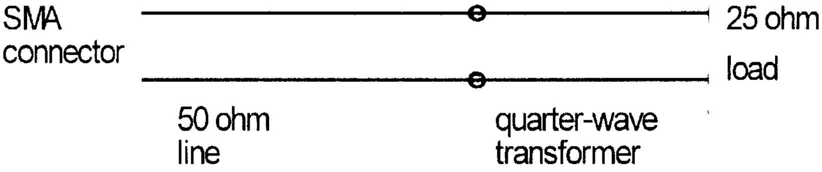
3. Broadband tuning:

Reduce the sweep range to 3-4 GHz, and calibrate again, and store the calibration. Measure and record the return loss of the mismatched load. Now insert the stub tuner, and adjust to achieve the lowest possible maximum return loss over the frequency band. Record this result. Repeat for a sweep range of 2-4 GHz. You don't need to calibrate again, since you should be able to recall the previously saved Cal Set for the 2-4 GHz range.



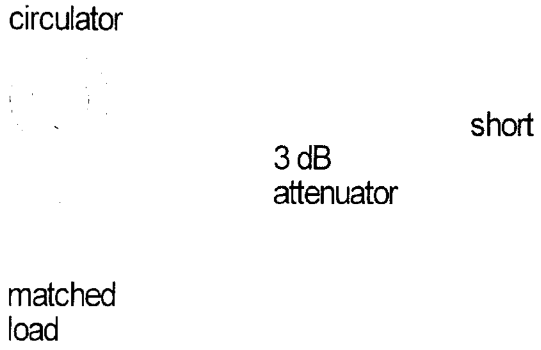
4. Quarter-wave matching transformer:

Design a quarter-wave matching transformer to match a 25 Ω load to a 50 Ω microstrip line at 3 GHz. Using the thickness and permittivity for the substrate (obtain from Teaching Assistant), calculate the necessary dimensions for a microstrip implementation of the circuit shown below:



Fabricate the circuit using copper tape and an Xacto knife. This is not a very accurate process, but if you are careful, and as precise as possible, reasonably good results can be obtained. Measure the return loss of your circuit from 2-4 GHz.

5. Optional work:
a) Use a circulator as shown below to "match" the load over a frequency range of 2-4 GHz. Measure the return loss.



b) Use the Fourier Transform menu and look at the time domain reflection response of the quarter-wave transformer. Try to identify the discontinuities and their locations. Repeat with the stub tuner.

Write-up:

Single-frequency tuning:
Calculate the return loss of the 3 dB attenuator and short circuit combination. Does this mismatch vary with frequency? Compare with your measured result. Tabulate the return losses which were achieved for the single-frequency tuning step. What additional information do you need to be able to calculate the tuning stub lengths for matching at a given frequency?

Broadband tuning:
List the worst return losses obtained for single-frequency tuning, the 3-4 GHz tuning, and the 2-4 GHz tuning. Discuss the implications of this trend.

Quarter-wave transformer:
Calculate the return loss of the quarter-wave transformer and 25 Ω load from 2-4 GHz, and plot. Compare with your measured results, and discuss the differences. How could your matching circuit be improved?

Optional work:
Using your measured load impedance, distance between stubs, stub lengths, and distance between the first stub and load, calculate the input impedance seen by the network analyzer. Compare with the measured return loss. For the circulator matching network, compare the worst return loss with the corresponding return loss from the broadband tuning step. Which is better? Discuss the advantages and disadvantages of the circulator tuning technique.

5. Cavity Resonators

Introduction:

Here we will construct a cavity resonator in waveguide and study its characteristics using the network analyzer and a frequency counter. Resonant circuits can be made with discrete elements (inductors and capacitors), or from distributed elements (transmission lines and cavities). The Q of a resonator depends on loss; since waveguide has very low loss, a resonator made from waveguide can have a very high Q.

Equipment Needed:

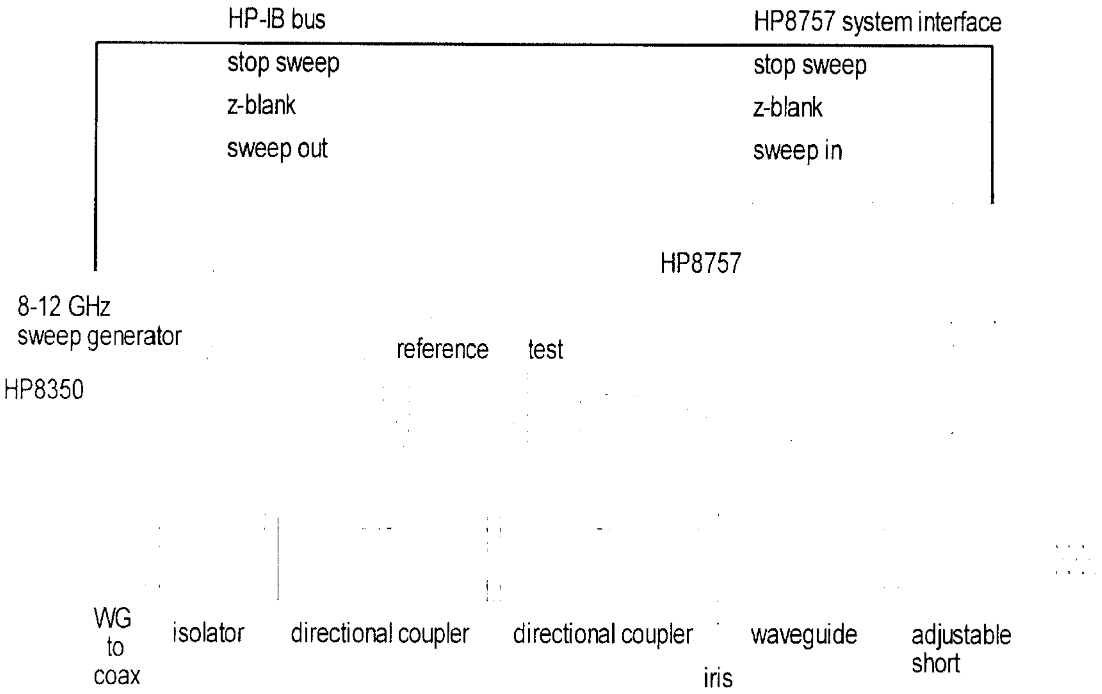
HP8350 X-band sweep generator
HP8757 Scalar Network Analyzer
two waveguide directional couplers
short section of waveguide
waveguide iris plate
waveguide adjustable short
blank flange
waveguide isolator
three waveguide-to-coax adapters
slide-screw tuner

Procedure:

1. Setup:

Arrange the equipment as shown below. Set the sweep range from 8-12 GHz. The scalar network analyzer is similar in function to the vector network analyzer, but only measures magnitudes of reflected and transmitted power, versus frequency. Instructions on the operation and calibration of the HP8757 scalar analyzer are outlined in the Appendix. For further details, consult the HP8757 operator's manual. To calibrate the analyzer at the plane of the iris, follow the procedure dictated by the Cal menus, and use a shorting plate and the open waveguide for the short and open, respectively. Like the calibration of the vector network analyzer, calibration of the scalar analyzer must be done for each frequency range. It is faster to store the "short" response in Memory and normalize the display by using *Display-Mem.*

The interconnection of cables between the sweep generator and the scalar network analyzer allows the display to sweep at the same rate as the sweep generator, and for frequency markers to be used on the display.



2. Measure resonant frequencies:

Build the resonant cavity shown above with the iris plate, the short length of waveguide, and a blank flange in place of the adjustable short. Use the frequency markers to accurately measure the resonant frequency of each resonance between 8 and 12 GHz. Define a resonance as any dip in the response with a return loss greater than 10 dB. Measure the physical length of the cavity.

3. Measure Q:

For each of the above resonances, use the frequency markers to measure Δf between the half-power points (return loss = 3 dB). on the response. Use a reduced sweep range for accuracy in this measurement. From this data the loaded Q of the resonator can be determined from $Q_L = f_0/\Delta f$.

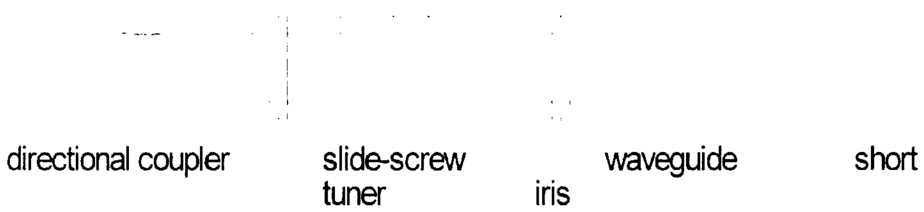
To see the effect of an increase in loss, place a small piece of absorber material inside the cavity, near the shorting plate end, and re-measure the Q of a few of the resonances. Remove the absorber when finished.

