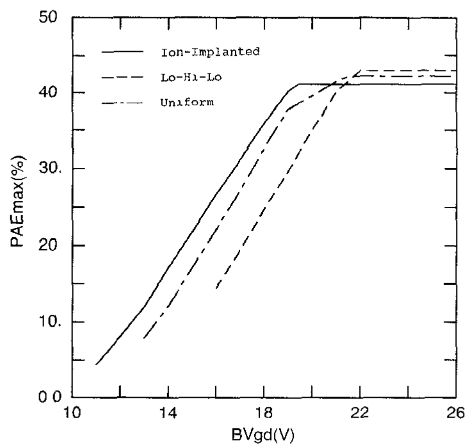

Fig. 6 Maximum power-added efficiency versus gate-drain breakdown voltage for the three devices ($V_{ds} = 7$ V, $I_{ds} = I_{dss}/2$, $F = 10$ GHz)

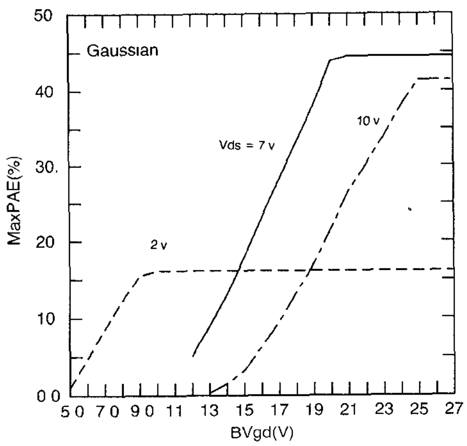

Fig. 7. Maximum power-added efficiency versus gate–drain breakdown voltage for the ion-implanted device for three different drain bias voltages.

implanted device is able to tolerate the lowest breakdown voltage before significant degradation in PAE occurs. Reducing the breakdown voltage below approximately 19 V for the ion-implanted device, 21 V for the uniform device, and 22 V for the lo–hi–lo device produces significant degradation in RF performance. The dependence of PAE upon BV_{gd} for the ion-implanted device is shown in Fig. 7. Data are shown for three drain bias voltages with the drain current equal to one half I_{dss}. The PAE degrades rapidly for BV_{gd} less than 25 V for $V_{ds} = 10$ V, 20 V for $V_{ds} = 7$ V, and 9 V for $V_{ds} = 2$ V. Higher breakdown voltages allow larger RF voltages to be applied before waveform clipping and RF performance degradation occur.

V. Conclusions

The RF large-signal performance sensitivities for GaAs MESFET's with uniformly doped, ion-implanted, and lo–hi–lo doping profiles have been investigated. All three device designs are capable of generating PAE in excess of 40 percent at 10 GHz. Optimized lo–hi–lo and uniform profile devices appear to produce the greatest saturated RF output power and gain and the most linear response. Ion-implanted devices produce the greatest linear gain, but have the least saturated RF power and gain and the most limited dynamic range. The RF performance of the devices is most sensitive to the conducting channel design and the gate–drain breakdown voltage when the breakdown voltages are relatively low.

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De-embedding Coplanar Probes with Planar Distributed Standards

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***Abstract* —Two methods are used to de-embed coplanar probes using offset coplanar waveguide shorts and transmission lines. The accuracy of the de-embedded measurements is verified. The *S* parameters of lumped standards provided by the manufacturer of the probes are measured and found to be suitable for purposes of calibration up to 26 GHz.**

I. Introduction

Coplanar probes are widely used by manufacturers of microwave integrated circuits to characterize the S parameters of microwave transistors and monolithic integrated circuits (MMIC's). The probes introduce significant measurement errors which must be removed if transistor S parameters are to be accurately measured. A procedure referred to as "de-embedding" has been developed for this purpose [1], [2].

The coplanar probes are usually de-embedded by measuring the uncorrected S parameters of a set of lumped impedance "standards" provided by the manufacturer. A numerical algorithm is then used to determine the error coefficients of the measurement system from the uncorrected measurements of the impedance "standards." The accuracy to which the impedance of these "standards" are known limits the accuracy of the calibration procedure.

