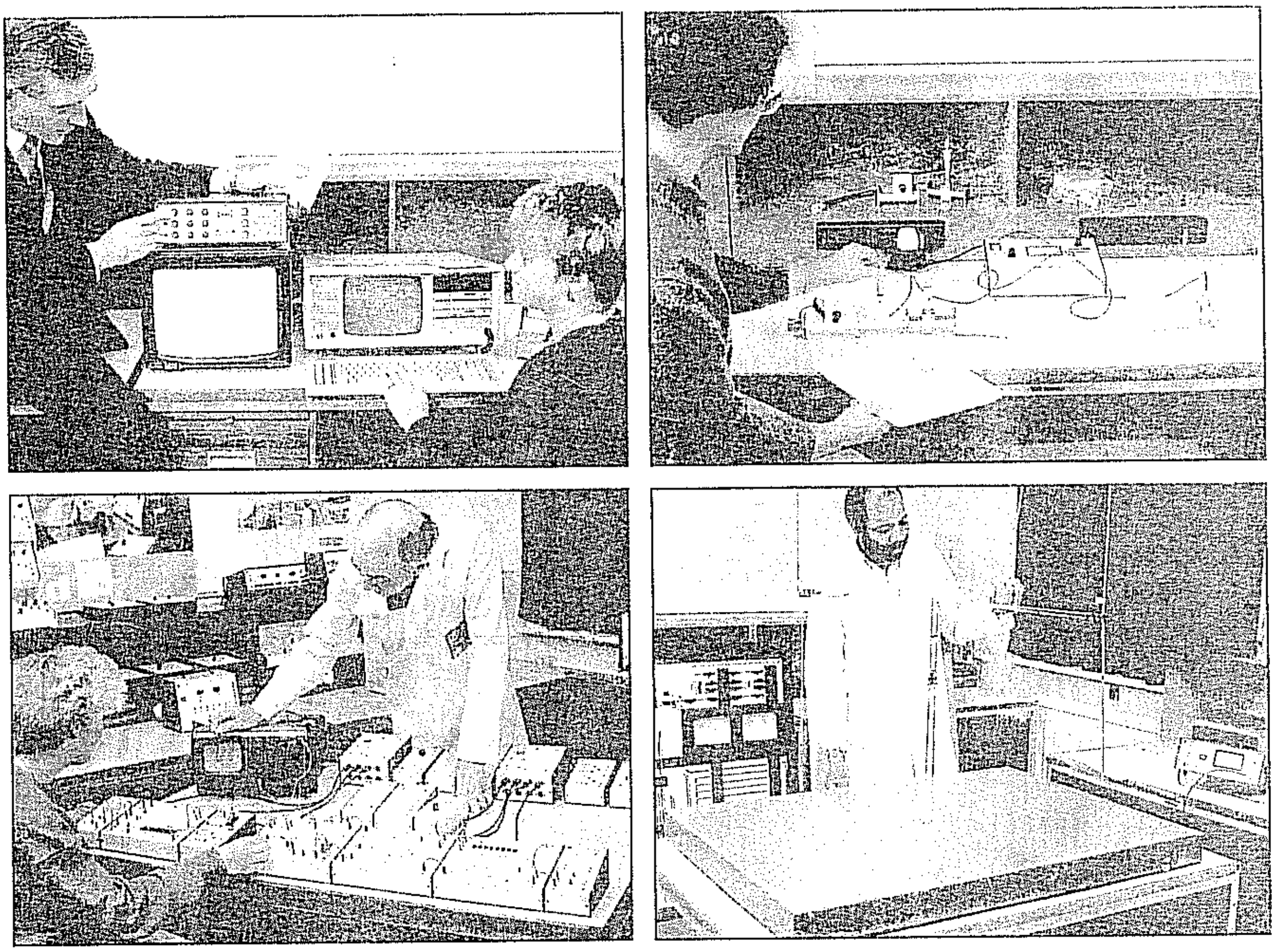
Feedback

Telecommunications



Microwave Trainer MWT530

Instruction Manual

MICROWAVE TRAINER

MWT530

Feedback

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THE HEALTH AND SAFETY AT WORK ACT 1974

We are required under the Health and Safety at Work Act 1974, to make available to users of this equipment certain information regarding its safe use.

The equipment, when used in normal or prescribed applications within the parameters set for its mechanical and electrical performance, should not cause any danger or hazard to health or safety if normal engineering practices are observed and they are used in accordance with the instructions supplied.

If, in specific cases, circumstances exist in which a potential hazard may be brought about by careless or improper use, these will be pointed out and the necessary precautions emphasized.

While we provide the fullest possible user information relating to the proper use of this equipment, if there is any doubt whatsoever about any aspect, the user should contact the Product Safety Officer at Feedback Instruments Limited, Crowborough.

PRODUCT IMPROVEMENTS

We maintain a policy of continuous product improvement by incorporating the latest developments and components into our equipment, even up to the time of dispatch.

All major changes are incorporated into up-dated editions of our manuals and this manual was believed to be correct at the time of printing. However, some product changes which do not affect the instructional capability of the equipment, may not be included until it is necessary to incorporate other significant changes.

COMPONENT REPLACEMENT

Whenever possible, replacement components should be similar to those originally supplied. These may be ordered direct from Feedback or its agents by quoting the following information.

1. Equipment type
2. Equipment serial number
3. Component reference
4. Component value

Standard components can often be replaced by alternatives available locally.

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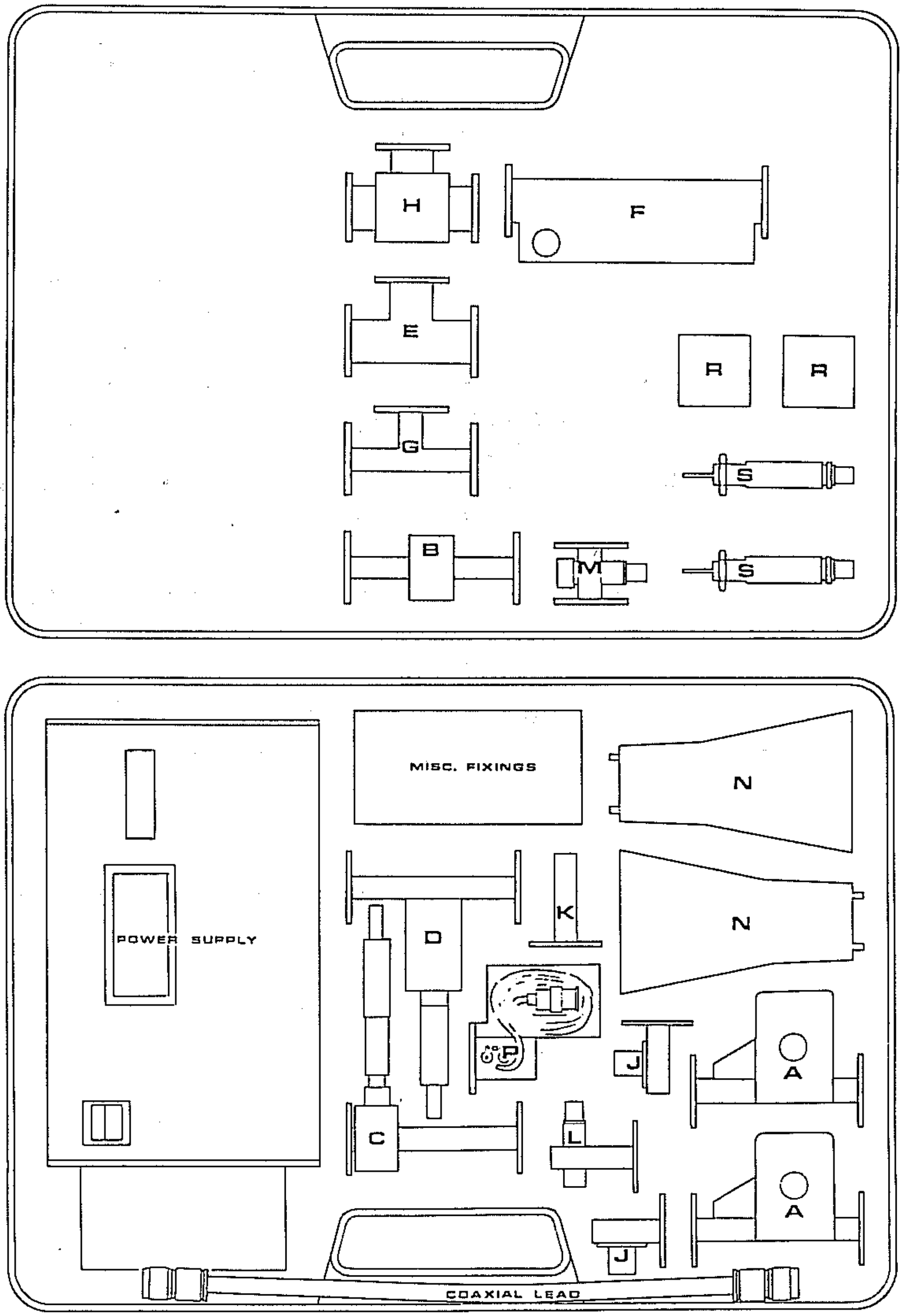
Chapter 1 Description of the System and Equipment

Case Content



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Chapter 1 Description of the System and Equipment

CHAPTER 1 DESCRIPTION OF THE SYSTEM AND EQUIPMENT

INTRODUCTION

The Feedback MWT530 is a basic trainer which enables students to investigate the principles of microwave transmission systems such as those used in radar and communication links. It is a bench-top microwave system which is completely self-contained and uses standard type WG16 waveguide components to illustrate the essential elements of this field of study.

The trainer together with this manual, provides a means for students to carry out realistic practical work, and is suitable for courses ranging from technician studies to degree level.

EQUIPMENT

The equipment comprises a set of waveguide components and a console which contains the power supply for a modulated solid-state X-band microwave source, a power-measuring bolometer bridge and a meter which may be switched to monitor either a detector output or the supply current to the bridge.

When not in use the system components should be stored in the protective carrying case, in which the equipment is supplied.

A detailed equipment list is shown overleaf.

SPECIFICATION

Oscillator

Frequency: 10.687 GHz.
Power Output: 8mW.

Waveguide

Dimensions: 10mm x 23mm.

Slotted Line

Dimension: Scaled in mm.

Chapter 1 Description of the System and Equipment

System Components

Qty	Ident letter	Description
1	–	Control Console
2	A	Variable Attenuator
1	B	Slotted-Line for use with Detector
1	C	Slotted-Line Tuner
1	D	Cavity Resonator
1	E	Shunt Tee
1	F	Directional Couple
1	G	Series Tee
1	H	Hybrid Tee
2	J	Waveguide/Coaxial Adaptor
1	K	Resistive Terminator
1	L	Bolometer (Thermistor-type)
1	M	Diode Detector (in waveguide section)
2	N	Horn Antenna
1	P	X-band Oscillator and Cable Assembly
2	R	Short-circuit Terminator

Chapter 1 Description of the System and Equipment

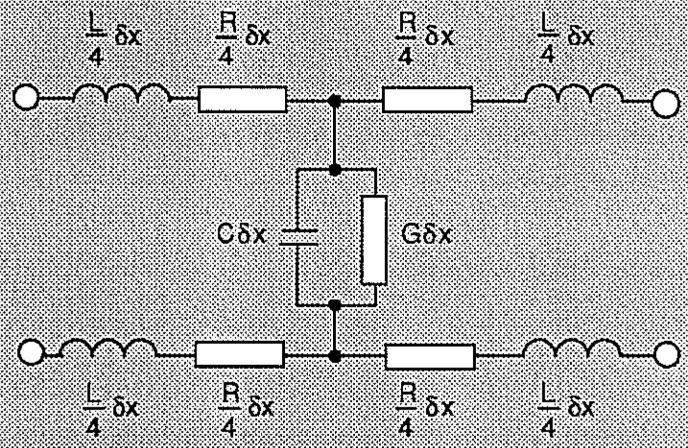
System Components (continued)

Qty	Ident letter	Description
1	–	Coaxial cable with 'n' series connector
2	S*	Probe Detector Assembly for use with items B or F
1	–	Accessory bag which contains:
	–	2 coaxial cables with BNC connectors
	–	24 coupling plates
	–	48 thumb nuts
	–	4 support plates
1	–	Manual MWT530

* Not marked on assemblies

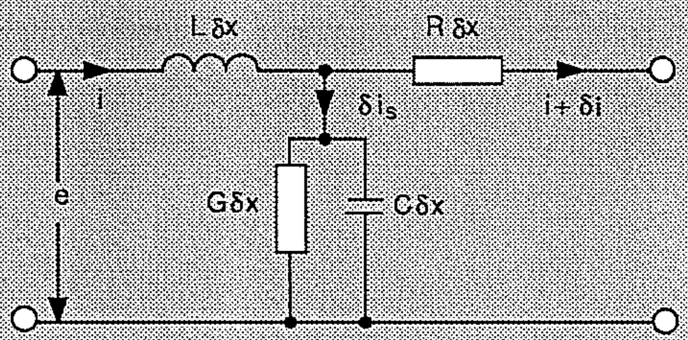
Chapter 2 Microwave Theory

Fig 1



Typical Microwave Circuit

Fig 2



Simplified Microwave Circuit (Ref: fig 1)

Chapter 2 Microwave Theory

CHAPTER 2 MICROWAVE THEORY

This chapter briefly discusses transmission line theory

A microwave signal is simply an electromagnetic wave whose wavelength is small compared with ordinary radio waves. Like any radio wave, microwaves can be sent through space, or guided by conductors. Any extended system of conductors intended to guide a signal between two separated points is called a *transmission line.*

The MWT530 Microwave Trainer is mainly concerned with a particular form of transmission line, known as a *waveguide*. This is rather like a pipe in appearance, and it is rather difficult to give easy definitions of 'voltage' and 'current' in it. Its behaviour however resembles that of an ordinary line, such as a pair of wires. It is therefore instructive to consider how such an ordinary line behaves.

If we consider a short length δx of the transmission line, we can represent it by four types of component:

1. Series inductance, $L\delta x$
2. Series resistance, $R\delta x$
3. Shunt capacitance, $C\delta x$
4. Shunt conductance, $G\delta x$, where,

L, R, C, G are values of inductance etc per unit length.

The line can be represented by the circuit, fig 1. The various elements are shown distributed along the line, to show that the line is isotropic (transmits equally well in both directions). Fig 2 shows a simpler representation, which is equally valid if δx is small enough.

Suppose that a voltage 'e' is applied between the conductors in fig 2. A shunt current δi_s will flow between the conductors. But if the line current changes by δi,

$$(i + \delta i) - i + \delta i_s = 0$$
$$\delta i = -\delta i_s$$

Consequently the current along the conductors will decrease, by the same amount. The shunt current will be the sum of the currents due to capacitance and due to conductance:

$$\therefore \delta i = -\delta_s = -\left(eG + C\frac{\partial e}{\partial t}\right)\delta x$$

Dividing by δx and allowing δx to tend to zero,

$$\frac{\delta i}{\delta x} = -\left(eG + C\frac{\partial e}{\partial t}\right) \qquad 1.1$$

The current flowing through the inductance and resistance of the length δx of line will produce a voltage drop –δe:

$$\delta e = -\left(iR + L\frac{\partial i}{\partial t}\right)\delta x, \qquad \text{so that:}$$

$$\frac{\delta e}{\delta x} = -\left(iR + L\frac{\partial i}{\partial t}\right) \qquad 1.2$$

Equations 1.1 and 1.2 are generally known as the 'line equations' which form the basis of an analysis of line behaviour. Such an analysis shows that R and G cause the signal to be weakened as it travels along the line. In useful lines however, the signal is weakened as little as possible, so that R and G are made small. The line behaviour can then be approximated quite well by putting R and G equal to zero, which greatly simplifies the analysis. The equations then reduce to:

$$\frac{\delta i}{\delta x} = \frac{-C\partial e}{\partial t} \qquad \text{and} \qquad 1.3$$

$$\frac{\delta e}{\delta x} = \frac{-L\partial i}{\partial t} \qquad 1.4$$

It can be shown* that these equations represent a wave of current and of voltage, travelling with velocity $\frac{1}{\sqrt{LC}}$. The voltage is equal to the current multiplied by $\sqrt{LC}$.

* See for example Johnson "Transmission Lines and Networks" McGraw Hill, 1950.

Chapter 2 Microwave Theory

Equation 1.3 specifies the ratio between the voltage and the current at any point in the line (assuming that a wave is travelling in either one direction but not the other).

Equation 1.4 describes a wave, of waveform f(x), travelling to the right (minus sign) or to the left (plus sign) with velocity v.

Solutions of these equations are:

$$e = iZ_0, \quad \text{and:} \qquad 1.5$$

$$e = f(x \pm vt) \qquad 1.6$$

where $Z_0 = \sqrt{\frac{L}{C}}$ and is called the *characteristic impedance* and:

$$v = \frac{1}{\sqrt{LC}}$$

This can be seen by using 1.5 to substitute for e in 1.3, giving:

$$\frac{\delta i}{\delta x} = -\sqrt{LC}\,\frac{\partial i}{\partial t}$$

NOTES:

Chapter 3 Practical Assignments

CHAPTER 3 PRACTICAL ASSIGNMENTS

This chapter consists of the following 11 assignments which will familiarise students with the fundamentals of microwave technology.

1 Basics of Frequency and Wavelength.

2 Measurement of Voltage Standing Wave Ratio.

3 Measurement of Microwave Power.

4 Detector Characteristic.

5 Measurement of Impedance.

6 Microwave Tuner.

7 Directional Coupler.

8 Series and Shunt Tees.

9 Horn Antenna - Microwave Propogation in Space.

10 Doppler Radar.

11 Use of Coaxial Cable.

Each assignment will specify the components required and the connections necessary. In addition, the positions of the switches will be stated except for the meter switch at the top of the control console; the position of this switch being dependent on the experiment requirements.

ASSIGNMENT 1 BASICS OF FREQUENCY AND WAVELENGTH

CONTENT

The relationship between frequency and wavelength is described. The electric and magnetic field patterns in a rectangular waveguide are investigated. The cavity resonator is investigated and the wavelength of the signal in the guide is measured using a slotted line.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
2	A	Variable Attenuator
1	B	Slotted Line
1	D	Cavity Resonator
1	K	Resistive Terminator
1	M	Diode Detector
1	P	X–Band Oscillator
1	S	Probe Detector Assembly

Chapter 3 Assignment 1

OBJECTIVES

When you have completed this assignment you should:

- Know how to measure the wavelength of a signal in a rectangular waveguide, using a slotted line.
- Understand the meaning of the term cut–off frequency (f_c).

KNOWLEDGE LEVEL

Before you start this assignment you should:

- Know how to read a micrometer
- Understand what is meant by an electromagnetic wave.

Chapter 3 Assignment 1

INTRODUCTION

The frequency f, velocity v and wavelength λ of any wave are related by the equation:

$$f\lambda = v$$

The velocity of an electromagnetic wave in free space is denoted by c. Its velocity in air is almost the same; the value being approximately:

$$c = 3 \times 10^8 \text{ m/s}$$

An electromagnetic wave passing through magnetic or dielectric material travels more slowly. Many microwave phenomena are frequency-dependent, or (amounting to the same thing) dependent on the relationship between a wavelength and some dimension of the apparatus in use.

When a waveguide is used to transmit the wave, there are other factors to consider. It turns out that the wavelength inside the guide is longer than that in free space. The reasons are discussed in Appendix A.

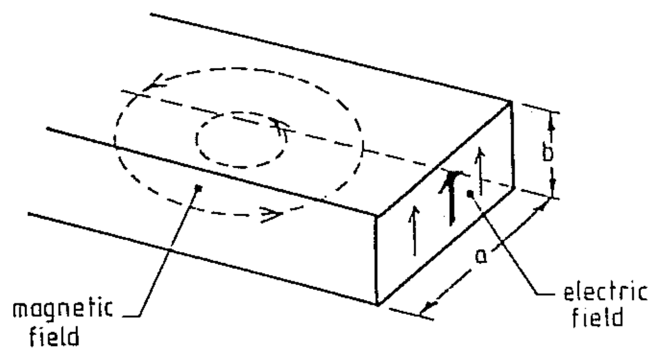
In a waveguide there is theoretically an infinite number of different modes, or field patterns, in which an electromagnetic wave can be transmitted. In general they are classified as:

Transverse electric (TE) or,

Transverse magnetic (TM).

Transverse electric indicates that the electric field is perpendicular to the direction of propagation.

Fig 1.1



Electric and Magnetic Fields in a Rectangular Waveguide

Chapter 3 Assignment 1

Fig 1.1 illustrates the electric and magnetic field patterns for the mode used in the rectangular waveguides of the MWT530 experiments. This mode is called $TE_{1,0}$ mode. The figures indicate that the electric field is unidirectional, and there is no transverse magnetic field. Other modes have different number suffixes indicating the number of changes of field direction which occur in each transverse direction. A special mode called TEM has both electric and magnetic fields perpendicular to the direction of propagation. This mode of propagation occurs in free space and in coaxial lines.

Each mode has a critical frequency, called the *cut–off frequency, (f_c),* below which it cannot propagate energy, dependent on the waveguide dimensions. A waveguide is generally used over a range of frequencies such that only one mode can propagate, so that useful energy is not lost by conversion between different modes.

The cutoff frequency can be calculated for a rectangular waveguide as follows:

- For the $TE_{m,n}$ mode:

$$f_c = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2},$$

where a and b are the waveguide dimensions.

- For the $TE_{1,0}$ mode:

$$f_c = \frac{c}{2a}$$

In this assignment the source of microwave power will be an oscillator based on a *field-effect transistor* (FET). Its frequency of oscillation is determined by the resonance of the waveguide cavity in which it is mounted. This cavity is coupled to the external waveguide by a narrow slit to reduce the influence the external load has on the oscillator's built-in resonance. Other forms of microwave oscillator exist. The Gunn diode, a form of negative-resistance device, can be used at low powers. For higher powers, vacuum tubes, such as klystrons and magnetrons can be used. These use the finite speed of electrons travelling in a vacuum.

Chapter 3 Assignment 1

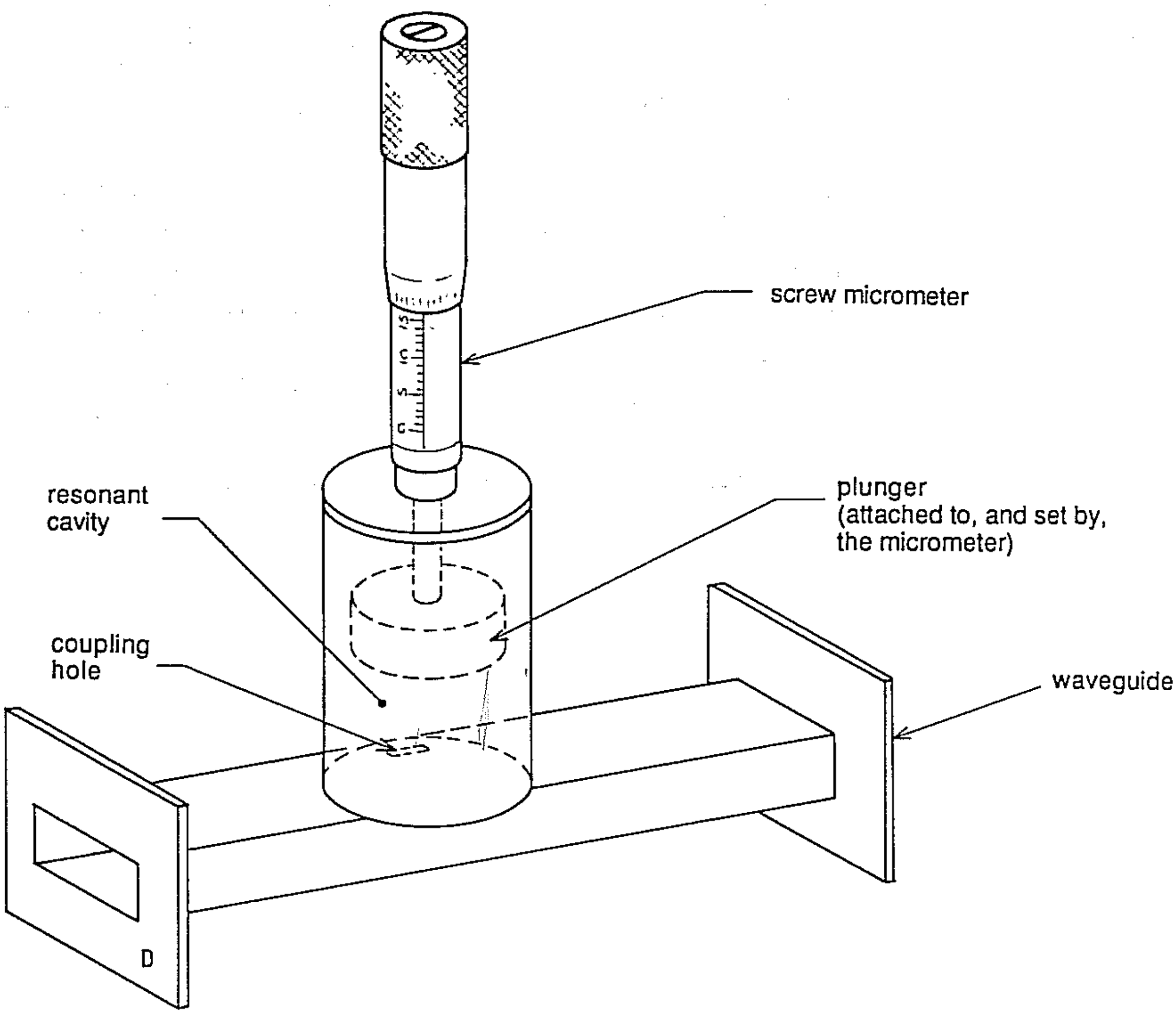
The FET Oscillator can be supplied with d.c from the MWT530 power supply, but in this and other assignments using the Diode Detector, the supply can be square-wave modulated or 'keyed' by repeated switching of the supply. This enables a simple a.c amplifier to increase a weak detector signal to the power level required for an indicating meter.

The Cavity Resonator to be used in this experiment has a cavity which is coupled to the waveguide by a small coupling hole (see fig 1.2). Because the hole is small it can normally absorb only a tiny fraction of the energy passing along the waveguide. That tiny amount of energy, once through the hole, bounces about between the walls of the cavity. It cannot escape except through the hole.

If a wave bouncing back to the hole and a wave entering reinforce each other, the strength of the wave will build up progressively to a large amplitude. This is a form of resonance. If the amplitude is large enough, even the small fraction of it which leaks back into the waveguide through the hole will have a significant effect, as we shall see. By making the size of the cavity variable, the resonant frequency can be varied. So, by adjusting the cavity size to the point where the cavity affects transmission of a particular signal, it can be resonated at the frequency of the signal.

Chapter 3 Assignment 1

Fig 1.2



Cavity Resonator

Chapter 3 Assignment 1

EXPERIMENTAL PROCEDURE

WARNING NEVER look directly into an energised waveguide.

Although the r.f power levels in this equipment are low and not normally dangerous, the human eye is especially susceptible to damage by microwave radiation.

Connect the apparatus as shown in fig 1.3.When attaching the Cavity Resonator, ensure the scale is positioned for easy reading. Gently screw in the micrometer head of the Cavity Resonator until resistance is felt. (Do not force it.) On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying; set the METER READS switch to 'detector output'

Set the 'source' Attenuator to 20. Set the sensitivity control of the amplifier to maximum and adjust the 'load' Attenuator until a reading of about 3 is obtained on the meter.

The meter indicates the amount of power received at the Diode Detector. Observe how it is affected as you unscrew the micrometer head. At first there will be little effect on the meter, some shallow nulls and then a deep null; i.e the meter reading will sharply fall to zero or near zero. The cavity is now resonating at a frequency corresponding to that of the signal in the waveguide. At resonance, even a small coupling can absorb a high proportion of the power travelling along the waveguide, so that the detector does not receive it. This principle is used, in practice, in the absorption type of frequency meter.

