VERIFICATION OF MMIC ON-WAFER MICROSTRIP TRL CALIBRATION

C.Woodin and M.Goff

Lockheed Sanders, Inc.
Microwave Technology Center
Nashua, NH 03061-2041

ABSTRACT

An on-wafer calibration verification technique is presented, comparing Thru-Reflect-Line (TRL) calibrated microstrip measurements with independent resonator measurements in the 1 to 26.5 GHz band. This is believed to be the first reported independent verification of any microstrip on-wafer calibration. The improved accuracy using a verified on-wafer microstrip TRL calibration is demonstrated to improve the ability to attain first iteration MMIC design success.

INTRODUCTION

A verification technique for the Thru-Reflect-Line (TRL) calibration method is presented for MMIC on-wafer microstrip measurements. Uncalibrated wafer level measurements of two port microstrip resonators were used to determine the loss coefficient (α) and phase coefficient (β) of a 96um wide transmission structure on 5 mil thick GaAs substrate. These values exhibit excellent correlation with the same parameters derived from on-wafer TRL calibrated measurements of transmission lines of the same dimensions. The phase of S11 for a 6652 um open circuited stub derived from resonator measurements is within 0.1% of the TRL measurements. This approach improves upon previously reported work [1] in that the resonator measurements do not require calibration and provide independent validation of the calibration. A coplanar verification has been reported [2] which uses resonators to verify parameters derived from measurements and spectral domain calculations.

A circuit decomposition/reconstruction example is presented which demonstrates the increased accuracy of the microstrip TRL calibration as compared to a coplanar Open-Short-Load-Thru (OSLT) calibration when characterizing microstrip elements. The improved accuracy contributes to the ability to perform single iteration MMIC designs utilizing CAD databases derived from on-wafer measured data.

APPROACH

The task of verifying any on-wafer calibration technique is formidable since no on-wafer microwave standards with traceability to the NIST exist yet [3]. The validation in microstrip is further complicated by varying parameters such as substrate thickness, via hole technology, and reference plane selection which inhibit the formation of universal standards. Previous authors have attempted verification by measuring residuals of their 'standards' [4] or examining a structure's performance using time domain gating techniques [5]. The former is merely an indication of measurement repeatability and the latter suffers from errors due to signal loss [6] of the probe discontinuities. The method presented here verifies a calibration by comparing parameters derived from a calibrated measurement with those derived from measurements independent of calibration altogether. The accuracy of this approach is limited only by the repeatability (not accuracy) of the measurement system and the repeatability of the physical parameters of the transmission, calibration and resonant structures used.

CALIBRATION VERIFICATION

Three resonators were used to validate the calibration at 7, 14 and 21 GHz. The resonators were gap-coupled microstrip transmission resonators with coplanar waveguide-to-microstrip launches as shown in Figure 1a. The insertion loss relative to a thru was approximately 48 dB for all three resonators. Figure 2 shows a typical resonator's measured response, modeled response, and the difference. The modeled response was generated by the capacitively coupled transmission line model shown in Figure 1b. This model facilitated a determination of the resonator's α and β at each center frequency.

Resonators were chosen for the validation structures because it can be shown that for a resonator with a low enough coupling coefficient, the contribution of the external Q of the measurement system is negligible and the loaded Q is equal to the unloaded Q. For

