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.

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 K₄ band. Features of the carrier include coupled-line direct-current (dc) blocks, input (gate) and output
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Figure 1.—Partially disassembled view of cosine-tapered ridge guide fixture along with through-reflector-delay (TRD) calibration standards. Monolithic 30-GHz gain control amplifier is mounted on carrier.

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

Figure 3.—Detailed schematic of calibration standards. (a) Through-short-delay (TSD) calibration standards. (b) Chip carrier 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 E-plane taper, surmounted these limitations and provided a convenient interface method. Figure 4(a) to (d) illustrates the transition mechanism. Notice that no 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 $\lambda_c$. 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:

$$1 - Z_{2010} \tan \varphi_2 - Z_0/Z_1 \tan \varphi_2 \tan \varphi_1 = 0 \quad (1)$$

where $Z_{2010}$ is the normalized junction reactance obtained from reference 5, and $Z_0/Z_1 = b/t$ is the impedance ratio of the equivalent parallel plate lines. The transmission line equivalent lengths at cutoff are $\varphi_1$ and $\varphi_2$. 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 $Z_0$, can be determined. Impedance $Z_0$ as a function of frequency can be related to the infinite frequency characteristic impedance $Z_{0\infty}$ through

$$\frac{Z_0(x)}{Z_{0\infty}} = \frac{\lambda_c}{\lambda_{0\infty}} = \frac{1.0}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \quad (2)$$

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 \( \lambda_g \) is the guide wavelength and \( \lambda_o \) is the free space wavelength. The impedance \( Z_{oo} \) for the TE\(_{10} \) mode is given by Cohn (ref. 4) as

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

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 \( Z_{oo} \) 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 sinusoidal transition performs as well as a linear transition but is only half as long. The length of the taper is \( \ell \), 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:

\[
t = \frac{Z_o(x) \sin \varphi_1}{\lambda_c \sqrt{1 - \left( \frac{f}{f_c} \right)^2}} \tag{5}
\]

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.

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, 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 $95^\circ$ 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 $e^{-j\gamma}$. Consequently, the exact length $\ell$ of the device must be known. The complex propagation constant $\gamma$, 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 \( \Omega \) (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 acquisition 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 describe 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 (thousandths 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 recompute 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):

\[
\begin{align*}
E_{DF} &= S_{11L} & E_{DR} &= S_{32R} \\
E_{SR} &= S_{22L} & E_{SR} &= S_{11R} \\
E_{RF} &= S_{21L}S_{12L} & E_{RR} &= S_{31R}S_{12R} \\
E_{XP} &= 0 & E_{XR} &= 0 \\
E_{LR} &= S_{11R} & E_{LR} &= S_{22L} \\
E_{TF} &= S_{21R}S_{12L} & E_{TR} &= S_{12R}S_{12L}
\end{align*}
\]

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 \textit{short}, a quarter-wavelength \textit{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).
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.

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 investigation 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.
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 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 characterization 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.

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National Aeronautics and Space Administration
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Figure 11.—Through-open-delay (TOD) 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.
Appendix A
Symbols

\begin{align*}
a & \quad \text{h-plane width of the waveguide} \\
a' & \quad \text{width of the ridge} \\
b & \quad \text{E-plane waveguide dimension} \\
c & \quad \text{junction capacitance} \\
E_{DF} & \quad \text{directivity error term in forward direction} \\
E_{DR} & \quad \text{directivity error term in reverse direction} \\
E_{LF} & \quad \text{load match error term in forward direction} \\
E_{LR} & \quad \text{load match error term in reverse direction} \\
E_{RF} & \quad \text{reflection tracking error term in forward direction} \\
E_{RR} & \quad \text{reflection tracking error term in reverse direction} \\
E_{SR} & \quad \text{source match error term in forward direction} \\
E_{TF} & \quad \text{transmission tracking error term in forward direction} \\
E_{TR} & \quad \text{transmission tracking error term in reverse direction} \\
E_{XF} & \quad \text{isolation error term in forward direction} \\
E_{XR} & \quad \text{isolation error term in reverse direction} \\
f_c & \quad \text{cutoff frequency} \\
\ell & \quad \text{length of taper} \\
M_{ij} & \quad \text{elements of matrix that is product of } T_{m,d} \text{ and inverse of } T_{m,t} \\
N_{ij} & \quad \text{elements of matrix that is product of inverse of } T_{m,t} \text{ and } T_{m,d} \\
S_{ijR}, S_{ijL} & \quad \text{equivalent scattering parameter elements of resolved error networks.} \\
S_{mij} & \quad \text{measured scattering parameter element of short} \\
S_{mij} & \quad \text{measured scattering parameter element of through} \\
T_d & \quad \text{chain matrix of isolated delay standard} \\
T_L & \quad \text{chain matrix of error network to left of device} \\
T_{Lij} & \quad \text{elements of } T_L \\
T_{m,d} & \quad \text{chain matrix representing measured delay standard} \\
T_{m,t} & \quad \text{chain matrix representing measured through standard} \\
T_R & \quad \text{chain matrix of error network to right of device} \\
T_{Rij} & \quad \text{elements of } T_R \\
T_i & \quad \text{chain matrix of isolated through standard} \\
t & \quad \text{distance between ridge and base at substrate} \\
t_{Lij} & \quad \text{entries in left error chain matrix} \\
t_{Rij} & \quad \text{entries in right error chain matrix} \\
x & \quad \text{position along taper from origin} \\
Z_L & \quad \text{characteristic impedance of ridge waveguide at } x = L \\
Z_o & \quad \text{characteristic impedance of microstrip line} \\
Z_{vc} & \quad \text{infinite frequency characteristic impedance} \\
Z_0 & \quad \text{characteristic impedance of open waveguide at } x = 0 \\
Z_1 & \quad \text{characteristic impedance of parallel plate line of height } t \\
Z_2 & \quad \text{characteristic impedance of parallel plate line of height } b \\
Z_2/Z_1 & \quad \text{impedance ratio of equivalent parallel plate lines} \\
Z_o\omega c & \quad \text{normalized junction reactance} \\
\gamma & \quad \text{complex propagation constant} \\
\lambda_c & \quad \text{ridge waveguide cutoff wavelength} \\
\lambda_g & \quad \text{guide wavelength} \\
\lambda_o & \quad \text{free space wavelength} \\
\varphi_1 & \quad \text{electrical length corresponding to } a'/2 \\
\varphi_2 & \quad \text{electrical length corresponding to } (a - a')/2 \\
\omega & \quad \text{radian frequency}
\end{align*}
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

