Sensitivity Analysis of Calibration Standards for Fixed Probe Spacing On-Wafer Calibration Techniques

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Abstract — **We investigate the sensitivity of different on-wafer calibration techniques to probe positioning. Calibration comparison derived error-bounds are calculated for various cases differing only by a single change in probe/standard overlap.**

I. INTRODUCTION

During the last two decades calibration techniques were developed to determine the error terms in vector network analyzer (VNA) measurements. A number of these techniques rely on the eight-term error model, often used for on-wafer applications [1]. In this model, only seven equations are needed to solve for the needed ratios. Different algorithms were implemented to generate these equations.

These algorithms go beyond the SOLT [1,2], which exists in every network analyzer. The SOLT algorithm is over determined and an alternative method has been defined where the thru is replaced by any reciprocal device in which $S_{12} = S_{21}$. This is known as the SOLR technique where the R stands for reciprocal device [3,4]. The short, open and load are considered as known reflects at each port creating 6 equations, and the reciprocal device generates the seventh equation. In both SOLT and SOLR, the short, the open and the load should be accurately modeled by frequency dependent lumped elements.

The TRL is an alternative technique in which the standards are a thru (T) with known S parameters (4 equations), unknown equal reflects (R) on port 1 and port 2 (1 equation) and line(s) (L) with known S_{11} and S_{22} (2 equations)[5]. Being less dependent on the models of the standards makes the TRL a very effective calibration technique. Unfortunately, it cannot be used with fixed probe spacing since the probes should be moved to measure the lines of different lengths. A second disadvantage is that at low frequency lines with known S_{11} and S_{22} cannot be realized with appropriate length. These disadvantages are overcome by the (Line, Reflect, Match) LRM technique in which a match replaces the lines [6].

By using the match standard in the LRM, we are back again to the problem of the SOLT and SOLR in which an accurate model to describe the match is required. The LRRM (Line, Reflect, Reflect, Match) calibration was developed in 1990 [7] to address this problem. The standards used in this case are a fully specified lne (L), two equal unknown reflects at port 1 and port 2 (RR) and one match at one of the two ports (M). The two reflects are usually the open and the short because they are located at the far ends of the Smith chart, which will reduce possible inaccuracies when calculating the error terms. After a rough determination of the error terms, the open measurement is used to automatically determine the inductance of the match. This is then followed by an accurate determination of the error terms.

Recently we have investigated the sensitivity of the SOLT and LRRM to probe positioning [8]. In this paper, the investigation is extended to cover SOLR, SOLT, LRM with fixed load inductance and the LRRM with automatic calculation of the load inductance.

II. METHODOLOGY AND RESULTS

We evaluated the probe placement impact on a calibration by comparing calibrations calculated from measurement data differing only for a single standard. All other standard data remained unchanged, allowing the investigation of sensitivity to each standard. The calculated error terms were compared using a method outlined by NIST [9] providing a bound on the magnitude of the vector difference between S-parameters of a theoretical passive device-under-test obtained from the two calibrations.

Initially these bounds were calculated for two LRRM calibrations differing only by the measurement of one standard type. The graph of the bound then shows the sensitivity of the LRRM calibration to the particular standard. Bounds were then found using SOLT, SOLR and LRM calibrations, showing the sensitivity of these methods to the standard. The identical data was used in each case so the plotted bounds reflect a direct comparison of the sensitivities of the calibration methods.

Measurements were performed using 150 μm pitch ground-signal-ground (GSG) Air Coplanar (ACP) probes connected to an Agilent 8510C VNA. The probes were precisely and automatically moved and placed on the impedance standard substrate during the calibration by controlling the mechanical motion of the probe station (Summit 12651) using Nucleus* automation software. The

* Wincal and Nucleus are commercial software developed by Cascade Microtech, Inc.

Wincal VNA calibration and measurement software calculates the error terms for the different techniques.

A. Repeatability

As a baseline for comparing measurements we first examined the basic repeatability and reproducibility of our calibrations. The repeatability error was first measured by comparison of two consecutive calibrations using automated moves and no manual adjustment of probe positioning. Initial probe positioning was determined by alignment marks on the Impedance Standard Substrate. Error coefficients were calculated using different methods. The Calibration was then repeated and the error bounds were determined. The repeatability error-bounds for all techniques are less than 0.01, as shown in Fig. 1, which is expected with the automatic placement of the probes.

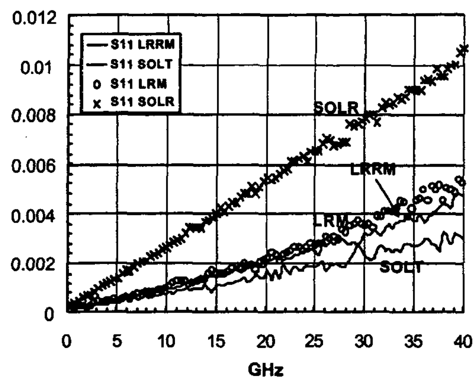

Fig. 1 Repeatability: Calibration sensitivity to measurement system repeatability is shown. Two consecutive calibrations were made and an error bounds reflecting the differences were calculated for different calibration techniques. In all cases these variations are very small.