4. Tuning the cavity:

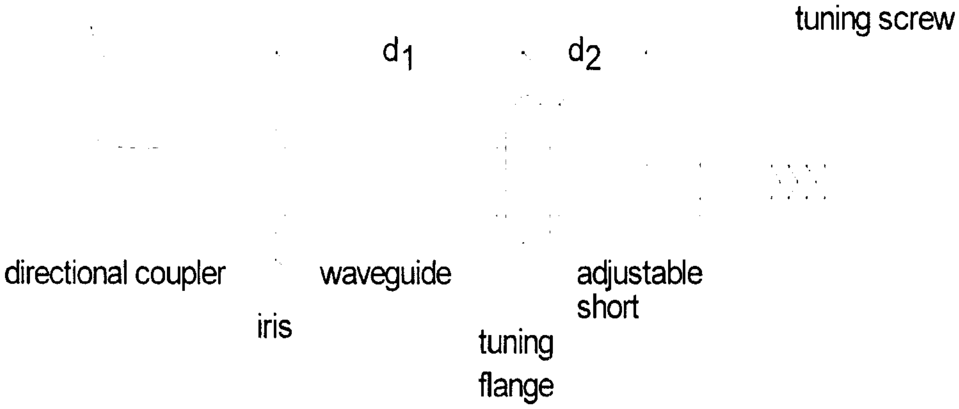
Replace the blank flange with the adjustable short. Initially, adjust the short to obtain a strong resonance at 10 GHz with the adjustable short near the middle of its mechanical range. Now adjust the short to tune the resonance from 9.5 to 10.5 GHz, in 100 MHz steps. Record the resonant frequency versus short position as given by the micrometer reading.

5. Match the cavity:

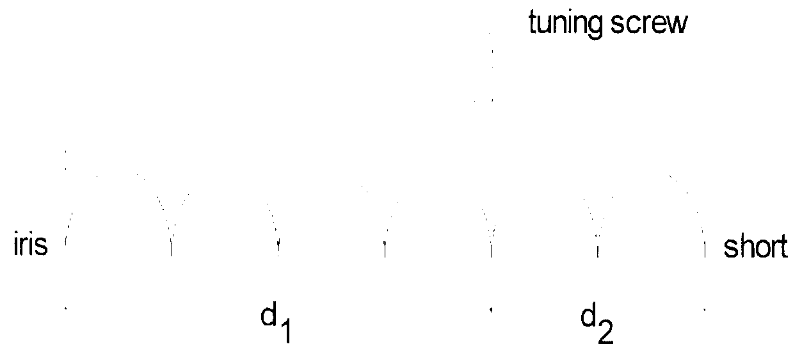
Replace the adjustable short with the blank flange, and insert a slide-screw tuner ahead of the iris plate, as shown below. Retract the tuning screw, and pick a resonance near 10 GHz. Record the return loss. Now use the tuner to maximize the return loss at the resonant frequency. Note the new return loss, and any change in resonant frequency or Q.



6. Optional:
Place the thick flange with a tuning screw between the waveguide and the adjustable short, as shown below.



Measure the distance between the iris and the tuning screw, d_1. Choose a frequency so that $d_1 = n\lambda_g/2$, where n is an integer and λ_g is the guide wavelength. Now set the movable short so that $d_2 = m\lambda_g/2$, where m is a different integer. The total cavity length is now $d = d_1 + d_2 = (m + n)\lambda_g/2$, and a tangential component of the electric field should exist at the tuning screw location, as shown below for $n = 4$ and $m = 2$:



Measure the resonant frequency versus depth of the tuning screw. Next, devise a similar procedure to place an H-field null at the tuning screw location. An H-field null corresponds to an E- field maximum at the tuning screw location. Measure the resonant frequency versus tuning screw depth for this case.

Write-up:

Setup:

Give a qualitative explanation of what goes on in this experiment. Explain why you see more than one resonance, and explain the function of the iris.

Resonant frequencies:

Using the length of the cavity, calculate the resonant frequencies and compare with the measured values. Identify the modes according to the TE_{10n} notation. Discuss reasons for differences between measured and calculated results.

Q:

Tabulate the measured Q and measured resonant frequency for each of the resonant modes. Is there a trend which is evident from the data? For one or two cases, calculate the unloaded Q of the cavity, and compare with the measured loaded Q. Are the results reasonable? Discuss the effect of placing absorber in the cavity.

Tuning the cavity:

Plot the measured resonant frequency versus short position. Can you predict this variation theoretically?

Matching the cavity:

Discuss the change in resonant frequency, loaded Q, and return loss when the cavity is matched with the slide screw tuner.

Optional work:

Plot the resonant frequency versus tuning screw depth for the two cases of an E-field and an H-field null at the tuning screw position. Which case gives a greater tuning range? Why?

6. Directional Couplers

Introduction:

In this experiment we will characterize a coaxial (stripline) directional coupler in terms of its insertion loss, coupling, and directivity. Along with the return loss, these quantities constitute all the non-zero elements of the S-matrix of the coupler. We will also learn some special measurement techniques for measuring the low-level signals associated with coupler directivity. The directivity of a directional coupler is very important in many applications (such as reflection measurements), and is difficult to measure directly because it involves a very low level signal.

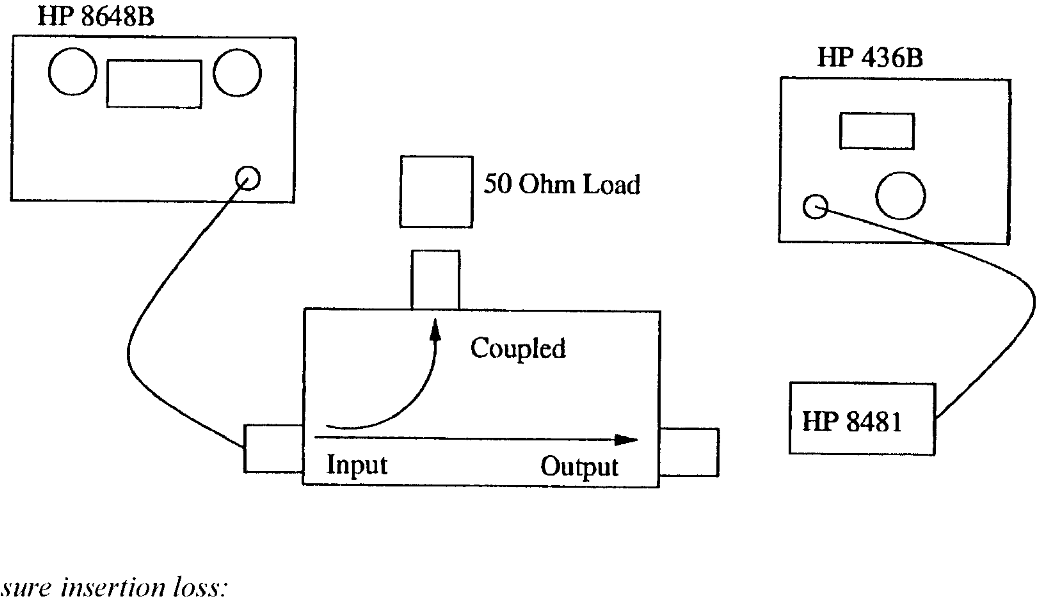
Equipment Needed:

HP8648B Synthesized Signal Generator
HP436B power meter with 8481 and 8484 sensors
Coaxial 10 dB directional coupler
Coaxial matched load
Coaxial sliding matched load
Coaxial double stub tuner
HP 8753C Network Analyzer

Procedure:

1. Setup:

Arrange the equipment as shown below, with the coupler in the forward direction. Set the source to a CW frequency between 2.5 and 3.0 GHz, and a power level of +13 dBm.



2. Measure insertion loss:

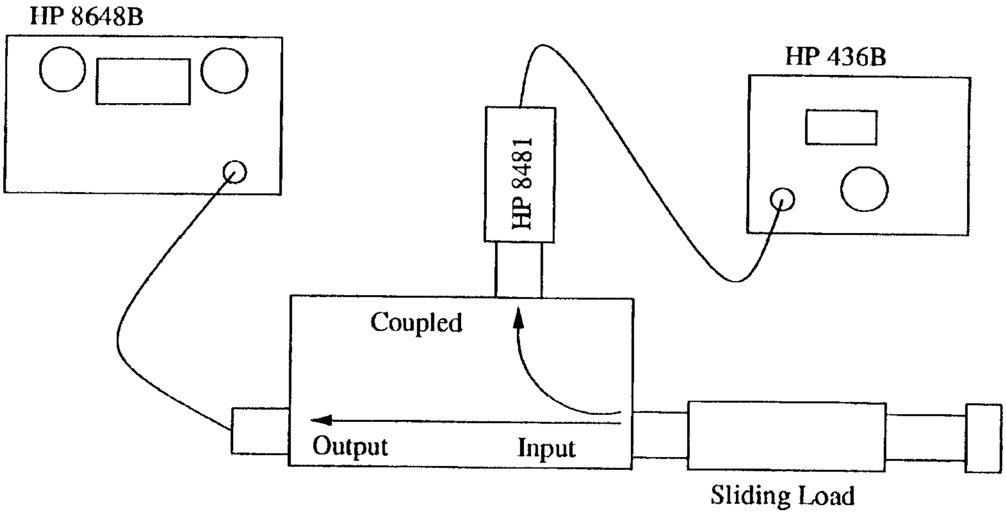
Remove the directional coupler and measure the incident power, P_i, at the end of the input cable. Reinstall the coupler and place a coaxial matched load on the coupled port. Measure the through power, P_t. The insertion loss of the coupler can be determined as,

$$L = \frac{P_t}{P_i} \qquad (L < 1)$$

3. Measure coupling:
Place the matched load at the through port, and measure the power at the coupled port, P_c. The coupling factor can be determined as,

$$C = \frac{P_i}{P_c} \qquad (C > 1)$$

4. Measure directivity (method #1):
Re-arrange the equipment with the coupler in the reverse direction, as shown below. Don't change the frequency or power settings on the generator, as you will need the previously measured values of incident power, coupled power, and through power.



Measure the output power, P_o, at the coupled port as the sliding load is moved. Record the minimum and maximum values of the output power.

