WAVEGUIDE PACKAGING

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Abstract

This paper presents a review of waveguide packaging techniques and issues, with particular reference to the millimetre wave frequency range. The term waveguide package is used in this context to refer to a package, with one or more waveguide interfaces, containing active components. In addition to the waveguide interface to the package, waveguide modes within the package housing must be considered.

Any housing or package can effectively be a waveguide provided it is large enough. In most instances RF packages are small enough that waveguide modes need not be considered. However, with the ever more common usage of the millimetre wave frequency range, the existence and control of waveguide modes within a package must usually be considered. Applications for the millimetre wave frequency range have driven the requirement to design fully integrated system packages which often include an antenna, millimetre wave components and baseband components. Interfaces between waveguide and active components, which are now predominantly planar circuits, are therefore also discussed.

Introduction

Rectangular waveguide supports an infinite set of waveguide modes. The lowest order mode of rectangular waveguide is the TE_{10} mode (Figure 1) and propagation, of this single mode only, occurs from the cut-off frequency to twice the cut-off frequency. The inner width (larger dimension) of the waveguide determines the cut-off frequency whilst the height essentially determines the impedance. The height is half of the width for the majority of standard waveguide sizes. The cut-off frequency is the frequency at which the width of the waveguide is equal to a free-space half wavelength. Any modification to the cross-section of the waveguide, such as rounding of internal corners, will change the cut-off frequency.

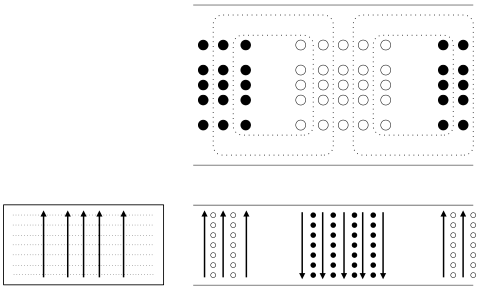

Figure 1: TE_{10} Mode in Rectangular Waveguide

Rectangular waveguides have band designations based upon their internal dimensions and thus operating frequency range. For example, the 26.5-40GHz band, once commonly referred to as the Ka-band, uses waveguide designated as WR28 (US) and WG22 (British) but other designations also exist. Connections between waveguide components are made using standard flanges which also have designations such as UG599/U, as is commonly used on 26.5-40GHz waveguide.

The (conductive) housing of any component or circuit can be considered to be a waveguide cavity at any frequency where the largest dimension is greater than a half wavelength. At low frequencies all packages are small enough such that no waveguide mode, within the frequency range of interest, can exist within the package cavity. However, even small boxes can be above cut-off at harmonics of the fundamental operating frequency which may result in problems. The frequency at which waveguide

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modes must be considered depends not only upon the physical size of the cavity but on the material filling the cavity. This is due to the dielectric loading of the cavity/box which makes the box appear electrically larger than dictated by its physical dimensions.

For the electrically small package, evanescent waveguide modes can be excited, but as the package is below cut-off the mode quickly decays and does not propagate. This means that the attenuation of this mode is very large. However, if the gain in the circuit is very high, for example in a receiver front-end, problems such as oscillation may still occur due to coupling of the output signal back to the input.

For the electrically large package a waveguide mode may be excited, usually at a discontinuity, and this can then propagate causing spurious responses and possibly circuit instability. To overcome this problem some means of dissipating the energy in the waveguide mode must be utilised. This has typically been tackled using some form of Radar Absorbent Material (RAM) within the package to attenuate the waveguide modes. This often takes the form of a low-density, high loss, flexible foam sheet. Other techniques, such as the inclusion of inductive posts (irises), are often used to break up the cavity and degrade its ability to support waveguide modes.

Waveguide Components

Millimetre wave circuits, such as oscillators and mixers, have been packaged in waveguide housings based upon the traditional ‘1 inch cube’ for many years now. These usually consist of a gold plated brass or aluminium housing featuring standard waveguide flange interfaces, coaxial IF/RF connectors and DC feedthroughs. They are still readily available but at a relatively high price and on long delivery.

Oscillators have traditionally been realised using simple metal/ceramic packaged devices, for example Gunn and IMPATT diodes, mounted directly within a waveguide channel forming a cavity. The cavity is necessarily above cut-off in this case. An example of this is shown in Figure 2 [1]. Bias is typically applied through a non-contacting radial choke structure protruding through one wall of the cavity.

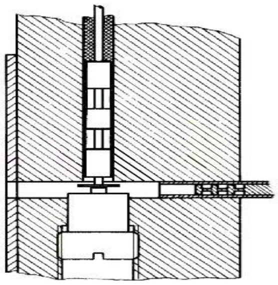

Figure 2: Cross-section of Waveguide Oscillator [1]

Mixers can be realised using Schottky barrier diodes mounted in small minimum parasitic packages such as flip-chip or a leadless inverted device (LID). The diodes are typically mounted on a microstrip substrate such as Quartz or a PTFE based material. This circuit is then mounted in a package with waveguide interfaces as shown in the example in Figure 3 [2]. The circuit design usually requires the use of an electrically large cavity and in this case RAM is often placed in the housing to reduce spurious responses.

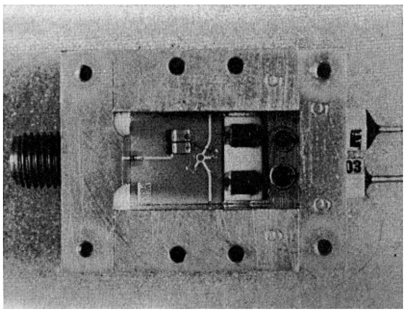

Figure 3: Microstrip Mixer in Waveguide Housing [2]

Higher levels of integration of such components, including couplers and ferrite devices, have generally been carried out in one-off designs. Examples have been presented over the years such as those in [3], [4] and [5] which use, respectively; a miniature milled waveguide block; an injection moulded plastic waveguide block; and a hybrid milled waveguide block and quartz microstrip substrate. A more recent example using injection moulding techniques combining waveguide components and MMICs within a waveguide housing is presented in [6].

MMICs

Millimetre wave MMICs, utilising short gate length MESFET and PHEMT devices, have made gain at these frequencies more readily available. Users are not always able to make use of bare die and require packaged MMICs hence some form of standard interface is required. For millimetre wave frequencies this is commonly either via waveguide or coaxial connectors. However, coaxial line losses are significant at millimetre wave frequencies and noise figure and power are critical, thus coaxial connectors are generally limited to the lower frequency bands or to broadband test equipment. For example, the 1mm connector is available which operates to approximately 110GHz. Losses in waveguide are much lower than in coaxial line but it should be remembered that waveguide has a limited operating frequency range for single mode operation which is an issue particularly for broadband test equipment.

An example of a millimetre wave multi-chip assembly [7] is shown in Figure 4. This is a W-band power amplifier module which combines four MMICs in a small package with waveguide E-plane probe interfaces. This appears to be an electrically large package (from the waveguide dimensions) and may require RAM on the lid to ensure correct operation.

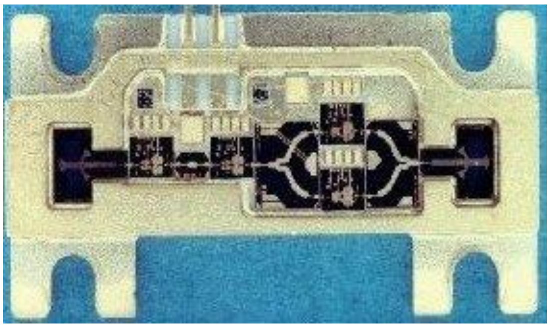

Figure 4: 350mW W-band Power Amplifier Module [7]

Waveguide Transitions

Circuits are commonly designed in planar transmission media such as microstrip or coplanar waveguide (CPW). To build a component with waveguide interfaces some form of transition between the waveguide and planar transmission medium must be utilised. Such transitions have typically included stepped or tapered ridge waveguide, finline and E-plane probes.

The electrical characteristics of any transition must primarily provide a good match and low insertion loss over the required operating bandwidth. The stepped or tapered ridge waveguide transition (as used in the mixer shown in Figure 3) can be broadband but the physical length required makes it large. It is also difficult to manufacture as tight tolerance machining is required. The finline structure can be very broadband but this is at the expense of increased insertion loss due to the electrically long length required. An example of a transition utilising a finline section is shown in Figure 5 [8].

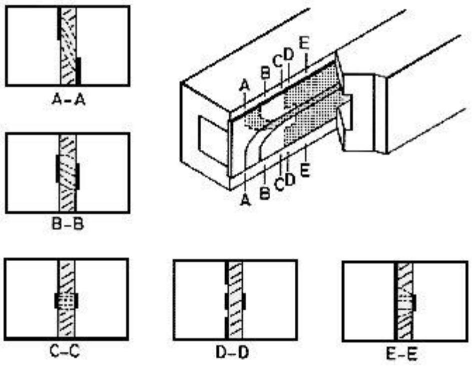

Figure 5: Waveguide to Finline to Microstrip Transition [8]

The E-plane probe is the most commonly used type of transition but tends to be narrow band unless additional matching elements are included which increases the physical size. The E-plane probe transition can take several forms including transitions to coaxial line and microstrip line as shown in Figure 6.

