Evaluation of Wafer-Level LRRM and LRM+ Calibration Techniques

Ralf Doerner[#1]

[#]*Ferdinand-Braun-Institut fuer Hoechstfrequenztechnik (FBH)*
Gustav-Kirchhoff-Str. 4, Berlin, D-12489, Germany.
[1]`ralf.doerner@ieee.org`

Abstract — **This paper presents a comparison of two well-known two-port wafer-level calibration methods, the enhanced line-reflect-reflect-match (eLRRM) and the advanced line-reflect-match (LRM+) approach. Both methods are based on the seven-term error model and involve self-calibration techniques. The reference impedance is established by the match standard. Therefore, accuracy is strongly influenced by the description of this standard. Experimental results for calibration accuracy up to 110 GHz are given.**

I. INTRODUCTION

The recent advances in semiconductor technologies offering transit frequencies in excess of 100 GHz do not only open up new possibilities for novel system applications, but also demand for appropriate characterization techniques. While wafer fabrication for mm-wave components using InP, GaAs, or SiGe processes is now available on a routine basis, testing of these devices at high frequencies still represents a challenge. This is because characterization should be accurate and reliable and, at the same time, it need to be fast and efficient since testing efforts may constitute a major part of the fabrication cost of a chip.

Accuracy of wafer-level mm-wave measurements depends strongly on the calibration techniques applied. In order to meet the efficiency requirements, they should allow fully automated calibration using fixed-spacing wafer probes. Furthermore, the number of calibration standards needed have to be as small as possible. On the commercial level, there are two software tools available providing such advanced wafer-level calibration. This is the eLRRM (enhanced line-reflect-reflect-match) [1, 2] and the LRM+ (advanced line-reflect-match) calibration technique. The first algorithm, eLRRM, is available in WinCal XE from Cascade Microtech. The second method, LRM+, is provided by SussCal Pro from Suss MicroTec. The purpose of this paper is to compare both techniques in terms of accuracy for the full frequency range up to 110 GHz.

II. THE LRRM AND LRM+ CALIBRATIONS

Both methods are based on the error model for a four-receiver VNA and involve self-calibration techniques [3]. This error model defines eight terms, of which seven are linearly independent and sufficient for S-parameter correction. A minimum set of three standards allows for 12 measurements to be solved for seven terms. It can be shown [4] that exploiting the overdetermination reduces the required a-priori knowledge about the standards. Typically, the thru and match standards are considered to be completely known. Particularly, the description of the match standard is crucial for these algorithms. The reflect standard is deduced from the algorithms. The degrees of freedom can be enhanced by adding more standards. This enables the possibility to calibrate with just one match standard.

LRRM [5], in contrast to conventional LRM [4], uses only one match standard, measured at one port. This advantage avoids problems due to asymmetries between two match standards. It is accomplished at the expense of an additional reflect standard – usually an off-wafer open. If the additional reflect standard is known, the introduction of a simple model for the match standard allows to determine its reactive part. This model consists of a known resistance in series with an unknown inductance, which is found by an extension of the LRRM algorithm called auto determination of load inductance [1]. Of course, the limitation to the simple model structure does not allow using customized standards that require a different model.

LRM+, on the other hand, relies on a-priori known match standards. One standard has to be measured at each port. Advantageously, two independently defined match standards can be used and taken into account. For definition of the match standards, either a model or table-based data can be chosen.

III. EXPERMENTAL SETUP USED FOR COMPARISON

The experimental setup for the 110 GHz wafer-level measurements includes an Agilent PNA, a manual wafer-probe station PM8 from Suss MicroTec, and APC-110L ground-signal-ground wafer probe tips with 125 μm pitch from Cascade Microtech. Two substrates were used throughout the experiment: The W-band Impedance Standard Substrate 104-783A (ISS) from Cascade Microtech and the Reference Material 8130 (RM 8130) from the National Institute of Standards and Technology (NIST).

The integrity of the setup [6] and the measurement system drift were verified following a procedure proposed by NIST [7]. It uses the RM 8130, the reference data of verification devices, the multiline TRL calibration method [8], and the MultiCal software package provided by NIST. Fig. 1 presents the results that prove the repeatability and reproducibility of the experimental setup.

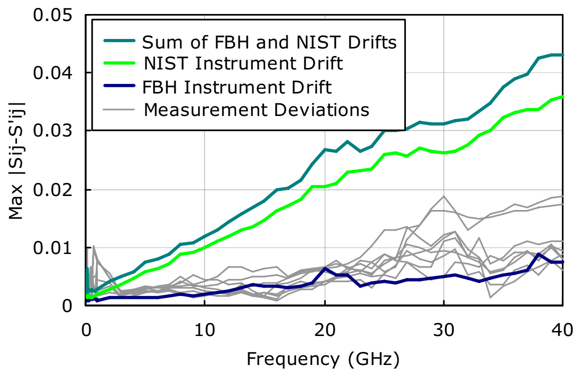

Fig. 1 Verification results on integrity of the 110 GHz wafer-level measurement setup used. Due to the frequency limitation of the reference data for the RM 8130 provided by NIST, the results for the setup are limited to 40 GHz.