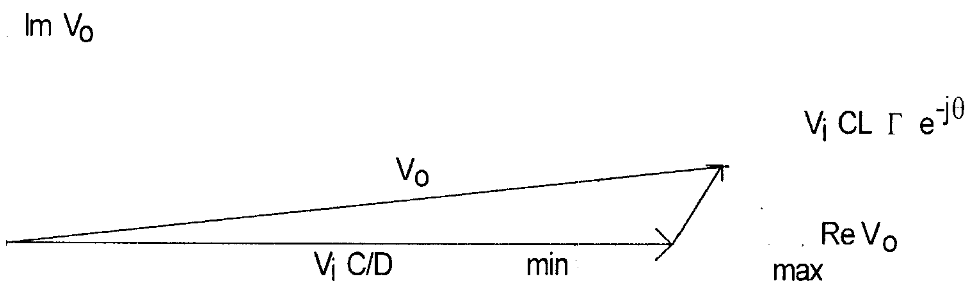
Part of the difficulty in measuring directivity is that even a small reflection from the through port will overshadow the small directivity signal. In the above setup the reflection, Γ, from the small mismatch of the sliding load is added to the directivity signal at the output of the coupled port. The phase of the reflection from the load can be changed by sliding the load, and made to add in phase or out of phase with the directivity contribution. The voltage at the output port is thus given by,

$$V_o = V_i \left[\frac{C}{D} + C|\Gamma| L e^{-j\theta} \right],$$

where

- D is the coupler directivity ($D > 1$)
- C is the coupling factor ($C > 1$)
- Γ is the (unknown) reflection coefficient of the sliding load ($|\Gamma| < 1$)
- L is the through loss of the coupler ($L < 1$)
- θ is the electrical path length through the sliding load

As the sliding load is moved, θ changes, so the resultant phasor output voltage, V_o, traces a circle, as indicated in the figure below:



The maximum output power is then,

$$P_{\max} = \left[\frac{C}{D} + C|\Gamma|L\right]^2 P_i.$$

And the minimum output power is,

$$P_{\min} = \left[\frac{C}{D} - C|\Gamma|L\right]^2 P_i.$$

If we define the following quantities,

$$M = \frac{P_c}{P_{\max}} = \frac{C^2 P_i}{P_{\max}} = \left(\frac{D}{1+|\Gamma|LD}\right)^2,$$

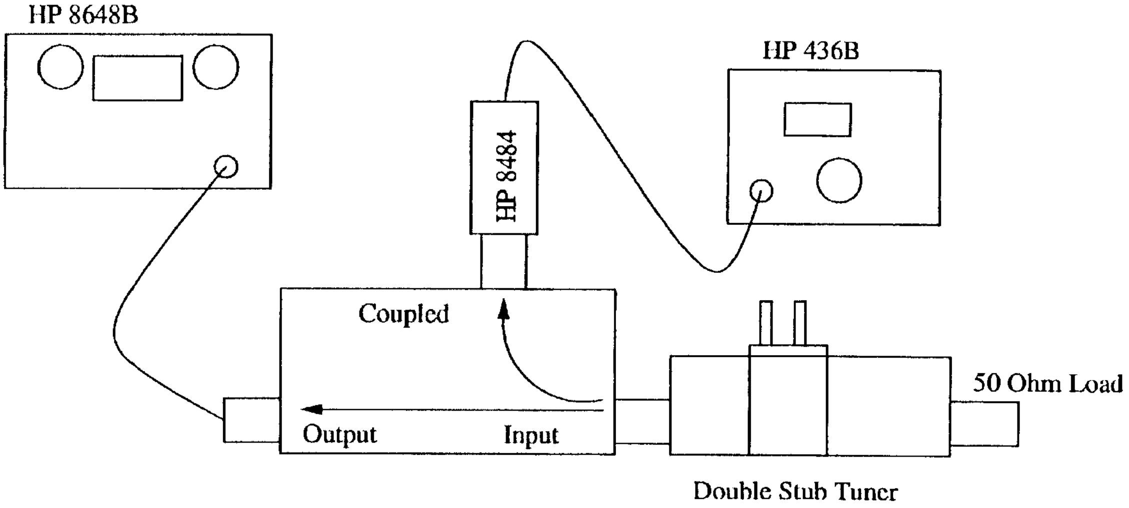
$$m = \frac{P_{\max}}{P_{\min}} = \left(\frac{1+|\Gamma|LD}{1-|\Gamma|LD}\right)^2,$$

then the directivity can be determined as

$$D = M\left(\frac{2m}{1+m}\right).$$

This method requires that $|\Gamma < 1/D$.

5. Measure directivity (method #2):
In the previous method the residual reflection from the load was accounted for by using a sliding load. In this method, the reflection from the load is adjusted to cancel the directivity signal. A separate measurement of this reflection then gives the directivity. Arrange the equipment as shown below.



When replacing the HP8481 sensor with the HP 8484 sensor, be sure to turn off the AC power to the power meter. When you connect the sensor for calibration, insert the 30 dB attenuator and adjust the level for -30 dBm.

As before, the output voltage at the coupled port is given by,

$$V_o = V_i\left[\frac{C}{D} + C|\Gamma|Le^{-j\theta}\right].$$

Now tune the double stub tuner to null the output power at the coupled port (this will require only a small reflection). Then $V_0 = 0$, so the directivity is given by,

$$D = \frac{1}{L|\Gamma|}.$$

We have already measured L and C; use the Network Analyzer to measure $|\Gamma|$. Repeat the above measurements at two other frequencies.

6. Stripline coupler design:
Use calipers to measure the width, length, and separation of the striplines in the opened coupler. Also measure the distance between the two ground planes. Determine the even and odd mode characteristic impedances (see text), and then the coupling factor:

$$C = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}.$$

Also determine the center frequency of the coupler, assuming a line length of λ/4. After calculating C, obtain the actual value from the Teaching Assistant.

Write-up:

Insertion loss:
Plot the measured insertion loss versus frequency, for the frequencies which were measured. Use a signal flow graph to account for the effect of a mismatched load on the insertion loss measurement, and apply your results to estimate the error in your measured insertion loss due to this effect. Discuss other sources of error.

Coupling:
Plot the measured coupling factor versus frequency, for the frequencies which were measured. Use a signal flow graph to account for the effect of mismatched coupled and through ports, and estimate the error in your measured coupling due to these effects.

Directivity:
Plot the measured directivity obtained with both measurement methods versus frequency. Discuss possible reasons for discrepancies, and the relative advantages and disadvantages of each method.

Stripline design:
Compare your calculated values with the actual values. Discuss the reasons for any discrepancies. Calculate the impedance of the stripline.

III. Appendices

Appendix 1: List of Major Equipment in the Microwave Instructional Lab.

Signal Generators:

HP 8350B sweeper main-frame	3
HP 83540A RF plug-in 2 - 8.4 GHz	1
HP 83592B RF plug-in 0.1 - 20 GHz	1
HP 83545A RF plug-in 8 - 12.4 GHz	2
HP 8648C 3.2-GHz synthesized sweeper	2

Network Analyzers:

HP 8753C Vector Network Analyzer	3
HP 8753B Vector Network Analyzer	1
HP 8510C Vector Network Analyzer	1
HP 8514A S- parameter test set	3
HP 8756A Scalar Network Analyzer	1
HP 8757C Scalar Network Analyzer	1
Wiltron 560 Scalar Network Analyzer	1

Frequency Counters:

HP 5350 Frequency Counter	2
HP 5351B Frequency Counter	1
HP 5342A Frequency Counter	1

Power Meters and Sensors:

HP 436A power meter	5
HP 8481A power sensor -30 to 20 dBm	7
HP 8481D power sensor -70 to -20 dBm	3

SWR Meters:

HP 415E SWR meter	6

Noise Measurement:

HP 8970S noise figure test set	1
HP 3048 phase noise test set	1

Power supplies:

HP E3610A power supply	2
HP E 3611A power supply	2
Lambda LL901 power supply	2

Multimeters:

Fluke 8840A	3
Keithley 177	1

SIVERS LAB
Quality in Microwaves

Test report

830316/OS

DIOD MODULATOR PM 7026X/01 with Diode PM 7745/01

1. Limiting ratings (25°C):

V_R	Reverse voltage	250 V	maximum
I_F	Forward current	500 mA	maximum
T_{stg}	Storage temperature	150°C	maximum

