

# Improving Wafer-Level S-parameters Measurement Accuracy and Stability with Probe-Tip Power Calibration up to 110 GHz for 5G Applications

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**Abstract** — Demands for mission critical wireless services such as autonomous driving and telehealth require higher data transfer rates and lower latencies. Such applications are now driving the use of radio frequencies (RF) at 28, 38, 60 and 73 GHz for the emerging 5G mobile communication systems. Wafer-level RF measurements of devices or circuits for 5G applications are extremely challenging due to huge system losses and calibrated state at the probe tips valid only for about 10 minutes. This paper presents a novel method of probe-tip power calibration for S-parameters calibration which is shown to greatly improve DC biasing accuracy, S-parameters measurement accuracy and post-calibration stability up to 110 GHz. The new method allows precise and low probe tip source power biasing of -20 dBm, without affecting calibration performance. It also increases system calibration stability to more than 4 hours, giving microwave engineers adequate time to test their RF devices and circuits by avoiding the need to perform frequent re-calibration, greatly enhancing test throughput.

**Keywords** — Radio frequency, Internet of Things (IOT), 5G mobile communication, calibration, stability, measurement techniques, millimeter wave measurements.

## I. INTRODUCTION

The need to support massive number of devices at higher data rates and lower latencies for wireless applications such as wireless multimedia, IOT, big data and vehicular positioning systems is driving the use of radio frequencies (RF) at 28, 38, 60 and 73 GHz in the 5G mobile communication systems [1]-[2]. To develop integrated circuits for these applications, semiconductor microwave devices such as RFCMOS transistors must be characterized up to at least 110 GHz. As these devices are fabricated with very advanced RFCMOS technology nodes, the total number of devices needed to be characterized has increased significantly, especially in the process fabrication and device SPICE model development phase. Henceforth, both high precision and high test throughput S-parameters systems are needed to support these wafer-level measurements.

Fig. 1 shows a typical example of 110 GHz wafer-level test system setup used to characterize a RF NMOSFET. Most commercial vector network analysers (VNA) can only support S-parameters measurements up to 67 GHz. Frequency extenders, consisting of up/down-converters and amplifiers are needed to expand the measurement capability of the VNA up to 110 GHz. Bias-tees are used to combine the RF test signal and DC biasing, which is usually provided by semiconductor

parametric analysers. Output of the bias-tees are then connected to Ground-Signal-Ground (GSG) RF probes which facilitates good electrical RF contacts on the device test pads.

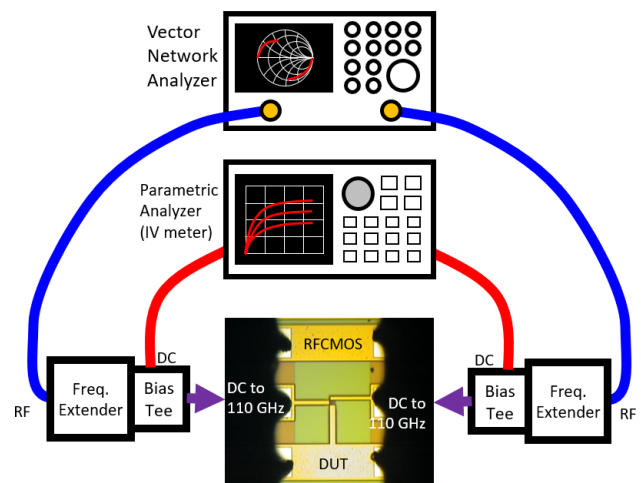


Fig.1 Schematic with die photo showing a typical wafer-level setup to test RF transistor up to 110 GHz.

## II. IMPORTANCE OF HAVING ACCURATE AND CONSISTENT PROBE-TIP RF SOURCE POWER

### A. Large RF Source Power results in Inaccurate Transistors' DC Characteristics

Usually inexperienced device modelling or device test engineers do not pay much attention to determine what is the most suitable RF source power to use when characterizing their microwave transistors. To determine the ideal RF source power, DC characteristics of the RFCMOS transistors must be obtained first without any RF interferences from the VNA. This can be achieved by setting the RF stimulus on the VNA to “hold” mode, which essentially prevents any RF signals going into the transistor during the DC measurements. The red plots in Fig. 2(a) and 2(b) show the transconductance ( $G_m$ ) versus gate voltage ( $V_g$ ) characteristics for different drain biases of a NMOSFET without any RF signal interfering the DC measurements.

When the stimulus setting on the VNA is changed from “hold” to “continuous”, with a large RF source power of 0 dBm, performing the same DC  $G_m$  measurement, a distorted transconductance or gain curve is observed (blue plot) as

depicted in Fig. 2(a). In Fig. 2(b), when the RF source power is reduced to -20 dBm, the measured transconductance is not distorted and matches very well with Gm obtained (red plot) when no RF signal is injected into the transistor. These results show that it is very important and highly critical to determine the ideal RF source power to be used in the characterization of active devices. When too large RF source power is used, it would distort the performance of the transistor which will result in incorrect DC biasing conditions and hence erroneous RF measured performance of the transistor.

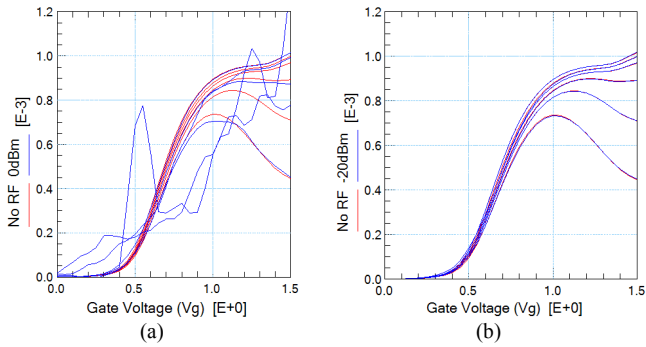


Fig. 2. DC transconductance versus gate voltage ( $G_m$  vs  $v_g$ ) at different drain voltages at 0.3, 0.6, 0.9, 1.2, 1.5 and 1.8V, for a RF nMOSFET with network analyser RF power OFF “HOLD” (Red plot) comparing with RF source power = 0 dBm (a) and RF source power = -20 dBm (b) (Blue plots).

**B. S-parameter Probe-tip Post-Calibration Stability Performance with Low RF source Power**

Using low RF source power, such as -20 dBm to perform probe-tip S-parameter calibration for a 110 GHz wafer-level measurement setup (shown in Fig. 7), the post-calibration stability is extremely poor. Fig. 3 shows the return loss of the RF probes in air (OPEN) measured over time. When adopting  $\pm 0.1$  dB criteria, it is observed that in about 10 minutes after calibration, the system has drifted out of specs and a re-calibration is needed for the measurement results to have low trace noise. Such poor post-calibration stability has serious impact on test throughput because each transistor typically requires test and measurement time of about 20 to 30 minutes.

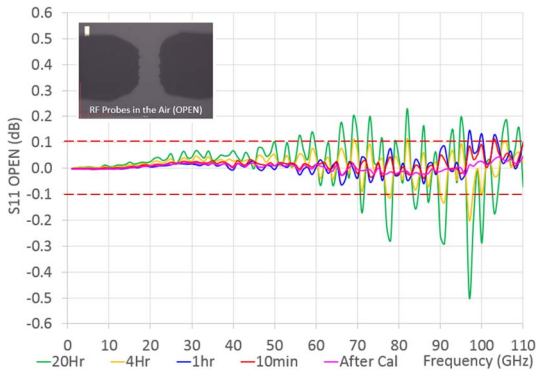


Fig. 3. Calibration Stability over time with probe-tip S-parameter calibration (monitoring Return Loss of Probes in Air) using RF source power of -20 dBm.

