On-Wafer Calibration Techniques for Measurement of Microwave Circuits and Devices on Thin Substrates

Jaime Plá, Wayne Struble, and François Colomb

Raytheon Advanced Device Center
358 Lowell Street, Andover, Massachusetts 01810

Abstract - Two sets of on-wafer microstrip calibration standards were fabricated on 50 μm GaAs and 25 μm Polyimide substrates for the purpose of measuring microwave circuits and devices up to 50 GHz. The accuracies of one and two tier LRM and TRL calibration techniques were investigated on PHEMT devices. Substantial improvements were found with the use of a weight function in the averaging of two tier TRL and LRM-TRL calibrations. The dependence of the isolation on the spacing between the input and output probes was also determined for these thin substrates.

INTRODUCTION

Most on-wafer microwave S-parameter measurements are performed using coplanar calibration standards fabricated on thick alumina substrates. However, most MMIC circuits are fabricated on thin GaAs wafers using microstrip transmission lines. To overcome this inconsistency, we have designed and fabricated LRM and TRL calibration standards on 50 μm thick GaAs and 25 μm thick polyimide substrates which can operate up to 50 GHz.

CALIBRATION STANDARDS

Commonly used 12-term error correction schemes do not account for MMIC wafer probe leakage and coupling [1]. Therefore, the first issue that was considered in the design of the calibration standards was the minimum separation between probes required to accurately measure microwave devices with high isolation. For example, Raytheon PHEMT devices have a reverse transmission (S12) of about -35 to -40 dB at high drain currents. To accurately measure S12, probe to probe coupling should be at least 20 dB lower. Isolation measurements were made to determine the minimum separation of the probes to achieve this degree of isolation. Figure 1 shows that at 50 GHz a separation of 1000 μm will provide an isolation of 51 dB when the probes are in the air and 61 dB when the probes are making contact to 50 μm thick GaAs. Therefore, 1000 μm minimum probe spacing was chosen in the design of the GaAs calibration standards. For the 25 μm thick polyimide substrate, a probe separation of 1000 μm will provide an isolation of 64.2 dB at 50 GHz.

The calibration standards for the 50 μm thick GaAs mask set included open and short circuited REFLECTs, a 1000 μm THRU, mesa and tantalum resistors used as lowband and broadband LOADs, various 50 ohm delay lines, offset open and shorts for calibration verification, and discrete PHEMT devices of different peripheries (Figure 2 and 3). With these standards, we were able to test several calibration techniques including OSL, LRM, TSD and TRL. As shown in Figure 4, the longest delay line is about 20 degrees at .75 GHz. The shorts are achieved by using a 25 μm square low inductance via hole to ground. The DC resistances of the mesa and tantalum resistors were within .15 ohms of each other.

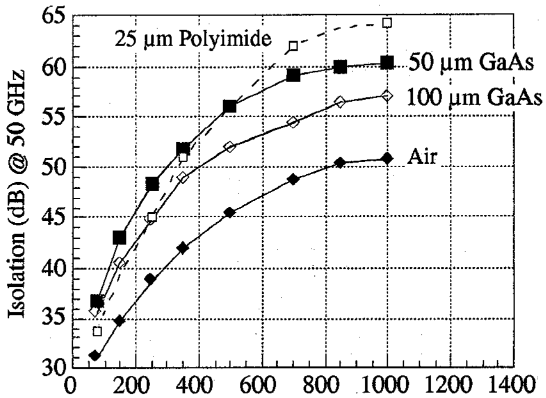


Fig 1: RF isolation of GGB 50A-GSG-100 wafer probes as a function of probe separation at 50 GHz.

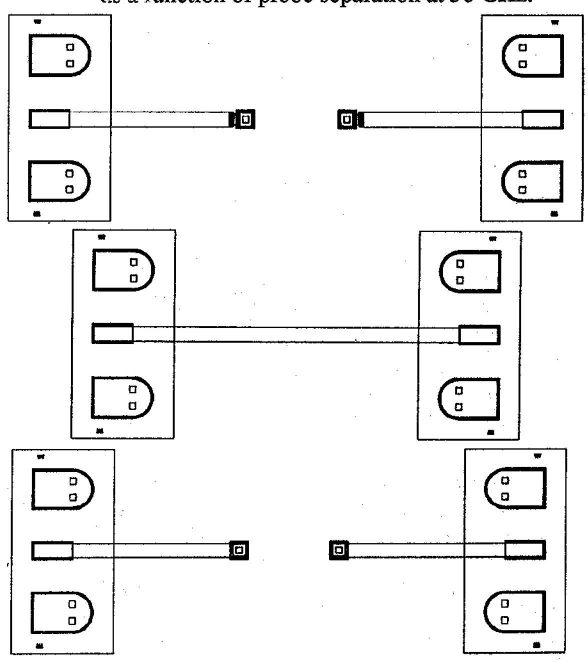


Fig 2: On-wafer microstrip 50 μm thick calibration standards. From top to bottom: 50 ohm mesa resistors, 1000 μm long THRU and low inductance REFLECT shorts.

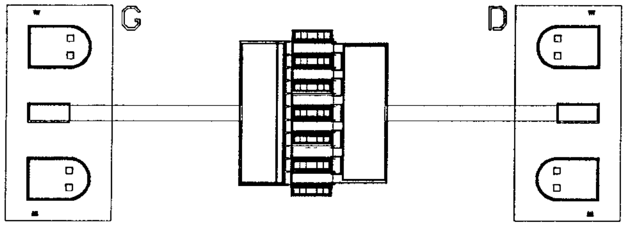


Fig 3: 0.15 μm x 1.2 mm PHEMT on 50 μm thick GaAs.

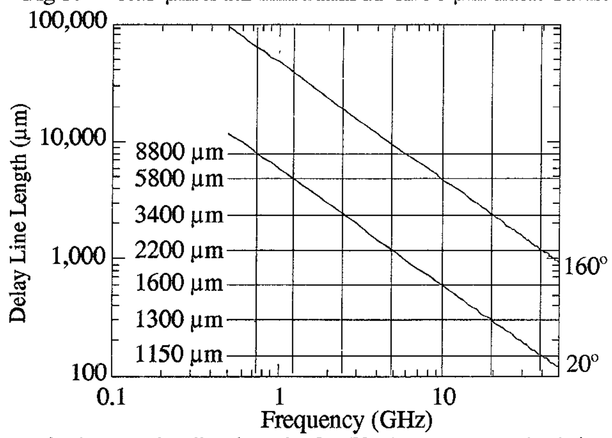


Fig 4: Delay line lengths for 50 ohm TRL standards in 50 μm thick GaAs.

A set of microstrip line calibration standards patterned on a 25 μm thick polyimide layer was also available for testing the calibration techniques presented in this paper. The standards include opens, low inductance shorts, and a set of 50 ohm lines for the purpose of TRL calibration with center frequency at 35 GHz (Figure 5).

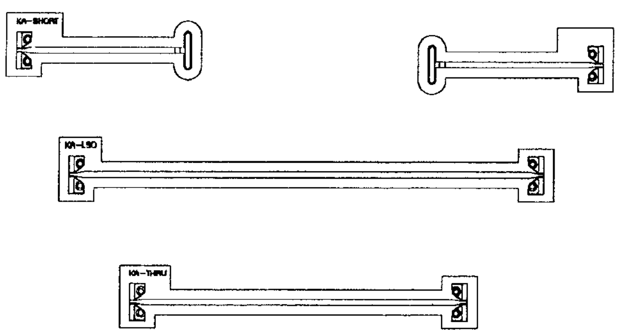


Fig 5: TRL standards on 25 μm thick polyimide layer. From top to bottom: low inductance REFLECT shorts, 90 degree LINE, and zero length THRU.

A tapered transition with a pair of ground vias was designed to provide a low insertion loss connection between the coplanar probe and the 50 ohm microstrip line. The design of the transition was fine tuned using *em*™ Sonnet. The width of the 50 ohm microstrip line was determined using LineCalc™ assuming ε_r =3.3. When two transitions are connected back to back with a 300 μm long section of 50 ohm line, the computed return loss is better than 20.2 dB from near DC to 50.0 GHz. The insertion loss increases from 0.06 dB at 5 GHz to 0.15 dB at 50.0 GHz including conductor loss with skin effect. The dielectric loss was not included.

TRANSMISSION LINE PARAMETERS NEEDED FOR CALIBRATION

If the change in characteristic impedance with frequency of the line standards is not properly accounted for, a TRL calibration can yield erroneous results particularly at low frequencies. As shown by R. G. Marks [2], the complex characteristic impedance is calculated with the equation:

$$Z_c = \frac{\gamma}{j\omega C + G} \qquad (1)$$

where γ is the propagation constant of the line, C and G are the shunt capacitance and shunt conductance per unit length. The propagation constant of the GaAs lines was measured using the difference between the longest and the shortest of the lines.

Two of the four line parameters that are needed to perform the calibration techniques presented here depend on the distributed parameters of the microstrip line. These are: 1) the capacitance per unit length C, and 2) the conductance per unit length G. These parameters were determined from the equations [3]

$$C = \frac{\sqrt{\varepsilon_{eff}}}{Z_c\, c} \quad (2a) \qquad G = \omega\, C \tan\delta \quad (2b)$$

where ε_{eff} is the effective dielectric constant, Z_C is the line characteristic impedance, c is the speed of light, ω is the angular frequency, and $\tan\delta$ is the loss tangent of the substrate.

In the case of GaAs, the conductance per unit length was assumed to be zero [2,4]. The effective dielectric constant was calculated using the phase difference between two known lengths of transmission line:

$$\varepsilon_{eff} = \left(\frac{c}{\lambda f}\right)^2 = \left(\frac{c(\theta_2 - \theta_1)}{360 f(l_2 - l_1)}\right)^2 \qquad (3)$$

where c is the speed of light (m/S), λ is the wavelength (m), f is the frequency (Hz), l is the physical length of the line (m), and θ is the electrical length of the line (degrees).

In the case of polyimide, the dielectric constant ε_r and the loss tangent $\tan\delta$ were determined from transmission measurements of lightly coupled microstrip line resonators [4] fabricated on the same wafer as the calibration standards. The dielectric constant was obtained by measuring resonators of several lengths and fitting the transmission data to simulations using ACADEMY™. The line attenuation, α_0, was determined from the measurement of the quality factor of the resonances of S_{21}, and can be written as the sum $\alpha_0=\alpha_c+\alpha_d$, where α_c is the attenuation due to conductor loss and α_d is attenuation due to dielectric loss. The conductor attenuation was evaluated numerically using LINECALC™ and the full-wave transmission line analysis program PCAAMT [5]. This allowed extraction of the dielectric attenuation α_d. Knowing ε_r, ε_{eff}, ω, and α_d, the loss tangent appearing in (2b) can be obtained using known formulas [6].

The values for the GaAs and the Polyimide substrates obtained from this procedure are given in Table I.

Parameter	GaAs	Polyimide
ε_r	13.0	3.33
ε_{eff}	8.13	2.64
$\tan\delta$	0.0001	0.0120
C	191.62 pF/m	107.0 pF/m
G	0.0	0.00807 GHz/Ω m

Table I. Parameters of 50 ohm microstrip lines on 50 μm thick GaAs and 25 μm thick polyimide.

CALIBRATION TECHNIQUES

In this paper, we are going to concentrate in assessing the accuracy of one tier and two teir LRM and TRL calibration techniques on thin substrates (50 μm GaAs and 25 μm polyimide). Both one tier, that is, standard vector network analyzer (VNA) calibrations without post processing of the data, and two tier TRL and LRM calibrations including combinations of TRL and LRM with post processing of the data after a VNA calibration were done. The post processing of the calibrated data included corrections for the complex characteristic impedance of the lines and averaging as described below since we are using multiple lines.

The conventional TRL calibration uses a split-band approach. That is even though multiple lines are used, adjacent frequency bands do not overlap. This is a basic limitation of the HP 8510C VNA. As shown by R. B. Marks [7] multiple, transmission lines with overlapping operating frequency ranges can be used to minimize the effects of random errors. In the one tier TRL calibration only three delay lines were used (1600 μm, 3400 μm and 8800 μm), while in the two tier calibration seven delay lines were used (see Figure 4). As shown in Figure 4, there are always at least two delay lines at any given frequency except for frequencies below 1.25 GHz.

In the two tier calibrations, all seven 50 ohm delay lines, the thru, and the short are measured after doing a calibration in the VNA. Additional error boxes are generated and loaded back on the VNA. In the two tier calibration a weighted average was used in the calculation of the error boxes when more than one line standard was used for a given frequency. The weighting function can be written as:

$$W(\theta_i) = \frac{e^{-A(90-\theta_i)^2}}{\sum_{k=1}^{N} e^{-A(90-\theta_k)^2}} \qquad (4)$$

where A is equal to 0.001409, N is the total number of lines and θ is the insertion phase of the delay line relative to the insertion phase of the thru line. This value of A will provide a weight at 20 and 160 degrees which is 0.001 times the weight at 90 degrees.

In addition to the one tier LRM calibration, a two tier LRM-TRL calibration was also done. Once an LRM calibration was made in the VNA, we proceeded to measure all seven 50 ohm delay line standards, the reflection standard (short) and the 1000 μm thru. With these measurements, error boxes were calculated as described for the two tier TRL calibration.

