FINAL PUBLISHABLE REPORT

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Project short name: PlanarMeT

Project full title: Knowledge transfer of planar calibration and measurement techniques at millimetre-wave frequencies

Project start date and duration:		01/06/20, 26 months
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Internal Funded Partners: 1. NPL, UK		Unfunded Partners: 2. Filtronic, UK

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1 Overview

This project has worked to maximise uptake by the industrial end-user community of outputs from the EMPIR 14IND02 PlanarCal project, related to planar on-wafer calibration and measurement techniques at millimetre-wave frequencies. On-wafer measurement is important for the precise characterisation of integrated circuits operating at millimetre-wave frequencies that benefit sectors such as telecommunications, automotive, and space. Knowledge about high frequency on-wafer measurement, developed in 14IND02 PlanarCal, was transferred to end-users, through a practical industrial User Guide, a training course, two papers produced for scientific/trade journals, and a full-day workshop at 2022 IEEE International Microwave Symposium (IMS).

2 Need

Millimetre-wave on-wafer calibration and measurement are underpinning technologies for the development of integrated planar circuits, which are in widespread use for a large variety of applications. Notable examples include high-capacity mobile backhaul links, automotive radar sensors, and space deployed radiometers for remote sensing of atmospheric constituents which are related to climate change. Precise on-wafer measurement is critical to the production of high quality, cost effective, and assured integrated circuits for these applications.

Previously, the 14IND02 PlanarCal project sought to establish measurement traceability for the characterisation of S-parameters of integrated planar circuits from radio frequencies to submillimetre-wave frequencies. The key output from 14IND02 PlanarCal was the establishment of traceability for on-wafer S-parameter measurements. 14IND02 PlanarCal also developed a Best Practice Guide (BPG) on how to perform precise on-wafer S-parameter measurements. However, this BPG was aimed primarily at top tier metrology laboratories, such as National Metrology Institutes (NMIs), rather than more general end-users working in industry.

Therefore, there was a need for an introductory guide (based on less complicated, practical, methods) that is 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). The Primary Supporter for this project is Filtronic Broadband Ltd. Like many electronics companies, Filtronic have been developing millimetre-wave technology to support the above-mentioned applications. This technology relies on electronic circuits that are realised on-wafer. Their characterisation can only be achieved using accurate and reliable on-wafer measurements. These needs were addressed by adapting and implementing the Best Practice Guide developed in 14IND02 PlanarCal for industrial applications, which in turn benefited other companies involved in this sector (i.e. in high-frequency electronics for communications).

3 Objectives

The overall aim of the project was to provide detailed practical guidance and design philosophy to the Primary Supporter, Filtronic, and to enable take-up of the knowledge gained and raise the profile of the outputs from 14IND02 PlanarCal work with industrial end users.

The specific objectives of this project were:

1. To provide an industrial User Guide to end users, that demonstrated industry-level methods to perform reliable and precise on-wafer calibration and measurement at millimetre-wave frequencies.
2. To work with the user community so they are aware of, and able to use, the User Guide and to promote its uptake. Dissemination has been done through training courses, the On-Wafer Users Forum, and a workshop.

4 Results

4.1 Objective 1: To provide an industrial User Guide to end users, that demonstrated industry-level methods to perform reliable and precise on-wafer calibration and measurement at millimetre-wave frequencies.

Accurate characterisation of S-parameters (scattering parameters) at chip level is of great importance to the development of next generation electronic devices. The EMPIR PlanarCal Joint Research Project (14IND02) developed a Best Practice Guide (BPG)[1] [1] for making precision planar measurements using network analysers. However, this BPG is a lengthy document and contains some complicated information that requires a high level of user expertise/knowledge. It is therefore aimed primarily at top tier measurement laboratories, such as National Metrology Institutes (NMIs), rather than more general end-users working in industry. As a consequence, there has been a need for an introductory guide (based on less complicated, practical methods) that is 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).

An introductory User Guide has now been written and published with open access at https://doi.org/10.47120/npl.9001. This guide has been developed based on the BPG and aims specifically to provide guidance to end users on implementing straightforward methods to perform reliable on-wafer calibration and measurement at millimetre-wave frequencies. High frequency on-wafer measurement is challenging and remains an active area of research. This guide briefly reviews key considerations affecting the accuracy of measurement and these include experimental setup, choice of calibration methods, testing environment, crosstalk/isolation between probes, measurement verification, and design considerations for Thru-Reflect-Line (TRL) calibration kits.

