

# Calibration, Repeatability and Related Characteristics of On-wafer, Broadband 70kHz-220 GHz Single-Sweep Measurements

Andrej Rumiantsev<sup>1</sup>, Jon Martens<sup>2</sup>, Steve Reyes<sup>2</sup>

<sup>1</sup>MPI Corporation, Chupei Hsinchu, Taiwan

<sup>2</sup>Anritsu, Morgan Hill, CA, US

**Abstract** — Broadband network analysis measurements can simplify on-wafer device and subsystem modeling (and related) efforts by minimizing setup changes and calibration cycles. Instrument coverage from low frequencies to 220 GHz has been recently presented but, as important, are the probes and the calibration and measurement characteristics. Broadband probes based on a single coaxial interface are presented along with basic measurement and calibration repeatability data based both on LRM and mTRL calibrations using transmission lines and symmetric attenuators as the primary DUTs. The process was exercised at low drive levels as might be required in active device characterization and the results show controlled repeatability and drift behaviors largely consistent with signal-to-noise ratios.

**Index Terms** — network analysis, millimeter-wave, broadband, calibration, on-wafer measurement, on-wafer probes, coplanar waveguides (CPW), measurement repeatability, measurement reproducibility, measurement uncertainty.

## INTRODUCTION

With the further increase of operating frequencies and performance requirements of modern semiconductor devices and integrated circuits, the need for broadband, accurate wafer-level characterization solution of such devices under test (DUT) becomes unavoidable. Discontinuities observed in measurement results obtained in different frequency bands make verification of the device model parameters for process development kit (PDK) creation and circuit design verification/debug challenging [1]. Moreover, measurement campaigns that need to cover multiple frequency bands are extremely time and resource consuming due to the need for multiple system reconfigurations, the required expensive hardware, and the high risk of damaging system components. Contact pads of a DUT drastically degrade with the number of touchdowns and thus, measurement of the same DUT across the entire frequency range becomes much more difficult.

A broadband vector network analyzer (VNA) system covering low frequencies through 220 GHz and accompanying probes can help resolve some of these measurement complications. The VNA instrumentation itself has been discussed previously [2] and this work focuses on the broadband probes and the measurement behavior of the instrument integrated with the probes.

## I. EXPERIMENTAL SETUP

### A. VNA and Probe System

The evaluated measurement system consisted of Anritsu ME7838G 70 kHz – 226 GHz broadband VNA (discussed in more detail in [2]), a manual wafer probe system TS200 and TITAN™ RF wafer probes model T220A-GSG075, both from MPI Corporation. The system is composed of a base microwave VNA and remote heads mounted at the probes (see Fig. 1). The sources and receivers are multiplexed for continuous coverage and a DC path to the probe tips exists for bias and low frequency coverage. Drive power is leveled at the module plane and controllable over generally > 40 dB of range. A simplified block diagram is shown in Fig. 2. The module receivers are used above 30 GHz and the module multipliers are used above 54 GHz while the base VNA handles the lower frequencies.

The interface to the probes supports a coaxial mode but, for reasons of controlling mechanical stresses on the < 0.4 mm center conductor, a conventional threaded outer conductor is not used. Instead a UG-387-like waveguide flange provides the mating for the outer conductor and the alignment pins of the flange guide the coaxial mating process. The female interface on the module is shown in Fig. 3 along with the male pin that is used on the probe side. Repeatability/durability exercises of the flange connector itself have been performed up to 1000 cycles with minor degradation observed.

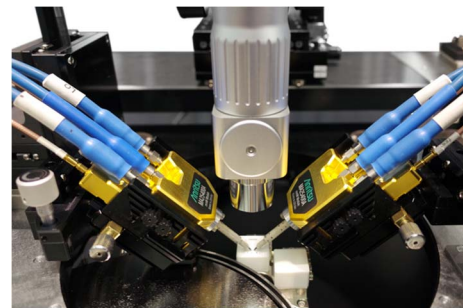


Fig. 1. The measurement configuration used for the data in this paper is suggested here.

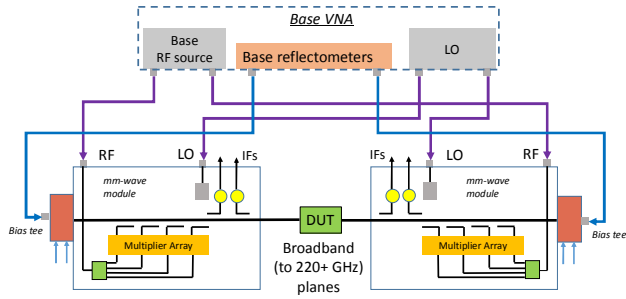


Fig. 2. A basic block diagram of the broadband VNA configuration is illustrated here.