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

(B1)

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

\[
[T_d] = \begin{bmatrix}
e^{-j\gamma t} & 0 \\
0 & e^{j\gamma t}\end{bmatrix}
\]  

(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

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

(B3)

Similarly, the chain matrix representation from the delay measurement is

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

(B4)

Multiplying \([T_{m,d}]\) by \([T_{m,l}^{-1}]\) yields equations of the form

\[
M_{21} \left( \frac{t_{L1}^{*2}}{t_{L21}} \right) + (M_{22} - M_{11}) \left( \frac{t_{L1}^{*}}{t_{L21}} \right) - M_{12} = 0
\]  

(B5)

\[
M_{21} \left( \frac{t_{L1}^{2}}{t_{L22}} \right) + (M_{22} - M_{11}) \left( \frac{t_{L2}^{*}}{t_{L22}} \right) - M_{12} = 0
\]  

(B6)

where the \(M_{ij}\) are entries in the resultant matrix \([M]\) and \(t_{Li}\) and \(t_{Ri}\) are entries in the left and right error matrices. Multiplying \([T_{m,l}^{-1}]\) by \([T_{m,d}]\) yields equations of the form

\[
N_{12} \left( \frac{t_{R1}^{2}}{t_{R22}} \right) + (N_{22} - N_{11}) \left( \frac{t_{R1}^{*}}{t_{R22}} \right) - N_{21} = 0
\]  

(B7)

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 \(|t_{L1}/t_{L21}| > |t_{L12}/t_{L22}|\) and that \(|t_{L11}/t_{L12}| > |t_{L12}/t_{L22}|\). 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:

\[
S_{22L} = \left( \frac{t_{L12}/t_{L22} - S_{M111}}{t_{L11}/t_{L21} - S_{M111}} \right)^{1/2} \]  

(B9)

\[
S_{11R} = \left( \frac{1}{S_{22L}} \right) \left( \frac{t_{L12}/t_{L22} - S_{M11}}{t_{L11}/t_{L21} - S_{M11}} \right)\]  

(B10)

\[
S_{21L}S_{12L} = (t_{L12}/t_{L22} - t_{L11}/t_{L21})S_{22L}\]  

(B11)

\[
S_{12L}S_{21R} = (t_{R1}/t_{R12} - t_{R21}/t_{R22})S_{11R}\]  

(B12)

\[
S_{21L}S_{21R} = S_{M21}(1 - S_{22L}S_{11R})\]  

(B13)
\[ S_{12R}S_{12L} = S_{M12}(1 - S_{22L}S_{11R}) \]  

(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 \( e^{-j\ell} \), where \( \ell \) 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 !
250 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 ""
460 PRINT ""
490 PRINT TAB(10):"You have just activated the THRU-SHORT-DELAY calibration"
500 PRINT TAB(10):"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 END "
630 DISP ""
640 !
650 OUTPUT 1;Clear$
650 ASSIGN @8510 TO 715 ! Establishes Input/Output data transfer path.
650 CLEAR #8510
660 ASSIGN @rem8510 TO 716:FORMAT OFF !
650 CLEAR #rem8510
670 ASSIGN @dataana TO 715:FORMAT OFF !
680 CLEAR #dataana
690 ASSIGN @pid TO 7 !

