Verification of Wafer-Level Calibration Accuracy at Cryogenic Temperatures

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***Abstract* — This article presents the results of accuracy verification of wafer level calibration at cryogenic temperatures based on coplanar calibration standards. For the first time, the electrical characteristics of commercially available coplanar calibration lines were extracted at the temperature of liquid helium. It was demonstrated that the temperature dependent variation of the characteristic impedance of the tested lines is within ±1% tolerance of the nominal value of 50 Ω for a temperature range from room temperature down to 4 K. Finally, the accuracy of the LRM+ calibration method at cryogenic temperatures was verified by definition of the worst case error bounds for the measurement of passive devices and compared to the reference NIST multiline TRL.**

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

I. INTRODUCTION

Accurate calibration is crucial for device measurement, characterization and modeling. Fabrication uncertainty, temperature instability, and mismatch in modeling of calibration standards significantly reduce the final calibration accuracy. Difficulties in traceability of wafer level (planar) calibration standards challenge alternative methods of their verification [1]. These difficulties increase if standards operate in extreme conditions like high vacuum and at the temperature of liquid helium.

The research undertaken by the National Institute of Standards and Technology (NIST) provides a technique for characterizing coplanar lines [2, 3], accurate system calibration [4] and accuracy verification of different calibration methods [5]. This technique is well-accepted in engineering practice and can be successfully used for calibration verification purposes [6]. However, traceable verification results can be achieved only at room temperature and using the reference material RM 8130: the NIST fabricated and characterized GaAs calibration elements [7].

Previously published results of calibration at low temperatures do not consider the temperature influence on the electrical characteristics of thru and line standards [8–11]. Investigations were primarily focused on the temperature stability of thin-film resistors (used as the load standard) as well as on comparing different calibration methods. However, as it was recently demonstrated in [1], even small variations of the electrical parameters of thru and line standards can lead to significant calibration and finally measurement errors. This paper will present the results of extracting electrical characteristics (capacitance per unit length, characteristic impedance Z_0, attenuation and relative phase constants) of commercially available alumina coplanar lines at temperatures down to 4 K, temperature stability of the thin-film load resistance, and finally the accuracy of the LRM+ calibration method at these temperatures.

Fig. 1. The PMC200 cryogenic measurement system used for experiments.

II. VERIFICATION METHOD

The calibration comparison technique [5] was used for the evaluation of time and temperature drift of the cryogenic wafer-level RF measurement system during the experiment and for the verification of the LRM+ calibration method. This technique provides the worst-case deviations of the measured S-parameters of passive devices for an examined (first-tier) calibration with respect to a 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.

The system drift can be quantitatively defined using the same calibration method with measurements of identical standards once, as the examined calibration, at the beginning of the experiment and again, as the benchmark calibration, at the end. In the ideal case, both calibrations, examined and benchmark, are equal and the error bounds $|S_{ij} - S_{ij}'|$ are zero. Remaining differences can be addressed mainly to system drift and contact repeatability.

Using the calibration comparison technique for the verification of the LRM+ calibration method requires a benchmark calibration. The multiline TRL [1, 4] is well-suited for this purpose and enables an accurate setting of reference plane and reference impedance if the parameters of the line standards are known.

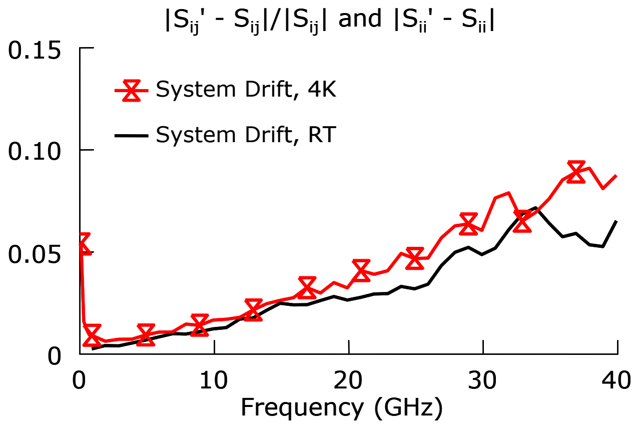

Fig. 2. The system drift of the experimental setup at different temperatures.