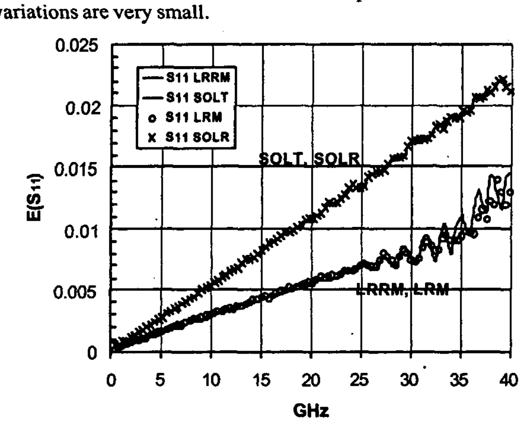

Fig. 2 Reproducibility: Calibration sensitivity to simple measurement system reproducibility is shown. Two consecutive calibrations were made differing only by a single repositioning of the probes precisely to the original alignment marks.

B. Reproducibility

For testing simple reproducibility the probes were repositioned and then carefully realigned to the alignment marks and the calibration was repeated. The resulting error coefficients were compared to a prior calibration. Fig. 2 shows that the worse error occurs with the SOLT and SOLR and that the LRRM and LRM have the smallest reproducibility error (0.015 at 40 GHz).

C. Load Standard Overlap

Calibrations were made differing only by two different positions of the probes relative to the load standard: at the middle of the load and at the end of it as shown in Fig. 3. Fig. 4 shows the magnitude of the calibration comparison derived error-bounds resulting from this ~25 µm change in position for each calibration. For LRRM the maximum deviation was 0.015 while the SOLT, SOLR and LRM exhibited considerably larger sensitivity to probe placement with a maximum deviation of 0.05.

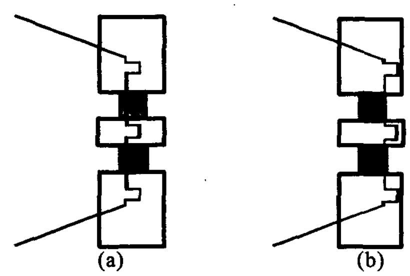

Fig. 3 Probe Placement: Two positions of the probe relative to the load and short standards were used. a) The middle of the standard. b) The end of the standard.

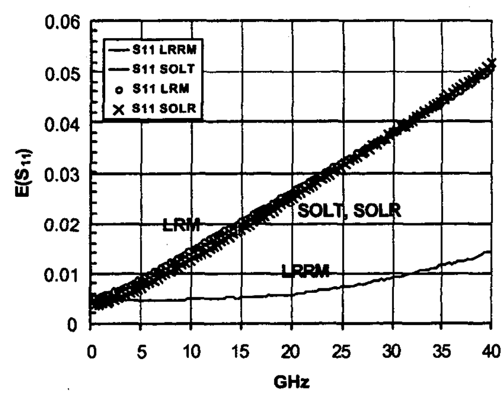

Fig. 4 Load Standard Overlap: Calibration sensitivity to the change in load standard placement of Fig. 3 is shown. The LRRM calibration is considerably less sensitive to load standard placement than other calibrations.

D. Short Standard Overlap

Calibrations were made differing only by two different positions of the probes relative to the short standard: at the middle of the short and at the end of it. A comparison of the sensitivities to probe placement is shown in Fig. 5. The LRRM calibration is far less sensitive to the probe position than the SOLT, which showed a constantly increasing error with frequency. For LRRM the maximum deviation was 0.01 while for SOLT the maximum deviation was greater than 0.14. The error in SOLR was around 0.1. The LRM is not shown since the short was not used to determine the error terms.

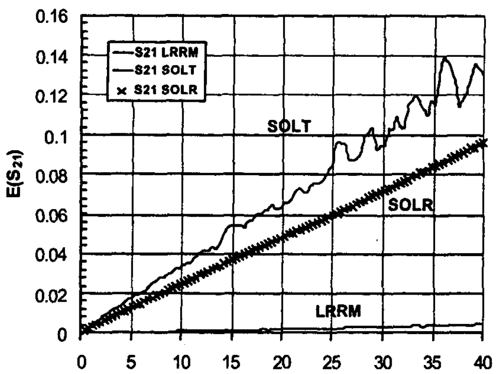

Fig. 5 Short Standard Overlap: Calibration sensitivity to the change in short standard placement of Fig. 3 is shown. The SOLT calibration is considerably more sensitive to short standard placement than LRRM and SOLR. The LRM is not shown since the short was not used to determine the error terms.