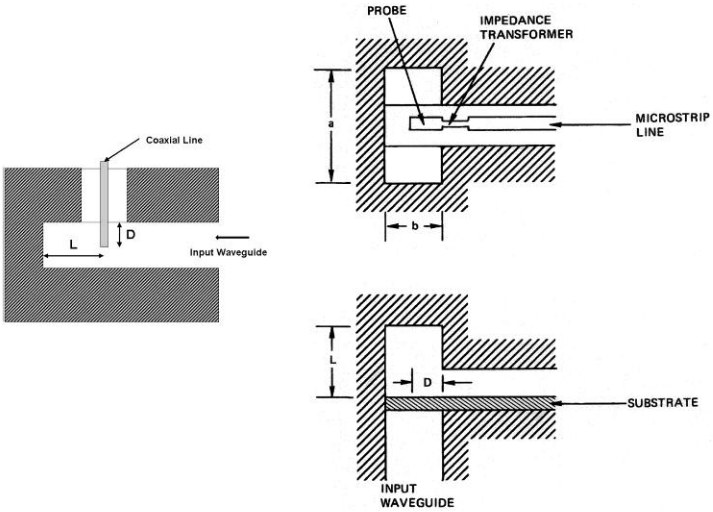

Figure 6: E-plane Probe Transitions – Coaxial and Microstrip Line

For some applications hermeticity is a requirement and in this case some form of glass or ceramic to metal seal must be used. Two transitions which can offer this are the E-plane probe with a glass-bead coaxial feedthrough and the E-plane probe to microstrip with the substrate soldered across the waveguide end to form a window (as shown in Figure 4). An example of the measured performance of an E-plane probe transition (back-to-back pair with time domain gated match) is shown in Figure 7. Return loss is better than 18dB over 24.25GHz to 28.75GHz and the insertion loss for a single transition is just 0.2dB.

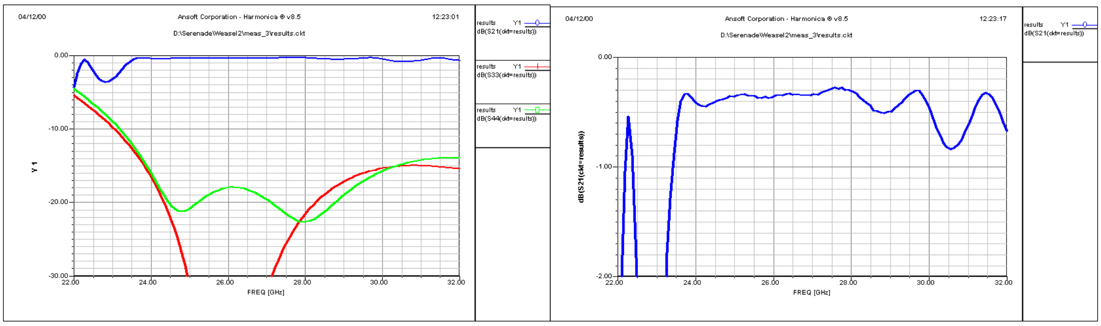

Figure 7: Measured Performance of E-plane Probe Transition in Ka-Band

Integrated Systems

When considering integrated systems it is often better, particularly at millimetre wave frequencies, to include the antenna interface as part of the housing design. This minimises losses and removes additional interfaces which could otherwise further degrade the input match. High levels of integration can also reduce manufacturing costs. The transition from free-space to the active circuits, in an integrated system, can take one of several forms. Waveguide probe transitions, as already discussed, with either a waveguide feed horn or dielectric rod antenna inserted into the waveguide have been used. Planar antennas, such as the Vivaldi or tapered slot antenna (TSA), can also interface to a waveguide section via finline [9]. Other planar antennas, such as a printed patch or dipole (as shown at the bottom of Figure 8) can interface directly to a MMIC. However, if hermeticity is an issue, neither of these solutions is a good choice.

