

Verification of the Wafer-Level LRM+ Calibration Technique for GaAs Applications up to 110 GHz

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Abstract — In this article the accuracy of the LRM+ calibration is compared to that of the benchmark NIST multiline TRL procedure for the first time. The comparison is performed on NIST verified GaAs coplanar waveguide calibration reference material 8130. The NIST calibration comparison method is used to quantify the difference between measured S-parameters corrected by NIST multiline TRL and an advanced LRM+ calibration. The worst-case error bounds for LRM+ corrected S-parameter measurements are determined up to 110 GHz. It is demonstrated that the difference between benchmark multiline TRL and LRM+ is comparable with the measurement system drift. Verification results prove that LRM+ can be successfully used for accurate GaAs on-wafer calibration with customized standards. This overcomes some drawbacks of multiline TRL while providing the same calibration accuracy.

Index Terms — calibration, error correction, calibration comparison, scattering parameters measurement.

I. INTRODUCTION

First attempts to calibrate wafer-level RF measurement setups were performed in the beginning of the 1980's. Yet, the verification of wafer-level calibration accuracy has remained a critical issue. Different calibration procedures have been developed in the past years (i.e. [1]–[7]). All of them rely on ideal, fully or partly known reference elements (calibration standards), realized in planar design (microstrip or coplanar).

In contrast to coaxial and waveguide applications, a great variety of fabrication techniques makes it almost impossible to trace back planar calibration standards to a natural reference. This substantially complicates the task of specifying and verifying planar calibrations.

However, research undertaken by the National Institute of Standards and Technology (NIST) provided a procedure comparing wafer-level calibrations to those performed by NIST [8]. It can be used by industrial laboratories for verification purposes. With the help of this approach, the LRM+ [7] procedure has been compared to a well-defined benchmarking multiline TRL calibration developed by NIST [2].

As demonstrated in [7], accurate measurement results can be achieved up to 110 GHz on conductive wafers using LRM+ and a customized set of standards. However, although results presented in [7] verify the calibration accuracy qualitatively,

the quantitative verification of the LRM+ procedure is still a challenge.

Several accuracy verification procedures for on-wafer calibration are currently in use, e.g. [9], [10]. But almost all of them rely on error-corrected measurements of well-known reference elements. The difficulty to realize an ideal verification element on the test wafer reduces the accuracy of such approaches.

In contrast to this, a method to define error boundaries of error-corrected measurements, in relation to a well-defined calibration, was proposed in [8] and realized in a software package developed by NIST.

This method is used here in order to assess accuracy of the LRM+ procedure quantitatively. The following section briefly describes the verification approach used while Section III presents experimental results.

II. VERIFICATION PROCEDURE

A. Calibration Comparison Procedure

The procedure used for accuracy verification provides the worst-case deviations of the measured S-parameters of passive devices for the examined (first-tier) calibration with respect to the benchmark (second-tier) calibration. Deviations are treated as $|S_{ij} - S_{ij}'|$, for $ij \in \{11, 12, 21, 22\}$, where S_{ij}' is the S-parameter measured by the calibration to be tested, and S_{ij} is the S-parameter measured by the benchmark calibration.

NIST multiline TRL was selected as the benchmark calibration. In conjunction with methods proposed in [12] and [13], this procedure allows accurate setting of the measurement system reference impedance to 50 Ohm as well as a precise definition of the measurement reference plane.

Both the LRM+ and the benchmark multiline TRL calibration were performed on the semi-insulating GaAs reference material 8130 (RM 8130), provided by NIST.

B. Reference Material 8130

The RM 8130 consists of a coplanar wave guide (CPW) multiline TRL calibration set: a 550 μm long thru line, five lines with lengths of 2.685 mm, 3.75 mm, 7.115 mm, 20.245 mm, and 40.55 mm, and two offset shorts located in a distance of 225 μm from the beginning of the line. There are

also additional 12 verification reference elements. For the LRM+ calibration we use the 550 μm thru line, the 225 μm offset short, and two offset loads. The paired load standard with the resistance of about 73 Ohm for both ports was used for the first LRM+ calibration, while the asymmetrical verification resistor with the port 1 resistance of about 46 Ohm and port 2 resistance of about 133 Ohm was used for the second LRM+ calibration.