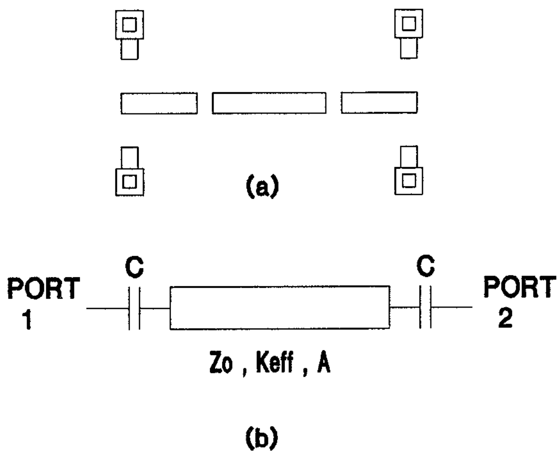


Figure 1: Microstrip Resonator Layout and Model

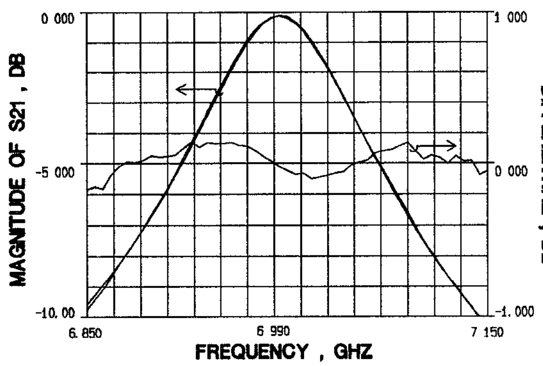


Figure 2: Resonator Measured and Modeled Response

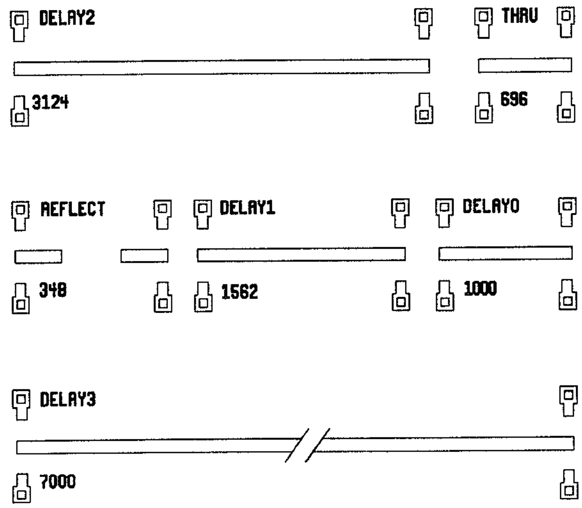


Figure 3: Microstrip TRL Calibration Structures

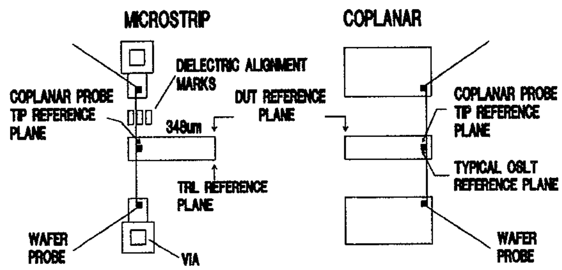


Figure 4: Microstrip and Coplanar Launches

example, reducing the coupling from -48 dB to -67 dB relative to a zero length thru results in a change in resonator center frequency of less than 0.43% . The deviation in the Q of the resonator is negligible under these conditions. When highly decoupled transmission resonators are used, only an uncalibrated relative amplitude measurement independent of the measurement system Zo need be made. The value of the coupling capacitance need not be known as long as it provides sufficient decoupling from the measurement system. The accuracy of the resonator's center and 3 dB bandwidth frequencies is set by the frequency accuracy of the source. The accuracy of the relative amplitude measurement is a function of the detector's amplitude response over the resonator 3 dB bandwidth.

The TRL calibration is performed using on-wafer microstrip structures (Figure 3) and the TRL algorithm supported by the HP8510B vector network analyzer. An open circuited transmission line is used for the reflection structure and three delay lines are used to cover the 100 MHz to 50 GHz band. A non-zero length thru is used to extend the reference plane a physical distance of 348 um into the microstrip line (Figure 4). This length is sufficient to allow for the decay of the evanescent modes introduced by the coplanar-waveguide-to-microstrip transition. Other benefits of the non-zero length thru approach are probe-to-probe crosstalk reduction and direct measurement at the desired reference plane of the device, eliminating further deembedding and its associated uncertainties. Probe placement was controlled using alignment marks patterned in the dielectric layer. A microstrip TRL calibration is used since all our MMIC circuit elements are microstrip based.

Calibration verification was achieved by comparing the TRL measured S11 of two open circuited transmission lines with the values of magnitude and phase determined by the independent resonator α and β measurements. The open circuit line widths were equal to the those used in the TRL calibration and resonator measurements to eliminate mismatch effects and the need to know Zo absolutely. The use of two open circuit lengths allowed the effects of the open ended fringing capacitance to be accounted for. Figure 5 shows a plot of the magnitude of S11 for each line length measured using TRL calibration versus the magnitude of S11 determined by the resonator measurements at three frequencies. The maximum deviation is less than .05 dB for all points. Figure 6 shows a similar plot of the phase

