A V-BAND WAFER PROBE USING RIDGE-TROUGH WAVEGUIDE

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ABSTRACT

A V-band (50-75 GHz) wafer probe is presented. The probe features a new type of waveguide developed to allow transition from rectangular waveguide to coplanar waveguide. This new waveguide consists of a ridge extending from the upper waveguide wall into a trough in the lower waveguide wall, and is known as ridge-trough waveguide.

INTRODUCTION

To allow development of a V-band probe a waveguide solution was required, since commercially available coaxial cable has overmoding present above 65 GHz.

The probing situation is shown in figure 1. A V-band waveguide enters from the right and is transformed to a coplanar waveguide (CPW) transmission line printed on the underside of an alumina board. Nickel fingers are added to the end of the CPW, that touches the wafer, to provide a well defined contact footprint. This is a ground-signal-ground (GSG) type contact. The signal line is biasable, with respect to the ground contacts, for characterization of active devices.

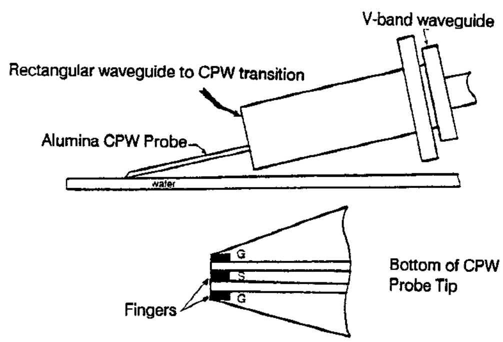

Figure 1. The waveguide input V-band probe.

BASIC CONCEPT

The transition from rectangular waveguide to coplanar waveguide is shown in figures 2, 3, 4, and 6. Figure 2 shows the TE_{10} mode within the rectangular waveguide.

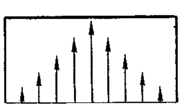

Figure 2. TE_{10} mode in rectangular waveguide

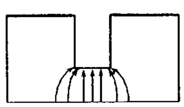

Figure 3. TEM fields in ridge waveguide.

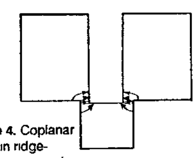

Figure 4. Coplanar fields in ridge-trough waveguide

A ridge is introduced (fig. 3), which causes the electric field to approximate the TEM fields found in a parallel plate structure.

The novel feature that allows coplanar fields to be generated is shown in figure 4. A trough is introduced in the waveguide bottom, permitting the ridge to be brought into proximity to the ground plane. This causes the TEM-like fields to rotate into a coplanar-type distribution. For comparison, a cross section of coplanar waveguide and the fields associated with it is shown in figure 5.

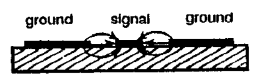

Figure 5. Coplanar waveguide , and the electric fields associated with it.

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Similar field patterns have been generated with a rectangular conductor in a slot [1] and with a ridge joining a printed circuit board with a center conductor in a slot to form a CPW structure [2]. All three structures have the inherent advantage of splitting the electric field equally in magnetude and phase, although in the latter two an odd mode may be excited across the slot side walls, since there is no transverse conductor across the slot to maintain an equal potential as energy propagates along the structure.

The method of joining the coplanar waveguide to the ridge-trough waveguide is illustrated in figure 6. The coplanar waveguide is flipped over to allow its ground planes to be placed in contact with the waveguide bottom. This establishes a continuous ground plane between the two waveguides. The signal line is bonded to the ridge.

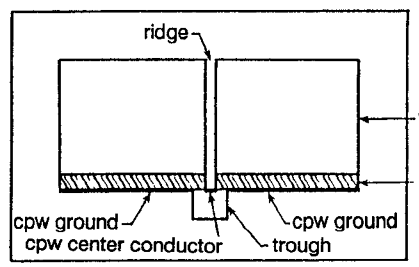

Figure 6. Coplanar waveguide inverted to join the grounds to the waveguide bottom.

25X MODEL RESULTS

To minimize insertion loss the impedance of coplanar waveguide and ridge-trough waveguide must be equal. A 25X model of the coplanar waveguide to ridge-trough waveguide interface was made for investigation purposes.

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A cross section of the ridge-trough waveguide model is shown in figure 7. The upper and lower ridge had a large selection of widths A and D to choose from. Both ridges could be adjusted up and down.

