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Structures and Properties of Transmission Lines

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STRUCTURES AND PROPERTIES OF TRANSMISSION LINES

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1 Introduction

The number of different transmission lines has greatly increased in recent years. This range of lines enables the microwave circuit designer to choose particular features which meet the specifications. For instance, it may be certain values of characteristic impedance, phase constant, dispersion or attenuation are required. Or it may be the ease with which these lines can be used to couple to various solid state devices. Or, finally, it may be the line has unique properties in certain configurations, for example, gives good coupling to other circuits or radiates in a special way. Since many microwave circuits are now completely integrated so that the largest dimension of the whole circuit could be less than a millimetre, special lines are required to couple signals into them.

Measuring microwave circuits is still as important as ever. Almost without exception, most microwave measurement equipment has remained with the same i output transmission lines. For most microwave frequencies, a coaxial output is used. Above 20 GHz a waveguide output is sometimes are used. One of the major problems in circuit measurement is designing transitions from the standard coaxial and waveguide ports to numerous transmission lines that now exist in modern circuits. In the case of integrated circuits special surface probes are used that involve a tapered transmission line. Since many microwave measurements of impedance, noise, gain etc. involve using transitions from either coaxial or waveguide to these other transmission lines the properties of transitions are critical in the measurement. Finally, most impedance measurements consist of a comparison with standard impedance. These standards are usually constructed out of either coaxial or waveguide transmission lines. Again, the properties of the coaxial or waveguide junctions can be the main limitation of these measurements, particularly at higher frequencies.

Most transmission lines are designed to operate with only one mode propagating. However, every transmission line will support higher order modes if the frequency is high enough. Since these higher order modes have separate velocities it is not usually possible to do measurements when they are present. So in the description which follows, the upper limit of mono-mode propagation is given. As a simple rule the transmission line has to get smaller as the wavelength gets smaller to avoid higher order modes. This has a marked effect on the attenuation of transmission lines using metallic conductors. The attenuation will rise due to the skin effect by a factor of $f^{1/2}$. However, in addition as the structures get smaller the increased current crowding means that the overall attenuation increases by a factor of $f^{3/2}$. Thus, a transmission line like coaxial cable is often made with a small diameter at high frequencies to ensure mono-mode propagation but the consequence is a large increase in attenuation which can greatly affect measurements.

Finally, dispersion has several causes. The first is caused by the permittivity of any dielectric used in a transmission line changing with frequency. In practice this is often quite a small effect. This is called material or chromatic dispersion. In transmission lines where the electromagnetic waves propagate in only one dielectric and the mode has only transverse fields e.g. coaxial line, the material dispersion is the only type. For standards in coaxial lines, often an air filled line is used to avoid even material dispersion. For transmission lines where the electromagnetic waves propagate in two or more dielectrics the modes are more complex. In general, as the frequency increases the energy concentrates in the dielectric with the highest dielectric constant. This dispersion is usually called waveguide dispersion and occurs in, for example, microstrip and mono-mode optical fibre. Waveguide dispersion also occurs where there is a firm cut-off frequency as in metallic rectangular waveguide. Modal dispersion occurs when there are many modes propagating which is the case in some forms of optical fibre. Since most transmission lines are designed to be mono-mode, modal dispersion is avoided.

2 Coaxial Lines

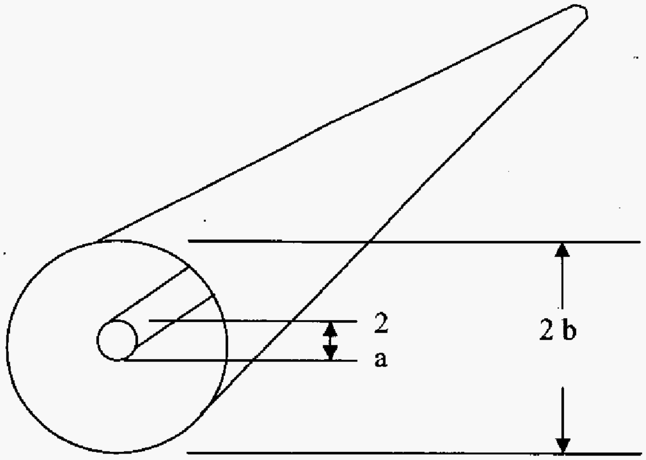

Figure 1: A Coaxial Line

A coaxial line is shown in figures 1. The radius of the inner conductor is a and the inner radius of the outer conductor is b. At microwave frequencies the transmission line parameters are:

$$L = \frac{\mu}{2\pi}\log_e\left(\frac{b}{a}\right)$$

$$C = \frac{2\pi\varepsilon}{\log_e\left(\frac{b}{a}\right)}$$

$$R = \frac{R_S}{2\pi}\left(\frac{1}{b} + \frac{1}{a}\right)$$

$$G = \frac{2\pi\sigma}{\log_e\left(\frac{b}{a}\right)}$$

This gives $Z_O = \sqrt{\frac{\mu}{\varepsilon}}\log_e\left(\frac{b}{a}\right)$

$v = \frac{1}{\sqrt{\mu\varepsilon}}$ See lecture on transmission lines

$\alpha = \frac{R}{2Z_O} + \frac{GZ_O}{2}$ See lecture on transmission lines

Where R_S is the skin resistance of the conductors and is proportioned to $f^{1/2}$, and σ is the conductivity of the dielectric which is also a function of frequency.

Coaxial lines can be easily made with a range of characteristic impedances from 20 - $100\,\Omega$. Their dispersion characteristics are good except at very low frequencies where

$Z_O = \sqrt{\frac{R}{G}}$ i.e. $\omega L << R$; $\omega C << G$

and at very high frequencies when higher order modes appear. These higher order modes are discussed in Marcuvitz (1) and an approximate guide to their appearance is the condition.

$$\lambda < \pi b$$

In order to maintain mono-mode propagation the coaxial cable is usually made smaller at higher frequencies. Typical values for *b* are 7,5,3,1 mm. Unfortunately, as *b* gets smaller, the attenuation increases. So most cables are designed to be an acceptable compromise between attenuation and mono-mode propagation.

Coaxial lines are used as the input and output ports for most measurement equipment up to about 25 GHz with 2b = 7mm. Connectors with low insertion loss and good repeatability make high accuracy measurements possible. Transitions to other transmission lines exist for most types and in particular to rectangular waveguide and microstrip. Both these transitions have insertion loss and in the latter case the losses include radiation loss. Since the microstrip transition has poor repeatability it is good measurement practice to measure at a coaxial junction where possible and use de-embedding techniques to find the circuit parameters.

3 Rectangular Waveguides

Along with coaxial lines, metallic rectangular waveguides are used extensively in microwave measurements particularly above 25 GHz. Some of the properties of these guides were given in the lecture on transmission lines. It is worth repeating the comments about bandwidth. Take TE_{10} mode in X Band guide as an example:

a	b	f_c	Usable frequency range	α
0.9"	0.4"	6.557GHz	8.20 – 12.40GHz	0.164dBm^{-1}

A waveguide is not normally used near its cut-off frequency, f_c, and so X Band guide is not used between 6.557 and 8.20 GHz. This is because all the properties of the guide are changing rapidly with frequency in this region. At 8.20 GHz most properties are within a factor of 1.66 of the free space values. In order to avoid higher order modes which start at $2f_c$ or 13.114 GHz, the usable frequency range ends at 12.4 GHz where the properties are within a factor of 1.18 of the free space values. So waveguide has a bandwidth of 4.2 GHz which is about two thirds of the octave band theoretically available for mono-mode propagation. Even in this bandwidth the waveguide is still more dispersive than most other transmission lines. To cover a wide frequency range a series of waveguides are used with different a and b values. As with coaxial lines, the attenuation rises sharply as the waveguide size reduces and around 100 GHz is unacceptably high for many applications. One reason for this is the surface roughness of the inner surface of the guide contributes significantly to the losses at these frequencies. Also at 100 GHz and above waveguide connectors do not have a satisfactory insertion loss or repeatability for accurate measurements.

At the lower microwave frequencies the waveguides have dimensions of several centimetres and are able to transmit high powers far better than any other transmission line. It is mainly for this reason that their use has continued at these frequencies.

4 Ridged Waveguide

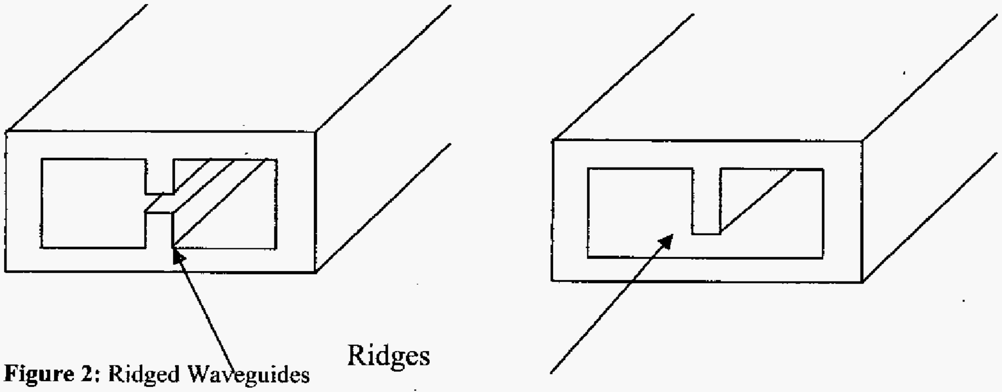

Figure 2: Ridged Waveguides

A technique for increasing the bandwidth of rectangular waveguide is to use a ridge in the centre of the guide as shown in figure 2.

This ridge has a minimal effect on those waveguide modes with a null of electric field at the centre of the guide. So the cut-off frequency of the TE_{20} mode is almost unchanged. However, the cut-off frequency of the TE_{10} mode is greatly reduced, in some cases by as much as a factor of four. For example, X Band guide this would lower the cut-off frequency to 1.64 GHz and the usable frequency range would be 2.054 – 12.4 GHz.

However, the concentration of fields in the gap also concentrates the currents in that region. This increases the attenuation and this factor limits the use of this transmission line to the lower microwave frequencies. However, the multioctave bandwidth with reduced dispersion are features which make its use, particularly in wideband sources, quite common. Details of the guide's properties are in the Microwave Engineer's Handbook (2).

5 Microstrip

Microstrip transmission line is one of the most common transmission lines used in microwave circuits. It is shown in figure 3.

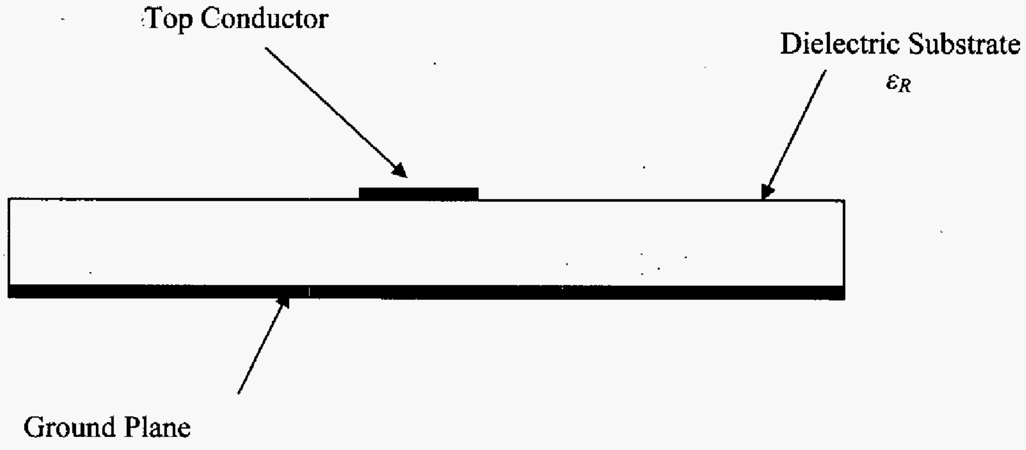

Figure 3: Cross-Section of a Microstrip Transmission Line

It can be manufactured using conventional photolithographical techniques with great accuracy approaching $\pm 0.5\mu m$. It has dimensions which make connections to solid state components relatively easy and since the circuit is usually on one side of the substrate access to the input and output ports is also straightforward. With modern integrated circuit technology these microstrip circuits can often be made so small that the transmission line effects disappear and simple low frequency circuit designs can be used.

Since the wave on a microstrip line moves partly in the air above the substrate and partly in the substrate itself the velocity, v, is in the range.

$$\frac{3.10^8 ms^{-1}}{\sqrt{\varepsilon_R}} < v < 3.10^8 ms^{-1}$$

Where ε_R is the relative permittivity of the substrate. The frequency range of microstrip is from 0 Hz to the cut-off frequency of the next higher order mode, λ_c. This is approximately given by

$$\lambda_c = 2w$$

where w is the width of the top conductor.

At X Band, for example, typical microstrip parameters might be:

Width	Thickness of Substrate	v	ε_R	f_c
0.6mm	0.6mm	$1.1510^8 ms^{-1}$	9.7	80 GHz

Dispersion in microstrip is much less than rectangular waveguide and the velocity and the characteristic impedance would typically change by only a few percent over several octaves. However, the attenuation in microstrip is much greater than rectangular waveguide, by about a factor of 100. This is because the currents are far more concentrated in microstrip. Surprisingly, this is often not a critical factor as the circuits are usually only a wavelength in size and in integrated form often very much smaller. The range of characteristic impedance can be varied, usually by changing the width, and values in the range 5 to 150Ω are possible.

Transitions to microstrip are usually made with miniature coaxial lines at the edge of the substrate. 'On-Wafer' Probing is not possible with microstrip, but probing using electro-optic methods is possible. To a greater and lesser extent microstrip circuits radiate. Indeed, microstrip antennas are indistinguishable from some circuits. For this reason most microstrip circuits need to be enclosed to prevent radiation leaving or entering the circuits. The design of this enclosure is often a critical part of the whole circuit. Various alternatives to microstrip exist which are discussed in references 4,5 and 6. These include inverted microstrip, stripline and triplate.

6 Slot Guide

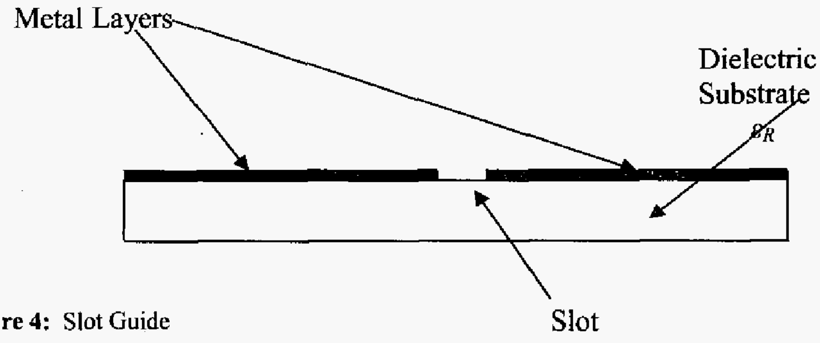

Figure 4: Slot Guide

Slot Guide is shown in figure 4 and is used in various forms of circuit.