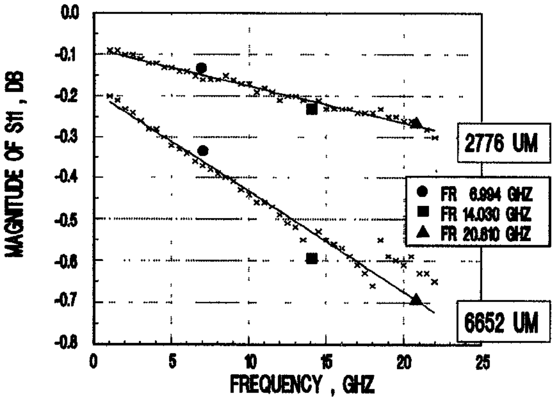


Figure 5: TRL Calibrated .vs. Resonator Derived Loss of Open Circuited Microstrip Lines

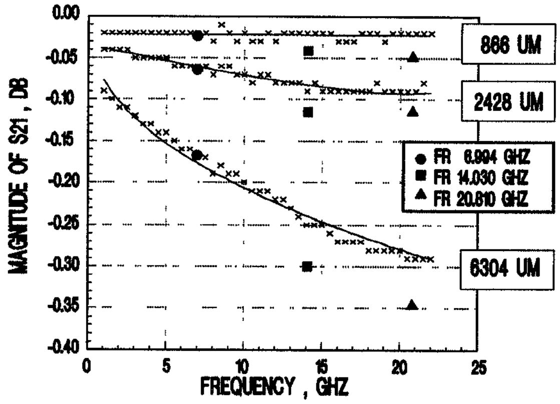


Figure 7: TRL Calibrated .vs. Resonator Derived Loss of 2 Port Transmission Lines

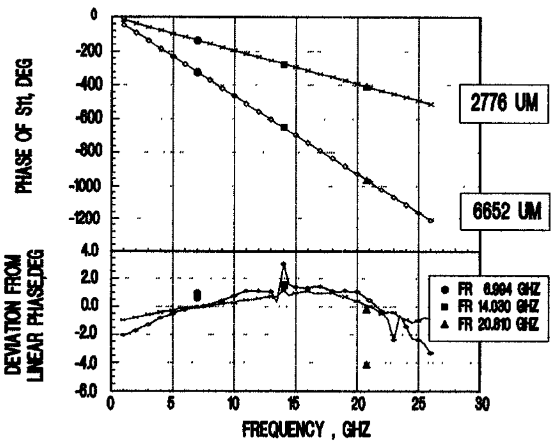


Figure 6: TRL Calibrated .vs. Resonator Derived Phase of Open Circuited Microstrip Lines

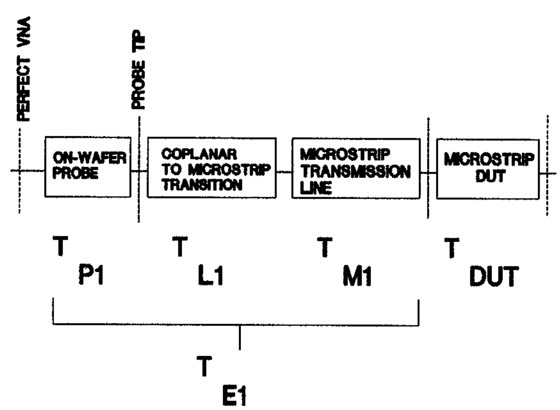


Figure 8: Typical Microstrip On-Wafer Measurement

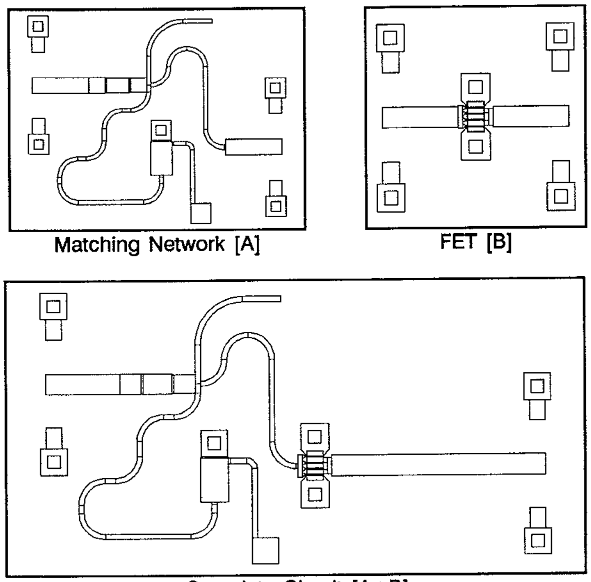
of S11. The deviation from linear phase of the open circuited line was less than +/-2 degrees. Agreement between the TRL measured phase and that determined by the resonator measurements was better than 1 degree for 5 of the 6 resonator points, which corresponds to a deviation of 0.2% for the 2776 um open and 0.1% for the 6652 um open. A similar measurement was undertaken on a two port transmission line of 96 um width. Figure 7 shows the TRL measured magnitude of S21 versus that determined by resonator measurements where the maximum magnitude deviation is less than 0.05 dB for 3 comparison frequencies and 3 line lengths. It should be emphasized that this verification technique is independent of the type of transmission lines employed. It is erroneous, however, to use a coplanar based calibration to measure microstrip devices since the effects of the coplanar to microstrip transition become embedded in the DUT S-parameters (Figure 8).The significance of this error is demonstrated in the next section.