2. Characteristics:

Insertion loss	2 dB maximum	Bias: -1V/20mA
Isolation	10 dB minimum	Bias: 0V

3. Modulation depth (independent of reverse voltage):

8.0	8.5	9.6	11.0	GHz
9	15	15	6	dB

4. Insertion loss (bias -1V/20 mA):

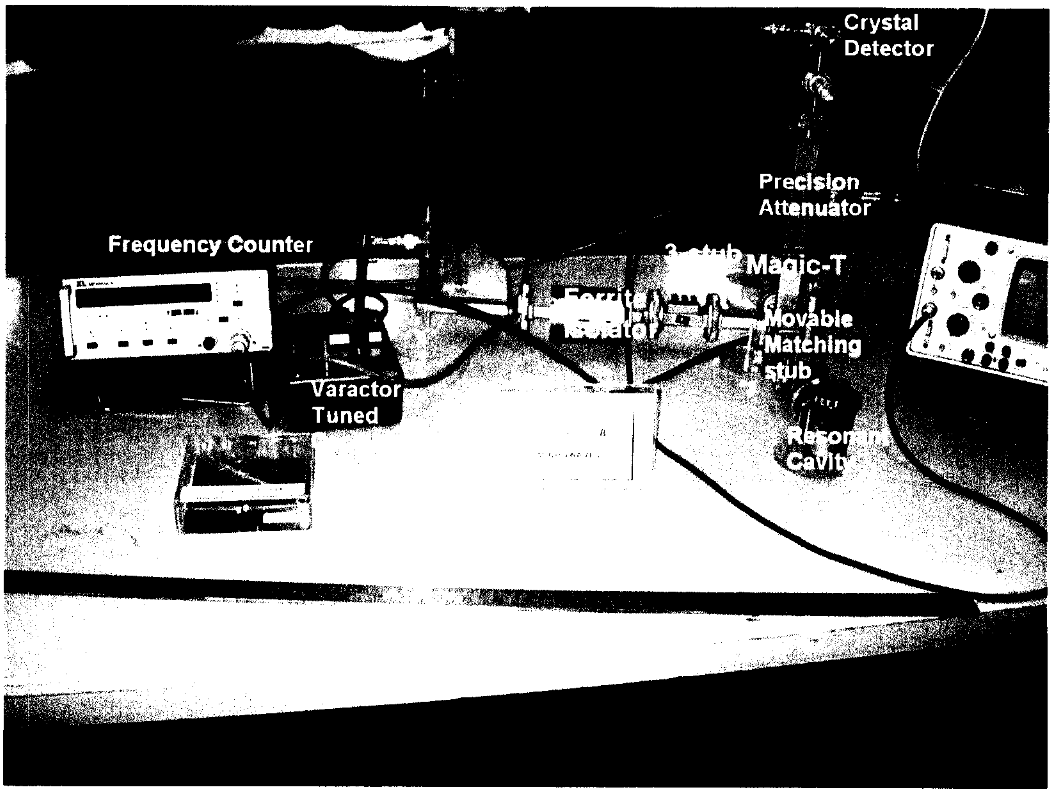
8.0	8.5	9.6	11.0	GHz
<2	<1	<1	-	dB

Note: Values of modulation depth and insertion loss indepentent of microwave power (-20 - +30 dBm)

5. Frequency range: 8.5 - 9.6 GHz

6. Switching time: 10 µs

Experiment 8. Microwaves



Updated BWJ 6 September 2011

General References:

S. Ramo, J.R. Whinnery and T. Van Duzer, *Fields and Waves in Communication Electronics*, (3rd edition), Wiley (New York, 1994)

E.L. Ginzton, *Microwave Measurements*, McGraw-Hill (New York, 1957)

1 Objective

The aim of this experiment is to examine the behaviour of microwave components, particularly a resonant cavity. We will study the Q of a cylindrical cavity, a parameter that describes the sharpness of the cavity resonance.

By measuring the shift in the resonant frequency when a small piece of dielectric material is placed in the cavity, the permittivity of the material at the resonant frequency is determined. A similar perturbation produced by inserting a small piece of conducting material allows the electric field in the cavity to be measured.

2 Introduction

Microwaves are electromagnetic radiation in the wavelength range of ~1 mm (300 GHz) to ~ 30 cm (1 GHz). There are two kinds of microwave generators: those based on electron beam excitation of electromagnetic oscillations in cavities, giving rise to devices such as klystrons, magnetrons, and gyrotrons; and semiconductor devices, such as varactor tuned oscillators (VTO), Gunn diodes[1] and IMPATT (impact ionisation avalanche transit time) diodes.

In this experiment we use a VTO, which is an LC oscillator based on a high frequency transistor, with a varactor as the tuning element. A varactor is a special back-biased diode in which the depletion layer acts as a capacitor's dielectric. The thickness of the depletion layer increases with back bias, in effect widening the gap between the capacitor plates and reducing its capacitance. A voltage applied to the varactor allows the frequency of the oscillator to be changed.

2.1 Waveguides

Microwaves can of course propagate through free space (e.g. microwave communications), but the usual way of propagating microwaves over short distances is through waveguides. A waveguide is a hollow pipe with conducting walls (the cross-section is usually rectangular, sometimes circular), filled with a dielectric (usually air at atmospheric pressure). Only certain transverse modes will propagate along a waveguide. The transverse distribution of electric and magnetic fields in a waveguide mode are determined by the waveguide geometry. There are, however, two classes of modes: transverse electric (TE) modes for which the transverse magnetic field is zero and correspondingly, transverse magnetic (TM) modes. A waveguide is a form of transmission line[2]. As with coaxial cables, we can define a characteristic impedance and use the same terminology to describe the matching of a waveguide to a load (in this case the cavity).

2.2 Microwave detectors

Diodes are commonly used to detect microwaves. With the aid of the diode characteristic, $I = I_0[1 - \exp(eV/kT)]$, the current in the diode due to incident radiation of frequency f can be found by substituting $V(t) = V_0 \sin(2\pi f t) = V_0 \sin(\omega t)$. For sufficiently low microwave power, such that $eV/kT << 1$, the exponential can be expanded. Taking a time average (we measure the current averaged over many microwave periods!), and retaining the first non-zero term we obtain

$$I = I_0 \frac{eV_0^2}{2kT} \tag{1}$$

Ideally, therefore we expect the diode output to be proportional to the square of the voltage induced across the diode junction. It is therefore proportional to the incident microwave power. Such detectors are called *square law detectors*. A diode detector is a current source; however, it is the voltage across a load resistor (e.g. the input impedance of an oscilloscope or DVM) that is usually measured.

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[1] These diodes exploit the Gunn effect: coherent oscillations generated at microwave frequencies when a sufficiently large dc electric field is applied across a short sample of n-type GaAs.

[2] An optical fibre is another example. In this case the radiation is confined to the dielectric fibre by the radial variation of refractive index - e.g. a central core region surrounded by a cladding of lower refractive index.

2.3 Microwave cavity

In this experiment we study the simplest resonant mode of a cylindrical cavity - the TM_{010} mode.[3] In order to describe the resonant fields in a cylindrical cavity we use cylindrical polar coordinates: the z axis is parallel to the axis of the cylinder; r and ϕ are polar coordinates in a plane perpendicular to the z axis. In the TM_{010} mode the only non-vanishing field components are E_z and B_ϕ, given by

$$\begin{aligned} E_z &= E_0 J_0(kr) & (2) \\ B_\phi &= (E_0/c) J_1(kr) & (3) \end{aligned}$$

where $J_{0,1}$ are Bessel functions of the zeroth and first order respectively (see Appendix B), and $k = 2\pi/\lambda$ is the wavenumber corresponding to a wavelength of λ. The condition that the parallel component of **E** be zero at a conducting surface, i.e. $J_0(ka) = 0$, where a is the radius of the cavity, which gives $ka = 2.405$. Thus the wavelength and frequency of the TM_{010} resonance are given by

$$\begin{aligned} \lambda &= 2\pi a/2.405 & (4) \\ f &= c/\lambda & (5) \end{aligned}$$

where c is the speed of light in the medium filling the cavity.

Figure 8-1 shows pictorially the variation of the fields inside the cavity; figure 8-2 shows E_z and B_ϕ as functions of radius within the cavity.

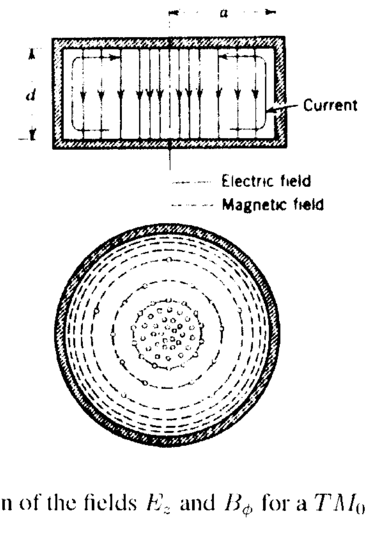

Fig. 8-1 : Pictorial representation of the fields E_z and B_ϕ for a TM_{010} mode in a cylindrical cavity

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[3] Two mode numbers are need to specify a waveguide mode, eg TM_{01}, where the mode numbers specify the structure of the mode in the two orthogonal transverse directions in the plane normal to the direction of propagation. Accordingly, three mode numbers are required to describe a cavity resonance - one for each orthogonal coordinate.

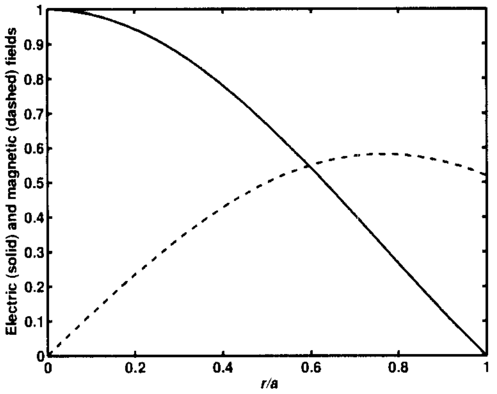

Fig. 8-2 : E_z (solid) and B_ϕ (dashed) as a function of radius for a TM_{010} mode in a cylindrical cavity

2.4 Q of the cavity

The Q of the cavity resonance is a *figure of merit* which characterises the sharpness of the resonance. The general definition of Q is

$$Q = 2\pi \frac{\text{Energy stored in the cavity}}{\text{Energy lost per oscillation cycle}} \tag{6}$$

It can be shown that this definition is equivalent to

$$Q = \frac{f_0}{f} = \frac{f_0}{f_2 - f_1} \tag{7}$$

where f_0 is the resonant frequency and $f_2 - f_1$ is the frequency difference between the half-power points of the resonance. Note that the wider the resonance, the lower the value of Q. The latter equation is more useful when the response of the cavity is measured as a function of frequency, as is the case in this experiment.