IV. EXPERIMENTAL RESULTS

Wafer-level calibration verification is generally hampered by instabilities of the measurement setup and contact repeatability. The stability issue was already verified by the above mentioned integrity check. To avoid uncertainties due to contact repeatability, all required standards were measured in one series in the frequency range from 100 MHz up to 110 GHz. Standards used in both calibration methods were measured only once and the data reused.

The standard measurement data was then introduced into both calibration software products. The computed error terms enable correction of arbitrary devices.

A. Verification

A simple evaluation was performed by comparing the corrected measurements of an additional reference structure at both ports. For a well-established calibration one expects equal results at both ports.

The following assumptions were applied by appropriate settings in the software setups:

- The thru is perfectly matched and lossless.
- The reflects are identical at both ports and also lossless.

In consequence, the algorithms were reduced to their key point, the definition of the match standard.

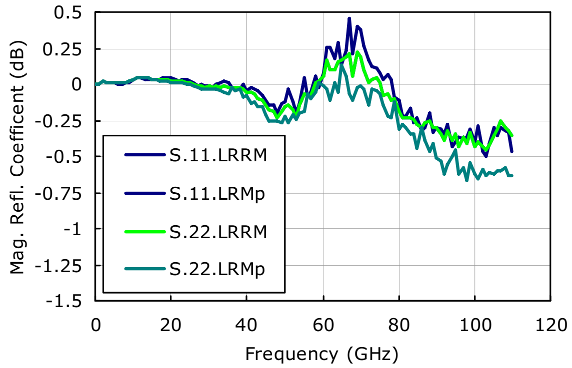

Fig. 2 Reflection coefficient of an open reflect corrected by both algorithms

For the first experiment, both calibrations were set up to use the same load model. Fig. 2 presents the reflection coefficient of an open reflect. Both methods yield similar results. LRM+ appears to have larger uncertainties. A possible explanation is the lack of information of an open standard, which will be particular critical for the high-impedance range. The corrected measurement of a matched load at port 1 is well reproduced for both algorithms, as can be seen from Fig. 3. However, if the same device is measured at port 2 (green curve in Fig. 3) the results show deviations from the expected behavior in the eLRRM case. The real part of the corresponding impedance is plotted in Fig. 4. This is a weak point of the LRRM algorithm, which is induced by eliminating the matched load measurement at the second port.

In a second experiment the auto determination of load inductance by the enhanced LRRM approach was used. The match standard inductance determined in this way strongly differs from the value provided for the combination of probe tip and match on the calibration substrate. This procedure should lead to an improvement accounting for probe placement errors. Nevertheless, the results in Fig. 5 indicate deteriorations with regard to symmetry. Obviously, the problem of port asymmetry is an inherent problem of LRRM and cannot be solved by employing a fitted model.

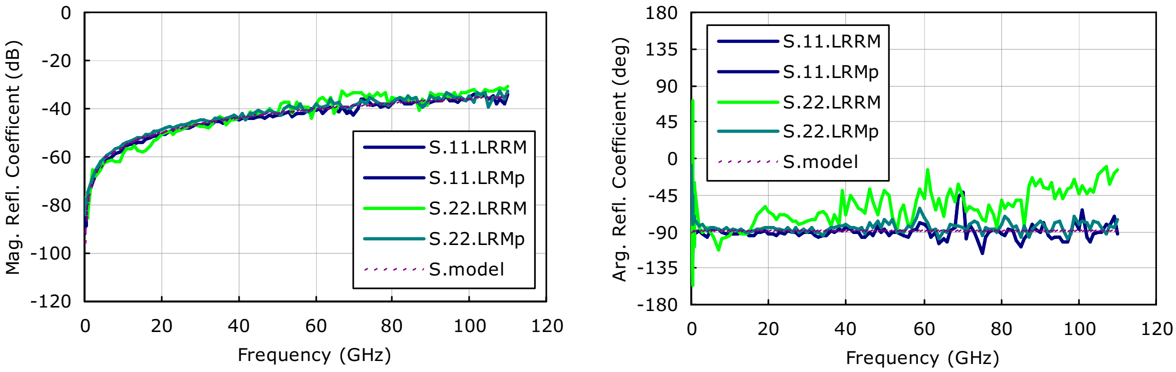

Fig. 3 Reflection coefficient against frequency for a matched load at both ports with fixed inductance; dashed lines refer to modeled data; S.11.LRRM and S.11.LRMp are identical.