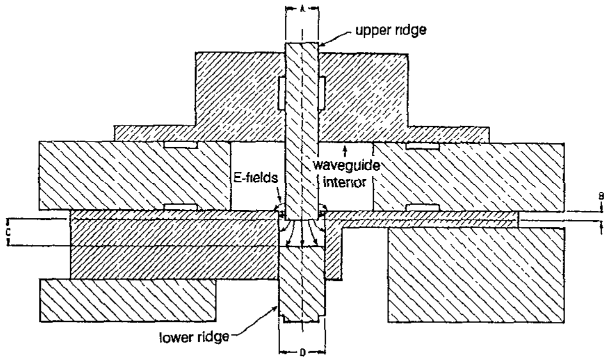


Figure 7. Cross-section of the ridge-trough waveguide 25X model

A Hewlett-Packard 8510 network analyzer was used to measure the reflection coefficient (Γ_2) of the interface, as various ridge-trough dimensions were investigated on the 25X model. The data was obtained with the equipment shown in figure 8. Additional reflection coefficients were caused by the coax-to-coplanar waveguide transition (Γ_1), and the open end of the ridge-trough structure (Γ_3).

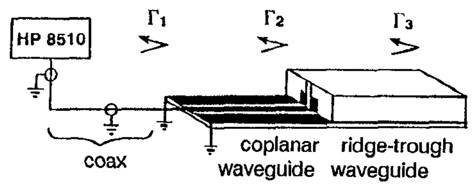


Figure 8. Test line for investigating the reflection at the coplanar waveguide to ridge-trough waveguide interface.

In figure 9, time domain reflection data of an optimized transition is shown. The lower trace is the reflection coefficient versus time, where Γ_1, Γ_2, and Γ_3 are shown. The transition reflection coefficient, Γ_2, is observed to be less than 0.05. The upper trace is a return loss versus frequency plot of the transition region only, which was selected with the gating function of the HP 8510. Return loss is observed to be better than 22 dB for 2-3 GHz, which corresponds to 50-75 GHz, due to the 25X scaling factor.

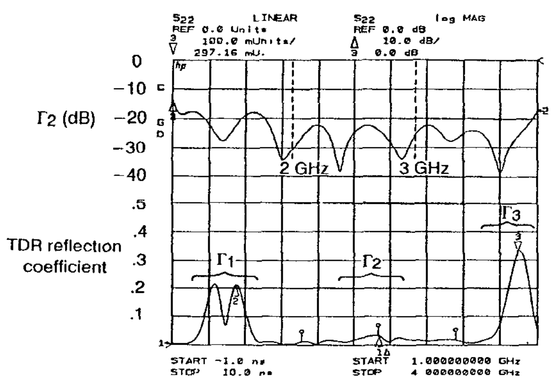


Figure 9. Results for a good impedance match at the CPW to ridge-trough waveguide Interface

MATHEMATICAL MODEL

At this point a mathematical model was developed to calculate the characteristic impedance and cutoff frequency of the ridge-trough waveguide structure [3]. Basic assumptions of the model are shown in figure 10. The model finds the cutoff frequency by assuming that for a well defined ridge structure in a waveguide most of the capacitance is located in the region between the ridge bottom and the floor of the waveguide due to the concentration of the electric fields in this area. The primary contributions are the fringing capacitances C_1 and C_2, and the parallel plate capacitances C_3 and C_4. Similarly the inductance is assumed to be located in the waveguide sidewalls due to the relatively large concentration of current flow there. Once the capacitance C and the inductance L of the structure are found the cutoff frequency is given as $f_c = 1/\sqrt{(L/2)C}$.

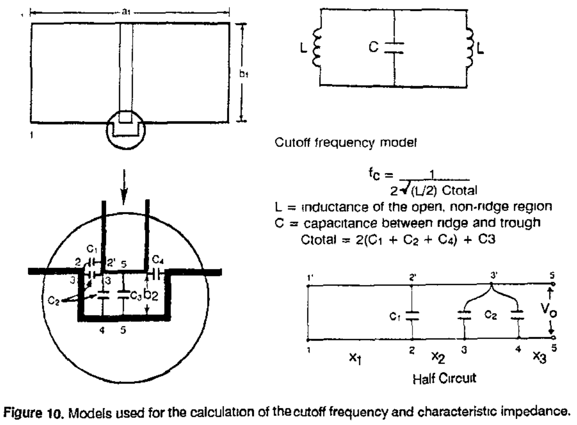


Figure 10. Models used for the calculation of the cutoff frequency and characteristic impedance.

