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RF Characterization of Monolithic Microwave and mm-Wave ICs

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RF CHARACTERIZATION OF MONOLITHIC MICROWAVE AND mm-WAVE ICs

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SUMMARY

A number of fixturing techniques compatible with automatic network analysis are presented. The fixtures are capable of characterizing GaAs Monolithic Microwave Integrated Circuits (MMICs) at K and Ka band. Several different transitions are used to couple the RF test port to microstrip. Fixtures which provide chip level de-embedding are included. In addition, two advanced characterization techniques are assessed.

The characterization of solid state devices poses a substantial challenge at and above K-band due to increased parasitics which introduce inaccuracy and nonrepeatability in RF measurements. Packaging and interconnects are critical as is the transition from the device to the test port. The RF characterization of large quantities of MMICs in chip form introduces an additional problem due to the time required to secure a single device in a fixture. A major impetus is phased array technology which requires a large cluster of radiating elements and demands accurate device data to insure predictable performance. Of paramount importance is the need to nondestructively test these chips. Unfortunately, conventional fixturing techniques require ribbon or wire bonds which can damage the chip or alter its characteristics if they are removed. The bonding process can be cumbersome and does not lend itself to extensive testing. Noninvasive techniques need to be established. Various fixturing schemes employing conventional frequency domain (scattering parameter) methods were investigated and new, potentially superior, characterization techniques are addressed. Fixtures using probe, antipodal finline, coaxial, and ridge guide transitions were developed by or for NASA Lewis and preliminary test data is included. Direct on wafer probing and time domain measurements using electrooptic sampling are assessed.

FUNDAMENTALS OF DEVICE CHARACTERIZATION

The quality of device characterization will inevitably affect overall system reliability. Since many applications can tolerate only marginal variations in device performance, much effort is spent in accurately quantifying device parameters. Small signal S-parameter techniques using automatic vector network analysis are fundamental to device evaluation. This paper highlights some of the many problems encountered during MMIC testing, presents several approaches intent on circumventing these problems, and addresses several promising new methods of MMIC characterization.

Typically, an MMIC, whether packaged or in die form, must be mounted in a fixture which provides a means to connect from the chip to the network analyzer via coaxial cables or rectangular waveguide. Calibration is normally done at the ANA transmission line to fixture interface using known standards. Historically, coax is used below 26 GHz while waveguide components tend to dominate above Ka-band. In either case, the measurement plane is removed from the physical device terminals by the fixture geometry. This discrepancy can be accounted for using a procedure known as de-embedding. A number of techniques exist, each requiring chip level microstrip standards to mathematically shift the reference plane to the device area (refs. 1 to 3)

The interconnection from the measurement plane to the chip requires a transition from one transmission media (coax or waveguide) to another (microstrip, coplanar lines, etc.). This transition is a critical component of the fixture and must provide broad bandwidth and low loss, especially if de-embedding standards are not used. The transition serves to realign the $\vec{E}$ field, if required, and provide an impedance match to the microstrip line. The fixture shown in figure 1 uses an SMA coax to microstrip transition and is operable to 26.5 GHz. With the advent of the K and 2.4 mm connector (ref. 4), the technique should be extendable to 50 GHz. The fixture in figure 2 uses a waveguide antipodal finline transition. Favorable characteristics include broad bandwidth and an in-line geometry. A possible draw-back is the requirement that the chip be placed parallel to the narrow wall of the guide, limiting chip dimensions. The fixture in figure 3 incorporates a probe type transition which is dc isolated but inherently possesses a slightly narrower bandwidth. The cosine tapered ridge guide transition of figure 4 has broad bandwidth and an in-line geometry. In addition, the chip is oriented parallel to the broad wall of the guide. However, a dc block is required for active devices.

The next level interconnect occurs from the transition to the chip or chip carrier. A chip carrier, usually quartz or alumina with printed microstrip and bias lines, is normally required since the GaAs MMIC is extremely fragile. A carrier is essential if the chip is to be reused. This interconnection is achieved with gold ribbon or parallel wire bonds. An alternative is to use spring loaded pressure contacts and gold ribbon beam lead type connections. That is, a length of ribbon, preferably the same width as the microstrip, is placed across the lines and held in place with a dielectric rod. With this technique, contact life and contact repeatability are a critical issue. Results of this approach are discussed later.

Interconnections at the chip level account for many discontinuities. Differences in substrate permittivity and thickness will cause a mismatch in line width. There will also be a step change from the chip to the carrier which will result in longer bonds and thus more inductance, as well as stray fringing capacitance (ref. 5). In order to preserve measurement integrity, these factors must be minimized as much as possible. An evaluation of the various fixturing techniques is presented in the following section.