Adjusting the micrometer of the Cavity Resonator alters the size of the cavity, and consequently its minimum resonant frequency. Every cavity has many modes of resonance, but the one with the lowest resonant frequency is usually most simply related to its dimensions.

Find and record the micrometer setting which gives the lowest meter reading.

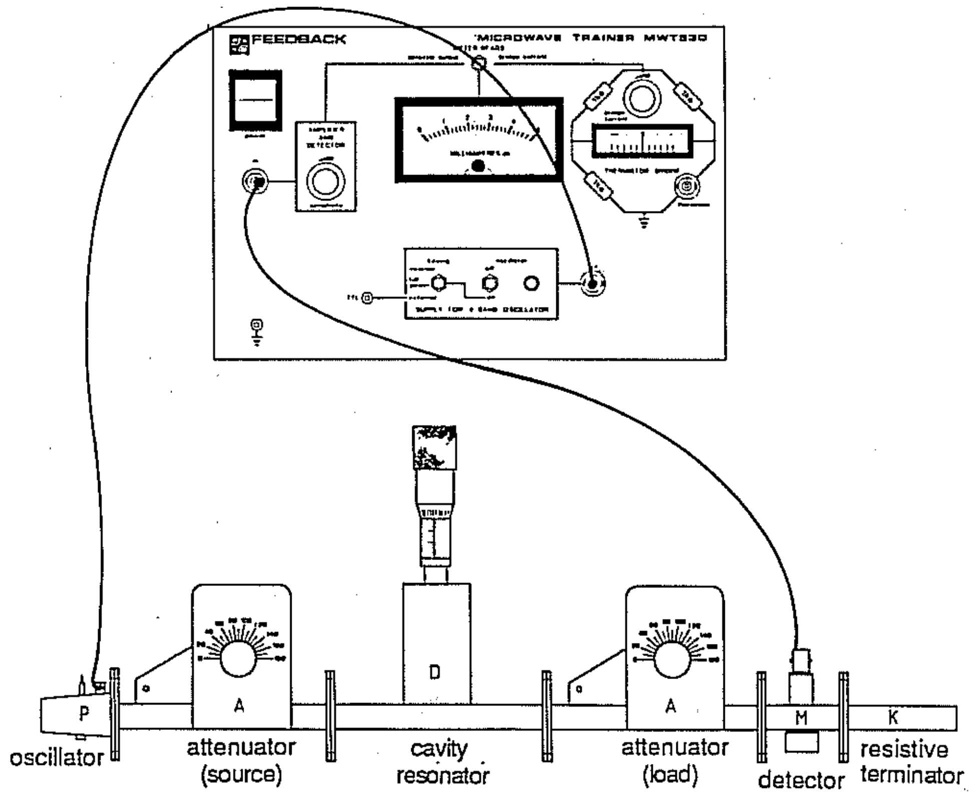
Chapter 3 Assignment 1

NOTE:

The micrometer barrel is graduated at half-millimetre intervals, with one turn of the screw advancing the plunger by one half-millimeter.

Unsrew the micrometer, again watching the meter. The reading will increase more or less to its original value, then dip a few times more as the whole lenght of the micrometer is unscrewed, thus illustrating the many modes of resonance possible in the cavity.

Fig 1.3

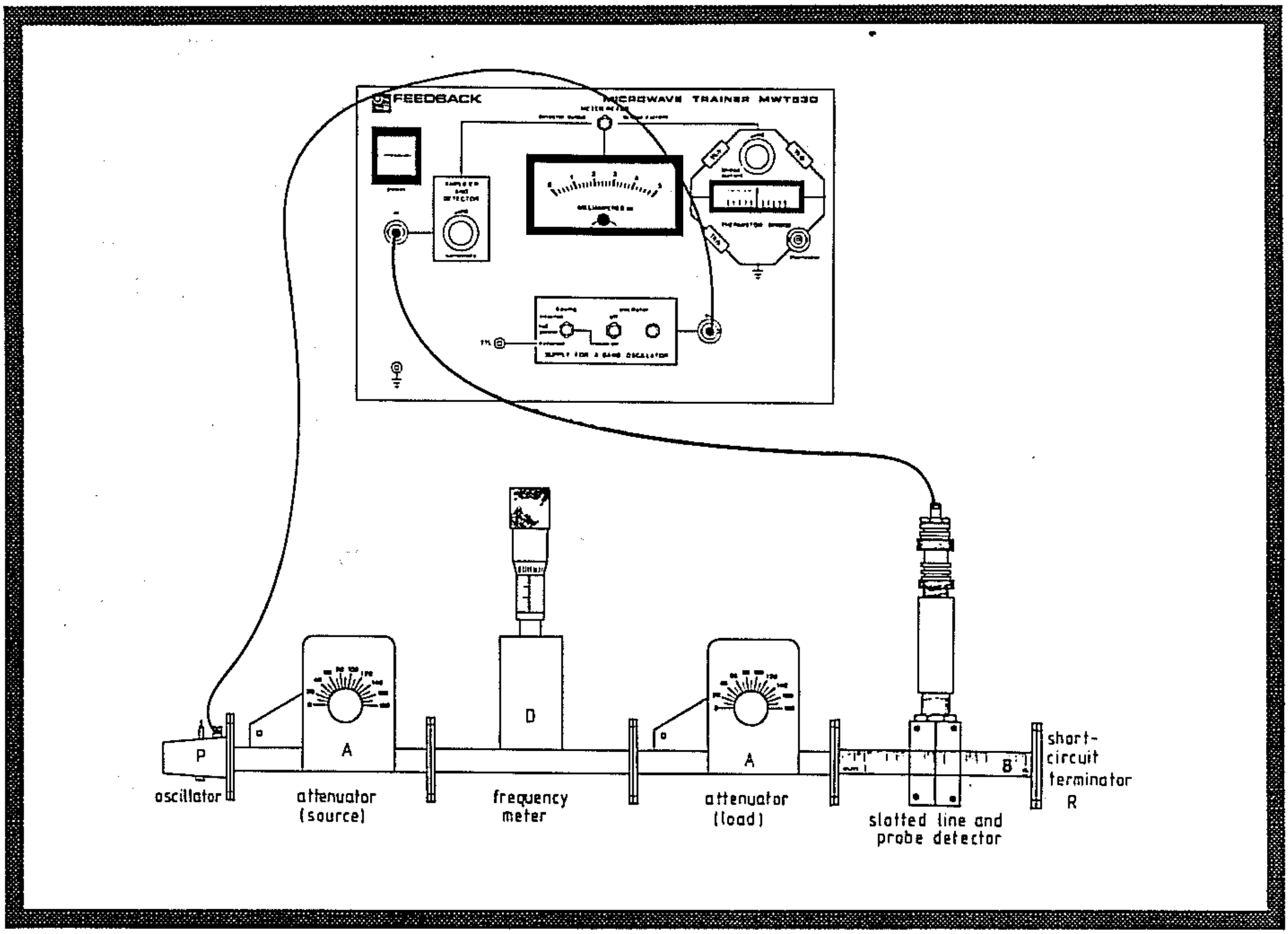


. To be useful as a frequency meter the cavity would need to be calibrated, preferably at several frequencies, so that the relationship between micrometer setting and frequency is known. Suppose that you were using a frequency meter calibrated in this way. How would you avoid getting a false reading from one of the secondary nulls?

Although the MWT530 has no means of altering the frequency of its microwave source, the wavelength of the signal in the waveguide can be measured using the slotted line.

Remove the Diode Detector and Resistive Terminator and connect the components as shown in fig 1.4, ensuring that the probe of the Slotted-line Detector is projecting no more than about 1mm into the slotted line. Connect its waveguide assembly where the Diode Detector was, and add a blanking plate to short-circuit the microwave.

Fig 1.4



Adjust the depth of penetration of the probe into the slotted-line and both attenuators to obtain full-scale deflection (fsd).

Use the Slotted-line Detector to find two successive positions at which the signal reaches a sharp null. Note each position carefully against the scale on the waveguide.

These nulls arise because the signal from the microwave oscillator travels along the guide to the short-circuited end. Its energy cannot be absorbed by the short-circuit, so the signal is reflected back along the guide. There are thus two waves; the original, or 'incident' wave, and the 'reflected' wave travelling in the opposite direction. There are places where their electric fields will be in phase, and other places where they will tend to cancel each other.

Calculate the distance between the two null positions, which is $\frac{\lambda}{2}$ That is; half the wavelength in the waveguide.

SUMMARY

A microwave signal is a short-wavelength electromagnetic signal like a radio wave, characterised by a frequency and a wavelength. It can be generated (at low power) by an FET oscillator, guided by a waveguide, and detected by a suitable diode.

A Cavity will resonate at a frequency determined by its physical dimensions. Such a cavity can be used in resonant circuits and filters, much in the same way as an LC circuit is used at lower frequencies. There are many modes of resonance possible in a cavity but the one with the lowest resonant frequency usually gives the deepest null and is most simply related to the cavity dimensions.

An absorption frequency meter is an application of a resonant cavity, loosely coupled to the transmission path, which absorbs r.f. energy when the frequency of the signal is matched by one of the cavity's resonances. Such a component could be calibrated for measurement of frequency.

The wavelength of the signal in the guide can be measured by sliding a detector probe along a slot in the guide. This component is commonly called a "slotted line".

Chapter 3 Assignment 1 - Typical Results and Answers

Typically the micrometer reading giving the deep (and very sharp) null could be 10mm. (It would normally be expressed to several significant figures, e.g 10.02 mm).

Other nulls will be found. In a typical experiment the next two nulls occured at 14.86mm (less deep) and 13.7 to 14mm (quite deep but broadly spread over this 0.3mm–long region). Other nulls may be found, becoming increasingly erratic.

As these results show, selection of the correct null is essential. The micrometer should be screwed fully in to start with, then unscrewed carefully until the deepest null is found.

NOTES:

ASSIGNMENT 2 MEASUREMENT OF VOLTAGE STANDING WAVE RATIO

CONTENT

Voltage Standing Wave Ratio (VSWR) is described and two methods of measuring it are investigated.

EQUIPMENT REQUIRED

Qty	Ident. Letter	Description
1	–	Control Console
2	A	Variable Attenuator
1	B	Slotted–line
1	P	X–Band Oscillator
1	R	Short–circuit Terminator
1	S	Probe Detector Assembly

Chapter 3 Assignment 2

OBJECTIVES

When you have completed this assignment you will:

- Be able to explain the meaning of Voltage Standing Wave Ratio.
- Know two methods of measuring VSWR and when to use them.

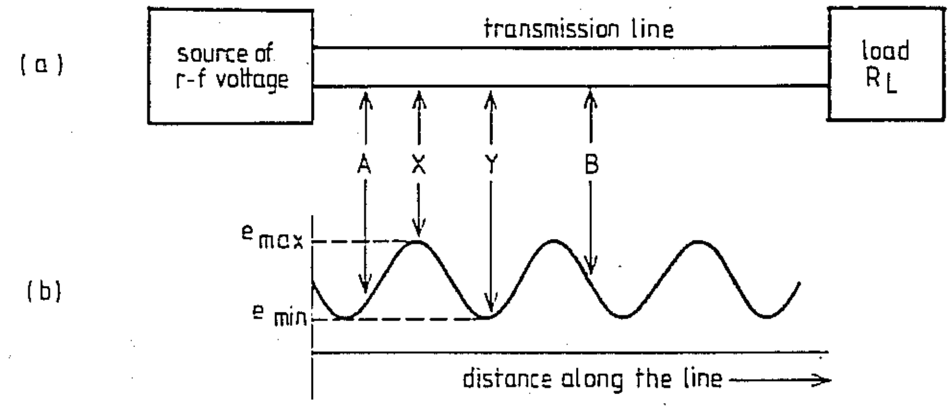
KNOWLEDGE LEVEL

Before you start this assignment you should:

- Know how to use logarithms.
- Have completed Assignment 1 'Basics of Frequency and Wavelength'

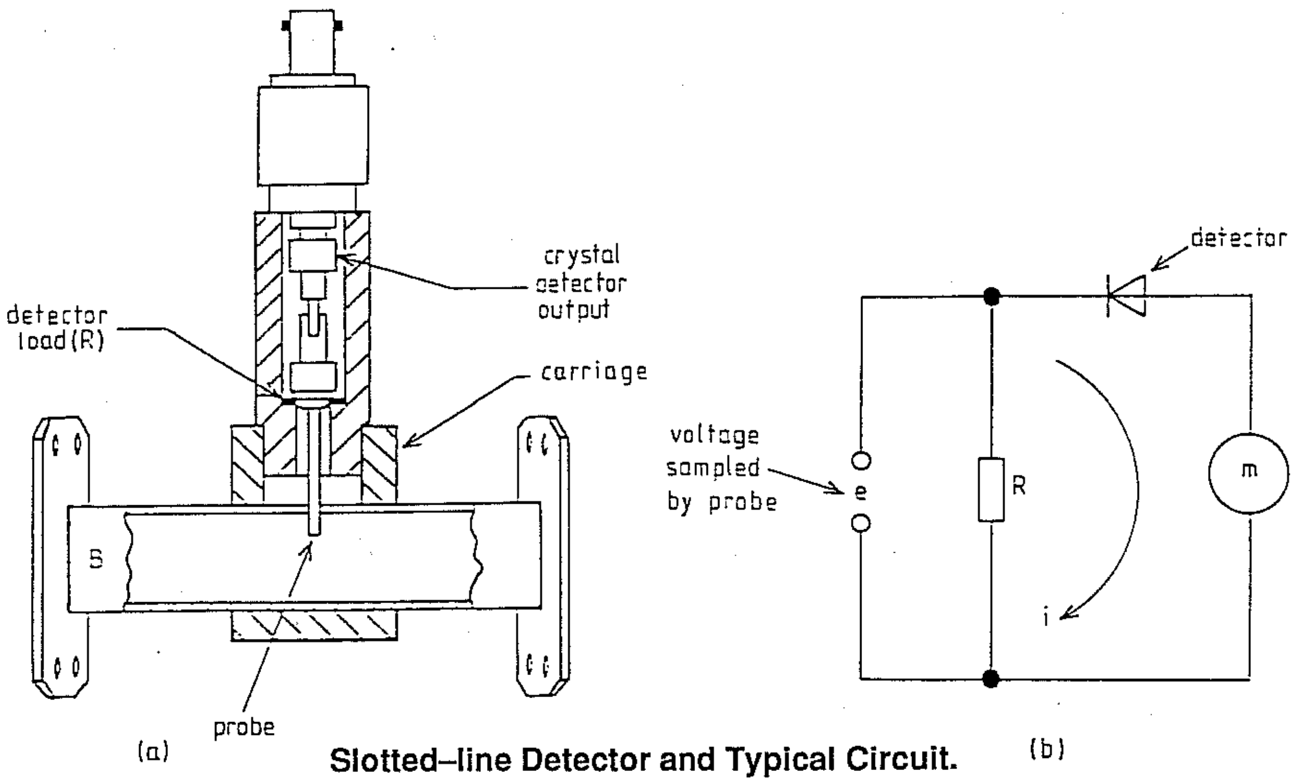
Chapter 3 Assignment 2

Fig 2.1



Voltage Distribution along a Transmission Line.

Fig 2.2



Slotted–line Detector and Typical Circuit.

Chapter 3 Assignment 2

INTRODUCTION

The electromagnetic field at any point of a transmission line (such as a waveguide) can be considered as the sum of two travelling waves, one travelling in each direction.

When a continuous wave (the 'incident wave') reaches a discontinuity in the transmission line, a portion of it (the 'reflected wave') is reflected back down the line. Usually we are trying to send r.f power from some source to a load. Consequently, any power that is reflected cannot enter the load. Often, therefore, we try to avoid reflections.

When reflection does occur, the incident and reflected waves will reinforce each other in some places, and in others they will tend to cancel each other out. The stationary pattern of larger and smaller amplitudes is called a 'standing wave'. The ratio between the largest and smallest amplitudes is called the 'standing wave ratio'. Usually the voltage amplitude is the one considered, so that the Voltage Standing Wave Ratio (VSWR) is defined as:

$$VSWR = \frac{e_{max}}{e_{min}}$$

Note that if there is no reflection, the VSWR becomes 1.

Fig 2.1 shows at (a) a signal source and load connected by a transmission line. If the load is not exactly matched to the line, the standing wave pattern shown at (b) is produced.

The instrument most commonly used to measure VSWR is a slotted length of waveguide section in which the electric field can be sampled by a movable probe. Fig 2.2 (a) shows the construction. A small probe, connected to a diode detector, extends through the slot in the waveguide wall to sample the voltage on the line. The probe and detector are mounted on a carriage which can be moved along to sample the voltage at different points along the line.

If the slotted line matches the remainder of the line, it can be inserted without introducing further reflections. Suppose that it extends between A and B in fig 2.1. Then e_{max} and e_{min} can be measured at points X and Y respectively. Note that absolute measurements are not required, but only a ratio.

Chapter 3 Assignment 2

Most microwave detectors, including the diode detector, have a square-law characteristic, $i = ke^2$, where i is output d.c current, e is the r.f voltage on the line and k is a constant introduced by the detector and the probe coupling. What is actually measured therefore is the ratio of maximum to minimum current, from which the VSWR is obtained as follows:

$$\frac{i_{max}}{i_{min}} = \frac{ke^2_{max}}{ke^2_{min}}$$

$$= \left(\frac{e_{max}}{e_{min}}\right)^2$$

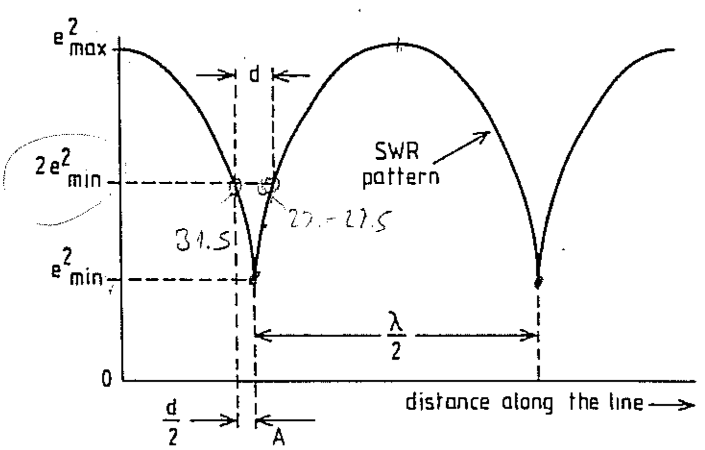
$$= (VSWR)^2$$

$$\therefore VSWR = \sqrt{\frac{i_{max}}{i_{min}}}$$

The preceding method is perhaps the simplest one, and is often referred to as the 'direct' method. It is satisfactory so long as accurate measurements of the relative values of e_{max} and e_{min} can be made. But when e_{max} becomes very large the detector can no longer be relied on to have a predictable characteristic

On the other hand if e_{min} is very small, the probe may have to penetrate so far into the field to get a measurable reading, that the field is distorted, changing the VSWR. Consequently for values of VSWR greater than about ten, the 'double minimum' method is usually employed.

Fig 2.3



Double–minimum Method

Chapter 3 Assignment 2

The principle is illustrated in fig 2.3, in which the detector output (proportional to field strength squared) is plotted against position. The probe is moved along the line to find the minimum value of signal. It is then moved either side to determine two positions at which twice as much detector signal is obtained. The distance d between these two positions then gives the VSWR according to the formula:

$$VSWR = \sqrt{1 + \frac{1}{\sin^2\left(\frac{\pi d}{\lambda}\right)}}$$

Another way of overcoming the problem of a large VSWR is to use a calibrated attenuator. The minimum signal is measured with a minimum value of attenuation. The maximum value is then found, and sufficient attenuation is introduced to reduce the detector reading to the same value as before. (This completely removes any doubts about the detector's characteristics). The VSWR is then simply the volt ratio corresponding to the change of attenuation. Thus if the attenuator is calibrated in dB,

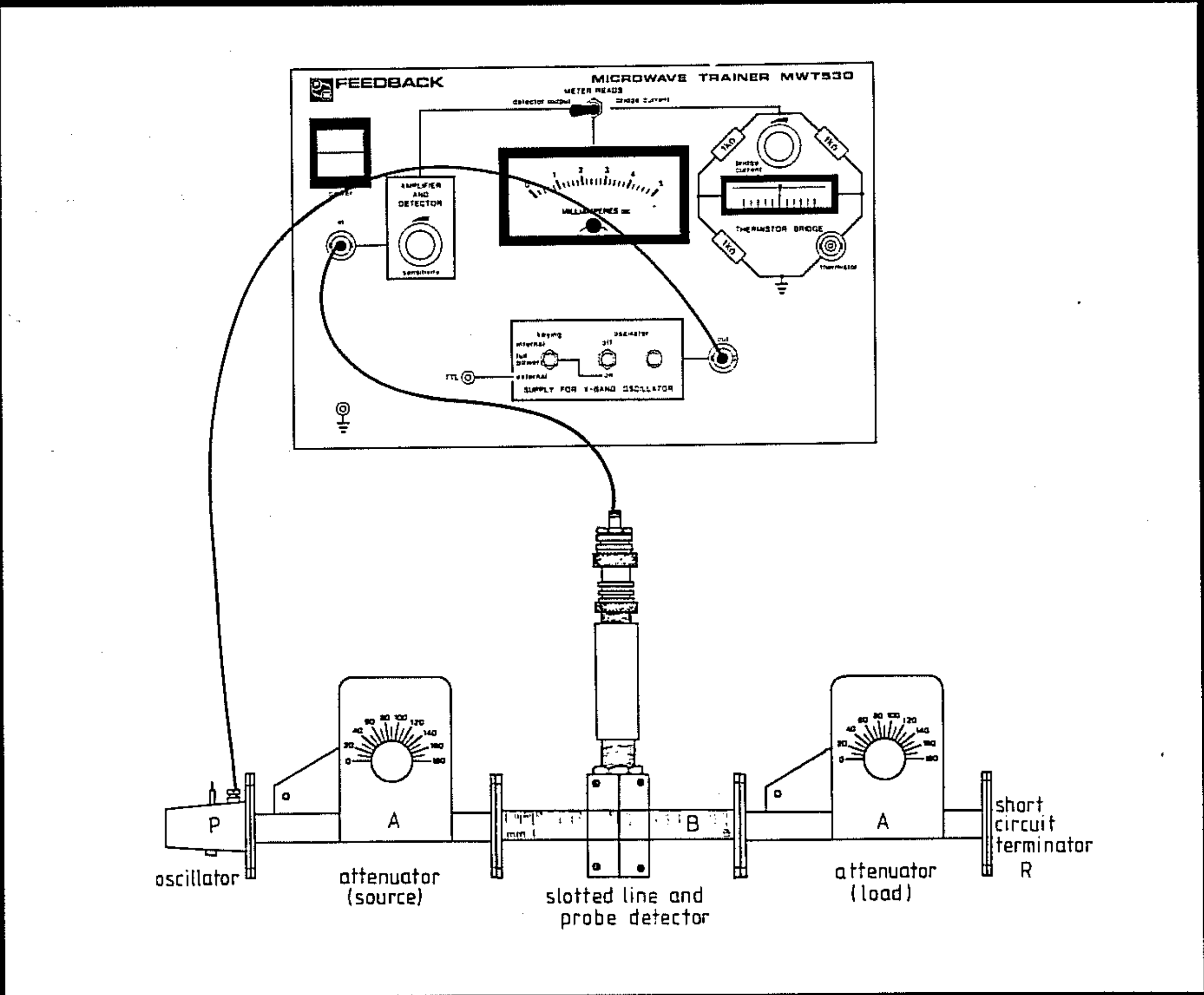
$$\begin{aligned} A_2 - A_1 &= 20 \log VSWR \\ &= 10 \log_{10}\left[1 + \frac{1}{\sin^2\left(\frac{\pi d}{\lambda}\right)}\right] \end{aligned}$$

EXPERIMENTAL PROCEDURE

REMEMBER **NEVER look into an energised waveguide**

Connect the apparatus as shown in fig 2.4. On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying. Make sure that the meter is switched to read the detector output.

Fig 2.4



Set the right-hand (load end) Attenuator to minimum attenuation (vane fully outside the waveguide). Set the sensitivity control to maximum. Start with the left-hand Attenuator (source end) at about 20° from 0 (maximum attenuation).

Chapter 3 Assignment 2

If the Detector carriage is now slid along the waveguide, the meter should move up and down. Adjust the source Attenuator so that the maximum reading of the meter is about full scale. If the source Attenuator is now set outside the range 20° to 60° open, the Detector probe may need adjusting. Slacken its locknut, and screw it in until a satisfactory reading is obtained. (It may be necessary to disconnect its lead if many turns are required).

The object is to get a full-scale reading (approximately) on the meter, with as little penetration of the Detector probe into the waveguide as possible, since the probe can upset the field in the waveguide. It is also desirable to have some attenuation between the microwave oscillator and the rest of.the equipment, so that reflected signals shall not detune the oscillator.

Standing Wave Pattern (large VSWR)

Now slide the Detector along its slot. It should be possible to observe very sharp drops (minima) in the meter reading. The reason is that, since there is nothing to absorb the incident energy, it is, all (very nearly) reflected back. The reflected wave will therefore now almost exactly cancel the incident wave at places where their phases are opposite. Record, in a table headed 'Large VSWR' the maximum and minimum meter readings, and the scale position at which they occur. **Plot a graph of meter reading against position.**

Standing Wave Pattern (small VSWR)

Set the load Attenuator for maximum attenuation (vane fully in). Without making any other adjustments, repeat the experiment, recording the results in a further table headed 'Low VSWR'. Some variation of the meter reading may be seen, but it should not be very great. The load Attenuator absorbs much of the energy travelling towards the end of the transmission line, and, if the remainder is reflected from the end, the Attenuator absorbs most of that. Plot the resulting graph on the same axes as before, labelling the two graphs to distinguish them.

The VSWR is the ratio between the maximum and minimum values of field strength. Since the Detector operates on a square law, the VSWR can be calculated as

$$\sqrt{\frac{\text{maximum meter reading}}{\text{minimum meter reading}}}$$

Make this calculation for the small VSWR experiment. Try it also with the large VSWR (load Attenuator at zero). It will be found very difficult to get sensible readings.

Chapter 3 Assignment 2

Double-minimum Method for Large VSWR

In order to establish a suitable high value of VSWR, remove the short-circuit terminator from the load attenuator, and set that attenuator for minimum attenuation (vane fully out).

Set the source Attenuator to approx. 20°. Move the Detector to find a minimum. Adjust the Detector position very carefully to find the true minimum meter reading. **Record the minimum reading.**

Now move the Detector carefully to the left until the meter reading is double the minimum value. Record the position on the scale. Move the Detector past, the minimum position to the right, and again find where the meter reading is double the minimum value. Note the distance between the two positions giving the twice-minimum reading.

Calculation

In order to calculate the VSWR you will need to know the wavelength, λg, of the r.f signal passing along the waveguide. This can be read from your graphs as twice the distance between successive minima (or the distance between two minima separated by a third).

The VSWR is then calculated as:

$$\text{VSWR} = \sqrt{1 + \frac{1}{\sin^2\theta}}$$

$$\text{where } \theta = \frac{\text{distance between twice-minimum points}}{\lambda_g}$$

This formula is explained in Appendix B. Use it to calculate the high value of VSWR.

SUMMARY

In this assignment it was seen that:

If the end (or other discontinuity) of a waveguide does not absorb the incident energy, a standing wave is set up, which is a stationary pattern of field intensity which repeats cyclically as a detector moves along the transmission path.

The ratio $\left(\frac{\text{maximum intensity}}{\text{minimum intensity}}\right)$ is known as the VSWR.

When it is small (near 1), it can be measured directly Because normal detectors produce an output proportional to the square of field intensity, the square root of the ratio of detector outputs is taken.

For large values of VSWR, direct measurement of the ratio becomes impracticable. The double-minimum method is then useful.