2.5 Matching the cavity to the waveguide

If the cavity reflects some power at resonance, it is said to be unmatched, and in this circumstance the Q of the resonance is referred to as the loaded Q, i.e. Q_L. The reflection can be eliminated by using a movable matching stub - a procedure referred to as matching the cavity to the waveguide. Figure 8-3 shows how the stub works. A second reflection of microwave power is produced by the stub. By inserting the stub this amplitude can be increased until it is equal to the amplitude of the microwaves reflected from the entrance iris of the cavity. It then remains to adjust the stub's horizontal position until the phases of each reflection differ by 180° so that the two reflections interfere destructively[4]. Inserting the stub by the right amount and at the right place has matched

---

[4] There is similarity between this situation and what happens in the antireflecting coatings applied to optical components such as camera lenses. The amplitudes of reflection from the front and back surfaces of the coatings have to be equal and to interfere destructively.

the line - so the effective impedance looking into the matching stub/cavity combination is equal to Z_0, the characteristic impedance of the waveguide.

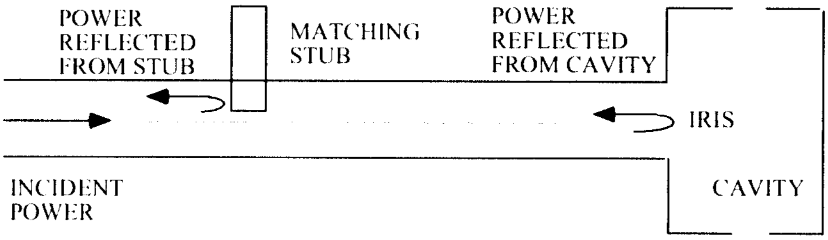

Fig. 8-3 : Matching the waveguide by means of a stub.

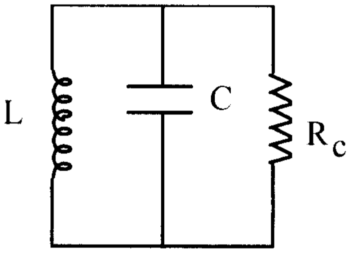

Fig. 8-4 : Equivalent electrical circuit of the cavity.

As an isolated component, the electrical equivalent of the cavity can be approximated as shown in Fig. 8-4. At resonance the admittances of L and C cancel and we are left with a purely resistive load, R_c. As the Q for a parallel LRC circuit is given by $\omega_0 RC$, where $\omega_0 = 2\pi f_0$ is the angular resonant frequency, the Q of the isolated (unloaded) cavity is given by[5]

$$Q_u = \omega_0 R_c C \tag{8}$$

We can say, therefore, that inserting the stub has the same effect as a transformer: it has changed the impedance from R_c to Z_0. We then have the situation shown in Fig. 8-5. Thus $Z_0 = n^2 R_c$ where n is the turns ratio of our effective transformer. From the point of view of the cavity, however, it 'sees' an extra load in parallel with R_c as it 'looks' up the line through the transformer in the opposite direction.

Consequently, in the matched case, we have (see Fig. 8-6)

$$Q_m = \frac{R_c}{2} C\omega_0 = \frac{1}{2} Q_u. \tag{9}$$

We identify 3 possible regimes for the cavity coupled to the waveguide.

(a) Cavity *undercoupled* to waveguide $Q_L > Q_u/2$

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[5] It should be clear why we referred earlier to the loaded Q: when the cavity is connected to the waveguide the equivalent circuit will include an impedance representing the waveguide in parallel with R_c.

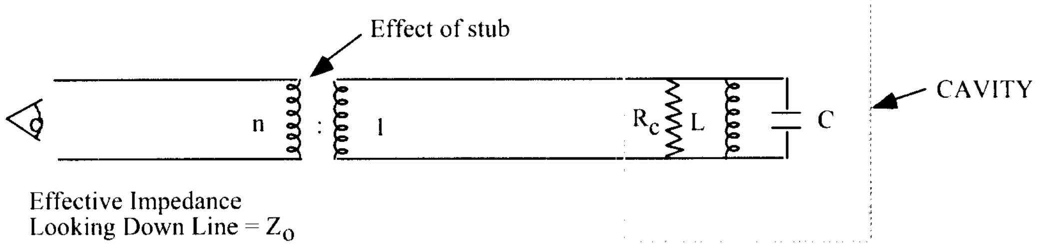


Fig. 8-5 : Equivalent electrical circuit of the matching process.

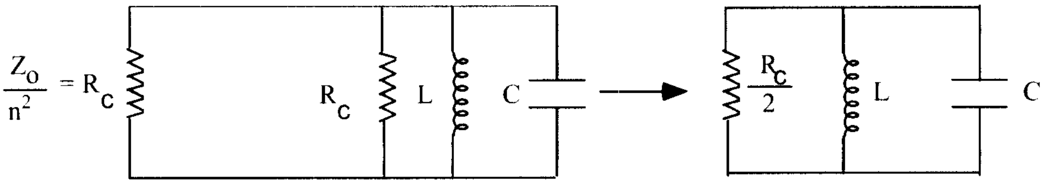


Fig. 8-6 : Equivalent electrical circuit for a matched cavity.

(b) Cavity *critically coupled* (matched) to waveguide $Q_L = Q_u/2$

(c) Cavity *overcoupled* to waveguide $Q_L < Q_u/2$

An analogy with a resistor R connected to a coaxial cable with characteristic impedance of 50 Ω may be helpful. The three regimes above correspond to, respectively, $R > 50\ \Omega$, $R = 50\ \Omega$, and $R < 50\ \Omega$.

2.6 Perturbation of the cavity

2.6.1 Effect of a dielectric

A dielectric is a material with low losses so that the Q is not significantly reduced by its insertion into the cavity. Many plastics are in this category, e.g. polystyrene, polyethylene and nylon. If the permittivity of the material is ϵ we commonly refer to the relative permittivity $\epsilon_r = \epsilon/\epsilon_0$ (also called dielectric constant, κ), which is dimensionless.

If a cavity is completely filled with this material we will find that the resonant frequency changes from f_0 to f where $f_0/f = \sqrt{\epsilon_r}$. As $\epsilon_r \geq 1$, the frequency is reduced. If a thin dielectric rod is inserted in the cavity, the proportion of the cavity's volume occupied by the rod is very small, so one might expect that the frequency shift on insertion will be correspondingly small. For a dielectric rod along the axis of a TM_{010} mode it can be shown that the frequency shift is given by [1, 2]

$$\frac{f_0 - f}{f_0} = 1.86(\epsilon_r - 1)\frac{V_1}{V_0} \tag{10}$$

where V_1 and V_0 are, respectively, the volume of the dielectric rod and the internal volume of the cavity.

2.6.2 Effect of a small conductive object

If a small conducting object is placed inside the cavity the resonant frequency will change by an amount which depends upon the relative amplitudes (with respect to the average fields in the cavity) of the E and B fields at the location of the object. For a small conducting sphere on the axis of a TM_{010} mode (i.e. at a location where $E \neq 0$, $B = 0$), the frequency shift depends on the local electric field only, and is given by [3]

$$\frac{f_0 - f}{f_0} = \frac{3}{4}\frac{V_{sp}}{U}\epsilon_0 E^2 \tag{11}$$

where V_{sp} is the volume of the sphere and U is the total energy stored in the cavity.

3 Experimental setup

The output from the microwave oscillator is fed by coaxial cable to an antenna inside the waveguide. Controls on the oscillator allow the frequency and the scan range (dispersion) at this frequency to be varied. The oscilloscope timebase voltage (a sawtooth waveform), available from a rear connector, is fed through a cable to the oscillator's *timebase in* terminal. An internal operational amplifier adds this voltage via the *dispersion* potentiometer to a dc voltage from the *frequency* potentiometer and the resulting waveform becomes the bias voltage for the VTO. Thus as the oscilloscope spot sweeps across the screen, there is a corresponding sweep of the oscillator frequency. This allows the cavity resonance to be displayed on the oscilloscope with a centre frequency and sweep range set by the *frequency* and *dispersion* controls. Although the latter are uncalibrated, a frequency meter is available for measuring the oscillator frequency, when required.

The microwave power radiated from the antenna propagates down the waveguide via a *magic tee* to the cylindrical cavity. At the cavity, some of the power is absorbed (and excites oscillations) and some reflected. The branch of the tee extending to the rear has an absorbing load in it so that entering microwaves are completely absorbed. Power from the left (via the isolator and three-stub tuner) is split between the branch to the absorbing load and the branch leading to the cavity. No power goes up through the precision attenuator to the diode detector. Some of the power reflected from the cavity is coupled into the upward branch and finds its way, via the attenuator, to the detector producing the y deflection on channel 2 of the oscilloscope. A fuller description of the operation of the magic tee can be found in Appendix B at the end of these notes.

The attenuator micrometer drive moves an absorbing plate across the waveguide, with attenuation increasing as the absorbing plate moves into the higher field region in the centre of the waveguide. Appendix C provides the calibration curve for the attenuator: dB of attenuation as a function of micrometer reading. If the attenuator transmits power P for incident power P_0, the attenuation in dB (decibels) is given by

$$\Delta\mathrm{dB} = 10\log\left(\frac{P}{P_0}\right) \tag{12}$$

4 Procedure

4.1 The TM$_{010}$ resonance

Answer the following questions:

1. where is the electric field zero and maximum
2. where is the magnetic field zero and maximum
3. where do currents flow
4. where is power dissipated.

4.2 Observing the resonance

Make sure that the movable stub is fully retracted (i.e. micrometer screw is fully anticlockwise) for these initial measurements.

