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INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

KULLIYYAH OF ENGINEERING

DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

MICROWAVE LABORATORY
ECE 3203

EXPERIMENT NO.3

(Measurement of Impedance and Impedance Matching)

CONTENT

The concept of impedance in waveguides and the use of the Smith Chart in impedance and matching calculations are introduced. The measurement of impedance of a waveguide component is carried out and the results used to determine the position of a capacitative probe to effect matching.

EQUIPMENT REQUIRED

Quantity	Identifying letter	Component description
1	---	Control console
1	A	Variable attenuator
1	B	Waveguide slotted line
1	C	Slotted line probe tuner
1	K	Resistive termination
1	P	X-band oscillator source
1	S	Probe-diode detector used with slotted line
1	R	Short-circuit plate

OBJECTIVES

When you have completed this assignment you

- Should understand the terms normalised impedance and admittance of a waveguide component
- Know how to measure normalised impedance by measuring the vswr and position of a electric field or voltage minimum in the standing wave pattern produced by the component
- Appreciate the use of the Smith Chart in aiding impedance determination
- Appreciate the need for matching
- Know how matching can be accomplished using a slotted line probe/screw tuner

KNOWLEDGE LEVEL

Before you commence this assignment you

- Should look at Assignment 2 and know the significance of vswr and how it can be measured
- Appreciate that a load terminating a waveguide or a transmission line will cause reflection and produce a standing wave unless matched

- Be familiar with the basic results of transmission line theory

INTRODUCTION

Summary of basic transmission line and standing wave results of a terminated line

(1) Input impedance normalised impedances and reflection coefficient of a terminated line

The impedance of a waveguide load is determined using the general result for the impedance of a terminated line given by transmission line theory. Since voltage and current cannot be measured in a waveguide, the actual measurement of impedance is deduced from the standing wave electric field pattern set up by the load.

From transmission line theory, we have for the input impedance of a line of characteristic impedance Z_0 when terminated in a load of impedance, Z_T, as indicate in Figure 2-4-1.

$$Z_{in}(l) = \frac{V(l)}{I(l)} = Z_0 \frac{Z_T + j Z_0 \tan\beta l}{Z_0 + j Z_T \tan\beta l} \qquad (1)$$

where l = line length

$\beta = 2\pi/l_g$, the phase constant of the line

l_g = guide wavelength

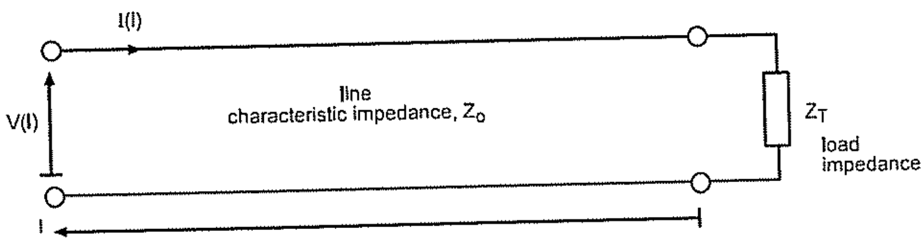


Figure 2-4-1

The result given by (1) is general and can be used to quantify waveguide loads as impedances in much the same way as impedances are used at lower frequencies and in coaxial and parallel wire type lines. In these types of lines voltage and current can be defined and their characteristic impedance uniquely determined. Typical Z_0 values for coaxial lines used in RF work are 50 Ω and 75 Ω.

The characteristic impedance of waveguides, however, cannot be uniquely specified and so to avoid this difficulty impedance levels are relative to Z_0 as normalised impedances.

$$z_{in}(l) = \frac{Z_{in}(l)}{Z_0}$$

$$= \frac{Z_T + jZ_0 \tan \beta l}{Z_0 + jZ_T \tan \beta l}$$

$$= \frac{Z_T / Z_0 = j \tan \beta l}{1 + jZ_T / Z_0 \tan \beta l}$$

$$= \frac{z_T + j \tan \beta l}{1 + jz_T \tan \beta l} \qquad (2)$$

where $z_T = Z_T/Z_0$ = normalised load impedance.

The reflection coefficient at the load is given by:

$$\Gamma = \frac{Z_T - Z_0}{Z_T + Z_0}$$

$$= \frac{z_T - 1}{z_T + 1} \qquad (3)$$

so unless $Z_T = Z_0$ or equivalently $Z_T = 1$ reflection will occur. If the load is matched to the line, that is $Z_T = Z_0$, then G = 0 and no reflection occurs.

(2) **Admittance**

As well as working in impedances it will be also convenient to work in admittances. This is especially so in matching applications where shunt elements are employed (elements connected in parallel).

Admittance is the reciprocal of impedance and so formulae (1), (2) and (3) can be expressed in terms of admittance as

$$Y_{in}(l) = \frac{I(l)}{V(l)} = Y_0 \frac{Y_T + jY_0 \tan \beta l}{Y_0 + jY_T \tan \beta l} \qquad (1^1)$$

$$y_{in}(l) = \frac{y_T + j \tan \beta l}{1 + jy_T \tan \beta l} \qquad (2^1)$$

$$\Gamma = \frac{Y_0 - Y_T}{Y_0 + Y_T} = \frac{1 - y_T}{1 + y_T} \qquad (3^1)$$

2. Measurement of normalised impedance of a waveguide load

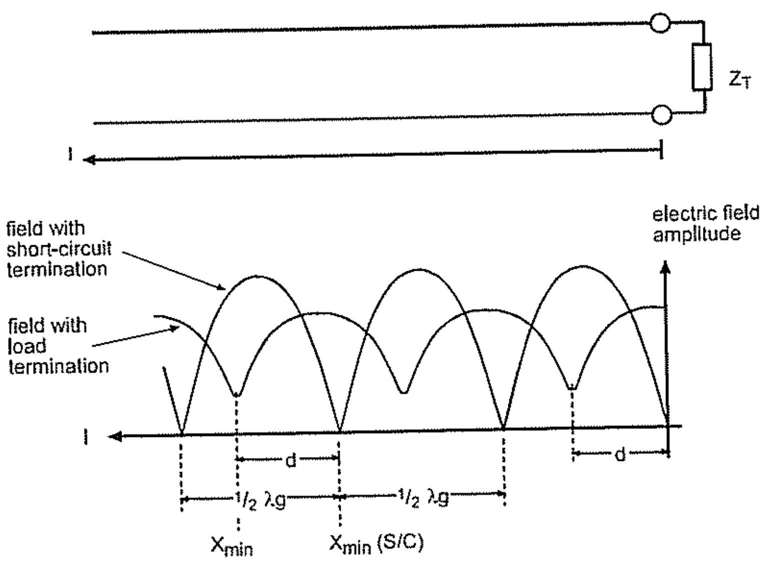


Figure 2-4-2

Figure 2-4-2 illustrates a typical standing wave pattern set up by a load terminating a line when a mismatch between line and load occurs. The plot of electric field amplitude versus distance from the load shows a variation between points of maximum E_{max} and minimum E_{min}. By measuring the voltage standing wave ratio, the VSWR, S, and the position of the first minimum, d, from the load, the normalised load impedance Z_T can be determined.

At a voltage or electric field minimum, the incident and reflected waves are in anti-phase and the normalised input impedance of the line at this point is resistive and equal to 1/S. Thus:

$$\text{when } l = d \qquad z_{in}(d) = \frac{1}{s} = \frac{z_T + j\tan\beta d}{1 + jz_T\tan\beta d} \qquad (3)$$

$$\text{where} \qquad S = \frac{E_{max}}{E_{min}} \quad \text{, the VSWR}$$

and $\quad d = \text{distance from load of first E - field minimum}$

We solve (3) for the normalised load impedance:

$$Z_T = \frac{1 - jS\tan\beta d}{S - j\tan\beta d}$$

and expressing z_T in terms of its real and imaginary parts, we have

$$\text{real or resistive part of } z_T, \quad r_T = \frac{S(1 + \tan^2\beta d)}{S^2 + \tan^2\beta d} \qquad (4)$$

$$\text{imaginary or reactive part of } z_T, \quad x_T = \frac{(1 - S^2)\tan\beta d}{S^{12} + \tan^2\beta d} \qquad (5)$$

In the practical experiment the vswr is measured by measuring the detector current I_{max} at a maximum and at a minimum I_{min} using the slotted line:

$$S = \frac{E_{max}}{E_{min}} = \sqrt{\frac{I_{max}}{I_{min}}}$$

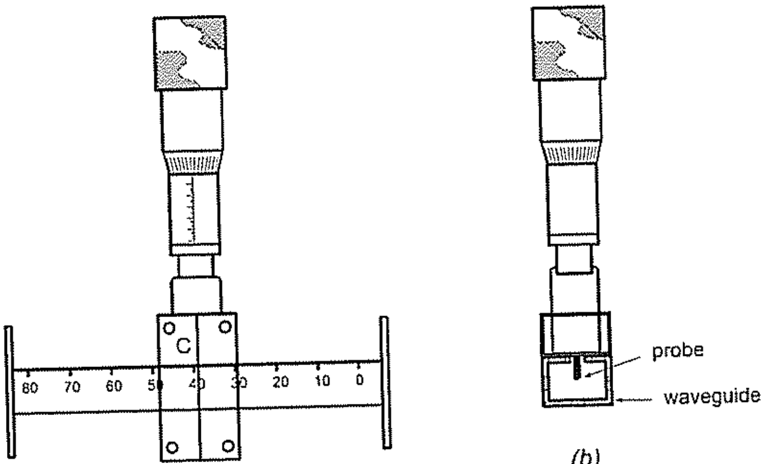
The distance, d, is best measured by recording the positions of minimum with load and short-circuit terminations, then with reference to Figure 2-4-2

$d = x_{min}\text{ (load)} - x_{min}\text{ (short-circuit)}$

The calculations to determine z_T expressed by the formulae (4) and (5) can be accomplished by use of a calculator or with the aid of a Smith Chart. The procedure using a Smith Chart is explained in the Typical Results section at the end of this assignment.

3. Matching a load using a reactive stub

The slotted line probe tuner, component C, shown in Figure 2-4-3, acts as a shunt reactance element and is a useful component in effecting matching. For small penetrations of the probe, capacitative susceptance can be introduced which increases the penetration, but eventually changes sign and becomes inductive. In most matching applications, units of this type consist of either a probe, post or screw and are inserted to produce capacitative susceptance.



(a)
Side view

(b)
cross-section view
looking down waveguide

Figure 2-4-3 Slotted Line Probe Tuner

The principle of shunt stub matching may be explained with reference to Figure 2-4-4(a). We look for a point at a distance from the load where the real part of the input admittance is unity, i.e. where:

$$y_{in}(l) = 1 \pm jb$$

Then if at this point we connect in a shunt stub of susceptance equal in magnitude but opposite in sign we can cancel out the load susceptance so that $y_{in} = 1$ and thus effect matching to the feed line.

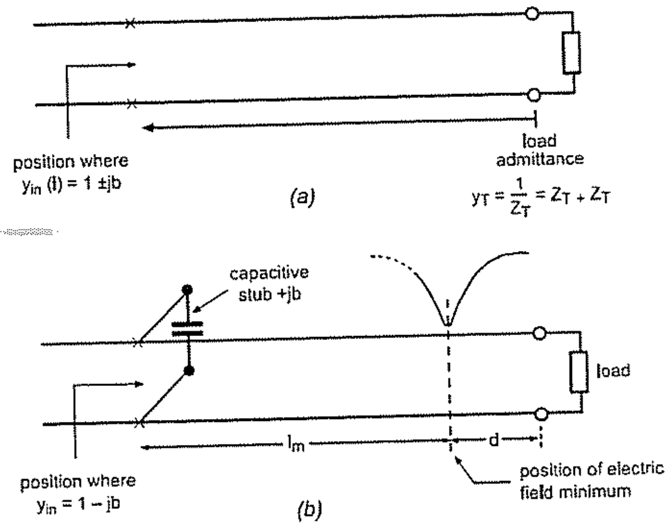


Figure 2-4-4 Shunt Stub Matching

We can locate the position where yin(l) = ±jb by finding the position d of the first electric field minimum and then using the known admittance at this point as a new load:

$y_T = S$ at a minimum

in the general formula for transmission line input admittance. We solve this for the condition that the real part of $y_{in} = 1$, i.e:

$$y_{in}(l_m) = \frac{y_T + j\tan\beta lm}{1 + jy_T \tan\beta lm} \quad \text{where } y_T = S$$

solving for the real part of yin and equating to unity, we obtain the condition:

$$\tan^2 \beta l_m = l/S$$

so $$l_m = \frac{1}{\beta}\tan^{-1}(l/S) = \frac{\pm\lambda g}{2\pi} = \tan^{-1}(l/S)$$

We have in fact two values, one positive and one negative, for lm, so there are two positions either side of the voltage minimum position satisfying real $[y_{in}] = 1$. The negative value of lm corresponds to yin = 1 + jb and would require inductive susceptance for matching, the positive value used in this assignment requires capacitative susceptance as yin = 1 –jb.

EXPERIMENTAL PROCEDURE

WARNING:
Microwave radiation can be harmful, especially to eyes.
NEVER look into energised waveguide.

Measurement of the normalised impedance of a waveguide

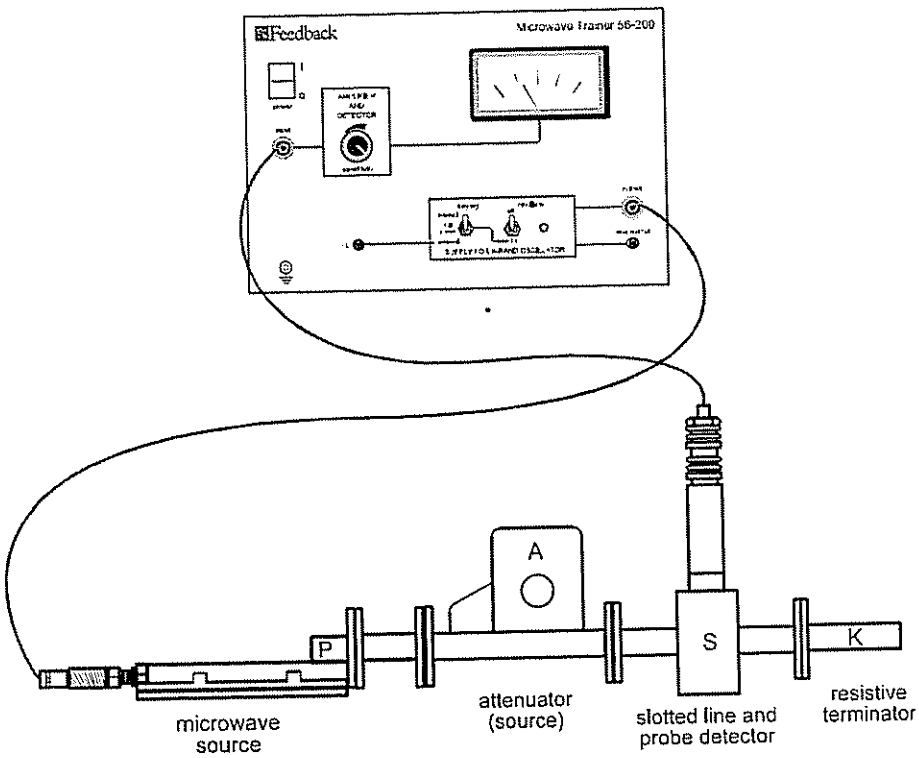


Figure 2-4-5

1. Set up the equipment as shown in Figure 2-4-5. The waveguide load whose impedance we are to measure is connected to the slotted line section. Our test load in this experiment is the resistive termination, component K.

> **Note:**
> The probe of the probe-detector S mounted on slotted line should be adjusted to penetrate between 1 to 2 mm through the slot into the waveguide. This should ensure sufficient coupling to measure the electric field in the waveguide without disturbing the standing wave set up by the load under

2. Set the attenuator to approximately 20° to provide a fairly good value of buffer attenuation, switch the X-band source to internal keying and meter to detector output. Switch on the console power supply and the X-band oscillator.

3. Move the detector carriage along the slotted waveguide section to locate a position of an electric field maximum. Adjust the sensitivity of the detector-amplifier on the console to provide a meter reading of 3 to 4 mA. If necessary adjust the attenuator setting.

4. The microwave bench is now set up to measure the VSWR of the resistive load. Move the probe-detector carriage to a position closest to the load and then moving away from the load record positions of electric field minima and values of detector output current at positions of both minima and maxim. Record results in a table similar to that given in Figure 2.-4-6 below.

With resistive load		With short-circuit
Positions of max. & min.	Detector Current	Positions of max. & min.
x_{1min} =	I_{min1} =	x_1 s/c min =
x_{2max} =	I_{max2} =	
x_{3min} =	I_{min3} =	x_3 s/c min =
x_{4max} =	I_{max4} =	
x_{5min} =	I_{min5} =	x_5 s/c min =

Figure 2-4-6: Table for Recording Results for Impedance Measurement

5. Remove the resistive load and replace by the short-circuit plate R so that the slotted line is now terminated in a short-circuit.

Locate and record positions of electric field minimum as the probe-detector carriage is moved along the slotted line starting closest to the short-circuit and moving progressively along the slot towards the source.

6. Calculate from your results the VSWR S of the load, the guide wavelength λ_g and the distance d of first electric field minimum from the load input.

