Reliable mmWave On-Wafer Measurement from Lab to Factory Floor

High-frequency on-wafer measurement is challenging and can be problematic. An introductory guide developed by NPL can help the industry undertake measurement with more confidence.

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On-wafer calibration and measurement are underpinning technologies for the development of millimeter-wave (mmWave) integrated planar circuits, which have found homes in a large variety of applications. Prominent examples include wireless backhaul links for 5G mobile networks, automotive radar sensors, space-deployed radiometers for Earth remote sensing, radio astronomy, and more. Accurate on-wafer measurement is critical to the production of high-quality and assured integrated circuits for the above-mentioned applications.

S-parameters are fundamental electrical quantities for the characterization of integrated circuits (ICs). Measurement equipment such as probes working at frequencies up to 1.1 THz are commercially available. However, for a long time, no traceability has been available for on-wafer, S-parameter measurements beyond 110 GHz.

Many factors can significantly impact on-wafer measurement results at mmWave frequencies, including (but not limited to):

- The choice of calibration methods and reference planes
- Parasitic circuit elements associated with the interconnection between the probe and contact pads
- The test environment (e.g., metallic or ceramic wafer chuck)
- Coupling between adjacent neighboring structures on the same wafer
- Crosstalk between probes
- Propagation of unwanted modes, particularly for coplanar-waveguide (CPW) structures
- Damage/wear and tear of probes or calibration standards

Not considering these factors can often lead to inaccurate or inconsistent measurement results.

Ample efforts have been devoted to tackling these challenges and establishing traceability for S-parameter measurements up to THz frequencies, particularly by metrology laboratories. For example, two large-scale European projects, PlanarCal (2015-2018)[1] and TEMMT (2019-2022),[2] include work packages dedicated to these challenges. PlanarCal also developed a Best Practice Guide (BPG)[3] on how to perform precise on-wafer S-parameter measurements using a VNA.

On an international level, the IEEE Standards Working Group P2822 was launched in 2021 to foster advances in the standardization of on-wafer measurements. This working group aims at developing recommended practices for performing accurate on-wafer calibrations, de-embedding, and measurements up to THz frequencies. NPL is actively involved in both the PlanarCal and TEMMT projects as well as the P2822 working group. However, all of these activities are aimed primarily at top-tier metrology laboratories rather than more general end-users working in the industry.

To facilitate the knowledge transfer from metrology laboratories to industrial end-users, NPL has been working with Filtronic Broadband on another European project: PlanarMeT. Filtronic designs and manufactures a broad range of microwave and mmWave modules for the point-to-point mobile backhaul market. On-wafer S-parameter measurements of integrated planar circuits, e.g. amplifiers, are a key step in their research and development process, and hence the work is very relevant to Filtronic.

Activities undertaken as part of PlanarMeT include production of a user-friendly industrial guide aimed at the non-measurement specialist and suitable for implementation on an industrial factory floor; and a measurement comparison exercise between NPL and Filtronic by following the user guide to demonstrate good quality measurements. These activities are discussed below.

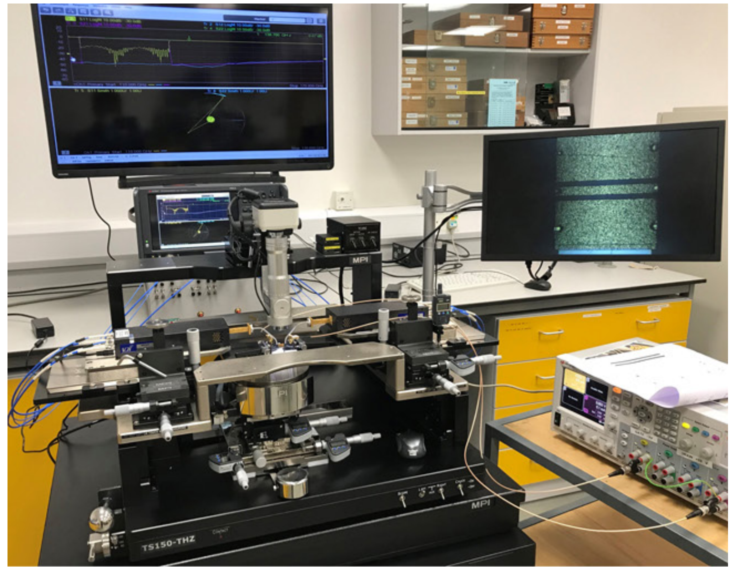
Introductory User Guide

The PlanarCal BPG is a lengthy document and contains some very complicated information that requires a high level of user expertise/knowledge. To complement this BPG, there's the need for a user guide (based on less complicated, practical, methods) that's a concise document aimed at the non-measurement specialist and suitable for implementation on an industrial factory floor (rather than a top-tier precision metrology laboratory).

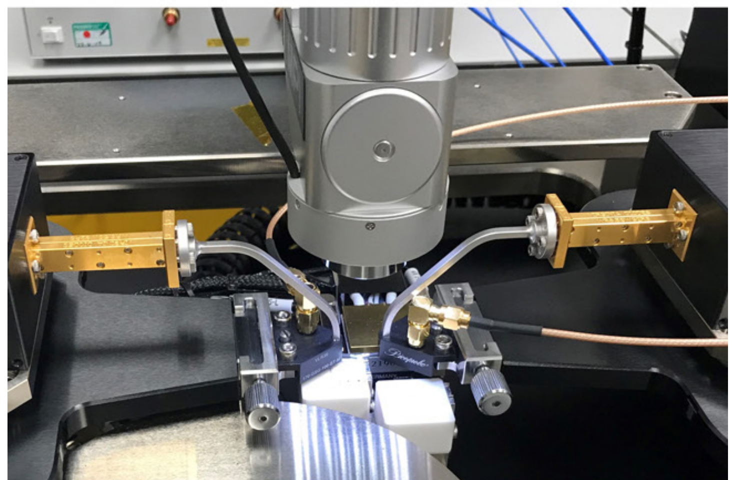
NPL and Filtronic addressed that issue by publishing a simple introductory user guide with open access.[4] This Introductory Guide tutors end users on implementing straightforward methods to perform reliable on-wafer calibration and measurement at mmWave frequencies. The guide describes the key considerations affecting the accuracy of measurements, including experimental setup, choice of calibration methods, testing environment, crosstalk/isolation between probes, measurement verification, and design considerations for calibration kits. More details can be found in Reference 4.

Measurement Comparison

Confidence in measurement results can often be achieved by demonstrating good agreement between measurements made by different institutes, particularly a reference laboratory such as a metrology laboratory. NPL and Filtronic participated in a measurement comparison at D-band



(a)



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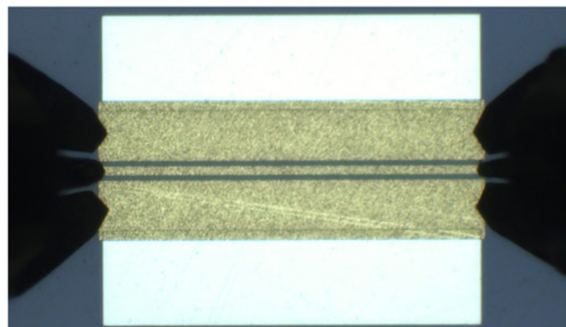


(c)

1. Shown is the mmWave on-wafer measurement system at NPL (a), a close-up view of the probes landed on an impedance standard substrate (ISS) (b), and a microscope image of the probes and one device under test (a CPW line) (c).

(110-170 GHz) by following the user guide.

CS-15, the commercially available Impedance Standard Substrate (ISS) manufactured by GGB Industries and designed for use above 110 GHz, was used to provide calibration standards and devices. Because the devices under test (DUTs) are on the same wafer as calibration standards, calibration was performed "on-wafer."

Figure 1 shows the measurement setup used at NPL, consisting of an MPI TS-150 manual probe station, Keysight's PNA-X N5247B VNA, a pair of D-band VDI mini frequency-extension modules, and a pair of D-band GSG probes with 100-µm pitch size. Calibrations and measurements were made using an IF bandwidth of 50 Hz and 601 frequency points. No averaging was utilized in the calibration or measurement.

The ISS was placed on a ceramic chuck during all calibrations and measurements made in this study, to ensure consistency of the test environment. The ceramic chuck is helpful in terms of suppressing some spurious modes.

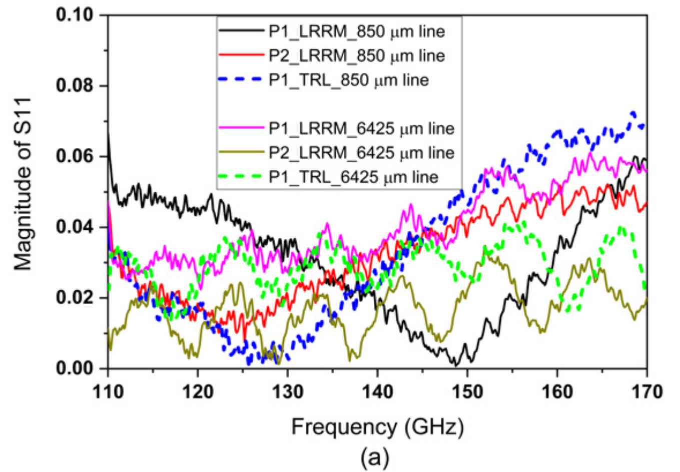
For the comparison, the participants used the line-reflect-reflect-match (LRRM) calibration method and the same set of calibration standards on CS-15—in other words, a 175-µm, 50-Ω coplanar-waveguide (CPW) line as the Line standard, a pair of open pads and shorting bars as the Reflect standards, and a pair of 50-Ω loads as the Match standard. The reference plane was set at the middle of the Line standard.

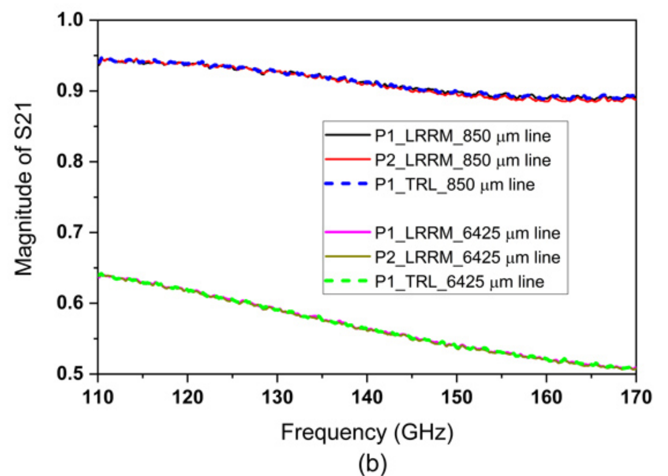
The study measured several devices (CPW lines with different lengths, offset short, offset open, and offset load) on the CS-15. A selection of measurement results of CPW lines with physical lengths of 1025 µm and 6600 µm is shown in *Figure 2*. After de-embedding, the effective lengths of these lines are 850 µm and 6425 µm.

As seen in *Figure 2*, the measured results from the two participants show very good agreement. The mean differences between the two participants' values are around ≤ 0.002 µm for transmission responses and ≤ 0.023 µm for the reflection responses. The small difference is believed to be mainly attributed to alignment errors when positioning/re-positioning the probes on the calibration standards and/or DUTs. This can be improved by repeating the calibration and measurement or utilizing an automatic probe station.

One participant also carried out through-reflect-line (TRL) calibration, the other popular calibration method utilized in the industry. The calibration used the same 175-µm line as the Thru standard, a pair of shorting bars as the Reflect standards, and a 355-µm line as the Line standard.

The difference in length between the Thru and Line standards, 180 µm, provides a phase delay of around 54°~83° across D-band. Again, the reference plane was set at the center of the 175-µm CPW line (i.e., the Thru standard). *Figures 2a* and *2b* show the comparison of measured results between TRL and LRRM, which are in good agreement.





2. The plots illustrate linear S_{11} (reflection coefficient) magnitude for two 50-Ω CPW lines with different lengths (850 µm and 6425 µm), measured by two participants (a), and linear S_{21} (transmission coefficient) magnitude for two 50-Ω CPW lines with different lengths (850 µm and 6425 µm), measured by two participants (b).

Conclusions

This article covers a knowledge-sharing activity between NPL and Filtronic related to on-wafer measurement. We've produced a concise User Guide to provide industry-level methods for validating planar calibrations and measurements at mmWave frequencies. The good agreement in the measurement comparison exercise shows that the guidance given in this user guide can help end-users achieve accurate and consistent results at these very high frequencies.

Acknowledgement

This work was supported by the European Metrology Programme for Innovation and Research (EMPIR) Project 19SIP02 "Knowledge transfer of planar calibration and measurement techniques at millimetre-wave frequencies."

The EMPIR Programme is co-financed by the participating states and from the European Union's Horizon 2020 Research and Innovation Programme.

Xiaobang Shang, who began working for NPL in 2017 as a senior research scientist, develops measurement techniques for mmWave and THz frequencies, particularly on-wafer measurements. His current research interests also include the characterization of dielectric materials and microwave technology for quantum applications.

Nick Ridler has worked at NPL for more than 25 years. His work focuses on developing accurate electrical measurement techniques from RF to THz frequencies.

Andrew Tucker has over 25 years' experience in the design and manufacture of RF and mmWave components and systems. Having joined Filtronic Defense, Shipley, in 1997, Andrew was involved in the design and characterizations of numerous switched filter banks and novel electronically tunable filters. Andrew was selected to manage the project transfer and subsequent engineering functions of a key Eurofighter product from Filtronic's Shipley site to the new Filtronic Compound Semiconductors facility in Newton Aycliffe. Andrew subsequently joined Filtronic Broadband in 2006, designing transceiver products for mobile backhaul before becoming engineering manager, overseeing the successful design and deployment of many custom mmWave communications solutions to leading technology companies.

Dr. Tudor Williams, who was appointed as director of technology in October 2021 to lead Filtronic's technical strategy and develop engineering roadmaps, is an experienced technical manager and strategic thinker.

Before joining Filtronic, Tudor was interim director of technology at the Compound Semiconductor Applications Catapult, where he built a team of skilled engineers and an advanced measurement and characterization facility from scratch. Tudor also worked as engineering manager at Mesuro, a startup company spun out of Cardiff University and sold to Focus Microwave in 2016, and as a MMIC design engineer at Selex Sensors and Airborne systems.

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