Chapter 3 Assignment 2 - Typical Results and Answers

The graph of detector output against detector position, with the load attenuator vane fully out, should resemble fig 2.3, with the minima probably too small to measure.

When the load attenuator vane is put right in, the resulting graph should ideally be a horizontal straight line. In practice some variation in height will probably be found, giving a VSWR of typically 1.4.

Double Minimum Method

With source attenuator and detector adjusted to give a minimum of 1mA, readings of 2mA were obtained at 35mm and 46mm, i.e 11 mm apart. From the graph resembling fig 2.3, the wavelength in the guide was 36mm,

$$\text{so } \theta \text{ was } \frac{11}{36} = 0.3055 \text{ rad.}$$

The VWSR was therefore:

$$\sqrt{1 + \frac{1}{\sin^2 0.3055}} = 3.47$$

(Note that if the direct-measurement method had been used, the ratio of meter readings would have been, possibly quite impractical)

ASSIGNMENT 3 MEASUREMENT OF MICROWAVE POWER

CONTENT

Microwave power is measured using a Bolometer in conjunction with a Wheatstone Bridge.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	L	Bolometer (Thermistor–type)
1	P	X–Band Oscillator

Chapter 3 Assignment 3

OBJECTIVES

When you have completed this assignment you will:

- Know how microwave power can be measured using a Bolometer device.

KNOWLEDGE LEVEL

Before you start this assignment you should:

- Know how a Wheatstone Bridge circuit operates.

Chapter 3 Assignment 3

INTRODUCTION

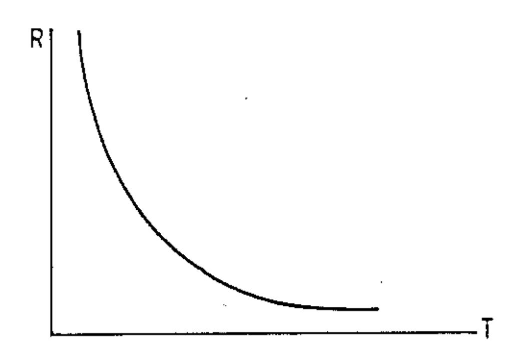
In relation to microwaves, just as with other forms of energy, 'power' means the rate at which energy is being transferred. However it is not generally possible to measure voltage and current of microwaves, so indirect methods of power measurement are employed. In this assignment a microwave power bridge will be used.

When microwave energy is absorbed by a material it is converted into heat, which causes a temperature rise. If the material has some physical property which changes with temperature, this change can be used to measure the microwave power.

A 'bolometer' is a device whose temperature coefficient of resistance is used in this way. Two common forms of bolometer are the barretter, which is a thin metallic wire, and the thermistor, which is piece of semiconductor material.

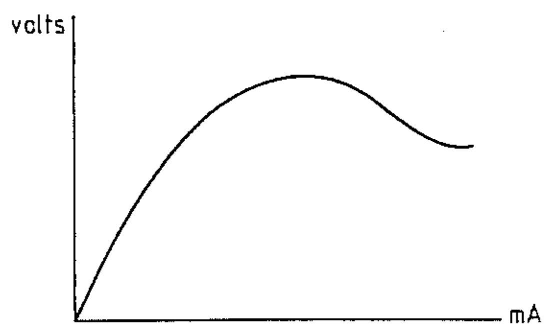
The barretter provides a linear relatonship between power absorbed and its resistance, but it is rather fragile and will not withstand electrical overloads well. The thermistor is more robust and sensitive, but the resistance change is not linearly related to the temperature or, therefore, the power absorbed (see Fig 3.1). The MWT530 therefore uses a thermistor-type bolometer in such a way that its non-linearity does not matter.

Fig 3.1



Resistance/Temperature Graph for a Thermistor

Fig 3.2

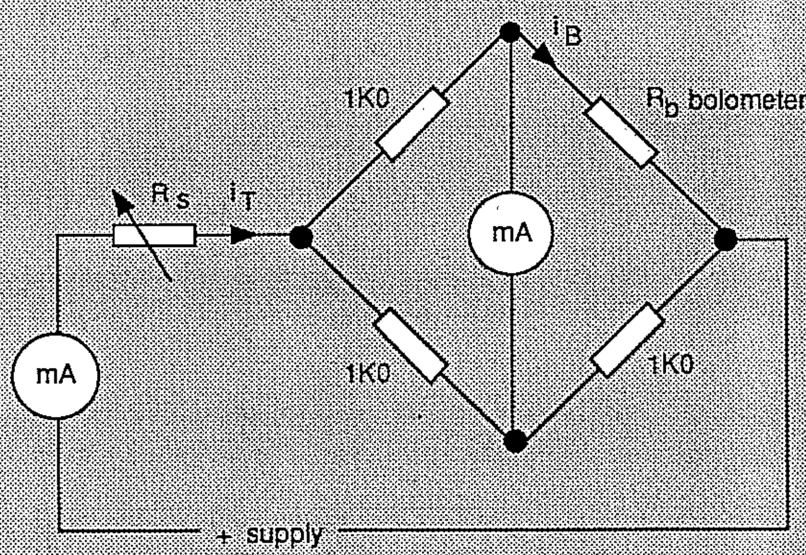


Voltage/Current Characteristics of a Thermistor

NOTE: If a slowly increasing current is applied to a thermistor, it will be progressively warmed up, and its resistance will fall. (A point is eventually reached when a further increase in current actually causes a decrease in voltage drop across the thermistor, as shown in fig 3.2).

Chapter 3 Assignment 3

Fig 3.3



Power Measuring Circuit

The circuit used for measuring power is a bridge, fig 3.3. The total current i_T can be controlled by the series resistor R_s. The power supplied to the bolometer, and consequently its temperature and resistance, can be adjusted by the series resistor. If the adjustment is made so that the bridge is balanced, the current in the bolometer will be half the total current,

$$i_B = \frac{i_T}{2}$$

and the power in the bolometer will be; $i_T^2 \frac{R_b}{4}$

If now r.f power is applied to the bolometer (thermistor), its temperature will rise, changing its resistance so that the bridge is unbalanced. If the bridge is re-balanced by adjusting the supply current to a new value $i_T - \delta i$, the bolometer resistance must have returned to the value R_b, so that the power supplied by the bridge is now:

$$P_{dc} = (i_T - \delta i)^2 \frac{R_b}{4}$$

The r.f power supplied will be the difference between these two power values,

$$P_{rf} = \frac{i_T^2 R_b}{4} - \frac{(i_T - \delta i)^2}{4} R_b$$
$$= \frac{R_b}{4}\left[i_T^2 - (i_T - \delta i)^2\right]$$
$$= \frac{R_b}{4}\left[\delta i(2i_T - \delta i)\right] \qquad 3.1$$

In most cases δi is very small compared with i_T, so that approximately:

$$P_{rf} = \frac{R_b}{2} i_T \delta i \qquad 3.2$$

When the bridge is balanced the resistance of the four arms in series-parallel is R_b, so that the voltage across the bridge, e_{dc}, is given by:

$$e_{dc} = i_T R_b \qquad 3.3$$

so that equation 3.2 can be rewritten as:

$$P_{rf} = \frac{1}{2} e_{dc}(-\delta i) \qquad 3.4$$

A bolometer bridge can be used in various ways. The balance can be adjusted by hand, or this can be done automatically. A simple alternative, used in cheap power meters, is simply to leave the bridge supply constant, and let the bridge become unbalanced when r.f power is applied; a meter displays the unbalance voltage, which is a measure of the r.f power.

In this experiment the source of microwave power will be the FET Oscillator, supplied with d.c from the MWT530 power supply.

The amount of power sent to the Bolometer will be adjusted by a variable Attenuator. This comprises a resistive card which can be inserted to an adjustable depth through a slot in the waveguide wall. The deeper it enters the waveguide, the more energy is absorbed by it, thus reducing the power at its output port.

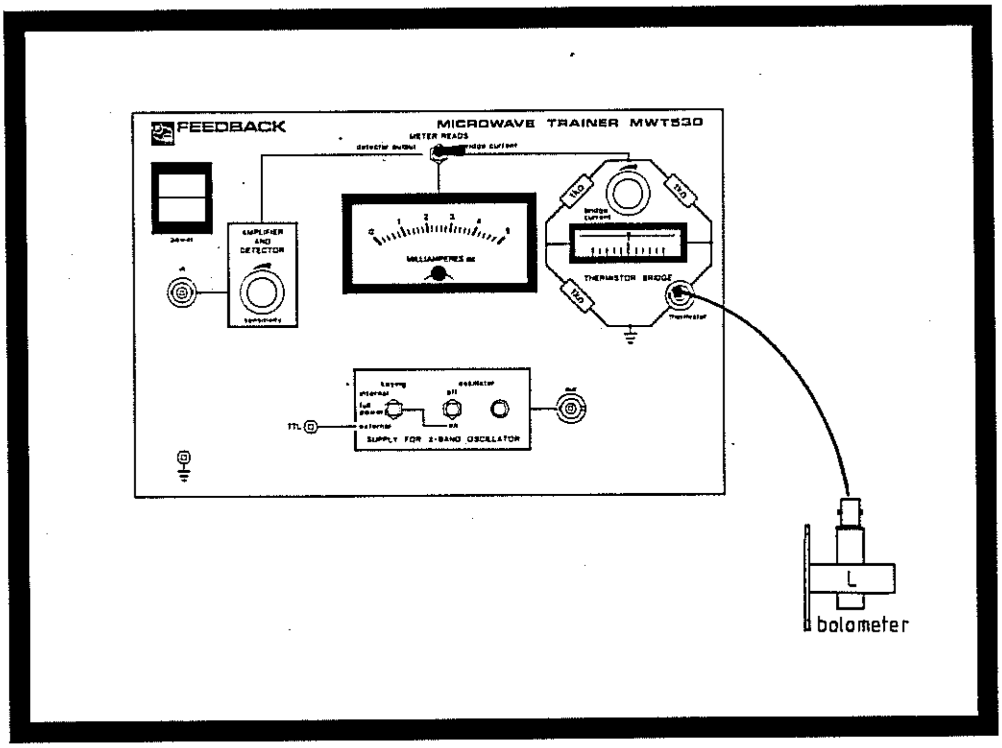
Chapter 3 Assignment 3

EXPERIMENTAL PROCEDURE

REMEMBER | **NEVER look into an energised waveguide**

Connect the Bolometer to the bridge as shown in fig 3.4. The meter should be switched to read bridge current. Set the bridge current to its minimum value by turning its control knob fully anticlockwise.

Fig 3.4



Now slowly raise the bridge current, watching the meter. It will at first go off the scale to the right. This is because a thermistor has a resistance much higher than the other bridge rms, which are each 1kΩ. As the current is raised, heating of the thermistor decreases its resistance, until eventually the bridge will pass through balance, shown by the meter needle moving to the left.

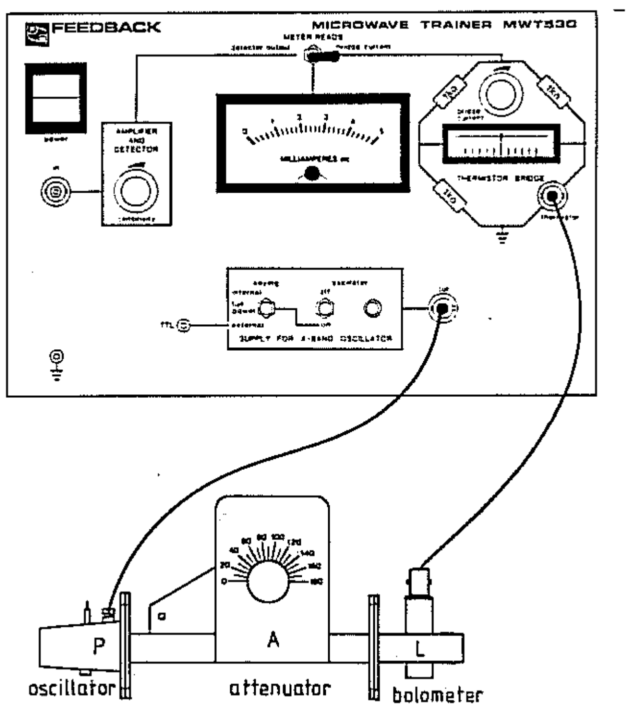
Adjust the bridge current until the meter needle is central.

NOTE: To check that it really is a temperature effect, try blowing gently into the Bolometer mount. Your breath will probably warm the thermistor, causing a change in the bridge balance. Another check is to switch off the power for a time; then, when the meters have stopped moving, switch it on again. The bridge meter will first swing to the left, then return to balance, owing to time taken to heat the thermistor to its steady temperature.

Chapter 3 Assignment 3

Next, after first making sure the supply for the microwave Oscillator is switched off, connect up the Oscillator, a Variable Attenuator and the Bolometer as shown in fig 3.5. Set the Attenuator to the '0' position on the scale (with the vane inside the slotted waveguide).

Fig 3.5



Check the balance of the bridge, and adjust it if necessary. Make a note of the bridge current, in a table prepared as in fig 3.6.

Fig 3.6

Attenuator Setting (° degrees)	Bridge Current (mA)	d.c Power in Thermistor (mW)	r.f Power in Thermistor (mW)
(oscill'r off)			
00			
10			
20			
30			
40			

Chapter 3 Assignment 3

Switch on the microwave Oscillator and set its left-hand switch to the central 'full power' position. Gradually rotate the Attenuator and observe the effect on the bridge balance. As the resistive vane is taken out of the waveguide, more power reaches the Bolometer, unbalancing the bridge.

Set the Attenuator to several different positions. Rebalance the bridge by adjusting the bridge current. Note the new value of bridge current in the table.

Calculations

The resistance of the bridge is 1kΩ whenever it is balanced, and one-quarter of the power put into it goes into the thermistor. Calculate the power in the Bolometer for each of the Attenuator settings.

SUMMARY

Microwave power from the Oscillator was transmitted through the Attenuator to a thermistor-type Bolometer. A bolometer is a device which absorbs power and produces an electrical response to the resulting temperature change, in this case by changing its resistance.

The bolometer was used with a Wheatstone bridge for measuring the r.f power. A preliminary adjustment, carried out with r.f power present, set the d.c power to a level which caused the bridge to be balanced. R.f power was then applied, and the d.c supply to the bridge was again adjusted until the bridge balanced. The r.f power was taken as the difference between the d.c power supplied to the Bolometer in the two cases, i.e one quarter of the difference between the d.c powers supplied to the bridge.

Chapter 3 Assignment 3 - Typical Results and Answers

Ref fig 3.6

Attenuator Setting (° degrees)	Bridge Current (mA)	d.c Power in Thermistor (mW)	r.f Power in Thermistor (mW)
(oscill'r off)	3.8	3.61	0
00	3.8	3.61	0
10	3.7	3.42	0.19
20	3.15	2.48	1.13
30	2.8	1.96	1.65
40	1.98	0.98	2.63

It is not possible to take more readings, because the microwave power then exceeds the maximum available d.c power at the thermistor. Operation with no attenuation after the oscillator is in any case likely to be upset by reflections from its load.

NOTES:

ASSIGNMENT 4 DETECTOR CHARACTERISTICS

CONTENT

The characteristic behaviour of a simple diode detector operating with small signals is investigated.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	B	Slotted–line
1	L	Bolometer (Thermistor–type)
1	P	X–Band Oscillator
1	S	Probe Detector Assembly

Chapter 3 Assignment 4

OBJECTIVES

When you have completed this assignment you will:

- Know that a diode detector has a square law characteristic for small signals.
- Understand the operation of a simple diode detector.

KNOWLEDGE LEVEL

Before you start this assignment you should:

- Have completed Assignment 3 'Measurement of Microwave Power.
- Understand the production of standing waves in an element of transmission line and preferably have completed Assignment 2 'Measurements of Voltage Standing Wave Ratio'.

Chapter 3 Assignment 4

INTRODUCTION

The most common device used for detecting microwaves is a semiconductor diode. This may be used either for producing a d.c whose magnitude is related to the strength of the microwave field, or it can be used as a mixer, in which the frequency of a received signal is changed by combining it with a locally-generated signal in a non-linear device.

When it is used as a simple detector, the signal is usually small, and for small signals the diode produces a current proportional to the square of the electric field. This implies that the diode output current is proportional to the power of the microwave signal. (For large signals the characteristic will depart from the square law, but diode crystals are usually protected from large signals).

The square-law behaviour applies to a range of different detector types, and can be explained in terms of the Taylor series. If the current i through a detector is given as a function of applied voltage v,

$$i = f(v)$$

then, expanding this function by Taylor's theorem,

$$i = a0 + a_1 v + a_2 v^2 + a_3 v^3 + a_4 v^4 + \dots$$

The first term must be zero if the diode has no source of energy associated with it. If an r.f voltage E cos qt is applied, the second term shows a proportional r.f component of current, which will in practice be filtered out in the detector circuit. The next term is the first one supplying a 'detected' d.c component of current, since it gives rise to a current

$$i = a_2^2 \cos^2 \omega t$$

$$= a_2^2 \left(\frac{1}{2} + \frac{1}{2} \cos 2\omega t \right)$$

so that the current has a high-frequency component at the second harmonic of the input frequency, and a d.c component

$$\frac{1}{2} a_2^2$$

This is the useful detected signal. If the input signal is small the higher terms will be insignificant in comparison. (They will however cause some departure from the square law as the signal level is increased).

Chapter 3 Assignment 4

This experiment will verify the square-law characterisic by measuring the power of a microwave signal with a bolometer and bridge (as in Assignment 3) and simultaneously measuring the diode detector's output. They should be proportional to one another.

EXPERIMENTAL PROCEDURE

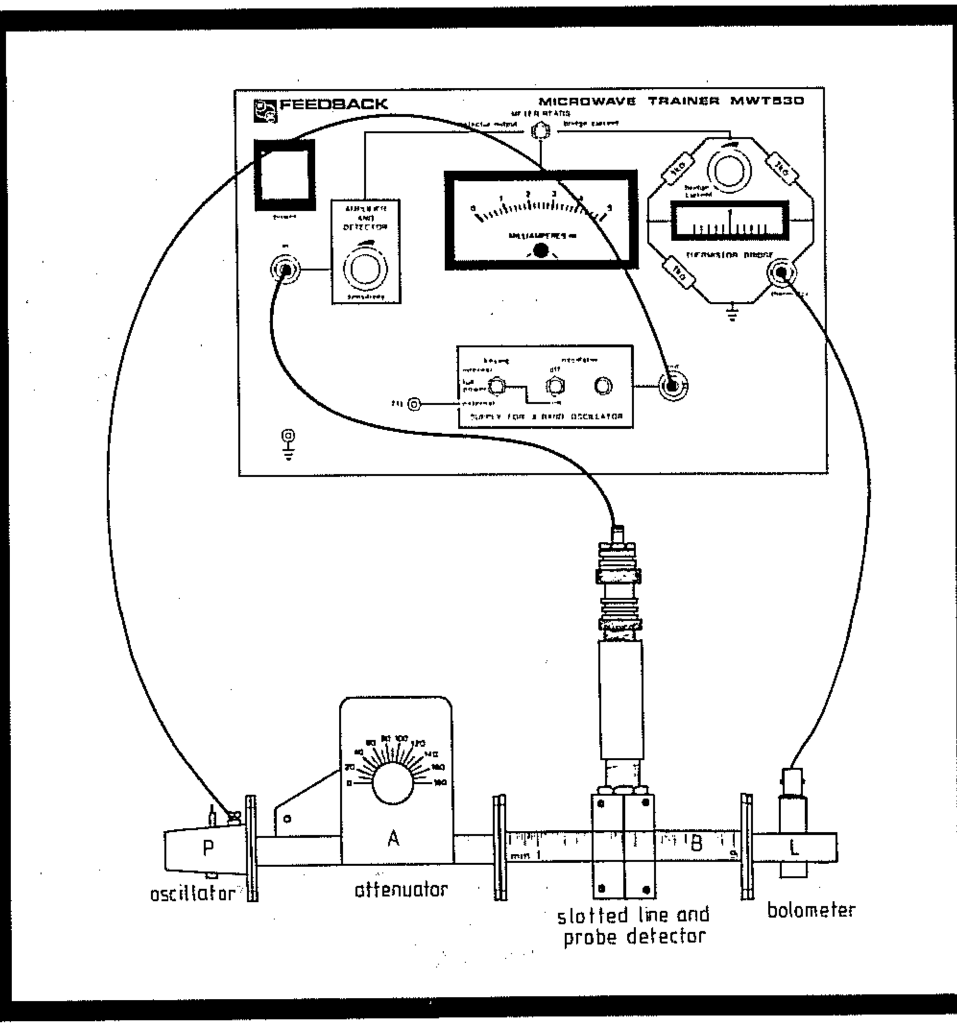
Preliminary adjustments

Before assembling the apparatus, adjust the probe of the Diode Detector for minimum penetration into the waveguide. (This Detector is being used essentially so that a small signal can be applied to it, proportional to the much larger signal required to work the Bolometer).

REMEMBER **NEVER look into an energised waveguide**

Connect the apparatus as shown in fig 4.1. On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying; set the METER READS switch to 'bridge current'.

Fig 4.1



Chapter 3 Assignment 4

It is important not to overload the Detector, so start with the Attenuator set for maximum attenuation and the sensitivity of the Detector amplifier to maximum. Switch the meter to read the Detector output. Switch on and carefully decrease the attenuation.

If the meter does not rise to full scale, the Detector probe may need adjustment. Slaken the locknut on the Detector, screw the Detector in slightly (a fraction of a turn may make a large difference), and repeat the operation of the last paragraph. Continue these adjustments until full scale reading is obtained on the meter, with the attenuation at minimum and the sensitivity control near maximum.

If necessary adjust the postion of the probe detector along the slotted line so as to produce a full scale reading.

Main experiment

The readings of the Detector and the Bolometer will now be compared at various power levels, set by adjusting the Attenuator. Start at maximum power (least attenuation).

Fig 4.2

Prepare a table for readings, as in fig 4.2

Detector Output (meter reading mA)	Bridge Current (mA)		Power in Thermistor		
	Oscillator OFF	Oscillator ON	Total (mW)	d.c (mW)	r.f (mW)
5.0					
4.5					
4.0					
3.5					
3.0					
2.5					
2.0					
1.5					
1.0					
0.5					
0.0					

Chapter 3 Assignment 4

Conduct the experiment, step-by-step, as follows:

1 Switch the meter to read the Detector signal and set the Attenuator for a suitable meter reading. Readings may be taken at 0.5mA intervals.

2 With the meter switched to read bridge current, and the r.f Oscillator off, balance the bridge and read and record the bridge current. Calculate the power in the Bolometer.

3 Repeat step 2, but with the r.f Oscillator on.

4 Repeat steps 1, 2 and 3 until the meter reading is down to 0.5mA.

NOTE: It may not be necessary to repeat step 2 every time, but temperature drifts may upset the smaller readings if care is not taken.

When the readings are all taken, plot a graph of detector output against power. It should ideally be a straight line and through the origin.

SUMMARY

A detector is a non-linear device, whose characteristic can be expressed as a power series. The term of first degree contributes nothing to the d.c output. The term of second degree is the first term which contributes to a d.c output. For small signals this is the only significant term, so that for small signals the detector output is proportional to the square of the field strength, and therefore to the power. The experiment verified that detector output varies in proportion to the power.

Chapter 3 Assignment 4 - Typical Results and Answers

Ref fig 4.2

Detector Output (meter reading mA)	Bridge Current (mA)		Power in Thermistor		
	Oscillator OFF	Oscillator ON	Total (mW)	d.c (mW)	r.f (mW)
5.0	3.9	3.68	3.8	3.38	0.42
4.5	3.9	3.72	3.8	3.46	0.34
4.0	3.9	3.74	3.8	3.50	0.30
3.5	3.9	3.77	3.8	3.55	0.25
3.0	3.9	3.79	3.8	3.59	0.21
2.5	3.9	3.80	3.8	3.61	0.19
2.0	3.9	3.81	3.8	3.63	0.17
1.5	3.9	3.82	3.8	3.65	0.15
1.0	3.9	3.83	3.8	3.67	0.13
0.5	3.89	3.86	3.78	3.72	0.06
0	3.89	3.89	3.78	3.78	0

NOTES:

ASSIGNMENT 5 MEASUREMENT OF IMPEDANCE

CONTENT

The concept of impedance in a waveguide is introduced and the use of a Smith Chart is explained.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	B	Slotted–line
1	C	Slotted–line Tuner
1	K	Resistive Terminator
1	P	X–Band Oscillator
1	S	Probe Detector Assembly

Chapter 3 Assignment 5

OBJECTIVES

When you have completed this assignment you will:

- Be able to define the impedance of a waveguide.
- Understand the meaning of the term 'characteristic impedance'
- Know a method of measuring impedance.
- Know how to use a Smith Chart.

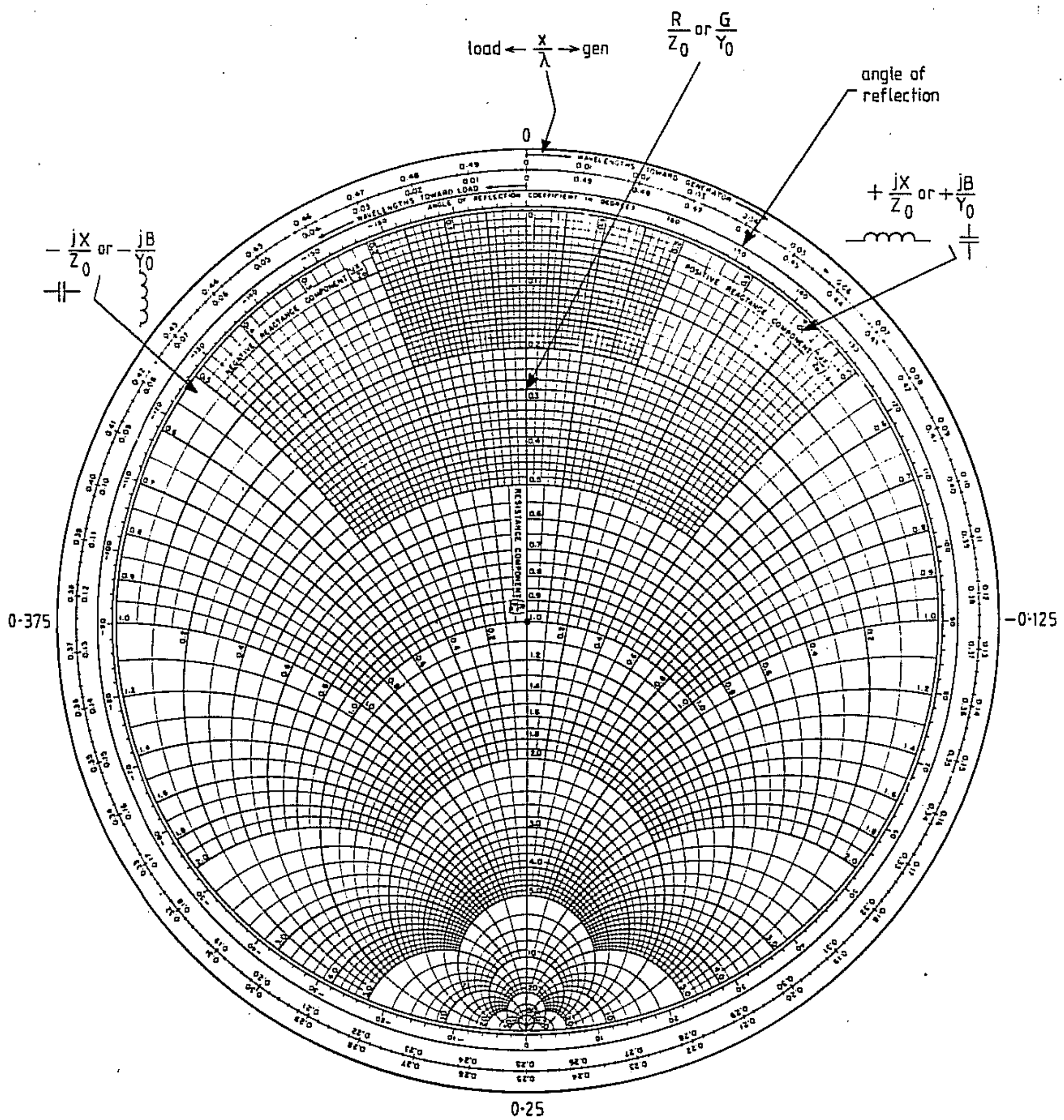
KNOWLEDGE LEVEL

Before you start this assignment you should:

- Have completed Assignment 2 'Measurement of Voltage Standing Wave Ratio'.