To find the characteristic impedance the half circuit shown in figure 10b was used. The parallel plate capacitors, C_3 and C_4, are accounted for by the transmission line lengths x_1 and x_2. For the TE_{10} mode the electric field distribution, E(x), across the half circuit (i.e. from nodes 1 to 5) is constant with frequency. This fact allows the distribution to be solved for at the cutoff frequency, since there must be 90 degrees of phase shift from node 1 to 5. If the frequency is now assumed to be infinite the wave propagation becomes TEM in nature, yielding the relation $H(x) = E(x)/120\pi$. Knowing the magnetic field distribution, H(x), allows the longitudinal current i(x) in the waveguide top and bottom surfaces to be calculated from Ampere's law. The characteristic impedance at infinite frequency, Z_{oi}, is then defined as the ratio of the voltage V_o across nodes 5 and 5' to the total longitudinal current I. This may be expressed as:

$$Z_{oi} = V_o/I = b_2E_o \,/\, \left(2\int_0^{a_1/2} i(x)dx\right) = 120\,\pi\, b_2E_o \,/\, \left(2\int_0^{a_1/2} E(x)dx\right), \text{ where}$$

$$i(x)dx = \oint H{\cdot}dl = H(x)dx = E(x)dx \,/\, 120\pi \text{, from Ampere's law.}$$

The characteristic impedance at a finite frequency, f, is obtained by using the previously obtained cutoff frequency, f_c, in the expression:

$$Z_o = \frac{Z_{oi}}{\sqrt{1-(f_c/f)^2}}.$$

From this model, nomographs similar to that shown in figure 11 were generated. The nomographs plot constant impedance contour lines. In this case, 30, 50 and 70 ohms are shown. The lines are traces of the path that the lower corners of a ridge would follow to maintain the indicated impedance. For example, if ridge A touches at points 1' and 1 and ridge B touches at points 2' and 2, both ridges will have the same impedance of 50 ohms, although their electric field distributions will be different.

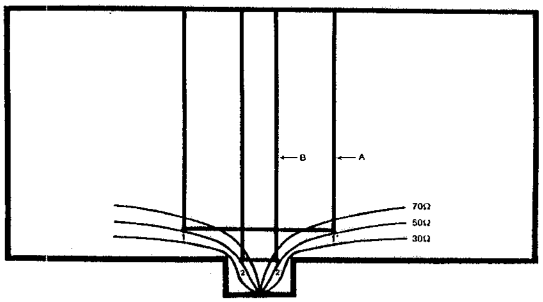
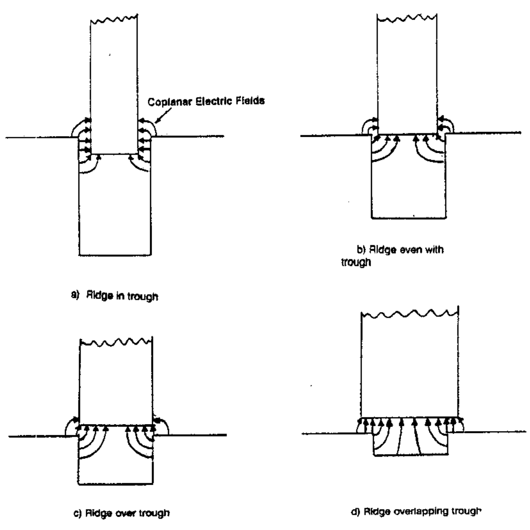


Figure 11. Ridge-trough waveguide impedance nomograph for 30, 50, and 70 ohms.

THE TRANSITION

Using the mathematical model, a five step transition was developed to rotate the coplanar electric fields in the ridge-trough section to TEM-like electric fields in a conventional ridge waveguide structure. This process is shown in figures 12a-12e. Each section's impedance was kept at 50 ohms. The 50-ohm ridge waveguide structure shown in figure 12e was then transformed to normal rectangular waveguide with a multisection binomial transformer.

The coplanar waveguide to rectangular waveguide transition was tested with a 25X model. The results are shown in figure 13. The upper trace reveals that the binomial transformer was optimized for 2-3 GHz, which corresponds to the V-band (50-75 GHz). Better than 20 dB return loss is observed in this region.