Fig. 3. The female side of the broadband interface is shown on the left (module side) and the male pin (used on the probe) is shown on the right. The outer conductor diameter is 0.6 mm.

### B. Wafer Probes

Conventional G-band wafer probes incorporate two signal transition points where the electromagnetic waves are converted from one type of the propagation mode to another: from the waveguide mode into a coaxial mode (in the probe body) and from the coaxial mode into the coplanar waveguide mode (at the probe tip) [3, 4]. The new system broadband interface enabled the design of micro coax-based RF probe with only one mode conversion point at its tips. Therefore, the loss of the probe is minimized and it is comparable with the conventional waveguide-based probes, despite the probe length being about 45 mm (Fig. 4).

T220A-GSG050 probe S-parameters were extracted from measurement results obtained after system calibration and sequential de-embedding yielded the measurement plane set to the module (female) side of the broadband interface. At first, the system was calibrated in the frequency range from 70 kHz to 140 GHz using the 0.8 mm coaxial calibration kit (merged OSLT<sup>1</sup> and SSST<sup>2</sup>). Next, the calibration in the frequency range from 140 GHz to 220 GHz was completed using a G-band WR5 waveguide calibration kit (SSLT<sup>3</sup>). At the end, the impact of the adapters from the broadband interface to the 0.8 mm coaxial interface as well as from the broadband interface to the WR5 waveguide were removed by a simple de-embedding procedure. Measurements were then made with the probe attached in order to extract the parameters [5, 6]. The uncertainty of this extraction was assessed using a Monte Carlo procedure and

resulted in a 2-sigma value of 0.5 dB at 220 GHz (in insertion loss). The uncertainty in return loss is more variable but is about 1.5 dB at 220 GHz and increases at the higher return loss levels at low frequencies (where match is somewhat limited by impedance control of the micro-coax cable).

Due to the relatively low insertion loss of the probe, it is possible to deliver the incident signal to the DUT with the power level range from about - 60 dBm to - 20 dBm (- 12 dBm at 200 GHz).

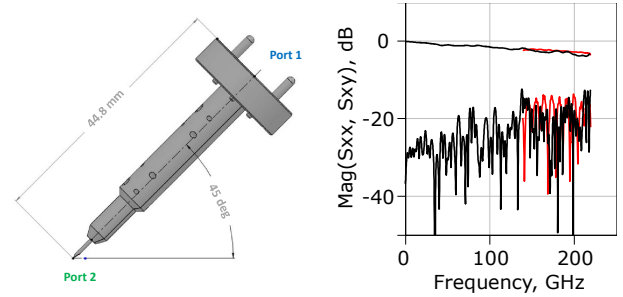


Fig. 4. Dimensions of the T220A-GSG050 probe (on the left) and its typical S-parameters (on the right, black traces) compared with conventional WR5 wafer probe S-parameters (on the right, red traces).

The CPW contact structure is manufactured using MEMS process and is available in Ground-Signal-Ground (GSG) trip configuration of 50  $\mu\text{m}$ , 75  $\mu\text{m}$ , and 100  $\mu\text{m}$  pitch. The contact shape is formed as a quasi-3D structure for better visibility of the point of electrical contact. Good tip and contact visibility improves repeatability and reproducibility of measurement results and system calibration.

The gross probe geometry is shown in Fig. 4 along with a plot of transmission and reflection characteristics (Fig. 4, right, black traces) compared with those parameters for a conventional G-band bandlimited probe (Fig. 4, right, red traces). The maximum insertion loss at 220 GHz is approximately 4.5 dB in both cases for this example. A close-up view of the probe tip is shown in Fig. 5.

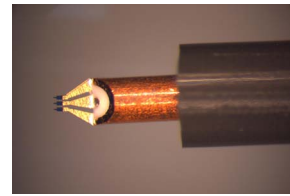


Fig. 5. A close-up view of the T220A-GSG050 probe.