Chapter 3 Assignment 5

Fig 5.1



Typical Smith Chart

Chapter 3 Assignment 5

INTRODUCTION

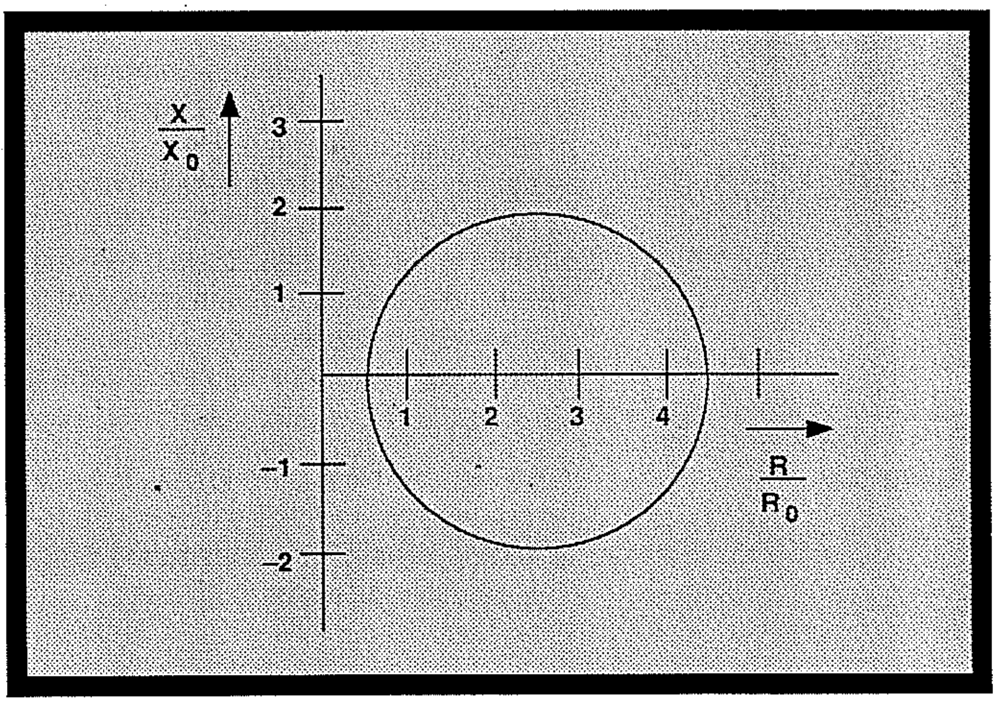
It is not possible to measure voltage in a waveguide with a voltmeter, nor current with an ammeter. The impedance is therefore defined as the ratio between the electric and magnetic fields. It has the dimensions Ω, as for an ordinary impedance and may be denoted by:

$$Z = R + jX$$

If there is no reflected wave, this ratio is the same at all points along the waveguide, and is called its 'characteristic impedance', and is denoted by Z_0. In a system with no losses, Z_0 is a pure resistance. If a reflected wave is present, causing standing waves, then the impedance varies periodically with distance along the transmission path. In general, therefore, the position, at which the impedance is measured, must be specified. The mathematical expressions for values of R and X are complicated. Graphical methods of analysis are, therefore often used.

It can be shown that for a given load $R_L + jX_L$ at the end of a uniform waveguide, the impedance at other places will take values represented by points on the circle in fig 5.2.

Fig 5.2



This diagram could be drawn with a family of circles for various resistive loads; it could then be used as a nomograph for calculating impedance at various points. However it would not cover all possible values of R up to infinity, and since the circles would not be concentric, it would be difficult to mark scales on each one to show distance along the transmission path.

Chapter 3 Assignment 5

A more convenient form of chart is therefore always used. It is called the Smith chart, fig 5.1, and is a conformal transformation of the rectangular R, jX diagram of fig 5.2.

The scale on the outer edge represents distance toward the generator, measured in wavelengths. It may sometimes be more convenient to use the scale inside the outer circle, marking distance toward the load.

Impedance values are normalised with respect to the characteristic impedance Z_0. The circles which touch the outer circle at the bottom of the diagram are curves of constant resistance $\frac{R}{Z_0}$; these are cut at right angles by another family of circles, each of which $\frac{jX}{Z_0}$ represents a particular value of reactance . Thus every point in the diagram specifies a particular, normalised impedance

$$\frac{Z}{Z_0} = \frac{(R + jX)}{Z_0}$$

The impedance at various points along the waveguide now lies always on a circle with its centre at the centre of the diagram. This circle is often called a circle of constant mismatch, since the matching in question is between two constant items, the load and Z_0. (If the load is equal to Z_0, there is no mismatch, and the circle shrinks to the point O). Thus if the impedance at one point is known, this establishes the radius of that circle. The impedance at various distances from the known point is then established by moving around the circle through the appropriate angle.

Example

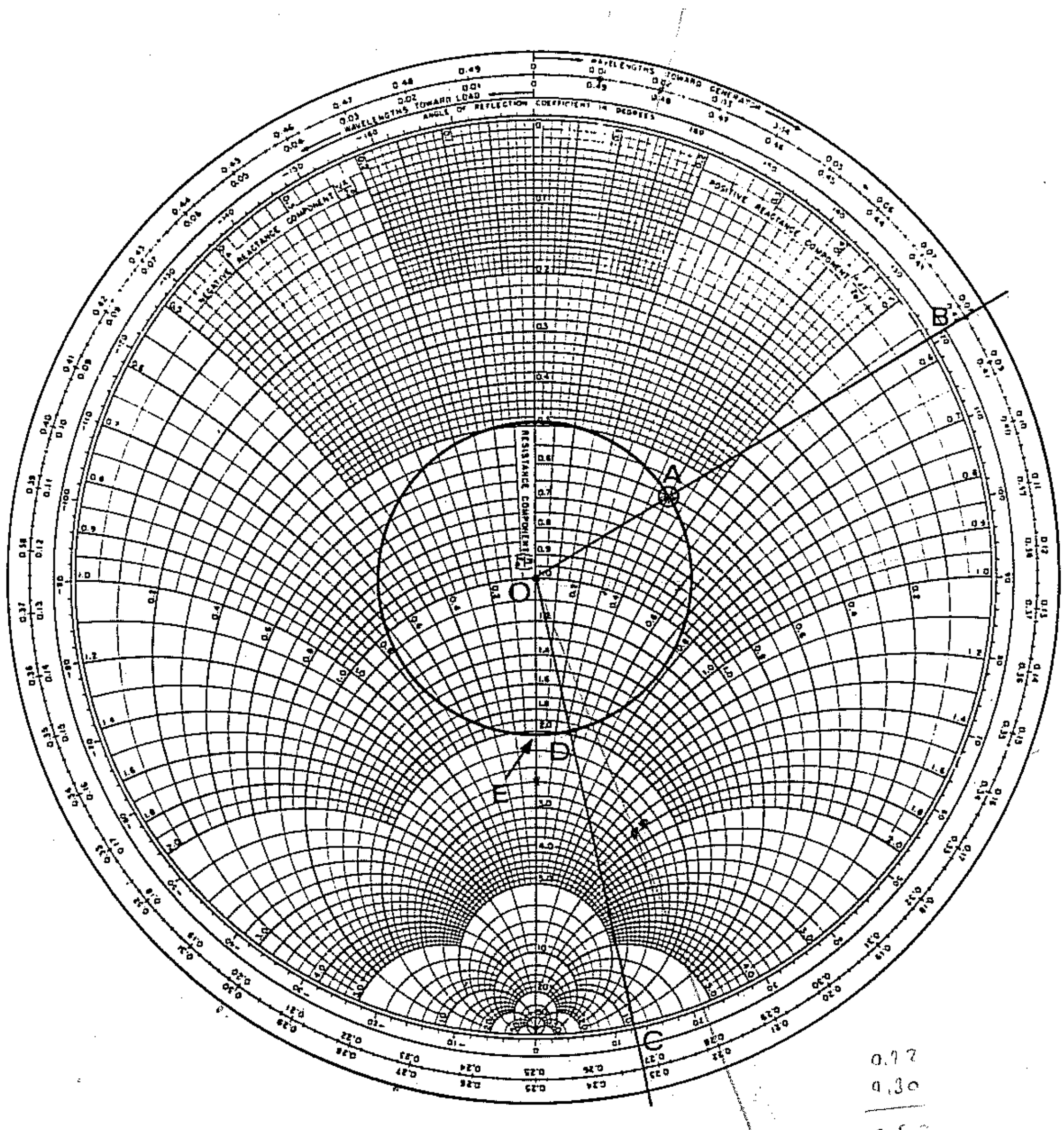
A waveguide having no losses is terminated by an impedance whose normalised value is 0.6 + j0.4 . The wavelength in the guide is 40mm. What is the impedance 6mm away from the termination? The solution is shown in fig 5.3.

Point A represents the terminating impedance, or load. The line OB is drawn to find its place on the scale (at the edge of the diagram) or distance.

It need not concern us for the problem given, but the point found on the scale, 0.082, shows that the line impedance will be resistive when measured at points $(0.5n - 0.082)\lambda$ from the load.

Chapter 3 Assignment 5

Fig 5.3



Results of Experiment-Smiths Chart

Chapter 3 Assignment 5

The problem concerns the point 6mm from the termination. 6mm is $\frac{6}{40}$ or 0.15 wavelengths. Moving this distance around the outer scale establishes point C, at a position 0.082 + 0.15 = 0.232 on the outer scale. The required impedance must lie on the line OC, because this is the specified position. It must also lie on the constant mismatch circle. It therefore is given by the point D. The required normalised impedance is therefore 2 + j0.36.

Notice that a little further away from the load, at E, the sign of the reactance X changes. This corresponds to a point of maximum electric field. It also gives the VSWR, since at this point the normalised resistance value is equal to the VSWR.

Notice also that travelling half a wavelength from a particular point corresponds to moving one complete revolution (360°) around the chart.

EXPERIMENTAL PROCEDURE

The two items, Slotted-line Tuner and Resistive Terminator (representing 'load'), at the right of the diagram represent the impedance which is to be measured. Adjust the tuner so that the probe protrudes approximately 5mm into the line.

Set up the apparatus as shown in fig 5.4.

On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying; set the METER SWITCH to 'detector output'.

REMEMBER NEVER look into an energised waveguide

Set the Attenuator initially to nearly maximum attenuation. Switch on the microwave Oscillator.

Move the Detector carriage to find a point of maximum signal. Adjust the sensitivity of the amplifier and, if necessary, the Attenuator, to obtain a full scale reading on the meter.

Record the meter reading.

Move the Detector carriage to find a minimum. Record the meter reading and the position of the carriage x_1. Calculate the VSWR:

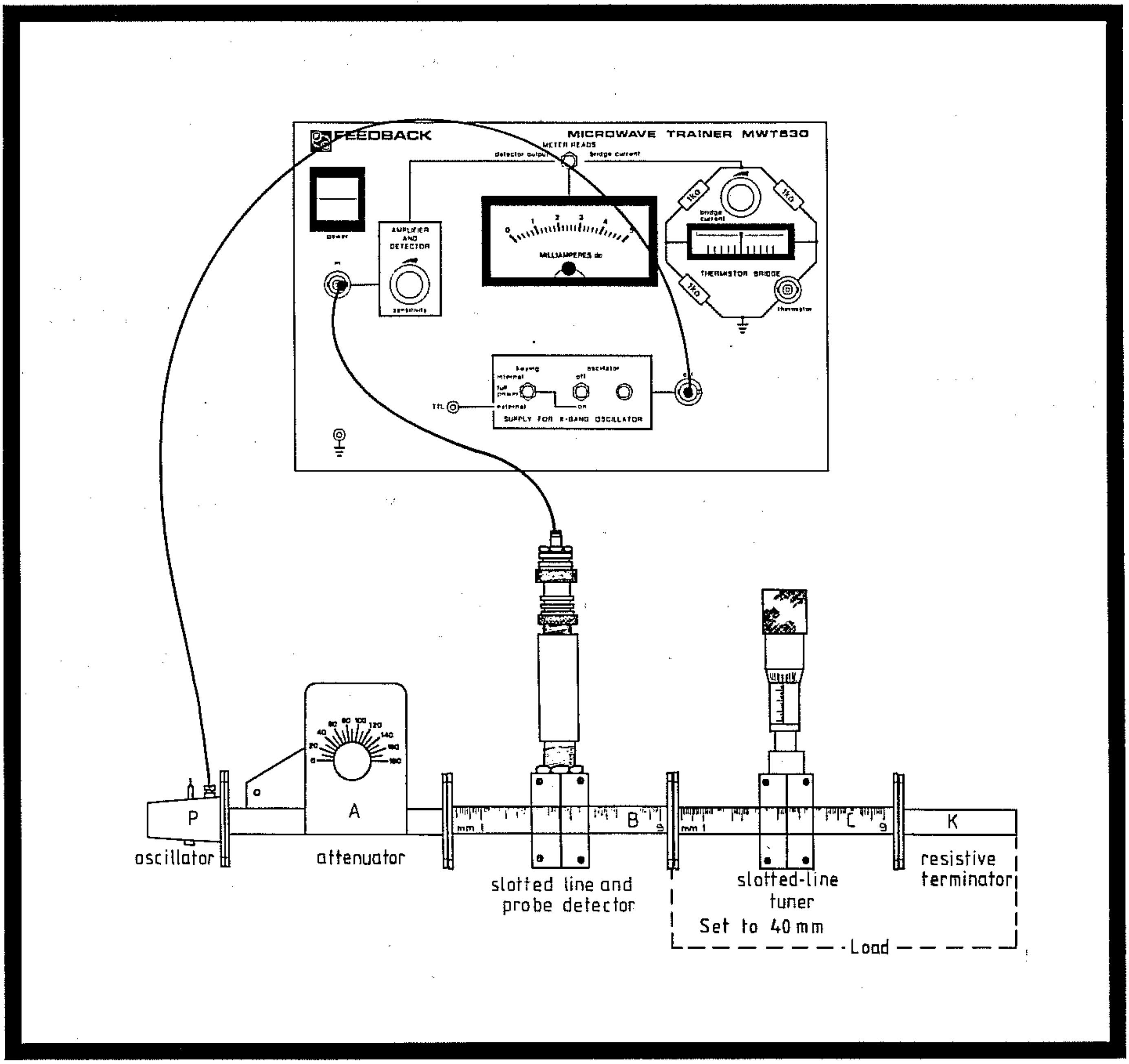
$$\text{VSWR} = \sqrt{\frac{\text{maximum meter reading}}{\text{minimum meter reading}}}$$

Chapter 3 Assignment 5

Draw on a Smith chart a circle the radius of which corresponds to this value on the R + j0 scale.

Remove the slotted-line Tuner and Terminator and create a short-circuit by replacing them with a blanking plate.

Fig 5.4



Find two consecutive positions x_2 (nearer the short-circuit) and x_3 which give minimum readings. Record the positions and calculate the guide wavelength λ_g, which is twice the distance between them.

Calculate $\frac{(x_1 - x_2)}{\lambda_g}$

On the Smith chart, starting from the top position (corresponding to $Z = 0 + j0$), move round the outside scale 'towards the load' the amount you have just calculated. If $x_2 > x_1$ (i.e the expression you calculated was negative) the movement will be 'toward the generator'.

Join the point you have reached to the centre O. Read the required impedance from the R and X scales at the point where this line intersects the constant mismatch circle.

SUMMARY

In a waveguide, the impedance at a given point is defined as the ratio between the electric and magnetic fields. It is measured in ohms.

A waveguide in which no reflections occur has, at a given operating frequency, a value of impedance called its 'characteristic impedance'.

When reflections do occur, the impedance varies with position along the waveguide, because of the standing waves. The VSWR, the impedance and distance (measured from the source, or from a position behaving like a resistive load) are related together by the Smith chart.

A method of measuring impedance is to measure the VSWR, then substitute a short-circuit for the impedance in question, and measure the displacement of the minima in the standing wave pattern.

Chapter 3 Assignment 5

NOTES:

Chapter 3 Assignment 5 - Typical Results and Answers

With maximum meter reading set to 5mA, minimum is 0.8mA, so

$$VWSR = \sqrt{\frac{5}{0.8}} = 2.5$$

(Note that the result is very dependent on exactly how the tuner was set up, so that the detailed figures are to be taken as examples only).

$$\text{Position of minimum, } x_1 = 54.5\text{mm}, x_2 = 29.2\text{mm},$$
$$x_3 = 47.0\text{mm}$$
$$\text{so } \lambda_g = 2(47 - 29.2) = 35.6\text{mm}$$
$$\frac{(x_1 - x_2)}{\lambda_g} = \frac{(54.5 - 29.2)}{35.6}$$
$$= 0.71 \text{ wavelength}$$

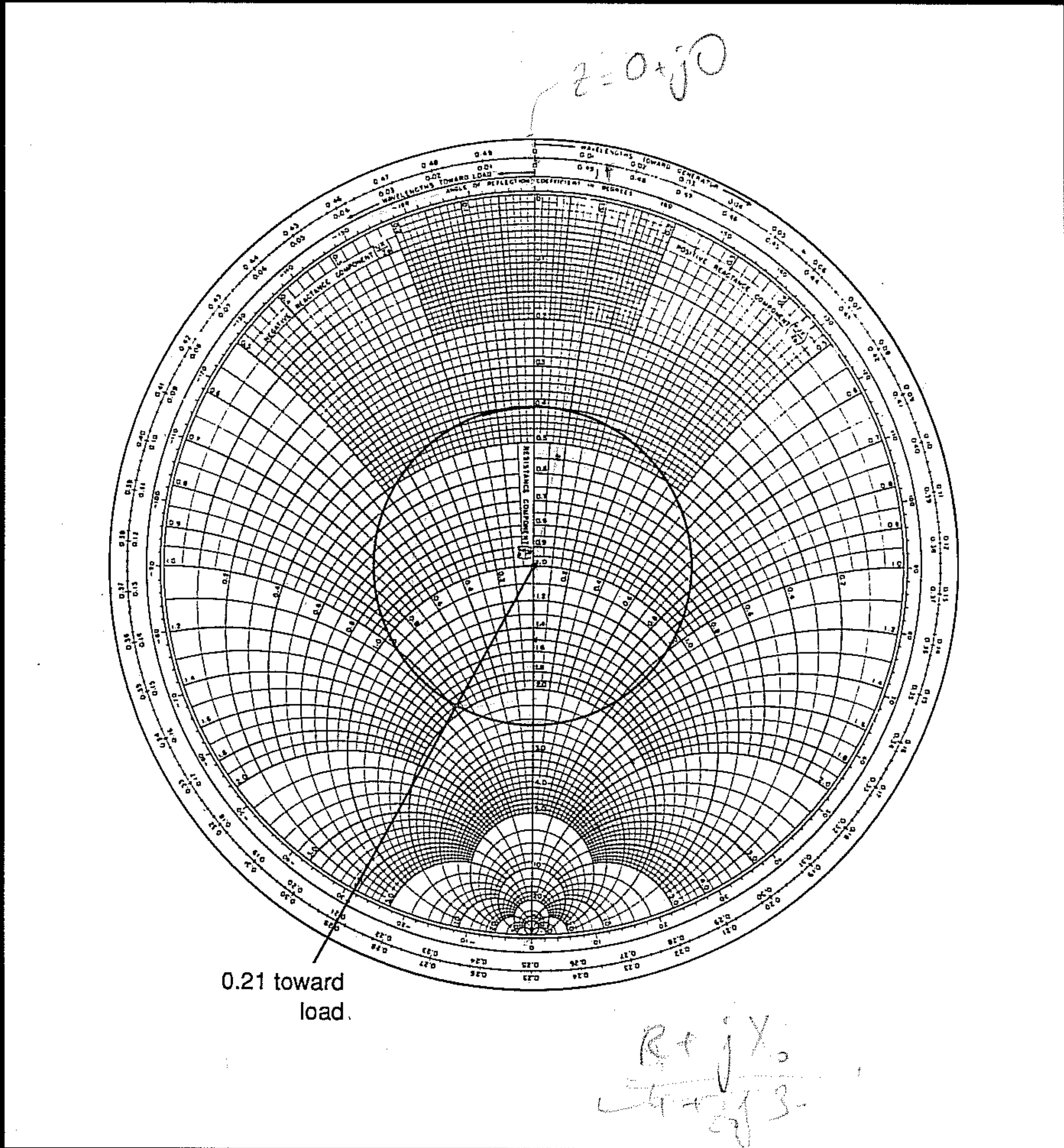
The normalised distance around the Smith chart is 0.5 wavelength, so an equivalent answer would have been:

$$0.71 - 0.5 = 0.21.$$

The impedance is given by the intersection of the circle and line shown in fig E.5.

Chapter 3 Assignment 5 - Typical Results and Answers

Fig E5



$0.55 + j0.09 \times Z_0$

ASSIGNMENT 6 MICROWAVE TUNER

CONTENT

The need to match a load to its source is introduced and the use of a slotted-line tuner is investigated.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	B	Slotted–line
1	C	Slotted–line Tuner
1	P	X–Band Oscillator
1	R	Short–circuit Terminator
1	S	Probe Detector Assembly

Chapter 3 Assignment 6

OBJECTIVES

When you have completed this assignment you will:

- Be aware of the need for tuning of a mismatched load.
- Be familiar with the concept of admittance in a waveguide.
- Know how to use a slotted–line tuner to achieve a match between a load and source.

KNOWLEDGE LEVEL

Before you start this assignment you should:

- Have completed Assignment 5 'Measurement of Impedance'

Chapter 3 Assignment 6

Fig 6.1

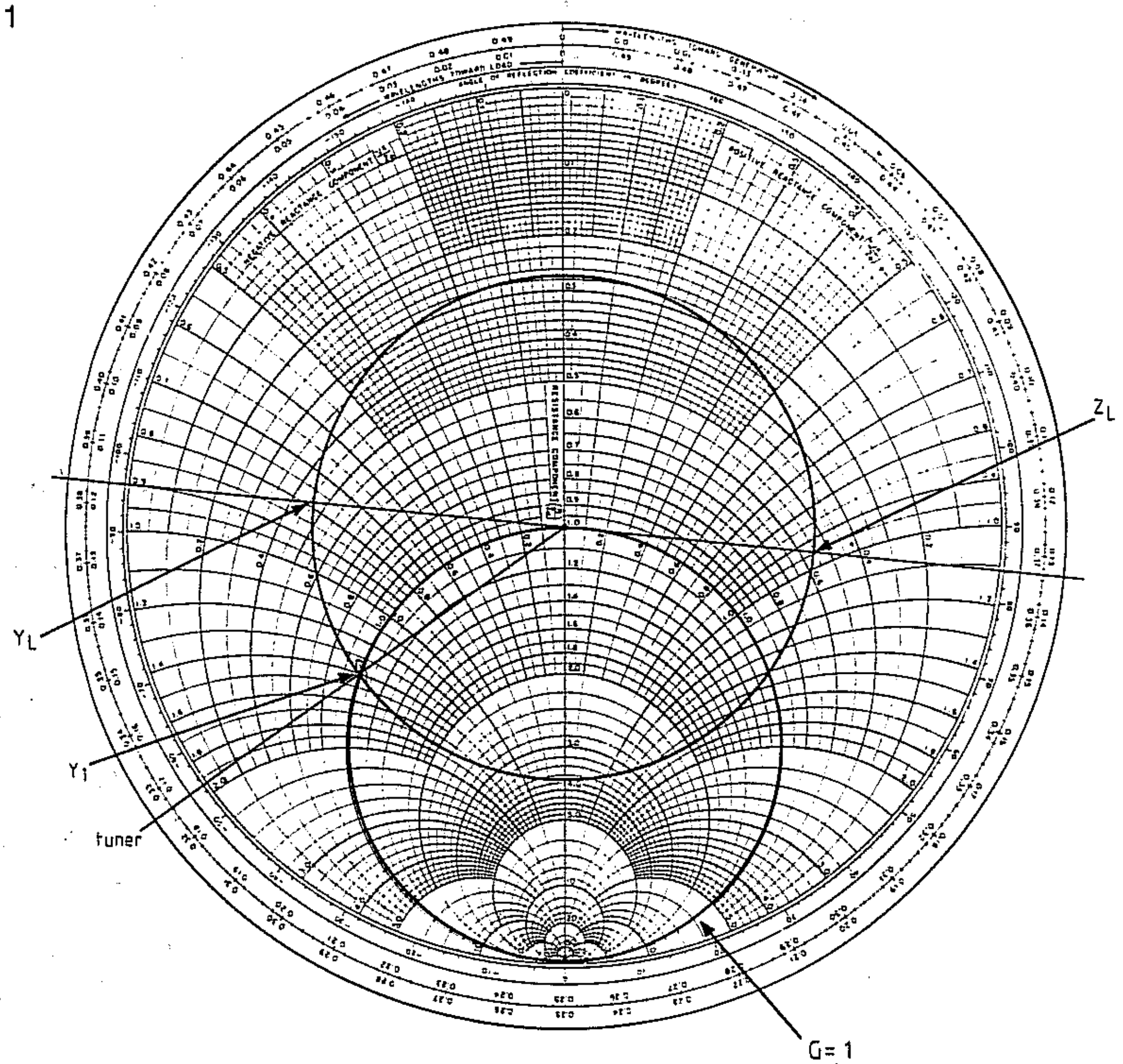


Fig 6.2

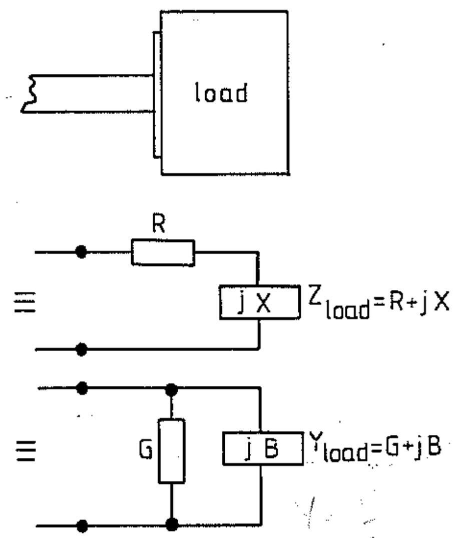


Fig 6.3

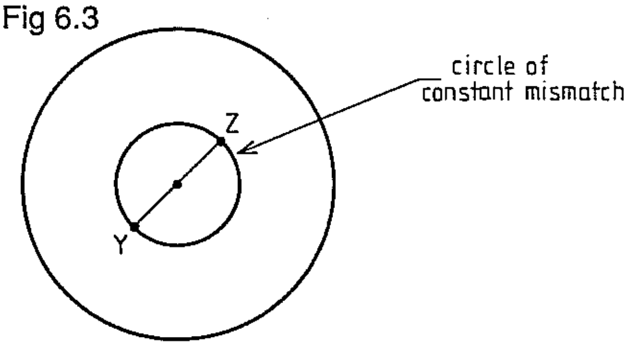
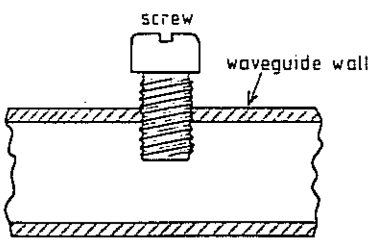


Fig 6.4



Capacitive Screw Mounted in a Waveguide

Chapter 3 Assignment 6

INTRODUCTION

When microwave power is being sent to a load, reflected energy is usually lost and standing waves are formed. Systems which have large standing waves in them, are much more difficult to handle and adjust than 'flat' systems (having no standing waves). Furthermore, they are much more liable to wide variations in performance when the conditions are disturbed, e.g by temperature or other ambient changes, or drift of the signal frequency.