In this work, two different and independent sets of "standards" were utilized for de-embedding. These consisted of the coplanar waveguide (CPW) through lines and offset CPW shorts that were developed for de-embedding the Cascade Microtech type WPH-105-10 probe heads from 5 to 25 GHz. In each case, the accuracy of the calibration was verified by measuring the S parameters of planar circuits not used in the de-embedding

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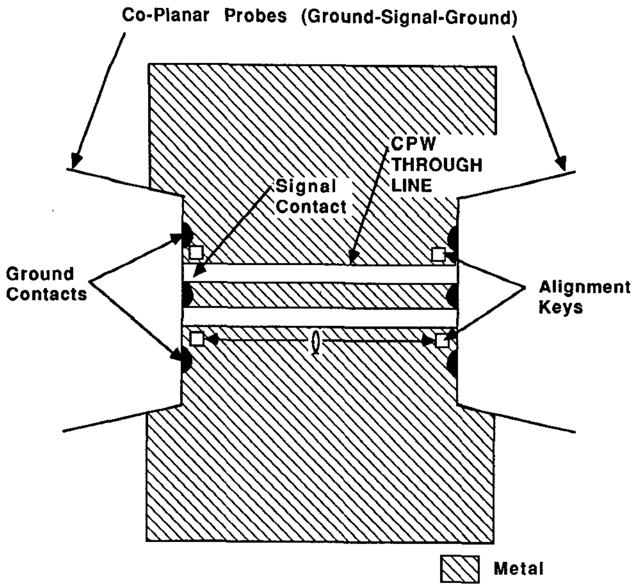

Fig. 1. A top view of a CPW through line of length 1 used as a "standard" for the purpose of de-embedding.

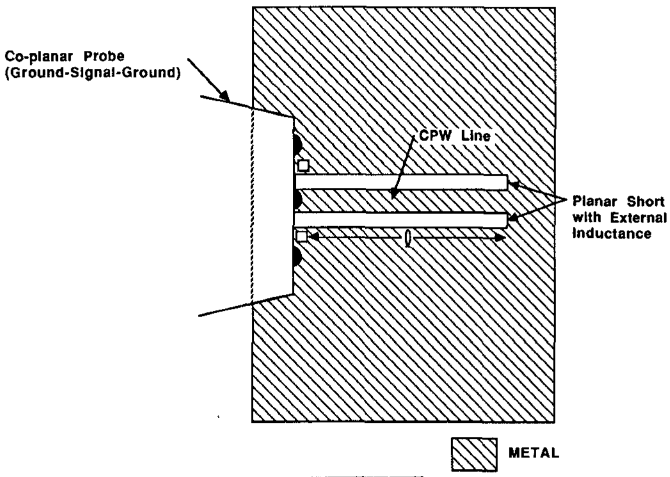

Fig. 2. A top view of a CPW offset short of length 1 used as a "standard" for the purpose of de-embedding.

procedure and analyzing the data for consistency with other measurements and predicted responses.

A set of impedance "standards" consisting of an open, short, load, and through line has been developed by Cascade Microtech of Beaverton, Oregon, for the purpose of de-embedding coplanar probes. The impedances of these "standards" were measured using both calibrations described above. To the authors' knowledge, this is the first direct impedance measurement of these "standards" at microwave frequencies.

II. Standard Characterization

The "standards" used to calibrate the network analyzer and de-embed the microwave probes are based on the CPW transmission lines shown in Fig. 1 and Fig. 2. These CPW structures were formed from a 1.7 μm gold film and a 500 Å titanium adhesion layer evaporated on a 125 μm thick GaAs substrate. The 100 μm wide center conductor and 50 μm wide gaps were patterned by photolithographic lift-off.

The first set of "standards" consisted of three CPW through lines of the type shown in Fig. 1 and an offset CPW short as shown in Fig. 2. The thru-reflect-line (TRL) calibration method

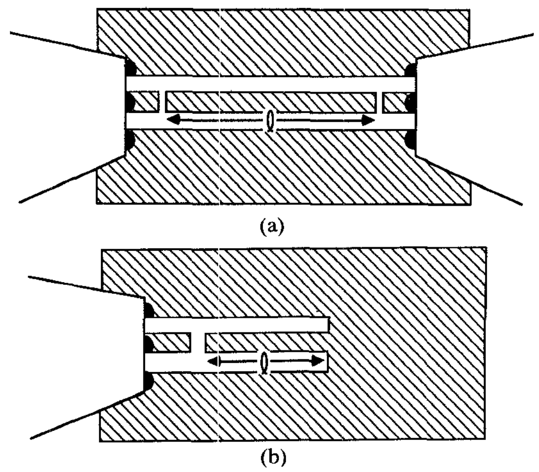

Fig. 3. A top view of two CPW resonators used to determine the CPW effective dielectric constant and external short inductance. (a) CPW resonator of length 1. (b) CPW resonator of length 1 terminated in a CPW short.

as implemented in the Hewlett Packard 8510B network analyzer [3] was used to calibrate the measurement system (network analyzer and microwave probes).

The second set of "standards" consisted of eleven CPW offset shorts of the type shown in Fig. 2 with different offset lengths. In this case, the network analyzer was first calibrated to a reference plane at the coaxial input to the probe assembly using 3.5 mm coaxial calibration standards. The least squares de-embedding algorithm developed by Bauer and Penfield [4] was then used to de-embed the microwave probes from measurements of these CPW offset shorts.

In both calibration methods the network analyzer and microwave probes are calibrated to the characteristic impedance of the CPW transmission lines. Thus it is required that the characteristic impedance of the CPW transmission lines be known in order to convert the measured S parameters to S parameters in a 50 Ω system. De-embedding with the least squares technique of Bauer and Penfield [4] requires that the impedance of the offset CPW short be known, which in turn requires that the propagation constant and loss of the CPW transmission lines and the external inductance of the CPW short be known as well. The characteristic impedance and propagation constant of the CPW transmission lines was calculated by the spectral domain technique [5]. The effects of both the finite thickness of the GaAs and a quartz base plate upon which the GaAs substrate was placed during the measurements were accounted for in this calculation. The effect of a finite metal thickness was calculated by a finite difference algorithm [6]. The calculated characteristic impedance Z_0 and effective dielectric constant ϵ_{eff} of the lossless line were found to be well approximated up to 26.5 GHz by

$$Z_0 = 50.45 - .6316\times10^{-3}f + .9889\times10^{-3}f^2 - .5682\times10^{-4}f^3 + .7522\times10^{-6}f^4 \quad (1)$$

and

$$\epsilon_{\text{eff}} = 6.7936 - .8309\times10^{-4}f + .1524\times10^{-3}f^2 - .3055\times10^{-5}f^3 + .4291\times10^{-7}f^4 \quad (2)$$

where f is the frequency in GHz. The loss of the CPW transmission lines was measured by comparing the reflection coefficients of offset shorts whose length differed by some multiple of a half wavelength. The CPW loss was found to be well described between 5 and 26.5 GHz by an attenuation constant α given by

$$\alpha = 0.0154\sqrt{f}\ \text{cm}^{-1} \quad (3)$$

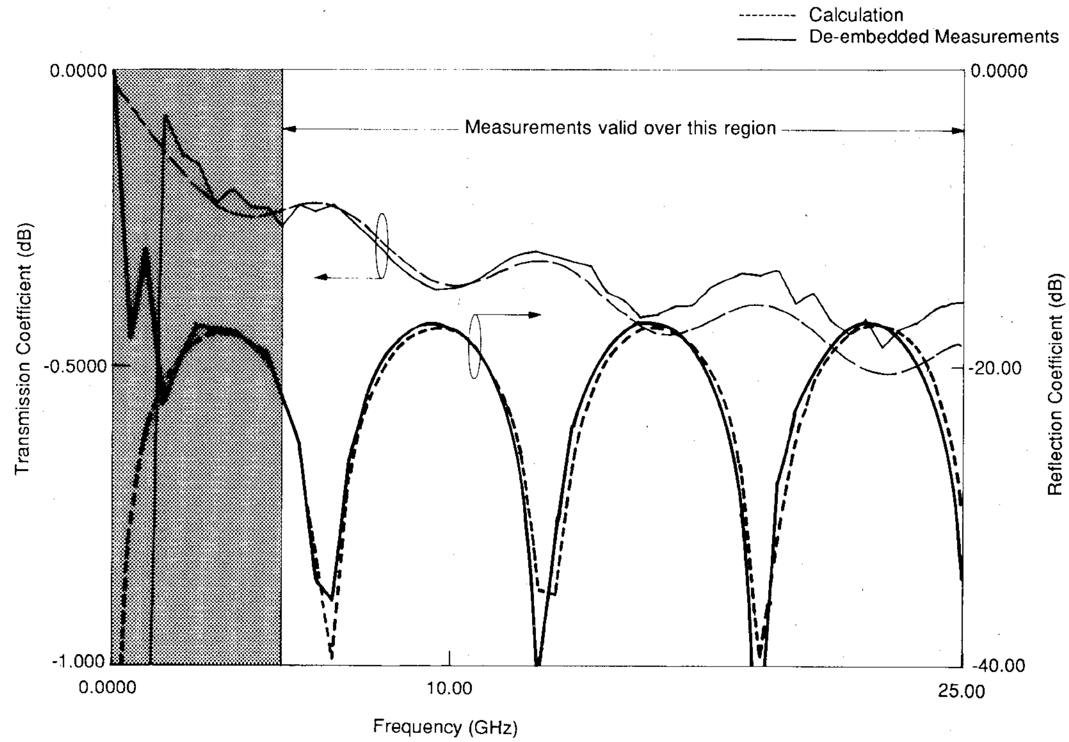

Fig. 4. The transmission and reflection coefficients of an 8-mm-long CPW through line de-embedded with the least squares de-embedding procedure are compared with their calculated values. The impedances of the standards, which are limited in length, approach one another at low frequencies, invalidating the de-embedding procedure there.

