



# National Institute of Standard and Technology

## Report of Investigation

### Reference Material 8130

#### Coplanar Waveguide Calibration Set

This Reference Material (RM) is intended for use by industrial laboratories that wish to implement the procedure described in Part 1 of the NIST/Industrial MMIC Consortium's "Proposed Procedures for Verifying Probe Station Integrity and On-wafer Measurement Accuracy" for the measurement of microwave probe station stability and for verifying the ability to repeat on-wafer microwave measurements performed at NIST. RM 8130 measures the instrument drift (stability) of microwave probe stations and verifies the ability of a laboratory to repeat NIST measurements. It consists of a coplanar waveguide (CPW) calibration set fabricated on a gallium arsenide wafer. Each RM is individually tested, bears a boule number, wafer number, a calibration set number (see Table 1), and comes with a data disk unique to the RM. The RM wafers are mounted on a glass slide for ease of handling.

Table 1. RM Calibration Set Data

Calibration Set Serial No.	
Boule No.	5634
Wafer No.	
Measured Line Capacitance (information value only)	1.7877 pF/cm

CPW is a planar microwave transmission line often used in microwave circuits and for microwave probe-station calibrations and is comprised of three conductors; a signal line, and two outer ground planes evaporated on the supporting wafer. Each NIST calibration set contains standards for a multiline CPW thru-reflect-line (TRL) calibration and twelve verification devices.

The data disk accompanying the RM, contains reference values measured at NIST and bounds on the measurement errors due to instrument drift. The values are only intended for comparison to those measured in the user's laboratory following the same calibration and measurement procedure as NIST. A complete error analysis is still in process for these reference values. For example, calibrations performed on some units have additional systematic errors, due to nonuniformity of the metal resistance, that are not included in the reported error bounds. Therefore, the RMs are for instrument verification only: calibrating other measurements with these RMs will result in significant systematic errors.

The technical direction leading to development of this RM was provided by D.F. Williams of the NIST Electromagnetic Fields Division. Assistance was provided by R.K.F. Kaiser, J.M. Morgan, R.B. Marks, D. Walker, R.M. Judish, and J.R. Juroskek of the NIST Electromagnetic Fields Division, M. Young of the NIST Optoelectronics Division, L.R. Vale of the NIST Electromagnetic Technology Division, and K.J. Coakley of the NIST Statistical Engineering Division.

The technical and support aspects involved in the preparation and issuance of this RM were coordinated through the Standard Reference Materials Program by N.M. Trahey.

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## Description of the RM

The RM consists of on-wafer calibration standards fabricated on a semi-insulating gallium arsenide (GaAs) substrate, with a thickness between 450  $\mu\text{m}$  and 550  $\mu\text{m}$ , and is mounted on a glass slide.

Figure 1 shows the layout of the RM. It contains a set of thru-reflect-lines (TRL) with a 550  $\mu\text{m}$  long CPW thru line, five longer lines of length 2.685 mm, 3.75 mm, 7.115 mm, 20.245 mm, and 40.55 mm, and two shorts offset 225  $\mu\text{m}$  from the beginning of the line. The lines are designed with a center conductor width of 64  $\mu\text{m}$  separated from two 261.5  $\mu\text{m}$  wide ground planes by two 42  $\mu\text{m}$  gaps. These dimensions are typically held to  $\pm 5 \mu\text{m}$  from wafer to wafer. The variation of these geometries within a wafer is typically less than  $\pm 2 \mu\text{m}$ .

The RM also contains twelve verification devices. The data disk provided contains the S-parameters of these passive test structures as measured by NIST. The RM also contains a large metalized contact test area useful for verifying that the probes are planar and make good contact with the metalization on the RM. The RM type and calibration set number are indicated on the left side of the RM.

## Storage and Handling

Store the RM in its plastic case in a cool and dry environment and avoid subjecting the RM to temperature extremes as mismatched thermal expansion coefficients can cause the GaAs calibration set to delaminate from the glass slide carrier. The RM may be handled by the edges of the slide on which it is mounted. The calibration substrate itself is fabricated on a GaAs substrate and should not be touched as GaAs is a toxic material. The RM should be replaced when the gold on the contact pads becomes dirty, worn, or damaged or when visual inspection of the RM under a microscope reveals physical deterioration of any kind.

## Instructions for Use

The proposed procedures require that the industrial laboratory perform a multiline TRL calibration [1] with reference impedance correction based on the methods of [2] and [3] using the artifacts supplied on the RM. The laboratory measures twelve verification devices on the RM and then repeats the initial calibration. A comparison of the measurements performed by the laboratory to the same measurements performed at NIST verifies the ability of the laboratory to repeat NIST measurements. The calibrations performed before and after the test structure measurements quantify the drift of the probe station with the method of [4]. The actual measurement differences are also compared to bounds on the measurement deviations estimated from the measurements of instrument drift at the industrial laboratory and at NIST.

Both NIST and the laboratory use the same calibration artifacts and test structures, all of which reside on the RM. Thus this procedure is strictly comparative. *It verifies only that the laboratory can repeat NIST's measurements using identical calibration standards and software.* The systematic error in the NIST measurements is not known at this time and is being assessed.

In addition, RM 8130 is not applicable to the measurement of user devices and *therefore cannot be used to verify the accuracy of user measurements.* The RM calibration standard results in a calibration that is customized for the test devices on the RM and cannot correct for the specific probe-tip-to-transmission-line launch leading to the user device. An accurate calibration for user devices usually requires custom standards embedded in the same launch. This is discussed at greater length in [4-6], and in the NIST/Industrial MMIC Consortium's "Proposed Procedures for Verifying Probe Station Integrity and On-wafer Measurement Accuracy."

## Characterization of the RM

The methods of [2] and [3] are used to determine the characteristic impedance of the CPW lines. These methods require low-loss, low-dispersion substrates. To insure that the NIST substrates have these properties, the dielectric constant of samples from each boule of substrate material is measured at approximately 10 GHz using the precision cavity method described in [7].

NIST performs an initial calibration on the control RM, measures the verification devices on the control RM, performs a calibration on the candidate RM, measures the twelve verification devices on the candidate RM, and recalibrates on the candidate RM. The two calibrations on the candidate RM are used to estimate the instrument drift during the NIST measurements using the method of [4]. The calibrations on the control and candidate RMs are compared with the method of [4] to insure the overall integrity of the calibration sets. The measurements of the twelve test structures on the control and candidate RMs are compared and evaluated to detect operator and other gross measurement errors.

## Instrument Drift Errors

The estimates of the bounds on the errors due to instrument drift are based on the assumption that measurement errors are caused by a small monotonic drift of the measurement instrumentation: *Random errors are assumed to be insignificant compared to this drift and, due to the comparative nature of the experiment, systematic calibration errors are neglected.* The bounds are estimated from a comparison of calibrations performed both before and after the measurements. The bounds and their estimation are discussed in detail in [4-6], and in the NIST/Industrial MMIC Consortium's "Proposed Procedures for Verifying Probe Station Integrity and On-wafer Measurement Accuracy."<sup>1</sup>

## Preliminary Preparation

Before beginning, a set of calibration structures and verification devices from NIST and a data disk with the NIST measurements of the verification devices are required. Measurement data and programs are available for both HP 9000 series computers running HP-BASIC 5.1 or greater and PCs running HTBasic 4.0 or greater with complex arithmetic.<sup>2</sup> Occasionally data saved on disks formatted on a different disk drive cannot be reread. The procedure also creates a number of new data files. Thus it is recommended that each verification be initiated by copying the files from the disk supplied by NIST to a hard drive or another disk.

## Measurement:

- Step 1. Insure that there is at least one free calibration set in the VNA. If a HP computer load is being used, run program LOADFREQ. This will set up the following frequency list (in GHz): 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, ..., 39, 40. The program will also set any VNA reference plane translations to zero. If a PC is being used, do this step directly using the VNA front panel. If an analyzer that is not capable of performing measurements over the entire range is being used, enter any continuous subset of these frequencies into the VNA frequency list.
- Step 2. Load and run program MultiCal<sup>®</sup>. The program should load the calibration menu CALMENU from the disk and recognize the analyzer. Using this calibration menu, contact each calibration standard on the NIST wafer; then, measure its uncorrected S-parameters by moving the cursor to the appropriate standard and pressing the "MEASURE" softkey. After all the measurements are complete, calibrate the probe station to the probe-tips by pressing the "DEEMBED" softkey and load the calibration into the analyzer. Now exit from the MultiCal<sup>®</sup> output menu back to the main menu.

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<sup>1</sup>Copy included with this document for information.

<sup>2</sup>The use of a tradename in this report of investigation is for identification only and does not imply endorsement of the product by the National Institute of Standards and Technology.

- Step 3. Load the menu “GAAS” into MultiCal by pressing the “GET menu” softkey. Contact each of the verification devices on the NIST wafer and measure its S-parameters by moving the cursor to the appropriate standard and pressing the “MEAS” softkey. One should now be reading data corrected by the calibration performed in Step 2. Do not press the “DEEMBED” softkey. Repeat for the menu “GAAS 1”.
- Step 4. Load the menu “CALMEN2” into MultiCal with the “GET menu” softkey. Reconnect each of the calibration standards on the NIST GaAs standard set and measure its S-parameters by pressing the “MEAS” softkey. Again, one should be reading data corrected by the calibration performed in Step 2.

#### Analysis:

- Step 5. With the menu “CALMEN2” still loaded in MultiCal, press the “A” key to disable the VNA interface and then press the “DEEMBED” softkey. After the program has finished with the calculations, it will enter the MultiCal output menu. From this output menu, save the S-parameters of the two probe heads in files S-P1 and S-P2 and the effective dielectric constant in file EPS. Now exit from MultiCal by pressing “Q”.
- Step 6. Load and run program VERIFY. Press the “start” softkey. After the calculations have finished, select the “50 ohm” softkey and save the data in BDAT format in the file “VER.”
- Step 7. Load and run the program EVALUATE. Select the default ‘V’ option to perform the instrument verification analysis and the one-tier ‘1’ option. EVALUATE will then plot the estimated bounds on measurement errors due to instrument drift during the experiment.

The preceding instructions are also found in Part 1 of the NIST/Industrial MMIC Consortium’s “Proposed Procedures for Verifying Probe Station Integrity and On-wafer Measurement Accuracy”.

#### Interpretation of Results

The RM comparison procedure generates a graph comparing the results just generated to those obtained at NIST. The curve labeled “laboratory instrument drift,” which is determined from a comparison of the calibrations performed in the user’s laboratory before and after the measurements of the twelve verification devices, is an estimated upper bound on measurement error due to instrument drift. This bound typically increases with frequency to a value between 0.01 and 0.1 at 40 GHz: values larger than this indicate either an atypically unstable instrument, poorly repeated probe placement, or operator error.

The program will also plot the worst case deviations of the scattering parameters of the twelve verification devices measured in the user’s laboratory and by NIST. The plotted value for each device is the maximum  $|S_{ij} - S_{ij}^{\oplus}|$  for  $ij \in \{11, 12, 21, 22\}$ , where  $S_{ij}$  is the device scattering parameter measured by the laboratory and  $S_{ij}^{\oplus}$  is the device scattering parameter measured by NIST.

The curve labeled “NIST instrument drift” is the estimated upper bound on the error in the NIST measurements due to instrument drift and the sum of the NIST and laboratory bounds is labeled “sum of laboratory and NIST instrument drift.” This sum should be greater than the maximum measurement deviations for the twelve devices plotted on the graph. Measurement deviations that exceed this sum indicate the presence of significant measurement errors not due to instrument drift. Some possibilities are reversed test ports, offsets in the frequency synthesizer, random contact error, or failure to properly contact a test device.

## REFERENCES

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- [7] Vanzura, E.J., Weil, C.M., and Williams, D.F., "Complex Permittivity Measurements of Gallium Arsenide Using a High-Precision Resonant Cavity," Proceedings of the 1992 Conference on Precision Electromagnetic Measurements, pp. 103-104, (1992).

Figure 1. The layout of the coplanar waveguide RM. The thru lines have a physical length of 550  $\mu\text{m}$ . The labels for the other lines in the calibration set indicate their additional length with respect to the 550  $\mu\text{m}$  thru line.

*Users of this RM should ensure that the certificate in their possession is current. This can be accomplished by contacting the SRM Program at: Telephone (301) 975-6776 (select "Certificates"), Fax (301) 926-4751, e-mail [srminfo@nist.gov](mailto:srminfo@nist.gov), or via the Internet <http://ts.nist.gov/srm>.*