There are therefore several reasons for wanting a load to accept all the r.f energy incident on it, without reflection. To illustrate this (ref. fig 6.2), suppose we have a waveguide terminated in a load which is mismatched.

We could say that the load has a normalised impedance $\frac{(R + jX)}{Z_0}$; but it is more convenient to think of its 'admittance', which is simply the reciprocal of impedance. So let the load admittance be $Y_L = G_L + jB_L$. In a similar way the waveguide can be said to have a characteristic admittance Y_0, which is simply the reciprocal of the characteristic impedance Z_0, and the normalised admittance is $\frac{Y}{Y_0}$

A convenient feature of a Smith chart is that if the normalised impedance is represented by one point, Z, on a constant-mismatch circle, then the normalised admittance Y is found simply moving to the other end of the diameter through Z, (see fig 6.3). This demonstrates the relationship between Z, a normalized impedance, and $Y = \frac{1}{Z}$ a normalized admittance.

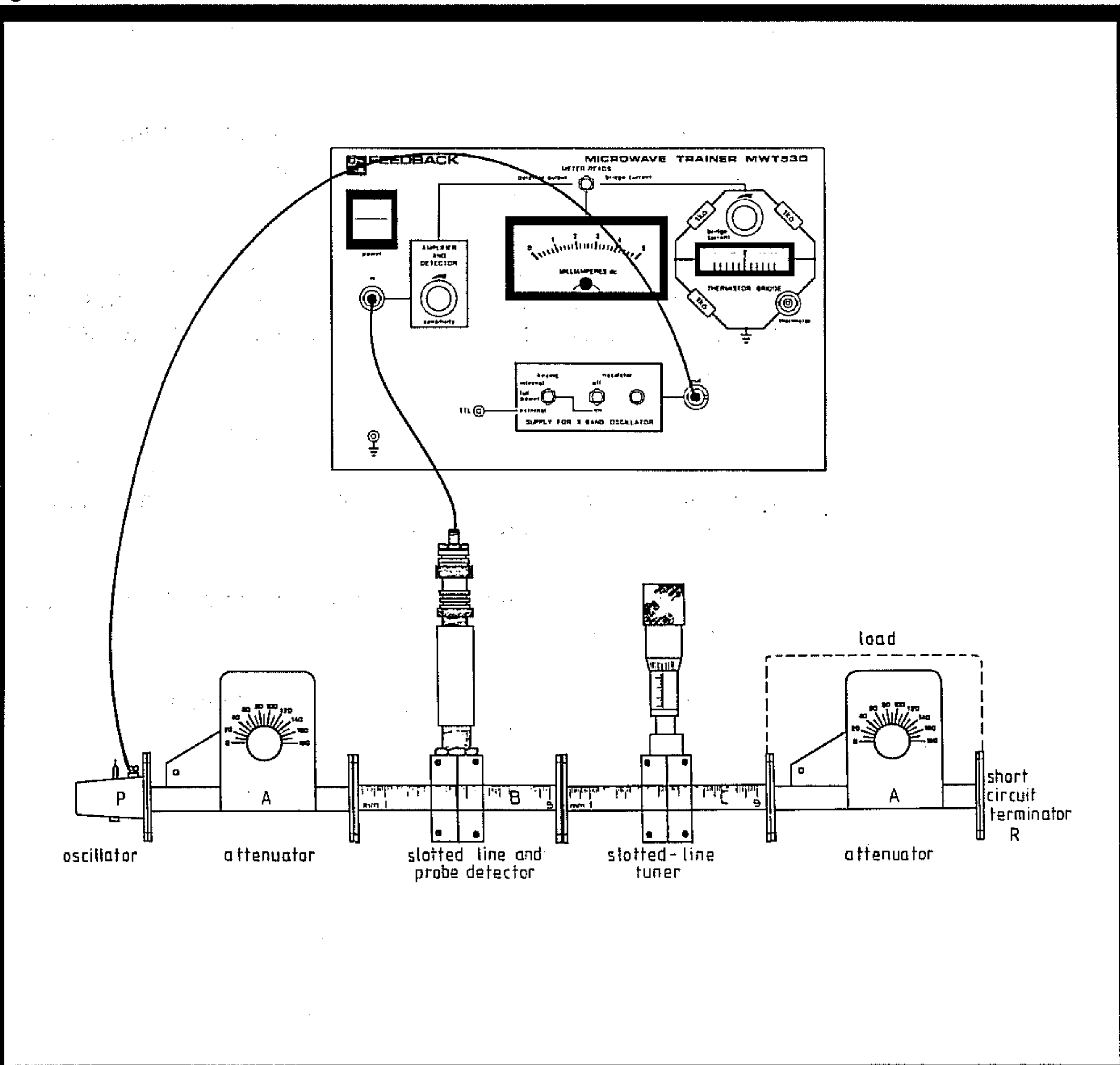
If we move along the waveguide, back toward the oscillator, the admittance Y= G+ jB will change, through values represented by the circle of constant mismatch in a Smith chart (see fig 6.1). A point Y_1 can be found where the conductance G becomes equal to Y_0. In general the '*susceptance*' jB will be non-zero. If we could put in parallel with Y at this point a susceptance –jB, the combined susceptance would be zero, and Y would simply become Y_0. A match would be thus be achieved, in the sense that no part of an incident wave arriving at Y_1 would be reflected. All the energy of the wave must therefore go to the load.

A convenient form of susceptance which can be connected in the waveguide line is a capacitive screw, (fig 6.4).

Chapter 3 Assignment 6

This of course can only provide a capacitive (positive-valued) susceptance. What if the jB which is to be cancelled is also capacitive? A moment's study of fig 6.1 will show that there is not just one point Y_1 where $G = Z_0$, but two. And the susceptance will be of opposite sign at the two points, so that one can always choose whichever kind is easier to cancel.

Fig 6.5



Chapter 3 Assignment 6

EXPERIMENTAL PROCEDURE

Connect the equipment as shown in fig 6.5. On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying; set the METER READS switch to 'detector output'.

REMEMBER NEVER look into an energised waveguide

Unscrew the Slotted-line Tuner as far as it will go (without undue force).

Move the Slotted-line Detector to find a maximum in the standing wave pattern. Adjust the source Attenuator until the meter reads about four-fifths full scale.

Find a minimum in the pattern and adjust the load Attenuator until the meter reads about one-tenth full scale. (It may be necessary to track the minimum position as it is disturbed by the Attenuator adjustment).

Use the Slotted-line Detector in the same way as in Assignment 5 to determine the impedance of the load there represented by the combination of the Tuner and Terminator. Write down the result and the intermediate results as in fig 6.6.

On a Smith chart, draw the constant-mismatch circle for this VSWR and the circle G = 1.

Choose their point of intersection (Y1) having negative susceptance, see fig 6.1.

Fig 6.6

minimum position:

initial conditions $x_1 =$

with short-circuit representing load $x_2 =$

and $x_3 =$

$\lambda_g = 2(x_2 - x_3) =$

$\frac{(x_1 - x_2)}{\lambda_g} =$

From the Smith chart, normalised $Z_L =$

Y_L (opposite end of diameter) =

Find the distance from the load at which it occurs. This is given (in wavelengths) by the distance along the outer scale from Y_L to Y_1, in the direction 'towards generator'. If necessary add one or more half-wavelengths to that distance (since the impedance pattern repeats every half wavelength). Record the position chosen.

Position the screw of the Tuner at a position along its slotted guide in accordance with your calculated position

ie (distance in λ) x (λ_g in mm).

It is then necessary to adjust the depth of penetration of the screw and make a fine adjustment to the slide position, to reduce the VSWR as much as possible. Do these two adjustments in sequence, as follows:

1 Make sure that the Detector is accurately at a minimum.

2 Adjust the Tuner's screw penetration to raise the meter reading and carefully try a small adjustment of its longitudinal position to raise the reading further.

3 By moving the Detector along the pattern, check that the adjustments have reduced the VSWR.

4 Repeat the sequence until further improvement becomes difficult.

Measure and record the final value of VSWR. Record the final position of the Slotted-line Tuner and compare it with that predicted from your impedance measurements.

Chapter 3 Assignment 6

SUMMARY

A tuner is a device which, used in conjunction with a mismatched load, presents a matched composite load to the source.

For matching at a single frequency, it suffices to find a point in the transmission path where the admittance has a real component (conductance) equal to the characteristic admittance, and to cancel out its reactive component by adding a parallel reactance of opposite sign.

Typically the added reactance is a screw probe adding parallel capacitance to the transmission path.

Alternative Tuning Methods

In principle matching could be achieved by adding reactance of either sign, either in parallel or in series with the waveguide path, in suitable positions. Where a series component (usually inductive) is added, the analysis would more conveniently be based on impedances rather than admittances.

Chapter 3 Assignment 6 - Typical Results and Answers

As instructed, the VSWR should be about $\sqrt{\frac{4}{0.5}} = 2.83$

Other details of the results may vary, as they will depend on the attenuator characteristics, which are not closely controlled.

Typical results, with reference to the Smith chart opposite, follow.

minimum position:

initial conditions $x_1 = 39.8\text{mm}$

with short-circuit representing load $x_2 = 35.5\text{mm}$

and $x_3 = 17.5\text{mm}$

18.0mm

$$\lambda_g = 2(x_2 - x_3) = 36.0\text{mm}$$

$$\frac{(x_1 - x_2)}{\lambda_g} = \frac{(39.8 - 35.5)}{36} = 0.119\lambda$$

From the Smith chart, normalised $Z_L = 0.60 + j0.73$

Y_L (opposite end of diameter) $= 0.67 + j0.84$

The position of the Smith chart, fig E.6, corresponding to Y_L on the 'toward generator' scale is 0.369λ.

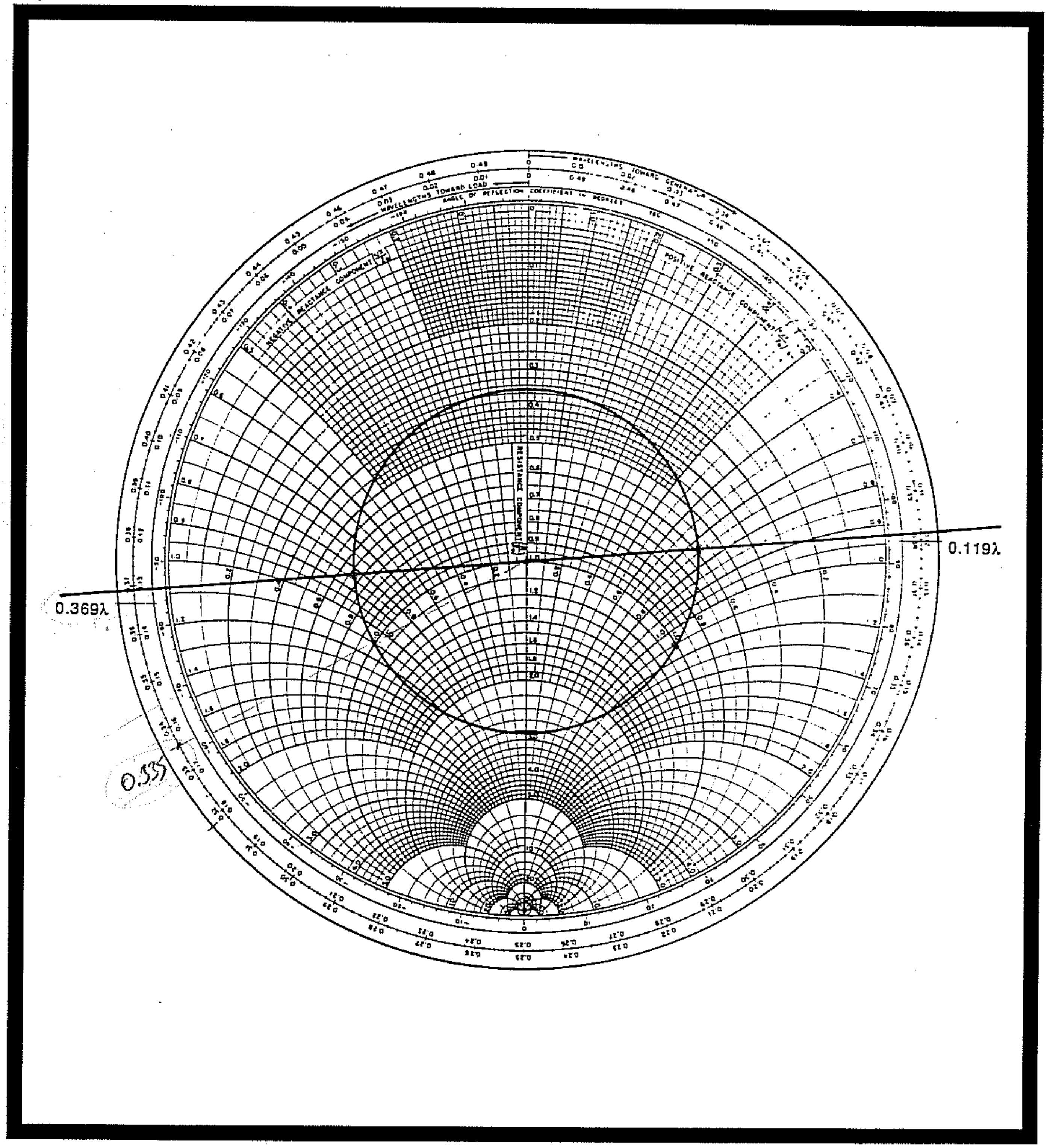
The constant mismatch circle for VSWR = 2.83 meets the circle G = 1 at 1, ±j1.1, so the tuner requires to be set at the point corresponding to 1,–j1.1, for which the 'toward generator' scale reading is 0.335.The tuner therefore requires to be set at a distance from the load equal to (0.335–0.369)λ = –0.034λ (plus any integral number of half–wavelengths). A convenient distance is

(1–0.034) x 36 = 34.8mm for practical purposes.

Chapter 3 Assignment 6 - Typical Results and Answers

In practice the prediction is unlikely to be perfect, but the experiment which gave these results produced a VSWR of 1.2 when the Tuner probe depth was suitably set at a distance of 38mm from the plane (and finding the correct distance was greatly eased by having a prediction accuracy within 11% of the half–wavelength).

Fig E.6



ASSIGNMENT 7 DIRECTIONAL COUPLER

CONTENT

The use of a directional coupler is investigated.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	B	Slotted–line
1	C	Slotted–line Tuner
1	F	Directional Coupler
1	K	Resistive Terminator
1	P	X–Band Oscillator
1	S	Probe Detector Assembly

Chapter 3 Assignment 7

OBJECTIVES

When you have completed this assignment you will:

- Understand how a directional coupler can be used to separate the incident and reflected waves in a transmission line.
- Know that the voltage reflection coefficient can be used to measure matching conditions in a transmission line.

KNOWLEDGE LEVEL

Before you start this assignment you should:

- Have completed Assignment 2 'Measurement of Voltage Standing Wave Ratio'.

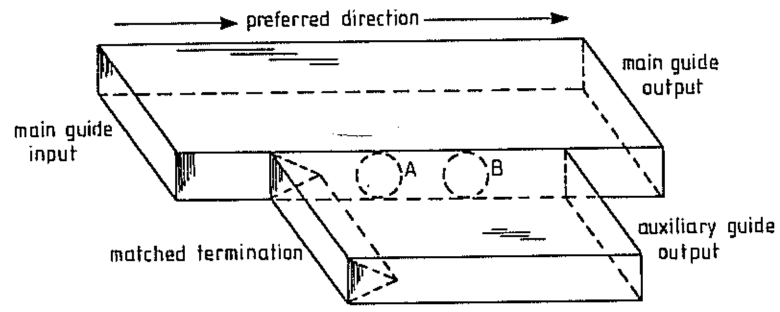
Chapter 3 Assignment 7

INTRODUCTION

A directional coupler is a device which allows a wave travelling in one direction along a transmission path to feed part of its energy to a secondary output port, but (ideally) prevents a wave travelling in the opposite direction to feed energy to the secondary port. Such a coupler may be used for various purposes, but probably the most important is that of separating incident from reflected waves in a transmission line.

Directional couplers can take many forms, but the one we shall use has holes in the side wall of a waveguide to let a small amount of energy pass through into an adjacent parallel wavegide. The arrangement is show diagramatically in fig 7.1.

Fig 7.1



Schematic Side-hole Coupler

The holes A and B are supposed to be exactly similar, and their distance apart is an odd number of quarter-wavelengths.

Suppose that a wave is travelling along the main guide. It will cause an alternating magnetic field to be present at each of holes A and B. At hole A, the field will start a secondary wave travelling to the left, where it will be absorbed by the matched terminator. It will also start a similar wave travelling to the right, towards the output port. The same thing happens at B. The two waves travelling to the left are of no importance (provided that the matched terminator does absorb them). What is important is how the waves travelling to the right combine.

If the main wave is going in the preferred (left to right) direction the main wave and the secondary wave, in travelling from A to B, are delayed by exactly the same amount. The secondary wave added at B will therefore be in phase with the one from A. The two secondary waves will combine and travel on to the output port.

Chapter 3 Assignment 7

However, if the main wave is going in the other direction (right to left) the main wave's magnetic field at hole A is delayed one quarter-period compared with that at B. The secondary wave is delayed a further quarter-period by travelling from A to B. Thus there is half a period difference in phase between the two secondary waves travelling toward the output port. Since they are equal in magnitude, they cancel one another out, and no signal reaches the output port.

In practice, of course, there are imperfections in the similarity of the holes, their spacing, and in the matching of the terminator. Some output is therefore obtained from the wave travelling in the non-preferred direction.

A measure of the quality of a directional coupler is its 'directivity', defined basically as:

$$\text{directivity} = \frac{P_A\,(\text{forward})}{P_A\,(\text{reverse})}$$

where P_A (forward) is the power sent to the auxiliary port for a given power sent along the main waveguide in the preferred, or forward, direction, and P_A (reverse) is the power sent to the auxiliary port for the same power sent along the main waveguide in the reverse direction.

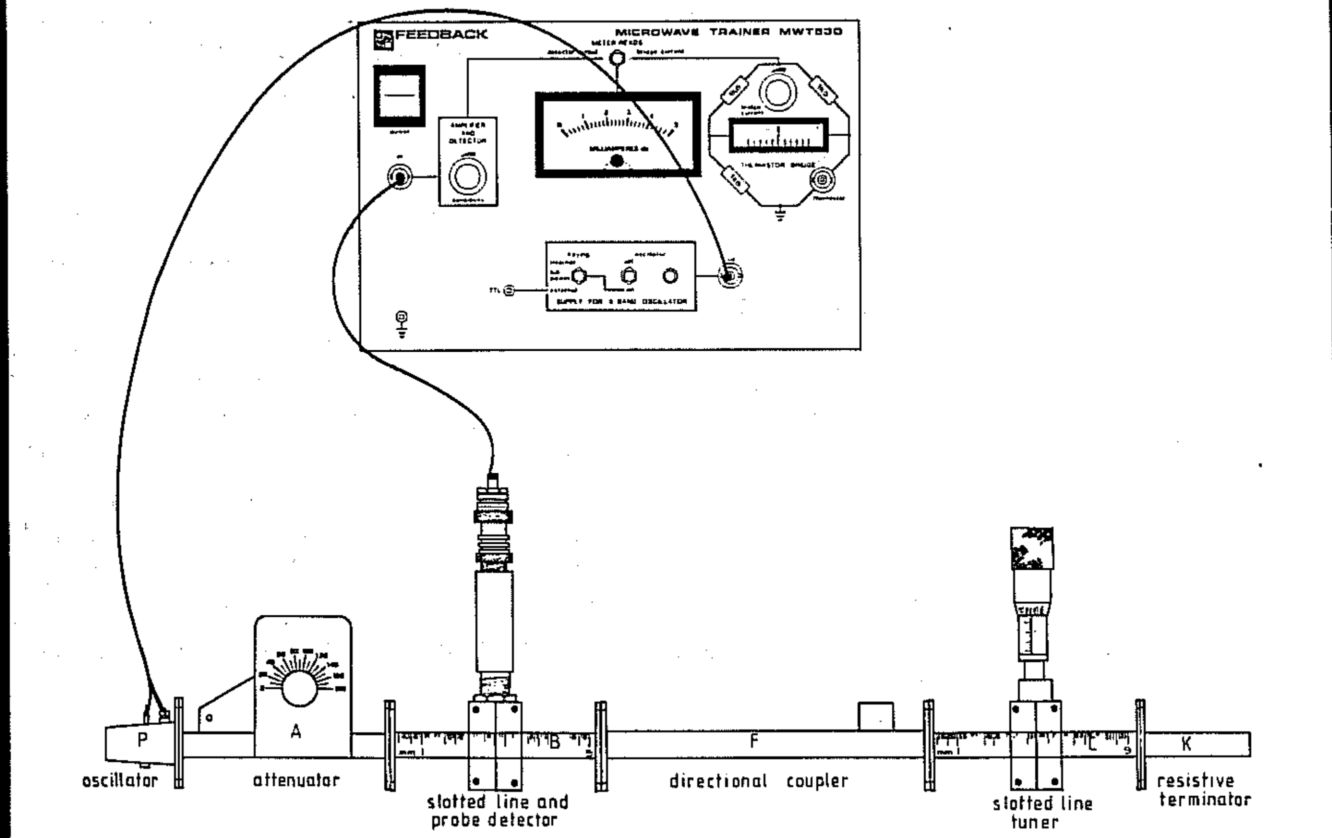
Usually however this is expressed in decibels, i.e

$$\text{directivity} = 10\log_{10} \frac{P_A\,(\text{forward})}{P_A\,(\text{reverse})}$$

Even if the hole spacing were exact for a given frequency, it would be wrong for other frequencies. High-performance directional couplers therefore usually have an array of several holes, arranged to improve directivity over a range of frequencies.

Chapter 3 Assignment 7

Fig 7.2



Chapter 3 Assignment 7

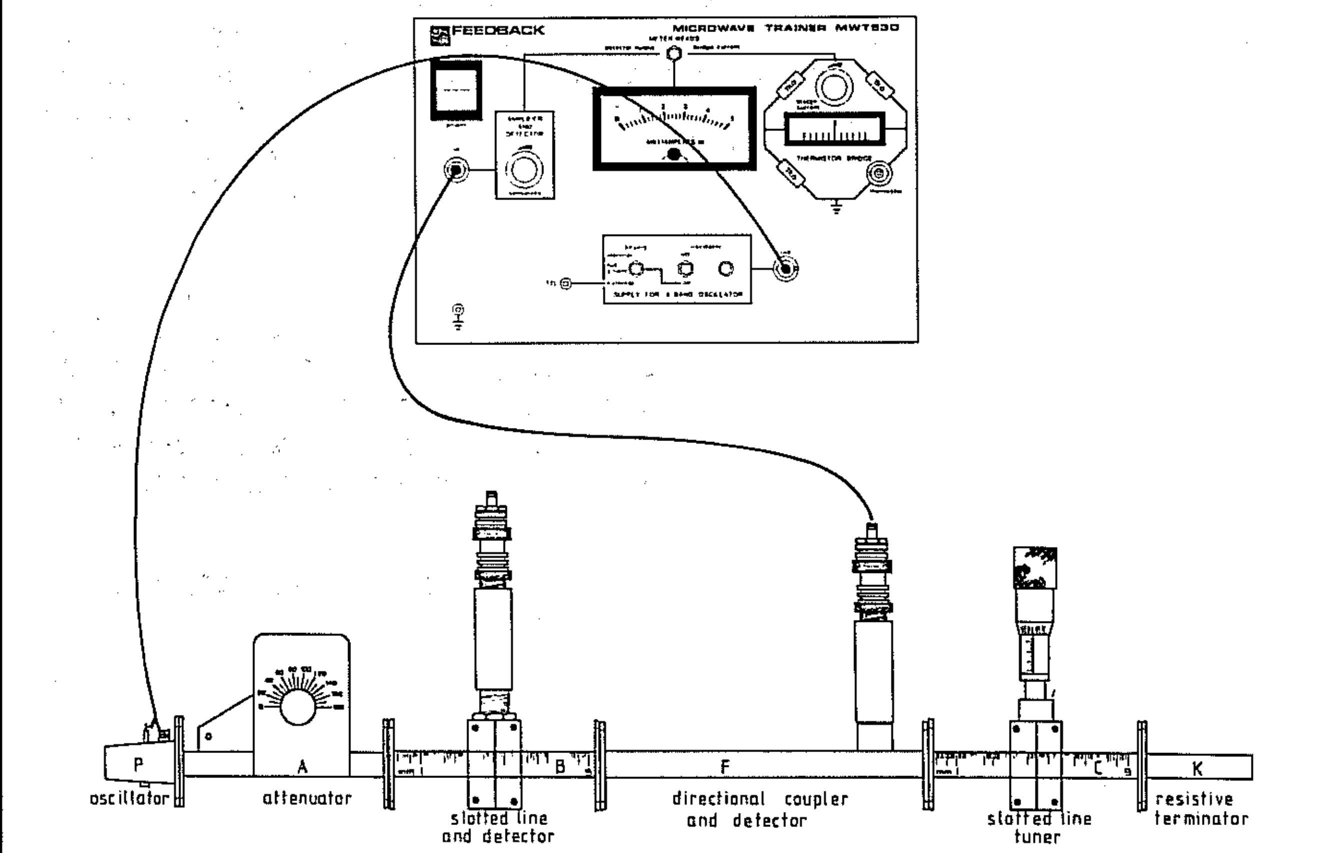
EXPERIMENTAL PROCEDURE

Mount the Detector probe into the carriage of the slotted waveguide, with the probe only just protruding into the guide. Unscrew the Tuner sufficiently for its probe not to appear inside the guide at all. Then connect the equipment as shown in fig 7.2. Make sure that the Directional Coupler is installed the correct way round. (It has no Detector mounted in it at this stage). On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying; set the METER READS switch to 'detector output'.

Set VSWR to 2

Set the sensitivity knob of the Detector Amplifier on the Control Console to maximum. Switch on the oscillator. Adjust the Attenuator to a convenient setting for checking the VSWR. At this stage the VSWR should be close to 1 (moving the Detector carriage should not change the meter reading much). We now want to set up a known, convenient VSWR value. To do this, screw the probe of the Tuner in until sliding its carriage alters the meter reading. Then adjust the Tuner screw until, sliding the carriage of the VSWR Detector, you observe a VSWR of about 2. (This corresponds to a 4:1 ratio between maximum and minimum meter readings). It may be necessary to adjust the attenuator to get the meter readings on scale.