Remember:

$$\text{VSWR } S = \sqrt{\frac{I_{max}}{I_{min}}}$$

$$\lambda_g = 2\left(x_{3s/c} - x_{1s/c}\right)$$

$$= x_{5s/c} - X_{1s/c}$$

(note: use short-circuit positions for l_g since these are well-defined nulls and hence can be measured very accurately)

$$d = x_1 = x_{1s/c}$$

$$= x_3 - x_{3s/c}$$

7. Finally calculate the normalised impedance of the load, $z_T = r_T + j x_T$ where the resistive part r_T and imaginary part x_T are given by the formulae (4) and (5) in the **Introduction** section.

8. Check your result using the Smith chart.

Matching a waveguide load using a slotted waveguide probe tuner

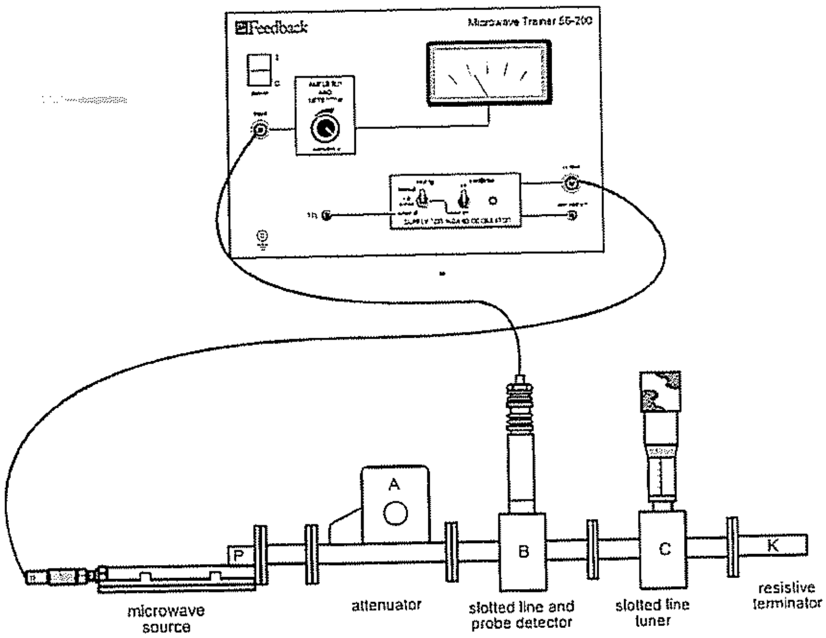


Figure 2-4-7

1. Set up the equipment as shown in Figure 2-4-7 with the probe tuner C inserted between the slotted line and the resistive termination K.

   The probe-tuner unit is to be used to match the resistive load and improve its VSWR, ideally to unity.

2. The probe position is to be located where the real part of the normalised input admittance of the load is unity and the imaginary part (the susceptance) is inductive, i.e. when

   $$y_{in}(l) = 1 - jb$$

   The inductive susceptance -jb can then be cancelled by introducing the probe at this point and adjusting the depth of penetration until the capacitive susceptance of the probe +jb cancels -jb. The resultant admittance,

$$y_{in} = 1 - jb + jb = 1$$

and so matching is achieved.

3. The desired position of the probe-tuner is given by the formula in the **Introduction** section:

$$l = d + l_m + \tfrac{1}{2}n\, l_g$$

where d = distance of first electric field minimum from load

$$l_m = \frac{\lambda_g}{2\pi} \tan^{-1}\left(\frac{1}{\sqrt{S}}\right)$$

$$S = \text{load VSWR}$$

$$n = 0, 1, 2, 3...$$

Using the results obtained in the previous impedance measurement section, calculate l_m and locate the probe at the required position l.

Notes:

(i) The scale of the probe-tuner carriage unit zero is at 10mm from its right-hand flange, so the probe should be positioned at (l - 10) mm relative to this scale.

(ii) The minimum practical value of l should be selected for most effective matching; the condition n = 0 is not usually physically obtainable so select n = 1 giving:

$$l = d + \tfrac{1}{2}l_g$$

4. Having set the probe at the position (l - 10) relative to the tuner scale gradually increase the probe penetration measuring the VSWR, at each position. With small penetration depths little improvement in VSWR is obtained. However, as the matching condition is approached where the capacitive susceptance of the probe cancels the load input susceptance a sharp decrease in VSWR can be observed.

Repeat the best value of VSWR and compare with the load VSWR before matching in terms of the percentage of the power reflected and percentage of power transmitted.

5. Check the values of l and l_m obtained above using a Smith chart.

SUMMARY

Methods of impedance measurement and matching have been investigated experimentally. The normalised impedance of a waveguide load has been measured and also matched using a shunt stub in the form of a probe tuner.

Results may be processed analytically using transmission line formulae and also with the aid of a Smith chart.

Notes