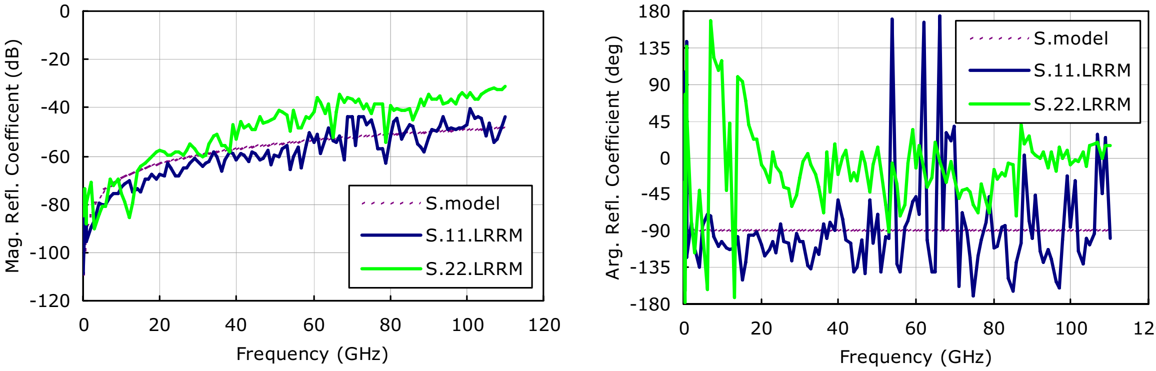

Fig. 5 Reflection coefficient of a matched load at both ports using auto determination of load inductance; dashed lines refer to modeled data.

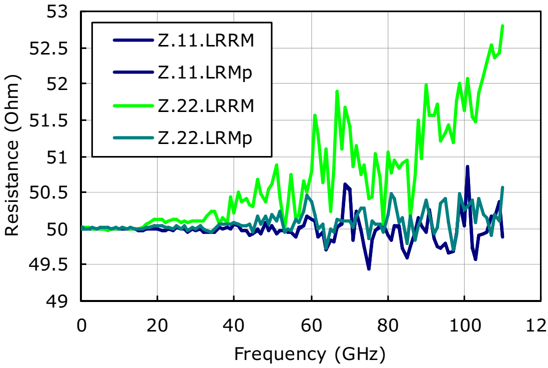

Fig. 4 Data of Fig. 3 in impedance form: Resistance (real part of impedance) of the matched load as a function of frequency; Z.11.LRRM and Z.11.LRMp are identical.

B. *Calibration Comparison*

A more sophisticated evaluation is possible by the calibration comparison analysis [9] using multiline TRL calibration. Two approaches are considered in the following.

First, multiline TRL calibration is carried out on the Impedance Standard Substrate for reference calibration as described in [10]. This procedure establishes a well-defined reference impedance by characterizing the lines on the ISS. Using the ISS and its non-offset reflection and match standards has the advantage that it represents the common calibration environment, which is well-proven for for both methods. The results of the calibration comparison are shown in Fig. 6. The difference between eLRRM and LRM+ is marginal. The maximum value of the upper bounds for worst-case deviations is in a reasonable range around 0.1. This validates the general qualification of both methods for measurements up to 110 GHz. However, calibration errors are still larger than the system drift. The reason is that the thru is assumed to be lossless and, more important, that the common load description as series of resistance and inductance is applied. This corresponds to the conditions of the first verification experiment described in Section IV-A.

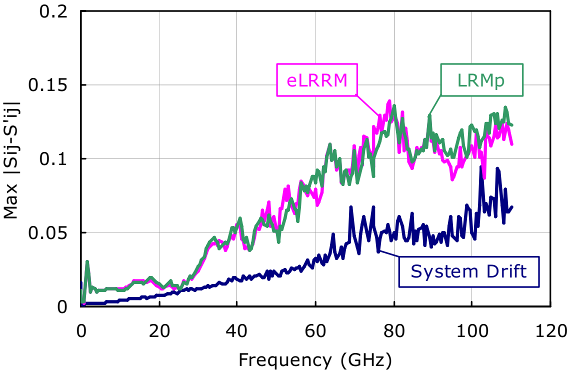

Fig. 6 Calibration comparison of eLRRM and LRM+ with respect to the NIST multiline TRL on ISS.

Secondly, the examined calibration methods were performed using the NIST Reference Material 8130. Due to the pre-characterized lines, the comparison to the multiline TRL on RM 8130 constitutes an independent means of verification. On the other hand, this offers a fair case study for employing custom standards.