Fig 7.3


FEEDBACK
MICROWAVE TRAINER MWT530
P
oscillator
A
attenuator
slotted line
and detector
B
F
directional coupler
and detector
slotted line
tuner
C
K
resistive
terminator

Chapter 3 Assignment 7

Forward Coupling

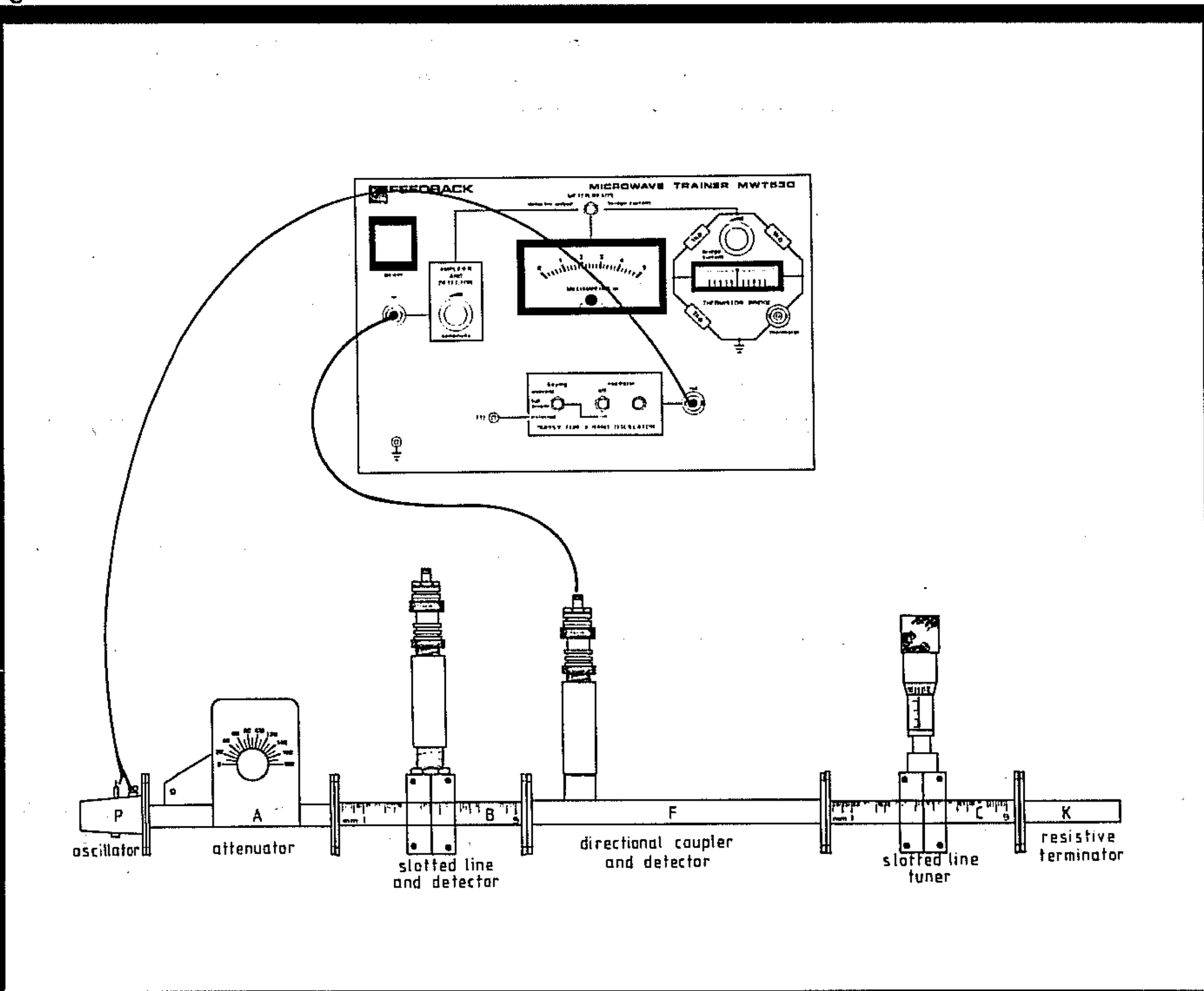
Taking care not to disturb the Tuner adjustment, arrange the equipment as shown in fig 7.3. It will be necessary to have the Probe inserted about half-way into the Directional Coupler. Adjust the Attenuator for maximum sensitivity. Finally set the Attenuator back so as to reduce the meter reading by about half. (This may reduce the meter reading well below full scale, showing that the coupling is fairly small even in the preferred 'forward' direction an appreciable attenuation by the Attenuator is necessary however, to ensure that the oscillator is shielded from the severe mismatches which will be introduced in the rest of the experiment).

The standing wave pattern is set up by the reflection from the Tuner screw. Without disturbing the screw, slide its carriage to alter the position of the standing-wave pattern, watching the meter. The reading should not vary much. This is because it is proportional to the forward-travelling wave, and ignores the reflected one; it therefore does not 'see' the standing-wave pattern at all.

Make a note of the meter reading, averaging out any small variations.

Chapter 3 Assignment 7

Fig 7.4



Chapter 3 Assignment 7

Reverse Coupling

Taking care not to disturb any adjustments, disconnect the Directional Coupler at both ends and reconnect it the other way round, fig 7.4. Record the new meter reading (for the reflected wave), again moving the sliding carriage of the Tuner and averaging readings if necessary.

Calculate:

- the ratio $\left(\frac{\text{reflected}}{\text{for ward}}\right)$ of the last two meter readings
- the square root of this ratio. (This is the voltage reflection coefficient, r, since the detector output is proportional to the square of voltage).
- the VSWR corresponding to this value of r, given by $\text{VSWR} = \frac{1+r}{1-r}$

Compare this value of VSWR with the original value set up at the start of the assignment.

Extreme matching conditions

Disconnect the Tuner from the Directional Coupler and replace it with a Short-circuit Terminator. Note and explain what happens to the reflection indicated by the meter.

Finally, replace the Short-circuit Terminator with a Resistive Terminator. Observe and explain the small or zero response of the meter.

SUMMARY

A directional coupler is used to separate the incident and reflected waves in a transmission line.

A waveguide directional coupler can comprise a length of secondary waveguide, coupled to the main waveguide by two holes separated by an odd number of quarter-wavelengths. It is important that, in the secondary waveguide, signals in the unwanted direction are absorbed by a resistive terminator. The ratio between the reflected and incident signals (voltage reflection coefficient) was seen to be an alternative to the VSWR, as a measure of the matching conditions in the transmission line.

Chapter 3 Assignment 7 - Typical Results and Answers

With initial VSWR of 2

Meter readings: for forward transmission 2.2

for reflection, 0.3 to 0.6 (average = 0.45)

So ratio of meter reading is:

$$\frac{0.45}{2.2} = 0.20$$

$$r = \sqrt{0.20} = 0.45$$

$$\text{VSWR} = \frac{1+r}{1-r}$$

$$\therefore \text{VSWR} = \frac{1.45}{0.55} = 2.93$$

With short–circuit

When the short–circuit termination is applied, all incident energy is reflected, so the meter reading would ideally go back to the same value as was originally measured for the forward signal. In practice it may go higher than this, because the reflected signal is not perfectly absorbed at the oscillator end of the system.

With matched terminator

A matched load absorbs all the incident power. The reflected signal should therefore be zero, and in practice will be small.

NOTES:

ASSIGNMENT 8 SERIES AND SHUNT TEES

CONTENT

Two basic forms of waveguide tee–junction are introduced; the Series Tee and the Shunt Tee. Their use is investigated.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	B	Slotted–line
1	E	Shunt Tee
1	G	Series Tee
1	K	Resistive Terminator
1	L	Bolometer (Thermistor–type)
1	P	X–Band Oscillator
1	S	Probe Detector Assembly

Chapter 3 Assignment 8

OBJECTIVES

When you have completed this assignment you will:

- Be able to describe the construction and operation of a Series Tee and Shunt Tee waveguide junctions.
- Be aware of the effect that Series and Shunt Tees have on matching.

KNOWLEDGE LEVEL

Before you start this assignment you should:

- Have completed Assignment 1 'Basics of Frequency and Wavelength', and Assignment 3 'Measurement of Microwave Power'.

Chapter 3 Assignment 8

INTRODUCTION

If a microwave source is required to supply power to two or more loads, various forms of junction can be made between waveguide sections connecting the source and the several loads. Two which will be considered here are the series and shunt-tee junctions. The names 'series' and 'shunt' serve as reminders of the way in which impedance in the system are combined, by analogy with the behaviour of series and shunt connections in low-frequency circuits.

Fig 8.1

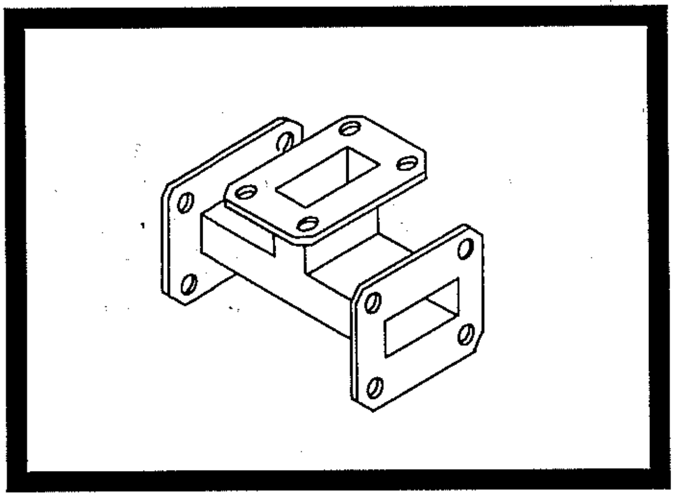
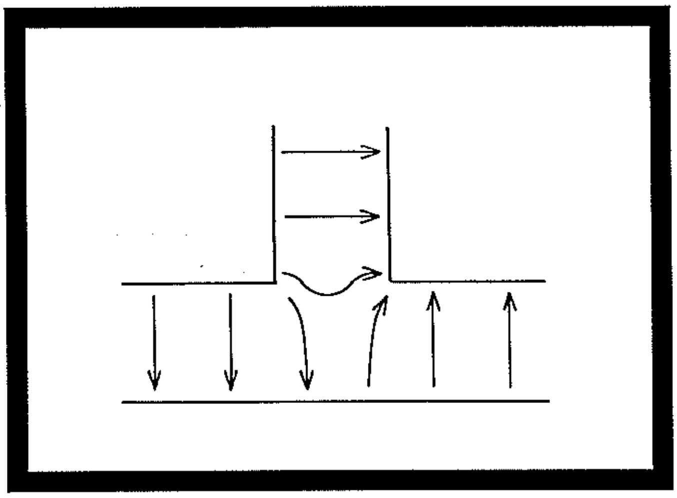


Fig 8.2



The Series-Tee junction, fig 8.1, is also called a '*TM plane tee*', because its three arms all lie in a plane containing the electric field in each arm. Fig 8.2 shows the electric field due to a wave entering the top arm.

The electric fields in the two lower arms are in opposite phase to one another, and their sum is equal to the incident electric field. The same could be said if fig 8.2 represented wires connecting series-connected loads in a low-frequency circuit.

Fig 8.3

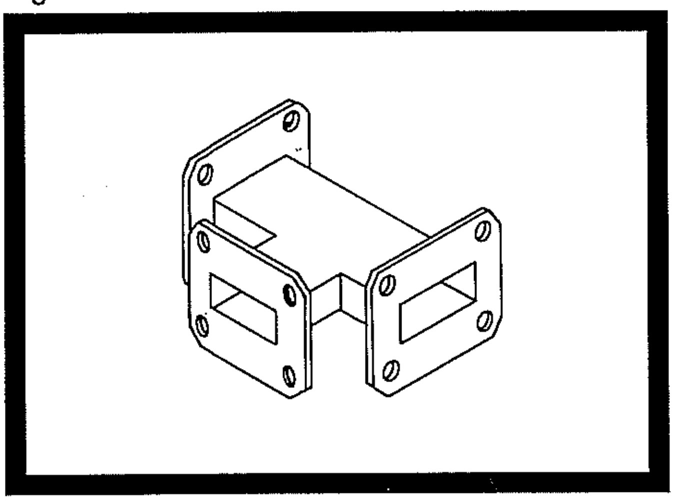
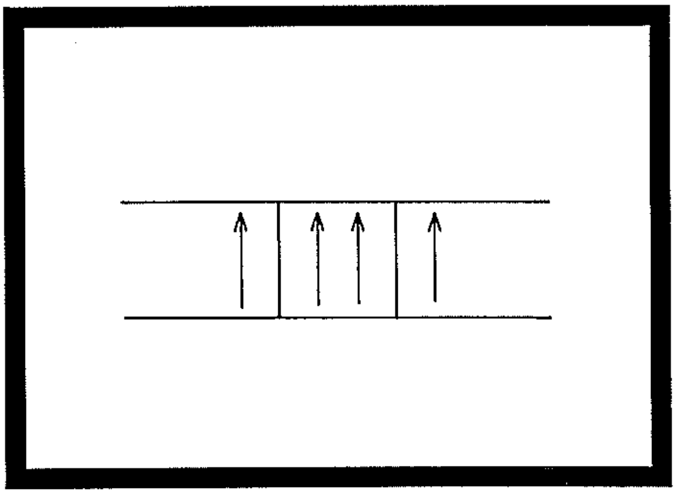


Fig 8.4



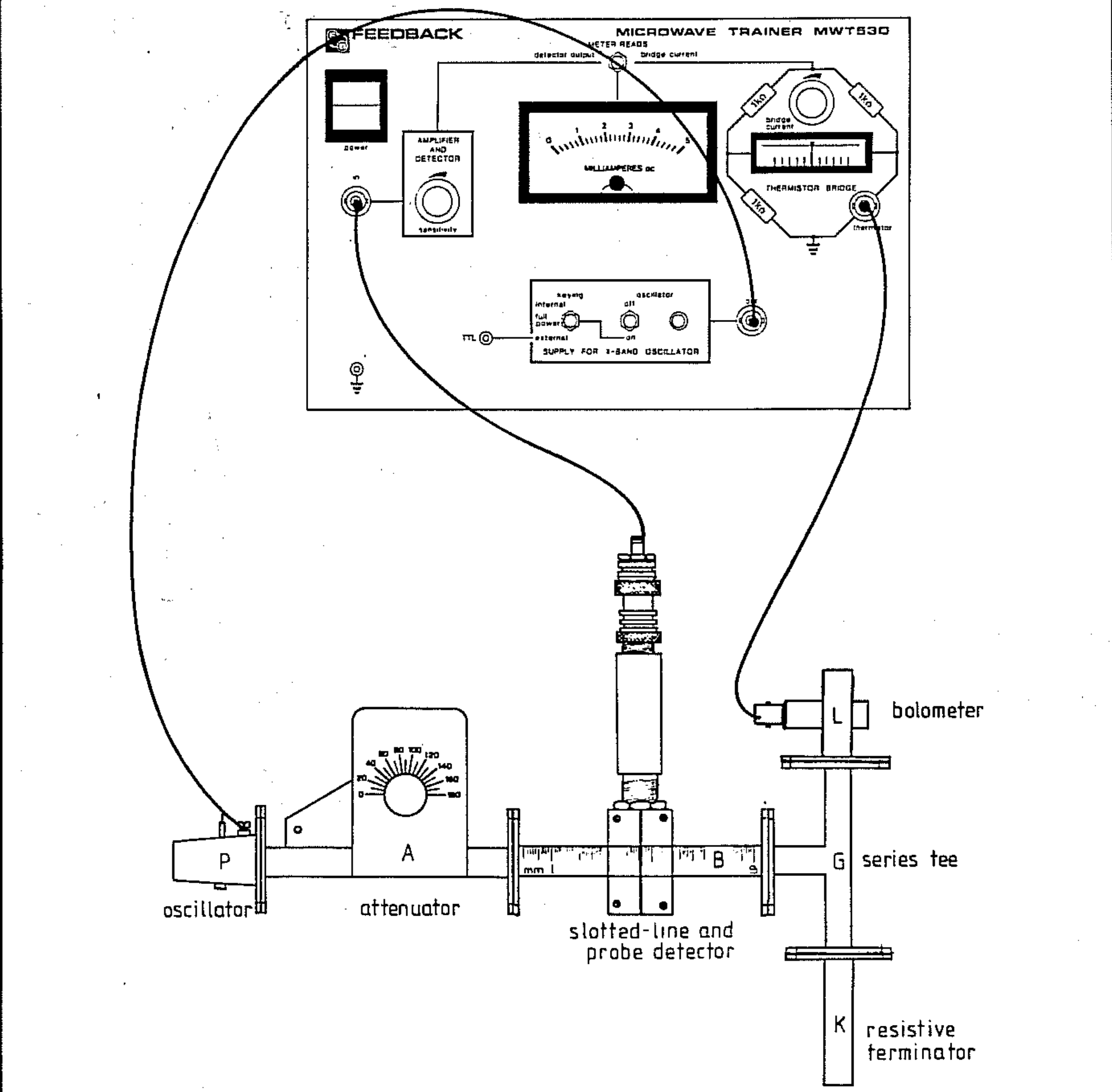
Chapter 3 Assignment 8

The Shunt-Tee junction, fig 8.3, is also called a '*TE-plane tee*', because its three arms all lie in a plane containing the magnetic field in each arm. Fig 8.4 shows the electric field due to a wave entering the centre of the diagram from a direction perpendicular to the paper.

Here the electric field is the same in all three arms. The magnetic field is less easy to visualise, but in effect it has to be shared between the two receiving arms.

Because in each case one of the fields is transferred to both output waveguides unchanged, while the other field is halved, the impedance of the receiving arms does not match the incident wave. Tees introduce a mismatch when connected in other ways too. They generally therefore give rise to reflections and standing waves, unless the reflections are tuned out by additional devices.

Fig 8.5


FEEDBACK
MICROWAVE TRAINER MWT530
METER READS
detector output
bridge current
power
AMPLIFIER AND DETECTOR
0
1
2
3
4
5
MILLIAMPERES dc
bridge current
THERMISTOR BRIDGE
1kΩ
1kΩ
1kΩ
thermistor
keying
internal
full power
external
oscillator
off
on
TTL
SUPPLY FOR X-BAND OSCILLATOR
P
oscillator
A
attenuator
0
20
40
60
80
100
120
140
160
180
mm
B
slotted-line and probe detector
L
bolometer
G
series tee
K
resistive terminator

Chapter 3 Assignment 8

EXPERIMENTAL PROCEDURE

REMEMBER NEVER look into an energised waveguide

Connect the apparatus as shown in fig 8.5. On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying; set the METER READS switch to 'bridge current'.

Adjust the probe of the Slotted-line Detector, if necessary, so that the projection into the waveguide is about 2mm. Adjust the bridge current to near the d.c balance, with the Oscillator switched off. Switch on the Oscillator at full power (no keying) and note the bridge meter deflection with the Attenuator vane fully out (minimum attenuation). Adjust the Attenuator so that the meter returns approximately half-way toward the balance position. This setting should then be recorded and left undisturbed for the rest of the experiment.

Measure the power in the Bolometer. (The method is the same as in Assignment 3). After this, move the Oscillator's switch to the 'internal' position and the meter switch to 'detector output'. Then estimate the VWSR, using the simple direct method; if it is greater than about 10, simply record '> 10'. Record the result in a table like fig 8.6 below:

Fig 8.6

	Bridge Current (mA)	d.c Power in Bolometer (mW)	r.f Power in Bolometer (mW)	VSWR
d.c only				
Tee–connected				
direct				

Switch off the Oscillator. Taking care not to disturb the Attenuator setting, remove the Series Tee from the Slotted-line Detector and move the Bolometer from the Tee to the end of the Slotted-line Detector. Again measure and record the power received by the Bolometer, and the VSWR.

If the Tee presented a perfect match at all ports, the incident power would be split equally between the two loads. If each port were correctly matched, so that only the internal mismatch of the tee were effective, then the theoretical voltage reflection coefficient would be $\frac{1}{3}$.

$$\text{This would make the VSWR} = \frac{1+\left(\frac{1}{3}\right)}{1-\left(\frac{1}{3}\right)} = 2$$

Compare with your measured VSWR.

$\frac{1}{9}$ of the incident power would then be reflected, leaving 0.44 of that power for each output port. Compare this figure with the ratio between powers measured by you; tee-connected and direct.

The whole experiment can be repeated using the Shunt Tee.

SUMMARY

When two loads must be connected by waveguide to a single microwave source, there are two forms of tee which can be used:

- the series (or 'TM-plane') tee, whose arms all lie in a plane containing the electric field.
- the shunt (or 'TE-plane') tee, whose arms all lie in a plane containing the magnetic field.

Each form of tee alters the ratio between electric and magnetic fields, and therefore causes mismatching, with consequent reflection of power and standing waves.

Chapter 3 Assignment 8 - Typical Results and Answers

For series–tee

	Bridge Current (mA)	d.c Power in Bolometer (mW)	r.f Power in Bolometer (mW)	VSWR
d,c only	3.92	3.84	0	—
Tee–connected	3.52	3.10	0.74	$\sqrt{\frac{5}{0.2}} = 5$
direct	2.45	1.50	2.34	$\sqrt{\frac{4}{0.5}} = 2.8$

$$\text{Rf power ratio: } \frac{0.74}{2.34} = 0.32$$

For shunt–tee

	Bridge Current (mA)	d.c Power in Bolometer (mW)	r.f Power in Bolometer (mW)	VSWR
d,c only	3.92	3.84	0	—
Tee–connected	3.42	2.92	0.92	>10
direct	2.45	1.50	2.34	$\sqrt{\frac{2.5}{0.5}} = 2.24$

$$\text{Rf power ratio: } \frac{0.92}{2.34} = 0.39$$

VSWR

Comparison with expected values shows experimental values much higher than the theoretical values 2, with T connected, and 1direct, expected for a well-matched bolometer.

Chapter 3 Assignment 9

CONTENT

The construction and operating characteristics of a horn antenna is investigated.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	K	Resistive Terminator
1	M	Diode Detector
2	N	Horn Antenna
1	P	X–Band Oscillator

Chapter 3 Assignment 9

OBJECTIVES

When you have completed this assignment you will:

- Be able to describe the operation and characteristics required of a horn antenna.
- Know what is meant by beam–width and gain with reference to a horn antenna.

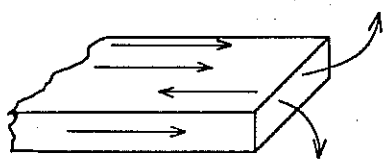
KNOWLEDGE LEVEL

Before you start this assignment you should:

- Have completed Assignment 2 'Measurement of Voltage Standing Wave Ratio'.

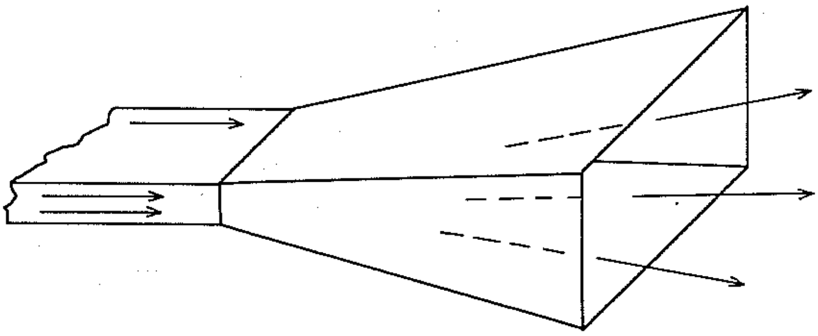
Chapter 3 Assignment 9

Fig 9.1



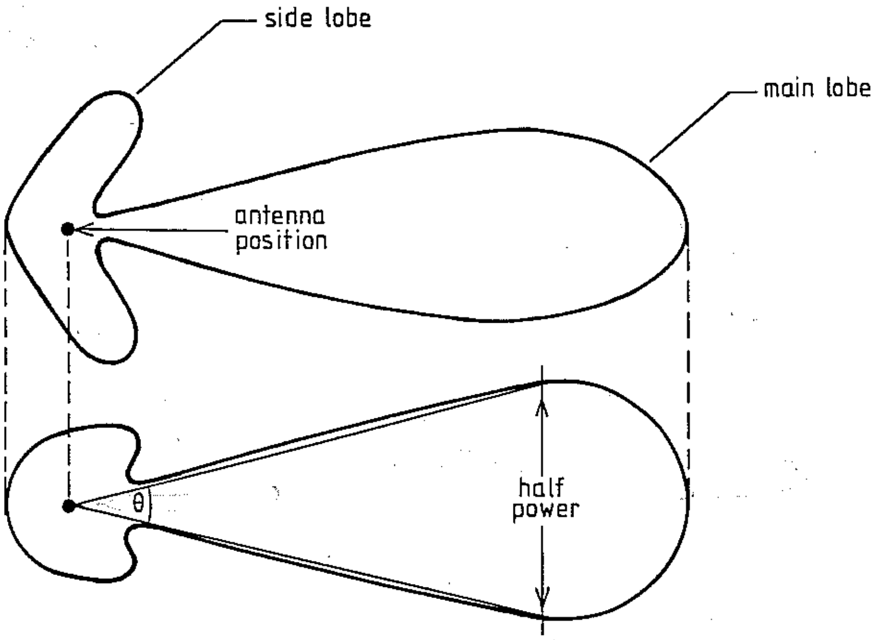
Energy Radiated and Reflected from an Open Waveguide End

Fig 9.2



Energy Radiated from a Horn Antenna (more concentrated in one direction)

Fig 9.3



Two Sections of a Three-dimensional Radiation Pattern

Chapter 3 Assignment 9

INTRODUCTION

If a waveguide which is propagating a signal is left with an open end,some of the signal energy will escape into space (Fig 9.1). Some will be reflected because the end is not well matched to free space, so a VSWR of about 2 will typically result.

Let us consider first the energy which does get radiated or transmitted into space. Suppose the transmitted power is P_t. If it were radiated in all directions equally, then at a distance r from the source the total power P_t would be spread evenly across the surface of a sphere of surface area $4\pi r^2$. A receiving antenna occupying area A of that sphere would receive a proportion of the transmitted power,

$$P_r = P_t \frac{A}{4\pi r^2}$$

When it is required to transmit energy efficiently into space, a device called an '*aerial*' or '*antenna*' is used. The horn is a very simple form of antenna, being no more than a flare-out of the shape of the waveguide walls. It improves the match between the waveguide and free space, and narrows the angle over which energy is radiated, fig 9.2.

By concentrating the radiation in a particular direction, the power radiated in that direction is increased (at the expense of reduced power in other directions). The factor by which it is increased is called the 'gain' of the transmitting antenna. Thus the power received by the receiving antenna of area A becomes:

$$P_r = P_t \frac{GA}{(4\pi r^2)}$$

The gain G is often expressed in decibels as:

$10 \log_{10} G$ dB, or dBi

(where the 'i' refers to an isotropic radiator; one which radiates equally in all directions).

An alternative definition for gain compares the antenna's performance not with an isotropic radiator, but with a half-wave dipole. The gain defined in this way is about 2.2dB less than the gain in dBi.

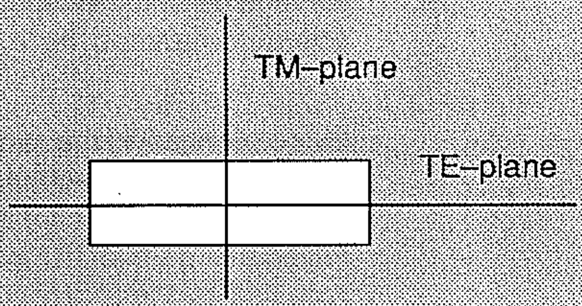
Chapter 3 Assignment 9

In most microwave applications we require as much energy as possible to be radiated in a particular direction. This is often important not only for maximising the power received, but also because the system (a radar, perhaps) requires directional information.

The directional characteristics of an antenna would ideally be shown as a three-dimensional graph in which, for each direction, the radius from a central point is proportional to the power density at a given distance. This is called the '*radiation pattern*'. For practical reasons the radiation pattern is normally shown by two-dimensional graphs which show a section or sections of the three-dimensional pattern, like figure 9.3.

Fig 9.4 shows the planes used for a rectangular waveguide, designated TM–plane and TE–plane because they contain the directions of the electric and magnetic field respectively.

Fig 9.4



End-view of Waveguide Showing TM and TE Planes

As shown in fig 9.3, a radiation pattern usually has several 'lobes'. Generally, most energy is concentrated into the main lobe. Radiation in side and back lobes represents a waste of power. It can in some applications have serious effects by, for instance, producing false radar images.

The '*3-dB beam width*' is often used as a measure of the directivity of an antenna. It is the angle (θ in fig 9.3) between the two points on the main lobe at which the radiated power density is half the maximum.