FIXTURING TECHNIQUES

Finline/Waveguide Test Fixture

As part of Contract NAS3-23356, Honeywell developed the fixture shown in figure 2 to test submodules of a 30 GHz monolithic receiver (ref. 6). The Van Heuven finline transition (ref. 7) is ribbon bonded to the MMIC. The chip and ribbon interconnect area is supported by gold plated brass carrier blocks which essentially cut the waveguide in half. This feature places the chip in waveguide below cutoff, insures ground plane continuity, and provides good isolation between input and output. Bias lines are printed on alumina and fed through slots in the guide near the MMIC. Direct current contacts are made using gold wire bonds. Typical insertion loss per transition, printed on 0.010" RT/Duroid, is less than 0.3 dB over a 50 percent bandwidth. The loss per ribbon bond, modelled as microstrip over an air dielectric, is at least 0.4 dB at 30 GHz.

The fixture provides accurate and repeatable data and the technique can be extended to higher waveguide bands. However, due to the number of ribbon and wire bonds required to secure each chip as well as the skill required to solder the chip to the carrier block, testing becomes an arduous task. In addition, it is almost impossible to reuse the chip following this procedure.

Universal Coaxial Test Fixture

The RF characteristics of Rockwell's "universal" coaxial test fixture (fig. 1) were measured using a Hewlett-Packard model 8510 automatic network analyzer (ANA). This selection permitted full 2-port vector characterization of the device from 2.0 to 26.5 GHz with 12-term error correction capability. The network analyzer was calibrated using standard techniques for the APC 3.5 connector family, thereby placing the calibration planes at the input and output connectors of the fixture. To reduce the number of systematic measurement errors, the test fixture and cables were firmly supported at all stress points and remained undisturbed throughout testing.

The forward transmission (S21) coefficients of the test fixure are shown in figure 5 for six consecutive measurements of a 7.5 mm offset transmission line. Each trace is the result of a complete disassembly and reassembly of the microstrip test section, including the beam lead pressure lid and MMIC cover. The removal and insertion of the through line section was performed each time by removing the pressure lid with the dielectric probe spring assembly which holds down the MMIC beam lead from the top of the fixture, then mechanically separating the coaxial transition pieces. In addition, the reinsertion procedure requires that the gold ribbon beam lead used as the RF bridge be carefully centered on the microstrip transmission line. The entire insertion procedure requires approximately 2 min.

The S21 test data indicates that the test fixture and microstrip transmission line test section present a total power loss of less than 5 dB over the full test frequency range. The RF performance improves to less than 2.5 dB of loss below 13 GHz. In both cases, the forward loss is repeatable within a range of ± 1.25 dB and often better than ± 0.5 dB. In all cases, the test fixture provides a low-loss, reliable, and stable environment to be used to test both passive and active microstrip devices.

The Rockwell test fixture was also tested to determine its ability to match the 50 Ω characteristic impedance of the network analyzer. The results of this test appear as either a return loss measurement, S11, or can be mathematically converted to standing wave ratio (SWR). This later data is presented in figure 6. As is shown in the figure, the standing wave ratio remains below 1.5:1 from 2.0 to 14.5 GHz. Above 14.5 GHz, the SWR varies to as much as 2.4:1.

As part of the forward loss (S21) RF testing, the phase response of the test fixture was measured. As expected, a conventional sawtooth pattern was recorded, indicating a linear phase shift with frequency. Repeated insertion of the through line yielded little deviation from the first phase trace.

The reverse RF scattering parameters S12 and S22 were also measured for each test run. The results of these tests indicate that the device is clearly reciprocal in nature.

The calibration technique described by Benet for the Rockwell test fixtures (ref. 8) is currently being assessed. In addition, time domain reflection measurements are being analyzed with the goal of determining areas of the fixture which need reworking to extend the flat band portion of the characteristics into the 14 to 26.5 GHz range. Possible solutions currently being tested are modifications to the MMIC cover to increase the cutoff frequency in that region to avoid any moding or resonance problems.

Modifications have been made to the Rockwell test fixture at NASA Lewis allowing characterization of various microwave solid state devices in the frequency range of 26.5 to 40 GHz. The coaxial to microstrip transition and its housing have been replaced by a waveguide to microstrip transition and a suitable housing. This modification allows the fixture to interface with existing test equipment in the 26.5 to 40 GHz band. The waveguide to microstrip transition housing was designed to be completely compatible with the existing fixture while keeping transition losses to a minimum and eliminating resonant modes. To further reduce moding problems at these higher frequencies, the beam lead pressure lid was also redesigned to continue the covered microstrip wave propagation mode from the transition housing to the device under test. The waveguide to microstrip transition chosen for use in the fixture was an antipodal finline-thpe transition. This transition has the advantage of being in line with the test setup, inexpensive, and easily replaceable.

Preliminary test results indicate a moding problem which will require modifications to the MMIC lid. Of a more critical nature is the problem of reproducibility. The fixture was designed with many moving or nonrigid parts to accommodate the testing of a wide variety of device structures and chip sizes. With flexible coaxial inputs to the fixture and some care, no problems resulted. But with rigid waveguide feed systems which are heavy and not easily moved for device insertion, excessive stress is applied to the fixture causing movement of the nonrigid parts and nonreproducible device characteristics.

Probe/Waveguide Test Fixture

The waveguide test fixture shown in figure 3 was designed and built for NASA Lewis as part of contract NAS3-23789 by General Electric. The design goal was to provide a nondestructive fixture that could be used to test a large number of MMIC chips for advanced phased array antenna applications. The result was a compact and simple assembly with several novel features.

The GE fixture was tested using the HP 8510 network analyzer. Although the fixture passband of 17.7 to 20.2 GHz was within the frequency range of the ANA, a transition to waveguide transmission media was required. To facilitate the waveguide testing, a set of WR-42 calibration standards was needed, along with a programming modification to the network analyzer. The end result of the ANA modification was then the ability to calibrate the test system at the waveguide input and output ports of the test fixture. Of some concern in the testing, however, were the waveguide ports of the GE fixture. As is shown in the photograph, the input and output ports of the test fixture support a WR-42 compatible flange (UG-595/V), but do not have the standard rectangular waveguide cross-section. Instead, for ease of machining the cavity, the waveguide was manufactured with parallel walls along the broad dimension but with rounded ends. To verify that this media was compatible with the standard rectangular waveguide, a short section of the round-end waveguide was machined and tested. An SWR of less than 1.1:1 was recorded across the frequency band.

All four scattering parameters were measured on the GE fixture. A typical measurement of the forward loss coefficient, S21, is shown in figure 7. These results, though currently less repeatable than on other fixtures, are expected to improve significantly with the addition of a precision probe alignment cover. This cover, similar to the one shown in figure 3, will be placed on top of the existing test fixture and will help guide the RF pressure pins onto the gold bridging ribbon. Initial tests indicate that this will reduce the insertion losses of the fixture to a more reasonable level. Initial estimates of the expected losses approach 3 dB. Comparison of the forward and reverse test data indicates that the device was reciprocal in terms of RF performance.

Cosine Tapered Ridge Guide Fixture

NASA Lewis is pursuing another "nondestructive" fixture using a ridge guide transition. A cosine tapered ridge is used to match the waveguide impedance to the microstrip. Contact is achieved through a critical pressure fit between the ridge and the chip carrier but promises good repeatability due to the elimination of ribbon bonds and the need for any spring mechanism. The design of the curve is based on a simple equivalent circuit model (ref. 9) and can accommodate a variety of chip thicknesses. A computer program was written to generate the curve and calculate the ridge thickness. A simple one port version is shown in figure 4. This fixture was used to test GaAs microstrip resonators in order to evaluate propagation characteristics. The typical response of a microstrip resonator and S11 repeatability data is presented in figure 9. The chip is affixed to the waveguide base by a vacuum hold down.

The MMIC test fixture will use spring loaded pins to provide dc bias and include a chip carrier similar to that shown in figure 8. The ridge is chamfered near the chip to provide a smooth transition. A coplanar carrier was chosen to provide a ground plane for the MMIC and ease interconnections. The ground planes are kept equipotential by the waveguide cover contact. Following the test, the carrier can be removed. If desired, the circuit can be diced to remove the dc block prior to reuse. The loss per transition is expected to be comparable to the finline structure. The coupled lines add an additional 0.2 to 0.3 dB loss each at Ka-band. Characterization will be performed on a modified HP-8409 automatic network analyzer. The standard ANA has been extended to 50 GHz using Ka and Q band waveguide test sets. The approach, which uses a multiply up/mix down technique, preserves the features of the standard ANA to a high degree (ref. 10). A V-band version has been designed and is being assembled.

ADVANCED CHARACTERIZATION TECHNIQUES

Two emerging technologies showing promise for device characterization are direct on wafer probing and electrooptic sampling. A brief review of the concepts, merits, and status of these techniques is presented.

Microwave Wafer Probing

The ability to evaluate devices at the wafer level with even greater accuracy than conventional fixtures is becoming routine through K-band. A wafer probe, which is essentially an adapter from coax to bonding pads, performs about as well as a normal SMA connector. However, by using chip level impedance standards, significant accuracy enhancement is possible. The technique developed by Cascade Microtech involves coplanar probe heads and one-tier de-embedding procedures. Coplanar probes are used to ease ground plane interconnections and reduce radiation effects. This approach does require that the wafer to be tested incorporate coplanar pads or ground vias near the test points for microstrip circuits. The de-embedding procedure requires short, open, and load standards for one port characterization and an additional through connection and isolation standards for two port characterization. Due to the small size of the impedance standards, parasitics are minimized (refs. 11 to 13).

The technique has already been extended to 26 GHz and will no doubt be pushed even further. Constraints may eventually be imposed due to radiation effects, crosstalk degradation, and physical limitations; but the approach is a welcome alternative to conventional measurements.

Electrooptic Sampling

A potentially revolutionary, and at the very least exciting new characterization method is electrooptic sampling. Recently, electrooptic sampling techniques are showing promise for providing noncontact high frequency characterization of high speed GaAs devices and integrated circuits (refs. 14 to 16). In addition to providing characterization without bonding of the device or circuit, the technique can also perform wide bandwidth measurements from 2 to 100 GHz. Short pulse lasers and ultra high speed photoconductors are used to generate wide-bandwidth electronic pulses to provide direct electronic sampling on a GaAs device or integrated circuit.

With this technique, S-parameters of GaAs MESFETs have been obtained. However, the technique requires several developments before it can be used routinely to obtain S-parameters of MMICs. The photodetector and sampler need to be integrated with GaAs circuits in order to eliminate bonding. Comparison between time domain characterization obtained by electrooptical techniques and S-parameters obtained by network analyzer techniques needs to be performed. High frequency solid state lasers need to be developed to reduce cost and simplify measurements (refs. 17 and 18). Figure 10 shows a 30 GHz gain control MMIC amplifier bonded to a GaAs photoconductor and Lithium Tantalate sampler for electrooptical measurements to be performed at the University of Rochester. These results will then be compared with network analyzer measurements at NASA Lewis.

CONCLUSION

A variety of fixturing techniques have been presented, with emphasis on methods of interfacing with the MMIC. Contact life and contact repeatability are a key issue. Preliminary evaluation of test data indicated where improvements were required, and suggested alternatives to implement these improvements. Noninvasive techniques need to be further developed. A brief review of on-wafer probing and electrooptic sampling was presented. These novel approaches are showing great promise for quick and reliable device and MMIC characterization.

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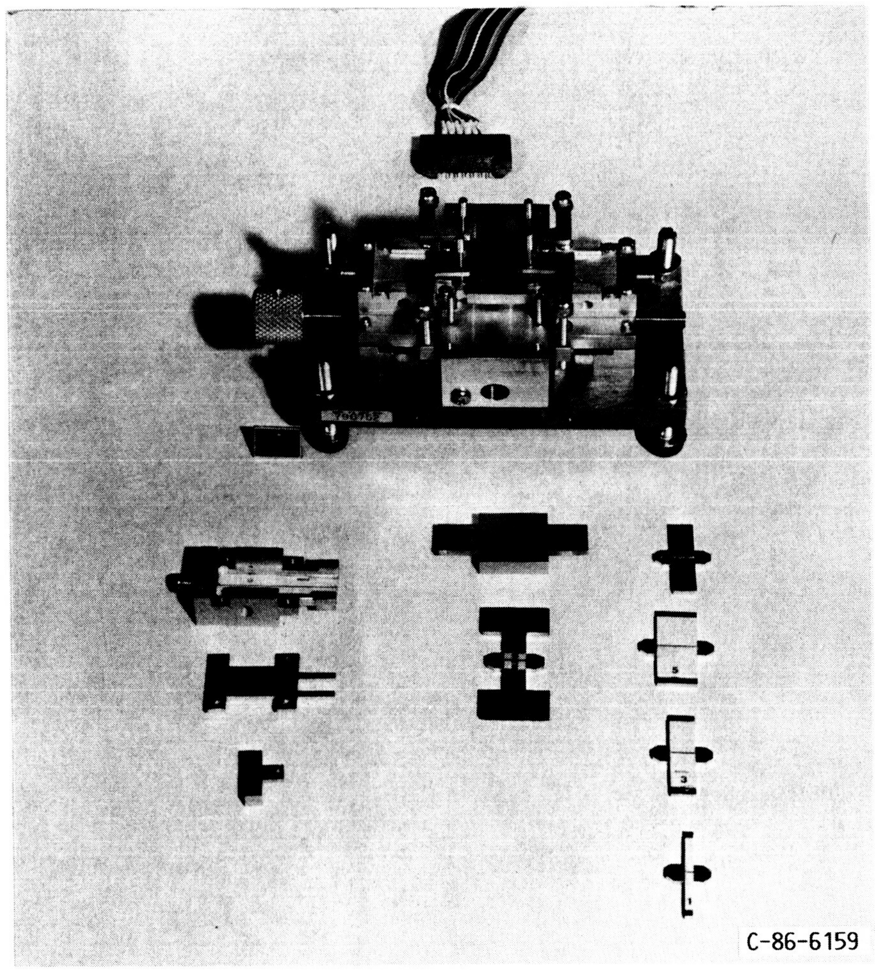

FIGURE 1. - THE ROCKWELL UNIVERSAL TEST FIXTURE WITH ACCOMPANYING CALIBRATION PIECES, CHIP CARRIER, AND SHIELDING LIDS. THIS ORIGINAL VERSION OF THE FIXTURE USES SMA CONNECTORS AND IS OPERABLE TO 26.5 GHz.

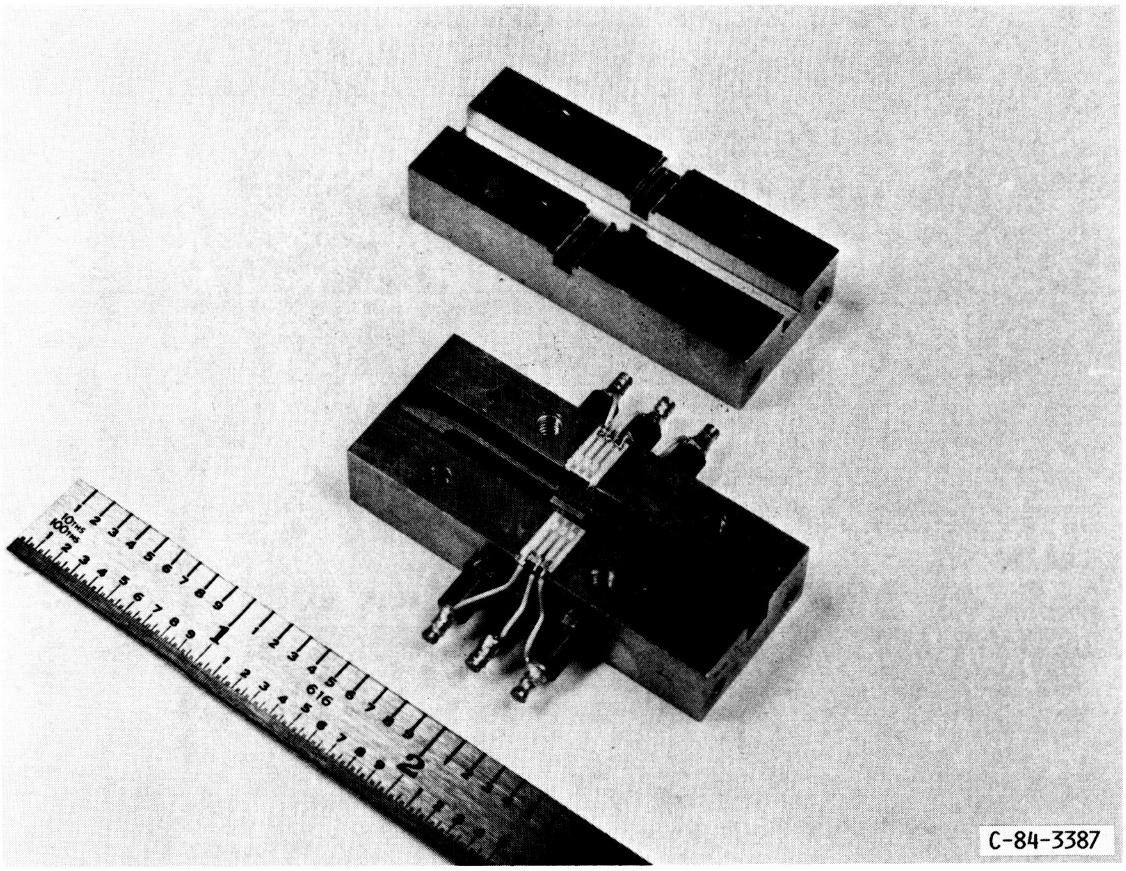

FIGURE 2. - A KA-BAND TEST FIXTURE DEVELOPED BY HONEYWELL AS A PART OF CONTRACT NAS3-23356 TO TEST MMIC SUBMODULES OF A 30 GHZ RECEIVER. A 3-BIT SWITCHED LINE PHASE SHIFTER IS SHOWN BONDED IN THE FIXTURE.

