Minimizing Discontinuities in Wafer-Level Sub-THz Measurements up to 750 GHz for Device Modelling Applications

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***Abstract* — Achieving accurate and continuous measurement for sub-THz wafer-level device characterization is particularly important for device modelling applications. This paper outlines, for the first time, challenges affecting measurement continuity and accuracy at such high frequencies. The newly proposed sub-THz measurement strategy with pre-calibration check for low probe contact resistance, combining power and S-parameter probe tip calibration, implementing post-calibration verification checks and ensuring consistent and accurate DC biasing of devices across all frequency bands, has been demonstrated in this work to improve measurement continuity and quality of wafer-level measurements up to 750 GHz.**

***Index Terms* — RF, Sub-millimeter wave, mmW, sub-THz, THz, Device Modelling, Vector Network Analyzers (VNA).**

I. INTRODUCTION

To develop device SPICE models that can accurately predict the behavior and performance of microwave circuits, device modelling engineers require precise measurement data. Accurate SPICE models depend entirely on test data being precise because even if the SPICE model fits against a set of flawed measurement data with no error, the extracted final model would still be incorrect. As sub-THz applications gain popularity, modelling engineers are faced with the daunting task of making several frequency banded measurements and merging these measurement results together for model development [1]. This is inevitable because to precisely extract all the SPICE model parameters, with some particularly sensitive at low frequencies and others critical at high frequencies, test engineers must fully characterize the devices from low to sub-THz frequencies. For the first time, this paper will discuss the difficulties in making wafer-level measurements up to 750 GHz and propose solutions that would help address these challenges.

II. CHALLENGES FOR PROBE TIP SUB-THZ MEASUREMENTS

A. Complex and Tedious Waveguide Sub-THz Test Setup

Preparing test systems to measure S-parameters of the same device from low frequencies to 750 GHz is a very tedious task as most network analyzers can only support up to 67 GHz. To extend measurement coverage up to 750 GHz requires banded frequency extenders and banded waveguide probes shown in Fig. 1. A total of 6 sets of frequency extenders and probes in frequency bands of 10MHz-110GHz, 110-170GHz, 140-220GHz, 220-325GHz, 325-500GHz and 500-750GHz are used to obtain the required experimental data. Using these 6 sets of frequency extenders and probes to characterize the same device, the combined overall measured results is extremely prone to discontinuities. Modelling engineers face a perplexing task if they have to re-setup and re-measure the device at a particular frequency band. The frequency extenders and waveguide probes have to be re-mounted onto the probe positioners and the probe tips have to be re-calibrated before any measurements could be made. A post calibration validation method is urgently needed to minimize measurement discontinuities, the first time the device is tested at every individual frequency bands so as to avoid tedious re-measurements.

Fig. 2 shows an example of discontinuities observed after combining measurement results from 2 frequency bands for a transmission line. With such measurement discontinuities, the device modelling engineer is unsure whether to fit the SPICE model to the 110 GHz or the 170 GHz test data. This issue can

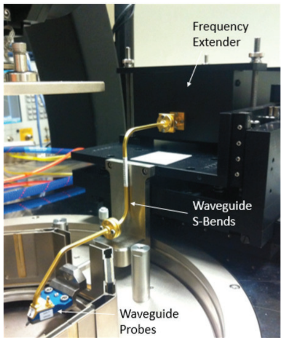

Fig. 1. 325GHz setup for sub-THz wafer-level measurements with frequency extender, waveguide S-bend and waveguide probe.

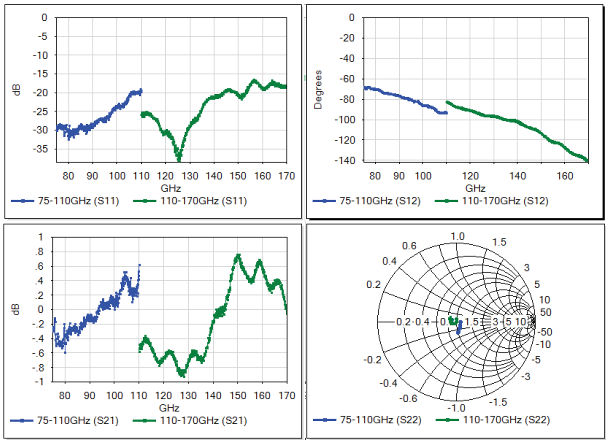

Fig. 2. Combined phase response, return and insertion loss for a line measured with frequency bands of 75 to 110 GHz and 110 to 170 GHz.