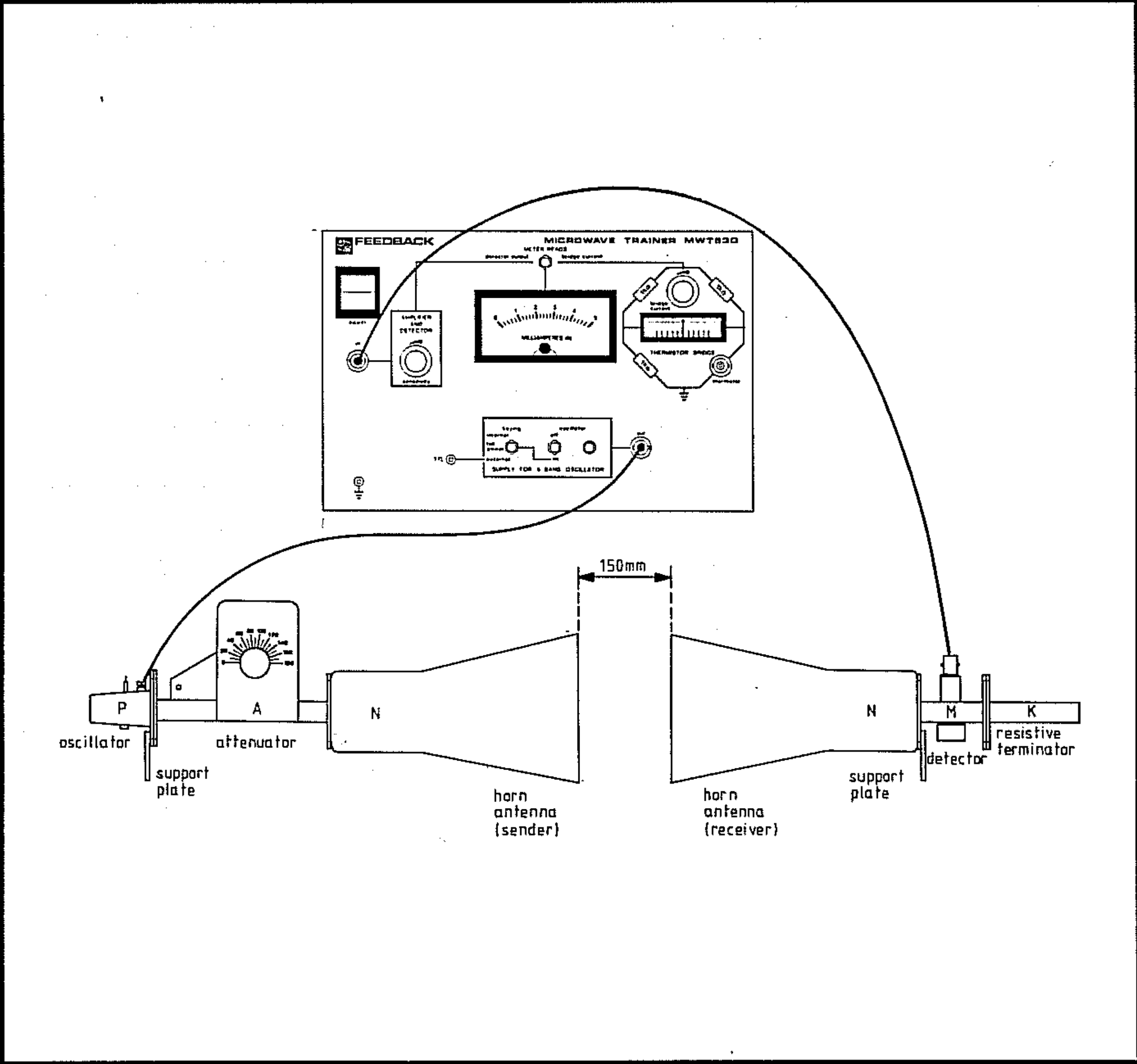
Chapter 3 Assignment 9

The gain is generally highest if the beam width is narrow and the side lobes are small, so that all the power is sent in the desired direction. An antenna which has these characteristics will also generally be an efficient receiver of radiation.

The radiation pattern differs when measured close to the antenna and at a distance. It is usually the latter condition which is of interest, referred to as the '*far field*'. For practical purposes, and in the case of a simple horn antenna, the far field may be taken to start at a distance $\frac{2D^2}{\lambda_0}$ from the horn, where D is its larger dimension at the opening, and λ_0 is the free-space wavelength.

Radiation measurements are easily disturbed by reflections from the ground and other objects. These problems are avoided as far as possible in practice by using clear areas out of doors, or by using 'anechoic' rooms having walls specially designed to absorb radiation.

Fig 9.5


FEEDBACK
MICROWAVE TRAINER MWT530
150mm
P
A
N
N
M
K
oscillator
support plate
attenuator
horn antenna (sender)
horn antenna (receiver)
support plate
detector
resistive terminator

Chapter 3 Assignment 9

EXPERIMENTAL PROCEDURE

Connect the apparatus as shown in fig 9.5, with one sending antenna and one receiving antenna. On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying; set the METER READS switch to 'detector output'.

Results will be improved if the sending and receiving antennas are each mounted so that no solid material is near the path between them. They may each for instance be mounted on the edge of a box, or on the edge of a table, leaving an open space between them. A space of about 150mm betwen the antennas may be tried for a start.

WARNING

Keep your eyes AWAY from the space in front of the transmitting antenna.

Set the amplifier to maximum sensitivity. Align the Antennas '0°' direction. Adjust the attenuator to give a meter deflection near maximum. Make a note of this reading in the 0° column of a table like fig 9.6. (Do not stand close to the transmisson path while taking readings, as they will be affected).

Notice that the antennas must be similarly 'polarised'. That is, the receiving antenna must be sensitive to electric field in the same direction as the electric field from the sending antenna. Try turning the receiving antenna on its side and note the effect.

Fig 9.6

Meter reading (mA)	Attenuator setting				
	0°	10°	20°	30°	40°
left side					
right side					

Chapter 3 Assignment 9

Using a protractor (or a copy of fig 9.7) to measure angles, rotate the receiving antenna about the centre of the broad edges of its aperture (opening). Set the angle to 10°, 20° 30° and 40° in each direction. Record the meter readings in each case. Plot them on a graph sheet like fig 9.7.

Use the graph to find the 3dB beam-width of the antenna.

Fig 9.7

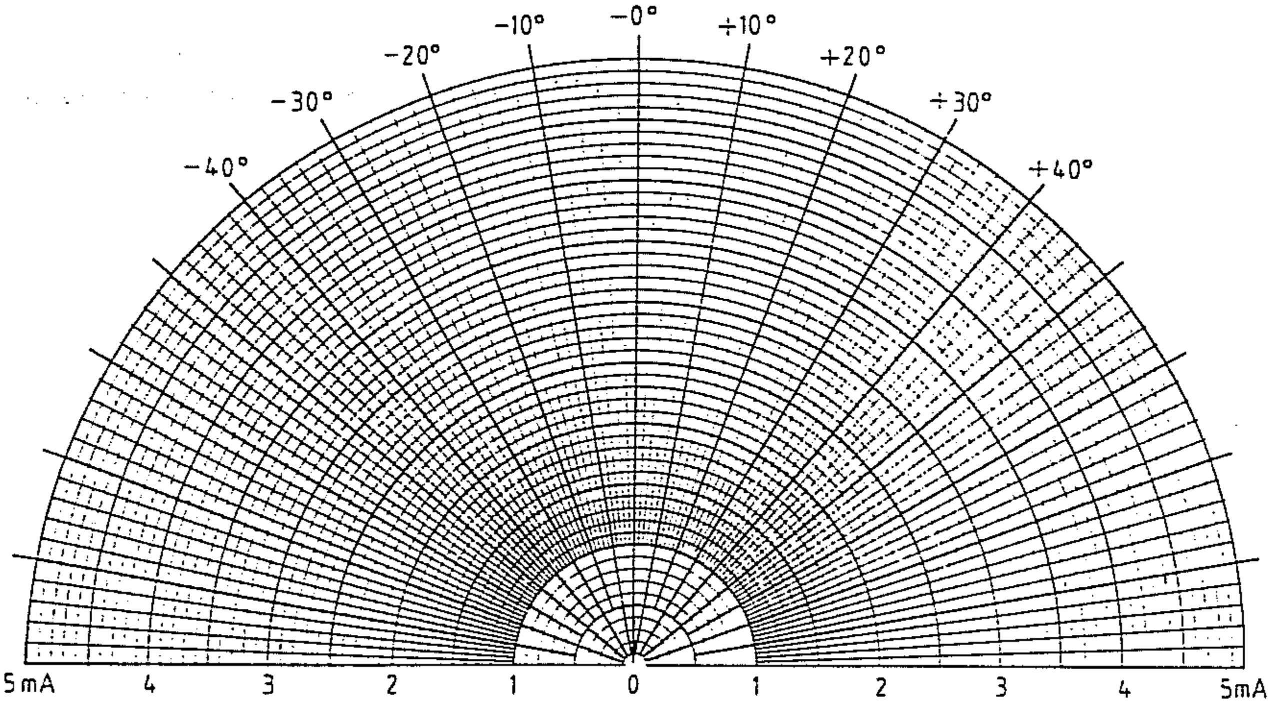


Chart for Plotting Radiation Patterns

Chapter 3 Assignment 9

SUMMARY

R.f energy reaching the open end of a waveguide will be partly radiated into space and partly reflected back into the waveguide. When it is desired to radiate the energy, an antenna is used. An antenna should:

- Provide a good match to the waveguide, thus avoiding reflections and standing waves in it.
- Launch radiation into space in required directions, not in others. This also increases the gain, which is the ratio between power radiated in a preferred direction and that which would be radiated by an isotropic (or omnidirectional) radiator.

An antenna may also be used to receive energy radiated from elsewhere in space. In general the properties of receiving antennas are closely related to those of the same antenna when used for transmitting.

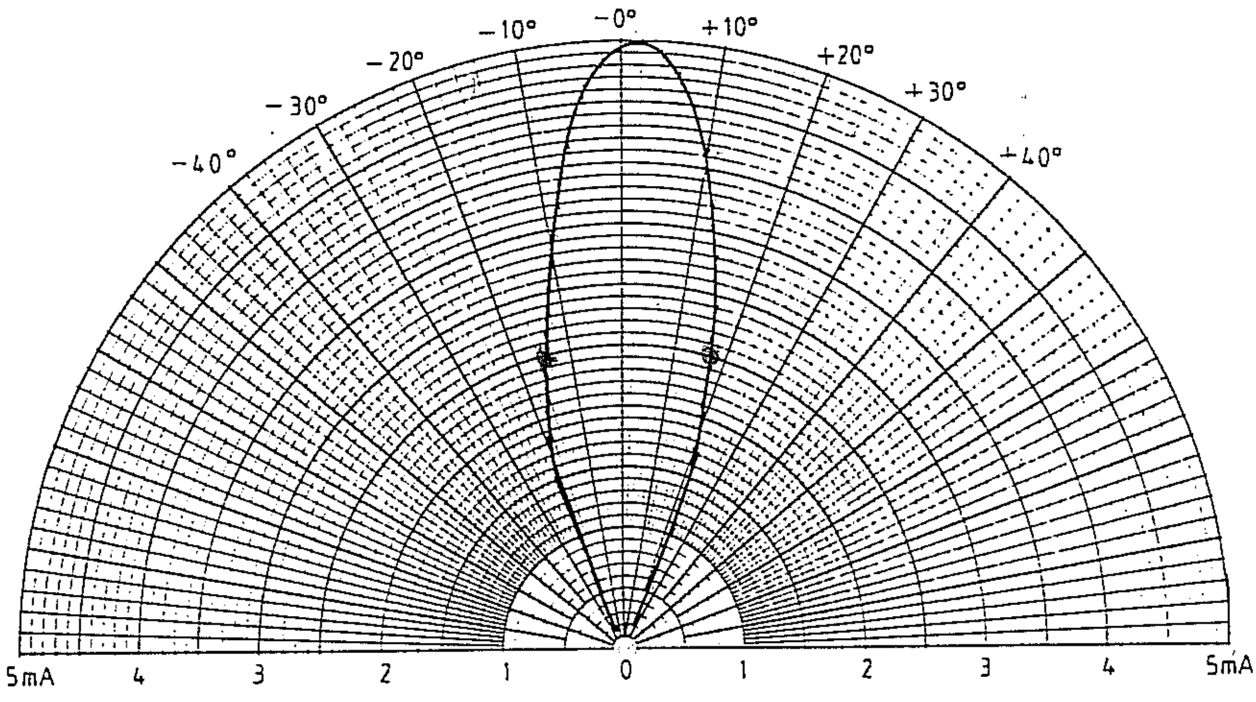
Other characteristics which may be of interest are the beam-width (often quoted for 3dB below peak gain) and the ratio by which side-lobes are suppressed.

Chapter 3 Assignment 9 - Typical Results and Answers

Ref. fig 9.6

Meter reading (mA)	Attenuator setting				
	0°	10°	20°	30°	40°
left side	5	3.4	1.8	0.6	0.1
right side	5	4.2	1.7	0.6	0.015

Fig E9



Since maximum power corresponds to 5mA, half power corresponds to 2.5mA. From a graph the 3dB beamwidth can be estimated as 26°.

NOTES:

ASSIGNMENT 10 DOPPLER RADAR

CONTENT

The principle of Doppler radar is introduced. The use of the hybrid tee junction and a mixer is demonstrated

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	H	Hybrid Tee
1	M	Diode Detector
2	N	Horn Antenna
1	P	X–Band Oscillator
1	R	Short-circuit Terminator

Chapter 3 Assignment 10

OBJECTIVES

When you have completed this assignment you will:

- Understand the operation of Doppler radar
- Be able to describe the construction and operation of a Hybrid Tee waveguide junction.
- Understand the use of a mixer.

KNOWLEDGE LEVEL

Before you start this assignment you should:

- Have completed Assignment 8 'Series and Shunt Tees' and Assignment 9 'Horn Antenna–Microwave Propogation in Space'.

Chapter 3 Assignment 10

INTRODUCTION

If a wave is transmitted toward an object which reflects some of the wave back to the source; at a particular point on the path, the outward and reflected waves may be in phase with one another, in antiphase, or anywhere between. If the distance x between source and reflecting object increases by δx, then the total path length, out and back, changes by $2\delta x$, so the relative phase of the two signals will alter by $\frac{2\delta x}{2\pi\lambda}$ radians, where λ is the wavelength in the space surrounding the reflecting object. If the object is moving, the result will be a change in frequency of the reflected wave, since, if $e \cos \omega t$ is the transmitted wave's electric field then, because of the distance 2x travelled, the reflected field will be:

$$ke \cos\left(\omega t - \frac{x}{\pi\lambda c}\right)$$

where k is a constant and c is the wave velocity.

If v is the velocity of the object away from the source, and x has the value x_0 when t = 0,

then: $x = vt + x_0$

so that the reflected wave becomes:

$$ke \cos\left[\omega t - \frac{vt + x_0}{\pi\lambda c}\right]$$

which $= ke \cos(\omega_1 t - \phi)$

where the angular frequency $\omega_1 = \omega - \left(\frac{v}{\pi\lambda c}\right)$

and ϕ is a fixed phase value.

The received frequency, ω_1, is thus displaced from that transmitted, ω, by an amount proportional to the velocity v. This is known as the '*Doppler principle*', and is similar in nature to the change in pitch of a sound, as heard by a stationary listener, which comes from an object moving past the listener at speed.

The change of frequency is detected by applying both the received and (suitably attenuated) the transmitted signals simultaneously to a 'mixer'. This is a non-linear device, such as the crystal detector.

Chapter 3 Assignment 10

If two signals ($e_0 \cos \omega t$) and ($e_1 \cos \omega_1 t$) are applied to a detector having the characteristic $i = Ke^2$, the output becomes:

$$i = (e_0 \cos \omega t + e \ \cos \omega_1 t)^2$$

$$= e_0^2 \cos^2 \omega t + e_1^2 \cos^2 \omega_1 t + 2e_0 e_1 \cos \omega t \cos \omega_1 t$$

$$\text{but since } \cos^2\theta = \frac{1}{2}(1 + 2\cos 2\theta)$$

$$\text{and } 2\cos A \cos B = \cos(A + B) + \cos(A - B)$$

$$\therefore i = \frac{1}{2}\left(e_0^2 + e_1^2\right) + \frac{1}{2} e_0^2 \cos 2\omega t + \frac{1}{2} e_1^2 \cos 2\omega_1 t + + e_0 e_1 \cos(\omega + \omega_1) t + e_0 e_1 \cos(\omega - \omega_1) t$$

The terms represent:

a d.c component $\frac{1}{2}\left(e_0^2 + e_1^2\right)$

two second harmonic components

$e_0^2\left(\frac{1}{2}\cos 2\omega t\right)$ and $e_1^2\left(\frac{1}{2}\cos 2\omega_1 t\right)$

the sum frequency $e_0 e_1 \cos(\omega + \omega_1) t$
and the difference frequency $e_0 e_1 \cos(\omega - \omega_1) t$

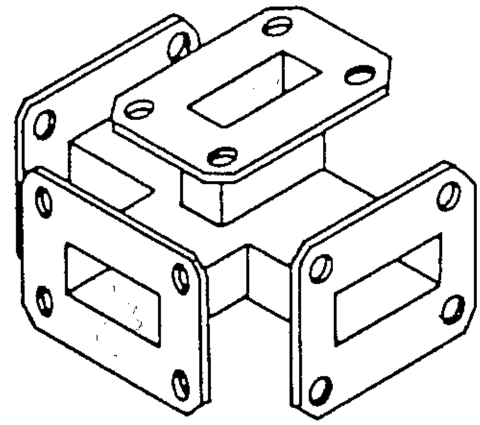
Usually all the terms except the last are ignored. One of the input frequencies to the mixer is always a signal of some kind; the other is usually generated in the equipment housing the mixer, and is therefore called the '*local oscillator*' signal.

In a Doppler radar the local oscillator is the same oscillator which supplies the transmitted signal. Only a very small fraction of its output is used by the mixer, so that the mixer works correctly in its small-signal, square-law range. In this case ω and ω_1 are the transmitted and reflected frequencies discussed earlier, and the last term has a frequency $\frac{v}{\pi \lambda c}$. It is therefore a measure of v, the velocity of the reflecting object.

Chapter 3 Assignment 10

In order to separate the transmitted and received signals sufficently, this assignment will use a '*hybrid tee*', as illustrated in fig 10.1.

Fig 10.1



Hybrid Tee (component H)

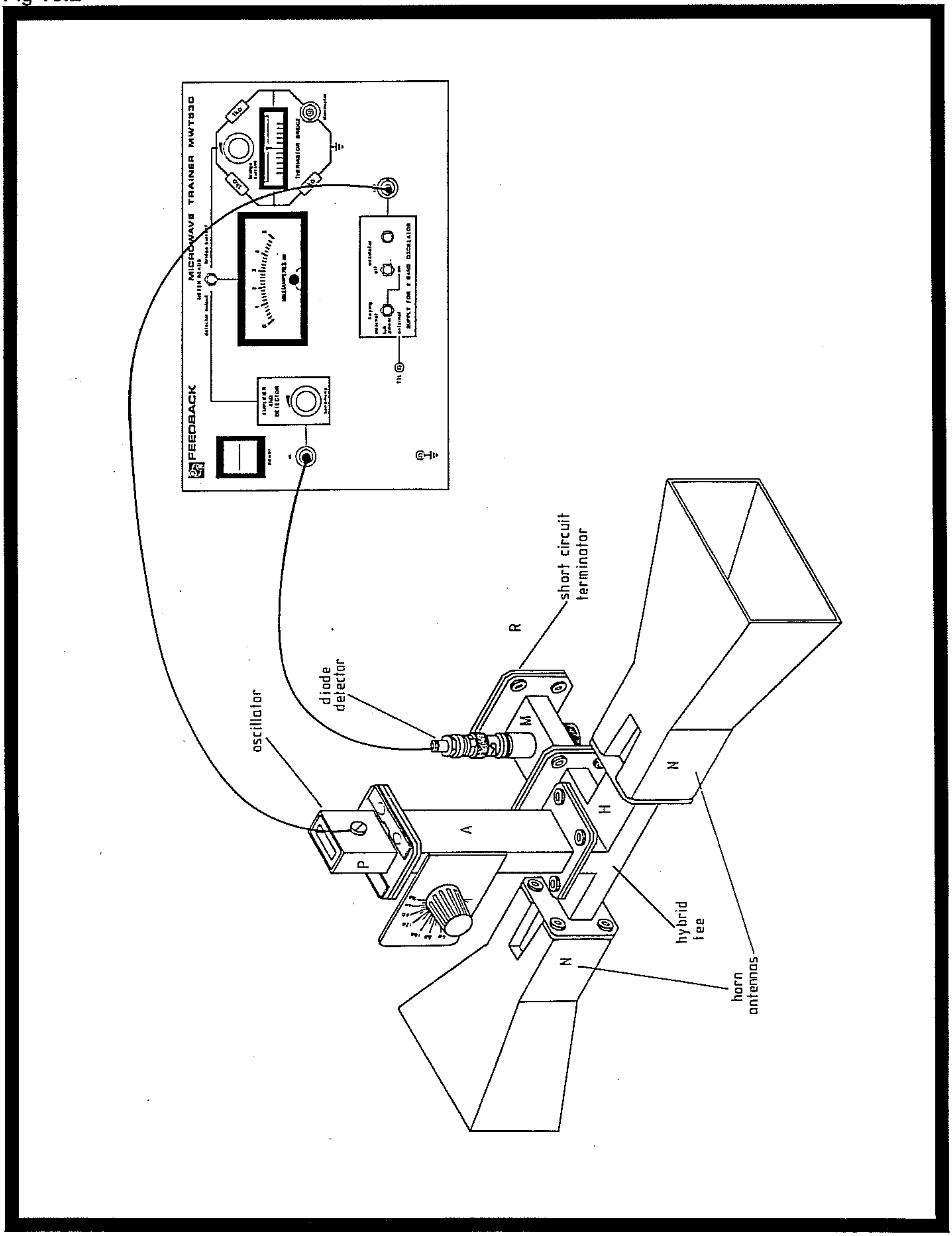
This is a combination of the series and shunt-type tees examined in Assignment 8. It operates in a similar manner to a hybrid transformer at low frequency. That is, it has two principal ports which are not directly coupled to each other, though each is coupled to two symmetrical load ports. These can produce reflections, which can pass to both principal ports. If the loads are symmetrical, the reflections from them cancel one another at the other principal ports, so that the latter are still not coupled together. If there is unbalance in the loads however, the reflections will not cancel and there will be some coupling between the principal ports.

In the hybrid tee a straight waveguide run has both a series-tee arm and a shunt-tee arm. These latter arms are the principal ports. They are not mutually coupled because in effect one is twisted through 90° relative to the other. Any field generated by one in the other must, from symmetry have equal strength in one direction and the other, so that the resultant field must be zero. Each is however coupled to the other arms in either series-tee or shunt-tee fashion.

NOTES:

Chapter 3 Assignment 10

Fig 10.2



Chapter 3 Assignment 10

EXPERIMENTAL PROCEDURE

Connect the apparatus in the way shown in fig 10.2.

WARNING **Keep your eyes AWAY from the antennas, at a distance of at least 30cm.**

On the Control Console set the METER READS switch to 'detector output', switch on the supply to the oscillator and set its left–hand switch for internal keying.

Adjust the Detector amplifier for maximum sensivity.

If the system were perfectly balanced, the Detector would receive no signal. In practice this is unlikely. Try the effect of moving objects close to one or other of the antennas. A signal should then appear at the Detector and be indicated by the meter. This signal shows that the Detector is now receiving a small amount of the microwave energy sent out by the Oscillator.

Place the system with one Horn Antenna pointing to the space in front of the bench. Adjust it and the surrounding objects to give a mid-scale reading on the meter. (It will probably be convenient to place one of the Antennas pointing at the Control Console, and approximately 300mm distant from it whose reflection will serve to unbalance the system suitably). Then use your body (BUT NOT your face!) as a reflecting object 'seen' by the outward-facing Antenna. Observe the effect of moving slowly toward the Antenna, and away from it.

Notice how the signal reflected by you can increase or decrease the Detector signal. Answer the following questions:

Question 10.1 ***Considering the meter current as having a d.c and an a.c component, what characteristic of the a.c component is related to your speed of motion?***

Question 10.2 ***Can you imagine how a Doppler system might measure position? What limitation would it have?***

Chapter 3 Assignment 10

SUMMARY

This experiment showed the principles of a Doppler radar, which has the following essential features:

- a microwave transmitter,
- an antenna to receive reflected signals (in this case the transmitting antenna both transmits and receives),
- a mixer, or detector fed with the received signal and a portion of the transmitted one.

A hybrid tee, has arms like a series tee combined with a shunt tee. If the two arms which are common to the shunt and series tees have equal impedance connected to them, the series arm and the shunt arm are not coupled, i.e a signal from one will not pass to the other. This fact was used to enable only a small fraction of the Oscillator power (controlled by a small unbalance) to go to the mixer.

Chapter 3 Assignment 10 - Typical Results and Answers

The results of this experiment are qualitative. Possible answers to the questions are:

Question 10.1

The meter reading fluctuates regularly as a reflecting object approaches. One cycle of fluctuation takes place for every half–wavelength travelled. Therefore the faster an object moves, the more rapid will be the fluctuations. In other words the *frequency* of the a.c component of received signal is proportional to the speed of approach.

Question 10.2

In order to measure changes in the distance of an object from the antenna, it would be necessary to count the cycles of signal fluctuation. A simple system would have several limitations.

- At least one position of the object would need to be known, since only changes can be observed.
- Two systems, or parts of the same system, would need to have signals of different phases, in order to distinguish between motion toward , and away from, the antenna(s).
- Either two systems, or procedures involving motion of a single one, are needed to discover the direction in which the object lies.

ASSIGNMENT 11 USE OF COAXIAL CABLE

CONTENT

Coaxial cable is introduced as an alternative to waveguides for transmission of microwave signals. Losses occurring during transmission and transition are investigated.

EQUIPMENT REQUIRED

Qty	Ident. letter	Description
1	–	Control Console
1	A	Variable Attenuator
1	B	Slotted–line
1	C	Slotted–line Tuner
2	J	Waveguide/Coaxial Adaptor
1	L	Bolometer (Thermistor–type)
1	P	X–Band Oscillator
1	S	Probe Detector Assembly

Chapter 3 Assignment 11

OBJECTIVES

When you have completed this assignment you will:

- Be aware that coaxial cable is a commonly used means of guiding microwave signals.
- Be able to compare the losses arising from the use of coaxial cable with those of waveguides.

KNOWLEDGE LEVEL

Before you start this assignment you should:

- Have completed Assignment 3 'Measurement of Microwave Power.