12
730  
740  DIM Smd_r(201,5),Smd_i(201,5)  ! Dimensions array space  
750  DIM Smd_r(201,5),Smd_i(201,5)  ! in computer memory.  
760  DIM Sns_r(201,3),Sns_i(201,3)  !  
770  DIM Sdat_r(201,5),Sdat_i(201,5)  ! (S-parameter measurements)  
780  DIM Smeas_r(201,5),Smeas_i(201,5)  !  
790  DIM Tmtr(2,2),Tmi(2,2)  ! (T-parameter matrices)  
800  DIM Tmtr(2,2),Tmi(2,2)  !  
810  DIM Tmtr_inv(2,2),Tmi_inv(2,2)  !  
820  
830  DIM Mr(2,2),Mr(2,2)  ! ("M" and "N" data matrices)  
840  DIM Mr(2,2),Mr(2,2)  !  
850  DIM Mr(2,2),Mr(2,2)  !  
860  DIM Mr(2,2),Mr(2,2)  !  
870  DIM Mr(2,2),Mr(2,2)  !  
880  DIM Mr(2,2),Mr(2,2)  !  
890  
900  DIM E00r(201),E00i(201)  ! (Calculated error coefficients)  
910  DIM E11r(201),E11i(201)  !  
920  DIM E10_e01r(201),E10_e01i(201)  !  
930  DIM E23_e32r(201),E23_e32i(201)  !  
940  DIM E10_e01r(201),E10_e01i(201)  !  
950  DIM E23_e32r(201),E23_e32i(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=5025  ! (5025 represents 64)  
1050 Size=3215  ! (3215 for 201 points, 6416 for 401 points)  
1060  
1070  
1080  
1090  
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+Fstop)/200  ! Freq step size  
1120 Freq=Fstart  
1130  
1140 LOCAL 7  
1150 OUTPUT @To8510:"CORROFF;"  ! HP 8510 setup instructions  
1160 OUTPUT @To8510:"POIN201;"  !  
1170 OUTPUT @To8510:"STEP;"  ! Activate for additional accuracy.  
1180 OUTPUT @To8510:"AVERN1000;"  ! 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 \text{Sms}_r(N,3)=\text{Freq} \\
1300 \text{Sms}_i(N,3)=\text{Freq} \\
1310 \text{Sout}_r(N,5)=\text{Freq} \\
1320 \text{Sout}_i(N,5)=\text{Freq} \\
1330 \text{Freq}=\text{req}\times\text{step} \\
1340 \textbf{NEXT } N \\
1350 ! \\
1360 ! \\
1370 \textbf{Menu: !} \\
1380 \text{DISP }"\text{ Enter desired function on softkeys below}" \\
1390 \text{ON KEY 0 LABEL } "\text{THRU}" \text{ GO\textbf{SUB Thru} } \\
1400 \text{ON KEY 1 LABEL } "\text{SHORT}" \text{ GO\textbf{SUB Short} } \\
1410 \text{ON KEY 2 LABEL } "\text{DELAY}" \text{ GO\textbf{SUB Delay} } \\
1420 \text{ON KEY 3 LABEL } "\text{MEAS OUT}" \text{ GO\textbf{SUB Out\text{meas} } } \\
1430 \text{ON KEY 4 LABEL } "" \text{ GO\textbf{TO Menu} } \\
1440 \text{ON KEY 5 LABEL } "\text{CALCULATE}" \text{ GO\textbf{SUB Calculate} } \\
1450 \text{ON KEY 6 LABEL } "\text{SEND MODEL}" \text{ GO\textbf{SUB Send} } \\
1460 \text{ON KEY 7 LABEL } "\text{SEND DATA}" \text{ GO\textbf{SUB Send\_actual} } \\
1470 \text{ON KEY 8 LABEL } "" \text{ GO\textbf{TO Menu} } \\
1480 \text{ON KEY 9 LABEL } "\text{EXIT}" \text{ GO\textbf{TO Exit} } \\
1490 \text{GO\textbf{TO Menu} } \\
1500 ! \\
1510 ! \\
1520 \text{STOP} \\
1530 ! \\
1540 ! \\
1550 ! \\
1560 ! \\
1570 ! \\
1580 !\\n\textbf{SUBROUTINES} \\
1590 ! \\
1600 \text{Thru: !} \quad \text{Reads } S\text{-parameter data on the } "\text{THRU}" \\
1610 ! \quad \text{calibration standard from the HP 8510.} \\
1620 ! \quad (\text{Data in real, imaginary data pairs.}) \\
1630 ! \\
1640 \text{DISP }"" \\
1650 \text{PRINTER IS Crt} \\
1660 \text{OUTPUT 1;Clear\$} \\
1670 \text{BEEP} \\
1680 \text{PRINT TABXY(10,5);"Insert the THRU standard in the FORWARD direction"} \\
1690 \text{DISP }"\text{Press CONTINUE to proceed}" \\
1700 \text{PAUSE} \\
1710 \text{OUTPUT 1;Clear\$} \\
1720 \text{DISP }"" \\
1730 \text{PRINT TABXY(35,5);"PLEASE WAIT"} \\
1740 \text{REMOTE 716} \\
1750 \text{OUTPUT @To8510;"CORROFF;" } \\
1760 ! \\
1770 \text{S11\text{thru: !} \quad \text{Reads } S11 "THRU" data from 8510} \\
1780 \text{OUTPUT @To8510;"S11;SING;"} \\
1790 \text{OUTPUT @To8510;"FORM;OUTPRAW1;"} \\
1800 \text{ENTER @From8510;Preamble,Size,Newdata(*)} \\
1810 \text{FOR } N=1 \text{ TO } 201 \\
1820 \text{Smt}_r(N,1)=\text{Newdata}(N,1) \\
1830 \text{Smt}_i(N,1)=\text{Newdata}(N,2) \\
1840 \textbf{NEXT } N
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1850       OUTPUT @To8510;"CONT;"
1860       1
1870       !
1880 S21_thru:  !  Reads S21 "THRU" data from 8510
1890       OUTPUT @To8510;"S21;SING;"
1900       OUTPUT @To8510;"FORM3;OUTTRAW1;"
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       1
1980       !
1990       !
2000       DISP ""
2010       PRINTER IS Crt
2020       OUTPUT 1;Clear$
2030       BEEP
2040       PRINT TABXY(10,5);"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(35,5);"PLEASE WAIT"
2100       1
2110       1
2120 S12_thru:  !  Reads S12 "THRU" data from 8510
2130       OUTPUT @To8510;"S12;SING;"
2140       OUTPUT @To8510;"FORM3;OUTTRAW1;"
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;OUTTRAW1;"
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!
2350       PRINTS "THRU" data
2360       FOR N=1 TO 201
2370       PRINT Smt_r(N,1),Smt_r(N,2),Smt_r(N,3),Smt_r(N,4)
2370       NEXT N
2380       DISPLAY "Press CONTINUE to proceed."
2390       PAUSE
2400       OUTPUT 1;Clear$
BEEP
PRINT "Transfer of 'THRU' data completed"
OUTPUT @To8510;"CONT;"
Thru_flag=1
LOCAL 7
RETURN
!
!
!
---------------------------------------------------------------------
Delay:  !
!
!
DISP ""
PRINTER IS Crt
OUTPUT 1;Clear$ 
BEEP
PRINT TABXY(10,6);"Insert the DELAY standard in the FORWARD direction"
PAUSE
OUTPUT 1;Clear$ 
DISP ""
PRINT TABXY(35,6);"PLEASE WAIT"
REMOTE 716
OUTPUT @To8510;"COROFF;"
!
!
S11_delay:  !
!
!
DISP ""
PRINTER IS Crt
OUTPUT 1;Clear$ 
DISP ""
PRINT TABXY(10,6);"Insert the DELAY standard in the REVERSE direction"
PAUSE
OUTPUT 1;Clear$ 
DISP ""
ORIGINAL PAGE IS OF POOR QUALITY
PRINT TABXY(35,5);"PLEASE WAIT"