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only be rectified by making tedious and time consuming re-measurements for both frequency bands as there is also a possibility that both sets of measurement data are flawed.

B. Post-Calibration Verification for Frequencies < 67 GHz

Inexperienced device modelling or test engineers are still making the mistake of validating their calibrated system with electrical standards that were used to calibrate the VNA. For applications up to 67 GHz, a 2-step verification is proposed in this paper. First, after calibration, the probes are lifted in the air and the OPEN return losses at Port 1 and Port 2 are measured. They are recommended to be within ±0.1dB. Being the most repeatable test, probes in the air can also be used to conveniently monitor the system drift over time. Next, verification lines such as 1ps transmission line is used to validate the accuracy of the measurement reference plane and monitor the contact resistance of the probe tips. Such verification must be performed after calibration as well as after completing all the device measurements to ensure accuracy and traceability of all measured data collected throughout the day.

Fig. 3 shows the extracted inductance, L_S and resistance, R_S of a 1ps verification line (gold metallization on an alumina calibration substrate). L_S and R_S are obtained using equations (1) and (2) [2] from Y-parameters (derived from the measured S-parameters) of the transmission line. This approach assumes that the line can be predicted by a lumped element pi-model.

$$R_S = Real\left[-\frac{1}{Y_{12}}\right] \tag{1}$$

$$L_S = \frac{Imag\left[-\frac{1}{Y_{12}}\right]}{2\times\pi\times frequency} \tag{2}$$

The theoretical inductance, L for the transmission line can be calculated using equation (3),

$$Line\ Delay = \frac{Inductance}{Resistance}$$

$$L = Line\ Delay \times (Z_0 + R) \tag{3}$$

where Z_0 is the reference load, R is sum of line resistance and contact resistances of the 2 waveguide probes.

Instead of just simply evaluating the measured S-parameters, extracting and monitoring L_S and R_S allow modelling engineers to quantify the accuracy of their test setup, enabling them to identify and rectify any anomalies, potential hardware issues or probe-on-standard placement errors made during calibration. From the R_S plot on Fig. 3, contact resistance for each RF probe on the gold metal line is less than 0.015 ohms at 300 MHz (R_S increases with frequency due to skin effects of verification line). This probe contact resistance obtained after each post-calibration validation should be less than 0.015 ohm. If the measured low frequency R_S is abnormally high, a new verification line should be used to determine if the verification line or the probes have worn out and needed new replacements.

From equation (3), as R is negligible at low frequencies, L_S is estimated to be about 50 pH for the 1ps line. This correlates very well with the measured L_S in Fig. 3. Monitoring L_S during post-calibration validation and after completing measurements for all the devices allow modelling engineers to determine the accuracy of measurement reference plane, providing traceability to all their measurements. For example, if erroneous probe placement on thru' standard have occurred with probes placed much closer to each other than the required separation distance or if an inaccurate load standard of say 45 ohms is used during calibration, then the extracted L_S will be about 45 pH instead of 50 pH. Therefore, monitoring L_S and R_S of verification lines with known delay empower test engineers to easily identify mistakes made during calibration or provide justifications when there is a need to purchase new replacement probes or calibration substrates. This verification method is now widely adopted by the top silicon foundries in the world.