### C. Calibration Substrate

The design of the TCS-050-100-W<sup>4</sup> calibration substrate used in this experiment was previously presented [7]. It

<sup>1</sup> Open-Short-Load-Thru

<sup>2</sup> Short1-Short2-Short3-Thru

<sup>3</sup> Short1-Short2-Load-Thru

<sup>4</sup> Available from MPI Corporation

incorporates five CPW lines optimized for multiline TRL<sup>5</sup> (mTRL) calibration up to 220 GHz, as well as Open, Short and Load standards for lumped-standard-based calibration schemes. Additionally, there is a set of symmetrical attenuators with design values of 3 dB, 6 dB and 10 dB for calibration verification purposes. Thru, Open, Load, Short standards and symmetrical attenuators were design for GSG probes with the pitch varying from 50  $\mu\text{m}$  to 100  $\mu\text{m}$  and for 150  $\mu\text{m}$  probe-to-probe distance. Five CPW transmission lines have effective length of 360  $\mu\text{m}$ , 610  $\mu\text{m}$ , 1175  $\mu\text{m}$ , 2425  $\mu\text{m}$ , and 5200  $\mu\text{m}$ , respectively.

The 250  $\mu\text{m}$ -thick calibration substrate was placed on the TS200 system auxiliary chuck made of the ceramic. The dielectric constant of the ceramic chuck was matched to the calibration substrate material properties suppressing propagation of possible higher-order modes, as suggested in [8] and later recommended in [9].

Five data series of the discussed standards and verification elements were acquired sequentially by one operator to calculate typical measurement and calibration repeatability.

## II. EXPERIMENTAL RESULTS

### A. Measurement Repeatability

To illustrate basic repeatability on on-wafer measurements, a few simpler experiments were initially run. A LRM calibration (using substrate TCS-050-100-W) was performed assuming perfect match return loss and a 3 dB verification attenuator was measured three times with a probe-lift in between each measurement. 50  $\mu\text{m}$  pitch probes were used.

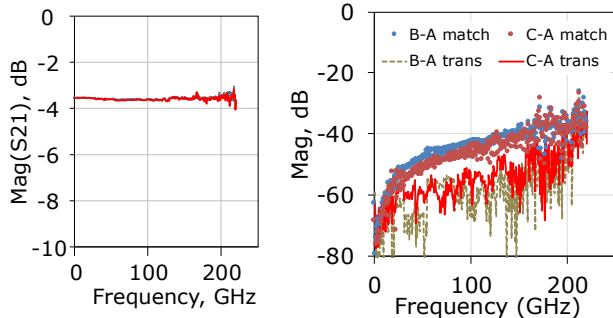


Fig. 6. Repeatability measurement results for a 3 dB attenuator are shown for transmission on the left and reflection on the right. For reflection, the results are plotted as vector differences relative to the first measurement ('A' in the legend).

These results are shown in Fig. 6 for transmission parameter. The drive power was -30 dBm and the IFBW set to 100 Hz as might be used in lower power device characterization measurements (> 15 dB below maximum available drive power for this system). With the limitations of the small number of

measurements, repeatability of about -30 dB in reflection was observed.

Another simple repeatability experiment was to perform three different LRM calibrations and then measure a short line (not used during the calibration) five times with each calibration (just a probe lift and touchdown in between). The measured match is shown in Fig. 7 for these 15 total measurements (again using 50  $\mu\text{m}$  pitch probes and the substrate TCS-050-100-W). These data suggests a fundamental repeatability on the order of -30 dB at 180 GHz and about -26 dB at 220 GHz in this challenging deep match measurement. The probe spacing did not significantly change during this exercise (although there was fine tuning on the landings as this was a manual operation). The outlier traces in the figure are likely a result of minor placement differences.

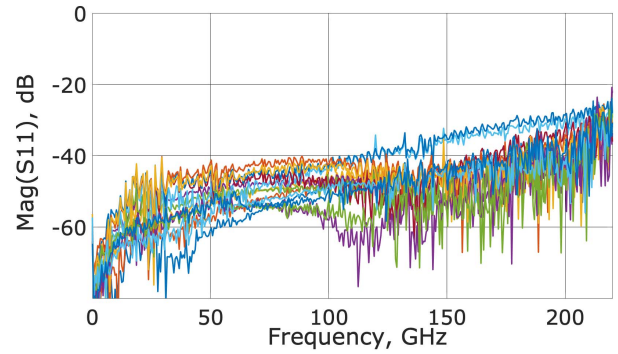


Fig. 7. The match of a short transmission line is shown here for three different LRM calibrations and five different measurements per calibration (probe lift between each).