PRINT TABXY(20,6);"Insert the SHORT at port 1 in FORWARD direction"

PRINT TABXY(35,5);"PLEASE WAIT"

PRINT TABXY(25,6);"PLEASE WAIT"

PRINT TFIBXY(20,6);"Insert the SWRT at port 1 in FWD direction"

PRINT TFIBXY(35,6);"PLEASE WAIT"

PRINT TFIBXY(20,6);"Insert the SHORT at port 1 in FORWARD direction"

PRINT TFIBXY(35,5);"PLEASE WAIT"

PRINT TFIBXY(25,6);"PLEASE WAIT"
3520 OUTPUT #10510:"S11;S12;FORM3;OUTPRAW1;"
3530 ENTER #fro510:Preamble,Size,Newdata(*)
3540 FOR N=1 TO 201
3550 Sm_r(N,1)=Newdata(N,1)
3560 Sm_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 BEEP
3670 PRINT TABXY(35,6);"PLEASE WAIT"
3680 !
3690 S22_short: !
3700 OUTPUT #10510:"S22;SING;FORM3;OUTPRAW1;"
3710 ENTER #fro510:Preamble,Size,Newdata(*)
3720 FOR N=1 TO 201
3730 Sm_r(N,2)=Newdata(N,1)
3740 Sm_i(N,2)=Newdata(N,2)
3750 NEXT N
3760 !
3770 !
3780 PRINTER IS Crt!
3790 FOR N=1 TO 201
3800 PRINT Sm_r(N,1),Sm_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 #10510:"CONT;"
3880 Short_flag=1
3890 LOCAL 7
3900 RETURN
3910 !
3920 !
3930 !
3940 Out_meas: !
3950 !
3960 !
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;"CORRFF;"
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 complete;"
4770 OUTPUT @To8510;'CONT;'
4780 Out_flag=1
4790 LOCAL 7
4800 RETURN
4810 !
4820 !
4830 !
4860 Calculate: Performs all TSO mathematics, including
4870 ! matrix manipulations and calculation
4880 ! of error coefficients.
4890 !
4900 DISPl""
4910 OUTPUT 1;Clear$
4920 !
4930 !
4940 IF (Thru_flag=0) THEN No.thru ! Ensures acquisition of all
4950 IF (Delay_flag=0) THEN No_delay ! calibration standard data.
4960 IF (Short_flag=0) THEN No_short !
4970 IF (Out_flag=0) THEN No_out !
4980 GOTO Stds_done !
4990 No.thru: !
5000 PRINT "You forgot to measure THRU standard!"
5010 BEEP 150,.35 !
5020 RETURN !
5030 No_delay: !
5040 PRINT "You forgot to measure DELAY standard!"
5050 BEEP 150,.35 !
5060 RETURN !
5070 No_short: !
5080 PRINT "You forgot to measure SHORT standard!"
5090 BEEP 150,.35 !
5100 RETURN !
5110 No_out!!
5120 PRINT "You forgot to measure the DUT!"
5130 BEEP 150,.35 !
5140 RETURN !
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 !
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(S1,2,3.4,5.6,7,8,9,10,11,12,13,14,15,16,Temp(1),2,3,4)
5480 CALL Tconv(C1,S10,11,12,13,14,15,16,Temp(1),2,3,4)
5490 !
5500 !
5510 !
5520 !
5530 !
5540 !
5550 !
5560 !
5570 !
5580 !
5590 !
5600 !
5610 !
5620 !
5630 !
5640 !
5650 !
5660 !
5670 !
5680 !
5690 !
5700 !
5710 !
5720 !
5730 !
5740 !
5750 !
5760 !
5770 !
5780 !
5790 !
5800 !
5810 !
5820 !
5830 !
5840 !
5850 !
5860 !
5870 !
5880 !
5890 !
5900 !
5910 !
5920 !
5930 !
5940 !
5950 !
5960 !
5970 !
5980 !
5990 !
6000 !
6010 !
6020 !
6030 !
6040 !
6050 !
6060 !
6070 !
6080 !
6090 !
6100 !
6110 !
6120 !
6130 !
6140 !
6150 !
6160 !
6170 !
6180 !
6190 !
6200 !
5710 Ele11_r=E1e22_r
5720 Ele11_i=Ele22_i
5730 Ele22_r=Temp_r
5740 Ele22_i=Temp_i
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= Tmtr*Temp_r
5880 MAT Mr2= Tmtr*Temp_i
5890 MAT Mi1= Tmti*Temp_r
5900 MAT Mi2= Tmti*Temp_i
5910 Mr(1,1)=Mr(1,1)-Mr(2,1) ! "M" coefficients
5920 Mi(1,1)=Mi(1,1)+Mi(2,1)
5930 Mr(1,2)=Mr(1,2)-Mr(2,2)
5940 Mi(1,2)=Mi(1,2)+Mi(2,2)
5950 Mr(2,1)=Mr(2,1)-Mr(2,1)
5960 Mi(2,1)=Mi(2,1)+Mi(2,1)
5970 Mr(2,2)=Mr(2,2)-Mr(2,2)
5980 Mi(2,2)=Mi(2,2)+Mi(2,2)
