A Novel Calibration Verification Procedure for Millimeter-Wave Measurements

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Abstract

A novel calibration procedure is presented for microstrip on-wafer SOLT calibration standards. In this procedure, an on-wafer multiline TRL calibration is used to measure on-wafer SOLT calibration standards. The measurements are compared to electromagnetic simulations of the SOLT standards. An SOLT calibration standard model is derived and used to measure on-wafer offset SOL standards. Close agreement of the SOLT standard measurements and the offset SOL measurements to electromagnetic simulated data provides verification. Accuracy of this calibration procedure is documented up to 75 GHz.

Introduction

With commercial MMIC applications moving into the millimeter-wave range, accurate high volume on-wafer testing at millimeter-waves is becoming more important. For S-parameter measurements, the short, open, load and thru (SOLT) calibration requires minimal operator interaction after the initial probe placement and is compact and wideband, but suffers from accuracy problems. The SOLT calibration requires precise knowledge of the S-parameters of all four standards. While the thru and open standards are easily analyzed, the short and load are much more difficult to characterize accurately. In comparison, the thru, reflect, line calibration (TRL) only requires knowledge of the line characteristic impedance (Z_0) and the reflect standard phase within +/-90 degrees. However, the TRL calibration requires the operator to move the probes to accommodate the different lengths of lines. At millimeter wave frequencies, this probe movement causes phase errors and must be done with some care, making the calibration more time consuming and difficult.

In order to develop a S-parameter calibration that is both easy to use and accurate at millimeter wave frequencies, we have developed a novel procedure to enhance the accuracy of SOLT calibration. This procedure is illustrated in Fig. 1. An on-wafer mulitline TRL calibration is used to measure on-wafer SOLT calibration standards. The measurements are compared to electromagnetic simulations of the SOLT standards. A SOLT calibration standard model is derived and used to measure on-wafer offset SOL standards. Close agreement of the SOLT standard measurements and the offset SOL measurements to electromagnetic simulated data provides verification. Accuracy of this calibration procedure is documented up to 75 GHz.

Microstrip TRL Calibration

An on-wafer set of TRL calibration standards was developed to allow measurement from 0.05 GHz through W-band. The thru and reflect standards of the TRL calibration are the thru and short standards, respectively, of our SOLT calibration. The TRL calibration follows the multi-line strategy of Marks [1]. Measurement software provided by NIST was used to perform the TRL calibrations. Measurements were taken from 0.05 to 50 GHz and 50-75 GHz.

The capacitance per unit length (C) and the conductance per unit length (G) of the lines at low frequencies were determined experimentally by the method of Marks and Williams [2]. In this method, the TRL calibration is used to measure the reflection coefficient Γ_{load} of a line terminated with a resistor. The C and G values are calculated over frequency from

$$C[1-j(G/\omega C)]=\gamma/(j\omega R_{load,dc}))*(1+\Gamma_{load})/(1-\Gamma_{load})$$

where $R_{load,dc}$ is the DC resistance of the resistor. Figure 2 shows a plot of C vs. frequency for our 70 μm wide lines on 100 μm GaAs substrate using the SOLT load standard as the resistively loaded line. Note that C vs. frequency curve is fairly flat,

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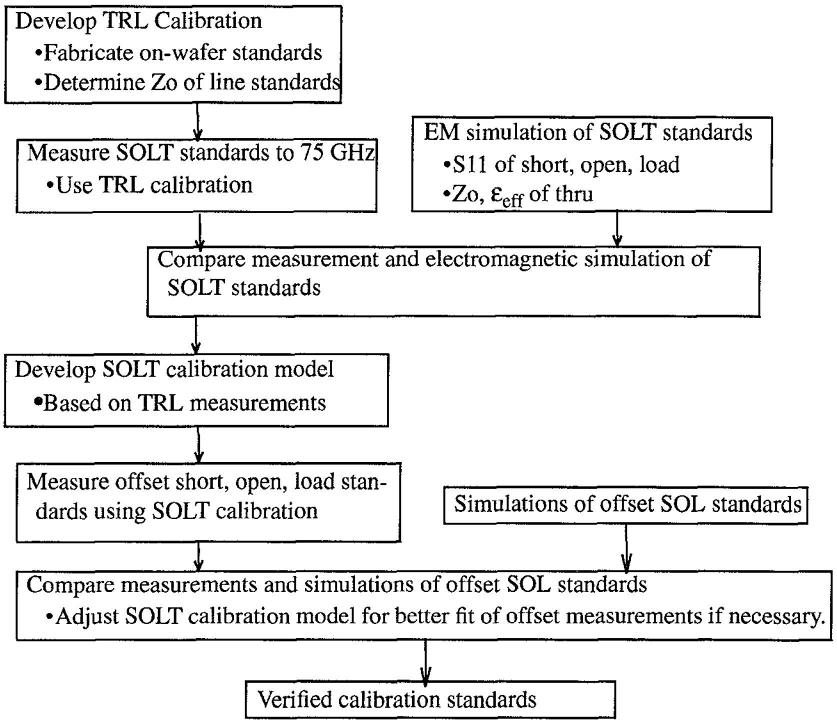