There are 2 factors contributing to this poor stability performance. First, RF source power at the probe tips varies with frequency as shown in Fig. 4 (for the 110 GHz system in Fig. 7). With source power setting of -20 dBm, actual probe

tips power start at around -20dBm and decreases to about -35 dBm at 67 GHz, contributed by losses associated with RF probes, cables and bias-tees. Up to 67 GHz, some RF test experts may argue that since RF power selected is still in small signal operation and with S-parameters measurements being relative measurements, a decreasing RF source power at probe-tips is not critical. However, the poor stability performance observed is also partly contributed by the decreasing RF source power at the probe tips as frequency increases to 67 GHz. From 67 to 110 GHz, with the frequency extenders, the probe-tip RF source power is amplified to about -5 dBm. This is too large and will affect the DC characteristics and operating conditions of the transistor during RF measurements as shown in Fig. 2.

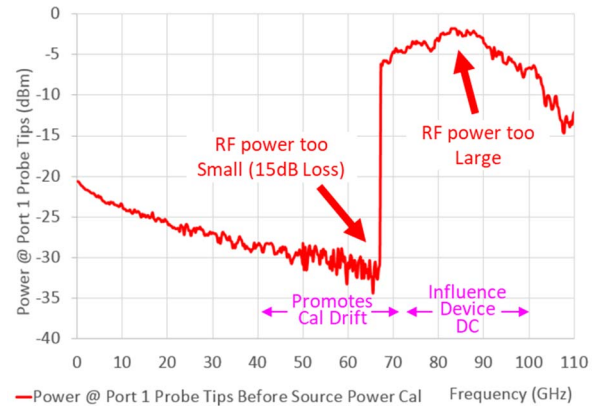


Fig. 4. Measured power at probe tips of Port 1 with VNA port 1 source power of -20 dBm.

Second, the receivers at port 1 and 2 of the VNA are not power calibrated (Calibrated probe-tip source power is a prerequisite to perform receiver power calibration) and this extensively affects the measurement performance of the whole system. Fig. 5 shows the measured RF power at port 2 of the VNA when both probes at port 1 and port 2 are connected through a 1ps line, with RF source power of port 1 set at -20 dBm. Ideally, regardless of frequency, the measured port 2 power should be constant at -20 dBm. The large losses of up to 40 dB observed between port 1 and the receiver at port 2, lead to huge S-parameters measurement uncertainties because of low signal-to-noise measurement performance.

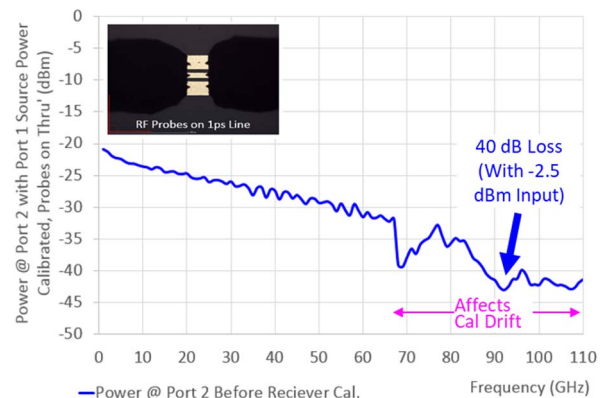


Fig. 5. Measured power at probe tips of Port 2 with both probes on a 1ps Line and VNA port 1 source power = -20 dBm.

### III. PROPOSED CHOON'S PROBE-TIP POWER CALIBRATION METHOD FOR S-PARAMETERS MEASUREMENTS

Important reasons as to why it is mandatory to have consistent and accurate RF probe-tip source power have been discussed in Section II. In this section, a novel probe-tip power calibration for S-parameters measurements, named Choon's method, as shown in Fig. 6(a), is proposed for the first time to help achieve accurate and consistent RF source power at the probe tips. Using a Cascade Microtech engineering probe station, Keysight's 110 GHz measurement system (Fig. 7(a)) and RF power sensors, the actual RF power at 1mm coaxial connector as shown in Fig. 7(b) can be accurately measured to characterize the RF loss versus frequency performance of the whole system, up to the coaxial cable. Combining this with the RF probe loss, power calibration tables valid at the probe tips are created (Red flowchart in Fig. 6(a)). If there is no significant change to the 110 GHz test setup, these power tables can be repeatedly use when performing probe tip source power calibration.

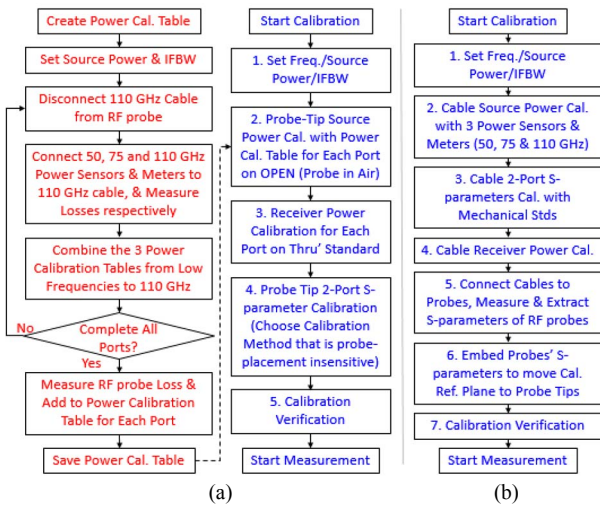


Fig. 6. Flowcharts comparing the proposed Choon's method of Probe-Tip Power + S-parameter Calibration (a) versus the VNA conventional method (b).

To calibrate the 110 GHz system, test engineers using Choon's method will first put the RF probes in the air to perform source power calibration with the power table. When RF power at the probe-tips have been accurately calibrated with the power table, the next step is to put the RF probes on the 1ps thru' standard to perform receiver power calibrations. After completing the RF source and receiver power calibration, test engineers can utilize a suitable probe-tip RF calibration method to complete the probe tip S-parameters calibration.

Comparing Choon's method, which requires only additional source power and receiver power measurements for power calibrations at each port, the conventional VNA method of performing probe-tip power and S-parameter calibrations, outlined in Fig. 6(b), is extremely tedious and time consuming. This method requires at least a morning to complete and must always have up-to-date measured performance of all the RF probes prior to calibration, for embedding S-parameters of the probes so that the calibration reference plane can be accurately move from the 1mm coaxial connectors to the probe tips.

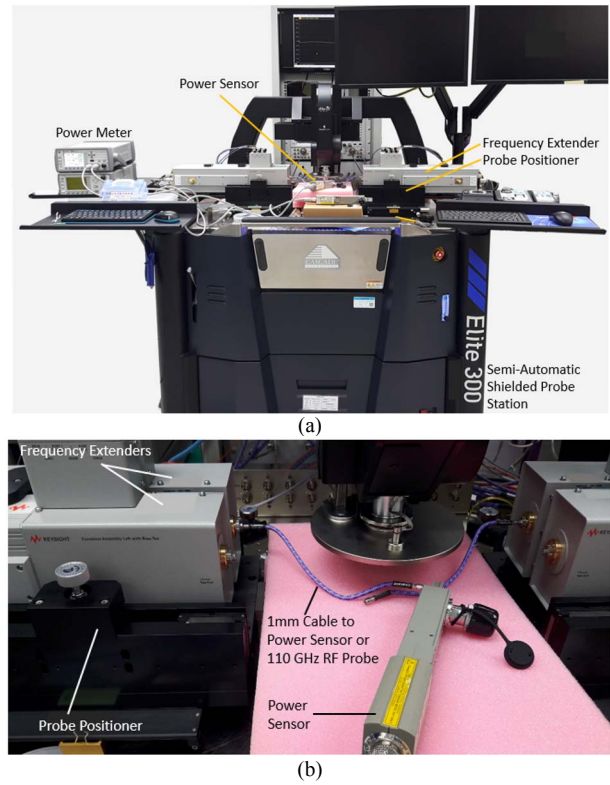


Fig. 7. Shielded Semi-Automatic Engineering Probe Station with 67 GHz VNA and 110 GHz Frequency Extenders (a) and Close-up view of a 75-110 GHz Power Sensor connected to the 110 GHz Frequency Extender through 1.0mm RF cable for Power Calibration (b).

### IV. RESULTS AND DISCUSSIONS

Adopting Choon's probe tip power calibration method with power table, the red plots in Fig. 8 shows the RF source power at the probe tips before and after source power calibration. It is observed that after calibration, the source power at the probe tips is constant with respect to frequency at the pre-set level of -20 dBm. The blue plots on the other hand, show massive receiver power corrections for the 40 dB loss with port 2 consistently measuring -20 dBm at all frequencies when receiver power calibration has been executed.

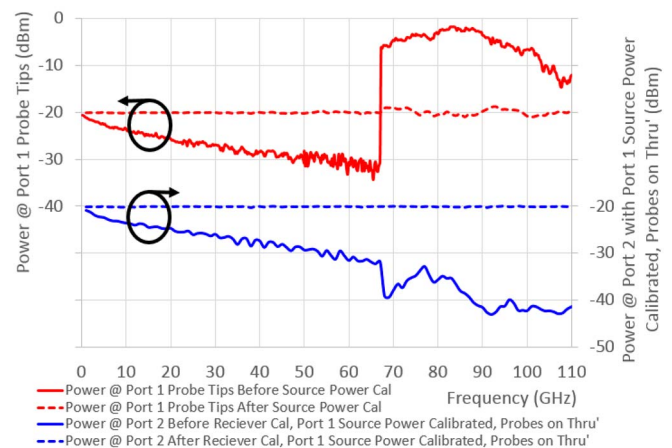


Fig. 8. Consistent source power at probe tips of port 1 (Fig. 4) and consistent receiver power at probe tips of port 2 (Fig. 5) after source and receiver power calibration.



With RF source and receiver power calibrated at the probe tips using Choon’s method, LRRM [3] is then used to perform probe-tip S-parameters calibration at a very low RF source power of -20dBm. Post-calibration drift performance of the system is monitored over time with the probes lifted up in the air. As shown in Fig. 9, using the criteria of not exceeding  $\pm 0.1$ dB, it is observed that with probe-tip power calibration, the post-calibrated state of the system can last for more than 4 hours, compared to the same setup without probe-tip power calibration, the system drifts quickly in only 10 minutes, requiring frequent tedious recalibration of the whole system.

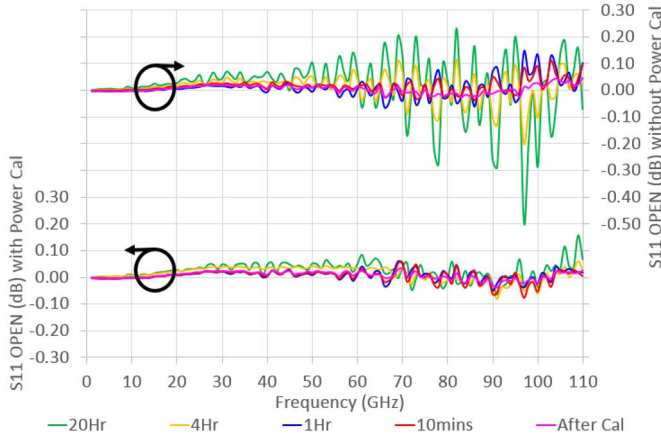


Fig. 9. Post-calibration stability performance over time, with and without probe-tip power calibration, monitoring return loss of probes in air.