According to the individual test results provided by NIST for every RM 8130, the actual line capacitance is 1.7877 pF/cm. This value is used by the benchmark multiline TRL calibration for the accurate definition of the characteristic impedance of the RM 8130 lines and the transformation of the measurement system reference impedance.

C. Wafer-Level Measurement Setup and Software

The experimental setup for the 110 GHz wafer-level measurements includes an Agilent 8510XF VNA, a manual wafer-probe station, and the 110 GHz wafer probe tips having a pitch of 125 μm . The examined first-tier LRM+ calibration was performed using external calibration software¹. The second-tier benchmark multiline TRL calibration as well as the accuracy analysis was performed with the help of the MultiCal[®] software package².

III. EXPERIMENTAL RESULTS

To avoid additional contact uncertainty, all RM 8130 calibration standards required for benchmarking multiline TRL and the LRM+ as well as the reference elements were measured in one measurement series in the frequency range from 150 MHz up to 110 GHz. At the end of the experiment, the multiline TRL calibration standards were re-measured providing the second measurement series.

A. Verification of the Measurement Setup Integrity

First, stability of the measurement instrument and its capability to reproduce NIST measurements was validated using a multiline TRL calibration, GaAs reference material RM 8130, and the software package MultiCal[®]. Acquired data were corrected externally, using the multiline TRL procedure and compared to the reference data provided with the RM 8130 by NIST. The second measurement series of TRL calibration standards was used to define the drift of the measurement setup within the experiment. Obtained results are presented in Fig. 1. They are limited to 40 GHz due to the frequency limitation of the original RM 8130 measurement reference data.

¹ The LRM+ calibration procedure is implemented in the commercially obtainable software SussCal[®] from SUSS MicroTec.

² The MultiCal[®] package is provided by National Institute of Standards and Technology.

According to [11], this bound increases with frequency and should not exceed 0.1 up to 40 GHz. As demonstrated in Fig. 1, the measurement setup generally meets this requirement. Thus, it forms a reliable basis for calibration comparison purposes. However, some discontinuities detected around 35 GHz may deteriorate verification accuracy in the range 32...39 GHz. Also, it has to be noted that due to the hardware limitation of the VNA it was not possible to measure accurately below 500 MHz. So, measured and calculated data below 500 MHz were not taken into consideration.

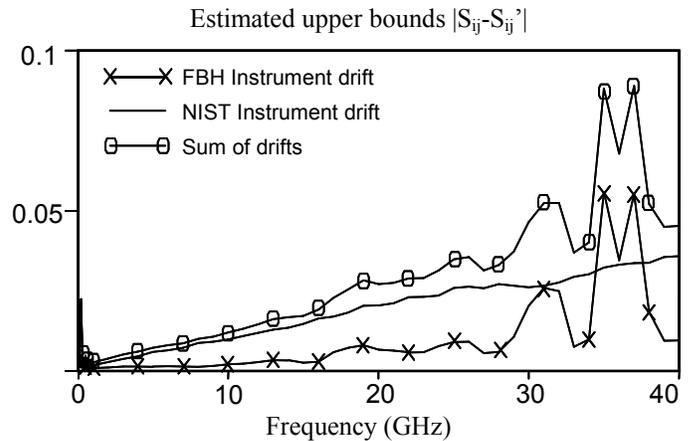


Fig. 1. Verification results on integrity of the wafer-level measurement setup used.

B. Accuracy and Repeatability Verification of the LRM+

In a second step, a multiline TRL calibration up to 110 GHz was performed for data obtained from the first and the second measurement series. The measurement system reference impedance was set to 50 Ohm and the measurement reference plane was defined at the center of the RM 8130 550 μm thru standard. The measurement system drift was determined up to 110 GHz from the second measurement series of all required multiline TRL standards by a second-tier multiline TRL.

Electrical parameters of a paired load standard (Load 1) were calculated for both cases. As shown in Fig. 3, the loads are almost symmetrical and have a resistance different from 50 Ohm (approximately 73 Ohm) and an additional reactive part. Loads are slightly dispersive. As discussed in [7], standards of this kind can be successfully used for the LRM+ calibration.