NOTES:

Chapter 3 Assignment 11

INTRODUCTION

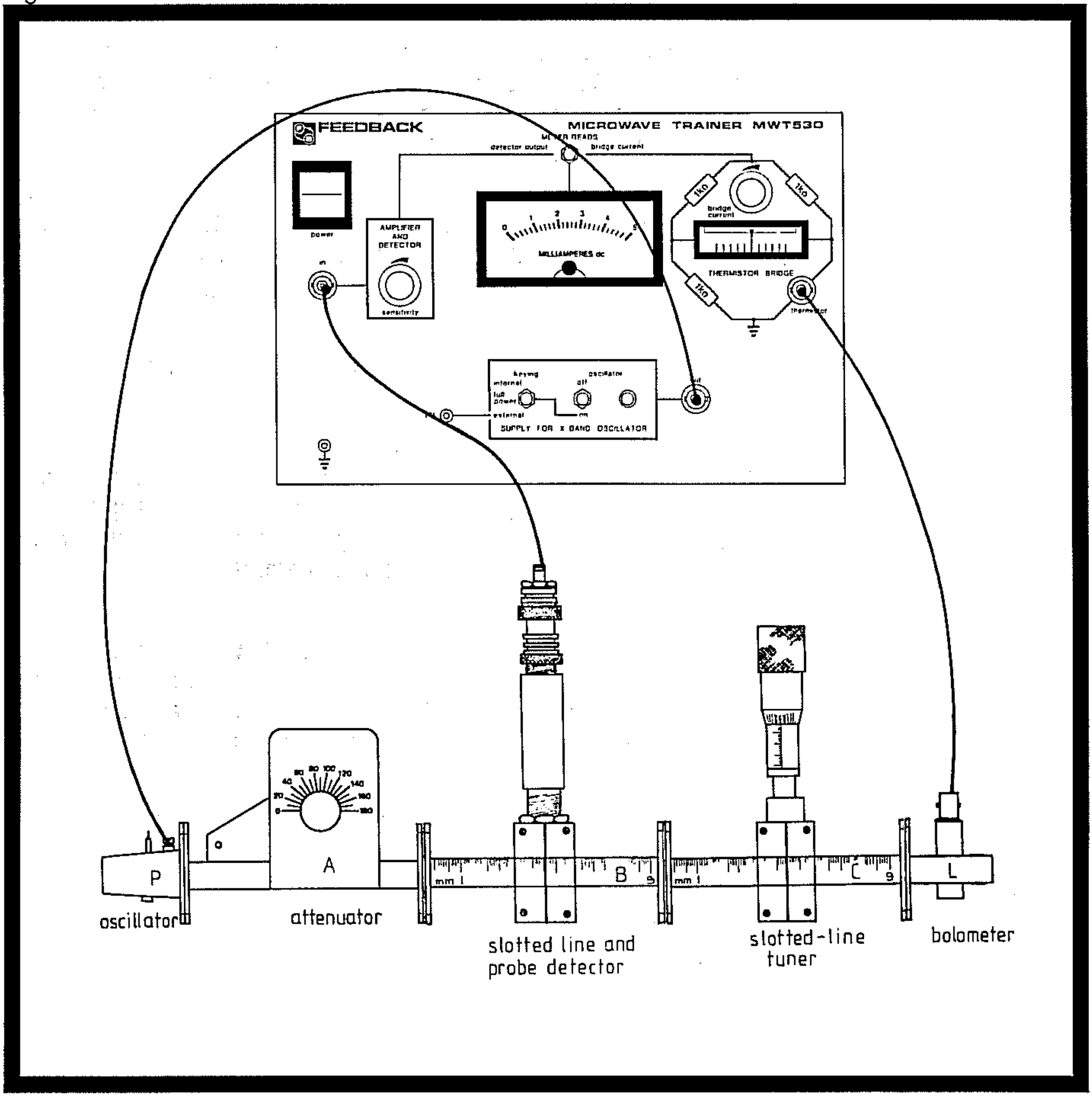
Although a waveguide is excellent from the point of view of transmitting microwave energy with low losses, it is not always convenient. Modern electronics tends to be on printed circuit boards, for which strip-line techniques are widely used (the conductors are tracks in the printed wiring). Also units are mounted in boxes which must be easy to interconnect and disconnect, for which purpose the flexibility of cables is convenient, and coaxial cable the most suitable. Both strip-lines and coaxial cables introduce fairly heavy losses, however. For this reason waveguide is generally preferred for antenna feeders, where loss of signal spoils the signal/noise ratio in reception, or wastes expensive power in transmission.

When a signal is transferred from one mode of propagation to another, as from waveguide to cable or vice versa, some special device is needed to accept the signal in one mode and launch it in a new mode. Such a transition device must attempt to convert an electromagnetic field in one form to another electromagnetic field of different form. This often presents some problem in matching.

In this assignment the losses and matching problems in a length of coaxial cable will be examined.

Chapter 3 Assignment 11

Fig 11.1



Chapter 3 Assignment 11

EXPERIMENTAL PROCEDURE

Before starting, adjust the penetration of the Tuner probe to approximately zero. Then set up the apparatus as shown in fig 11.1. On the Control Console, switch on the supply to the oscillator and set its left-hand switch for internal keying; set the METER READS switch to 'bridge current'.

The Attenuator may be set to minimum attenuation. In this conditon it should be realised that reflections from any mismatch can upset the Oscillator, possibly preventing it from working.

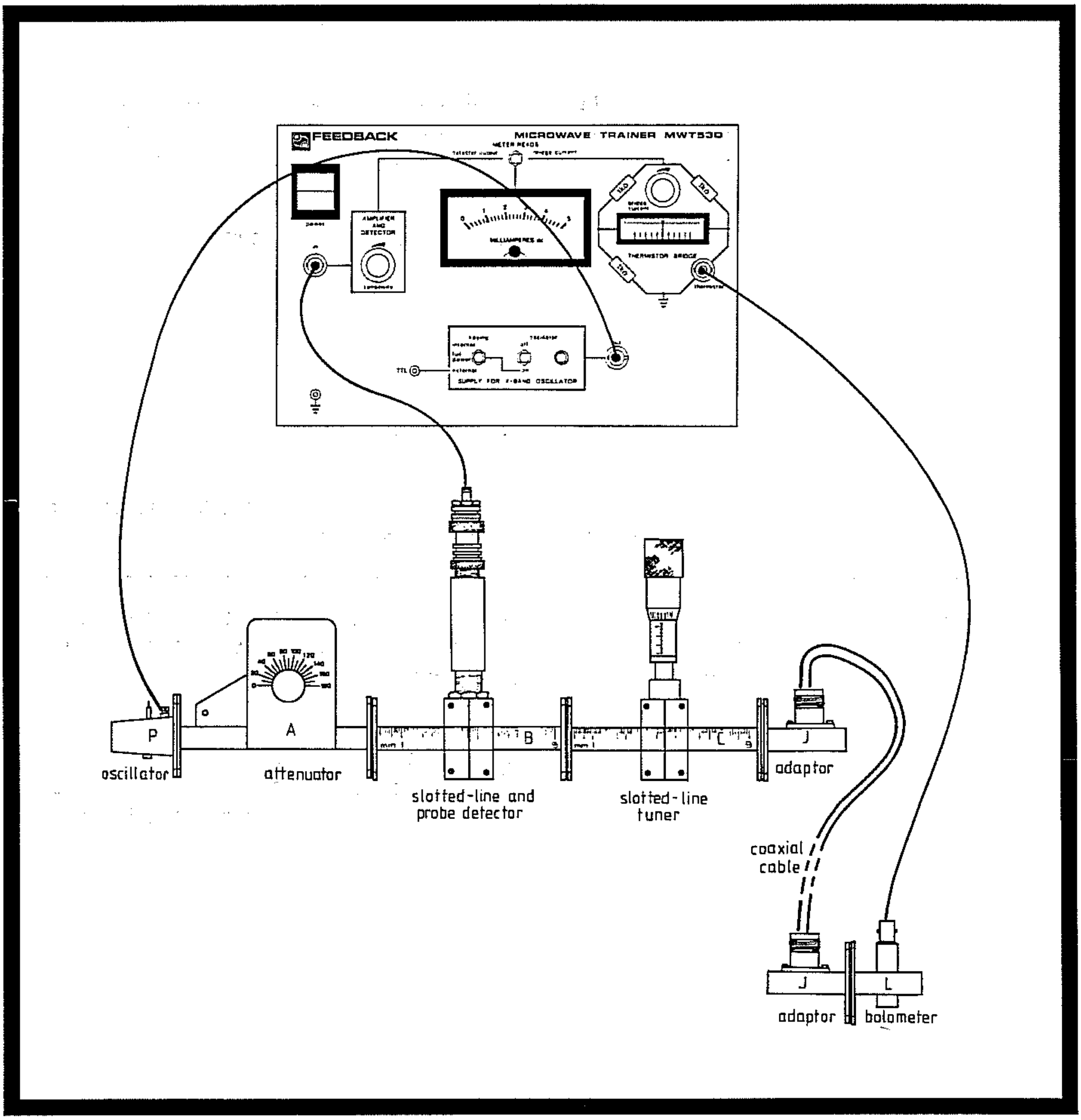
Using the Bolometer bridge, measure the power sent to the Bolometer while the Tuner is doing nothing.

Then use the Tuner to maximise the amount of power sent to the Bolometer. To do this, increase the probe penetration slightly, and find the position of the carriage giving greatest power; then adjust the probe depth and carriage position alternately.

It may be found that too much power is available for the bolometer bridge to be balanced at minimum d.c. If so, adjust the Attenuator to give a measurable power. Make sure that Attenuator setting is not disturbed during the following part of the experiment.

Measure the maximum power obtained in the Bolometer.

Fig 11.2


FEEDBACK
MICROWAVE TRAINER MWT530
MILLIAMPERES dc
THERMISTOR BRIDGE
SUPPLY FOR X-BAND OSCILLATOR
TTL
P
A
B
C
J
L
oscillator
attenuator
slotted-line and
probe detector
slotted-line
tuner
adaptor
coaxial
cable
adaptor
bolometer

Chapter 3 Assignment 11

Next disconnect the Bolometer from the Tuner, and insert the two Waveguide/Coaxial Adaptors and Coaxial Cable per fig 11.2.

Without altering the Attenuator, again adjust the Tuner for maximum bolometer power. (It may be helpful to reduce the probe penetration of the Tuner first). Measure the new value of power.

Calculate the ratio of powers obtained with and without the cable link.

Calculate the cable loss in dB, which is:

$$\text{loss} = 10 \log_{10} (\text{power ratio})$$

Examine the waveguide/coaxial cable Adaptors and describe in your own words how you think they work.

SUMMARY

Microwaves can be transmitted along several different kinds of conductors. Waveguides generally provided least loss, but other forms are used for convenience.

The experiment showed that an appreciable loss occurs in even quite a short length of coaxial cable. The necessity for tuning also demonstrated that the transition introduced a significant mismatch.

Chapter 3 Assignment 11 - Typical Results and Answers

With the Tuner probe set to zero, the r.f power in the Bolometer

$= 3.9^2$ mW

$= 15.21$mW

With the Tuner adjusted to obtain the maximum r.f power, the bridge current is 1.2mA.

Therefore, the r.f power

$= 15.21 - 1.2^2$ mW

$= 13.77$mW

With the coaxial cable inserted and, again the Tuner adjusted to the maximum r.f power, the bridge current is 3.2mA.

Therefore, the r.f power

$= 15.21 - 3.2^2$ mW

$= 4.97$mW

The ratio of powers

$$= \frac{13.77}{4.97}$$

$= 2.77$

The power loss

$= 10\log_{10} 2.77$dB

$= 4.4$dB

Appendix A Wavelength in a Waveguide

APPENDIX A

WAVELENGTH IN A WAVEGUIDE

For radio-frequency energy to travel along a waveguide, it must be possible for the associated electric and magnetic fields to exist inside the guide. One of the conditions that must be met is that there can be no electric field acting along a conducting surface. How is this possible with a transverse electric ware?

Imagine two plane waves in free space, having the same frequency (and therefore wavelength), and travelling at an angle to one another.

Fig A1

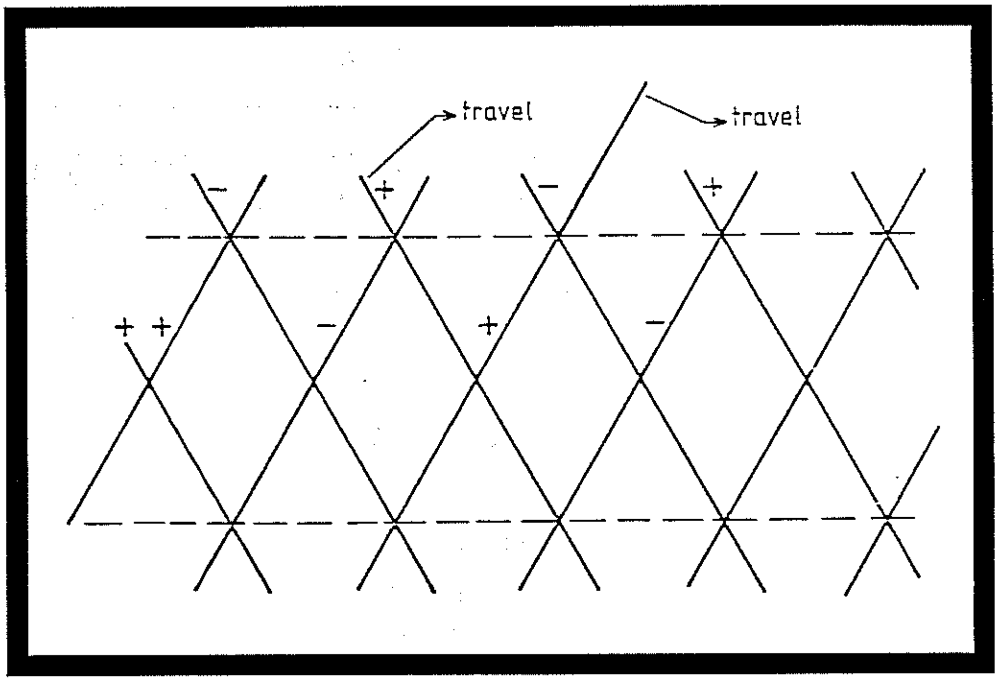


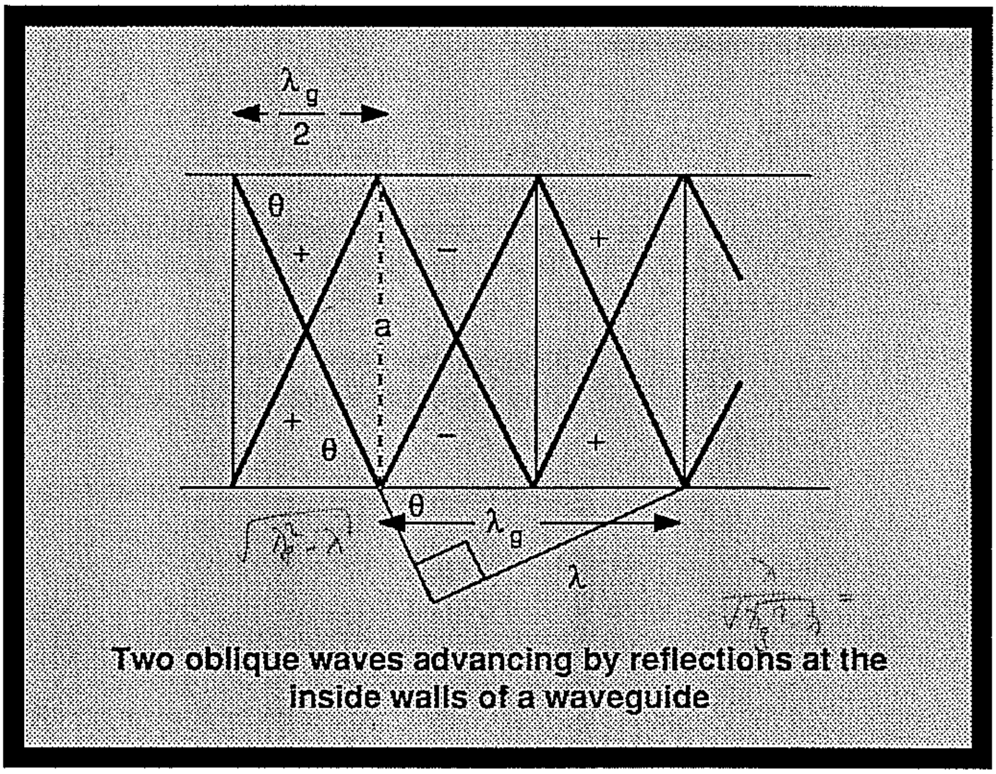
Fig A1 shows the waves as a series of lines representing the places where maximum positive and negative electric field strength are obtained (at a given instant).

Also shown in fig A1 is a pair of broken lines at which the maximum positive value of one of the waves is cancelled out by the maximum negative value of the other wave. These broken lines are therefore places where the electric field strength is zero.

It is possible therefore to place conductors at the site of the broken lines without altering the wave pattern. These can be the walls of a waveguide. We have thus shown a possible pattern of waves which could exist in a waveguide. (Clearly, however, the pattern will not be generated by the process we have imagined).

Appendix A Wavelength in a Waveguide

Fig A2



Two oblique waves advancing by reflections at the inside walls of a waveguide

Fig A2 shows the waveguide, with its internal field pattern.

In this situation the original pair of waves, meeting the conducting wall of the waveguide, has electric field reduced to zero by current induced in the waveguide wall. This current causes the generation of a reflected wave. During the time that the two oblique waves advance through one wavelength λ, the combined wave appears (as measured by its phase) to have advanced through the greater distance λ_g. From geometrical considerations, all the angles marked θ are equal. By equating values of tanθ, or otherwise, it is easy to show that:

$$\frac{\lambda_g}{\lambda} = \frac{1}{\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}} \qquad \text{A.1}$$

It will be evident that λg is always greater than l.

What has been described leads to a waveguide propagating the wave in $TE_{1.0}$ mode.

Appendix A Wavelength in a Waveguide

Cutoff frequency

As the free-space wavelength λ is increased, the angle between the guide's direction and that of each oblique wave increases. Eventually, at the cutoff frequency, the denominator of equation A.1 becomes zero (and therefore the calculated λ_g becomes infinite). The 'oblique' waves are now travelling perpendicular to the waveguide direction. No signal is therefore propagated along the waveguide at all.

In-guide wavelength in terms of cutoff frequency

It can be shown that, for all modes,

$$\frac{\lambda_g}{\lambda} = \frac{1}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \qquad \text{A.2}$$

where f is the signal frequency

f_c is the waveguide's cut–off frequency

the wavelength in the guide is therefore always longer than the free-space wavelength, by a factor which increases as the cutoff frequency is approached.

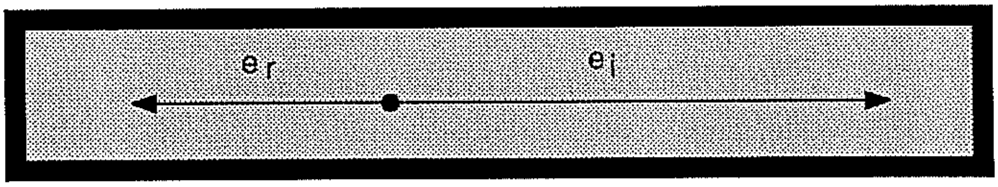
NOTES:

Appendix B Analysis of Double-Minimum Method for VSWR

APPENDIX B ANALYSIS OF DOUBLE-MINIMUM METHOD FOR VSWR

An incident wave of strength e_i and a reflected wave of strength e_r produce a standing wave whose maximum value is e_{max} and whose minimum value is e_{min}. For a point where the minimum signal (e_{min}) is obtained, fig B1 shows the phasors for e_i and e_r to be in antiphase.

Fig B1

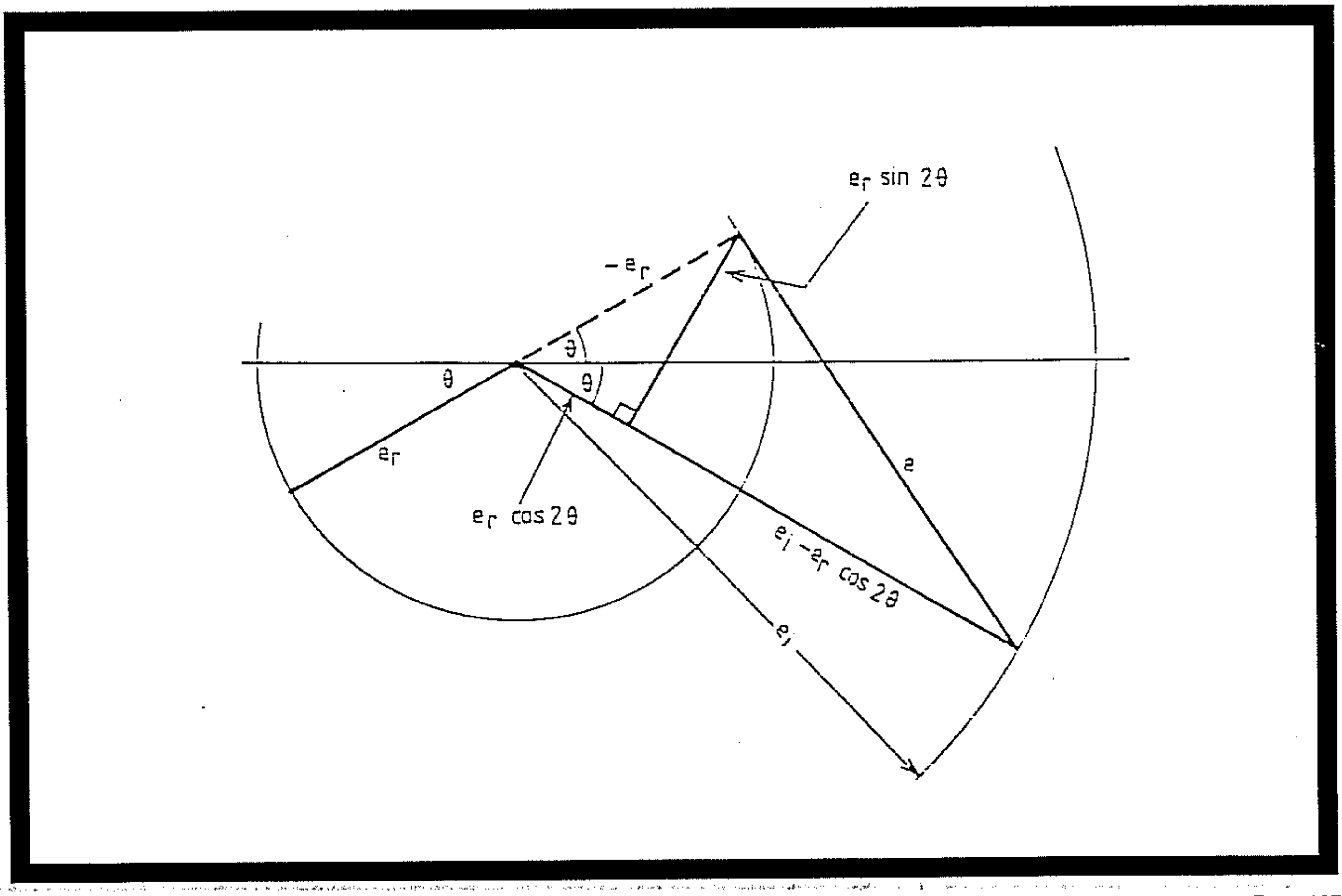


On moving a distance $\frac{d}{\lambda_g}$ from the minimum point, where λ_g is the wavelength within the guide, the phasor of the incident wave will be retarded $\frac{2\pi d}{\lambda_g}$ radians, and that of the reflected wave will be advanced by the same amount.

For convenience let $\theta = \frac{2\pi d}{\lambda_g}$

Then fig B2 shows the displaced phasors (whose tips move around circles, since the magnitudes of incident and reflected waves are supposed constant).

Fig B2



Appendix B Analysis of Double-Minimum Method for VSWR

The resultant e is most easily calculated as the difference between the larger phasor ei and the negative of the smaller, $-e_r$.

Thus from fig B2, with Pythagoras' Theorem,

$$e^2 = e_r^2 \sin^2 2\theta + \left(e_i^2 - e_i e_r \cos 2\theta + e_r^2 \cos 2\theta\right)$$
$$= e_r^2 + e_i^2 - 2e_i e_r \cos 2\theta$$

It is easy to verify that for $\theta = n\pi$, $\cos 2\theta = 1$

and $e^2 = (e_i - e_r)^2 = e_{min}^2$

while for $\theta = n\pi + \frac{\pi}{2}$, $\cos 2\theta = -1$

so that $e^2 = \left(e_1 + e_r\right)^2 = e_{max}^2$

The double-minimum method finds the value of θ for which the detector current

$i = ke^2$ is doubled, i.e when $i = 2ke_{min}^2$.

For this condition $ke_0^2 = 2ke_{min}^2$

$$\text{or } k\left(e_r^2 + e_i^2 - 2e_i e_r \cos 2\theta\right) = 2k\left(e_i^2 + e_r^2 - 2e_i e_r\right)$$
$$\therefore e_r^2 + e_i^2 - 2e_i e_r (2 - \cos 2\theta) = 0$$
$$\therefore \left(\frac{e_i}{e_r}\right)^2 + 1 - 2\frac{e_i}{e_r}(2 - \cos 2\theta) = 0 \qquad (1)$$

Now the VSWR is defined as $\frac{e_{max}}{e_{min}}$.

Let us denote it by s

$$\text{Then } s = \frac{e_i + e_r}{e_i - e_r}$$

Appendix B Analysis of Double-Minimum Method for VSWR

$$e_i(s-1) = e_r(s+1)$$

$$\frac{e_i}{e_r} = \frac{s+1}{s-1} \qquad (2)$$

Also $\cos 2\theta = 1-2\sin^2\theta$

$$\therefore 2-\cos 2\theta = 2-\left(1-2\sin^2\theta\right)$$

$$= 1+2\sin^2\theta \qquad (3)$$

Substituting (2) and (3) into (1) gives:

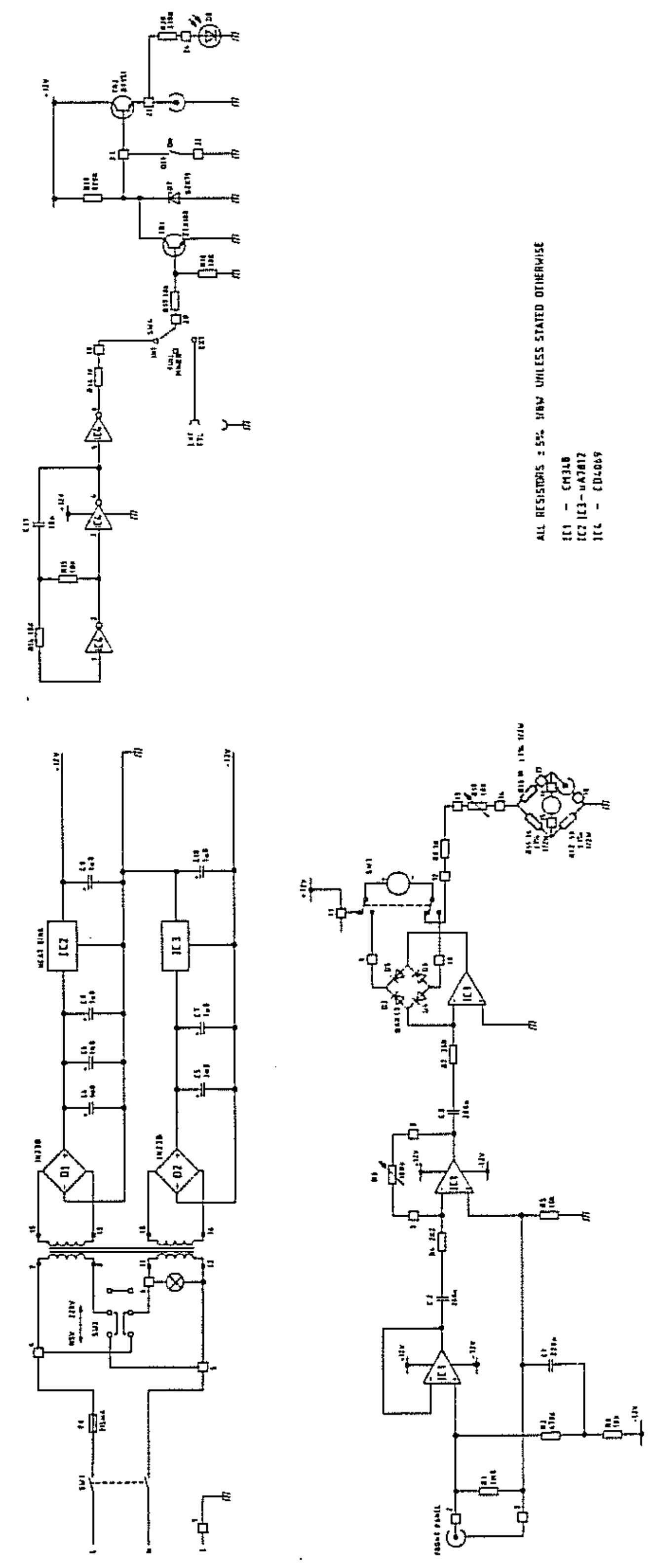
$$\left(\frac{s+1}{s-1}\right)^2 + 1-2\frac{s+1}{s-1}\left(1+2\sin^2\theta\right) = 0$$

which reduces to:

$$s^2 = 1+\frac{1}{\sin^2\theta}$$

NOTES:

Appendix C Circuit Diagram – Control Console



Drawing Reference: 1–530–11339, issue 2

NOTES: