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Universal Test Fixture for Monolithic mm-Wave Integrated Circuits Calibrated With an Augmented TRD Algorithm

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Summary

The design and evaluation of a novel fixturing technique for characterizing millimeter-wave solid-state devices is presented. The technique utilizes a cosine-tapered ridge guide fixture and a one-tier de-embedding procedure to produce accurate and repeatable device-level data. Advanced features of this technique include nondestructive testing, full waveguide bandwidth operation, universality of application, and rapid, yet repeatable, chip-level characterization. In addition, only one set of calibration standards is required regardless of the device geometry.

Introduction

The accurate characterization of solid-state devices at and above K-band is hindered by limited metrological techniques due to increased parasitics, diminutive physical dimensions, and inconvenient interface methods (ref. 1). The quality of device characterization will inevitably affect the integrity of the intended application. Since many system applications can tolerate only marginal variations in device performance, much effort is spent in accurately quantifying radiofrequency (RF) parameters. Small-signal *S*-parameter techniques that use automatic vector network analyses are fundamental to this device evaluation.

Typically, microwave and millimeter-wave monolithic integrated circuits (MMIC's), whether packaged or in die form, must be mounted in a fixture which provides a means to connect the chip to the automatic network analyzer (ANA) via coaxial cables or rectangular waveguide. The fixture introduces substantial insertion and return loss effects, both in magnitude and phase, often masking the true device characteristics. Calibration is normally done at the ANA transmission line-to-fixture interface by using known standards. Consequently, the measurement (reference) plane is removed from the physical device terminals by the fixture geometry. This discrepancy can be compensated for with a procedure known as de-embedding. The technique requires applying chip-level microstrip standards to mathematically shift the reference plane to the device area. A detailed discussion of the calibration and de-embedding procedures is given in the section Fixture Calibration.

Drawbacks of existing fixtures include the inability to obtain repeatable data, the difficulty in securing a device in the fixture, the complexity of calibrating the fixture, and the limitations on bandwidth imposed by the waveguide-to-microstrip transition. In addition, most techniques are destructive to the device and are labor intensive. This report describes the evolution of a new test fixture with several innovative features that is operable over the K_a band (26.5 to 40.0 GHz). A photograph of the fixture is shown in figure 1.

A cosine-tapered ridge transition matches the high waveguide impedance to the 50-Ω microstrip. The taper length and profile have been analytically determined to provide maximum bandwidth and minimum insertion loss. Integrated circuits and devices are mounted on a customized carrier which is inserted between the bottom of the ridge and the base of the waveguide. The electric field is concentrated by the ridge and launched onto the carrier microstrip via direct pressure contact. Isolation between the device under test and the fixture, as well as bias/control circuitry, is also provided by the carrier. Control voltages are applied to the carrier by a self-aligned bias module with integral spring-loaded contacts. The carrier assembly is designed for direct insertion into a given system, such as a phased array, and thus serves the dual role of test vehicle and package. De-embedding is accomplished with *through-reflect-delay* (TRD) microstrip standards and software. These calibration standards set the ancillary reference plane at the bisector of the chip carrier. Then, the complex propagation constant of the carrier microstrip line is determined from the standards, and the reference plane is subsequently shifted to the device boundaries. Figure 2 illustrates this concept.

Chip Carrier Design

The most complex component of the test fixture is the chip carrier. Since the fixture itself is mechanically rigid to improve data repeatability, the required versatility was built into the carrier. A 0.020-in. alumina substrate was chosen for its manufacturability, good dielectric properties, and relatively good thermal and mechanical characteristics. The substrate thickness was constrained to a narrow range by line-width restrictions. Whereas the lithography process imposed a minimum feature size on the coupled-line section, the possibility of generating surface waves imposed a maximum substrate thickness. A 0.020-in. substrate was a suitable compromise for K_a band. Features of the carrier include coupled-line direct-current (dc) blocks, input (gate) and output

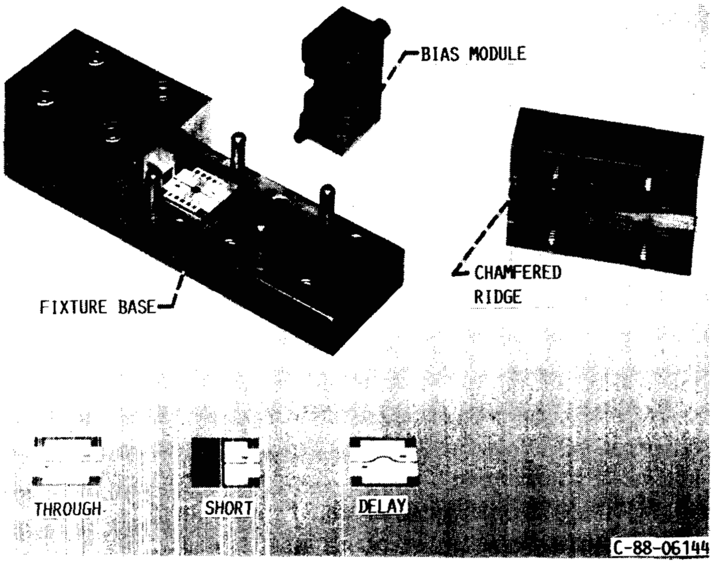


Figure 1.—Partially disassembled view of cosine-tapered ridge guide fixture along with *through-reflect-delay* (TRD) calibration standards. Monolithic 30-GHz gain control amplifier is mounted on carrier.

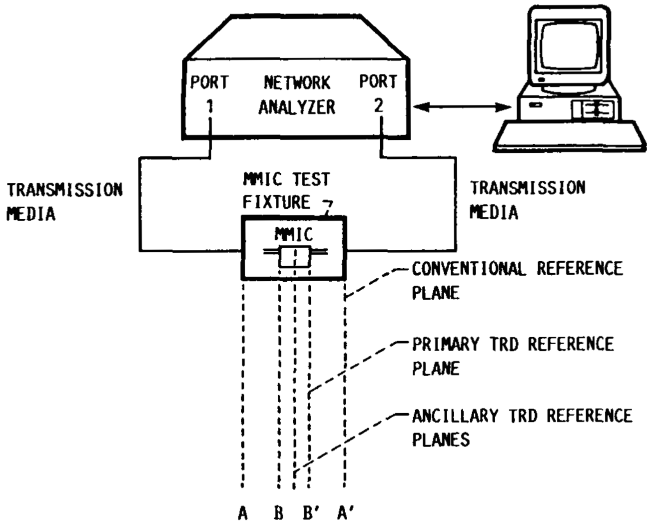
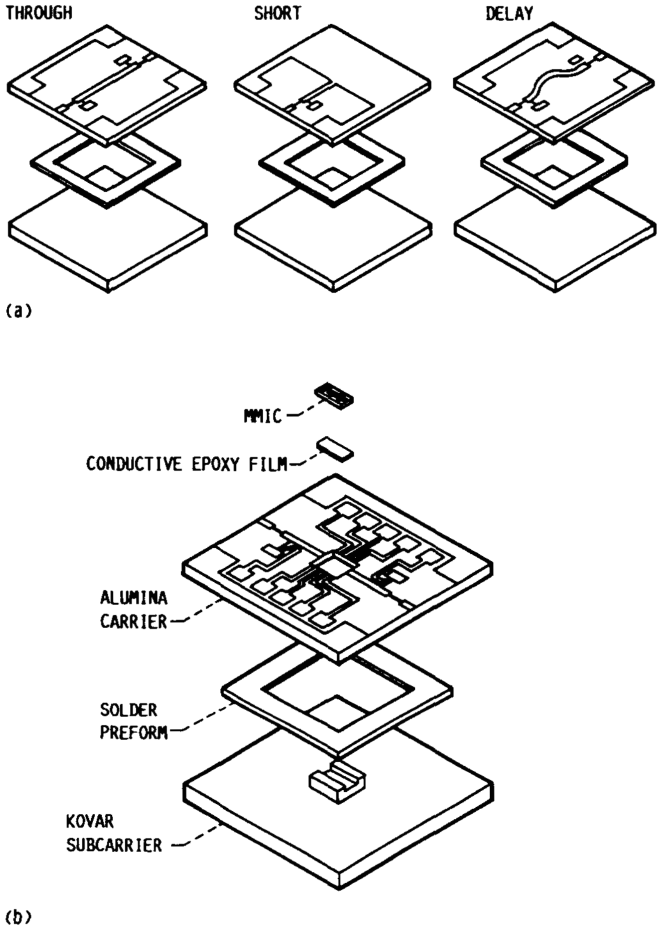


Figure 2.—Simplified diagram denoting relationship among various reference planes.



(a) *Through-short-delay* (TSD) calibration standards.
(b) Chip carrier assembly.

Figure 3.—Detailed schematic of calibration standards.

(drain) bias filters, and 10 bias pads. A key feature of the design is a generic footprint; that is, except for a central area on the carrier, the metalization pattern is common for all chip and device types. Figure 3 highlights the carrier topology and demonstrates the assembly.

The dc blocks are required since the carrier microstrip lines are in contact with the fixture body, which is at ground potential. The obtainable bandwidth of the dc blocks is a strong function of the gap between the coupled lines. A 0.002-in. gap and a 0.032-in.-long coupled section with 0.0029-in.-wide fingers were found to be optimum (refs. 2 and 3). The dc block design was modeled with commercially available software which predicted an insertion loss of less than 0.25 dB over most of the band. The chip was mounted in a laser-machined well in the center of the carrier and supported by a gold-plated kovar subcarrier. A mesa was machined on the kovar subcarrier such that the surfaces of the chip and alumina carrier were flush. The mesa was extended beyond the width of the chip to accommodate chip capacitors, if necessary, and to facilitate grounding requirements. The carrier was bonded to the kovar with a special indium alloy preform by heating to 210 °C. Subsequent to this procedure, the die was attached with silver-impregnated epoxy which was cured at 125 °C. The carrier can accommodate chips up to 0.250 in. long.

Bias could be fed directly to the chip input and output microstrip lines, if required, through two bias filters. The filters consisted of a midband quarter-wavelength high impedance line cascaded with a quarter-wavelength, open-circuit, low impedance line. The input impedance of this combination was extremely high over a significant bandwidth and served to isolate the RF from the bias supply. Actual dc contact was made at the junction of the two quarter-wavelength lines so as not to perturb the impedance.

Transition Design

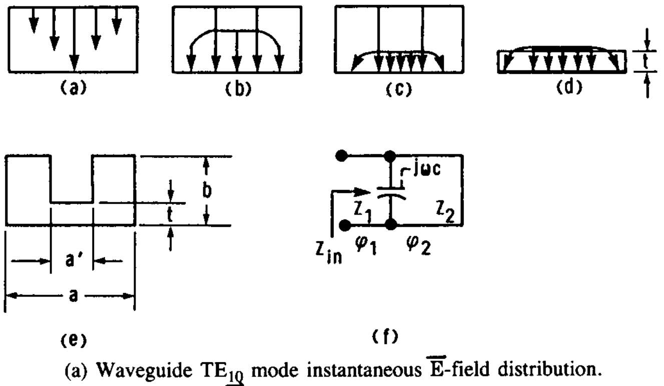
A number of transition candidates were reviewed for coupling the waveguide to the microstrip. Most had inherent bandwidth limitations and required complex mounting arrangements. In addition, bonding was normally required to attach the transition to the microstrip. The finline transition, for example, possesses an in-band resonance which must be tuned-out from the desired frequency range. The probe-type transition must be mounted perpendicular to the waveguide axis and is sensitive to placement. Both transitions must be wire- or ribbon-bonded to the microstrip, which adds to the fixturing complexity and testing time and compromises data repeatability. The ridge waveguide transition, which is an $\vec{E}$-plane taper, surmounted these limitations and provided a convenient interface method. Figure 4(a) to (d) illustrates the transition mechanism. Notice that no $\vec{E}$-field realignment was required. The use of ridge waveguides as transition elements spans several decades (ref. 4). A ridge waveguide has a lower cutoff frequency and greater higher order mode separation than a conventional waveguide with the same aspect ratio. The lower cutoff frequency results from the capacitive effect of the ridge. Although, in principle, the cutoff wavelength could be extended indefinitely, it is limited in practice because of the corresponding impedance limitations. As mentioned earlier, the attractiveness of the ridge waveguide stems from its superior bandwidth, and loss performance, as well as manufacturability. Actually designing the transition involved finding the correct ridge thickness and an acceptable profile to produce an impedance-matching transformer.

The design method first outlined by Singh and Seashore (ref. 5) can be subdivided into three calculations. (Symbols are defined in appendix A.) The first calculation entails evaluating the ridge waveguide cutoff wavelength λ_c. At the cutoff frequency, propagation may be considered to be restricted to a wave traveling transversely across the guide with no longitudinal component. This can be modeled by an equivalent network consisting of a discontinuity capacitance shunted by two transmission lines. The parallel plate transmission line terminates in a short circuit representing the waveguide wall. The cutoff wavelength is obtained by deriving an expression for the input impedance, which becomes infinite at cutoff. If the ridge is thick and approaches the waveguide sidewall, proximity effects should be taken into account (ref. 6). The resulting equation is transcendental and must be solved numerically. Based on the equivalent circuit model in figure 4(f), the following expression results:

$$1 - Z_2\omega c \tan \varphi_2 - Z_2/Z_1 \tan \varphi_2 \tan \varphi_1 = 0 \qquad (1)$$

where $Z_2\omega c$ is the normalized junction reactance obtained from reference 5, and $Z_2/Z_1 = b/t$ is the impedance ratio of the equivalent parallel plate lines. The transmission line equivalent lengths at cutoff are φ_1 and φ_2. Figure 5 illustrates cutoff wavelength in ridge guide as a function of ridge width for various substrate thicknesses. Once the cutoff wavelength is known, the ridge thickness, which is used to tailor the characteristic impedance Z_o, can be determined. Impedance Z_o as a function of frequency can be related to the infinite frequency characteristic impedance $Z_{o\infty}$ through

$$\frac{Z_o(x)}{Z_{o\infty}(x)} = \frac{\lambda_g}{\lambda_o} = \frac{1.0}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \qquad (2)$$



(a) Waveguide TE_{10} mode instantaneous $\vec{E}$-field distribution.
(b) Reconfigured $\vec{E}$-field geometry due to ridge protrusion.
(c) Concentrated $\vec{E}$-field as ridge approaches bottom wall.
(d) Microstrip quasi-TEM mode instantaneous $\vec{E}$-field distribution.
(e) Cross section of single ridge guide.
(f) Equivalent circuit at cutoff based on transverse resonance.

Figure 4.—Schematic depicting how ridge guide transition couples waveguide TE_{10} mode to microstrip quasi-TEM mode and its equivalent circuit at cutoff.

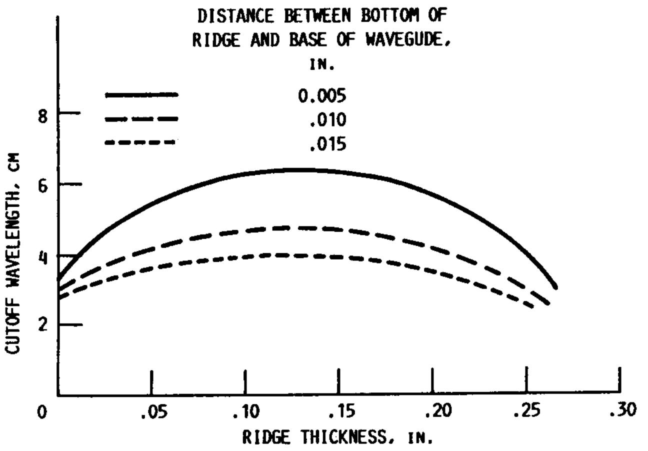


Figure 5.—Cutoff wavelength in ridge guide.

where λ_g is the guide wavelength and λ_o is the free space wavelength. The impedance $Z_{o\infty}$ for the TE_{10} mode is given by Cohn (ref. 4) as

$$Z_{o\infty} = \frac{120\pi^2 t}{\lambda_c \left[\sin \varphi_1 + \frac{t}{b} \cos \varphi_1 \tan \left(\frac{\varphi_2}{2} \right) \right]} \tag{3}$$

Since the band of interest is significantly above the cutoff frequency, the radical in equation (2) approaches unity and Z_o can be approximated by $Z_{o\infty}$ for the ridge thickness calculation. As for the cutoff wavelength, numerical techniques are required for the solution. The impedance Z_o is a function of ridge height and, hence, a function of position along the taper. The final stage of the design process involves solving for the physical taper, the length of which should provide adequate bandwidth without introducing unnecessary loss. A sinusoidal variation of the form

$$Z_o(x) = \frac{Z_0 + Z_L}{2} - \frac{Z_L + Z_0}{2} \cos \frac{\pi x}{\ell} \tag{4}$$

is assumed (ref. 8). With the possible exception of a Dolph-Tchebycheff profile, the sinusoidal taper outperforms other candidate tapers by minimizing the return loss in a given length. For example, a sinusodial transition performs as well as a linear transition but is only half as long. The length of the taper is ℓ, and x is the position along the taper from its origin. The characteristic impedances of the open waveguide at $x = 0$ and the ridge guide at $x = \ell$, are Z_0 and Z_L, respectively. Both impedances were calculated at the midband frequency. The taper provides a smooth transition from the full waveguide height to the substrate thickness and couples the dominant TE_{10} waveguide mode to the quasi-TEM microstrip mode. Substituting equation (3) into equation (2) yields an expression for the taper height t as a function of position:

$$t = \frac{\lambda_c \sqrt{1 - \left(\frac{f_c}{f} \right)^2} Z_o(x) \sin \varphi_1}{120\pi^2 - \frac{\lambda_c}{b} \sqrt{1 - \left(\frac{f_c}{f} \right)^2} Z_o(x) \cos \varphi_1 \tan \frac{\varphi_2}{2}} \tag{5}$$

A computer program was written to calculate the ridge geometry, given the basic waveguide and substrate dimensional parameters. Based on the previous calculations, a taper length of 1.366 in. ($3\lambda_g$ at 26.5 GHz) and a ridge thickness of 0.0695 in. were chosen. A smooth chamfer was machined at the end of each transition to eliminate sharp edges and, hence, reduce radiation. Performance data are included in the section Test Fixture Radiofrequency Performance. Taper profile coordinates are included in table I for this 26.5- to 40.0-GHz case as well as other waveguide bands up to 110 GHz.

Bias Module Design

A single-piece bias module was developed to supply the device being tested with the necessary bias and control power. The most important feature of this module is its ability to make solid, repeatable, nondestructive electrical connections to metalized pads on the alumina chip carrier. To do this, the bias module relies on the contacting properties of miniature spring-loaded plunger contacts. The contacts are mounted vertically in a single block of insulating material that serves as an alignment guide, contact support structure, and RF shield. This block is manufactured from a machinable material with dielectric properties similar to Lexan or Rexolite.

The bias module feeds power directly to the chip carrier through 10 spring-loaded contacts. Each contact consists of two parts—a spring-loaded plunger contact and a contact sleeve. Each plunger contact body has a slight deformation (bow) to retain it by friction in the contact sleeve. The obvious advantage of the two-piece design is that the pin contact can be easily replaced if damaged, or changed to another contact type if desired. A solder cup in the closed end of the contact sleeve provides a solderable connection to the pin assembly. Both the contact and contact sleeve are manufactured from nickel-silver alloy for high electrical conductivity. Each contact sleeve has a small rectangular collar on its open end. If the collar is carefully designed and machined, it can be used to seat the pin assembly and oppose the compression forces of the contact springs. This seating then maintains the vertical clearance of the pins over the chip carrier and ensures uniform contact pressure at all times.

To achieve the proper contact positioning, the bias module is equipped with precisely aligned holes parallel to the vertical axis of the contact block. Cylindrical posts inserted into the fixture base guide the bias module down vertically onto the chip carrier. The bias module is then secured to the test fixture with two thumbscrews to enable quick assembly and disassembly. Center-to-center contact spacing for this application was selected as 0.062 in. to provide firm mechanical support for the pin assemblies. The insulating material of the bias block provides electrical isolation.

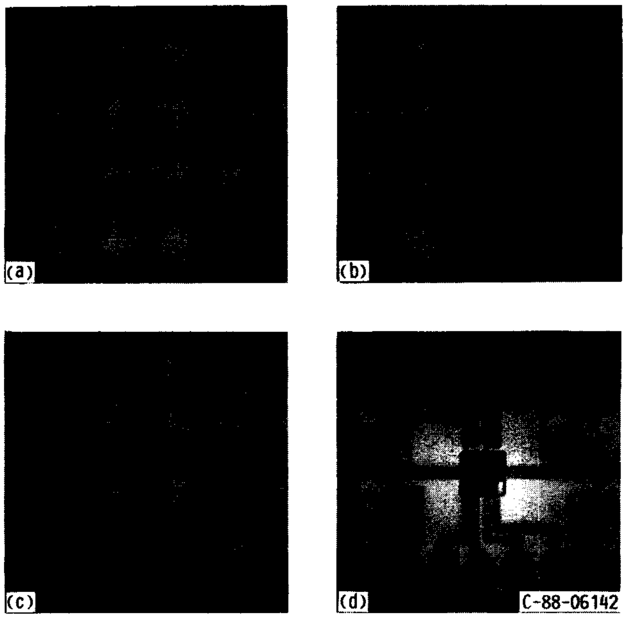
If testing indicates the presence of severe electromagnetic interference, the bias module is designed to facilitate the insertion of an RF shielding structure. This shield may be nothing more than conductive foil lining the clearance cavity inside the bias module, or it may be a machined insert to the module. In either case, the cavity resonances must be considered to prevent misleading test results or unpredictable side effects.

In all, the bias module represents a novel, yet simple, way to apply the bias to the chip carrier. The design can be used for a variety of carrier layouts and can be scaled to meet the needs of various frequency ranges.

Fixture Calibration

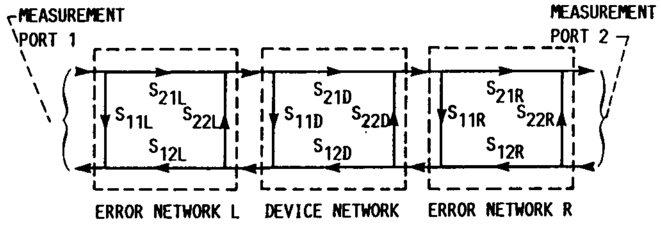
To extract device-level data, a de-embedding technique which removes all systematic errors, including those introduced by the fixture, must be used. Numerous de-embedding procedures exist, each offering a unique set of advantages and disadvantages. Since each measurement required by a specific technique introduces some additional error, it is desirable to minimize the number of calibration standards. Furthermore, standards such as accurate loads and predictable open circuits are difficult to implement in a microstrip, especially at millimeter wavelengths. To curtail the proliferation of measurement errors, a novel technique, first proposed by Franzen and Speciale (ref. 9) was chosen. The method uses a one-tier calibration and assumes an eight-term error model. Only three standards are required. A photograph of the set of a typical calibration standard along with a chip carrier is provided in figure 6.

The model topography is illustrated in figure 7. The two-port networks to the left and right of the device represent hardware and fixture effects as well as the carrier coupled lines and bias filters. Recall that the primary reference plane is adjacent to the chip and excludes much of the carrier topology.



(a) *Through* standard.
(b) *Reflection* standard.
(c) *Delay* standard.
(d) Carrier and MMIC.

Figure 6.—Cosine-tapered ridge guide fixture calibration standards and chip carrier.



$$\underset{\text{DEVICE}}{\begin{bmatrix} t_{D11} & t_{D12} \\ t_{D21} & t_{D22} \end{bmatrix}} = \underset{\text{L}}{\begin{bmatrix} t_{L11} & t_{L12} \\ t_{L21} & t_{L22} \end{bmatrix}^{-1}} \underset{\text{MEASURED}}{\begin{bmatrix} t_{M11} & t_{M12} \\ t_{M21} & t_{M22} \end{bmatrix}} \underset{\text{R}}{\begin{bmatrix} t_{R11} & t_{R12} \\ t_{R21} & t_{R22} \end{bmatrix}^{-1}}$$

Figure 7.—Eight-term cascaded two-port error model for *through-reflect-delay* (TRD) technqiue and equivalent chain matrix derivation of device parameters.

Three measurements must be made to acquire the needed calibration data and resolve the individual error terms of the model. The first entails measuring a microstrip *through* calibration standard for which the input and output reference planes are coincident. The second requires measuring a *delay* microstrip line which is inserted between the reference planes. A prior knowledge of the length and propagation constant of the line is not required to establish the ancillary reference plane; however, the length is constrained to a limited range because of mathematical considerations which are described in appendix B. For the K_a band on the 0.020-in. alumina, a 0.028-in.-long *delay* was chosen. This corresponds to a theoretical phase shift of $\sim 60^\circ$ to 95° across the band. The line, which uses a slight bow in the microstrip for the added length, is assumed to behave as a linear delay—that is, there are no discontinuity or coupling effects from the curvature. The final calibration standard is a highly reflective termination which is required to resolve a phase ambiguity in the equations and results in a solution to error terms S_{22L} and S_{11R}. Initially, a microstrip short circuit was used to provide this standard. Note that all three standards incorporate the dc blocks and bias filters so that their effects are accounted for in the de-embedding routine.

To place the primary reference planes at the chip boundaries, error coefficients are shifted through an electrical translation. Initially, the reference plane is set at the center of the carrier. Subsequent to the initial physical calibration, this ancillary reference plane is mathematically shifted to the device boundaries through the translation $e^{-\gamma \ell}$. Consequently, the exact length ℓ of the device must be known. The complex propagation constant γ, however, is determined from the *through* and *delay* measurements. This manipulation permits the use of only one set of standards, regardless of device periphery.

Since the topography of the model consists of three cascaded two-port networks, the measured S-parameters of the error networks and inserted device can be converted to T-parameters for convenience. The T-matrix of the model is equal to the product of the individual T-matrices; therefore, the matrix of the de-embedded device can be extracted and reconverted to S-parameters (fig. 7). The mathematical derivation, which assumes that the microstrip characteristic impedance is 50 Ω (independent of frequency), treats the left and right halves of the fixture independently—that is, no assumption is made regarding symmetry and reciprocity (ref. 10). Furthermore, the model neglects fringing capacitance from the microstrip line to ground at the input and output of the chip as well as any coupling admittance. Including these parasitic reactances would require additional standards, and this was contrary to the design philosophy of maximizing repeatability and accuracy by minimizing mechanical and electrical complexity. From the TRD measurements and the stated assumptions, all 16 terms (magnitude and phase) of the error networks can be determined.

Software was created to carry out the enhanced TRD calibration algorithm on a Hewlett-Packard 9836 desktop computer. The computer program, written in BASIC, performs all the instrument control functions, the data acquistion and transfer routines, and the TRD matrix calculations. This de-embedding code is shown in Appendix C.

The TRD program begins with the transfer of raw, uncorrected S-parameter data from the ANA. The data arrive in 10 sets: 4 sets describe the *through* standard (S_{11}, S_{12}, S_{21}, S_{22}); 4 sets describe the *delay* standard (S_{11}, S_{12}, S_{21}, S_{22}); and 2 sets decribe the *reflection* standard (S_{11}, S_{22}). Each data set includes a complete 201-point frequency sweep and presents data in real/imaginary pairs. The data can be transferred directly from the active ANA trace memory or from storage locations on an internal tape drive. The transferred data are then held in computer memory and withdrawn by the TRD calculation subroutine as needed.

The second section of the TRD code performs the actual error-coefficient calculations. During this subroutine, each of the necessary calculations is performed at each step in the frequency range. The entire calculation procedure takes approximately 2 minutes. Once completed, the error-terms are stored in memory arrays. Each error term is made up of a real and an imaginary component, thereby correcting for both magnitude and phase aberrations of the test system. This set of eight error terms establishes the reference plane at the bisector of the *through* line.

To mathematically shift the reference plane to the edges of the device under test, the computer program must know the exact device length. The value is entered from the keyboard in mils (thousanths of an inch). This section of the program is isolated from the rest of the calculations so that different lengths can be entered without having to recalculate the eight basic error terms. This approach saves time and allows convenient testing of various sized chips. The original set of unshifted terms is retained for later use if needed. The shifted error terms are placed in complex data arrays in a format compatible with the ANA protocol.

After the TRD error model has been generated, there are two possible methods to extract the device data from the full measurement. One choice is to extract the device data by using the set of eight error terms with the HP 9836 computer, and then to return the S-parameter data to the ANA for display. Since this is the most straightforward and accurate approach, it was adopted for this application. Unfortunately, the quasi-real-time display of the data is compromised. An alternative approach would be to translate the 8 TRD error terms to the HP 12-term error model. In this way, the ANA would resume control of the test system and the data trace would be updated virtually in real time. This approach is appealing because it would allow the engineer to actively tune or control the device under test while viewing the results. However, the adaptation to the 12-term model requires additional assumptions which may not be justified. The following error-term translations between the two models are (as given in ref. 11):

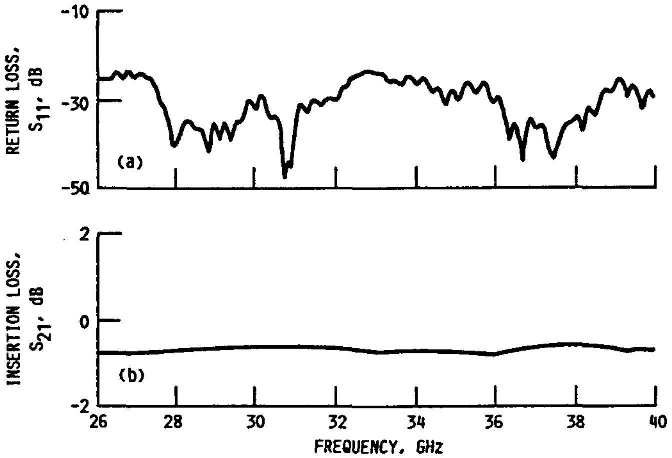
$$\begin{aligned} E_{DF} &= S_{11L} & E_{DR} &= S_{22R} \\ E_{SF} &= S_{22L} & E_{SR} &= S_{11R} \\ E_{RF} &= S_{21L}S_{12L} & E_{RR} &= S_{21R}S_{12R} \\ E_{XF} &= 0 & E_{XR} &= 0 \\ E_{LF} &= S_{11R} & E_{LR} &= S_{22L} \\ E_{TF} &= S_{21R}S_{21L} & E_{TR} &= S_{12R}S_{12L} \end{aligned}$$

Test Fixture Radiofrequency Performance

The RF characteristics of the ridge waveguide test fixture were measured with a Hewlett-Packard 8510 ANA. To extend the operating range of the analyzer to include the K_a band, it was configured with a 26.5- to 40-GHz waveguide test set and the appropriate components to coherently up and down convert the test signals. This arrangement allowed error-corrected, two-port, S-parameter measurements to be made across the full 26.5- to 40.0-GHz frequency range while still maintaining the resolution and functionality of the standard HP 8510 ANA. Because the test set operates in WR-28 waveguide media, direct connection of the ridge waveguide test fixture to the measurement system is possible without transitions of any type.

The RF measurements were made on the ANA by using two different techniques. For evaluation of the test fixture, the ANA was calibrated with precision waveguide standards at the test set waveguide flange. This technique placed the calibration reference planes at the input and output of the fixture so that the RF characteristics of the complete assembly could be measured. The waveguide standards included a flush *short*, a quarter-wavelength *offset short*, and a sliding termination.

Figure 8 displays the results of measurements made when the two cosine-tapered ridge sections were connected back-to-back on a special baseplate (no carrier or transmission line).

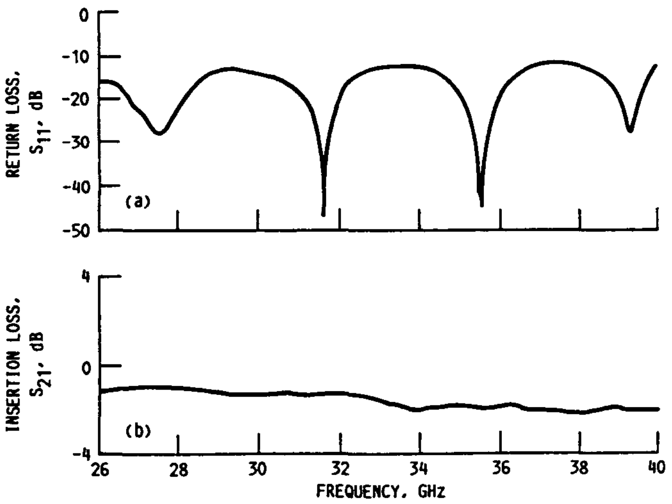


(a) S_{11} return loss.
(b) S_{21} insertion loss.

Figure 8.—Characteristics for two back-to-back cosine-tapered ridge guide transitions.

The results show approximately 0.7 ± 0.1 dB of insertion loss (S_{21}) with a corresponding return loss (S_{11}) of greater than 25 dB across the full waveguide band. These measurements verify the predicted performance of low loss and large operating bandwidth.

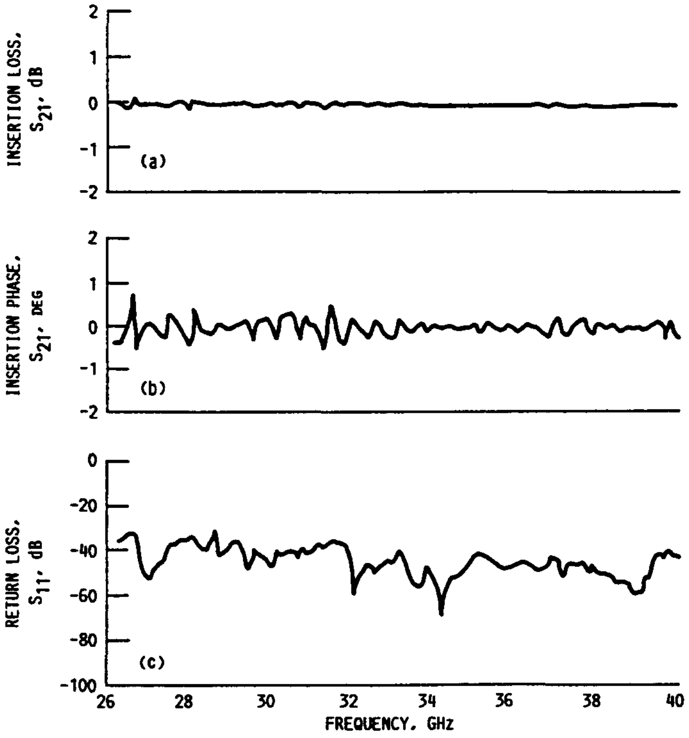
The next test was also performed with the reference planes placed at the flanges of the test fixture. A section of matched transmission line placed between the two ridge sections was used to test the quality of the compression connection to the microstrip. Figure 9 displays the results of this measurement; the transmission line and interconnect added from 0.25 to 1.25 dB to the loss total. Since the microstrip line itself imparts several tenths of a dB loss, each connection is apparently responsible for a maximum of about 0.5 dB. The TRD algorithm can compensate for these effects.



(a) S_{11} return loss.
(b) S_{21} insertion loss.

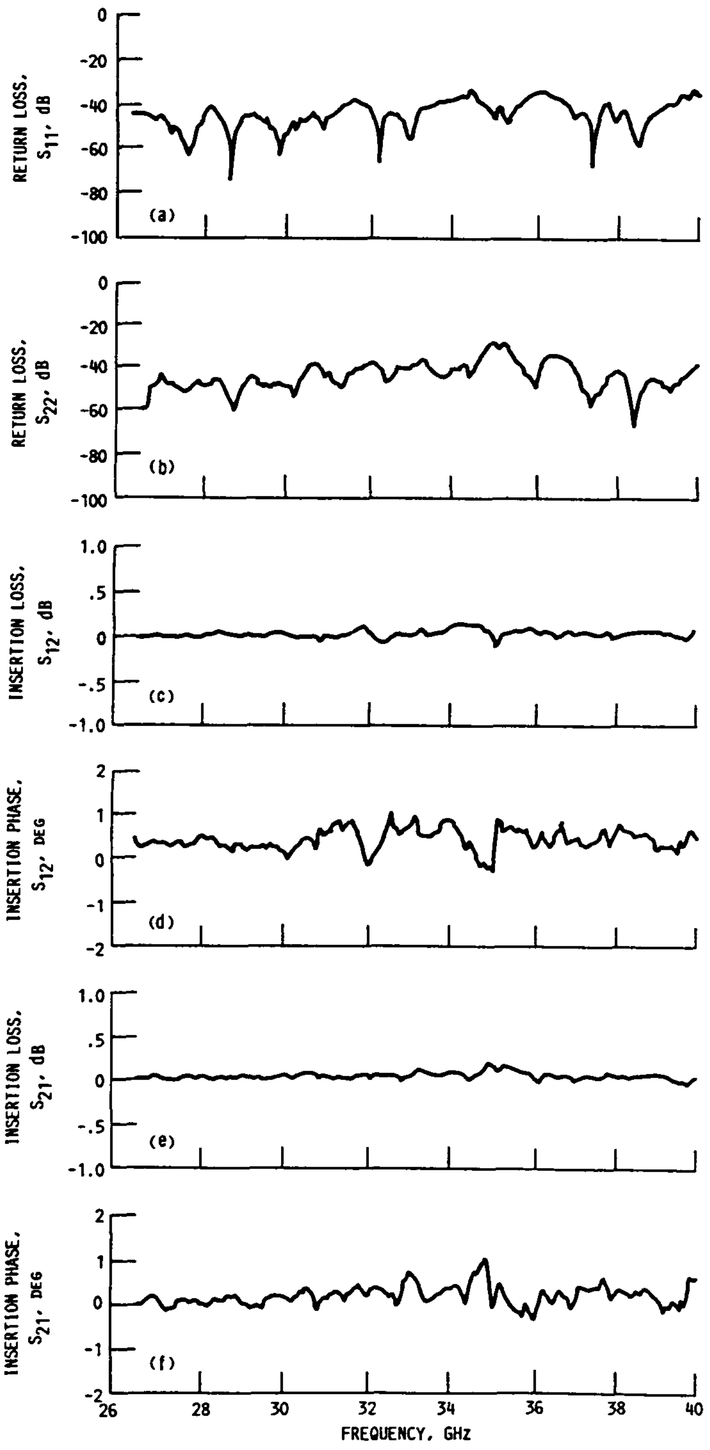
Figure 9.—Characteristics of uncalibrated fixture with 0.5-in. section of microstrip line inserted between transitions.

To test the accuracy of the TRD algorithm and associated hardware, the fixture was calibrated by using the *through*, *short*, and *delay* microstrip standards, and the error correction was verified by reinserting the *through* standard. This is equivalent to connecting the system without a test device. Ideally, this would result in 0-dB insertion loss, 0° phase shift, and infinite return loss. The actual test results are presented in figure 10. The insertion loss was measured at approximately 0.1 dB and the phase shift was 0.5°. The return loss was measured at nearly 40 dB across the frequency range, thereby indicating a high quality calibration. During initial testing, S_{22} performance was marginal. Upon further investiation the electrical quality of the short circuit was found to be questionable. Therefore, an open circuit was substituted, and the fixture was recalibrated. These results are shown in figure 11. Insertion loss was better than 0.1 dB with a corresponding phase accuracy of 1.0°. Return loss at both ports exceeded 40 dB across most of the band. The accuracy of these measurements approaches that of lower frequency calibrations and exceeds the accuracy and capabilities of similar systems currently available.



(a) S_{21} insertion loss.
(b) S_{21} insertion phase.
(c) S_{11} return loss.

Figure 10.—*Through-short-delay* (TSD) calibration results.



(a) S_{11} return loss.
(b) S_{22} return loss.
(c) S_{12} insertion loss.
(d) S_{12} insertion phase.
(e) S_{21} insertion loss.
(f) S_{21} insertion phase.

Figure 11.—*Through-open-delay* (TOD) calibration results.

Conclusions

An innovative fixture was proposed to overcome many of the limitations of conventional techniques for characterizing solid-state devices. Combining a cosine-tapered ridge guide transition, a versatile chip carrier, and an enhanced *through-reflect-delay* calibration algorithm resulted in a mechanically simple, yet functionally sophisticated, fixture. This development provided a unique, previously unavailable ability to perform accurate, nondestructive, and repeatable characterizations of a variety of millimeter-wave devices. Furthermore, the demonstrated RF performance of the fixture and calibration scheme across the K_a band indicated its potential to operate at much higher frequencies.

A primary motive for designing this fixture was the need for a universal solid-state-device charcterization method. This method was achieved through the interrelationship of a flexible carrier and a customized software package. The technique enables the fixture to accommodate numerous types of devices without compromising accuracy or convenience. An additional feature of the method is the ability to utilize the device carrier as both the test vehicle and the package; that is after a successful operational test, the carrier is incorporated into a generic package that can then be directly inserted into a system.

NASA Lewis Research Center is pursuing the development of advanced solid-state components, including state-of-the-art discrete devices and monolithic microwave integrated circuits, operating at frequencies up to and beyond 50 GHz. Our fixture is being used to evaluate devices developed under this research effort and to characterize and select those devices suitable for potential use in NASA missions.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 23, 1989

Appendix A
Symbols

a	*h*-plane width of the waveguide
a'	width of the ridge
b	$\vec{E}$-plane waveguide dimension
c	junction capacitance
E_{DF}	directivity error term in forward direction
E_{DR}	directivity error term in reverse direction
E_{LF}	load match error term in forward direction
E_{LR}	load match error term in reverse direction
E_{RF}	reflection tracking error term in forward direction
E_{RR}	reflection tracking error term in reverse direction
E_{SF}	source match error term in forward direction
E_{SR}	source match error term in reverse direction
E_{TF}	transmission tracking error term in forward direction
E_{TR}	transmission tracking error term in reverse direction
E_{XF}	isolation error term in forward direction
E_{XR}	isolation error term in reverse direction
f_c	cutoff frequency
ℓ	length of taper
M_{ij}	elements of matrix that is product of $T_{m,d}$ and inverse of $T_{m,t}$
N_{ij}	elements of matrix that is product of inverse of $T_{m,t}$ and $T_{m,d}$
S_{ijR}, S_{ijL}	equivalent scattering parameter elements of resolved error networks.
S_{msij}	measured scattering parameter element of *short*
S_{mtij}	measured scattering parameter element of *through*
T_d	chain matrix of isolated *delay* standard
T_L	chain matrix of error network to left of device
T_{Lij}	elements of T_L
$T_{m,d}$	chain matrix representing measured *delay* standard
$T_{m,t}$	chain matrix representing measured *through* standard
T_R	chain matrix of error network to right of device
T_{Rij}	elements of T_R
T_t	chain matrix of isolated *through* standard
t	distance between ridge and base at substrate
t_{Lij}	entries in left error chain matrix
t_{Rij}	entries in right error chain matrix
x	position along taper from origin
Z_L	characteristic impedance of ridge waveguide at $x = L$
Z_o	characteristic impedance of microstrip line
$Z_{o,\infty}$	infinite frequency characteristic impedance
Z_0	characteristic impedance of open waveguide at $x = 0$
Z_1	characteristic impedance of parallel plate line of height t
Z_2	characteristic impedance of parallel plate line of height b
Z_2/Z_1	impedance ratio of equivalent parallel plate lines
$Z_2\omega c$	normalized junction reactance
γ	complex propagation constant
λ_c	ridge waveguide cutoff wavelength
λ_g	guide wavelength
λ_o	free space wavelength
φ_1	electrical length corresponding to $a'/2$
φ_2	electrical length corresponding to $(a - a')/2$
ω	radian frequency

Appendix B
Through-Reflect-Delay (TRD) Mathematics

The basis for the derivation of the TRD algorithm is available in the cited references. An abbreviated summary of the mathematical technique is included herein to acquaint the reader with the procedure. A copy of the de-embedding routine, written in HP BASIC, is included for convenience. The TRD augmentation procedure, which relocates the reference plane to the device terminals, is also explained.

The measured scattering matrices are converted to chain (or transfer) matrices for mathematical convenience. By definition, the chain matrix for the *through* standard is

$$[T_t] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{B1}$$

and the *delay* standard chain matrix, which assumes a frequency-independent 50-Ω match, is

$$[T_d] = \begin{bmatrix} e^{-\gamma\ell} & 0 \\ 0 & e^{\gamma\ell} \end{bmatrix} \tag{B2}$$

The error networks to the left and right of the device are designated $[T_L]$ and $[T_R]$, respectively. The equivalent chain matrix representation of the measured S-parameters of the *through* can be defined by

$$[T_{m,t}] = [T_L][T_t][T_R] = [T_L]\ [T_R] \tag{B3}$$

Similarly, the chain matrix representation from the *delay* measurement is

$$[T_{m,d}] = [T_L][T_d][T_R] \tag{B4}$$

Multiplying $[T_{m,d}]$ by $[T_{m,t}]^{-1}$ yields equations of the form

$$M_{21}\left(\frac{t_{L11}}{t_{L21}}\right)^2 + (M_{22} - M_{11})\left(\frac{t_{L11}}{t_{L21}}\right) - M_{12} = 0 \tag{B5}$$

$$M_{21}\left(\frac{t_{L12}}{t_{L22}}\right)^2 + (M_{22} - M_{11})\left(\frac{t_{L12}}{t_{L22}}\right) - M_{12} = 0 \tag{B6}$$

where the M_{ij} are entries in the resultant matrix $[M]$ and t_{Lij} and t_{Rij} are entries in the left and right error matrices. Multiplying $[T_{m,t}]^{-1}$ by $[T_{m,d}]$ yields equations of the form

$$N_{12}\left(\frac{t_{R11}}{t_{R12}}\right)^2 + (N_{22} - N_{11})\left(\frac{t_{R11}}{t_{R12}}\right) - N_{21} = 0 \tag{B7}$$

$$N_{12}\left(\frac{t_{R21}}{t_{R22}}\right)^2 + (N_{22} - N_{11})\left(\frac{t_{R21}}{t_{R22}}\right) - N_{21} = 0 \tag{B8}$$

where the N_{ij} are entries in the resultant matrix $[N]$. As mentioned in the section on fixture calibration, there are some constraints on the length of the *delay*. If the *delay* is very short, its chain matrix will approach the identity matrix and $[T_L]$ and $[T_R]$ will be indeterminate. Also, if the *delay* is a half-wavelength multiple of the *through* and the associated propagation loss is small, a similar situation results. Therefore, the length must be chosen to avoid these extremes by some margin. This constraint limits the TRD technique to octave bandwidth performance. However, the method is ideally suited to conventional waveguide operation for which the bandwidth ratio is typically 1.5. To utilize the full potential, one could design the entire measurement system in ridge guide, if a corresponding bandwidth could be realized with the chip carrier. Comparing the S-parameter equivalents of $[T_L]$ and $[T_R]$ shows that $|t_{L11}/t_{L21}| > |t_{L12}/t_{L22}|$ and that $|t_{L11}/t_{L12}| > |t_{L21}/t_{L22}|$. With this information, the four unknowns can be resolved.

Although the *reflection* calibration standard is necessary to determine S_{22L}, it results in a quadratic, which implies a 180° phase ambiguity. Since the *reflection* should represent a low return loss with roughly a 180° phase shift, the uncertainty can be eliminated. Similarly, an open circuit should result in an in-phase (0°) reflection. Also, the fixture uses the same *reflection* standard during the S_{11} and S_{22} measurement; therefore, no assumption is made regarding the equality of the measured reflection coefficients. The remaining equations result from straightforward algebraic manipulation and signal flow analysis and are listed for convenience as follows:

$$S_{22L} = \left[\left(\frac{t_{L12}/t_{L22} - S_{Ms11}}{t_{L11}/t_{L21} - S_{Ms11}}\right)\left(\frac{t_{R11}/t_{R12} + S_{Ms22}}{t_{R21}/t_{R22} + S_{Ms22}}\right)\left(\frac{t_{L12}/t_{L22} - S_{Mt11}}{t_{L11}/t_{L21} - S_{Mt11}}\right)\right]^{1/2} \tag{B9}$$

$$S_{11R} = \left(\frac{1}{S_{22L}}\right)\left(\frac{t_{L12}/t_{L22} - S_{Mt11}}{t_{L11}/t_{L21} - S_{Mt11}}\right) \tag{B10}$$

$$S_{21L}S_{12L} = \left(t_{L12}/t_{L22} - t_{L11}/t_{L21}\right)S_{22L} \tag{B11}$$

$$S_{12R}S_{21R} = \left(t_{R11}/t_{R12} - t_{R21}/t_{R22}\right)S_{11R} \tag{B12}$$

$$S_{21L}S_{21R} = S_{Mt21}\left(1 - S_{22L}S_{11R}\right) \tag{B13}$$

$$S_{12R}S_{12L} = S_{Mt12}\left(1 - S_{22L}S_{11R}\right) \tag{B14}$$

The conventional TRD algorithm and the given standards would establish the reference plane at the bisector of the carrier. To shift the error coefficients to the chip terminals, the equivalent electrical length (including loss and dispersion) representing the chip must be known. This requires knowing the length of the chip and the complex propagation constant, the latter of which is determined from the *through* and *delay* measurements. Both the products of the transmission error coefficients and the *reflection* error coefficients are shifted through the translation $e^{-\gamma \ell}$, where ℓ is the device length. The BASIC program that solves for all eight complex error coefficients and interfaces with the network analyzer is included in appendix C.

Appendix C
Program to Solve for Complex Error Coefficients

This program implements the *through-reflect-delay* de-embedding technique using the Hewlett-Packard model 8510B network analyzer and the model 9836 computer/controller. This version of the software (B3) is designed for use with the millimeter-wave test set for frequencies between 26.5 and 40.0 GHz.

Currently configured for *open* standard. See lines 6910,6920.

```
270   !
280   !
290 Initialization:  !
300   Clear$=CHR$(12)
310   OUTPUT 1;Clear$
320   Crt=1
330   Printer=701
340   PRINTER IS Crt
350   OPTION BASE 1
360   DEG
370   !
380   Thru_flag=0
390   Short_flag=0
400   Delay_flag=0
410   Out_flag=0
420   Calc_flag=0
430   Model_flag=0
440   !
450   BEEP
460   PRINT TAB(10);"******************** TSD_CAL_B3 ***********************"
470   PRINT ""
480   PRINT ""
490   PRINT TAB(10);"You have just activated the THRU-SHORT-DELAY calibration "
500   PRINT TAB(10);"program.  To operate the program, please follow the "
510   PRINT TAB(10);"instructions as they appear on this screen."
520   PRINT ""
530   PRINT ""
540   PRINT TAB(10);"NOTE:  An IEEE-488 cable must connect this computer"
550   PRINT TAB(10);"       to the HP 8510.  Install the cable on the connector"
560   PRINT TAB(10);"       labeled 'HP-IB' on the rear of the analyzer."
570   PRINT ""
580   PRINT ""
590   PRINT TAB(10);"*******************************************************"
600   !
610   DISP " Press CONTINUE to proceed"
620   PAUSE
630   DISP ""
640   !
650   OUTPUT 1;Clear$                        !  Establishes Input/Output
660   ASSIGN @To8510 TO 716                  !  data transfer paths .
670   CLEAR @To8510                          !         "
680   ASSIGN @From8510 TO 716;FORMAT OFF     !         "
690   CLEAR @From8510                        !         "
700   ASSIGN @Datatoana TO 716;FORMAT OFF    !         "
710   CLEAR @Datatoana                       !         "
720   ASSIGN @Hpib TO 7                      !         "
```

```
730   !
740   DIM Smt_r(201,5),Smt_i(201,5)          !  Dimensions array space
750   DIM Smd_r(201,5),Smd_i(201,5)          !  in computer memory.
760   DIM Sms_r(201,3),Sms_i(201,3)          !           "
770   DIM Sdut_r(201,5),Sdut_i(201,5)        ! (S-parameter measurements)
780   DIM Smeas_r(201,5),Smeas_i(201,5)
790   DIM Tmdr(2,2),Tmdi(2,2)                !  (T-parameter matrices)
800   DIM Tmtr(2,2),Tmti(2,2)                !           "
810   DIM Tmtr_inv(2,2),Tmti_inv(2,2)        !           "
820   !
830   DIM Mr(2,2),Mi(2,2)                    !  ("M" and "N" data matrices)
840   DIM Mr1(2,2),Mi1(2,2)                  !           "
850   DIM Mr2(2,2),Mi2(2,2)                  !           "
860   DIM Nr(2,2),Ni(2,2)                    !           "
870   DIM Nr1(2,2),Ni1(2,2)                  !           "
880   DIM Nr2(2,2),Ni2(2,2)                  !           "
890   !
900   DIM E00r(201),E00i(201)                !   (Calculated error
910   DIM E11r(201),E11i(201)                !         coefficients)
920   DIM E10_e01r(201),E10_e01i(201)        !           "
930   DIM E23_e32r(201),E23_e32i(201)        !           "
940   DIM E10_e32r(201),E10_e32i(201)        !           "
950   DIM E23_e01r(201),E23_e01i(201)        !           "
960   DIM E22r(201),E22i(201)                !           "
970   DIM E33r(201),E33i(201)                !           "
980   !
990   DIM Data(201,2)                        !   (Data for transfer)
1000  DIM Newdata(201,2)                     !           "
1010  !
1020  !
1030  INTEGER Preamble,Size   !  Used in 8510 data transfer
1040  Preamble=9025           !  (9025 represents #A)
1050  Size=3216               !  (3216 for 201 points,6416 for 401 points)
1060  !
1070  !
1080  !
1090  INPUT "Enter Start Frequency in GHz",Fstart   ! Enters start freq.
1100  INPUT "Enter Stop Frequency in GHz",Fstop     ! Enters stop freq.
1110  Fstep=(Fstart-Fstep)/200                      ! Freq step size
1120  Freq=Fstart
1130  !
1140  REMOTE 716
1150  OUTPUT @To8510;"CORROFF;"                  ! HP 8510 setup instructions
1160  OUTPUT @To8510;"POIN201;"                  !           "
1170 !OUTPUT @To8510;"STEP;"            <--- Activate for additional accuracy.
1180 !OUTPUT @To8510;"AVERON1000;"      <--- Activate for additional accuracy.
1190  OUTPUT @To8510;"SINC;CHAN1;"               !           "
1200  OUTPUT @To8510;"STAR";Fstart;"GHZ;"        !           "
1210  OUTPUT @To8510;"STOP";Fstop;"GHZ;"         !           "
1220  OUTPUT @To8510;"ENTO;"                     !           "
1230  LOCAL 7
1240  FOR N=1 TO 201                         !  Assigns freq to memory
1250     Smd_r(N,5)=Freq                     !  locations to ease in later
1260     Smd_i(N,5)=Freq                     !  data recall.  (Presently
1270     Smt_r(N,5)=Freq                     !  unused.)
1280     Smt_i(N,5)=Freq                     !           "
```

```
1290     Sms_r(N,3)=Freq                         !           ''
1300     Sms_i(N,3)=Freq                         !           ''
1310     Sout_r(N,5)=Freq                        !           ''
1320     Sout_i(N,5)=Freq                        !           ''
1330     Freq=Freq+Fstep                         !           ''
1340  NEXT N                                     !           ''
1350  !
1360  !
1370 Menu: !
1380  DISP " Enter desired function on softkeys below"
1390  ON KEY 0 LABEL "THRU" GOSUB Thru
1400  ON KEY 1 LABEL "SHORT" GOSUB Short
1410  ON KEY 2 LABEL "DELAY" GOSUB Delay
1420  ON KEY 3 LABEL "MEAS DUT" GOSUB Dut_meas
1430  ON KEY 4 LABEL "" GOTO Menu
1440  ON KEY 5 LABEL "CALCULATE" GOSUB Calculate
1450  ON KEY 6 LABEL "SEND MODEL" GOSUB Send
1460  ON KEY 7 LABEL "SEND DATA" GOSUB Send_actual
1470  ON KEY 8 LABEL "" GOTO Menu
1480  ON KEY 9 LABEL "EXIT" GOTO Exit
1490  GOTO Menu
1500  !
1510  !
1520  STOP
1530  !
1540  !
1550  !
1560  !
1570  !
1580  !******************* SUBROUTINES ************************
1590  !
1600 Thru: !                             Reads S-parameter data on the "THRU"
1610       !                             calibration standard from the HP 8510.
1620       !                             (Data in real, imaginary data pairs.)
1630       !
1640       DISP ""
1650       PRINTER IS Crt
1660       OUTPUT 1;Clear$
1670       BEEP
1680       PRINT TABXY(10,6);"Insert the THRU standard in the FORWARD direction"
1690       DISP "Press CONTINUE to proceed"
1700       PAUSE
1710       OUTPUT 1;Clear$
1720       DISP ""
1730       PRINT TABXY(35,6);"PLEASE WAIT"
1740       REMOTE 716
1750        OUTPUT @To8510;"CORROFF;"
1760        !
1770 S11_thru:   !                            Reads S11 "THRU" data from 8510
1780        OUTPUT @To8510;"S11;SING;"
1790        OUTPUT @To8510;"FORM3;OUTPRAW1;"
1800        ENTER @From8510;Preamble,Size,Newdata(*)
1810        FOR N=1 TO 201
1820             Smt_r(N,1)=Newdata(N,1)
1830             Smt_i(N,1)=Newdata(N,2)
1840        NEXT N
```

```
1850         OUTPUT @To8510;"CONT;"
1860          !
1870          !
1880 S21_thru:    !                        Reads S21 "THRU" data from 8510
1890         OUTPUT @To8510;"S21;SING;"
1900         OUTPUT @To8510;"FORM3;OUTPRAW1;"
1910         ENTER @From8510;Preamble,Size,Newdata(*)
1920         FOR N=1 TO 201
1930            Smt_r(N,3)=Newdata(N,1)
1940            Smt_i(N,3)=Newdata(N,2)
1950         NEXT N
1960         OUTPUT @To8510;"CONT;"
1970          !
1980          !
1990          !
2000        DISP ""
2010        PRINTER IS Crt
2020        OUTPUT 1;Clear$
2030        BEEP
2040        PRINT TABXY(10,6);"Insert the THRU standard in the REVERSE direction"
2050        DISP "Press CONTINUE to proceed"
2060        PAUSE
2070        OUTPUT 1;Clear$
2080        DISP ""
2090        PRINT TABXY(35,6);"PLEASE WAIT"
2100          !
2110          !
2120 S12_thru:    !                        Reads S12 "THRU" data from 8510
2130         OUTPUT @To8510;"S12;SING;"
2140         OUTPUT @To8510;"FORM3;OUTPRAW1;"
2150         ENTER @From8510;Preamble,Size,Newdata(*)
2160         FOR N=1 TO 201
2170            Smt_r(N,2)=Newdata(N,1)
2180            Smt_i(N,2)=Newdata(N,2)
2190         NEXT N
2200         OUTPUT @To8510;"CONT;"
2210          !
2220          !
2230 S22_thru:    !                        Reads S22 "THRU" data from 8510
2240         OUTPUT @To8510;"S22;SING;"
2250         OUTPUT @To8510;"FORM3;OUTPRAW1;"
2260         ENTER @From8510;Preamble,Size,Newdata(*)
2270         FOR N=1 TO 201
2280            Smt_r(N,4)=Newdata(N,1)
2290            Smt_i(N,4)=Newdata(N,2)
2300         NEXT N
2310         OUTPUT @To8510;"CONT;"
2320          !
2330          !
2340       PRINTER IS Crt!                 Prints "THRU" data
2350       FOR N=1 TO 201
2360          PRINT Smt_r(N,1),Smt_r(N,2),Smt_r(N,3),Smt_r(N,4)
2370       NEXT N
2380       DISP "Press CONTINUE to proceed."
2390       PAUSE
2400       OUTPUT 1;Clear$
```

```
2410      BEEP
2420      PRINT "Transfer of 'THRU' data completed"
2430      OUTPUT @To8510;"CONT;"
2440      Thru_flag=1
2450      LOCAL 7
2460      RETURN
2470      !
2480      !
2490      ! ------------------------------------------------------------
2500      !
2510 Delay:     !                        Reads S-parameter data on the "DELAY"
2520      !                              calibration standard from the HP 8510.
2530      !                              (Data in real, imaginary pairs.)
2540      !
2550      DISP ""
2560      PRINTER IS Crt
2570      OUTPUT 1;Clear$
2580      BEEP
2590      PRINT TABXY(10,6);"Insert the DELAY standard in the FORWARD direction "
2600      DISP "Press CONTINUE to proceed"
2610      PAUSE
2620      OUTPUT 1;Clear$
2630      DISP ""
2640      PRINT TABXY(35,6);"PLEASE WAIT"
2650      REMOTE 716
2660      OUTPUT @To8510;"CORROFF;"
2670      !
2680      !
2690 S11_delay:     !                           Reads S11 "DELAY" data from 8510
2700      OUTPUT @To8510;"S11;SING;FORM3;OUTPRAW1;"
2710      ENTER @From8510;Preamble,Size,Newdata(*)
2720      FOR N=1 TO 201
2730         Smd_r(N,1)=Newdata(N,1)
2740         Smd_i(N,1)=Newdata(N,2)
2750      NEXT N
2760      !
2770      !
2780 S21_delay: !                               Reads S21 "DELAY" data from 8510
2790       OUTPUT @To8510;"S21;SING;FORM3;OUTPRAW1;"
2800       ENTER @From8510;Preamble,Size,Newdata(*)
2810       FOR N=1 TO 201
2820          Smd_r(N,3)=Newdata(N,1)
2830          Smd_i(N,3)=Newdata(N,2)
2840       NEXT N
2850      !
2860      !
2870      DISP ""
2880      PRINTER IS Crt
2890      OUTPUT 1;Clear$
2900      BEEP
2910      PRINT TABXY(10,6);"Insert the DELAY standard in the REVERSE direction "
2920      DISP "Press CONTINUE to proceed"
2930      PAUSE
2940      OUTPUT 1;Clear$
2950      DISP ""
```

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```
2960      PRINT TABXY(35,6);"PLEASE WAIT"
2970      !
2980      !
2990 S12_delay:!                              Reads S12 "DELAY" data from 8510
3000      OUTPUT @To8510;"S12;SING;FORM3;OUTPRAW1;"
3010      ENTER @From8510;Preamble,Size,Newdata(*)
3020      FOR N=1 TO 201
3030         Smd_r(N,2)=Newdata(N,1)
3040         Smd_i(N,2)=Newdata(N,2)
3050      NEXT N
3060       !
3070       !
3080 S22_delay:  !                            Reads S22 "DELAY" data from 8510
3090       OUTPUT @To8510;"S22;SING;FORM3;OUTPRAW1;"
3100       ENTER @From8510;Preamble,Size,Newdata(*)
3110       FOR N=1 TO 201
3120          Smd_r(N,4)=Newdata(N,1)
3130          Smd_i(N,4)=Newdata(N,2)
3140       NEXT N
3150       !
3160       !
3170       PRINTER IS Crt!                    Prints "DELAY" data
3180      FOR N=1 TO 201
3190          PRINT Smd_r(N,1),Smd_r(N,2),Smd_r(N,3),Smd_r(N,4)
3200      NEXT N
3210      DISP "Press CONTINUE to proceed."
3220      PAUSE
3230       OUTPUT 1;Clear$
3240       BEEP
3250       PRINT "Transfer of 'DELAY' data completed"
3260       OUTPUT @To8510;"CONT;"
3270       Delay_flag=1
3280       LOCAL 7
3290       RETURN
3300        !
3310        !
3320        !--------------------------------------------------------------
3330        !
3340 Short:    !                      Reads S-parameter data on the "SHORT"
3350      !                           calibration standard from the HP 8510.
3360      !                           (Data in real, imaginary pairs.)
3370      !
3380      DISP ""
3390      PRINTER IS Crt
3400      OUTPUT 1;Clear$
3410      BEEP
3420      PRINT TABXY(20,6);"Insert the SHORT at port 1 in FORWARD direction"
3430      DISP "Press CONTINUE to proceed"
3440      PAUSE
3450      OUTPUT 1;Clear$
3460      DISP ""
3470      PRINT TABXY(35,6);"PLEASE WAIT"
3480      REMOTE 716
3490      OUTPUT @To8510;"CORROFF;"
3500      !
3510 S11_short:     !                         Reads S11 "SHORT" data from 8510
```

```
3520     OUTPUT @To8510;"S11;SING;FORM3;OUTPRAW1;"
3530     ENTER @From8510;Preamble,Size,Newdata(*)
3540     FOR N=1 TO 201
3550        Sms_r(N,1)=Newdata(N,1)
3560        Sms_i(N,1)=Newdata(N,2)
3570     NEXT N
3580     !
3590      PRINTER IS Crt
3600      OUTPUT 1;Clear$
3610      BEEP
3620      PRINT TABXY(20,6);"Insert the SHORT at Port 2 in REVERSE direction"
3630      DISP "Press CONTINUE to proceed"
3640      PAUSE
3650      OUTPUT 1;Clear$
3660      DISP
3670      PRINT TABXY(35,6);"PLEASE WAIT"
3680     !
3690 S22_short: !                          Reads S22 "SHORT" data from 8510
3700      OUTPUT @To8510;"S22;SING;FORM3;OUTPRAW1;"
3710      ENTER @From8510;Preamble,Size,Newdata(*)
3720      FOR N=1 TO 201
3730         Sms_r(N,2)=Newdata(N,1)
3740         Sms_i(N,2)=Newdata(N,2)
3750      NEXT N
3760      !
3770      !
3780     PRINTER IS Crt!                    Prints "SHORT" data
3790     FOR N=1 TO 201
3800         PRINT Sms_r(N,1),Sms_r(N,2)
3810     NEXT N
3820     DISP "Press CONTINUE to proceed."
3830     PAUSE
3840      OUTPUT 1;Clear$
3850      BEEP
3860      PRINT "Transfer of 'SHORT' data completed"
3870      OUTPUT @To8510;"CONT;"
3880      Short_flag=1
3890      LOCAL 7
3900      RETURN
3910      !
3920      !
3930      !
3940 Dut_meas:  !                    Reads S-parameter data on the "DUT"
3950       !                         from the HP 8510.
3960       !                         (Data in real, imaginary data pairs.)
3970       !
3980       DISP ""
3990       PRINTER IS Crt
4000       OUTPUT 1;Clear$
4010       BEEP
4020       PRINT TABXY(10,6);"Insert Device Under Test in FORWARD direction "
4030       DISP "Press CONTINUE to proceed"
4040       PAUSE
4050       OUTPUT 1;Clear$
4060       DISP ""
4070       PRINT TABXY(35,6);"PLEASE WAIT"
```

```
4080        REMOTE 716
4090         OUTPUT @To8510;"CORROFF;"
4100         !
4110         !
4120 S11_meas:   !                           Reads S11 "DUT" data from 8510
4130         OUTPUT @To8510;"S11;SING;"
4140         OUTPUT @To8510;"FORM3;OUTPRAW1;"
4150         ENTER @From8510;Preamble,Size,Newdata(*)
4160         FOR N=1 TO 201
4170              Smeas_r(N,1)=Newdata(N,1)
4180              Smeas_i(N,1)=Newdata(N,2)
4190         NEXT N
4200         OUTPUT @To8510;"CONT;"
4210         !
4220         !
4230 S21_meas:   !                           Reads S21 "DUT" data from 8510
4240         OUTPUT @To8510;"S21;SING;"
4250         OUTPUT @To8510;"FORM3;OUTPRAW1;"
4260         ENTER @From8510;Preamble,Size,Newdata(*)
4270         FOR N=1 TO 201
4280            Smeas_r(N,3)=Newdata(N,1)
4290            Smeas_i(N,3)=Newdata(N,2)
4300         NEXT N
4310         OUTPUT @To8510;"CONT;"
4320         !
4330         !
4340        DISP ""
4350        PRINTER IS Crt
4360        OUTPUT 1;Clear$
4370        BEEP
4380        PRINT TABXY(10,6);"Insert Device Under Test in REVERSE direction "
4390        DISP "Press CONTINUE to proceed"
4400        PAUSE
4410        OUTPUT 1;Clear$
4420        DISP ""
4430        PRINT TABXY(35,6);"PLEASE WAIT"
4440         !
4450         !
4460 S12_meas:   !                           Reads S12 "DUT" data from 8510
4470         OUTPUT @To8510;"S12;SING;"
4480         OUTPUT @To8510;"FORM3;OUTPRAW1;"
4490         ENTER @From8510;Preamble,Size,Newdata(*)
4500         FOR N=1 TO 201
4510            Smeas_r(N,2)=Newdata(N,1)
4520            Smeas_i(N,2)=Newdata(N,2)
4530         NEXT N
4540         OUTPUT @To8510;"CONT;"
4550         !
4560         !
4570 S22_meas:   !                           Reads S22 "DUT" data from 8510
4580         OUTPUT @To8510;"S22;SING;"
4590         OUTPUT @To8510;"FORM3;OUTPRAW1;"
4600         ENTER @From8510;Preamble,Size,Newdata(*)
4610         FOR N=1 TO 201
4620            Smeas_r(N,4)=Newdata(N,1)
```

```
4630          Smeas_i(N,4)=Newdata(N,2)
4640        NEXT N
4650        OUTPUT @To8510;"CONT;"
4660        !
4670        !
4680      PRINTER IS Crt!                     Prints "DUT" data
4690      FOR N=1 TO 201
4700         PRINT Smeas_r(N,1),Smeas_r(N,2),Smeas_r(N,3),Smeas_r(N,4)
4710      NEXT N
4720      DISP "Press CONTINUE to proceed."
4730      PAUSE
4740      OUTPUT 1;Clear$
4750      BEEP
4760      PRINT "Transfer of 'DUT' data completed"
4770      OUTPUT @To8510;"CONT;"
4780      Dut_flag=1
4790      LOCAL 7
4800      RETURN
4810      !
4820       !
4830       !----------------------------------------------------------
4840       !
4850 Calculate:       !                Performs all TSD mathematics, including
4860                  !                matrix manipulations and calculation
4870                  !                of error coefficients.
4880         DISP ""
4890         OUTPUT 1;Clear$
4900         !                                   Ensures acquisition of all
4910         !                                   calibration standard data.
4920         IF (Thru_flag=0) THEN No_thru !                "
4930         IF (Delay_flag=0) THEN No_delay !              "
4940         IF (Short_flag=0) THEN No_short !              "
4950         IF (Dut_flag=0) THEN No_dut !                  "
4960         GOTO Stds_done !                               "
4970 No_thru:    !                                          "
4980         PRINT "You forgot to measure THRU standard"!   "
4990         BEEP 150,.35 !                                 "
5000         RETURN  !                                      "
5010 No_delay:   !                                          "
5020         PRINT "You forgot to measure DELAY standard" ! "
5030         BEEP 150,.35 !                                 "
5040         RETURN  !                                      "
5050 No_short:   !                                          "
5060         PRINT "You forgot to measure SHORT standard" ! "
5070         BEEP 150,.35 !                                 "
5080         RETURN !                                       "
5090 No_dut:!                                               "
5100         PRINT "You forgot to measure the DUT"!         "
5110         BEEP 150,.35 !                                 "
5120         RETURN !                                       "
5130 Stds_done:  !
5140       !
5150       !
5160       !                Ldelay is the physical length (in mils)
5170       !                of the delay line calibration standard
```

```
5180         !
5190         DISP ""
5200         Ldelay=27.85    !        <------ change this as required
5210         !
5220 Enter_delay: !
5230         !                  L_dut is the length (in mils) of the DUT
5240         !
5250         INPUT "Enter length of device under test in mils",L_dut
5260         IF (L_dut<0) THEN Enter_delay
5270         !
5280         !
5290          FOR F=1 TO 201                          !      -v-
5300          DISP "CALCULATING ERROR COEFFICIENT";F  !       ''
5310          S1=Smd_r(F,1)                           !       ''
5320          S2=Smd_i(F,1)                           !       ''
5330          S3=Smd_r(F,2)                       !  Puts acquired S-parameter
5340          S4=Smd_i(F,2)                       !  data into real and imaginary
5350          S5=Smd_r(F,3)                       !  matrix pairs
5360          S6=Smd_i(F,3)                           !       ''
5370          S7=Smd_r(F,4)                           !       ''
5380          S8=Smd_i(F,4)                           !       ''
5390          S9=Smt_r(F,1)                           !       ''
5400          S10=Smt_i(F,1)                          !       ''
5410          S11=Smt_r(F,2)                          !       ''
5420          S12=Smt_i(F,2)                          !       ''
5430          S13=Smt_r(F,3)                          !       ''
5440          S14=Smt_i(F,3)                          !       ''
5450          S15=Smt_r(F,4)                          !       ''
5460          S16=Smt_i(F,4)                          !       ''
5470          CALL Tconv(S1,S2,S3,S4,S5,S6,S7,S8,Tmdr(1,1),Tmdi(1,1),Tmdr(1,2),Tm
di(1,2),Tmdr(2,1),Tmdi(2,1),Tmdr(2,2),Tmdi(2,2))
5480          CALL Tconv(S9,S10,S11,S12,S13,S14,S15,S16,Tmtr(1,1),Tmti(1,1),Tmtr(
1,2),Tmti(1,2),Tmtr(2,1),Tmti(2,1),Tmtr(2,2),Tmti(2,2))
5490          Ele11_r=Tmtr(1,1)                       !      -v-
5500          Ele11_i=Tmti(1,1)                       !       ''
5510          Ele12_r=Tmtr(1,2)                  !  Generates "THRU" T-matrix
5520          Ele12_i=Tmti(1,2)                       !       ''
5530          Ele21_r=Tmtr(2,1)                       !       ''
5540          Ele21_i=Tmti(2,1)                       !       ''
5550          Ele22_r=Tmtr(2,2)                       !       ''
5560          Ele22_i=Tmti(2,2)                       !       ''
5570          CALL Cmult(Ele11_r,Ele11_i,Ele22_r,Ele22_i,X3,Y3)
5580          Det1r=X3
5590          Det1i=Y3
5600          CALL Cmult(Ele21_r,Ele21_i,Ele12_r,Ele12_i,X3,Y3)
5610          Det2r=X3
5620          Det2i=Y3
5630          Detr=Det1r-Det2r
5640          Deti=Det1i-Det2i
5650          Ele12_r=-Ele12_r               !  Used in calculating inverse
5660          Ele12_i=-Ele12_i               !  T-matrix of THRU standard
5670          Ele21_r=-Ele21_r                          !    ''
5680          Ele21_i=-Ele21_i                          !    ''
5690          Tempr=Ele11_r                             !    ''
5700          Tempi=Ele11_i                             !    ''
```

```
5710        Ele11_r=Ele22_r                                  !    "
5720        Ele11_i=Ele22_i                                  !    "
5730        Ele22_r=Tempr                                    !    "
5740        Ele22_i=Tempi                                    !    "
5750        CALL Cdiv(Ele11_r,Ele11_i,Detr,Deti,X3,Y3)       !    "
5760        Tmtr_inv(1,1)=X3                                 !    "
5770        Tmti_inv(1,1)=Y3                                 !    "
5780        CALL Cdiv(Ele12_r,Ele12_i,Detr,Deti,X3,Y3)       !    "
5790        Tmtr_inv(1,2)=X3                                 !    "
5800        Tmti_inv(1,2)=Y3                                 !    "
5810        CALL Cdiv(Ele21_r,Ele21_i,Detr,Deti,X3,Y3)       !    "
5820        Tmtr_inv(2,1)=X3                                 !    "
5830        Tmti_inv(2,1)=Y3                                 !    "
5840        CALL Cdiv(Ele22_r,Ele22_i,Detr,Deti,X3,Y3)       !    "
5850        Tmtr_inv(2,2)=X3                                 !    "
5860        Tmti_inv(2,2)=Y3                                 !    "
5870        MAT Mr1= Tmdr*Tmtr_inv
5880        MAT Mi1= Tmdr*Tmti_inv
5890        MAT Mi2= Tmdi*Tmtr_inv
5900        MAT Mr2= Tmdi*Tmti_inv
5910        Mr(1,1)=Mr1(1,1)-Mr2(1,1) !          "M" coefficients
5920        Mi(1,1)=Mi1(1,1)+Mi2(1,1) !           "
5930        Mr(1,2)=Mr1(1,2)-Mr2(1,2) !           "
5940        Mi(1,2)=Mi1(1,2)+Mi2(1,2) !           "
5950        Mr(2,1)=Mr1(2,1)-Mr2(2,1) !           "
5960        Mi(2,1)=Mi1(2,1)+Mi2(2,1) !           "
5970        Mr(2,2)=Mr1(2,2)-Mr2(2,2) !           "
5980        Mi(2,2)=Mi1(2,2)+Mi2(2,2) !           "
5990        MAT Nr1= Tmtr_inv*Tmdr
6000        MAT Ni1= Tmtr_inv*Tmdi
6010        MAT Ni2= Tmti_inv*Tmdr
6020        MAT Nr2= Tmti_inv*Tmdi
6030        Nr(1,1)=Nr1(1,1)-Nr2(1,1) !          "N" coefficients
6040        Ni(1,1)=Ni1(1,1)+Ni2(1,1) !           "
6050        Nr(1,2)=Nr1(1,2)-Nr2(1,2) !           "
6060        Ni(1,2)=Ni1(1,2)+Ni2(1,2) !           "
6070        Nr(2,1)=Nr1(2,1)-Nr2(2,1) !           "
6080        Ni(2,1)=Ni1(2,1)+Ni2(2,1) !           "
6090        Nr(2,2)=Nr1(2,2)-Nr2(2,2) !           "
6100        Ni(2,2)=Ni1(2,2)+Ni2(2,2) !           "
6110        Br=Mr(2,2)-Mr(1,1)
6120        Bi=Mi(2,2)-Mi(1,1)
6130        CALL Quad(Mr(2,1),Mi(2,1),Br,Bi,-Mr(1,2),-Mi(1,2),Rrp,Rip,Rrm,Rim)
6140        CALL Rtop(Rrp,Rip,Mag,Phase)
6150        Rmp=Mag             !   'plus' root of quadratic
6160        Rpp=Phase           !          "
6170        CALL Rtop(Rrm,Rim,Mag,Phase)
6180        Rmm=Mag             !   'minus' root of quadratic
6190        Rpm=Phase           !          "
6200        IF (Rmp>Rmm) THEN
6210         Ar_m=Rrp !TL11/TL21 REAL
6220         Ai_m=Rip !TL11/TL21 IMAG
6230         Br_m=Rrm !TL12/TL22 REAL
6240         Bi_m=Rim !TL12/TL22 IMAG
6250        ELSE    !                      Selects larger magnitude root
6260         Ar_m=Rrm !                    for a, smaller for b
```

```
6270      Ai_m=Rim
6280      Br_m=Rrp
6290      Bi_m=Rip
6300     END IF
6310     Br=Nr(2,2)-Nr(1,1)
6320     Bi=Ni(2,2)-Ni(1,1)
6330     CALL Guad(Nr(1,2),Ni(1,2),Br,Bi,-Nr(2,1),-Ni(2,1),Rrp,Rip,Rrm,Rim)
6340     CALL Rtop(Rrp,Rip,Mag,Phase)
6350     Rmp=Mag
6360     Rpp=Phase
6370     CALL Rtop(Rrm,Rim,Mag,Phase)
6380     Rmm=Mag
6390     Rpm=Phase
6400     IF (Rmp>Rmm) THEN
6410      Cr_n=Rrp ! TR11/TR12 REAL
6420      Ci_n=Rip ! TR11/TR12 IMAG
6430      Dr_n=Rrm ! TR21/TR22 REAL
6440      Di_n=Rim ! TR21/TR22 IMAG
6450     ELSE    !                     Selects larger magnitude root
6460      Cr_n=Rrm !                   for c, smaller for d.
6470      Ci_n=Rim
6480      Dr_n=Rrp
6490      Di_n=Rip
6500     END IF
6510     Tnr=Br_m-Sms_r(F,1)                 ! Used in calculation of e11
6520     Tni=Bi_m-Sms_i(F,1)                 !            "
6530     Tdr=Ar_m-Sms_r(F,1)                 !            "
6540     Tdi=Ai_m-Sms_i(F,1)                 !            "
6550     CALL Cdiv(Tnr,Tni,Tdr,Tdi,X3,Y3)    !            "
6560     Tr=X3                               !            "
6570     Ti=Y3                               !            "
6580     Unr=Cr_n+Sms_r(F,2)                 !            "
6590     Uni=Ci_n+Sms_i(F,2)                 !            "
6600     Udr=Dr_n+Sms_r(F,2)                 !            "
6610     Udi=Di_n+Sms_i(F,2)                 !            "
6620     CALL Cdiv(Unr,Uni,Udr,Udi,X3,Y3)    !            "
6630     Ur=X3                               !            "
6640     Ui=Y3                               !            "
6650     Vnr=Br_m-Smt_r(F,1)                 !            "
6660     Vni=Bi_m-Smt_i(F,1)                 !            "
6670     Vdr=Ar_m-Smt_r(F,1)                 !            "
6680     Vdi=Ai_m-Smt_i(F,1)                 !            "
6690     CALL Cdiv(Vnr,Vni,Vdr,Vdi,X3,Y3)    !            "
6700     Vr=X3                               !            "
6710     Vi=Y3                               !            "
6720     CALL Cmult(Tr,Ti,Ur,Ui,X3,Y3)       !            "
6730     Wr=X3                               !            "
6740     Wi=Y3                               !            "
6750     CALL Cmult(Wr,Wi,Vr,Vi,X3,Y3)       !            "
6760     Zr=X3                               !            "
6770     Zi=Y3                               !            "
6780     CALL Rtop(Zr,Zi,Mag,Phase)          !            "
6790     Zm=Mag                              !            "
6800     Zp=Phase                            !            "
6810     S22a_m=SQR(Zm)
6820     S22a_p=Zp/2
```

```
6830        CALL Ptor(S22a_m,S22a_p,X,Y)
6840        S22a_r=X
6850        S22a_i=Y
6860        CALL Cdiv(Tr,Ti,S22a_r,S22a_i,X3,Y3)
6870        Gam_r=X3
6880        Gam_i=Y3
6890        CALL Rtop(Gam_r,Gam_i,Mag,Phase)
6900        !                            Selects proper root for e11
6910        IF (ABS(Phase)<90) AND (ABS(Phase)>270) THEN Gamma_skip  !OPEN
6920        IF (ABS(Phase)>90) AND (ABS(Phase)<270) THEN Gamma_skip  !SHORT
6930        S22a_r=-S22a_r
6940        S22a_i=-S22a_i
6950 Gamma_skip:        !             Uses a,b,c,d and e11 to compute
6960                    !                 remaining error coefficients.
6970        CALL Cdiv(Vr,Vi,S22a_r,S22a_i,X3,Y3)
6980        S11b_r=X3
6990        S11b_i=Y3
7000        B_ar=Br_m-Ar_m
7010        B_ai=Bi_m-Ai_m
7020        CALL Cmult(B_ar,B_ai,S22a_r,S22a_i,X3,Y3)
7030        E10_e01r(F)=X3 !S21aS12a real
7040        E10_e01i(F)=Y3 !S21aS12a imag
7050        C_dr=Cr_n-Dr_n
7060        C_di=Ci_n-Di_n
7070        CALL Cmult(C_dr,C_di,S11b_r,S11b_i,X3,Y3)
7080        E23_e32r(F)=X3 !S12bS21b real
7090        E23_e32i(F)=Y3 !S12bS21b imag
7100        CALL Cmult(S22a_r,S22a_i,S11b_r,S11b_i,X3,Y3)
7110        E11_e22r=X3
7120        E11_e22i=Y3
7130        Var=1-X3
7140        CALL Cmult(Smt_r(F,3),Smt_i(F,3),Var,-E11_e22i,X3,Y3)
7150        E10_e32r(F)=X3 ! S21aS21b real
7160        E10_e32i(F)=Y3 ! S21aS21b imag
7170        CALL Cmult(Smt_r(F,2),Smt_i(F,2),Var,-E11_e22i,X3,Y3)
7180        E23_e01r(F)=X3 ! S12bS12a real
7190        E23_e01i(F)=Y3 ! S12bS12a imag
7200        E00r(F)=Br_m ! S11a real
7210        E00i(F)=Bi_m ! S11a imag
7220        E33r(F)=-Dr_n ! S22b real
7230        E33i(F)=-Di_n ! S22b imag
7240        E11r(F)=S22a_r
7250        E11i(F)=S22a_i
7260        E22r(F)=S11b_r
7270        E22i(F)=S11b_i
7280        !
7290        !
7300        ! Determines complex propagation coefficient gamma
7310        !
7320        ! NOW SHIFT REFERENCE PLANE TO ACTUAL CHIP BOUNDARY
7330        CALL Cmult(Mr(2,1),Mi(2,1),Br_m,Bi_m,X3,Y3)
7340        Gr=X3+Mr(2,2)
7350        Gi=Y3+Mi(2,2)
7360        CALL Rtop(Gr,Gi,Mag,Phase)
7370        Gam_lm=LOG(Mag)
```

```
7380            Gam_lp=Phase*PI/180
7390            Alpha=Gam_lm/Ldelay
7400            Beta=Gam_lp/Ldelay
7410            RAD
7420            Er_ref=EXP(-Alpha*L_dut)*COS(-Beta*L_dut)
7430            Ei_ref=EXP(-Alpha*L_dut)*SIN(-Beta*L_dut)
7440            DEG
7450            !
7460            ! Multiplies error coefficients by shifting terms
7470            !
7480            CALL Cmult(Br_m,Bi_m,Er_ref,Ei_ref,X3,Y3)
7490            E00r(F)=X3
7500            E00i(F)=Y3
7510            CALL Cmult(S22a_r,S22a_i,Er_ref,Ei_ref,X3,Y3)
7520            E11r(F)=X3
7530            E11i(F)=Y3
7540            CALL Cmult(S11b_r,S11b_i,Er_ref,Ei_ref,X3,Y3)
7550            E22r(F)=X3
7560            E22i(F)=Y3
7570            CALL Cmult(-Dr_n,-Di_n,Er_ref,Ei_ref,X3,Y3)
7580            E33r(F)=X3
7590            E33i(F)=Y3
7600            E10_e01rt=E10_e01r(F)
7610            E10_e01it=E10_e01i(F)
7620            CALL Cmult(E10_e01rt,E10_e01it,Er_ref,Ei_ref,X3,Y3)
7630            E10_e01r(F)=X3
7640            E10_e01i(F)=Y3
7650            E10_e32rt=E10_e32r(F)
7660            E10_e32it=E10_e32i(F)
7670            CALL Cmult(E10_e32rt,E10_e32it,Er_ref,Ei_ref,X3,Y3)
7680            E10_e32r(F)=X3
7690            E10_e32i(F)=Y3
7700            E23_e32rt=E23_e32r(F)
7710            E23_e32it=E23_e32i(F)
7720            CALL Cmult(E23_e32rt,E23_e32it,Er_ref,Ei_ref,X3,Y3)
7730            E23_e32r(F)=X3
7740            E23_e32i(F)=Y3
7750            E23_e01rt=E23_e01r(F)
7760            E23_e01it=E23_e01i(F)
7770            CALL Cmult(E23_e01rt,E23_e01it,Er_ref,Ei_ref,X3,Y3)
7780            E23_e01r(F)=X3
7790            E23_e01i(F)=Y3
7800 Extraction:  !
7810            S12m_rt=Smeas_r(F,2)
7820            S12m_it=Smeas_i(F,2)
7830            E23_e01rt=E23_e01r(F)
7840            E23_e01it=E23_e01i(F)
7850            CALL Cdiv(S12m_rt,S12m_it,E23_e01rt,E23_e01it,X3,Y3)
7860            Ar=X3
7870            Ai=Y3
7880            S21m_rt=Smeas_r(F,3)
7890            S21m_it=Smeas_i(F,3)
7900            E10_e32rt=E10_e32r(F)
7910            E10_e32it=E10_e32i(F)
7920            CALL Cdiv(S21m_rt,S21m_it,E10_e32rt,E10_e32it,X3,Y3)
7930            Br=X3
```

```
7940          Bi=Y3
7950          Cnum_r=Smeas_r(F,1)-E00r(F)
7960          Cnum_i=Smeas_i(F,1)-E00i(F)
7970          E10_e01rt=E10_e01r(F)
7980          E10_e01it=E10_e01i(F)
7990          CALL Cdiv(Cnum_r,Cnum_i,E10_e01rt,E10_e01it,X3,Y3)
8000          Cr=X3
8010          Ci=Y3
8020          Dnum_r=Smeas_r(F,4)-E33r(F)
8030          Dnum_i=Smeas_i(F,4)-E33i(F)
8040          E23_e32rt=E23_e32r(F)
8050          E23_e32it=E23_e32i(F)
8060          CALL Cdiv(Dnum_r,Dnum_i,E23_e32rt,E23_e32it,X3,Y3)
8070          Dr=X3
8080          Di=Y3
8090          E11rt=E11r(F)
8100          E11it=E11i(F)
8110          CALL Cmult(E11rt,E11it,Cr,Ci,X3,Y3)
8120          E1_r=1+X3
8130          E1_i=Y3
8140          E22rt=E22r(F)
8150          E22it=E22i(F)
8160          CALL Cmult(E22rt,E22it,Dr,Di,X3,Y3)
8170          Er_r=1+X3
8180          Er_i=Y3
8190          CALL Cmult(E1_r,E1_i,Er_r,Er_i,X3,Y3)
8200          E1_r=X3
8210          E1_i=Y3
8220          CALL Cmult(E11rt,E11it,E22rt,E22it,X3,Y3)
8230          E11_e22r=X3
8240          E11_e22i=Y3
8250          CALL Cmult(E11_e22r,E11_e22i,Ar,Ai,X3,Y3)
8260          E2_r=X3
8270          E2_i=Y3
8280          CALL Cmult(E2_r,E2_i,Br,Bi,X3,Y3)
8290          E3_r=X3
8300          E3_i=Y3
8310          Er=E1_r-E3_r
8320          Ei=E1_i-E3_i
8330          CALL Cmult(Cr,Ci,Dr,Di,X3,Y3)
8340          Cdr=X3
8350          Cdi=Y3
8360          CALL Cmult(Ar,Ai,Br,Bi,X3,Y3)
8370          Abr=X3
8380          Abi=Y3
8390          Cd_abr=Cdr-Abr
8400          Cd_abi=Cdi-Abi
8410          CALL Cmult(E22rt,E22it,Cd_abr,Cd_abi,X3,Y3)
8420          S11num_r=Cr+X3
8430          S11num_i=Ci+Y3
8440          CALL Cdiv(S11num_r,S11num_i,Er,Ei,X3,Y3)
8450          Sdut_r(F,1)=X3 !S11_r
8460          Sdut_i(F,1)=Y3 !S11_i
8470          CALL Cdiv(Br,Bi,Er,Ei,X3,Y3)
8480          Sdut_r(F,3)=X3 !S21_r
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```
8490        Sdut_i(F,3)=Y3 !S21 i
8500        CALL Cdiv(Ar,Ai,Er,Ei,X3,Y3)
8510        Sdut_r(F,2)=X3 !S12 r
8520        Sdut_i(F,2)=Y3 !S12 i
8530        CALL Cmult(E11rt,E11it,Cd_abr,Cd_abi,X3,Y3)
8540        S22num_r=Dr+X3
8550        S22num_i=Di+Y3
8560        CALL Cdiv(S22num_r,S22num_i,Er,Ei,X3,Y3)
8570        Sdut_r(F,4)=X3 !S22 r
8580        Sdut_i(F,4)=Y3 !S22 i
8590        NEXT F
8600        DISP " "
8610        PRINTER IS Crt
8620        OUTPUT 1;Clear$
8630        PRINT "Calculation of error coefficients completed"
8640        Calc_flag=1
8650        BEEP
 8660        RETUN
 8670        !
 8680        !
 8690        !
 8700       !
 8710       !-------------------------------------------------------------
 8720       !
 8730 Send: !                          Transfers fake error coefficient
 8740       !                          sets to 8510 memory
 8750       DISP ""
 8760       BEEP
 8770       OUTPUT 1;Clear$
 8780       DISP ""
 8790   !   IF (Calc_flag=1) THEN Go
 8800   !      BEEP
 8810   !      PRINTER IS Crt
 8820   !      PRINT "You must calculate error coeficients before transfer"
 8830   !      RETURN
 8840 Go:   !
 8850       PRINTER IS Crt
 8860       PRINT TABXY(15,6);"The TSD calibration will be stored in CAL SET 1"
  8870       PRINT TABXY(10,8);"Transfer the contents of this cal set or loss ofd
  ata will result"
  8880       DISP "Press CONTINUE to send TSD calibration data"
  8890       BEEP
  8900       LOCAL 7
  8910       PAUSE
  8920       DISP ""
  8930       REMOTE 716
  8940       OUTPUT @To8510;"DELC;CALS1;"
  8950       OUTPUT 1;Clear$
  8960       DISP "SENDING DATA"
  8970       BEEP
  8980       OUTPUT 1;Clear$
  8990       DISP ""
  9000       PRINTER IS Crt
  9010       OUTPUT 1;Clear$
  9020       !
```

```
9030         !
9040         FOR N=1 TO 201
9050            Data(N,1)=0
9060            Data(N,2)=0
9070         NEXT N
9080         OUTPUT @To8510;"DISPDATA"
9090         OUTPUT @To8510;"CORROFF;CAL1;CALIFUL2;FORM3;INPUCALC01;"
9100         OUTPUT @Datatoana;Preamble;Size;Data(*)
9110         PRINT "COEFFICIENT 01 DATA SENT"
9120         !
9130         FOR N=1 TO 201
9140            Data(N,1)=0
9150            Data(N,2)=0
9160         NEXT N
9170         OUTPUT @To8510;"INPUCALC02;"
9180         OUTPUT @Datatoana;Preamble;Size;Data(*)
9190         PRINT "COEFFICIENT 02 DATA SENT"
9200         !
9210         FOR N=1 TO 201
9220            Data(N,1)=1
9230            Data(N,2)=0
9240         NEXT N
9250         OUTPUT @To8510;"INPUCALC03;"
9260         OUTPUT @Datatoana;Preamble;Size;Data(*)
9270         PRINT "COEFFICIENT 03 DATA SENT"
9280         !
9290         FOR N=1 TO 201
9300            Data(N,1)=0
9310            Data(N,2)=0
9320         NEXT N
9330         IF Isol_flag=0 THEN Omit_isol_1
9340         FOR N=1 TO 201
9350            Data(N,1)=Smi_r(N,2)
9360            Data(N,2)=Smi_i(N,2)
9370         NEXT N
9380 Omit_isol_1:      !
9390         OUTPUT @To8510;"INPUCALC04;"
9400         OUTPUT @Datatoana;Preamble;Size;Data(*)
9410         PRINT "COEFFICIENT 04 DATA SENT"
9420         !
9430         FOR N=1 TO 201
9440            Data(N,1)=0
9450            Data(N,2)=0
9460         NEXT N
9470         OUTPUT @To8510;"INPUCALC05;"
9480         OUTPUT @Datatoana;Preamble;Size;Data(*)
9490         PRINT "COEFFICIENT 05 DATA SENT"
9500         !
9510         FOR N=1 TO 201
9520            Data(N,1)=1
9530            Data(N,2)=0
9540         NEXT N
9550         OUTPUT @To8510;"INPUCALC06;"
9560         OUTPUT @Datatoana;Preamble;Size;Data(*)
9570         PRINT "COEFFICIENT 06 DATA SENT"
```

```
9580        !
9590        FOR N=1 TO 201
9600           Data(N,1)=0
9610           Data(N,2)=0
9620        NEXT N
9630        OUTPUT @To8510;"INPUCALC07;"
9640        OUTPUT @Datatoana;Preamble;Size;Data(*)
9650        PRINT "COEFFICIENT 07 DATA SENT"
9660        !
9670        FOR N=1 TO 201
9680           Data(N,1)=0
9690           Data(N,2)=0
9700        NEXT N
9710        OUTPUT @To8510;"INPUCALC08;"
9720        OUTPUT @Datatoana;Preamble;Size;Data(*)
9730        PRINT "COEFFICIENT 08 DATA SENT"
9740        !
9750        FOR N=1 TO 201
9760           Data(N,1)=1
9770           Data(N,2)=0
9780        NEXT N
9790        OUTPUT @To8510;"INPUCALC09;"
9800        OUTPUT @Datatoana;Preamble;Size;Data(*)
9810        PRINT "COEFFICIENT 09 DATA SENT"
9820        !
9830        FOR N=1 TO 201
9840           Data(N,1)=0
9850           Data(N,2)=0
9860        NEXT N
9870        IF Isol_flag=0 THEN Omit_isol_2
9880        FOR N=1 TO 201
9890           Data(N,1)=Smi_r(N,1)
9900           Data(N,2)=Smi_i(N,1)
9910        NEXT N
9920 Omit_isol_2:      !
9930        OUTPUT @To8510;"INPUCALC10;"
9940        OUTPUT @Datatoana;Preamble;Size;Data(*)
9950        PRINT "COEFFICIENT 10 DATA SENT"
9960        !
9970        FOR N=1 TO 201
9980           Data(N,1)=0
9990           Data(N,2)=0
10000       NEXT N
10010       OUTPUT @To8510;"INPUCALC11;"
10020       OUTPUT @Datatoana;Preamble;Size;Data(*)
10030       PRINT "COEFFICIENT 11 DATA SENT"
10040       !
10050       FOR N=1 TO 201
10060          Data(N,1)=1
10070          Data(N,2)=0
10080       NEXT N
10090       OUTPUT @To8510;"INPUCALC12;"
10100       OUTPUT @Datatoana;Preamble;Size;Data(*)
10110       PRINT "COEFFICIENT 12 DATA SENT"
10120       !
10130       !
```

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```
10140       OUTPUT @To8510;"SAVC;CALS1;CONT;CORRON;CALS1;"
10150       OUTPUT @To8510;"DISPDATA;"
10160       OUTPUT @To8510;"MENUPRIO;"
10170       LOCAL 7
10180       DISP ""
10190       PRINT "DATA TRANSFER COMPLETED"
10200       FOR N=1 TO 201
10210       PRINT USING "SD.DDDD";E00r(N);E11r(N);E10_e01r(N);E22r(N);E10_e32r(N)
;E33r(N);E23_e32r(N);E23_e01r(N)
10220       NEXT N
10230       Model_flag=1
10240       BEEP
10250       DISP "ERROR COEFFICIENTS TRANSFERED"
10260       WAIT 3
10270       DISP ""
10280       RETURN
10290       !
10300       !
10310       !
10320 Send_actual:      !
10330      BEEP
10340      OUTPUT 1;Clear$
10350      DISP ""
10360      PRINTER IS Crt
10370       IF (Calc_flag=1) THEN Mod_flag
10380          PRINT "You must calculate error coefficients before transfer"
10390          RETURN
10400 Mod_flag:    !
10410       IF (Model_flag=1) THEN Go_to_it
10420          PRINT "You must send error model before DUT data"
10430          RETURN
10440 Go_to_it:  !
10450      REMOTE 716
10460      OUTPUT @To8510;"CORRON;CALS1;"
10470       FOR N=1 TO 201
10480         Data(N,1)=Sdut_r(N,1)
10490         Data(N,2)=Sdut_i(N,1)
10500       NEXT N
10510       OUTPUT @To8510;"HOLD;FORM3;INPURAW1;"
10520       OUTPUT @Datatoana;Preamble,Size,Data(*)
10530       PRINT "S11 Sent"
10540       !
10550       FOR N=1 TO 201
10560         Data(N,1)=Sdut_r(N,3)
10570         Data(N,2)=Sdut_i(N,3)
10580       NEXT N
10590   !   OUTPUT @To8510;"HOLD;FORM3;INPURAW2;"
10600       OUTPUT @To8510;"INPURAW2;"
10610       OUTPUT @Datatoana;Preamble,Size,Data(*)
10620       PRINT "S21 Sent"
10630       !
10640       FOR N=1 TO 201
10650         Data(N,1)=Sdut_r(N,2)
10660         Data(N,2)=Sdut_i(N,2)
10670       NEXT N
10680   !   OUTPUT @To8510;"HOLD;FORM3;INPURAW3;"
```

```
10690     OUTPUT @To8510;"INPURAW3;"
10700     OUTPUT @Datatoana;Preamble,Size,Data(*)
10710     PRINT "S12 Sent"
10720     !
10730     FOR N=1 TO 201
10740       Data(N,1)=Sdut_r(N,4)
10750       Data(N,2)=Sdut_i(N,4)
10760     NEXT N
10770  !  OUTPUT @To8510;"HOLD;FORM3;INPURAW4;"
10780     OUTPUT @To8510;"INPURAW4;"
10790     OUTPUT @Datatoana;Preamble,Size,Data(*)
10800     PRINT "S22 Sent"
10810  !  OUTPUT @To8510;"CONT;"
10820     LOCAL 7
10830  !  PRINTER IS 701
10840  !  FOR N=1 TO 201
10850  !       PRINT N;Sdut_r(N,1);Sdut_r(N,2);Sdut_r(N,3);Sdut_r(N,4)
10860  !       PRINT N;Sdut_i(N,1);Sdut_i(N,2);Sdut_i(N,3);Sdut_i(N,4)
10870  !  NEXT N
10880     PRINTER IS 1
10890    RETURN
10900     !
10910 Exit:    !
10920     DISP ""
10930     OUTPUT 1;Clear$
10940     DISP ""
10950     PRINTER IS Crt
10960     PRINT TABXY(15,6);"The program has ended.  Press run to restart"
10970     END
10980     !
10990     !
11000     !*********************SUBPROGRAMS************************
11010     !
11020     !   Returns the roots of a quadratic equation
11030     !
11040     SUB Quad(Ar,Ai,Br,Bi,Cr,Ci,Rrp,Rip,Rrm,Rim)
11050         CALL Cmult(Br,Bi,Br,Bi,X3,Y3)
11060         Bsqr=X3
11070         Bsqi=Y3
11080         CALL Cmult(Ar,Ai,Cr,Ci,X3,Y3)
11090         Ac4r=4*X3
11100         Ac4i=4*Y3
11110         Tr=Bsqr-Ac4r
11120         Ti=Bsqi-Ac4i
11130         CALL Rtop(Tr,Ti,Mag,Phase)
11140         Radm=SQR(Mag)
11150         Radp=Phase/2
11160         CALL Ptor(Radm,Radp,X,Y)
11170         Numx_p=-Br+X
11180         Numy_p=-Bi+Y
11190         Numx_m=-Br-X
11200         Numy_m=-Bi-Y
11210         Denomx=2*Ar
11220         Denomy=2*Ai
11230         CALL Cdiv(Numx_p,Numy_p,Denomx,Denomy,X3,Y3)
11240         Rrp=X3
```

```
11250         Rip=Y3
11260         CALL Cdiv(Numx_m,Numy_m,Denomx,Denomy,X3,Y3)
11270         Rrm=X3
11280         Rim=Y3
11290         SUBEND
11300         !
11310         !
11320         !   Converts an S-parameter matrix to a T-parameter matrix
11330         !
11340         SUB Tconv(S11r,S11i,S12r,S12i,S21r,S21i,S22r,S22i,T11r,T11i,T12r,T
12i,T21r,T21i,T22r,T22i)
11350         CALL Cmult(S11r,S11i,S22r,S22i,X3,Y3)
11360         D1r=X3
11370         D1i=Y3
11380         CALL Cmult(S12r,S12i,S21r,S21i,X3,Y3)
11390         Drr=X3
11400         Dri=Y3
11410         Del_r=D1r-Drr
11420         Del_i=D1i-Dri
11430         CALL Cdiv(-Del_r,-Del_i,S21r,S21i,X3,Y3)
11440         T11r=X3
11450         T11i=Y3
11460         CALL Cdiv(S11r,S11i,S21r,S21i,X3,Y3)
11470         T12r=X3
11480         T12i=Y3
11490         CALL Cdiv(-S22r,-S22i,S21r,S21i,X3,Y3)
11500         T21r=X3
11510         T21i=Y3
11520         CALL Cdiv(1,0,S21r,S21i,X3,Y3)
11530         T22r=X3
11540         T22i=Y3
11550         SUBEND
11560         !
11570         !
11580         !   Multiplies two complex numbers
11590         !
11600         SUB Cmult(X1,Y1,X2,Y2,X3,Y3)
11610         X3=X1*X2-Y1*Y2
11620         Y3=X1*Y2+Y1*X2
11630         SUBEND
11640         !
11650         !
11660         !   Divides two complex numbers
11670         !
11680         SUB Cdiv(X1,Y1,X2,Y2,X3,Y3)
11690         Denom=X2*X2+Y2*Y2
11700         Denom1=X1*X1+Y1*Y1
11710         IF (Denom<1.E-30*Denom1) THEN
11720           X3=1.E+30
11730           Y3=1.E+30
11740         ELSE
11750           X3=(X1*X2+Y1*Y2)/Denom
11760           Y3=(Y1*X2-X1*Y2)/Denom
11770         END IF
11780         SUBEND
11790         !
```