The fields like microstrip are partly in the air and the substrate, but the dispersion is less than microstrip. The characteristic impedance is mainly a function of the width of the slot and can have a range of values typically 50 - 200Ω. There are some applications of couplers of slot line to microstrip line which have series rather than the normal parallel configurations. They are discussed in reference 7. The main reason for including them in this list is to lead on to forms of slot line which are widely used, namely coplanar waveguide and finline.

7 Coplanar Waveguide

Coplanar Waveguide is shown in figure 5 and is used in many integrated circuits as it can be measured on the chip using on-wafer probes. These probes are in the form of partly a tapered coplanar waveguide followed by a transition to either coaxial line or rectangular waveguide.

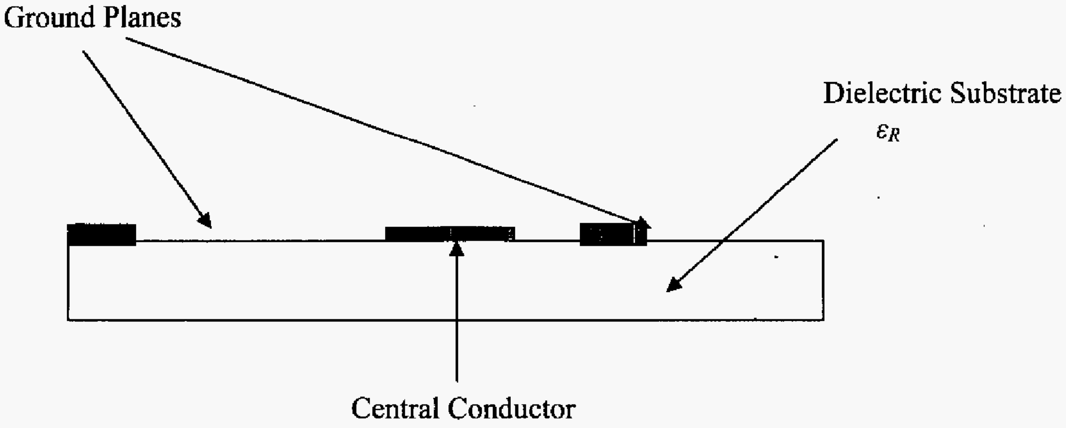

Figure 5: Coplanar Waveguide

Since the guide has two slots in parallel, the low dispersion of slot guide is also present in coplanar waveguide. The range of characteristic impedances is typically 25 - 100 Ω depending on the width of the slots and the relative permittivity of the substrate. The velocity of coplanar waveguide, like that of slot line is approximately the average of the velocities of a TEM wave in air and in the substrate, i.e.

$$v = \frac{3.10^8 ms^{-1}}{\left(\frac{\varepsilon_R + 1}{2}\right)^{\frac{1}{2}}} \quad (7)$$

Like microstrip the currents are concentrated and the attenuation of both slot line and coplanar waveguide is much higher than waveguide. However, if the circuit dimensions are much smaller than a wavelength this is not a limitation. The main advantage of the structure is that unlike microstrip the ground plane is easily accessible and connections to solid state and other devices in series and parallel are possible. Higher order modes do exist in these structures but one of the limitations is not these modes but box modes in the dielectric substrate and enclosing box. The design of circuits to avoid losing energy to these modes requires special care.

8 Finline

Finline is shown in figure 6. It is used in conjunction with conventional rectangular waveguide and enables circuits to be used with transitions to waveguide ports. It also avoids the use of an enclosure as the waveguide provides this. It is similar to ridged waveguide in that the printed circuit board provides the ridge. It is discussed in reference 7. The advantage of finline is that solid state components can be mounted on the substrate as in slot line and thus avoiding the difficult problem of mounting such components in rectangular waveguide.