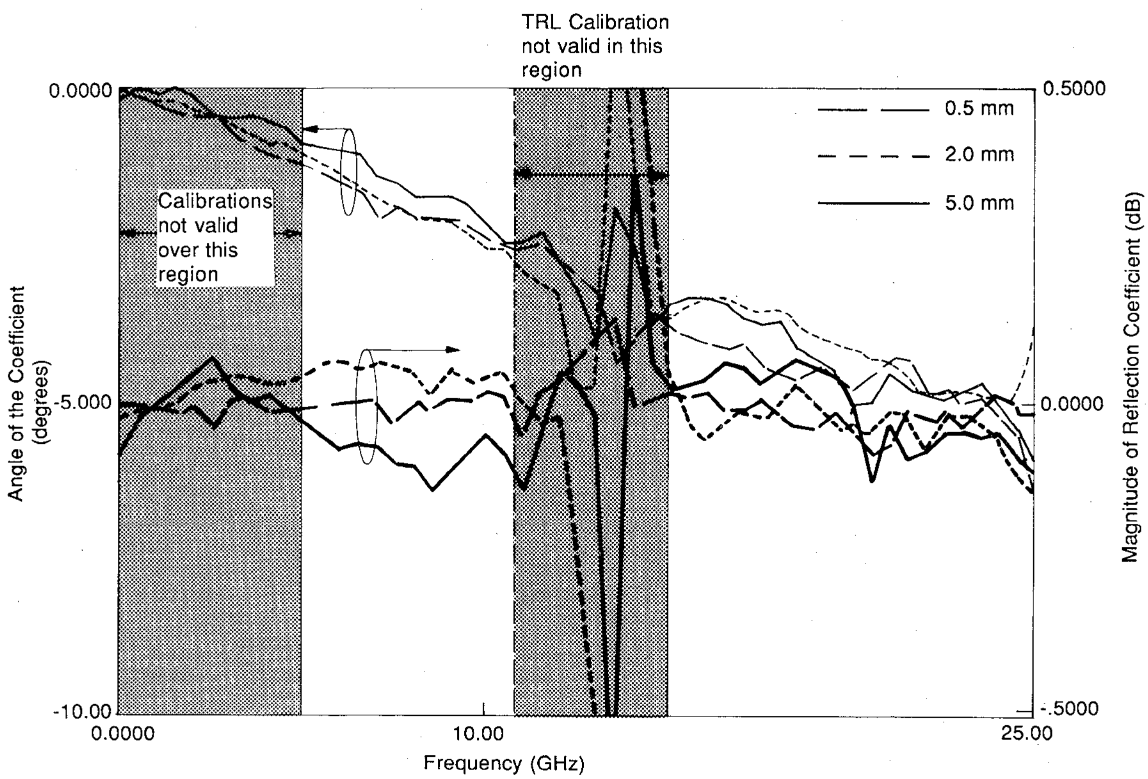

Fig. 5. The deviation of the measured and predicted reflection coefficients of CPW shorts offset from the probe tips by 0.5, 2.0, and 5.0 mm are plotted. The TRL calibration was employed and the calculated loss and line length of the offset sections subtracted. The deviation in the angle of the reflection coefficient is due to the external inductance of the CPW back-short. The TRL calibration is not valid over the frequencies indicated on the plot because the length of the through calibration standard approaches a half wavelength there.

TABLE I
A COMPARISON BETWEEN PREDICTIONS, MEASUREMENTS CALIBRATED WITH THE TRL CALIBRATION PROCEDURE, AND MEASUREMENTS DE-EMBEDDED WITH THE LEAST SQUARES DE-EMBEDDING PROCEDURE

TERMINATION	QUANITY	PREDICTION	TRL	LST SQRs
CPW Short	$\angle S_{11}$ AT 20 GHz	-6.3°	-4 8°	-6.3°
Gap	$\angle S_{11}$ AT 20 GHz	-7 5°	-5°	-7°
CPW Thru (5mm)	$\angle S_{21}$ AT 20 GHz	0°	+ 2°	-3.2°
CPW Shorts	$\lvert S_{11} \rvert$	0 dB	± .15 dB (5-25 GHz)	± 10 dB (5-25 GHz)
CPW Thru	$\lvert S_{11} \rvert$	0	< 02 (5-25 GHz)	< .05 (5-25 GHz)
CPW Thru	$\lvert S_{12} \rvert$	0 dB	± 05 dB (5-15 GHz)	± .10 dB (5-15 GHz)

In each case the appropriate phase and loss predicted by equations (1)–(3) for each line length were subtracted from the measurements before the comparisons were made. The values given are the worst-case deviations, which invariably occurred for the longest length of line (10.0 mm) tested.

where f is the frequency in GHz. The characteristic impedance and effective dielectric constant of the lossy CPW line was then calculated from the lossless values using the attenuation constant α and the procedure outlined in Williams and Miers [7].

The calculated effective dielectric constant was verified at 17 GHz to within 0.4 percent by comparing the resonant frequencies of two end-coupled resonators (shown in Fig. 3(a)) with lengths of 4.0 and 8.0 mm, which allowed the effects of fringing fields at the gaps to be subtracted from the measurements. The external inductance of the CPW shorts were derived from measurements of scaled models and verified to within 10 percent at 17 GHz by comparing the resonant frequencies of the gap-coupled CPW resonators shown in Fig. 3(a) and (b) with lengths of 4.0 (approximately one guided wavelength) and 2.0 mm (approximately one-half guided wavelength), respectively. Again, the use of two resonators allowed the effects of the fringing fields in the coupling gaps to be subtracted from the measurements.

III. VERIFICATION OF MEASUREMENT ACCURACY

Systematic errors, such as those due to errors in the calculation of the characteristic impedance and effective dielectric constant of the CPW transmission lines used to fabricate the CPW impedance standards and errors inherent in the fabrication of those structures, can not be easily estimated from measurements of these "standards." This is because their S parameters are mapped into their definitions by the de-embedding process. In order to better estimate systematic measurement errors in the de-embedding process, de-embedded measurements of circuits not used in the de-embedding procedure should be compared with calculated or predicted values.