CIRCUIT RECONSTRUCTION

The success of many MMIC designs relies upon the ability to cascade the models of various elements and predict the performance of the elements combined as a whole. Accurate measurement calibration is essential to producing models which will satisfy the above criteria. A circuit decomposition/reconstruction exercise was performed which illustrates the ability of a microstrip TRL calibration to predict the measured whole based on the sum of the measured parts, ie:

Measured [A] + Measured [B] = Measured [A + B]

Figure 9 shows an amplifier circuit (denoted [A+B]) comprised of an input matching network (denoted [A]) and a FET (denoted [B]). Replicas of the input circuit and FET were placed on the wafer in close proximity to the amplifier. A site was selected such that the DC parameters of the FET [B] matched those of the circuit FET [A+B]. The input matching network [A], FET [B] and circuit [A+B] were then measured using the microstrip TRL calibration and a coplanar OSLT calibration. The probes were not moved between the



Matching Network [A] FET [B]

Complete Circuit [A+B]

Figure 9: Circuit Reconstruction Layouts

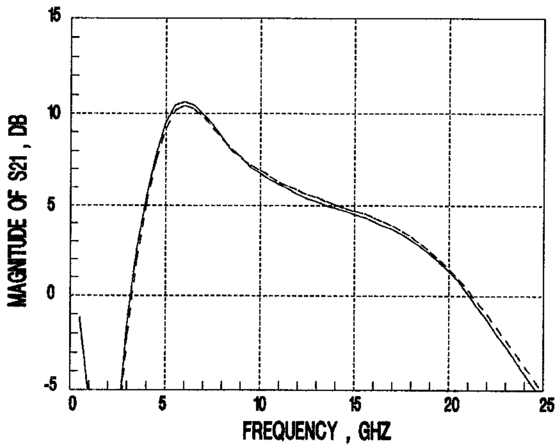


Figure 10: Microstrip TRL Calibrated Measured Whole .vs. Measured Sum of the Parts

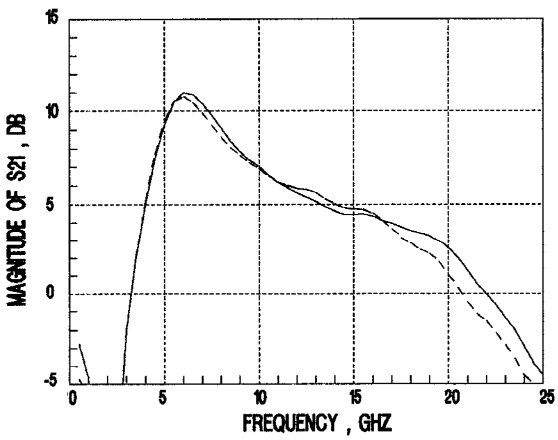


Figure 11: Coplanar OSLT Calibrated Measured Whole .vs. Measured Sum of the Parts

measurements of each structure to reduce comparison uncertainty due to probe position and contact. The excellent measured agreement for MS21 between the whole and the sum of the parts using a microstrip TRL calibration is shown in Figure 10. A similar reconstruction versus measured plot for the OSLT coplanar calibration is presented in Figure 11. The TRL calibrated agreement for S11, S22 and S12 was excellent whereas discrepancies occurred for all the S-parameters using the coplanar OSLT calibration. Note that the TRL agreement is possible even though the impedance of the transmission lines used for calibration is not exactly known. The actual value of Zo is only significant when translating the measured S-parameters to a particular system impedance. Although not a verification of the calibration, this circuit example demonstrates the effect the superior accuracy of the microstrip TRL calibration has on MMIC passive and active element characterization.

SUMMARY

A novel approach to the verification of a microstrip on-wafer TRL calibration has been presented which utilizes independent measurements of resonators and transmission line structures. Agreement between the calibrated and independent measurements is excellent, indicating the accuracy of the microstrip TRL calibration. A circuit decomposition/reconstruction example was presented which demonstrates the superior capability of a microstrip based TRL calibration when characterizing MMIC microstrip elements.

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