In the next step, two LRM+ calibrations were performed up to 110 GHz using the first and the second measurement series. The system reference impedance was set back to 50 Ohm by means of an LRM+ algorithm for each port individually. According to the calibration comparison technique proposed in [11], a second-tier multiline TRL calibration was used as benchmark calibration to determine the upper error bound for both cases.

The error bounds of these two LRM+ calibrations as well as a measurement system drift are shown in Fig. 2. It is obvious that the difference between the first and the second LRM+ calibration is marginal. Experimental results prove that both LRM+ calibrations provide the same measurement accuracy as the benchmarking NIST multiline TRL up to 110 GHz. The variation of the measurement accuracy is comparable with the measurement system drift over the whole frequency range.

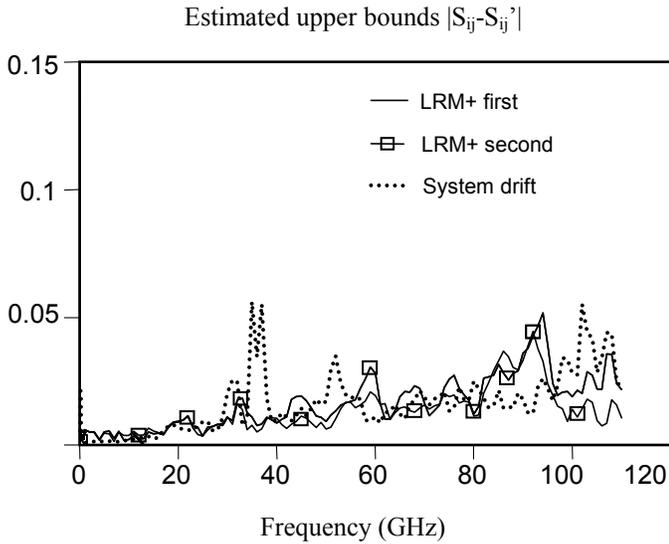


Fig. 2. The maximum possible differences from the benchmark NIST multiline TRL calibration for two 110 GHz LRM+ calibrations and actual system drift.

C. LRM+ with Asymmetrical Load Standard

A combination of two different load elements was used for the next experiment, namely the port-1 element of the RM 8130 verification resistor (see Fig. 3, Fig. 4, Load 2: Z11) and the port-2 element of the RM 8130 load standard used in the previous experiment (see Fig. 3, Fig. 4, Load 1: Z22). This combination artificially repeats the calibration conditions typically occurring in practice for customized wafer-embedded LRM calibration kits. The load model was defined based on measurement data corrected with the multiline TRL.

Using this load combination together with the 550 μm thru and the offset short, four different variants of the LRM calibration procedures can be performed: the simple LRM [3], the LRM, normalized to the port-2 load impedance [4], the LRM+ with the DC load ($R_1 = 45.92 \text{ Ohm}$, $R_2 = 72.71 \text{ Ohm}$) correction, and the LRM+ with the complete correction of the load standard imperfectness. The accuracy of each of them was compared to the benchmark multiline TRL. Fig. 5 presents the experimental results.

As expected, the simple LRM differs from the benchmarking multiline TRL by a value of about 0.6 over the whole frequency range. The estimated measurement error of a simple LRM procedure in the low-frequency range is caused

by the deviation of the load resistance from 50 Ohm and its port asymmetry. Fig. 3 shows that the real part of the port-1 impedance is nearly constant over frequency. At the same time, the imaginary part increases slightly (Fig. 4). The real part of the port-2 load impedance decreases with frequency, while its imaginary part increases. This results in a nearly constant port asymmetry of the load standard used.