CPW through lines were not used as "standards" in the least squares de-embedding procedure. A comparison of the measured S parameters de-embedded with the least squares de-embedding procedure described by Bauer and Penfield [4] of CPW through lines with the calculated values is shown in Fig. 4. CPW offset shorts were not used as "standards" during the TRL calibration procedure, except for a single offset length to present identical reflection coefficients at each port. A comparison of the measured S parameters calibrated with the TRL method of CPW offset shorts with the calculated values is shown in Fig. 5. In each case, the measurements show close agreement with the calculated results.

In both calibration methods some of the "standards" were not used for the purposes of de-embedding over the entire frequency range of the measurements. (The offset shorts of lengths 0.0, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 6.0, 7.0, 8.5, and 10.0 mm were used for purposes of de-embedding with the least squares algorithm over the frequency ranges 0–26.5, 0–26.5, 0–26.5, 0–26.5, 0–17, 0–12.5, 0–9.5, 0–8, 0–6.5, 0–5.5, and 0–4.5 GHz, respectively. The thru lines of lengths 0.84, 5.0, and 10.0 mm were used for the purposes of de-embedding with the TRL algorithm over the frequency ranges 0–26.5, 5–26.5, and 0–5 GHz, respectively.) The de-embedded S parameters of these "standards" were compared at the frequencies for which they were not used in the de-embedding procedure with the predicted response and close agreement was found.

Another circuit, a 0.05 mm gap in the center conductor of a CPW line, was tested with both calibrations. This circuit was not used as a standard in either calibration method. This allowed a direct comparison of measurements. The actual S parameters of the gaps were determined accurately at 14 GHz by choosing the capacitances in a pi model of the gap so as to fit the measured resonant frequencies, quality factors, and insertion losses of the resonant structures of Fig. 3(a).

The results of the comparison of the two calibration techniques are summarized in Table I. It is not surprising that the TRL calibration results in superior measurement accuracy of through lines while the least squares de-embedding technique results in superior measurement accuracy of reflective loads, since through lines were used as standards in the former technique while reflective loads were used as standards in the latter technique.

IV. MEASUREMENTS OF MANUFACTURER STANDARDS

Cascade Microtech has developed a set of "standards" [8] composed of a short consisting of a 100 μm (4 mil) wide strip of metallization, a load consisting of two planar 100 Ω thin film resistors in shunt, an open slightly offset in the direction of the analyzer consisting of lifted probe tips, and a through line consisting of a short section of coplanar waveguide. To the authors' knowledge, the impedances of these standards have never been measured directly at microwave frequencies. Measurements of the S parameters of the lumped impedance "standards" supplied by Cascade Microtech allow their suitability for use in de-embedding the transition from microwave probes to CPW to be determined, and gives some insight into the suitability of these standards for de-embedding to the probe tips, as the transition from the probe tips to the CPW is expected to only slightly perturb the measurements.

The return loss of the planar load is shown in Fig. 6. The return loss was found to be better than -30 dB (approximately the estimated measurement accuracy of the calibrations) between 5 and 25 GHz. The return loss of the load could not be measured accurately below 5 GHz because the lengths of the standards approach zero at low frequencies, rendering the calibration inaccurate. The inductance of the short was also measured and plotted as a function of probe position in Fig. 7. The inductance of this short will result in a 5° offset of the reference plane at 20 GHz when it is used as a standard and the probe tip is placed in the center of the strip, as suggested by the manufacturer. The open circuit plane of the lifted probes was found to be offset in the direction of the analyzer, resulting in an effective negative capacitance of -0.012 pF. This is consistent with the value of -0.013 pF suggested by Cascade Microtech in the reference plane used for their measurements.