To characterize calibration lines at different temperatures the procedure proposed in [2] and evaluated in [1] was used. The resistance R of the load standard can be measured using the 4-terminal method. Then, a first-tier multiline TRL can be performed setting the calibration reference impedance to the characteristic impedance Z_0 of the alumina lines used. The propagation constant known from multiline TRL can be used to extract the value of the line capacitance per unit length C in the frequency range where the tested lines are no longer dispersive and the load reactance is negligible [2, 3]. Once the line capacitance per unit length is found, the characteristic impedance can be obtained from the propagation constants with the help of the MultiCal®[1] software package. The exact determination of the load is essential for accurate line parameter extraction.

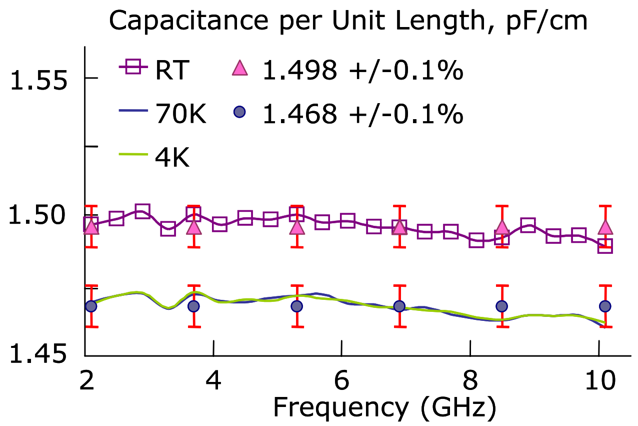

Fig. 3. The results of the line capacitance extraction for different temperatures: room temperature (RT), 70 K, and 4 K. The mean values of 1.498 pF/cm for room temperature and 1.468 pF/cm for 70 K and 4 K data are calculated with maximum error bounds of ±0.1%.

III. EXPERIMENTAL SETUP

The experimental setup (Fig. 1) included a high-frequency, manual cryogenic probe system PMC200, 40 GHz GSG |Z| Probes with 150 µm pitch, CSR-8 calibration substrate, SussCal® calibration software (all available from SUSS MicroTec), the Agilent 8722ES opt. 400 40 GHz vector network analyzer (VNA) and the NIST MultiCal® software package. To avoid additional uncertainty due to contact repeatability, all required data were acquired in one measurement series in raw-data format with the help of the calibration software SussCal® and saved externally for further analysis.

Three measurement experiments were performed: one each at room temperature, 70 K and 4 K. The system drift was defined for two extremely different conditions: experiments performed at room temperature and at 4 K and over a time period of 3.5 hours and 4 hours respectively (Fig. 2).

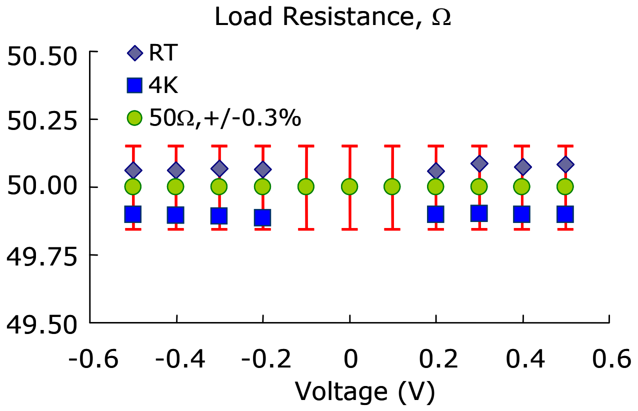

Fig. 4. Load resistance measured over applied voltage of -0.6…+0.6 V at room temperature (RT) and 4 K. The values within -0.1…+0.1 V does not provide acceptable measurement accuracy and are not shown in the graph.

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[1] Available from NIST, USA

It was found that, considering the 30-minutes difference in experiment time, the drift at 4 K is comparable with the drift at room temperature. It proves that the test system reached a stable condition and validates the measurement data acquired at cryogenic temperatures.

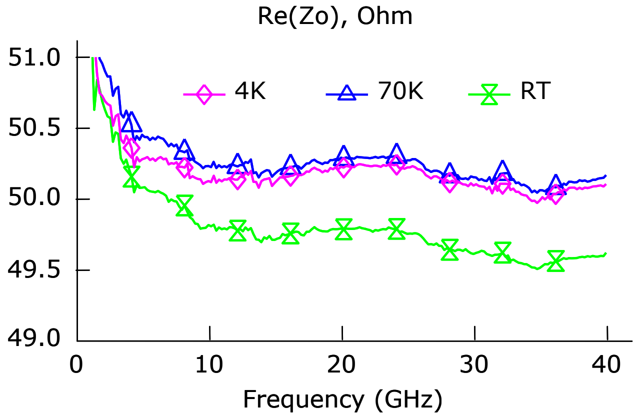

Fig. 5. The extraction results of the line characteristic impedance for the CSR-8 substrate at different temperatures. The extracted values are within the error bounds of ±1% over the range from room temperature down to 4 K.

IV. RESULTS

The line capacitance of the tested CSR-8 alumina substrate was extracted at room temperature, 70 K and 4 K (Fig. 3). To guarantee accurate extraction results, the load resistance was measured at required temperatures. Fig. 4 shows the value of the load resistance provided by the four-terminal method and used for definition of the CSR-8 line capacitance per unit length. The capacitance values are: 1.498 pF/cm at room temperature and 1.468 pF/cm at 70 K and 4 K with maximum error bounds of ±0.1%. The line capacitance per unit length was also extracted at 70 K. No significant difference was observed between the results at 4 K and 70 K.

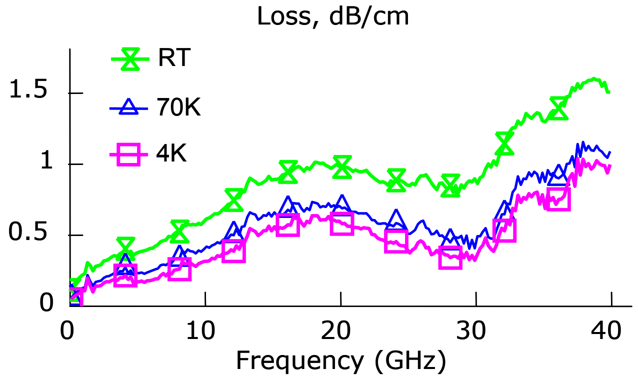

Fig. 6. The extraction results of the attenuation constant at different temperatures.

Next, the characteristic impedance (Fig. 5) was obtained from the measured propagation constant (Fig. 6 and 7). The temperature stability of the characteristic impedance is within ±1% over the range from room temperature down to 4 K. Additionally, the room temperature results demonstrate very good agreement with those extracted using a different setup [1].

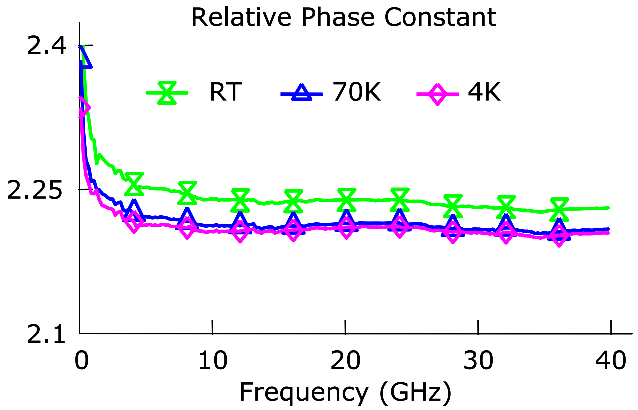

Fig. 7. The extraction results of the relative phase constant at different temperatures.

The temperature dependence of line attenuation and relative phase constants demonstrated expected behavior: decreasing loss and electrical lengths with decreasing temperature. If these effects are not considered when calibrating at different temperatures, they decrease calibration and, finally, measurement accuracy.

Finally, the accuracy of the lumped LRM+ calibration was examined and compared to the multiline TRL in different conditions: at room temperature and 4 K as well as with a full and simplified description of the thru standard. The full description considered the extracted characteristic impedance and propagation constant of the thru standard. The simplified description assumed that the thru standard was lossless, its characteristic impedance was 50 Ω, and the electrical length was known (e.g. 1.16 ps for the used CSR-8 calibration substrate).

Fig. 8 and 9 demonstrate the verification results of the LRM+ calibration with full and simplified characterization of the thru standard at RT and 4 K. The error due to the simplified thru description is negligible for 4 K and slightly decreases calibration accuracy at room temperature from approximately 35 GHz. This effect can be explained by the fact that the LRM+ calibration defines the system reference impedance from the impedance of the load standard. As demonstrated, the electrical characteristics of the used thin-film load element remain stable and ensure the quality of the cryogenic LRM+ calibration over the whole temperature range of interest.

The mismatch between the simplified model of the thru standard and its real characteristics can lead to the error in definition of the measurement reference plane. According to the experimental results, this error is marginal at cryogenic temperatures and at room temperature up to 40 GHz. Therefore, the simple model of the CSR-8 thru standard can be used at low-temperature calibration and will not lead to significant calibration error.

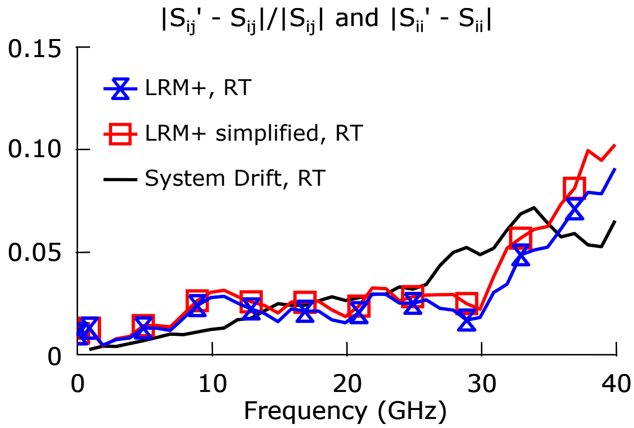

Fig. 8. Verification of the LRM+ calibration method at room temperature using a full and simplified thru description.

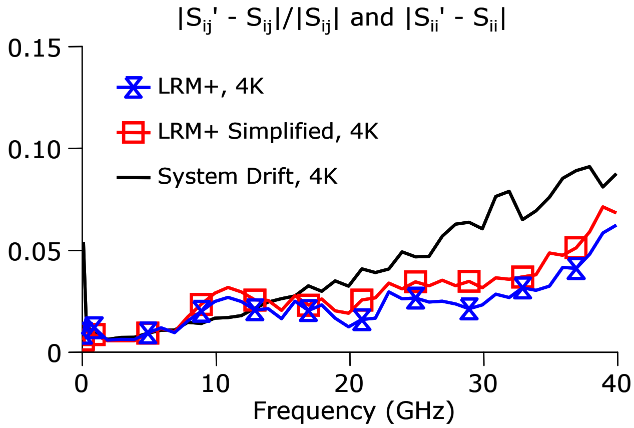

Fig. 9. Verification of the LRM+ calibration method at 4K using a full and simplified thru description.

V. CONCLUSION

Summarizing, the proven worst-case deviations of the measured S-parameters of passive devices at the temperature of 4 K for the examined LRM+ calibration with respect to the benchmark NIST multiline TRL are less than 0.1 up to 40 GHz and they are less then the measurement system drift within the experiment time. Therefore, the LRM+ method provides calibration accuracy comparable to the NIST reference multiline TRL for the extremely wide temperature range: from room temperature down to 4 K.

The demonstrated temperature stability of the thin-film resistor of the CSR-8 load standard is ±0.3% for the evaluated temperature range. The full characterization of the CSR-8 thru standard is not necessary at low-temperatures. Therefore no additional efforts in characterizing calibration standards are required for accurate LRM+ calibration of a cryogenic wafer-level measurement system.

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