Comparing the Accuracy and Repeatability of On-Wafer Calibration Techniques to 110GHz

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Abstract

Many methods of making corrected S-Parameters measurements are available for on-wafer devices and circuits. This is a comparative study of calibration techniques, presented as most accurate and repeatable for making on-wafer measurements.

Introduction

An on going concern when making on-wafer calibrations and measurements is exactly how accurate and repeatable are the measurements you're making. Because of the complexity and diversity of the measurement system it makes traceability back to a physical reference impractical. We can however compare the complete measurement system, including probes, calibration standards and algorhythms to a benchmark standard defined by the National Institute of Standards and Technology (NIST). With the growing interest in millimeter-wave devices due to growth in the aerospace, automotive and optical industry, it is important to understand which calibration set up will offer the most superior measurement performance for any particular application.

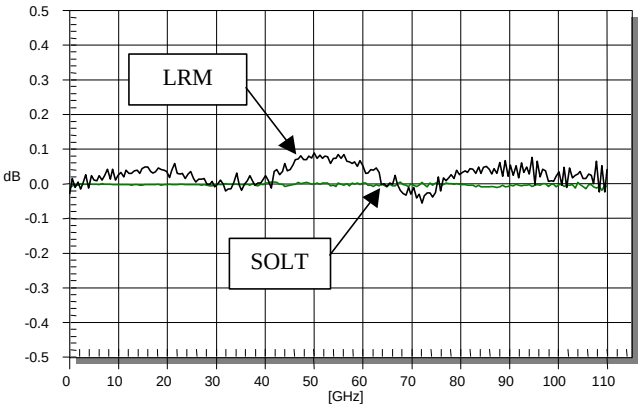


Fig. 1. Measurement of open standard after calibration falsely shows SOLT to be perfect, which is a result of the SOLT calibration forcing the reflections to be 0.0dB

To identify the true integrity of the SOLT calibration we require independent verification standards. Re-measuring the same standards will only show the repeatability of the
Contact. This is shown in Fig. 1. The SOLT calibration is not self-consistent and the open circuit response shows a perfect reflection, where the LRM calibration method is self-consistent and errors can be identified looking at the magnitude of Sii. It is not a safe assumption to believe SOLT is more accurate because it looks like a perfect open.

Methods & Limitations

Three different calibration standard substrates were used for the comparisons. One GaAs substrate for the NIST Multi-Line (LRL) calibration [1], and two alumina substrates for Short-Open-Load-Through (SOLT), Line-Reflect Match (LRM) and Line-Reflect-Reflect-Match (LRRM) calibrations. One alumina substrate being 625um thick, and the other 250um thick. As a recommendation from Ref. [2], the thin ISS included a layer of Radiation Absorption Material (RAM) between the Impedance Standard Substrate and metal chuck surface.

A major limitation of the paper is lack of a reliable precision reference measurement, to 110GHz. An extrapolation was made from the results of Ref. [3] to cover the higher frequency band. The NIST LRL calibration standards are not a modelled 50ohm transmission line to 110GHz and a miss-match to 50ohm calibrations can be expected. My LRL calibration reference planes were at the centre of the 500um thru' line, and the Zo was referenced to the Line. To compare the common calibration methods used by engineers today for on-wafer microwave measurements I have performed several calibrations using SOLT, LRM, LRRM with Auto Load Inductance Compensation [4], and LRL. Measurements were collected, using each resulting calibration co-efficients, of both active and passive devices to determine if a measurement difference is apparent by using different techniques. A commercially available software package [5] was used for performing calibrations and recording measurements.