1. Set the oscillator's frequency dial to 460, the attenuator to a low attenuation setting, and the dispersion to 200.
2. Adjust the oscilloscope so that both traces are on the screen, and set the vertical positions so that when switched to 'ground' both traces coincide at the bottom of the screen.
3. Connect the reflected power to channel 2 and leave channel 1 on 'ground' to define zero power. Ensure both inputs are on DC.
4. Carefully vary the oscillator's frequency control so that the absorption dip is centred, as shown in Fig. 8-7.
5. Check that this dip is indeed due to the cavity by inserting the detuning rod[6]. The dip should move to one side and disappear.

C1 ▷

4.3 Detector calibration

Use the precision attenuator to check the dependence of the detector output on microwave power.

1. Set the frequency control to about 460 (i.e. close to, but not at the cavity resonance) and the dispersion control to zero.

---

[6] This is a wire bent into an 'L' shape; the long arm can be inserted through the hole in the top of the cavity, along its axis and out the hole in the bottom. By forcing the electric field on the axis to zero, the mode pattern is changed, shifting the resonance outside the swept frequency range

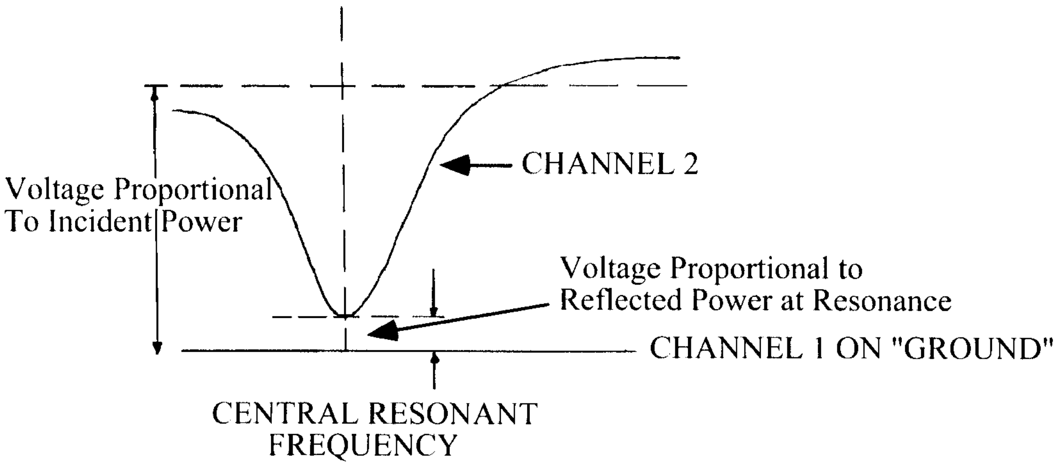


Fig. 8-7 : Profile of reflected power versus frequency near resonance.

2. Measure the DC voltage output of the crystal, V, using the multimeter. Take measurements for at least 15 different settings of the attenuator over the range which produces variation in V.
3. Using the attenuator calibration graph provided, the attenuator settings can be transformed into dB.

Assuming $V \propto P^n$, plot your detector output as a function of P in an appropriate way[7] in order to determine the value of n. (For an ideal square law detector, we expect $n = 1$.)

Does the detector behave as a square law detector over some or all of the power range investigated?

4.4 Measurement of resonance frequency

1. To measure the frequency of the resonance we need to gradually reduce the dispersion whilst keeping the resonance central on the screen. Reduce the dispersion to zero and ensure that the frequency is set at the centre of the resonance.
2. Measure the frequency using the frequency meter. This meter is capable of high precision, but the oscillator is not perfectly stable. Estimate the frequency and an uncertainty.
3. The reliability of the resonance frequency measurement is also dependent upon your ability to set the oscillator on the resonant frequency. Set the oscillator off resonance, then reset on resonance and make another measurement. Do this at least 5 times and find the mean and standard error of the mean. Comment on the latter with respect to the single measurement uncertainty estimated above.
4. From the measured resonant frequency determine a value for the internal radius of the cavity a, including an uncertainty. Unscrew the top of the cavity and check that your result for a is consistent with a direct measurement.

---

[7] If you suspect a power law for V as a function of P, how would you plot the measurements to confirm this and at the same time find a value for n? Note that equation 12 gives a relationship between P and attenuation, ΔdB.

4.5 Measurement of the cavity Q

1. With the dispersion set to zero, and by changing the frequency control we can measure on the oscilloscope screen (you may wish to connect a DVM to the oscilloscope input via a BNC T-piece for making voltage measurements)

   (a) The voltage for the *off-resonance* frequencies (the detuning rod will be useful). This should be roughly proportional to P_0, the incident power.

   (b) The voltage for the central resonant frequency f_0

   (c) The voltages for the two half-power frequencies (f_1 and f_2) where the power absorbed in the cavity is half the power absorbed at f_0.

   (d) From these measurements determine the Q of the cavity. As mentioned before, the latter is Q_L, the loaded Q.

NOTE: What is the experimental uncertainty of your value for Q_L? Although frequencies can be measured to high precision, $f_2 - f_1$ is the difference between two closely equal values. This will be significant in determining the uncertainty of the Q_L value!

C2 ▷

4.6 Matching the cavity to the waveguide

1. Carry out the matching procedure by inserting the stub (screw in the micrometer handle that controls it) so that the dip on the oscilloscope moves lower. Then minimize the dip further by moving the stub along the slot with the other knob.

2. Repeat this procedure until the minimum in the dip is at *ground* level. The cavity is then matched: there is no reflected power at the resonant frequency

3. Measure the matched Q_m, and hence obtain a value for the unloaded Qm (Q_u).

4. Compare Q_L and Q_u to determine whether the cavity is *undercoupled, critically coupled* or *overcoupled.*

Question 1: It is the size of the iris which determines whether undercoupling or overcoupling applies. Open the cavity and inspect the hole. How would the iris diameter need to change to achieve the other coupling regimes?

Question 2: If there is no power reflected back up the waveguide in the matched case, where is the incident power going?

C3 ▷

4.7 Measurement of relative permittivity

By measuring the shift in resonance frequency when a piece of nylon fishing line is extended along the axis of the cavity, determine the relative permittivity of nylon. Compare your result with accepted values quoted in a reference book (such as the *Rubber Handbook*).

Question 3: Slacken the tension on the line so that it bows out of the cavity's axis and observe change in resonant frequency. Explain your observation.

4.8 Measurement of electric field in the cavity

By measuring the shift in resonance when a small metal sphere is held on the axis of the cavity, determine the electric field on the axis of the cavity. You need to estimate U, the total energy stored in the cavity. which may be obtained using Equation 6. Under steady conditions we can take the power the power coming from the oscillator (~ 5 mW) as an estimate of the power dissipated in the cavity (i.e. ignoring the small amount of power dissipated in the matching components).

C4 ▷

References

[1] R.A. Waldron, *Theory of Guided Electromagnetic Waves*. Van Norstand Reinhold (London, 1969), p306

[2] R.G. Carter, *IEEE Trans Microwave Theory Tech* **49** (2001) 918

[3] S.W. Kitchen and A.D. Schelberg, *J Appl Phys* **26** (1955) 618

Appendix A: Fields for cavity resonances

Standing waves in a cylindrical cavity can be classified as **Transverse Magnetic**, TM_{mnp}, or **Transverse Electric**, TE_{mnp}, modes. In the first case the magnetic field is transverse to the axial direction (z), i.e. $B_z = 0$, and in the latter case $E_z = 0$. In the mode notation

1. first index gives the number of cycles as the azimuthal coordinate ϕ goes through 360°
2. the second index gives the number of half-cycles of the Bessel function across the diameter of the cylinder, and
3. the third index gives the number of cycles in the axial (z) direction

For the TM modes the radial component of the magnetic field, the azimuthal and axial components of the electric field all depend on radius as Bessel functions of integral order J_m. The azimuthal component of the magnetic field and the radial component of the electric field depend on radius as the first derivative of the Bessel function J'_m . For TE modes, swap the words electric and magnetic. For both sets of modes the boundary conditions must be obeyed: the electric field must be normal to the walls and the magnetic field tangential. If the radius of the cavity is a and the height h, then the TM_{mnp} modes are given by:

$$\begin{aligned} E_r &= AJ'_m(k_c r)\cos(m\phi)\sin(\pi pz/h) && (13)\\ E_\phi &= (B/r)J_m(k_c r)\sin(m\phi)\sin(\pi pz/h) && (14)\\ E_z &= CJ_m(k_c r)\cos(m\phi)\cos(\pi pz/h) && (15)\end{aligned}$$

The TE_{mnp} modes are given by :

$$\begin{aligned} E_r &= (D/r)J_m(k_c r)\sin(m\phi)\sin(\pi pz/h) && (16)\\ E_\phi &= FJ'_m(k_c r)\cos(m\phi)\sin(\pi pz/h) && (17)\\ E_z &= 0 && (18)\end{aligned}$$

with $J_m(k_c r) = 0$ and $J'_m(k_c r) = 0$ at $r = a$ in order to satisfy the boundary conditions for **E**. The constants A, B, C, D, F depend on the wave amplitude and $k_c^2 = (\omega/c)^2 - k_z^2$, with $k_z = 2\pi/\lambda_z$ and $p\lambda_z = 2h$.

We have that $\sin(\pi pz/h) = 0$ at the ends ($z = 0, h$) while $\cos(\pi pz/h)$ is a maximum there.