The guide has also been sent to the Chair of the IEEE Working Group P2822. This Working Group has been developing an international (IEEE) standard titled “Recommended Practice for Microwave, Millimeter-wave and THz On-Wafer Calibrations, De-Embedding and Measurements”. It is expected that some of the information given in the User Guide will be incorporated into this new IEEE standard. Between January 2021 and September 2022, the guide has been downloaded more than 460 times. This large number of downloads in a short period indicates that this guide has great potential to be widely adopted by end-users in academia and industry.

4.2 Objective 2: To work with the user community so they are aware of, and able to use, the User Guide and to promote its uptake. Dissemination has been done through training courses, On-Wafer User Forums, and a workshop.

Two specific outputs were planned in relation to the objective:

- Training course for end users (including the project’s Primary Supporter) to demonstrate the use and implementation of the User Guide.
- A workshop to further disseminate the activities undertaken in this project to industrial end users, including members of the IEEE On-wafer Users Forum.

4.2.1 Training course and measurement comparison

NPL provided a one-day training to the Primary Supporter (Filtronic Broadband Ltd) during August 2021. The use and implementation of the user guide developed in Objective 1 has been demonstrated using the measurement facilities at NPL.

A measurement comparison was carried out to validate the measurements made by Filtronic. 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. The measurement comparison was undertaken at D-band (110-170 GHz) by following the user guide. CS-15, the commercially

[1] U. Arz, T. Probst, K. Kuhlmann, N. Ridler, X. Shang, F. Mubarak, J. Hoffmann, M. Wollensack, M. Zeier, G. N. Phung, W. Heinrich, K. Lomakin, G. Gold, K. Helmreich, R. Lozar, G. Dambrine, K. Haddadi, M. Spirito, R. Clarke, “Best Practice Guide for Planar S-Parameter Measurements using Vector Network Analysers”, EMPIR — 14IND02 PlanarCal, 2018, Physikalisch-Technische Bundesanstalt (PTB). https://doi.org/10.7795/530.20190424B

available Impedance Standard Substrate (ISS) manufactured by GGB Industries and designed for use above 110 GHz, was used to provide calibration standards and devices.

Figure 1 below shows the measurement setup used at NPL, which is composed of an MPI TS-150 manual probe station, Keysight 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.

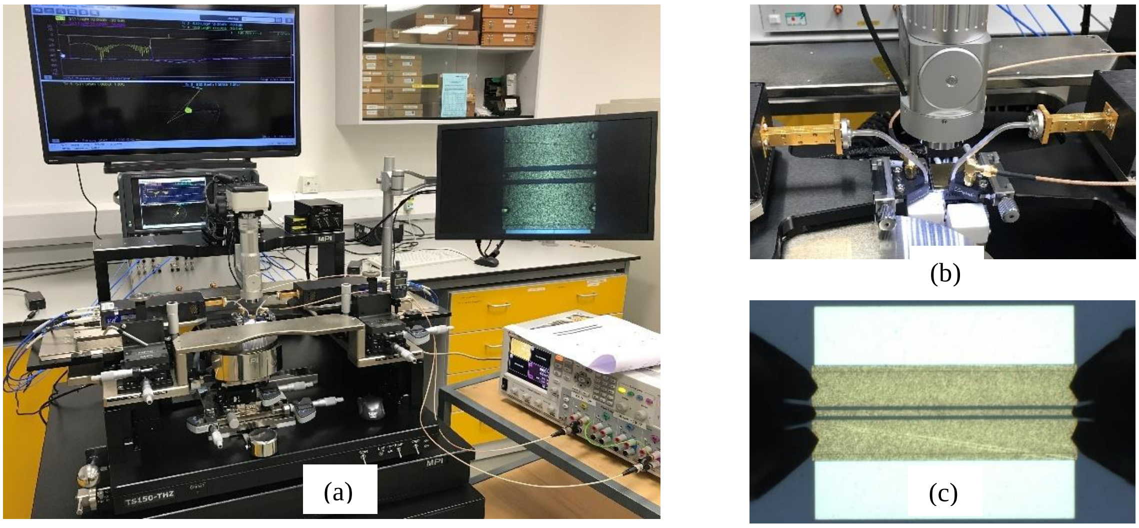

Figure 1: (a) Photograph of the mmWave on-wafer measurement system at NPL; (b) Close-up view of the probes landed on an impedance standard substrate (ISS); (c) Microscope image of the probes and one device under test (a CPW line).