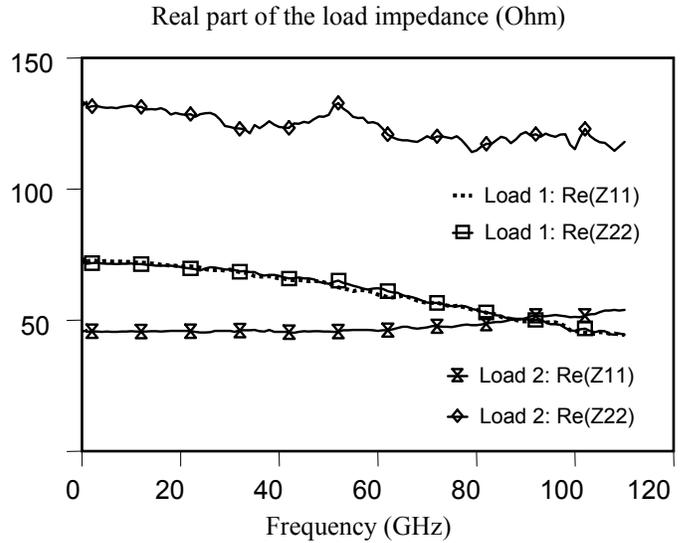


Fig. 3. The real part of the measured port 1 (Z11) and port 2 (Z22) impedance of the load standard (Load 1) and a resistor (Load 2), located on the RM 8130.

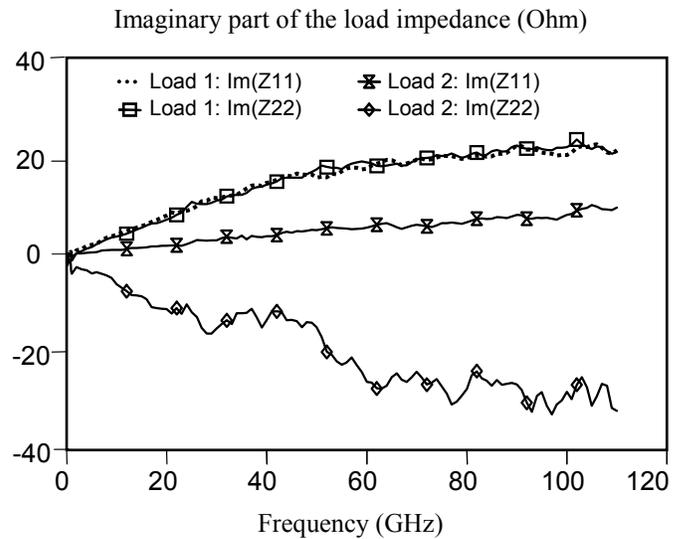


Fig. 4. The imaginary part of the measured port 1 (Z11) and port 2 (Z22) impedance of the load standard (Load 1) and a resistor (Load 2), located on the RM 8130.

Normalizing LRM to the impedance of the port-2 load provides better accuracy beyond 40 GHz than using the simple LRM. This arises from the decreasing difference in magnitude of the load impedances at both ports due to their reactive parts.

Results for the DC load corrected LRM+ generally correspond to those presented in [4]. However, in contrast to the experimental results, the procedure from [4] used the same load standard for both calibration ports.

The complete LRM+ calibration provides the best accuracy with full individual correction of the load imperfectness for each measurement port. The upper error bounds are comparable with the system drift. It has to be noted that the LRM+ error bounds of this experiment are comparable with those found in Section III.B (Fig. 2), while the used load standard was strongly asymmetrical.

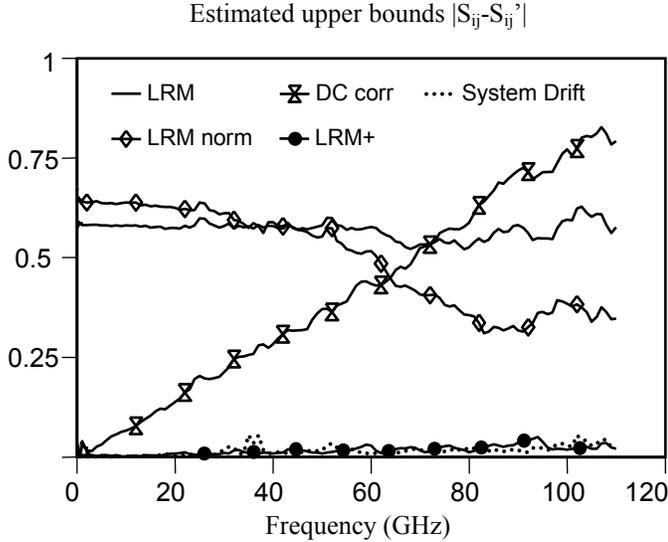


Fig. 5. The maximum possible differences between measurements of passive devices from NIST multiline TRL calibration for the simple LRM, the normalized LRM, the DC load corrected LRM+, and the complete LRM+ calibration.