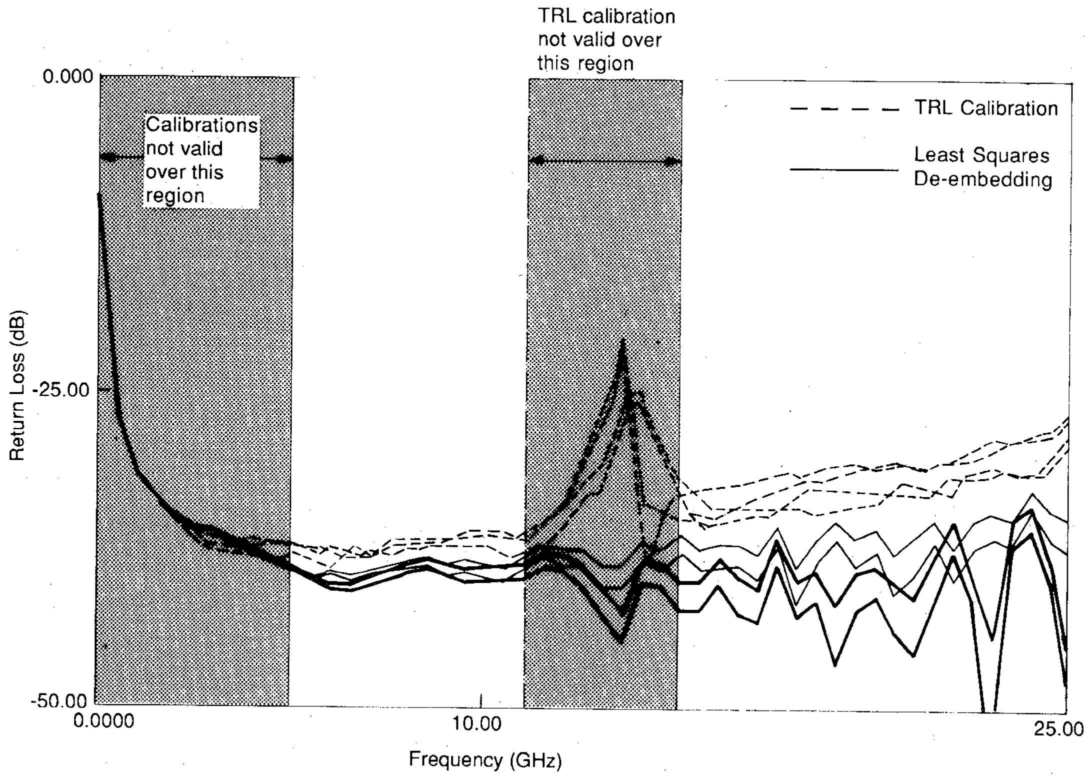

Fig. 6. The return loss of a planar load (reference [8]) de-embedded in two ways is plotted as a function of frequency. The TRL calibration is not valid over the frequencies indicated on the plot because the length of the through calibration standard approaches a half wavelength there.

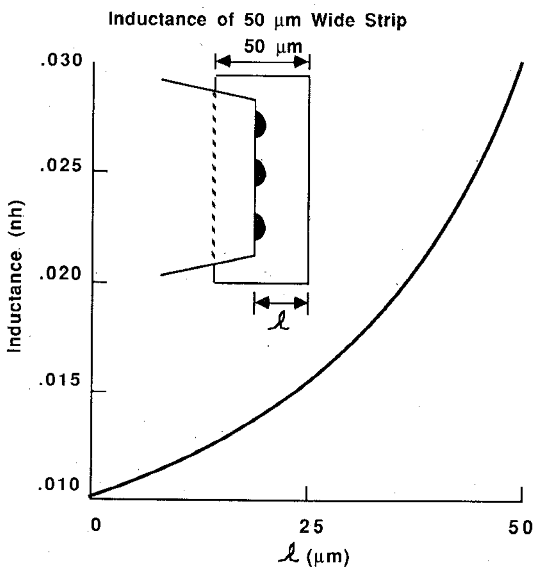

Fig. 7. The inductance of a 50-μm-wide strip as a function of probe position. The measurements were de-embedded with the least squares de-embedding procedure.

V. Conclusion

An accurate method of de-embedding coplanar probes requiring only planar CPW standards was described. This de-embedding method was shown to be suitable for making a number of microwave S parameter measurements. De-embedded measurements of commercially supplied standards independently verified their suitability for use as standards as well.

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Millimeter-Wave Components for Use in a Variable State Four-Port Network Analyzer

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***Abstract*—Components developed for use with a new type of network analyzer are presented. The analyzer contains a phase shifter which varies the state of the network, thus allowing accurate measurements to be made**

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