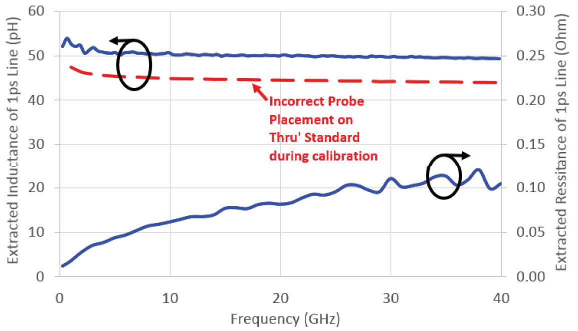


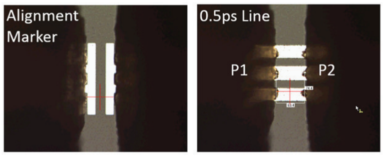
Fig. 3. Measured L_S and R_S versus frequency for 0.1ps verification line (solid blue plots). Dashed red plot shows incorrect L_S of 1ps line due to wrong probe placement on thru' standard during calibration.

C. Post-Calibration Verification at sub-THz Frequencies

At sub-THz frequencies, post calibration verification is even more critical to ensure minimal measurement discontinuity and highest accuracy. Regardless of calibration methods adopted for the sub-THz wafer-level measurements, it is recommended to design verification lines on the calibration substrates (if probe tip calibration is used) or on wafers (if multi-line TRL is used). Fig. 4 shows an example of a verification line with probe alignment markers to help detect measurement discontinuity.

Fig. 5, 6 and 7 present the post-calibration measured insertion/return losses, L_S, R_S and phase of a 0.5ps verification line for 6 frequency bands from 1 to 750 GHz. Between 1 to 500 GHz, eLRRM [4] probe tip calibration is performed with calibration standards on an alumina substrate. For 500 to 750 GHz, multi-line TRL calibration is used with the measurement reference plane in the middle of the thru' standard. In each of these 3 figures, there is an additional plot showing an example of measurement discontinuities of the 0.5 ps line at the 220-325 GHz frequency band due to inaccurate probe placement on standards during calibration.

Modelling engineers are not able to prevent measurement discontinuities by monitoring the return loss of the 0.5ps line utilizing Fig. 5. Instead, inductance and phase plots of the verification line in Fig. 6 and 7 reveal trends which engineers can exploit as continuity checks to detect measurement discontinuities after calibration. It is important to note that the



(a) (b)

Fig. 4. Example of probe alignment marker (a) and 0.5ps verification line (b) on alumina substrate with waveguide probes.

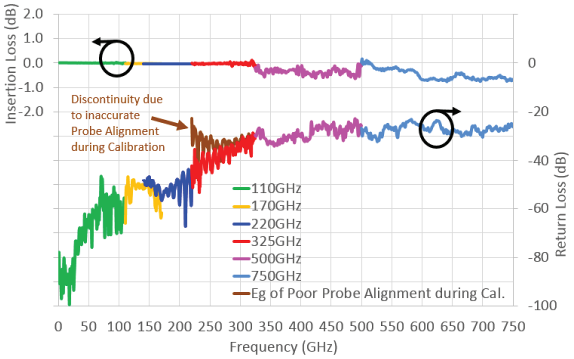


Fig. 5. Insertion loss and return loss for a 0.5ps verification line over 6 frequency bands from 1 GHz to 750 GHz.

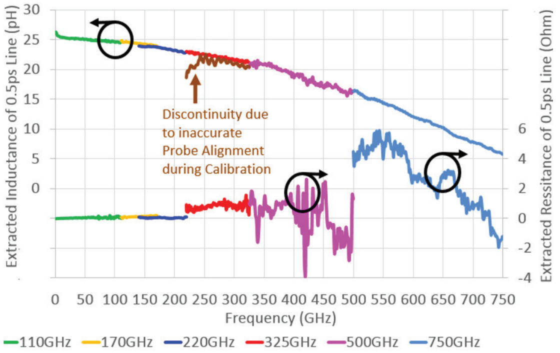


Fig. 6. Extracted L_S and R_S versus frequency of the 0.5ps line.