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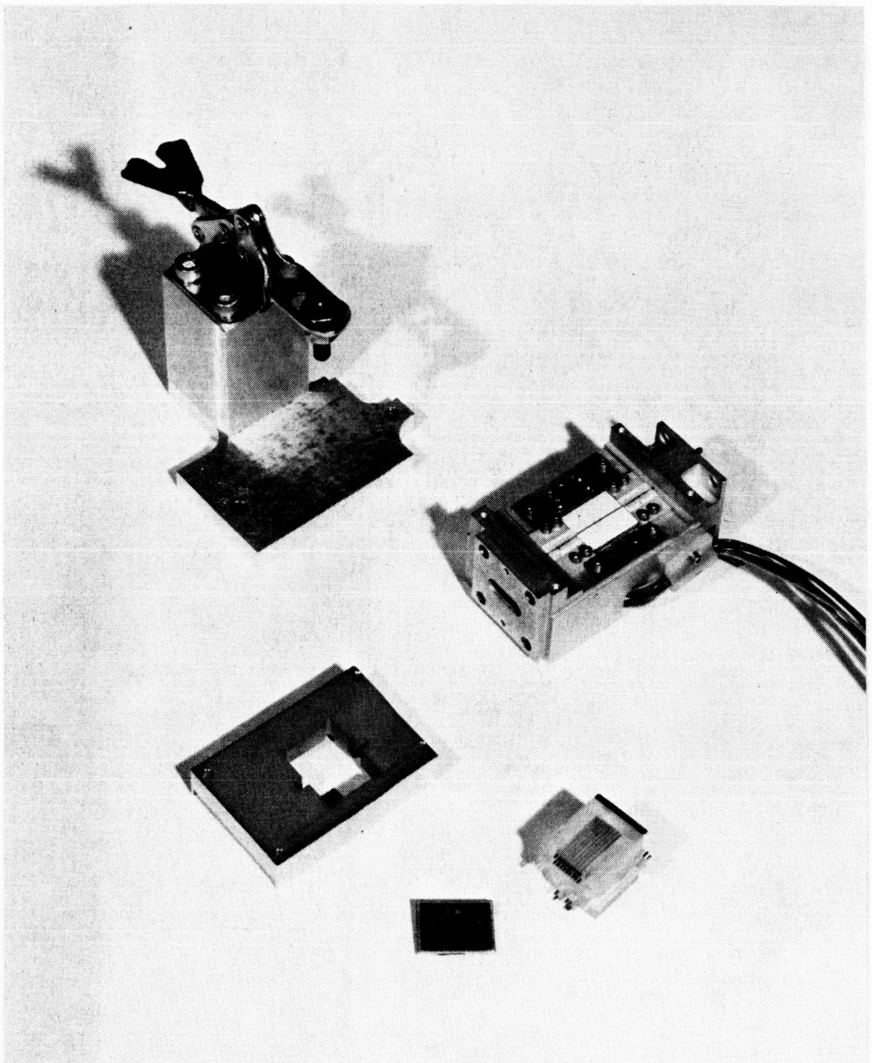

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FIGURE 3. - A K-BAND TEST FIXTURE DEVELOPED BY GENERAL ELECTRIC AS PART OF CONTRACT NAS3-23789. THIS FIXTURE WAS DESIGNED TO TEST PACKAGED COMPONENTS OF A 20 GHz MMIC TRANSMITTER. THE ALIGNMENT COVER (LOWER LEFT) WAS DESIGNED AND MACHINED AT NASA LEWIS TO GUIDE THE PROBE MODULE (LOWER RIGHT) ONTO THE MMIC.

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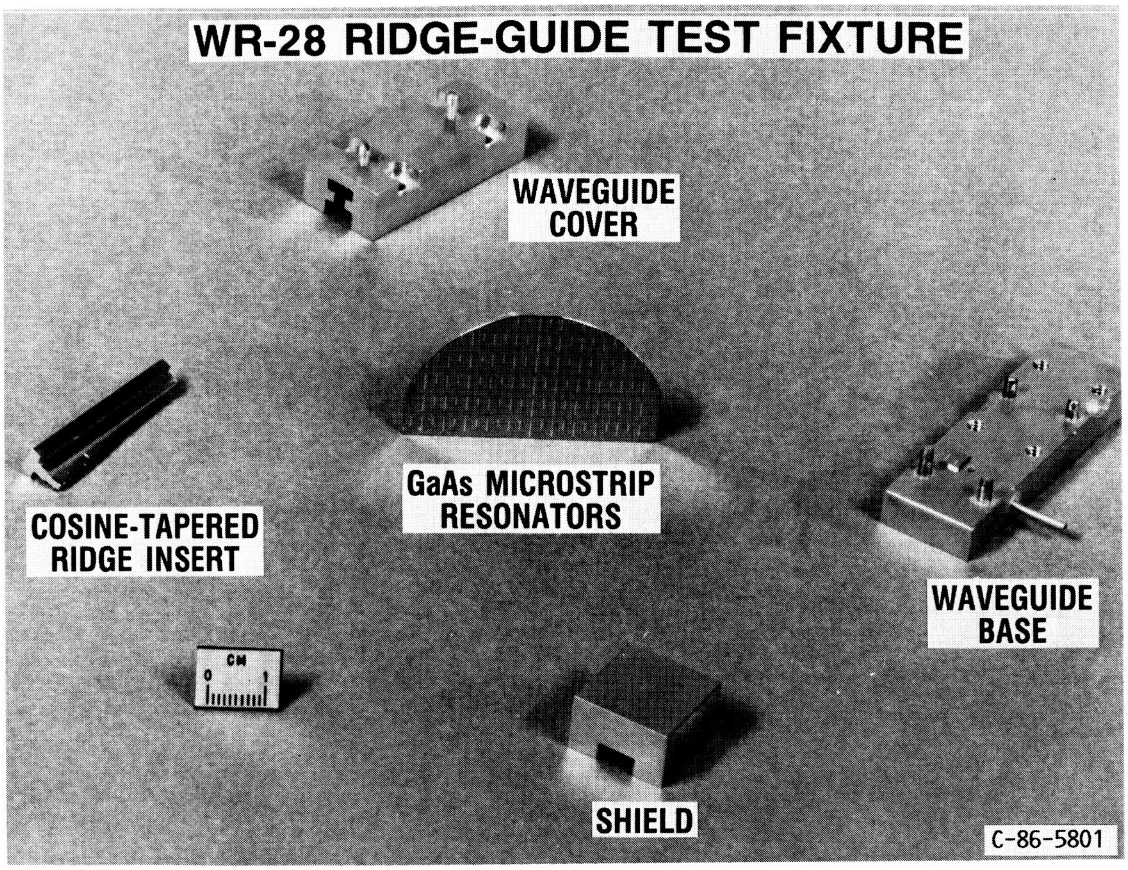