The middle of the thru is chosen as reference plane. This avoids the necessity to include information about the thru characteristic into the calibration. The load is an offset-type non-matched standard. Therefore, the best calibration accuracy for both, eLRRM and LRM+, is expected for a complete load description using table-based data from a multiline TRL corrected measurement of the match. Unfortunately, eLRRM does not accommodate to apply table-based data for the match standard. As a workaround, the load was described using several variations of the built-in model (resistance and inductance in series and additional phase shift). One obtains the calibration comparison results presented in Fig. 7. The table-based load model data applied to LRM+ serves as a reference.

The most simple model is the dc resistance of the load. Expectedly, this leads to an unacceptable value for calibration deviations. Next, the load was modeled by an additional inductance taken from the auto determination feature of enhanced LRRM. The result is also unacceptable and clearly demonstrates the inadequate description of the load by such a simple model. Taking into account an additional offset delay yields a much better load approximation. Now, the worst-case deviations are in an acceptable range near the system drift. Obviously, the model fits well the actual match standard. However, this restricted load model may not be suited in all cases, e.g. for a load realization with high parasitics. This represents a drawback of the eLRRM implementation.

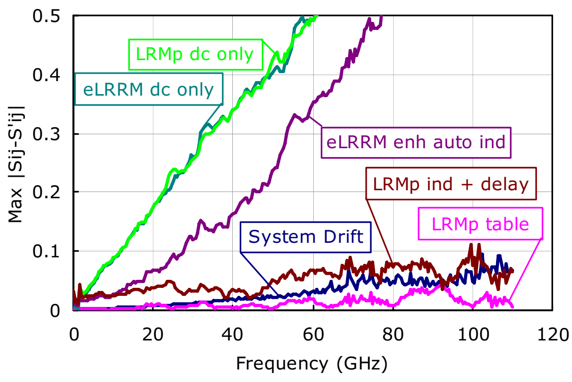

Fig. 7 Calibration comparison of eLRRM and LRM+ with respect to the NIST multiline TRL on RM 8130 using several load descriptions.

V. CONCLUSIONS

Summarizing one can state that both calibration methods are well-suited for accurate wafer-level calibrations to the probe-tip up to 110 GHz. The LRRM technique needs an additional standard to compensate the lack of the match measurement at the second port. As a consequence, it suffers from an inaccurate reference impedance at this port. Furthermore, the use of custom standards is complicated due to the restricted standard model description. This renders wafer-embedded eLRRM calibrations with WinCal XE difficult.

LRM+ requires the smallest number of standards. One has to pay for this by the necessity of a complete load description. These efforts, however, result in a very accurate reference impedance and good port symmetry, also in cases when the load standards are not equal. Therefore, LRM+ is suited for both off-wafer and wafer-embedded calibrations. LRM+, implemented in SussCal Pro, offers versatility with regard to device type and is especially recommended for matched or high-Q devices.

REFERENCES

[1] A. Davidson, K. Jones, E. Strid, "LRM and LRRM Calibrations with Automatic Determination of the Load Inductance," *36th ARFTG Conference Digest*, Dec. 1990, pp. 57–64.
[2] L. Hayden, "An Enhanced Line-Reflect-Reflect-Match Calibration," *67th ARFTG Conference Digest*, June 2006.
[3] H.-J. Eul, B. Schiek, "A generalized theory and new calibration procedures," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 724–731, April 1991.
[4] H.-J. Eul, B. Schiek, "Thru-Match-Reflect: One Result of a Rigorous Theory for De-embedding and Network Analyzer Calibration," *Proceedings of the 18th European Microwave Conference*, Stockholm, pp. 909–914, 1988.
[5] F. Purroy and L. Pradell, "New theoretical analysis of the LRRM calibration technique for vector network analyzers," *IEEE Trans. Instrument. and Meas.*, vol. 50, no. 5, pp. 1307–1314.
[6] R. Doerner, A. Rumiantsev, "Verification of the Wafer-Level LRM+ Calibration Technique for GaAs Applications up to 110 GHz," *65th ARFTG Conference Digest*, June 2005.
[7] "Proposed Procedures for Verifying Probe Station Integrity and On-Wafer Measurement Accuracy," *NIST/Industrial MMIC Consortium*, NIST.
[8] R. Marks, "A Multiline Method of Network Analyzer Calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1205–1215, July 1991.
[9] D. Williams, R. Marks, A. Davidson, "Comparison of on-Wafer Calibrations," *38th ARFTG Conference Digest*, pp. 68–81, Dec. 1991.
[10] A. Rumiantsev, R. Doerner, S. Thies, "Calibration Standards Verification Procedure Using the Calibration Comparison Technique," *36th European Microwave Conference Digest*, Sept. 2006.