Two applications at millimetre wave frequencies, that require very compact packaging, are active phased arrays and focal plane array receivers. An example of the former is the W-band active phased array antenna [10] as shown in Figure 8. The assembly can be configured as either an eight channel receiver or transmitter. All components are common except the final MMIC element which is either a power amplifier or a low noise amplifier depending upon whether transmit or receive functionality is required. A printed dipole antenna is used at the front end. The lid of the package is made from doped Silicon which acts as a lossy medium to absorb any waveguide modes present in the electrically large channel housing.

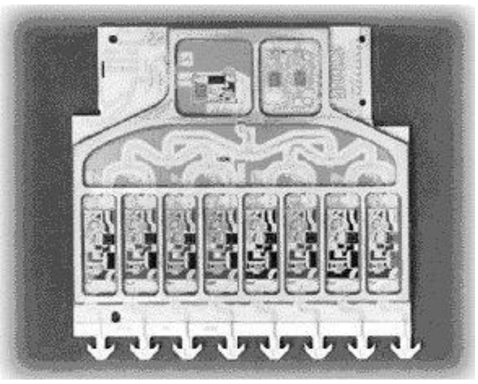

Figure 8: W-Band Active Phased Array Antenna [10]

The second application, focal plane array receivers, has been investigated by other groups as discussed in [11], [12] and [13] and an example is shown in Figure 9 [14]. One use is in remote sensing utilising the broadband receiver as a radiometer providing a reasonable degree of (angular) resolution and operation in inclement weather. Using a multi-channel receiver, near real-time imaging has been performed. Packaging of the receiver channels requires the housings to be below waveguide cut-off frequency due to the high gain (circa 50dB) required. However, power dissipation is a major problem due to the low efficiency and compact dimensions of the components. The example shown uses TSAs on a thin soft substrate. All millimetre wave MMICs are contained in a waveguide channel below cut-off.

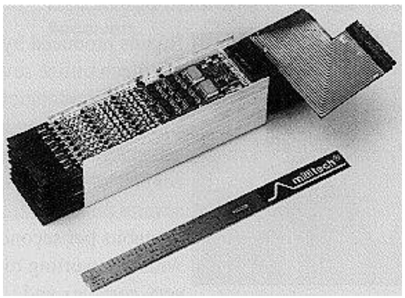

Figure 9: Focal plane array module [14]

Future Trends in Waveguide Packaging

To reduce costs, and ease manufacture, housings can be made with metallised injection moulded plastic as used in [4] and [6]. This may not be the optimum solution for example if using power amplifiers when heat management is a critical issue. However, inserted metal slugs can be used to assist in this area.

Automotive collision avoidance radar is presently a key area of interest for highly integrated cheap structures. Examples demonstrate the novel integration of waveguide oscillators, planar receiver components and free space antennas as discussed in [15] and [16]. Millimetre-wave radio is a further area where high volumes, and thus low cost, are key areas of interest [17].

For the higher millimetre wave frequencies micro-machined structures have been discussed extensively in, for example, [18]. Micro-machining essentially attempts to integrate waveguide structures directly onto the active device wafer. Methods of manufacturing the waveguides have been successfully demonstrated [19] but the compatibility of the process with active device processes have yet to be fully realised. An example of micro-machined waveguide is shown in Figure 10.

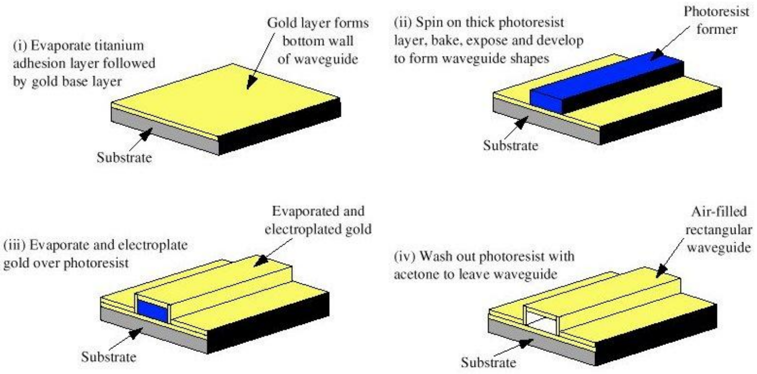

Figure 10: Fabrication of Micro-machined Air-filled Rectangular Waveguides [19]

Conclusions

This paper has presented a review of waveguide packaging techniques and issues with particular reference to the millimetre wave frequency range. The fundamental issues of package dimensions and waveguide modes have been discussed. Methods of controlling waveguide modes within housings above cut-off have been outlined. Finally examples of sub-systems and systems utilising small packages in the millimetre wave frequency ranges have been presented.

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