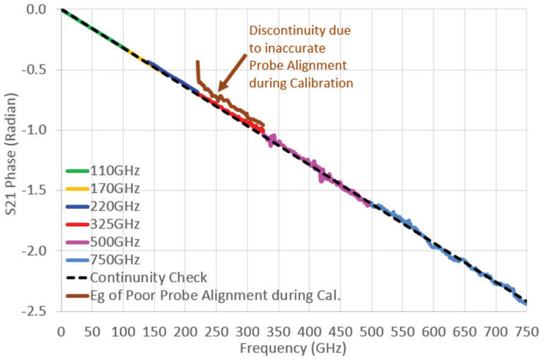


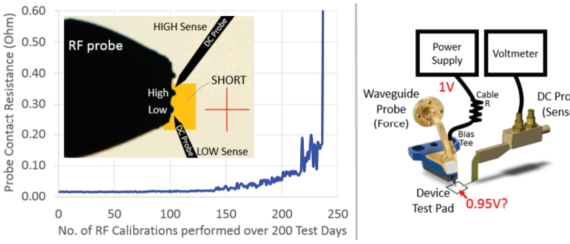
Fig. 7. Phase versus Frequency (-0.185 Deg/GHz) for the 0.5ps Line.

measured low frequency line inductance of 25 pH shown in Fig. 6 correlates very well with equation (3), revealing very accurate probe tip calibration. This inductance plot has a very continuous and smooth decreasing characteristic as frequency increases (The assumption that 0.5 ps line can be modeled by pi-model in equation (2) is not valid at sub-THz frequencies), allowing it to be used as a continuity check. The phase plot in Fig. 7 has a very linear decreasing slope of -0.185 Degree/GHz, which can offer ease and convenience for device engineers to perform quick post-calibration continuity checks at each frequency bands. Both plots may seem very obvious now but prior to this work, it is not apparent to modelling engineers how measurement continuity can be monitored and maintained when performing measurements for each frequency bands.

Utilizing these 2 plots for continuity check is valid even when eLRRM probe tip calibration is adopted from 1 GHz to 500 GHz and TRL calibration is used between 500 and 750 GHz. Therefore, regardless of calibration method used, modelling engineers must characterize all their frequency extenders and test setup with a short verification line (on the calibration substrate or wafer) so that similar Fig 6 and 7 plots are available for post-calibration validation at each frequency bands prior to characterization of devices to minimize measurement discontinuity. It is also recommended to fabricate multiple duplicates of such verification lines so that if they are worn out, new ones are readily available.

D. Probe Contact Resistance & DC Biasing Voltage

Fig. 6 reveals a challenge in monitoring low frequency probe contact resistance described in Fig. 3 since it is not possible to measure R_S from second to the sixth frequency bands. This work proposes, prior to calibration, that device engineers measure the DC contact resistance of the waveguide probes for each frequency band as shown in Fig. 8(a) to ensure probe contact resistances are consistently low and identical for all frequency bands. Signal and ground tips of the waveguide probes are placed on a common gold pad and the probe contact resistance is measured with Kelvin sense probes. This is particularly important when measuring low resistive passive devices as waveguide probe tip can wear out with use, exhibiting abnormally high contact resistance which will result in measurement discontinuity as depicted in Fig 8 (a).



(a) (b)

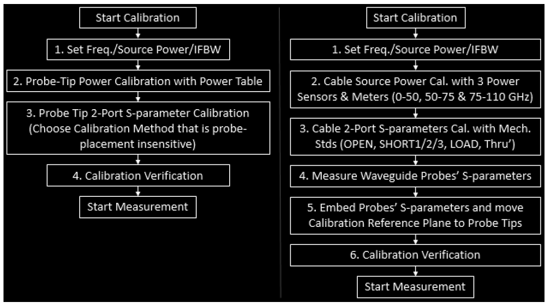
Fig. 8. Proposed setups to measure waveguide probe DC contact resistance (a) and voltage compensation required to overcome cabling resistance, waveguide probe bias-tee and probe contact resistance (b).

DC biasing voltage, when testing active devices such as transistors, are added through the built-in bias-tee in waveguide probes. These bias-tees have been optimized to perform specifically for each frequency bands. As such, to ensure identical DC voltage applied at the device test terminals, it is vital to adopt the setup in Fig. 8(b) to measure the voltages at device test pads so that voltages drop across parasitic resistances of the DC cables, bias-tee and probe contacts are duly compensated. This will help ensure identical bias voltages on the device terminals for every frequency band to eliminate measurement discontinuities.