FIGURE 4. - A KA-BAND ONE-PORT PASSIVE TEST FIXTURE DEVELOPED AT NASA LEWIS. THE FIXTURE WAS DESIGNED TO TEST GAAS MICROSTRIP RESONATORS IN ORDER TO EVALUATE PROPAGATION CHARACTERISTICS. A TWO-PORT MMIC TEST FIXTURE VERSION IS BEING DEVELOPED.

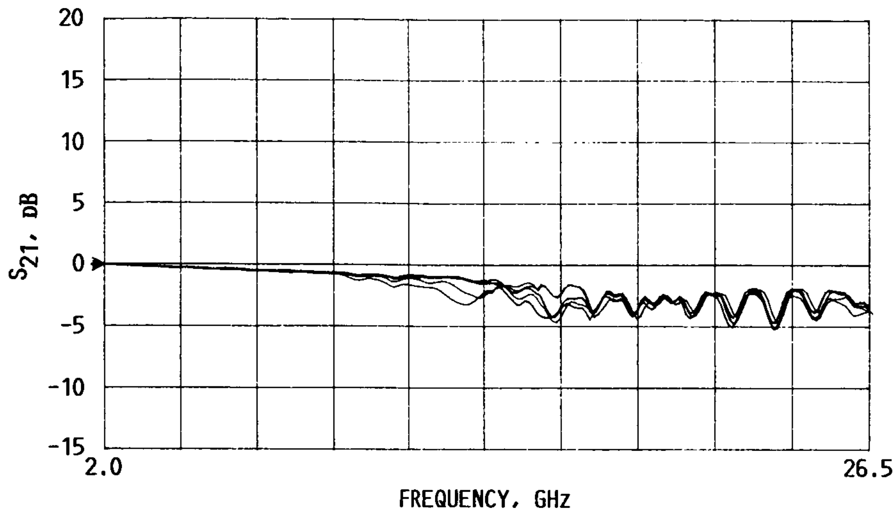

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FIGURE 5.- FORWARD LOSS CHARACTERISTICS OF THE ROCKWELL COAXIAL TEST FIXTURE.

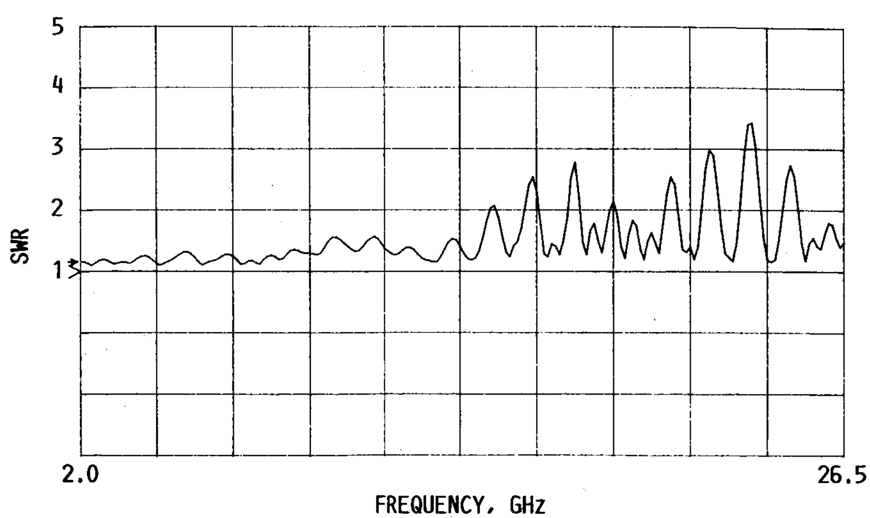

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FIGURE 6.- STANDING WAVE RATIO OF THE ROCKWELL COAXIAL TEST FIXTURE.