By using Eq. (13)-(15) and the data given in Fig. 8-8 we can deduce that for the TM_{010} only E_z is non-zero. Moreover, the tangential component at the cavity wall ($E_\phi = 0$). The radial mode number 1 corresponds to the first zero of the Bessel function, i.e. $ka = 2405$. To obtain the magnetic field, B, we use

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{19}$$

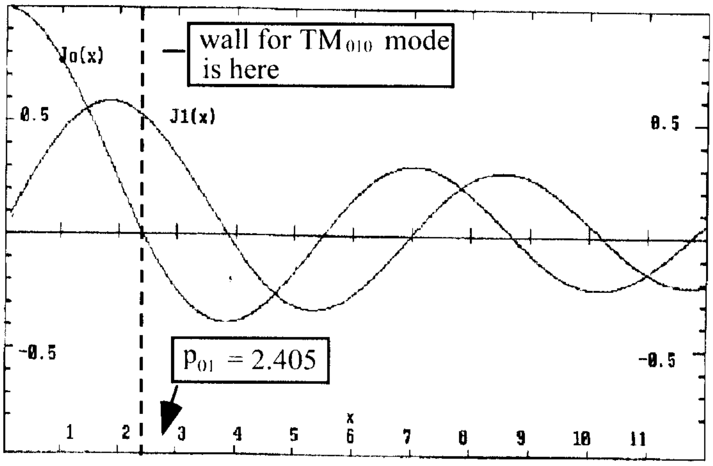


Fig. 8-8 : This shows a plot of $J_0(x)$. It has an infinite number of zeros at $x = p_{0l}$. The first zero $p_{01} = 2.405$. We also show the first order Bessel function $J_1(x) = -J_0'(x)$.

The only non-zero component of **B** is B_ϕ where

$$B_\phi \propto -J_1(k_c r) \tag{20}$$

Note that B is not zero at the walls. It is in fact (as required by the boundary conditions) tangential to the walls. This of course means that wall currents flow up the cylindrical walls from one end to the other. The wall currents can be found using Ampere's law: the wall current per unit width is equal to B_ϕ/μ_0.

Appendix B: Magic tee

A magic tee is a junction of 4 rectangular waveguide 'branches' " which form a reciprocal 4-port device with the useful property that ports 1 and 2 are totally isolated from each other. ("Port" is the term conventionally used to refer to points where the device is connected to the external circuit).

Each branch of the magic tee can be excited only in the TE_{10} mode where the E field is parallel to the short (a) side of the guide, and is purely transverse. The B field by contrast does have a component in the direction of propagation.

To understand how it works, consider first a signal entering branch 1. At the junction, components of the E and B fields are able to excite the TE_{10} mode in branches 3 and 4. However the fields are orthogonal to the TE_{10} fields in branch 2 and thus cannot excite the mode. Thus the energy entering branch 1 leaves (equally divided) via branches 3 and 4. The decoupling of branch 1 from branch 2 is reciprocal: a signal entering branch 2 cannot excite a wave in branch 1, and the energy leaves via branches 3 and 4.

In the microwave experiment, branch 1 is connected to the signal generator, branch 3 is connected to the cavity and branch 4 is terminated in a matched (i.e., non-reflecting) load resistor. The signal detected by the crystal detector (branch 2) is then proportional to the power reflected by the cavity

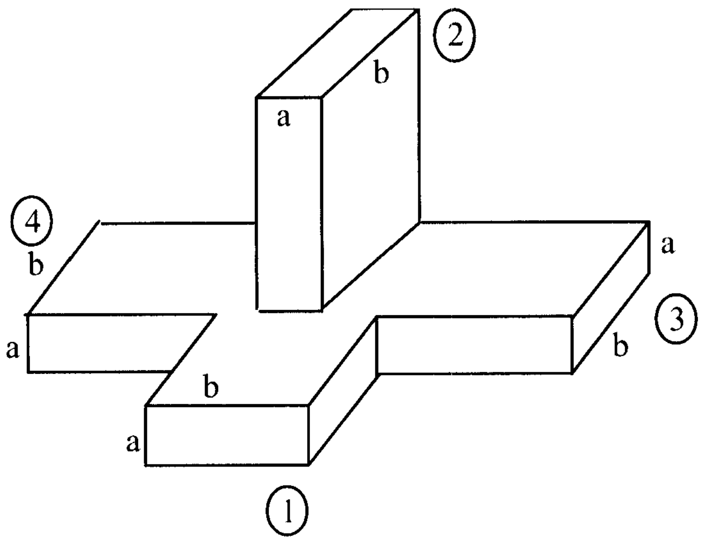


Fig. 8-9 : The magic tee

back into branch 3, as branch 2 does not "see" the signal entering branch 1. In other words, in this experiment the magic tee is used as a directional coupler.

The diagram does not show the internal construction of the magic tee. To work properly there must be no reflection of signals at the junction (for example none of the signal entering branch 1 may be reflected directly back to the generator). To achieve this condition "matching elements" are built into the junction. They comprise a carefully designed "matching post" parallel to the E field in branches 1, 3 and 4 and a diaphragm in branch 2. These details are vital to the operation of the magic tee, but the device can be understood qualitatively without considering them.

Appendix C: precision attenuator calibration

Figure 8-10 is the calibration curve for the precision attenuator.

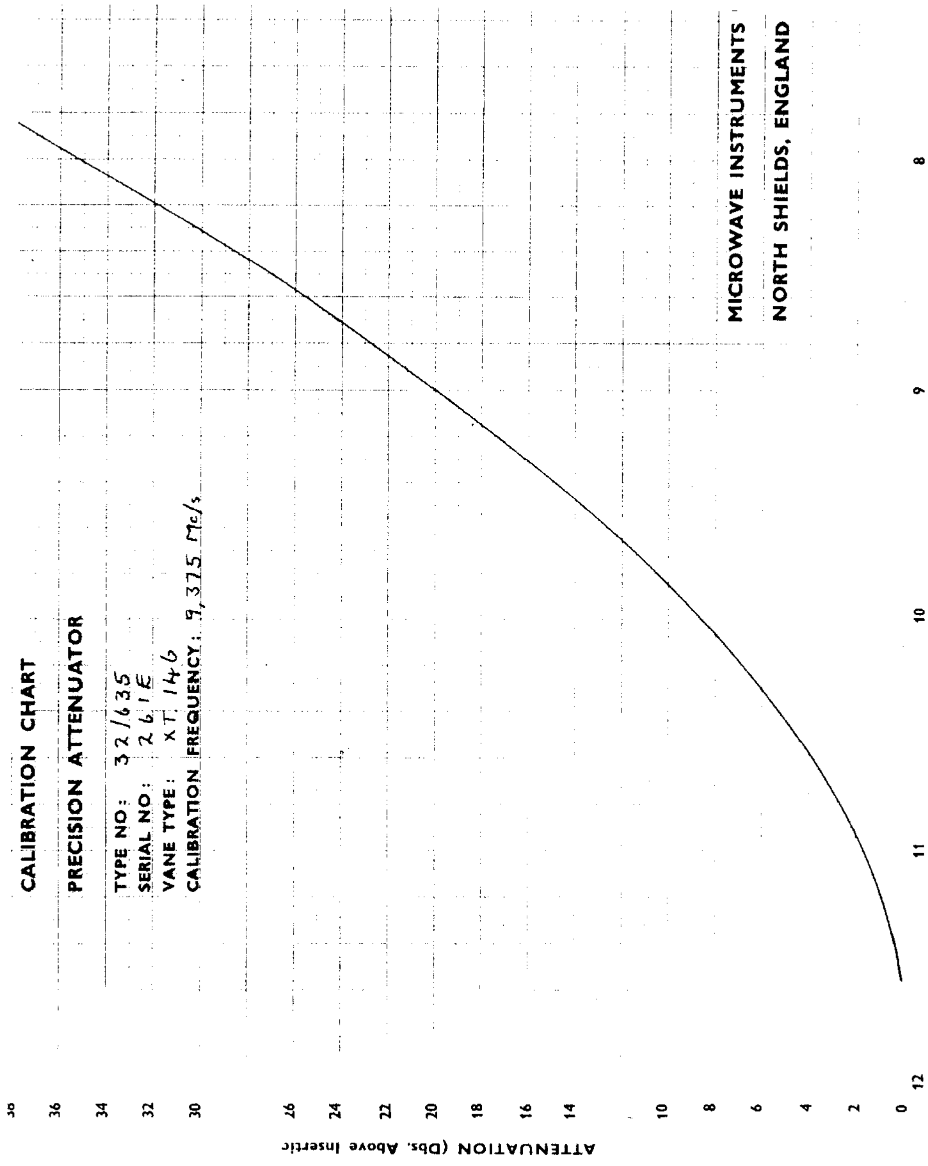


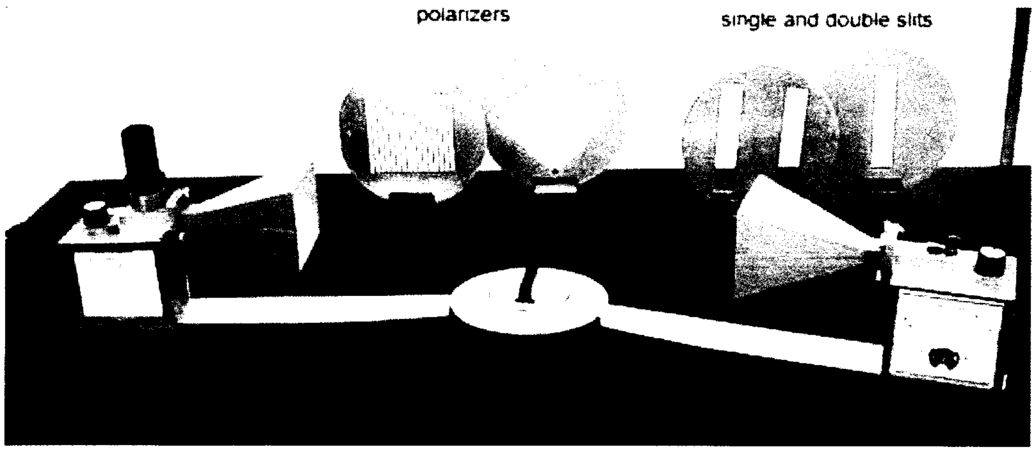
Fig. 8-10 : Calibration curve for the precision attenuator: attenuation in dB as a function of micrometer reading.