Measurements & Results

Open Circuit Measurement

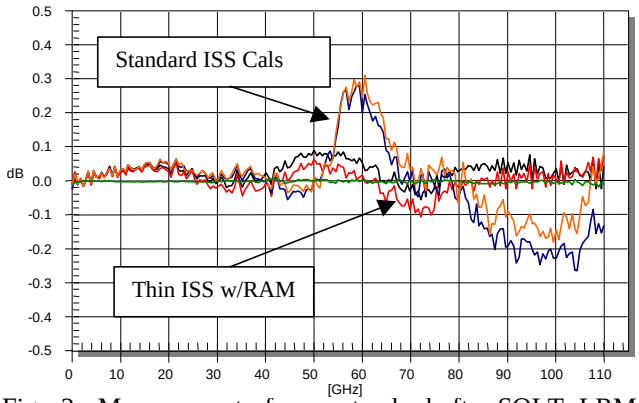


Fig. 2. Measurement of open standard after SOLT, LRM & LRRM calibrations.

The open standard measurements using the SOLT calibrations co-efficients indicates a near perfect reflect, since we are only performing a repeatability measurement

of the contact. The thinned 250um ISS and layer of RAM material reduced the magnitude of error on both LRM and LRRM calibrations. The large error using the 625um thick ISS was due to the substrate moding being more significant at millimetre wave frequencies. The 250um ISS pushes the substrate moding above 110GHz. This now meets the commonly used error limits of +/-0.1dB for open circuit verification.

Open Stub Measurement

A more reliable way of verifying the integrity of the calibration is to measure an independent verification standard. I used a 3.2mm open stub and 3.2mm line of the NIST reference substrate. The ISS calibrations (LRM, LRRM and SOLT), using both the 625um and 250um thick substrates, show a ripple effect. This is due to the line not being exactly 50ohm and is miss-matched to our 50ohm ISS calibrations. The LRL calibration shows a more linear response, but a phase and magnitude offset is present due to the reference plane being in the centre of the LRL thru, not the probe tips, as with the ISS calibrations.

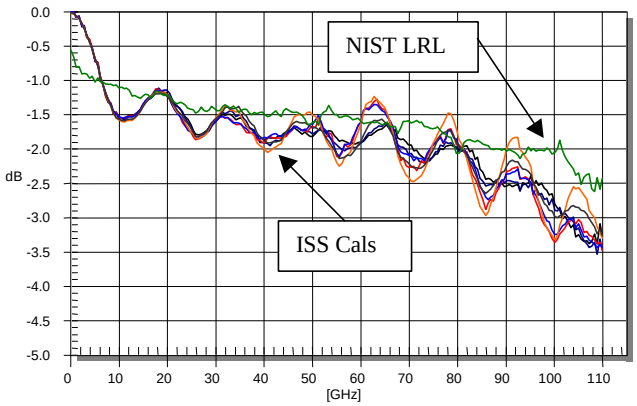


Fig. 3. S11 LogMag measurement of 3.2mm open stub.

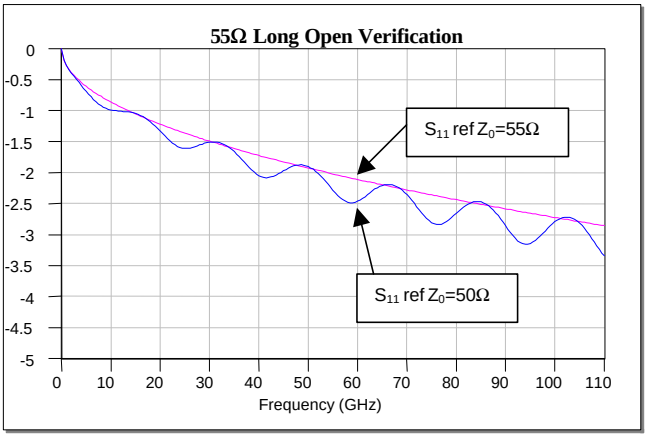


Fig. 4. Model of 3.2mm open verification standard, making the assumption that the GaAs line is not 50ohms

Line Measurement

The GaAs line measurement show the LRL being comparable to the ISS based calibrations up to 70GHz, where afterwards the ISS calibrations shows greater loss. This may be a result of the miss-matched line acting as a low pass filter for the 50ohm calibrations.