5990 CPU
6000 CPU
6010 CPU
6020 CPU
6030 Mr(1,1)=Mr(1,1)-Mr(2,1) ! "M" coefficients
6040 Mi(1,1)=Mi(1,1)+Mi(2,1)
6050 Mr(1,2)=Mr(1,2)-Mr(2,2)
6060 Mi(1,2)=Mi(1,2)+Mi(2,2)
6070 Mr(2,1)=Mr(2,1)-Mr(2,1)
6080 Mi(2,1)=Mi(2,1)+Mi(2,1)
6090 Mr(2,2)=Mr(2,2)-Mr(2,2)
6100 Mi(2,2)=Mi(2,2)+Mi(2,2)
6110 Br=Mr(2,2)-Mr(1,1)
6120 Bi-Mr(2,2)-Mi(1,1)
6130 CALL Quac(Mr(1,1),Mr(1,2),Br,Bi,-Mr(1,2),-Mi(1,2),Rmp,Rip,Rmp,Rmp)
6140 CALL Rtop(Rmp,Rip,Rmp,Phase)
6150 Rmp=Mag ! 'plus' root of quadratic
6160 Rmp=Phase !
6170 CALL Rtop(Rmp,Rmp,Phase)
6180 Rmp=Mag ! 'minus' root of quadratic
6190 Rmp=Phase !
6200 IF (Gmp>Rmp) THEN
6210 Ar_m=Rmp !T1L11/T1L21 REAL
6220 Ai_m=Rmp !T1L11/T1L21 IMAG
6230 Br_m=Rmp !T1L11/T1L22 REAL
6240 Bi_m=Rmp !T1L11/T1L22 IMAG
6250 ELSE ! Selects larger magnitude root
6260 Ar_m=Rmp ! for a, smaller for b
ENC 1:
Br=Nr(2,2)-Nr(1,1)
Bi=Ni(2,2)-Ni(1,1)
CALL Quad(Nr(1,2),Ni(1,2),Br,Bi,-Nr(2,1),-Ni(2,1),Rrp,Rip,Rrm,Rim)
CALL Rtop(Rrp,Rip,Mag,Phase)
Rmp=Mag
Rrp=Phase
CALL Rtop(Rrm,Rim,Mag,Phase)
Rmn=Mag
Rpm=Phase
IF (Rmp>Rmn) THEN
Cr_r=Rmp ! TR11/TR12 REAL
Cl_r=Rmn ! TR11/TR12 IMAG
Dr_r=Rpm ! TR21/TR22 REAL
Di_r=Rmn ! TR21/TR22 IMAG
ELSE ! Selects larger magnitude root
Cr_r=Rmn ! for c, smaller for d.
Cl_r=Rmp
Dr_r=Rmn
Di_r=Rmp
END IF
Tnr=Br_m-Sme_r(F,1)
Tni=Br_m-Sme_i(F,1)
Tdr=Ar_m-Sme_r(F,2)
Tdi=Ar_m-Sme_i(F,2)
CALL Cdiv(Tnr,Tni,Tdr,Tdi,X3,Y3)
Tr=X3
Ti=Y3
Unr=Cr_r+Sme_r(F,2)
Uni=Cr_r+Sme_i(F,2)
Udr=Dr_r+Sme_r(F,2)
Udi=Di_r+Sme_i(F,2)
CALL Cdiv(Unr,Uni,Udr,Udi,X3,Y3)
Ur=X3
Ui=Y3
Vnr=Br_m-Smt_r(F,1)
Vni=Br_m-Smt_i(F,1)
Vdr=Ar_m-Smt_r(F,1)
Vdi=Ar_m-Smt_i(F,1)
CALL Cdiv(Vnr,Vni,Vdr,Vdi,X3,Y3)
Vr=X3
Vi=Y3
CALL Cmult(Tr,Ti,Ur,Ui,X3,Y3)
Wr=X3
Wi=Y3
CALL Cmult(Wr,Vi,Vr,Vi,X3,Y3)
Zr=X3
Zi=Y3
CALL Rtop(Zr,Zi,Mag,Phase)
Zm=Mag
Zp=Phase
S22a_m=SQRT(Zm)
S22a_p=Zp/2
CALL Ptor(S22a_m,S22a_p,X,Y)
S22a_r=X
S22a_i=Y
CALL Cdiv(T1,T2,S22a_r,S22a_i,X3,Y3)
Gam_r=X3
Gam_i=Y3
CALL Rtop(Gam_r,Gam_i,Mag,Phase)
! Selects proper root for e11
IF (ABS(Phase)<90) AND (ABS(Phase)>270) THEN Gamma_skip !OPEN
! If ABS(Phase)<90 AND (ABS(Phase)<270) THEN Gamma_skip !SHORT
S22a_r=-S22a_r
S22a_i=-S22a_i
Gamma_skip:
! Uses a,b,c,d and e11 to compute remaining error coefficients.
CALL Cdiv(Vr,V1,S22a_r,S22a_i,X3,Y3)
S11b_r=X3
S11b_i=Y3
B_ar=Br_m-Ar_m
B_ai=Bi_m-Ai_m
CALL Cmult(B_ar,B_ai,S22a_r,S22a_i,X3,Y3)
E10_e01r(F)=X3 !S21_aS12a real
E10_e01i(F)=Y3 !S21_aS12a imag
C_dr=Cr_n-Br_n
C_di=Ci_n-Bi_n
CALL Cmult(C_dr,C_di,S11b_r,S11b_i,X3,Y3)
E23_e32r(F)=X3 !S12bS21b real
E23_e32i(F)=Y3 !S12bS21b imag
CALL Cmult(S22a_r,S22a_i,S11b_r,S11b_i,X3,Y3)
E11_e22r=F3
E11_e22i=Y3
Var=1-X3
CALL Cmult(Smt_r(F,3),Smt_i(F,3),Var,-E11_e22i,X3,Y3)
E10_e32r(F)=X3 !S21_aS21b real
E10_e32i(F)=Y3 !S21_aS21b imag
CALL Cmult(Smt_r(F,2),Smt_i(F,2),Var,-E11_e22i,X3,Y3)
E23_e01r(F)=X3 !S12bS12a real
E23_e01i(F)=Y3 !S12bS12a imag
E00r(F)=Br_m !S11a real
E00i(F)=Bi_m !S11a imag
E33r(F)=Br_n !S22b real
E33i(F)=Bi_n !S22b imag
E11r(F)=S22a_r
E11i(F)=S22a_i
E22r(F)=S11b_r
E22i(F)=S11b_i
! 
! Determines complex propagation coefficient gamma
!
! NOW SHIFT REFERENCE PLANE TO ACTUAL CHIP BOUNDARY
CALL Cmult(Mr(2,1),Mi(2,1),Br_m,Bi_m,X3,Y3)
Gr=X3+Mr(2,2)
Gi=Y3+Mi(2,2)
CALL Rtop(Gr,gi,Mag,Phase)
Gam_im=LOG(Mag)
Gam_lp = Phase × PI/180
Alpha = Gam_lm / Ldelay
Beta = Gam_lp / Ldelay
RAD