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```
11800     !
11810     !  Performs polar to rectangular conversion
11820     !
11830     SUB Ptor(Mag,Phase,X,Y)
11840       DEG
11850       X1=Mag
11860       X=X1*COS(Phase)
11870       Y=X1*SIN(Phase)
11880     SUBEND
11890     !
11900     !
11910     !   Performs rectangular to polar conversion
11920     !
11930     SUB Rtop(X,Y,Mag,Phase)
11940       DEG
11950       Mag=SQR(X^2+Y^2)
11960       Phase=2*ATN(Y/(X+Mag))
11970     SUBEND
11980     !
11990     !
12000     !
12010     !
```

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TABLE I.—TAPER PROFILE COORDINATES FOR RIDGE GUIDE TRANSITION

[Microstrip line characteristic impedance = 50Ω]

(a) WR-42

Substrate thickness, *T*, mils					
0.005		0.010		0.020	
Ridge thickness, W, mils					
32.500		66.500		139.000	
y, mils	*x*, mils	*y*, mils	*x*, mils	*y*, mils	*x*, mils
000.00	0000.00	000.00	0000.00	000.00	0000.00
000.68	0033.46	000.35	0033.58	000.18	0035.85
002.67	0066.91	001.39	0067.15	000.74	0067.70
005.91	0100.37	003.10	0100.73	001.65	0101.54
010.24	0133.83	005.45	0134.31	002.92	0135.39
015.53	0167.28	008.38	0167.88	004.53	0169.24
021.56	0200.74	011.86	0201.46	006.47	0203.09
028.17	0234.20	015.80	0235.03	008.72	0236.93
035.16	0267.66	020.16	0268.61	011.27	0270.78
042.36	0301.11	024.85	0302.19	014.08	0304.63
049.64	0334.57	029.82	0335.76	017.14	0338.48
056.86	0368.03	034.99	0369.34	020.43	0372.32
063.94	0401.48	040.31	0402.92	023.92	0406.17
070.79	0434.94	045.72	0436.49	027.59	0440.02
077.38	0468.40	051.16	0470.07	031.41	0473.87
083.65	0501.85	056.60	0503.64	035.35	0507.71
089.59	0535.31	061.99	0537.22	039.40	0541.71
095.18	0568.77	067.29	0570.80	043.53	0575.41
100.44	0602.22	072.48	0604.37	047.72	0609.26
105.36	0635.68	077.55	0637.95	051.95	0643.11
109.96	0669.14	082.46	0671.53	056.20	0676.95
114.24	0702.59	087.21	0705.10	060.44	0710.80
118.22	0736.05	091.78	0738.68	064.67	0744.65
121.93	0769.51	096.18	0772.25	068.87	0778.50
125.37	0802.97	100.39	0805.83	073.03	0812.34
128.56	0836.42	104.41	0839.41	077.12	0846.19
131.53	0869.88	108.25	0872.98	081.15	0880.04
134.28	0903.34	111.91	0906.56	085.09	0913.89
136.84	0936.79	115.39	0940.14	088.95	0947.73
139.21	0970.25	118.69	0973.71	092.72	0981.58
141.40	1003.71	121.82	1007.29	096.38	1015.43
143.44	1037.16	124.78	1040.86	099.93	1049.28
145.34	1070.62	127.58	1074.44	103.37	1083.13
147.10	1104.08	130.22	1108.02	106.70	1116.97
148.73	1137.53	132.72	1141.59	109.90	1150.82
150.24	1170.99	135.07	1175.17	112.99	1184.67
151.64	1204.45	137.28	1208.75	115.95	1218.52
152.94	1237.91	139.37	1242.32	118.78	1252.36
154.15	1271.36	141.32	1275.90	121.49	1286.21
155.27	1304.82	143.15	1309.47	124.08	1320.06
156.31	1338.28	144.86	1343.05	126.53	1353.91
157.26	1371.73	146.47	1376.63	128.86	1387.75
158.15	1405.19	147.96	1410.20	131.07	1421.60
158.97	1438.65	149.35	1443.78	133.15	1455.45
159.72	1472.10	150.64	1477.36	135.10	1489.30
160.41	1505.56	151.83	1510.93	136.93	1523.14
161.04	1539.02	152.94	1544.51	138.63	1556.99
161.62	1572.47	153.95	1578.08	140.22	1590.84
162.14	1605.93	154.87	1611.66	141.68	1624.69
162.62	1639.39	155.72	1645.24	143.02	1658.54
163.05	1672.85	156.48	1678.81	144.24	1692.38
163.43	1706.30	157.16	1712.39	145.34	1726.23
163.77	1739.76	157.77	1745.97	146.32	1760.08
164.06	1773.22	158.30	1779.54	147.19	1793.93
164.31	1806.67	158.75	1813.12	147.94	1827.77
164.52	1840.13	159.45	1846.69	148.57	1861.62
164.70	1873.59	159.45	1880.27	149.08	1895.47
164.83	1907.04	159.69	1913.85	149.48	1929.32
164.92	1940.50	159.86	1947.42	149.77	1963.16
164.98	1973.96	159.97	1981.00	149.94	1997.01
165.00	2007.41	160.00	2014.58	150.00	2030.86

TABLE I.—CONTINUED.

[Microstrip line characteristic impedance = 50Ω]

(b) WR-28

Substrate thickness, *T*, mils					
0.005		0.010		0.020	
Ridge thickness, W, mils					
34.000		69.500		149.000	
y, mils	*x*, mils	*y*, mils	*x*, mils	*y*, mils	*x*, mils
000.00	0000.00	000.00	0000.00	000.00	0000.00
000.38	0022.66	000.20	0022.76	000.11	0023.08
001.51	0045.33	000.81	0045.53	000.44	0046.16
003.36	0067.99	001.81	0068.29	000.99	0069.23
005.88	0090.66	003.19	0091.05	001.76	0092.31
009.00	0113.32	004.94	0113.82	002.73	0115.39
012.65	0135.98	007.02	0136.58	003.91	0138.47
016.75	0158.65	009.43	0159.34	005.29	0161.55
021.20	0181.31	012.13	0182.11	006.87	0184.63
025.92	0203.97	015.08	0204.87	008.63	0207.70
030.83	0226.64	018.27	0227.63	010.56	0230.78
035.86	0249.30	021.65	0250.40	012.66	0253.86
040.94	0271.97	025.19	0273.16	014.91	0276.94
046.01	0294.63	028.87	0295.92	017.31	0300.02
051.02	0317.29	032.66	0318.69	019.83	0323.09
055.93	0339.96	036.52	0341.45	022.48	0346.17
060.71	0362.62	040.43	0364.21	025.24	0369.25
065.34	0385.29	044.36	0386.97	028.10	0392.33
069.79	0407.95	048.30	0409.74	031.04	0415.41
074.06	0430.61	052.21	0432.50	034.05	0438.49
078.14	0453.28	056.09	0455.26	037.12	0461.56
082.02	0475.94	059.92	0478.03	040.25	0484.64
085.71	0498.61	063.68	0500.79	043.41	0507.72
089.20	0521.27	067.36	0523.55	046.59	0530.80
092.50	0543.93	070.96	0546.32	049.80	0553.88
095.61	0566.60	074.46	0569.08	053.01	0576.96
098.55	0589.26	077.85	0591.84	056.21	0600.03
101.31	0611.92	081.14	0614.61	059.40	0623.11
103.91	0634.59	084.32	0637.37	062.57	0646.19
106.35	0657.25	087.38	0660.13	065.70	0669.27
108.65	0679.92	090.33	0682.90	068.80	0692.35
110.80	0702.58	093.16	0705.66	071.85	0715.42
112.82	0725.24	095.86	0728.42	074.85	0738.50
114.71	0747.91	098.46	0751.19	077.78	0761.58
116.47	0770.57	100.93	0773.95	080.65	0784.66
118.13	0793.24	103.29	0796.71	083.44	0807.74
119.68	0815.90	105.53	0819.48	086.16	0830.82
121.12	0838.56	107.66	0842.24	088.79	0853.89
122.47	0861.23	109.68	0865.00	091.34	0876.97
123.73	0883.89	111.59	0887.77	093.79	0900.05
124.90	0906.55	113.40	0910.53	096.15	0923.13
125.99	0929.22	115.10	0933.29	098.41	0946.21
127.00	0951.88	116.69	0956.06	100.57	0969.28
127.94	0974.55	118.19	0978.82	102.63	0992.36
128.81	0997.21	119.59	1001.58	104.57	1015.44
129.61	1019.87	120.89	1024.35	106.41	1038.52
130.34	1042.54	122.10	1047.11	108.14	1061.60
131.02	1065.20	123.21	1069.87	109.76	1084.68
131.63	1087.87	124.24	1092.64	111.26	1107.75
132.19	1110.53	125.18	1115.40	112.64	1130.83
132.69	1133.19	126.03	1138.16	113.91	1153.91
133.14	1155.86	126.79	1160.92	115.06	1176.99
133.54	1178.52	127.47	1183.69	116.10	1200.07
133.88	1201.18	128.07	1206.45	117.01	1223.15
134.18	1223.85	128.58	1229.21	117.80	1246.22
134.43	1246.51	129.02	1251.98	118.47	1269.30
134.64	1269.18	129.37	1274.74	119.02	1292.38
134.80	1291.84	129.65	1297.50	119.45	1315.46
134.91	1314.50	129.84	1320.27	119.76	1338.54
134.98	1337.17	129.96	1343.03	119.94	1361.61
135.00	1359.83	130.00	1365.79	120.00	1384.69

TABLE I.—CONTINUED.

[Microstrip line characteristic impedance = 50Ω]

(c) WR-22

Substrate thickness, *T*, mils					
0.005		0.010		0.020	
Ridge thickness, W, mils					
34.000		70.500		161.500	
y, mils	*x*, mils	*y*, mils	*x*, mils	*y*, mils	*x*, mils
000.00	0000.00	000.00	0000.00	000.00	0000.00
000.25	0018.22	000.13	0018.33	000.07	0018.86
000.99	0036.44	000.53	0036.65	000.29	0037.73
002.21	0054.66	001.19	0054.98	000.64	0056.59
003.87	0072.88	002.10	0073.31	001.14	0075.45
005.95	0091.10	003.26	0091.64	001.78	0094.31
008.40	0109.32	004.65	0109.96	002.55	0113.18
011.18	0127.55	006.26	0128.29	003.46	0132.04
014.24	0145.77	008.08	0146.62	004.50	0150.90
017.52	0163.99	010.09	0164.94	005.66	0169.77
020.98	0182.21	012.27	0183.27	006.95	0188.63
024.57	0200.43	014.61	0201.60	008.35	0207.49
028.25	0218.65	017.08	0219.92	009.87	0226.35
031.97	0236.87	019.67	0238.25	011.49	0245.22
035.70	0255.09	022.36	0256.58	013.21	0264.08
039.40	0273.31	025.13	0274.91	015.03	0282.94
043.06	0291.53	027.96	0293.23	016.93	0301.81
046.65	0309.75	030.84	0311.56	018.92	0320.67
050.15	0327.97	033.75	0329.89	020.98	0339.53
053.54	0346.19	036.68	0348.21	023.11	0358.40
056.82	0364.41	039.62	0366.54	025.30	0377.26
059.98	0382.64	042.54	0384.87	027.55	0396.12
063.02	0400.86	045.44	0403.19	029.84	0414.98
065.92	0419.08	048.31	0421.52	032.16	0433.85
068.70	0437.30	051.14	0439.85	034.53	0452.71
071.34	0455.52	053.93	0458.18	036.91	0471.57
073.85	0473.74	056.65	0476.50	039.32	0490.44
076.24	0491.96	059.32	0494.83	041.73	0509.30
078.50	0510.18	061.91	0513.16	044.15	0528.16
080.64	0528.40	064.44	0531.48	046.56	0547.02
082.67	0546.62	066.89	0549.81	048.97	0565.89
084.58	0564.84	069.26	0568.14	051.36	0584.75
086.39	0583.06	071.55	0586.47	053.73	0603.61
088.09	0601.28	073.76	0604.79	056.06	0622.48
089.69	0619.50	075.88	0623.12	058.37	0641.34
091.20	0637.73	077.92	0641.45	060.63	0660.20
092.61	0655.95	079.87	0659.77	062.85	0679.06
093.94	0674.17	081.73	0678.10	065.01	0697.93
095.18	0692.39	083.51	0696.43	067.13	0716.79
096.35	0710.61	085.20	0714.75	069.17	0735.65
097.44	0728.83	086.81	0733.08	071.16	0754.52
098.46	0747.05	088.33	0751.41	073.07	0773.38
099.40	0765.27	089.77	0769.74	074.91	0792.24
100.28	0783.49	091.12	0788.06	076.67	0811.10
101.10	0801.71	092.39	0806.39	078.35	0829.97
101.86	0819.93	093.57	0824.72	079.95	0848.83
102.55	0838.15	094.68	0843.04	081.45	0867.69
103.19	0856.37	095.70	0861.37	082.87	0886.56
103.78	0874.60	096.64	0879.70	084.19	0905.42
104.31	0892.82	097.51	0898.03	085.41	0924.28
104.79	0911.04	098.30	0916.35	086.54	0943.15
105.22	0929.26	099.00	0934.68	087.57	0962.01
105.60	0947.48	099.64	0953.01	088.49	0980.87
105.93	0965.70	100.19	0971.33	089.30	0999.73
106.22	0983.92	100.67	0989.66	090.02	1018.60
106.46	1002.14	101.08	1007.99	090.62	1037.46
106.65	1020.36	101.41	1026.31	091.12	1056.32
106.81	1038.58	101.67	1044.64	091.50	1075.19
106.91	1056.80	101.85	1062.97	091.78	1094.05
106.98	1075.02	101.96	1081.30	091.94	1112.91
107.00	1093.24	102.00	1099.62	092.00	1131.77

TABLE I.—CONTINUED.

[Microstrip line characteristic impedance = 50Ω]

(d) WR-15

Substrate thickness, *T*, mils			
0.005		0.010	
Ridge thickness, W, mils			
34.500		74.000	
y, mils	*x*, mils	*y*, mils	*x*, mils
000.00	0000.00	000.00	0000.00
000.11	0012.06	000.06	0012.21
000.45	0024.12	000.24	0024.42
001.01	0036.19	000.55	0036.63
001.77	0048.25	000.97	0048.84
002.74	0060.31	001.51	0061.05
003.90	0072.37	002.16	0073.26
005.24	0084.44	002.93	0085.47
006.72	0096.50	003.80	0097.68
008.35	0108.56	004.77	0109.90
010.11	0120.62	005.83	0122.11
011.96	0132.68	006.98	0134.32
013.90	0144.75	008.22	0146.53
015.91	0156.81	009.53	0158.74
017.97	0168.87	010.92	0170.95
020.07	0180.93	012.36	0183.16
022.18	0192.99	013.87	0195.37
024.30	0205.06	015.42	0207.58
026.42	0217.12	017.02	0219.79
028.52	0229.18	018.66	0232.00
030.60	0241.24	020.32	0244.21
032.64	0253.31	022.01	0256.42
034.64	0265.37	023.71	0268.63
036.59	0277.43	025.43	0280.84
038.49	0289.49	027.15	0293.05
040.34	0301.55	028.87	0305.26
042.12	0313.62	030.58	0317.47
043.85	0325.68	032.29	0329.69
045.51	0337.74	033.97	0341.90
047.11	0349.80	035.64	0354.11
048.65	0361.86	037.28	0366.32
050.12	0373.93	038.90	0378.53
051.52	0385.99	040.48	0390.74
052.87	0398.05	042.03	0402.95
054.14	0410.11	043.54	0415.16
055.36	0422.18	045.01	0427.37
056.52	0434.24	046.44	0439.58
057.61	0446.30	047.82	0451.79
058.65	0458.36	049.15	0464.00
059.63	0470.42	050.43	0476.21
060.55	0482.49	051.66	0488.42
061.42	0494.55	052.84	0500.63
062.24	0506.61	053.96	0512.84
063.00	0518.67	055.03	0525.05
063.72	0530.74	056.04	0537.26
064.38	0542.80	056.99	0549.48
064.99	0554.86	057.89	0561.69
065.56	0566.92	058.72	0573.90
066.08	0578.98	059.50	0586.11
066.56	0591.05	060.21	0598.32
066.99	0603.11	060.87	0610.53
067.38	0615.17	061.46	0622.74
067.72	0627.23	061.99	0634.95
068.02	0639.29	062.46	0647.16
068.28	0651.36	062.87	0659.37
068.50	0663.42	063.21	0671.58
068.68	0675.48	063.50	0683.79
068.82	0687.54	063.72	0696.00
068.92	0699.61	063.87	0708.21
068.98	0711.67	063.97	0720.42
069.00	0723.73	064.00	0732.63

**ORIGINAL PAGE IS
OF POOR QUALITY**

ORIGINAL PAGE IS OF POOR QUALITY

TABLE I.—CONCLUDED.

[Microstrip line characteristic impedance = 50Ω]

(e) WR-12

Substrate thickness, *T*, mils			
0.005		0.010	
Ridge thickness, W, mils			
35.005		78.000	
y, mils	*x*, mils	*y*, mils	*x*, mils
000.00	000.00	000.00	000.00
000.08	010.08	000.04	010.29
000.31	020.15	000.17	020.59
000.70	030.23	000.38	030.88
001.23	040.31	000.67	041.18
001.91	050.38	001.05	051.47
002.73	060.46	001.50	061.76
003.67	070.54	002.04	072.06
004.72	080.61	002.65	082.35
005.89	090.69	003.33	092.64
007.15	100.77	004.08	102.94
008.50	110.84	004.90	113.23
009.92	120.92	005.78	123.53
011.40	131.00	006.73	133.82
012.94	141.07	007.72	144.11
014.52	151.15	008.78	154.41
016.12	161.23	009.88	164.70
017.75	171.30	011.02	175.00
019.39	181.38	012.20	185.29
021.03	191.46	013.42	195.58
022.66	201.53	014.67	205.88
024.29	211.62	015.95	216.17
025.89	221.69	017.24	226.47
027.48	231.76	018.56	236.76
029.03	241.84	019.89	247.05
030.55	251.92	021.23	257.35
032.04	261.99	022.58	267.64
033.49	272.07	023.92	277.93
034.89	282.15	025.27	288.23
036.26	292.22	026.61	298.52
037.58	302.30	027.94	308.82
038.85	312.38	029.25	319.11
040.07	322.45	030.55	329.40
041.25	332.53	031.83	339.70
042.37	342.61	033.09	349.99
043.45	352.68	034.32	360.29
044.49	362.76	035.52	370.58
045.47	372.83	036.69	380.87
046.40	382.91	037.83	391.17
047.29	392.99	038.93	401.46
048.13	403.06	039.99	411.76
048.93	413.14	041.02	422.05
049.68	423.22	042.00	432.34
050.38	433.29	042.94	442.64
051.04	443.37	043.83	452.93
051.65	453.45	044.67	463.22
052.23	463.52	045.47	473.52
052.76	473.60	046.22	483.81
053.24	483.68	046.91	494.11
053.69	493.75	047.56	504.40
054.10	503.83	048.15	514.69
054.46	513.91	048.68	524.99
054.79	523.98	049.17	535.28
055.07	534.06	049.59	545.58
055.32	544.14	049.97	555.87
055.53	554.21	050.28	566.16
055.70	564.29	050.54	576.46
055.83	574.37	050.74	586.75
055.92	584.44	050.88	597.05
055.98	594.52	050.97	607.34
056.00	604.60	051.00	617.63

(f) WR-10

Substrate thickness, *T*, mils	
0.005	
Ridge thickness, W, mils	
35.500	
y, mils	*x*, mils
000.00	000.00
000.05	008.08
000.22	016.16
000.48	024.24
000.85	032.32
001.32	040.40
001.89	048.48
002.55	056.56
003.29	064.64
004.12	072.72
005.02	080.80
005.98	088.88
007.01	096.96
008.09	105.04
009.22	113.12
010.38	121.20
011.58	129.28
012.80	137.36
014.05	145.44
015.30	153.52
016.57	161.60
017.83	169.68
019.10	177.76
020.35	185.84
021.60	193.92
022.82	202.00
024.03	210.08
025.22	218.16
026.38	226.24
027.52	234.32
028.62	242.40
029.70	250.48
030.74	258.56
031.75	266.64
032.72	274.72
033.66	282.80
034.56	290.88
035.43	298.96
036.25	307.04
037.04	315.12
037.79	323.20
038.51	331.28
039.18	339.36
039.82	347.44
040.42	355.52
040.98	363.60
041.50	371.68
041.99	379.76
042.44	387.84
042.85	395.92
043.22	404.00
043.56	412.08
043.87	420.16
044.13	428.24
044.36	436.32
044.56	444.40
044.72	452.48
044.84	460.56
044.93	468.64
044.98	476.72
045.00	484.80

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16. Abstract

The design and evaluation of a novel fixturing technique for characterizing millimeter-wave solid-state devices is presented. The technique utilizes a cosine-tapered ridge guide fixture and a one-tier de-embedding procedure to produce accurate and repeatable device-level data. Advanced features of this technique include nondestructive testing, full waveguide bandwidth operation, universality of application, and rapid, yet repeatable, chip-level characterization. In addition, only one set of calibration standards is required regardless of the device geometry.

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