CALIBRATION RESULTS

To compare the accuracy of TRL, two tier TRL, LRM and two tier LRM-TRL calibration techniques on the 50 μm thick GaAs substrate, S-parameters were measured on a 1.2 mm PHEMT device (Figure 3) manufactured on the same 50 μm thick GaAs calibration wafer. Figures 6 and 7 show the S-parameters at two different bias points that indicate discrepancies between the different calibration techniques. At the high current bias (Figure 6) the LRM calibration gives incorrect values for the magnitude of S11 at high frequencies. At the below pinchoff bias (Figure 7) the LRM calibration yields incorrect values for the magnitude of S11 and S22. The measured S22 is even greater than unity at some frequencies. This data shows that the two tier TRL and the two tier LRM-TRL combination measurements are almost identical.

The conclusion is that once the second tier TRL error boxes have been generated from the VNA LRM calibration, the same measurement accuracy as the two tier TRL calibration can be

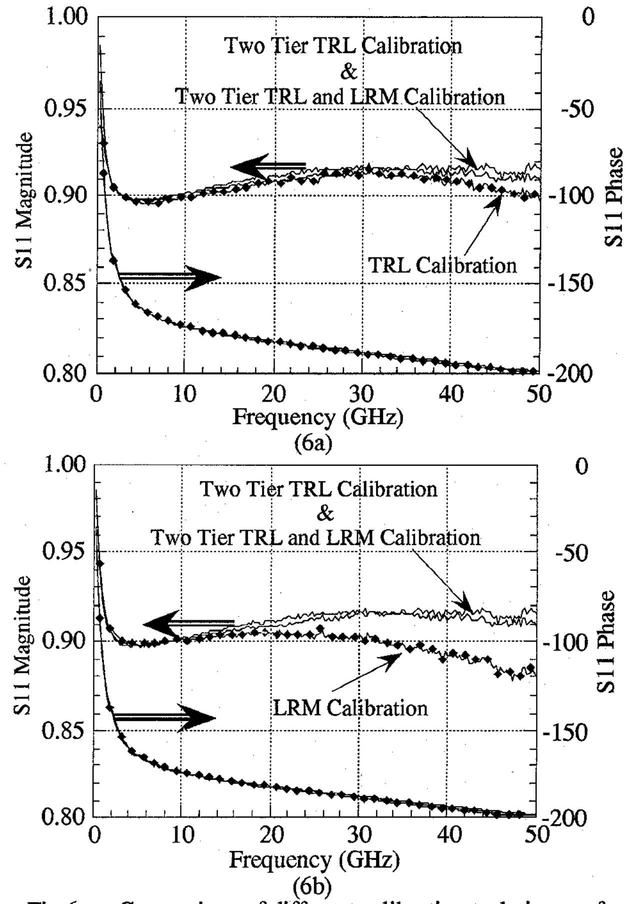
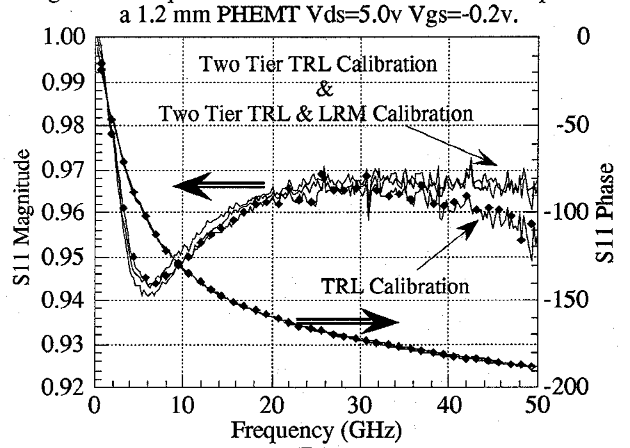


Fig 6: Comparison of different calibration techniques of a 1.2 mm PHEMT Vds=5.0v Vgs=-0.2v.



(7a)

achieved with the conveniences of LRM. That is fewer standards and a fixed probe separation can be used.

For the 25 μm thick polyimide, one and two tier TRL calibrations were performed. In the one tier calibration only the 90 degree line, which covers the 8 to 64 GHz range, was used. In the two tier calibration the 45, 90 and 135 degree lines were used. Figure 8 shows the input return loss of a 50 ohm transmission line on 25 μm thick polyimide that was not used as a calibration standard. In that figure we show the one tier TRL calibration, the two tier TRL calibration with uniform averaging, that is, all lines have the same weight as long as they are within 20 and 160 degrees range, and a two tier TRL