Er_ref = EXP(-Alpha × L_dut) × COS(-Beta × L_dut)
Ei_ref = EXP(-Alpha × L_dut) × SIN(-Beta × L_dut)

DEG

! Multiplies error coefficients by shifting terms

CALL Cmult(Br_m, Bi_m, Er_ref, Ei_ref, X3, Y3)

E00r(F) = X3
E00l(F) = Y3

CALL Cmult(S22a_r, S22a_i, Er_ref, Ei_ref, X3, Y3)

E11r(F) = X3
E11l(F) = Y3

CALL Cmult(S11b_r, S11b_i, Er_ref, Ei_ref, X3, Y3)

E22r(F) = X3
E22l(F) = Y3

CALL Cmult(-Dr_n, -Dl_n, Er_ref, Ei_ref, X3, Y3)

E33r(F) = X3
E33l(F) = Y3

E10_e01rt = E10_e01r(F)
E10_e01lt = E10_e01l(F)

CALL Cmult(E10_e01rt, E10_e01lt, Er_ref, Ei_ref, X3, Y3)

E10_e01r(F) = X3
E10_e01l(F) = Y3

E10_e32rt = E10_e32r(F)
E10_e32lt = E10_e32l(F)

CALL Cmult(E10_e32rt, E10_e32lt, Er_ref, Ei_ref, X3, Y3)

E10_e32r(F) = X3
E10_e32l(F) = Y3

E23_e32rt = E23_e32r(F)
E23_e32lt = E23_e32l(F)

CALL Cmult(E23_e32rt, E23_e32lt, Er_ref, Ei_ref, X3, Y3)

E23_e32r(F) = X3
E23_e32l(F) = Y3

E23_e01rt = E23_e01r(F)
E23_e01lt = E23_e01l(F)

CALL Cmult(E23_e01rt, E23_e01lt, Er_ref, Ei_ref, X3, Y3)

E23_e01r(F) = X3
E23_e01l(F) = Y3

Extraction:

S12m_r = Smeas_r(F, 2)
S12m_l = Smeas_i(F, 2)
E23_e01rt = E23_e01r(F)
E23_e01lt = E23_e01l(F)

CALL Cdiv(S12m_r, S12m_l, E23_e01rt, E23_e01lt, X3, Y3)

Ar = X3
A_l = Y3

S21m_r = Smeas_r(F, 3)
S21m_l = Smeas_i(F, 3)
E10_e32rt = E10_e32r(F)
E10_e32lt = E10_e32l(F)

CALL Cdiv(S21m_r, S21m_l, E10_e32rt, E10_e32lt, X3, Y3)

Br = X3
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 Cmul(E11t,E11t, Cd_abr, Cd_abi, X3,Y3)  
8540  S22num_r=O+r*X3  
8550  S22num_i=O+i*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  RETURN  
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 coefficients 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 of data 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 @Te8510;"DEL: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  !
! FOR N=1 TO 201
  Data(N,1)=0
  Data(N,2)=0
NEXT N
OUTPUT @To6510;"DISPDATA"
OUTPUT @To6510;"CURRFF;CAL1;CALIFUL2;FORM;INPUCALC01;"
OUTPUT @Datatoana;Preamble;Size;Data(*)
PRINT "COEFFICIENT 01 DATA SENT"
!
FOR N=1 TO 201
  Data(N,1)=0
  Data(N,2)=0
NEXT N
OUTPUT @To6510;"INPUCALC02;"
OUTPUT @Datatoana;Preamble;Size;Data(*)
PRINT "COEFFICIENT 02 DATA SENT"
!
FOR N=1 TO 201
  Data(N,1)=1
  Data(N,2)=0
NEXT N
OUTPUT @To6510;"INPUCALC03;"
OUTPUT @Datatoana;Preamble;Size;Data(*)
PRINT "COEFFICIENT 03 DATA SENT"
!
FOR N=1 TO 201
  Data(N,1)=0
  Data(N,2)=0
NEXT N
IF Isol_flag=0 THEN Omit_isol_1
FOR N=1 TO 201
  Data(N,1)=Smi_r(N,2)
  Data(N,2)=Smi_i(N,2)
NEXT N
Omit_isol_1:
!
OUTPUT @To6510;"INPUCALC04;"
OUTPUT @Datatoana;Preamble;Size;Data(*)
PRINT "COEFFICIENT 04 DATA SENT"
!
FOR N=1 TO 201
  Data(N,1)=0
  Data(N,2)=0
NEXT N
OUTPUT @To6510;"INPUCALC05;"
OUTPUT @Datatoana;Preamble;Size;Data(*)
PRINT "COEFFICIENT 05 DATA SENT"
!
FOR N=1 TO 201
  Data(N,1)=1
  Data(N,2)=0
NEXT N
OUTPUT @To6510;"INPUCALC06;"
OUTPUT @Datatoana;Preamble;Size;Data(*)
PRINT "COEFFICIENT 06 DATA SENT"
FOR N=1 TO 201
Data(N,1)=0
Data(N,2)=0
NEXT N

OUTPUT @To510:"INPUCALC07;"
OUTPUT @Dataana:Preamble;Size;Data(*)
PRINT "COEFFICIENT 07 DATA SENT"

 FOR N=1 TO 201
Data(N,1)=0
Data(N,2)=0
NEXT N

OUTPUT @To510:"INPUCALC08;"
OUTPUT @Dataana:Preamble;Size;Data(*)
PRINT "COEFFICIENT 08 DATA SENT"

 FOR N=1 TO 201
Data(N,1)=1
Data(N,2)=0
NEXT N

OUTPUT @To510:"INPUCALC09;"
OUTPUT @Dataana:Preamble;Size;Data(*)
PRINT "COEFFICIENT 09 DATA SENT"

 FOR N=1 TO 201
Data(N,1)=0
Data(N,2)=0
NEXT N

IF Isol_flag=0 THEN Omit_isol_2
 FOR N=1 TO 201
Data(N,1)=Sml_r(N,1)
Data(N,2)=Sml_i(N,1)
NEXT N

Omit_isol_2: !

OUTPUT @To510:"INPUCALC10;"
OUTPUT @Dataana:Preamble;Size;Data(*)
PRINT "COEFFICIENT 10 DATA SENT"

 FOR N=1 TO 201
Data(N,1)=0
Data(N,2)=0
NEXT N

OUTPUT @To510:"INPUCALC11;"
OUTPUT @Dataana:Preamble;Size;Data(*)
PRINT "COEFFICIENT 11 DATA SENT"