D. Port Symmetry Verification

Accurate calibration aims for the exact definition of the reference impedance at both ports to the same value (i.e. 50 Ohm). As discussed in [5], LRM-like procedures set the reference impedance to the impedance of the load standard. Typically, on-wafer load standards are realized in pair. This should provide measurements of identical loads at both ports. Supposed that these loads are not equal (i.e. due to the fabrication tolerances), the reference impedance will involve errors, with regard to both the desired value and the difference between ports. The observed effect is called “port asymmetry”: measurements of the same one-port device show different results at each port. The positive or negative offset from the expected value depends on the amount of the load asymmetry. To avoid this, either the load standard has to be realized symmetrically or its asymmetry should be accounted for by the calibration procedure.

The series attenuator embedded in RM 8130, symmetrical for return loss measurements, was used to verify the port

symmetry of simple LRM, normalized LRM, DC load corrected LRM+, and the complete LRM+. The verification results are presented in Fig. 6. In contrast to other LRM procedures, the return loss measurements of the attenuator corrected by LRM+ calibration are highly symmetrical. The results of port symmetry verification obviously correspond with those obtained from the calibration verification (Fig. 5). Again, it is demonstrated clearly that conventional LRM-like procedures do not yield sufficient calibration accuracy for non-symmetrical non-ideal load standards.

The method [8], which is used in this work for the accuracy analysis of different LRM calibrations, also covers the measurement error caused by the “port asymmetry” problem. However, there are cases where this method is not applicable (i.e. for conductive wafers, or if the RM 8130 is not available). As demonstrated, the measurement of a suited symmetrical two-port element provides an alternative tool to verify calibration accuracy utilizing the port symmetry.

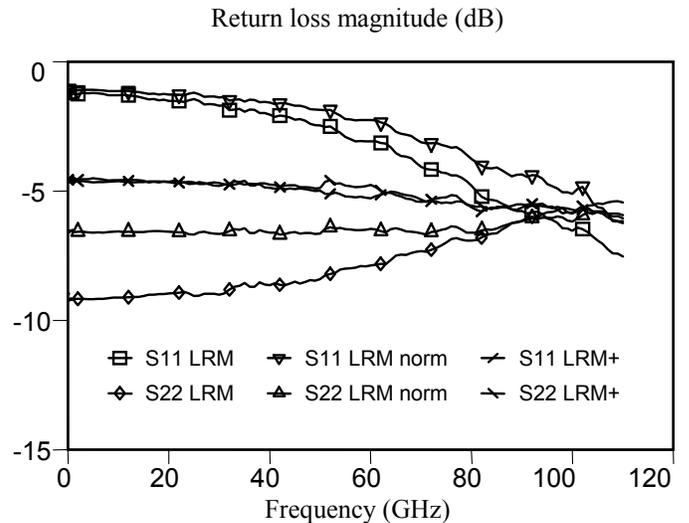


Fig. 6. Results of port symmetry verification for the LRM, the normalized LRM, and the LRM+ calibration using the RM 8130 series attenuator.

IV. CONCLUSIONS

Summarizing one can state that our experimental results demonstrate that the difference of benchmarking multiline TRL and LRM+ accuracy is comparable to the measurement system drift over the whole frequency range studied (500 MHz...110 GHz). This proves LRM+ to be a valuable tool as it overcomes the main drawback of multiline TRL: LRM+ does not require a large set of calibration standards but nevertheless provides calibration accuracy comparable to the NIST multiline TRL. LRM+, therefore, saves wafer space, minimizing the test chip size to only three standards, realized in the same design. Thus, a fully automated calibration is possible even when using a fixed wafer probes configuration.

The required determination of the electrical model of the used load standards can be done easily, e.g., by means of the approaches presented in [7], [14]. As shown above, LRM+ can be successfully used for GaAs applications up to 110 GHz.

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