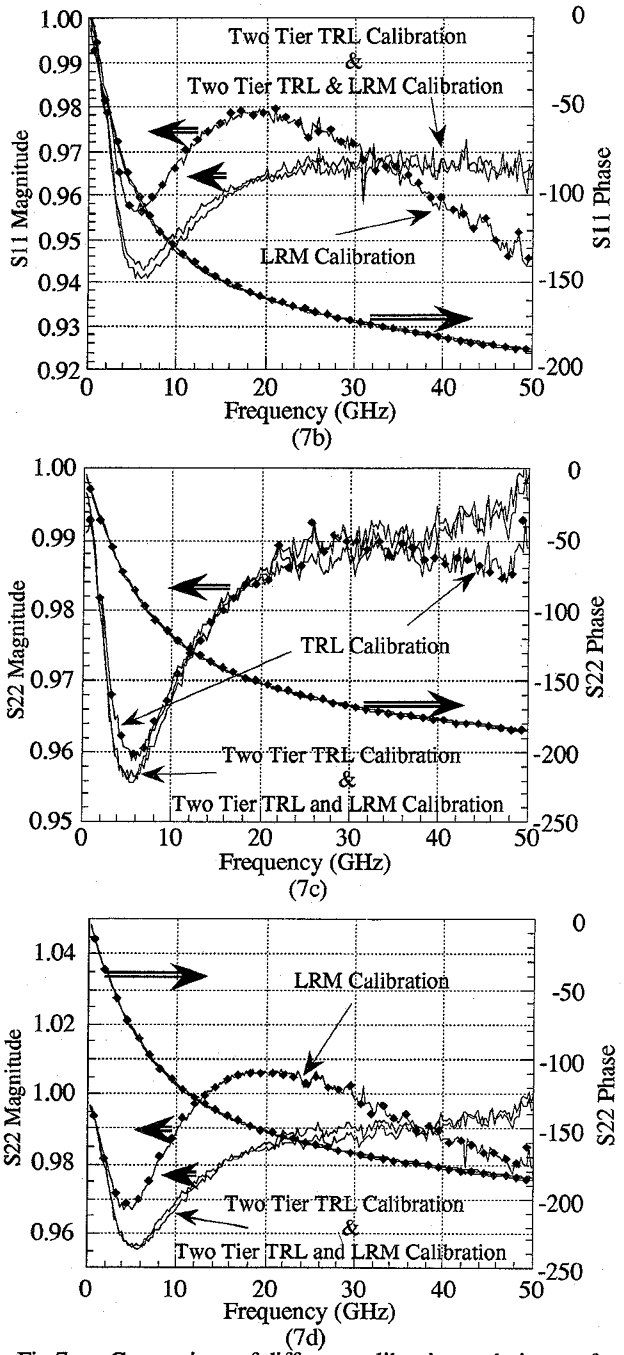


Fig 7: Comparison of different calibration techniques of a 1.2 mm PHEMT Vds=5.0v Vgs=-1.0v.

calibration with the weight function shown in equation (4). There is an overall improvement of 5 to 8 dB in return loss between the one and two tier calibrations. With the uniform averaging two tier calibration we see a discontinuity in the magnitude of the return loss at 15 GHz. This discontinuity is caused by an additional line standard being added to the overall averaging at 15 GHz. This newly added standard has a phase delay slightly greater than 20 degrees at this frequency and introduces a noticeable error despite averaging. However, in the two tier weighted average calibration this discontinuity has completely disappeared.

CONCLUSIONS

We have demonstrated the viability of doing on-wafer microstrip calibrations on thin substrates for the purpose of measuring circuits and devices up to 50 GHz. We have shown excellent performance of microstrip calibration standards on 50μm thick GaAs and 25μm thick polyimide at frequencies up to 50 GHz. We have also investigated the accuracy of the one and two tier LRM and TRL calibration techniques. Substantial improvements were found with the use of a weighting function in the averaging of two tier TRL and LRM-TRL calibrations.

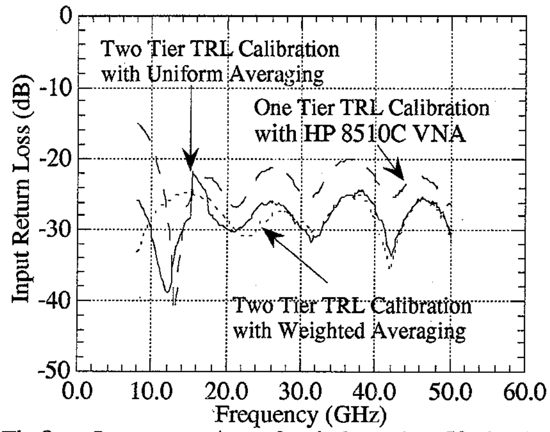


Fig 8: Input return loss of an independent 50 ohm transmission line on 25 μm thick polyimide.

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