E. RF Source Power and Probe Tip Power Calibration

Probe tip power calibration is mandatory for active devices because source power set by device engineers on the VNA has no effects on the sub-THz frequency extenders, leading to incorrect and inconsistent source power applied to the device for different frequency bands [5]-[6]. Since S-parameters are relative measurements, most instrumentation and test engineers believe that probe tip power calibration is not required for passive devices. This paper demonstrates for the first time that even for passive devices, having power at the probe tips calibrated for S-parameters measurements can actually reduce system drift over time, which is one of the key culprits in causing measurement discontinuities. A new probe tip S-parameter and power calibration approach outlined in Fig. 9(a) is proposed. A single sweep 10 MHz-110 GHz system with a 67 GHz VNA is used in this work as it allows unbiased studies of power calibration and measurement discontinuities in a single setup, avoiding the need to change frequency extenders, RF probes and combining test data from two frequency bands.

The overall system losses at the end of the 1.0mm cable for port 1 and 2 (Connected to the frequency extenders, without RF probes) are measured with 3 different power sensors (10MHz-50GHz, 50-75GHz, 75-110GHz). Combining these 3 sets of power loss tables and incorporating loss of the 110 GHz RF probes, power calibration tables for Port 1 and Port 2 can be constructed and extended to the probe tips. Device modelling engineers can then conveniently perform power calibrations prior to S-parameter calibrations. Compared to the VNA coaxial calibration method outlined in Fig. 9(b) [3], which could take up to a morning to complete, the proposed method can be easily completed in less than 15 minutes.



(a) (b)

Fig. 9. Proposed probe tip S-parameter and power calibration (a) versus VNA coaxial method (b) for wafer-level applications.

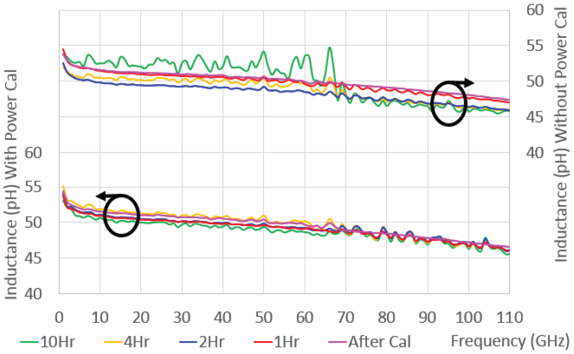


Fig. 10. Calibration drift performance, monitoring extracted inductance versus frequency for 1ps line over 10 hours, comparing with and without probe tip power calibration, with source of -20dBm.

Fig. 10 reveals negligible deviations and no discontinuities in measured inductance over 10 hours for post-calibration system drift tests of a 1ps verification line, measured with a very low source power of -20 dBm, when both Power and S-parameter probe tip calibrations are used. Without power calibration, inductance of the 1ps line starts to drift in 2 hours and by 10 hours, more than 10% change is observed, exhibiting significant measurement discontinuities at around 67 GHz which is the transition frequency between the VNA and the frequency extenders. Such discontinuities are expected to worsen as frequency increases due to larger losses in the system when waveguide extensions and waveguide probes are used. Fig. 11 proposes a new sub-THz wafer-level measurement strategy for device modelling engineers to perform pre-calibration checks and post-calibration validations so that better measurement accuracy and continuity can be achieved.

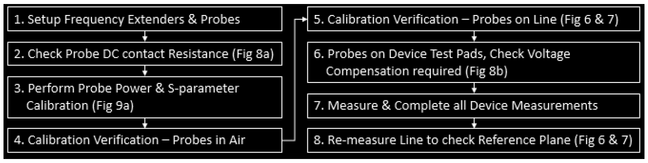


Fig. 11. Proposed calibration and validation strategy for sub-THz wafer-level measurements.

III. CONCLUSIONS

To achieve accuracy and continuity in wafer-level sub-THz measurements from low frequency to 750 GHz, it is critical to ensure low probe contact resistance and accurate DC bias applied to the device for all frequency bands. The proposed post-calibration verification techniques as well as performing probe tip power calibration with S-parameter calibration are critical and have been shown in this work to eliminate sub-THz measurement discontinuities.

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