For the comparison, the participants used the LRRM calibration method and the same set of calibration standards on CS-15, i.e. a 175 µm 50 Ω 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 below. After de-embedding, the effective lengths of these lines are 850 µm and 6425 µm. It can be observed from Figure 2 that the measured results from the two participants show very good agreement. The mean differences between the two participants' values are around ≤0.002 for transmission 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 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 centre of the 175 µm CPW line (i.e. the Thru standard). Figure 2 shows the comparison of measured results between TRL and LRRM, which are in good agreement.

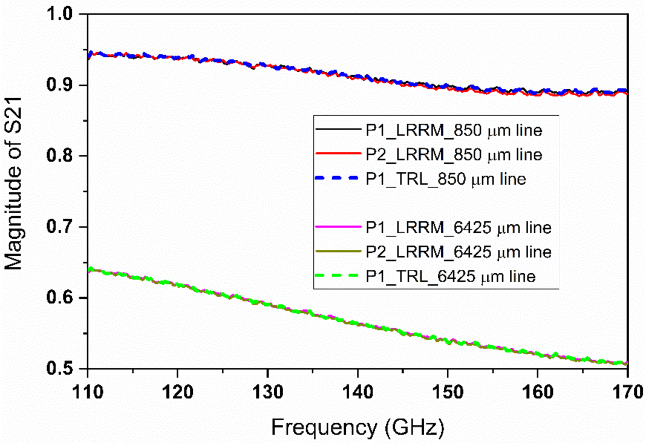

Figure 2: Linear S21 (transmission coefficient) magnitude for two 50 Ω CPW lines with different lengths (850 µm and 6425 µm), measured by two participants.

In summary, the measured results from the two participants showed very good agreement, and this demonstrates that the user guide can help end-users achieve accurate and consistent results at these very high frequencies. This measurement comparison was summarised in an article and published in Microwaves & RF Magazine[2] .

4.2.2 Workshop

A full-day workshop entitled "On-wafer mm-wave measurements" was held as part of the 2022 IEEE International Microwave Symposium (IMS), Denver, Colorado, USA, 19-24 June 2022. IMS is an annual, week-long, scientific conference which regularly attracts around 10,000 attendees. The workshop was endorsed by the IEEE MTT-3 Microwave Measurements Technical Committee and was branded as a joint workshop between IMS 2022 and the 99th Automatic Radio Frequency Techniques Group (ARFTG) Conference. The ARFTG conference is another primary international conference with a particular focus on microwave measurement techniques. This year, the 99th ARFTG was co-located with IMS 2022. The NPL/Filtronic-run workshop was held on Monday 20th June and was attended by more than 35 people from industry and academia.

The workshop featured eight technical presentations from international experts in the on-wafer measurement field, and two open-discussion sessions. The agenda of the workshop is given in the table below.

No	Presenters	Presentatioin Title
1	Xiaobang Shang, Nick Ridler, Andy Tucker, Tudor Williams	Review of Calibration Techniques for On-Wafer Measurements at mm-Wave Frequencies
2	Andrej Rumiantsev, Ralf Doerner	Wafer-Level RF Measurement System Integrity: How to Verify and When and Why we have to do it
3	Uwe Arz, Gia Ngoc Phung	Guidelines for Performing Accurate On-Wafer Measurements Including the Suppression of Parasitic Effects
4	Chong Li	Modeling and Correction of Probe-Probe Crosstalk at mm-Wave Frequencies

[2] X. Shang, A. Tucker, T. Williams, N. Ridler, "Reliable mmWave On-Wafer Measurement from Lab to Factory Floor", Microwaves & RF Journal, pp. 1-5, 1st April 2022, https://www.mwrf.com/technologies/test-measurement/article/21237915/filtronic-reliable-mmwave-onwafer-measurement-from-lab-to-factory-floor

	Open Discussion 1	On-Wafer Measurement: Challenges and Opportunities for the Future
5	Jon Martens	Instrumentation Aspects of mm-Wave On-Wafer Measurements
6	Gavin Fisher, Anthony Lord	Broadband RF to mm-Wave S-Parameter Measurements for Semiconductor Transistor and IC Test
7	Robert M. Weikle, *et al*	On-Wafer Measurements and Calibration at Sub-mm-Wave Frequencies Using Micromachined Probes
8	Kamel Haddadi	Combined mm-Waves and Nanorobotics for Traceable Electronics Technology
	Open Discussion 2	Bring Your Own Measurement Problem