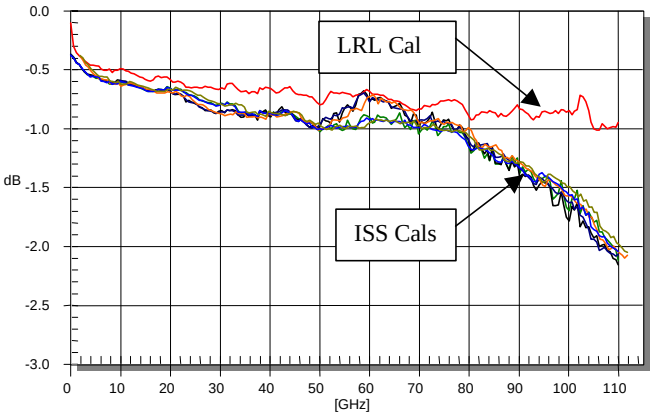


Fig. 5. S21 LogMag measurement of NIST 3.2mm line

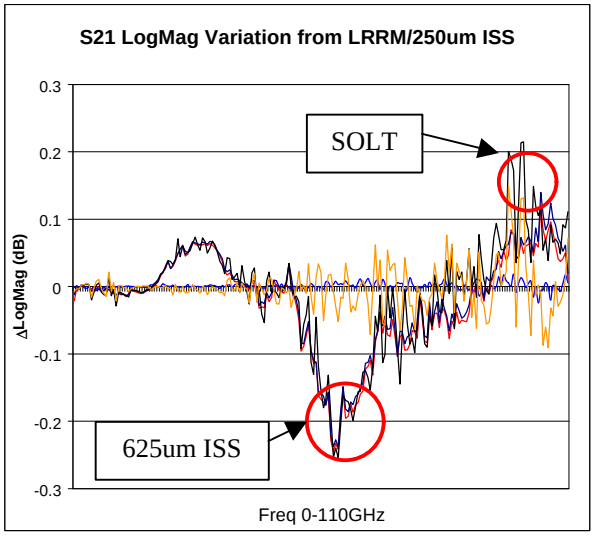


Fig 6. LogMag variations of line using LRRM/250um ISS as reference. (ISS calibrations only)

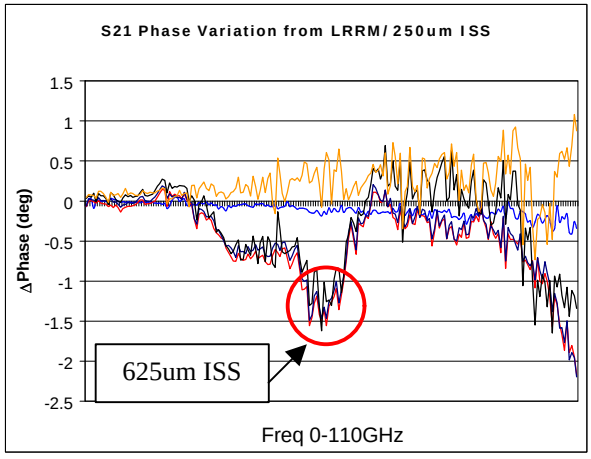


Fig. 7. Phase variation of line using LRRM/250um ISS as reference. (ISS calibrations only)

The ISS calibrations have approximately the same deviation from the LRL measurement, as shown in Fig. 5. Using the LRRM calibration as a reference, the variation of the LRM and SOLT calibrations can be observed. The 625um ISS and SOLT calibrations show greater variation in phase and magnitude. The phase variation of the ISS calibrations from the LRL calibration shows a linear phase

change due to the reference planes of my LRL calibration being the centre of the 500um thru' standard and not the tip of the probes as with the ISS calibrations.

Field Effect Transistor (FET) Measurement

The measurement accuracy very much relies on the calibration and the measurement application. Fig. 8 shows a measurement made of a GaAs FET device. The SOLT, LRM and LRRM calibrations are grouped together. The only stray measurements are the NIST LRL calibration. The difference between the LRL and other calibrations is probably not due to inaccuracy of the ISS based calibrations. It is likely due to the inaccuracy of the LRL calibration due to the change in pad parasitic, the change of effective dielectric constants and the low-end limitation of the calibration due to the restrictions of long line standards.

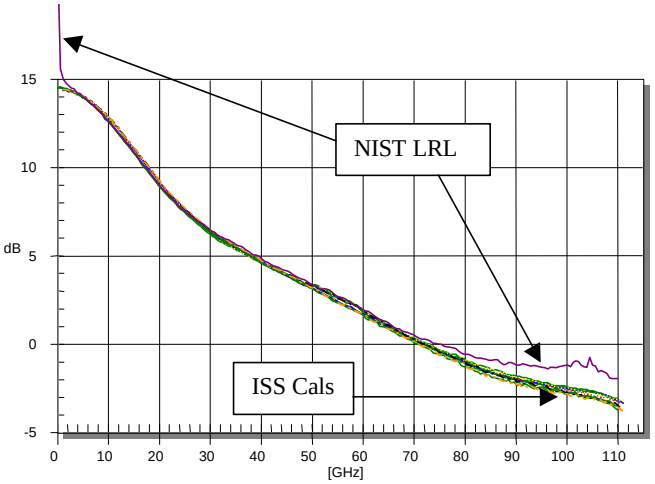


Fig. 8. Measurements of a GaAs FET device.

The SOLT calibration performed on the 250um ISS indicates a linear increase in magnitude and phase, Fig. 9 & 10. The SOLT, LRM and LRRM calibrations performed on the 625um ISS shows the same errors when measuring the open circuit during calibration verification. Only the LRM calibration made on the 250um ISS is comparable to the LRRM reference calibration.

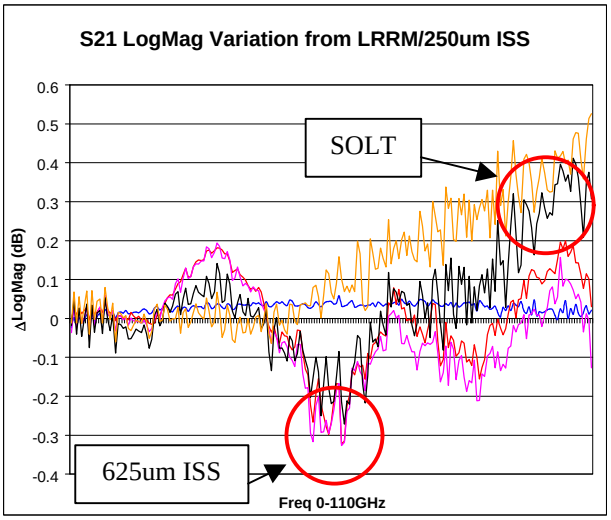


Fig. 9. S21 LogMag variation of GaAs FET device with reference to LRRM calibration using 250um ISS.

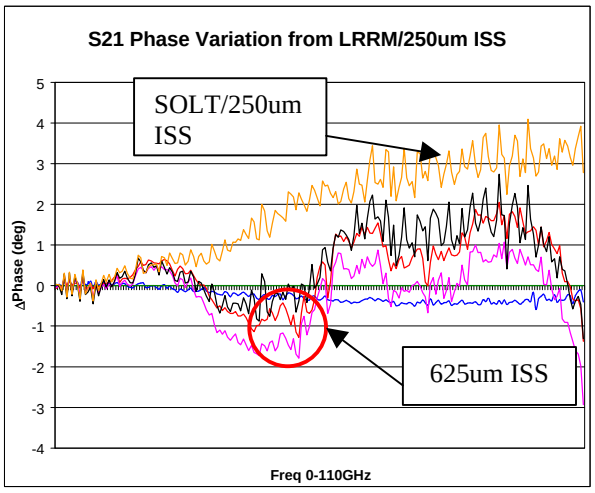


Fig. 10. S21 Phase variation of GaAs FET device with reference to LRRM calibration using 250um ISS.