E. Thru Standard Delay Definition

To test the sensitivity to the accuracy of the thru standard definition, error terms were calculated for each calibration type with two values for the definition of the thru standard delay. The resulting bounds show each calibration method's sensitivity to the change in definition from the nominal 1.0 ps to a deliberately incorrect 1.1 ps. The same measured data was used for all calibrations, only the thru delay definition was changed. For the SOLT and the SOLR, the S_{11} and S_{22} comparison results in zero difference since both calibrations at each port are independent of any measurement or standard definition related to the thru. For the S_{12} and S_{21} comparison, shown in Fig. 6, the sensitivity to the change is approximately equal between SOLT, LRRM and LRM not unexpected since the thru standard must be fully known in each case. As for the SOLR, it is only required that $S_{12} = S_{21}$, therefore the error bound should be zero which is obtained experimentally.

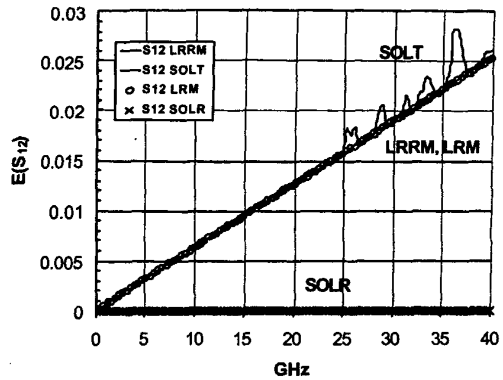

Fig. 6 Thru Delay Standard Definition: Sensitivity to a change in thru delay standard definition from 1.0 ps to 1.1 ps is shown. For the SOLT the maximum error in S_{12} equals to 0.28 while for LRM and LRRM the error is smoother and limited to 0.25. The error in SOLR is zero since it does not depend on the definition of the thru.

F. Open Standard Change

For one open standard the VNA was calibrated with the probes in air well above the substrate (~700 μm). The second case of open standard used probes landed on pads that were otherwise unconnected (essentially the load standards with the load resistors removed). Fig. 7 shows that the SOLT is extremely sensitive to the open standard change. In this case, the maximum error bound exceeds 0.7 while in the LRM, which is the least sensitive, the error is less than 0.02.

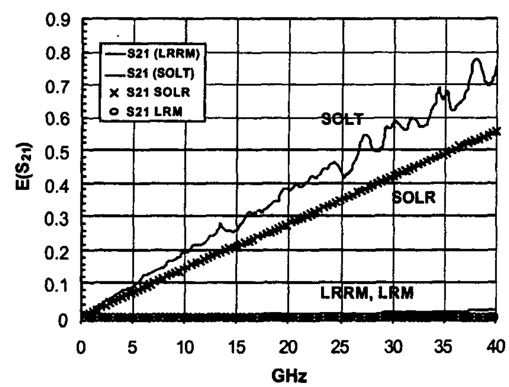

Fig. 7 Open Standard Change: This figure shows the sensitivity of different calibration methods to a change in the open standard. Two open standard sets were used, one with the probes in air ~700 μm above the substrate and the second with probes on pads with no connections. The SOLT is extremely sensitive to this open standard change. The error exceeds 0.75 while in the LRM it is less than 0.01.

III. CONCLUSION

In vector network analyzer calibration, it is clear that the uncertainty in the standard definition leads to inaccurate measurement. In this paper, uncertainty was generated by probing at different positions relative to the standards, an effect that is present in all practical on-wafer measurements. The resulting inaccuracy was calculated using the maximum error bound, which represents the maximum error in the magnitude of the S parameter after two different calibrations. These bounds for different on-wafer calibration techniques were quantified and they are summarized in Table 1. Table 1 shows that the LRRM with automatic load inductance gives the best accuracy with inaccurate definition or positioning of the thru, load and short standards.

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	LRRM	SOLT	SOLR	LRM
Repeatability (Measurement system drift only)	0.0048	0.0032	0.01	0.008(S22)
Reproducibility (Probe realignment)	0.014	0.03(S22)	0.03(S22)	0.014
Load (≈ 25 µm change in overlap)	0.014	0.052	0.052	0.052
Short (≈ 25 µm change in overlap)	0.01	0.14	0.1	NA
Thru delay (0.1 ps change in definition)	0.025	0.028	NA	0.025
Open (Probes in air vs open pads)	0.05	0.75	0.56	0.016

Table 1. Maximum Errors bound for the LRRM (with automatic load inductance calculation), the SOLT, the SOLR and the LRM (Open-match, fixed load inductance) calculated between 0.4 GHz and 40 GHz. This bound corresponds to the maximum error can be obtained in the magnitude of the S parameters. The LRRM with automatic load inductance gives the best accuracy with inaccurate definition or positioning of the thru, load and short standards and the LRM has a better performance with variations in the open.