Fig. 1 Procedure for developing and verifying the SOLT microstrip calibration.

indicating that the assumption of no parasitics in the resistive load is valid at these frequencies. The glitch at 8 GHz is caused by coupling of the half-wave resonance of the 19,400 μm TRL line standard to the other line standards. The effect of this resonance

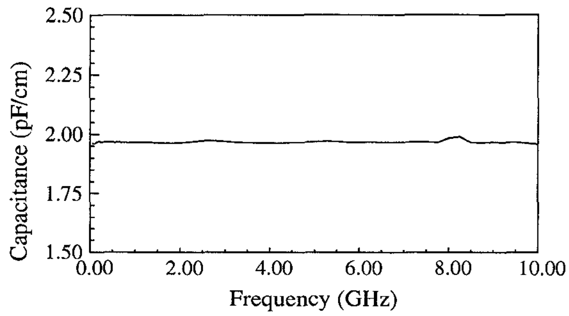

Fig. 2. Measured capacitance per unit length of the 70μm wide microstrip line on 100μm thick GaAs

coupling to the adjacent lines was detectable in the measurements in spite of the 730 μm edge to edge spacing between lines. When this line was removed, the resonances in our S-parameter data at multiples of 8 GHz disappeared. The final values of C and G were obtained by extrapolating the C and G curves to zero frequency. Given C, the characteristic impedance Z_0 of the lines can be determined from [3]:

$$Z_0=\gamma/\omega C$$

and is shown in Fig. 3. The knowledge of Z_0 allows the S-parameter data to be referenced to 50 ohms rather than to Z_0. Note that the propagation constant γ is a by- product of the TRL calibration.

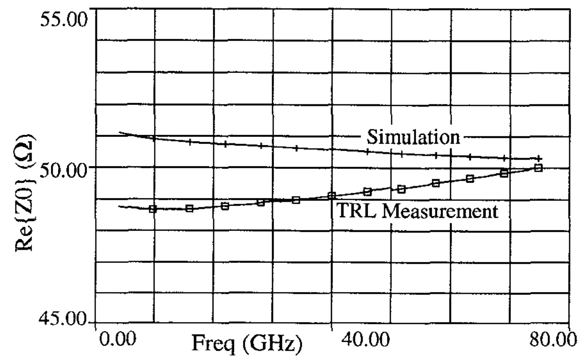

Fig. 3. Simulated vs. measured Zo for the 70μm wide thru standard.

Simulations of SOLT Standards

Sonnet [4] electromagnetic simulation software was used to characterize the SOLT standards. While the metal loss was taken into account, the metal thickness was not. The short and load standards share the same via which has a rectangular pyramid

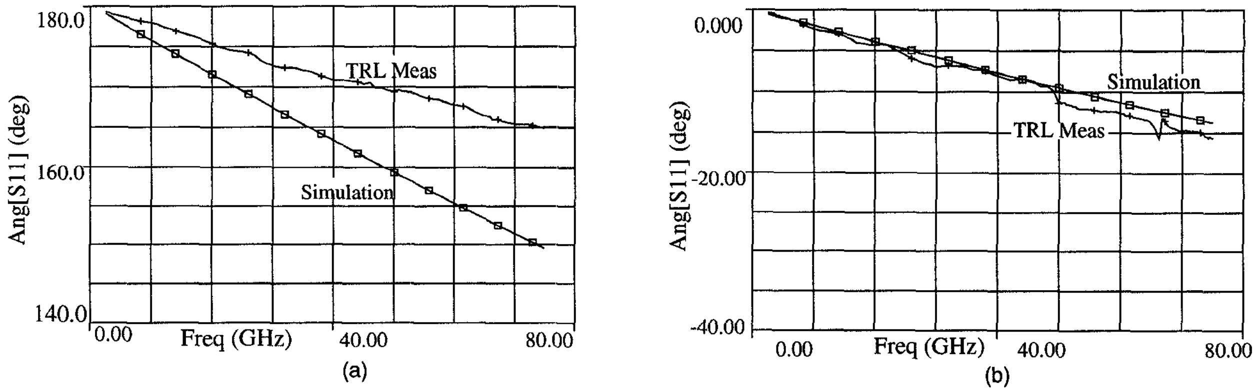

Fig. 4. 2.5-75 GHz measurement of reflection coefficient angle for the microstrip short (a) and open (b) standards compared to simulations.