Repeatability of Calibrations

The need to make an accurate calibration and measurement is equalled by the requirement to make repeatable calibrations and measurements. It is shown in Fig. 11 and 12 the worst case error bounds for repeating two identical calibration techniques. The results show that the LRRM calibration with load inductance compensation was more repeatable than SOLT, which was particularly sensitive when using different sets of standards.

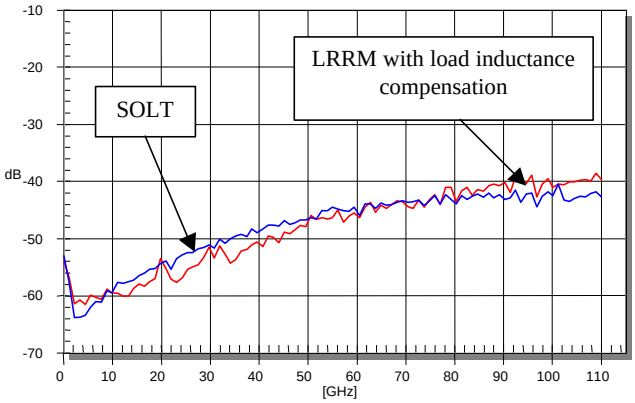


Fig. 11. The worst case errors for calibration repeatability using the same set of standards

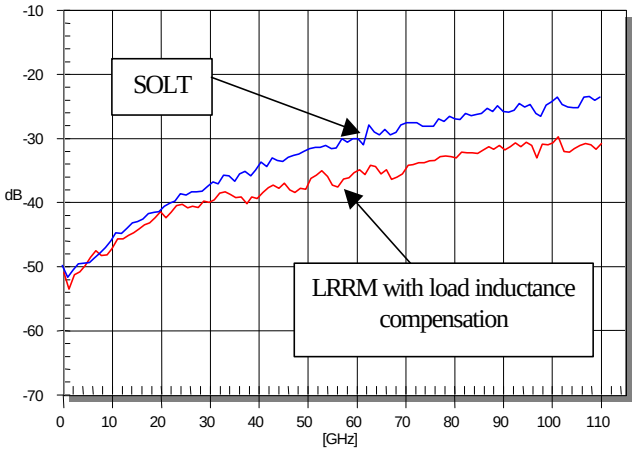


Fig. 12. The worst case errors for calibration repeatability, using two different sets of standards.

I performed eight LRRM calibrations using the same set of ISS standards, but replacing the probes manually on the ISS alignment mark. Even though my probe placement was not exact due to the limitation of the optics and resolution of the positioners, the open standard verification has a worst case spread of 0.15dB. The same experiment was repeated but using eight different sets of standards. The repeatability of calibration was decreased, but only marginally, to 0.2dB. All the calibration verifications were within the general recommended limits of +/- 0.1dB up to 110GHz. Open measurements phase error is expected to be more sensitive to probe placement errors causing small changes in reference plane location.