### B. Calibration Repeatability

Calibration repeatability is another important figure of merit of an integrated measurement test cell. In contrast to calibration in a coaxial and waveguide environment, the repeatability of the wafer-level calibration is limited by the mechanical characteristics of the RF probes, mechanical stability of the probe system and probe positioners, resolution of the optical system and lead screws of probe positioners, contact pad material, contact pad size as well as design of calibration standards and the calibration method. The NIST mTRL [10] is a preferable calibration method for measurements beyond 110 GHz. However, one calibration cycle is usually longer than a simple lumped-standard based calibration used at lower frequencies (such as SOLT<sup>6</sup>, LRM<sup>7</sup>, TMR<sup>8</sup> or others): more standards need to be measured and probe require accurate re-adjustment from one measurement to another. Therefore, the repeatability of the mTRL calibration is well-suited parameter for estimation of the potential measurement accuracy of a wafer-probe system.

<sup>5</sup> Thru-Reflect-Line

<sup>6</sup> Short-Open-Load-Thru

<sup>7</sup> Line-Reflect-Match

<sup>8</sup> Thru-Match-Reflect

The repeatability of the mTRL calibration was calculated by MultiCAL and Verify<sup>9</sup> programs from two uncorrected calibration standard data sets acquired sequential within about 30 minutes. The experiment resulted in the worst-case error bound  $|S_{ij}' - S_{ij}|/|S_{ij}|$  and  $|S_{ii}' - S_{ii}|$  for S-parameters measured on the system (Fig. 8).

The sum of the system drift, contact repeatability and LRM calibration repeatability was calculated using a similar approach with two different LRM calibration runs, the first and the fifth (again assuming perfect match return loss, Fig. 7, red trace) and five different DUT measurements (symmetrical 6 dB attenuator). The five DUT measurements were performed in between the two LRM calibration sequences. The corrected  $S_{11}$  and  $S_{21}$  attenuator measurement mean is shown in Fig. 9 along with the worst-case error bounds. The slight upslope in attenuator transmission at high frequencies may be due to capacitive coupling between the pads/probes.

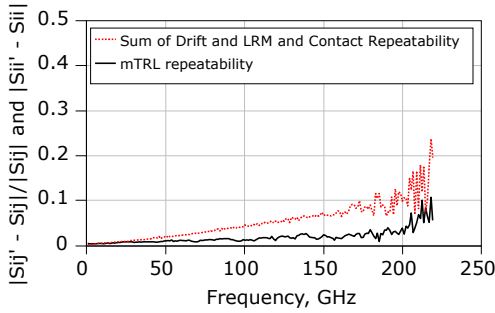


Fig. 8. Repeatability of the mTRL calibration.

The increase in the error bound spread above 200 GHz is primarily due to degrading signal to noise ratio as these calibrations and measurements were performed at a relatively low - 30 dBm (flange-referenced) power level as might be needed for active device characterization. As such, this measurement was intended to explore the boundaries of possible characterizations.

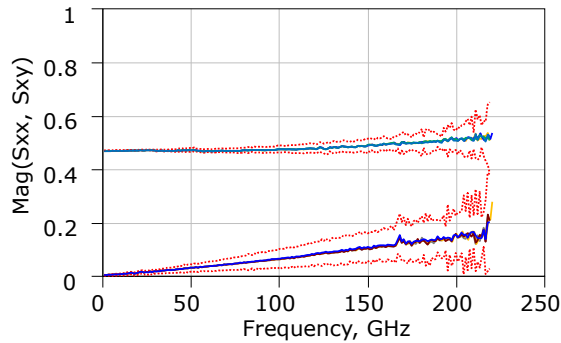


Fig. 9. Magnitude of  $S_{11}$  and  $S_{21}$  of a symmetrical 6 dB attenuator (colored traces) with worst-case error bounds calculated from the contact repeatability, calibration repeatability and system drift during the experiment.

### III. CONCLUSION

This paper has presented measurement and calibration characteristics of an on-wafer broadband 70 kHz to 220 GHz single-sweep measurement system. Critical and challenging parameters of the system, such as measurement repeatability of well-matched devices, multiline TRL calibration repeatability as well as the system drift were discussed. It was demonstrated that the fundamental repeatability on the order of - 30 dB at 180 GHz and of order - 26 dB at 220 GHz can be achieved for challenging deep-match measurements and for port powers as low as - 30 dBm. Finally, the measurement results of the return and insertion loss of a verification symmetrical 6 dB attenuator are shown including the maximal error-bound estimates as a sum of contact and calibration repeatability, and system drift. The results demonstrate system characteristics that are possible to achieve in a conventional measurement laboratory environment and could be used for further investigation of measurement accuracy and for cross-laboratory measurement comparisons of data acquired on similar systems.

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