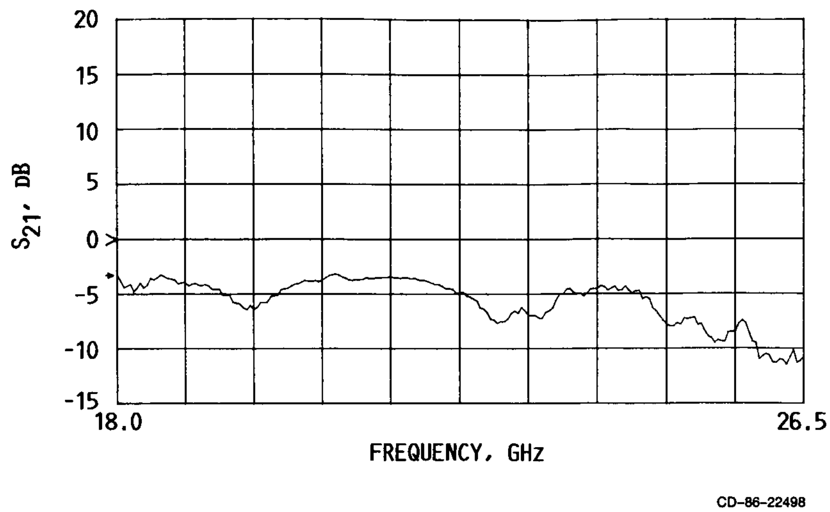

FIGURE 7.- FORWARD LOSS CHARACTERISTICS OF THE GE TEST FIXTURE.

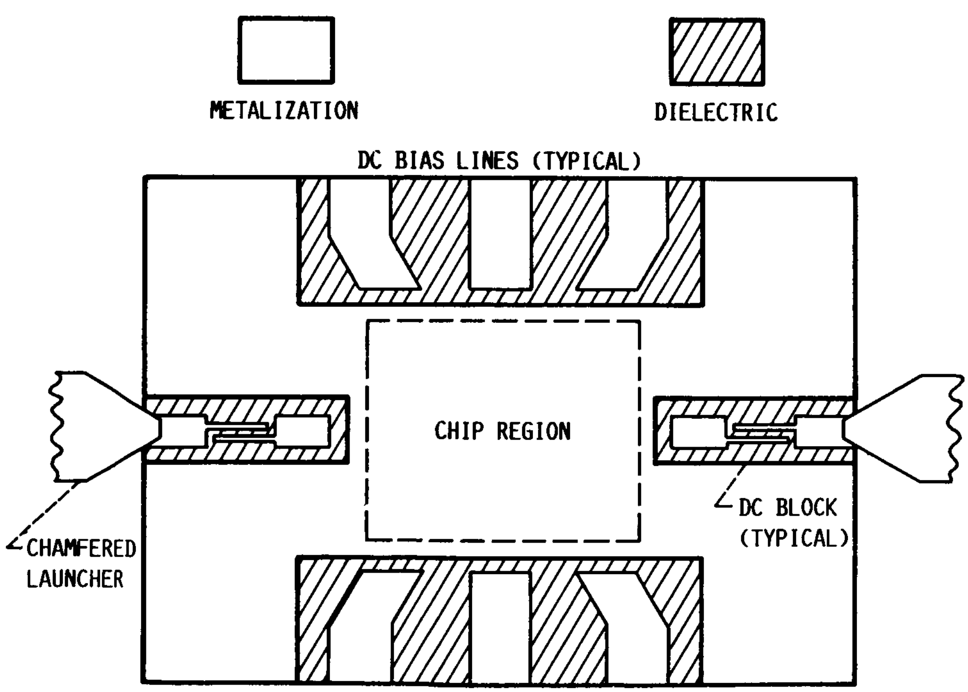

FIGURE 8. - A COPLANAR CHIP CARRIER TO BE USED WITH A COSINE TAPERED RIDGE GUIDE TEST FIXTURE. DC BLOCKS ARE REQUIRED SINCE THE TAPER IS PART OF THE WAVEGUIDE HOUSING. IT IS BELIEVED THAT THE RIDGE CONNECTION WILL PROVE MORE REPEATABLE THAN A SPRING LOADED PRESSURE CONTACT.

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