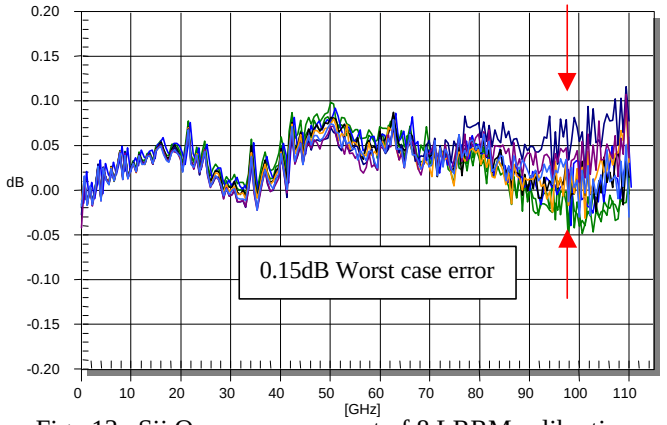


Fig. 13. Sii Open measurement of 8 LRRM calibrations

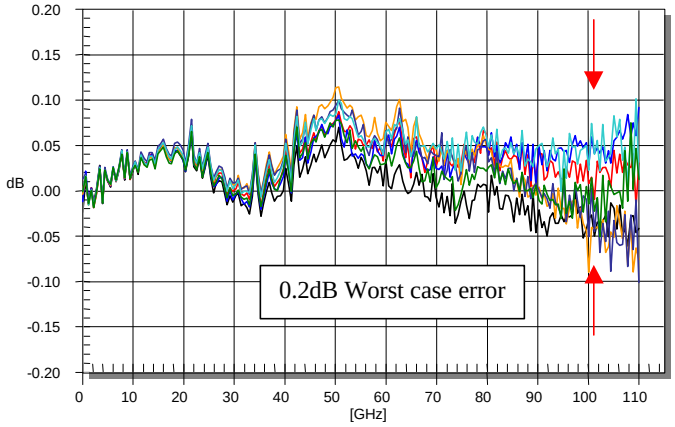


Fig. 14. Sii Open measurement of 8 LRRM calibration using different sets of calibration

Conclusions

Analysis of the measurements showed differences in magnitude and phase of the Devices Under Test. The extent of the differences was found to be dependent on the DUT and calibration technique used.

From the measurements made of the open stub and line, on the GaAs NIST reference material, the results approximated what we expected. The ISS calibrations did not have the same Zo as the GaAs line. This resulted in a loss increasing with frequency combined with a ripple effect. The LRL measurement did not exhibit the ripple, due to the Zo of the calibration being the same as the line, but had an offset in phase and magnitude due the incorrect positioning of the reference planes.

The FET device results identified large variations at low and high frequencies between the LRL calibration and the ISS based calibrations. The low-end variation was a limitation due to the line length required for low frequencies and the large imaginary component of the characteristic impedance at low frequencies due to conductor resistance. The high frequency was a result of differences in pad parasitic between the calibration standard and DUT.

The 625um thick ISS exhibited a larger error in magnitude when verifying the calibration, using an open standard. This error is noticeable when measuring a reflective DUT such as an open or open stub and was also noticeable on the S21 of a FET measurement.

Whilst performing the calibrations, my observations included how essential probe placement accuracy was for all calibration methods, but was even more so important when making LRL and SOLT calibrations. The probe placement error was not critical when using load inductance compensation, which was used for the LRRM measurements. Several calibration attempts were required to achieve satisfactory results for the techniques not using load inductance compensation. Indeed, I encounter long and tedious problems trying to achieve a 'good' NIST LRL calibration, and it was not easy to achieve repeatability.

Also whilst making my calibrations it was noted that a good LRRM calibration with load inductance compensation was achieved after every attempt. The repeatability of making numerous LRRM calibrations proved to be better than –30dB of repeatability, even when using different sets of standards.

References

[1] Roger Marks, "A Mult-line method of network analyzer calibration," *IEEE Trans. On MTT*, Vol. 39, No. 7, pp. 1205-1215, July 1991.

[2] Ed Godshalk, "Surface wave phenomenon in wafer probing environments," *40th ARFTG Conference Digest*, Dec. 1992.

[3] Cascade Microtech Inc, "Technique Verifies LRRM Calibrations for GaAs Measurements."

[4] John Pence, "Verification of LRRM calibrations with load inductance compensation for CPW measurements on GaAs substrates," *42nd ARFTG Conference Digest*, Nov. 1993.

[5] WinCal 2.30 Calibration and Measurements Tool, Commercial Product, Cascade Microtech Inc.

Acknowledgements: Hewlett Packard SRSD Division