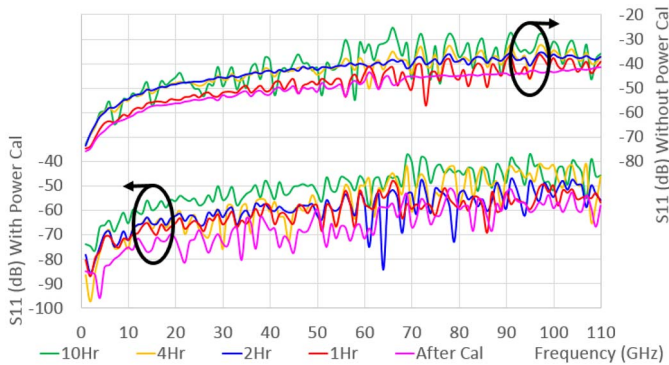


Fig. 10. Post-calibration stability performance over time, with and without probe-tip power calibration, monitoring return loss of a 1ps line.

The same experiment is then repeated on a 1ps line, monitoring the system drift over time. Fig. 10 reveals that when probe-tip power calibration is used, the return loss of the same line is about -40 dB, offering better measurement system dynamic range by about 10 dB as compared to without probe-tip power calibration. Fig. 11 uses extracted series inductance  $L_S$  over frequency of the 1 ps line to monitor system drift.  $L_S$  is extracted with equation (1), where  $Y$  is the measured admittance parameters of the line [4].

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

The low frequency inductance  $L_S$ , extracted to be about 50 pH, is in good agreement with the expected 1ps delay of the line.

With probe-tip power calibration, it is noted that the extracted inductance  $L_S$  is very consistent and stable for over 10 hours. Without probe tip power calibration, Fig. 11 shows decreasing  $L_S$  with time as well as significant discontinuities in  $L_S$  from low frequencies to about 67 GHz, 10 hours after the probe-tip S-parameters calibration. The root causes are due to very low RF source power of about -32 dBm instead -20 dBm at port 1 probe tips and huge loss in the actual measured receiver power at port 2. Contrary to most test engineers’ perceptions that with small signal condition maintained and because S-parameters are relative measurements, power calibrations are therefore unnecessary and redundant, the results presented in Fig. 9, 10 and 11 suggest mandatory probe-tip power calibrations as the post-calibrated state is very stable over time with better measurement accuracies and system dynamic range.

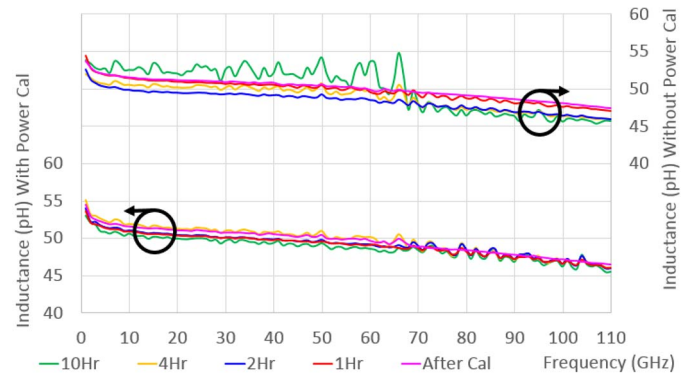


Fig. 11. S-parameter post-calibration stability performance with and without Probe-Tip power calibration, monitoring Extracted Inductance of a 1ps line over time.

## V. CONCLUSIONS

An accurate and stable wafer-level 110 GHz system is needed to support measurements of devices and circuits for 5G applications. A novel method of probe-tip power calibration with S-parameter calibration has been proposed in this paper. The new instrumentation technique, named Choon’s probe-tip power calibration method is demonstrated to improve DC biasing accuracy, S-parameters measurement consistencies and accuracy as well as post-calibration stability. Using this probe-tip power calibration method, 110 GHz system calibration stability is improved from 10 minutes to more than 4 hours, greatly improving the measurement throughput of such test setup, making power calibration mandatory for achieving accurate wafer-level S-parameters measurements.

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