Physics 313: Laboratory 1 – Experiments with Microwaves

Introduction: Microwaves offer an opportunity to study optical phenomena on length scales of centimeters rather than hundreds of nanometers. This makes it very easy to investigate wave phenomena at a qualitative level. After completing the experiments, you should be able to answer the following questions:

- What are the characteristics (angular distribution and polarization state) of the microwave beam produced by the repeller?
- How do polarizers work?
- What are standing wave patterns and how can you produce them?
- What is the wavelength and speed of the microwave radiation?
- What do diffraction patterns look like? How do they arise?

The following equipment is required to collect the data:



Microwave source	Metal slit arrangements	Simulation software	Computer
Microwave detector	Metal polarizers	Goniometer (angle measurer)	Ruler, tape measure

The basic equipment for the experiments in this lab consists of a microwave source or transmitter, which generates about 10 mW of vertically polarized electromagnetic radiation with a frequency around 10 GHz, and a simple diode detector/receiver. Both transmitter and receiver have a small microwave horn to give them some directionality. Operation of the equipment is simple. After plugging in, the source requires about 20 seconds to warm up. It has just one control, labeled "repeller". Adjust this control so that a maximum reading is achieved on a detector facing the source. The detector itself has a sensitivity control, labeled "gain" which can be adjusted to avoid an overload condition on the readout. Note: do not work on the metal optics table to avoid reflections.

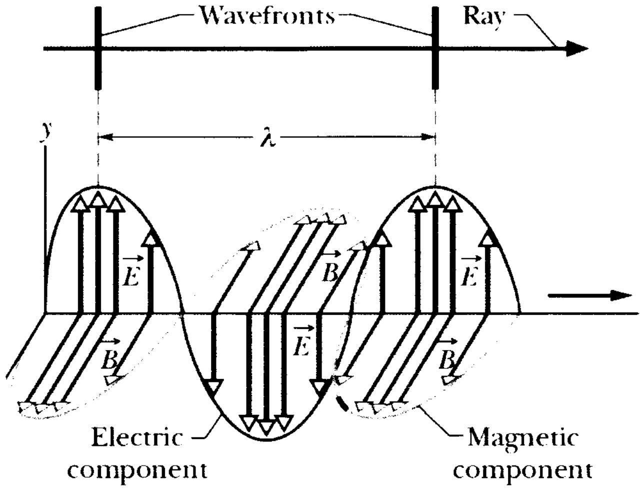


Figure 1: Vertically polarized electromagnetic plane wave.

Experiment 1: Microwave beam characterization

The microwave beam generated by the source is fairly broad both in horizontal and vertical direction. The detector also responds to electromagnetic fields with only limited directionality. Determine the angular resolution of the transmitter/detector combination, using the goniometer. Plot the detector reading as a function of angle between the transmitter and detector.

The transmitter produces vertically polarized microwaves. The detector is only sensitive to electric fields parallel to the diode in the detector. Verify that when you rotate the detector by 90°, while facing the source, the detector reading falls to zero.

Experiment 2: Polarizers

There are many devices that can be used to affect or determine the polarization state of an electromagnetic wave. In a very common situation, realized in the visual wavelengths by Polaroid material, electrical current is free to flow in one direction but not in the perpendicular one. If the electric field is polarized in the direction in which a current can flow, there is a strong interaction between the field and the "polarizer". Energy is transferred from the field to the grid due to Joule heating of the moving electrons in the metal. The accelerated electrons will radiate in a manner which will tend to cancel the incident wave.

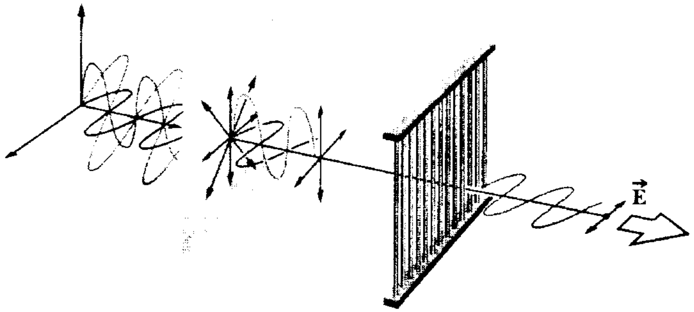


Figure 2: A wire-grid polarizer. The grid eliminates the vertical component (I.e., the one parallel to the wires) of the E-field and passes the horizontal component.

If currents potentially induced by the E-field are not free to flow, no interaction is possible and the electromagnetic wave passes through as if the polarizer is not present.

At the frequency that we are using here, one can achieve this directionality in electrical conductivity by just cutting slots in a piece of aluminum sheet metal. Investigate the effects of placing a polarizer in between the transmitter and detector for various orientations of the polarizer and detector. Also, investigate the effects of a second polarizer.

Experiment 3: Standing waves and wavelength determination

Stable 1D standing waves form when low amplitude waves interfere which are traveling in both directions and which have fixed phase relationships. One physical system which can produce standing waves is a perturbed string. If the distance between string ends is equal to nλ/2 (n an integer and λ the wavelength), multiply reflected waves will be in phase and standing waves will form. Investigate the formation of standing waves using the "standing waves" applet available by opening the file applets\HRM\index.htm. What frequencies produce standing waves? Is this consistent with the condition given above?

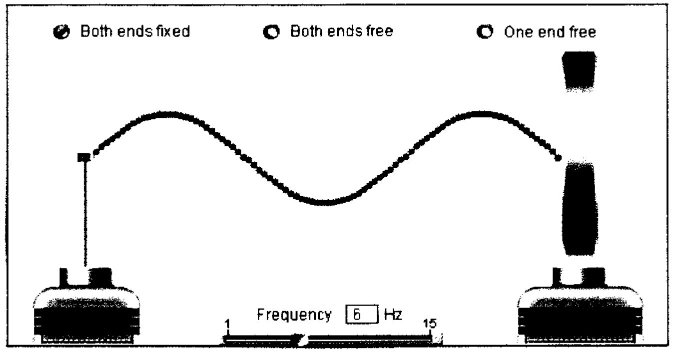


Figure 3: Standing waves applet.

The microwave horns of the transmitter and detector do not perfectly adsorb incoming waves, but will partially reflect them. If the distance between reflecting surfaces is equal to nλ/2, the detector reading will show a maximum. By determining positions of subsequent maxima it is possible to obtain the wavelength of the microwaves. Instead of using just the transmitter and receiver, you can put a polarizer at 45° in between them. This provides better reflections and much more pronounced maxima and minima. What wavelength do you measure for the microwaves? If their frequency is 10 GHz, what speed for electromagnetic waves does that imply?

Experiment 4: Diffraction

When a plane electromagnetic wave "illuminates" an aperture in a sheet of metal, the aperture becomes a smaller "source" of electromagnetic radiation. When the dimensions of the aperture are of the order of the wavelength, points in the aperture are at different distances to the detector, and radiation from those points will in general have different phases. Thus for some angular positions the interference of the waves coming from different parts of the aperture will be constructive, for others there will be destructive interference. The result is a diffraction pattern.

Investigate diffraction patterns with the "2D Electrodynamics (TE)" applet in the applets\Falstad directory, or go to the website at www.falstad.com. Open directions.html for information on the applet. You can add or subtract conducting surfaces with the mouse. Qualitatively, what do you get when you have a tiny aperture and thus a line source? What happens as you open up the aperture? Does this pattern make sense in terms of interference?

Next, observe and record microwave diffraction patterns for various arrangements of apertures. Are these consistent with the simulations?

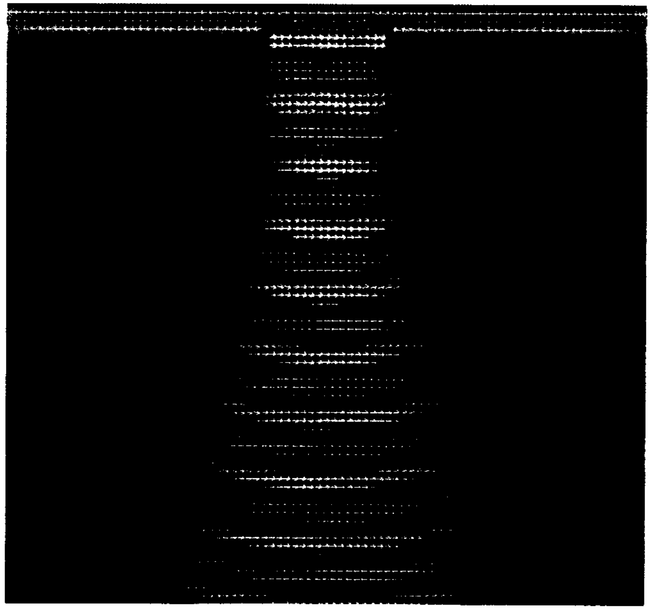


Figure 4: 2D Electrodynamics (TE) applet using the single slit setup.