 FOR N=1 TO 201
Data(N,1)=1
Data(N,2)=0
NEXT N

OUTPUT @To510:"INPUCALC12;"
OUTPUT @Dataana:Preamble;Size;Data(*)
PRINT "COEFFICIENT 12 DATA SENT"
10140 OUTPUT @To6510;"SAVC;CALS1;CONT;CORRON;CALS1;"
10150 OUTPUT @To6510;"DISPDATA;"
10160 OUTPUT @To6510;"MENUPRID;"
10170 LOCAL 7
10180 DISP ""
10190 PRINT "DATA TRANSFER COMPLETED"
10200 FOR N=1 TO 201
10210 PRINT USING "SD,00000":E00r(N);E11r(N);E10_e01r(N);E22r(N);E10_e32r(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$;
10350 DISP ""
10360 PRINTER IS Crt
10370 IF Calc_flag=1) THEN Mod_flag:
10380 PRINT "You must calculate error coefficients before transfer"
10390 RETURN
10400 Mod_flag: !
10410 IF (Model_flag=1) THEN Go_to_it
10420 PRINT "You must send error mode before OUT data"
10430 RETURN
10440 Go_to_it: !
10450 REMOTE 716
10460 OUTPUT @To6510;"CORRON;CALS1;"
10470 FOR N=1 TO 201
10480 Data(N,1)=Scut_r(N,1)
10490 Data(N,2)=Scut_i(N,1)
10500 NEXT N
10510 OUTPUT @To6510;"HOLD;FORM1;INPRHR1;"
10520 OUTPUT @Datataon;Preamble,Size,Data(*)
10530 PRINT "Sl Sent"
10540 !
10550 FOR N=1 TO 201
10560 Data(N,1)=Scut_r(N,3)
10570 Data(N,2)=Scut_i(N,3)
10580 NEXT N
10590 !
10600 OUTPUT @To6510;"HOLD;FORM1;INPRHR2;"
10610 OUTPUT @To6510;"INPRHR2;"
10620 OUTPUT @Datataon;Preamble,Size,Data(*)
10630 PRINT "S21 Sent"
10640 !
10650 FOR N=1 TO 201
10660 Data(N,1)=Scut_r(N,2)
10670 Data(N,2)=Scut_i(N,2)
10670 NEXT N
10680 !
10690 OUTPUT @To6510;"HOLD;FORM1;INPRHR3;"
10590  OUTPUT @Tc8510:"INPUH3;"
10700  OUTPUT @DataOana;Preamble,Size,Data(*)
10710  PRINT "S12 Sent"
10720  !
10730  FOR N=1 TO 201
10740    Data(N,1)=Sdut_r(N,4)
10750    Data(N,2)=Sdut_i(N,4)
10760  NEXT N
10770  !  OUTPUT @Tc8510:"HOLD;FORMS;INPUH4;"
10780  OUTPUT @Tc8510:"INPUH4;"
10790  OUTPUT @DataOana;Preamble,Size,Data(*)
10800  PRINT "S22 Sent"
10810  !  OUTPUT @Tc8510:"CONT;"
10820  LOCAL 7
10830  !  PRINTER IS 701
10840  !  FOR N=1 TO 201
10850    PRINT N;Sdut_r(N,1);Sdut_r(N,2);Sdut_r(N,3);Sdut_r(N,4)
10860    PRINT N;Sdut_i(N,1);Sdut_i(N,2);Sdut_i(N,3);Sdut_i(N,4)
10870  !  NEXT N
10880  !  PRINTER IS 1
10890  RETURN
10900  !
10910  Exit:  !
10920  DISP ":"
10930  OUTPUT 1;Clear$
10940  DISP ":"
10950  PRINTER IS Crt
10960  PRINT TA8XY(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, Rr, Rr, Rm, Rm)
11050    CALL Cmult(Br, Bi, Br, Bi, X3, Y3)
11060    Bsqr=X3
11070    Bsci=Y3
11080    CALL Cmult(Ar, Ai, Cr, Ci, X3, Y3)
11090    Ac4r=4*X3
11100    Ac4i=4*Y3
11110    Tr=Bsqr-Ac4r
11120    Ti=Bsci-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=Br*+Y
11190    Numx_m=Br*-X
11200    Numy_m=Br*-Y
11210    Denomx=2*Ar
11220    Denomy=2*Ai
11230    CALL Cdiv(Numx_p, Numy_p, Denomx, Denomy, X3, Y3)
11240    Rrp=X3
Rip=Y3
CALL Cdiv(Numx_m,Numy_m,Denomx,Denomy,X3,Y3)
Rm=X3
Ri=Y3
SUB END
!
!
! Converts an S-parameter matrix to a T-parameter matrix
!
!
SUB Cdiv(S11r,S11i,S12r,S12i,S21r,S21i,S22r,S22i,T11r,T11i,T12r,T12i)
CALL Cmul(S11r,S11i,S22r,S22i,X3,Y3)
D1r=X3
D1i=Y3
CALL Cmul(S12r,S12i,S21r,S21i,X3,Y3)
Drr=X3
Dri=Y3
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Performs polar to rectangular conversion

```
11820 SUB Ptor(Mag,Phase,X,Y)
11840 DEG
11850 X1=Mag
11860 X=X1*COS(Phase)
11870 Y=X1*SIN(Phase)
11880 END
11900 SUB Rtop(X,Y,Mag,Phase)
11940 DEG
11950 Mag=SQRT(X^2+Y^2)
11960 Phase=2*ATN(Y/(X+Mag))
11970 END
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Note: [Microstrip line characteristic impedance = 500]
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**Table 1—Continued.**

[Microstrip line characteristic impedance = 50Ω]

(b) WR-28
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TABLE 1—CONTINUED.

[Microstrip line characteristic impedance = 50Ω]

(d) WR-15

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ORIGINAL PAGE 13
OF POOR QUALITY
**TABLE I—CONCLUDED.**

[Microstrip line characteristic impedance = 500]

(e) WR-12

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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.