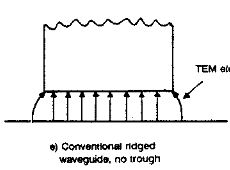


Figure 12. Five different waveguide sections, all 50 ohms, used to transition from coplanar to TEM electric field patterns.

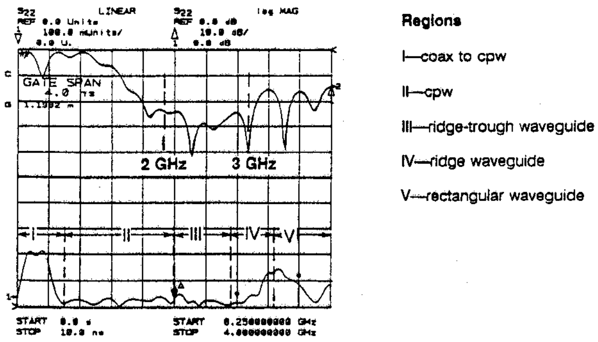


Figure 13. TDR and S_{11} data for the 25X coplanar to rectangular waveguide transition.

PROTOTYPE

A prototype V-band probe was built, based on the 25X model results. The basic structure is shown in figure 14. The alumina coplanar waveguide probe board is clamped between the ridge and trough blocks. In the event of a worn or broken probe board a new one may be installed. Insulation between the halves provides dc isolation between signal line and ground planes, allowing biasing.

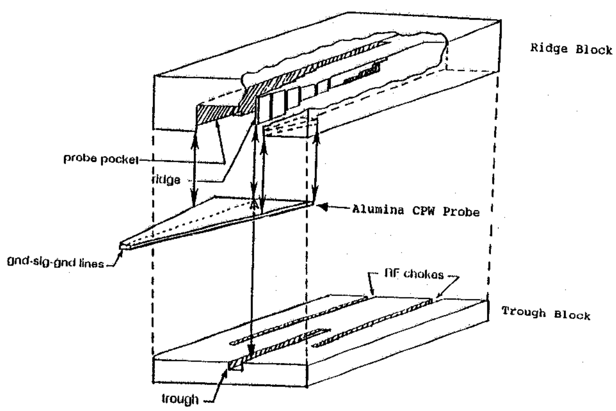


Figure 14. Exploded view of the complete V-band probe

Insertion loss and return loss of the V-band prototype wafer probe is shown in figure 15. Insertion loss (S_{21}) is less than 4 dB across the 50-75 GHz band. Return loss at the waveguide input (S_{11}) is 10.9 dB or better, which results in $|S_{11}| - |S_{21}| > 6.9$ dB over the band. A minimum difference of 5 dB yields good correctable data with the HP-8510.

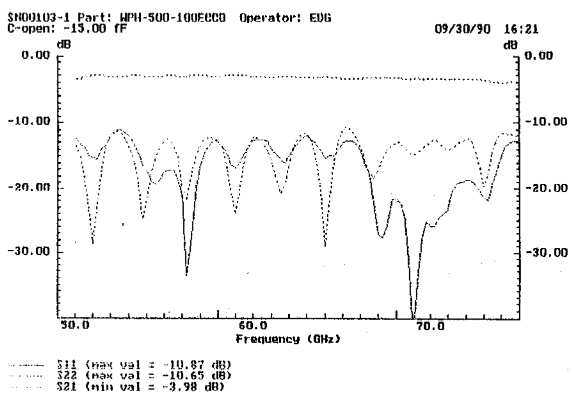


Figure 15. Insertion loss and return loss for the V-band probe. Port 1 is the rectangular waveguide input and port 2 is the probe tip.

Return loss at the probe tip (S_{22}) is also shown, and found to be better than 10.6 dB, providing a good load to devices under test.

TWO PORT DATA

Construction of a second probe permitted two-port measurements. In figure 16 the two probes are shown on a wafer probing station. Flexible waveguide (W. L. Gore & Associates, Inc.) allowed probe movement. Bias cables are connected to each probe body.