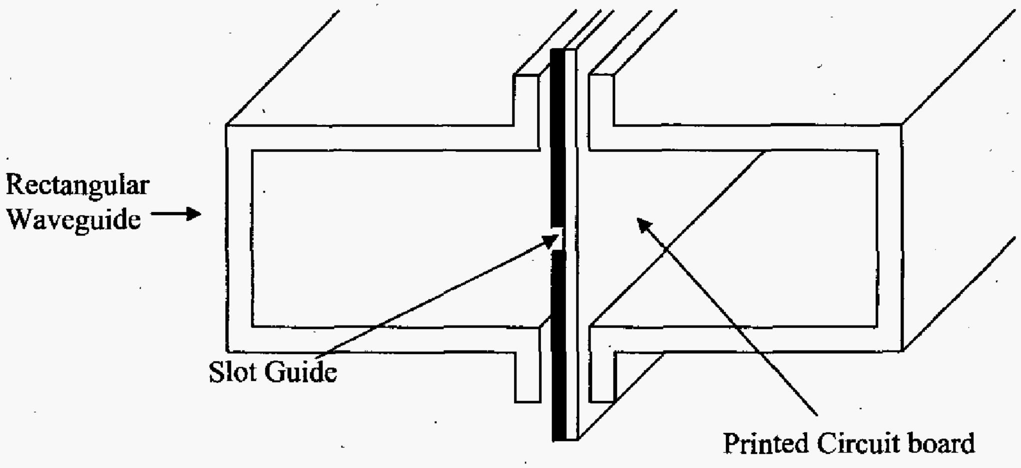

Figure 6: Finline

9 Dielectric Waveguide

The increasing attenuation in all transmission lines using conductors makes their use less practical above 100Ω GHz. The Dielectric Waveguide shown in figure 7. is a transmission line which overcomes these problems. Its operation is similar to optical fibre in that the energy is trapped inside the waveguide by the principle total internal reflection. The obvious difference between this waveguide and other lines described so far is that there is no easy way to connect many devices to it. However, good transitions to rectangular metallic waveguide are available along with various circuit components.

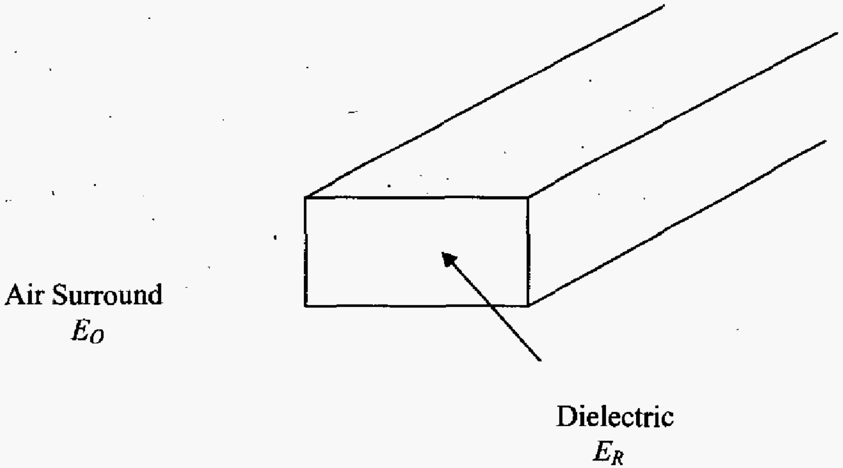

Figure 7: Dielectric Waveguide

The guide does have fields outside the structure which decay away rapidly in the directions transverse to the direction of propagation. These fields can be used for various circuit components. Supporting the guide requires a dielectric of lower dielectric constant and in the case of optical fibre this is made sufficiently large to ensure all the external fields have decayed to zero. For a dielectric guide at 100 GHz the dimensions might be 2 mm × 1 mm. The dispersion is less than metallic rectangular waveguide and bandwidths of an octave are possible. Recent research has shown that junctions between dielectric waveguides have superior repeatability and insertion loss to metallic waveguides. It is anticipated that dielectric waveguides will be commonly used in the future for frequencies above 100 GHz.

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