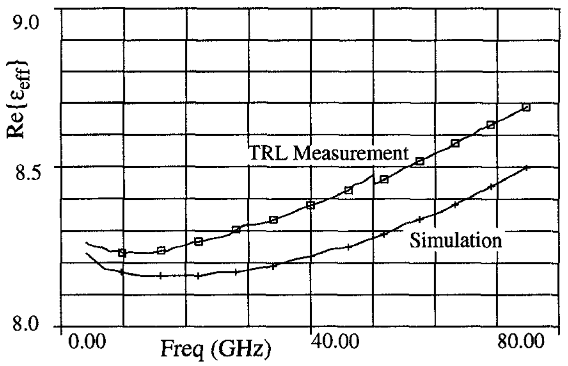

Fig 5. Relative effective dielectric constant 2.5-75 GHz TRL measurement vs. simulation

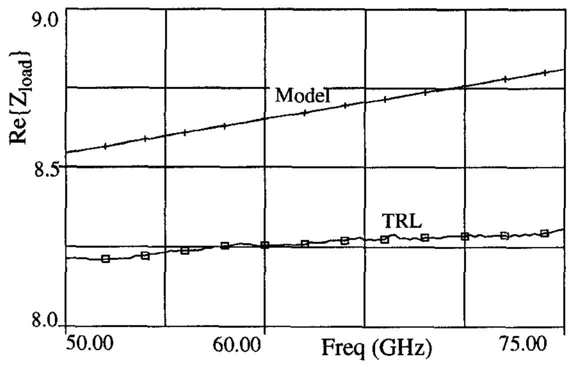

Fig 6. V-band measurement of real part of load standard impedance vs. load model. Model DC resistance value set to the DC value of the measured standard.

shape. The via was actually modeled as a rectangular cylinder. In addition, we suspect the via dimensions are not as close to the layout dimension as other dimensions because of the depth (100μm) of the etch required. Thus the short and load simulations may be less accurate than the open and thru simulations.

Measurement of SOLT Standards

The S-parameters of the SOLT standards were measured from 0.05 to 50 GHz and 50-75 GHz using the SOLT short standard as the reflect standard. For the V-band measurements, we found that the unloaded short standard had a quarter wave resonance at 66 GHz and that this resonance coupled to the adjacent open and thru standards. The effect of this resonance can be seen in the open standard measurement in Fig.4(b). Subsequent measurements using standards that were not adjacent to a short standard removed the resonance. In these later measurements, the open was used as the TRL reflect standard.

In both the low frequency and V-band data, the value of C given above was used, along with the value of γ determined by the TRL calibration, to calculate the value of the line Z_0.

Figures 4-6 show the measurements of the SOLT standards compared to electromagnetic simulations. The match between the simulations and measurements for Z_0, ε_{eff}, and the open standard are fairly good. The open standard was measured both with and without the adjacent short standard present. This data clearly shows the coupled resonance of the short affecting the open. We believe the poorer match between simulation and measurement for the short and load standards to be caused by the inaccuracies in the simulation of the via hole (Fig. 4(a) and 6).

Offset SOL Measurement

Models of the calibration standards were developed for interpolation of the TRL data. These models were then used for measuring offset open, short and load standards using the SOLT calibration. These measurements are now compared with the electromagnetic simulations of the offset SOL standards. At this step, fine adjustment to the SOLT calibration can be made to better fit the offset measurements if necessary. The offset SOL data will be presented at the symposium along with device data taken with the original and improved SOLT calibrations to demonstrate enhancement in SOLT accuracy up to 75 GHz.

Conclusion

With electromagnetic simulation and TRL calibrated measurements of the standards, an SOLT calibration procedure good up to 75 GHz was presented. The calibration was verified using SOLT measurements of offset short, open and load standards. The verified SOLT calibration will allow accurate high volume S-parameter measurements at millimeter wave frequencies.

Acknowledgment

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