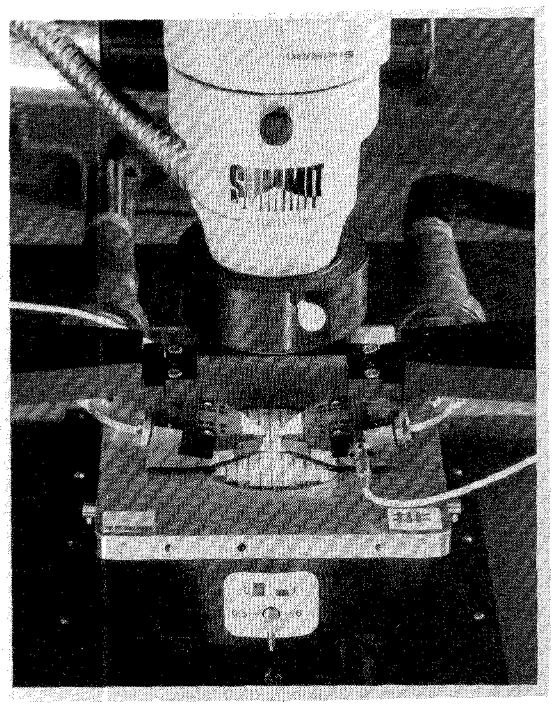


Figure 16. V-band probe station for two port measurements. Note the waveguide at each end and bias cables plugged into each side.

At Boeing Research Labs a 0.25 micron GaAs pseudomorphic MODFET was measured. Figure 17 displays the MODFET's gain characteristics. The data agreed with expectations for the device, confirming that the probes were performing properly.

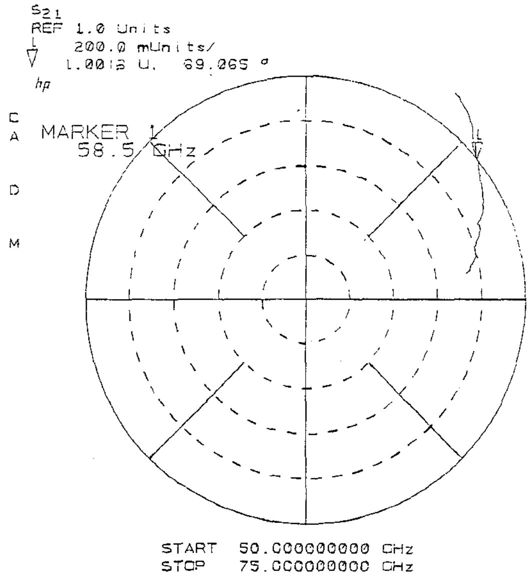


Figure 17. S_{21} polar plot for the MODFET.

CONCLUSIONS

A V-band wafer probe was successfully designed and built. A new type of waveguide, the ridge-trough waveguide, was used in the transition from rectangular waveguide to coplanar waveguide, and a mathematical model was developed to describe its principle characteristics. A 25X model was built to confirm the mathematical model predictions and to model the performance of the transition from rectangular waveguide to coplanar waveguide used in the V-band probe.

Reinforced by the 25X model results, a working V-band probe was constructed with bias capability. This probe performed well and measurements could be easily corrected. Devices were measured at 50-75 GHz to demonstrate that two V-band probes could successfully perform two-port measurements.

ACKNOWLEDGMENTS

This work was sponsored by Ball Aerospace under the Navy MMIC Phase III contract.

Thanks to Keith Jones for his help and advice in the design and realization of the V-band probe. Other important help was supplied by Bernie Duman, Gerry Benedict, Rick Warner, Dan DeLessert, Joyce Martin, Dan d'Almeida, and Glen Orr.

The MODFETs were supplied by Dr. Michael Trippe of Martin Marietta Labs, and Glenn Martin of Boeing Research Labs. Frank Beckous of W. L. Gore & Associates, Inc. provided the flexible waveguide.

REFERENCES

[1] Dalman, G.C., "New Waveguide-to-Coplanar Waveguide Transition for Centimeter and Millimeter Wave Applications," Electronic Letters, Vol. 26,June, 1990, pp. 830-831.

[2] Ponchak, G.E. and R.N. Simons, "A New Rectangular Waveguide to Coplanar Waveguide Transition ," IEEE MTT-S Symposium Digest, 1990, pp. 491-493.

[3] Cohn, S.B., "Properties of Ridge Waveguide," Proc. IRE, August 1947, Vol. 35, pp. 783-788.

PATENT INFORMATION

The Ridge-Trough Waveguide is covered under United States Patent Number 4,992,762. European and Japanese patents applied for.