This workshop provided an opportunity for a group of international experts in this field to share their experience of making reliable on-wafer measurements at high frequencies (i.e. above 100 GHz). The presenters came from a variety of backgrounds — instrumentation manufacturers, metrology institutes, end-users in industry and academia — and so provided different perspectives on this topic. The emphasis of the workshop was on sharing practical tips (i.e. good practice) so that attendees can subsequently implement such methods in their own workplaces. The workshop covered topics including calibration techniques, verification methods, guides on the design of custom calibration standards, instrumentation, applications, etc. The workshop included two open discussions: (i) on the challenges/opportunities/outlooks for research into on-wafer measurements in coming years; and (ii) an opportunity for attendees to describe their own on-wafer measurement problems so that these can be discussed and solved during the workshop.

NPL and Filtronic chaired the workshop and delivered a presentation titled “Review of calibration techniques for on-wafer measurements at mm-Wave frequencies”. The consortium also attended and contributed to the IEEE On-wafer Users Forum, held together with the IMS, and interacted with the participants (most were industrial end users).

5 Impact

In terms of short-term impact, three follow-on collaborations with the Primary Supporter have been established as a direct result of the outputs from this project. These three collaborations received national funding from the UK government (Department of Business, Energy and Industrial Strategy, as part of its M4R programme) and helped demonstrate the advantages of following procedures for reliable measurements, as outlined in this project’s User Guide.

Direct impact has been achieved by working with the Primary Supporter, who manufactures millimetre-wave transceiver modules for mobile backhaul systems, to transfer knowledge so that industrial end users (including the Primary Supporter) will be able to perform precise on-wafer measurements at high frequencies. This is being done via the User Guide which demonstrated practical methods developed in 14IND02 PlanarCal on typical measurement requirements provided by key industrial stakeholders (e.g. members of the IEEE On-Wafer Users Forum). Work undertaken within this project has been communicated to the end users in industry and academia via training courses, a workshop at a premier international conference (2022 IEEE International Microwave Symposium (IMS)), and interaction with the On-wafer Users Forum that is sponsored by the IEEE Automatic RF Techniques Group (ARFTG). This ensured the widest possible uptake of the outputs from 14IND02 PlanarCal via this project.

The impact spreads beyond the Primary Supporter to the wider community through the delivery of a training course, a workshop on “On-wafer mm-wave measurements” at the 2022 IEEE International Microwave Symposium (IMS), and, papers/articles published in a trade journal (Microwave & RF Magazine) and at the 2022 IEEE conference. In addition, the industrial User Guide produced in this project has been communicated to the IEEE On-wafer Users Forum which has recently been launched to foster advancements in the standardisation of on-wafer measurements.

An example of good impact is the joint article (published in Microwave & RF Magazine) written by NPL and Filtronic has already been featured and re-posted by other industrial end-users (e.g. Virginia Diodes, Inc – the leading global supplier of high frequency measuring equipment, as shown here: https://www.vadiodes.com/en/news/34-2022-news/1022-reliable-mmwave-on-wafer-measurement-from-lab-to-factory-floor). This helps promote the User Guide produced in PlanarMeT, in terms of reaching an even wider audience.

With the User Guide, training activities and workshop, manufacturers were able to provide their customers with confidence in measurements and specifications of their products. This is very important for customer/supplier relationships and where products need to demonstrate compliance with specifications or directives, regardless of who is doing the testing or where the test is being done. All sectors of the electronics industries involved in the characterisation and modelling of high-frequency integrated circuits will benefit from this project.

Economic impact will be achieved through support for the digitisation of products and services across Europe. Social impact will include retaining a competitive advantage in Europe over the foreign competition on technology and thereby retaining and growing expertise and much needed highly skilled electronic engineering and support staff jobs. Environmental impact will be achieved through more accurate and traceable measurements for sensor networks comprised of ground-based millimetre-wave cloud radars and passive multi-channel millimetre-wave space deployed radiometers. Such sensor networks play a key role in weather forecasting and earth observation which provides essential information concerning global climate change.

6 List of publications

[1] Xiaobang Shang, Nick Ridler, Jian Ding, Mike Geen, "Introductory Guide to Making Planar S-parameter Measurements at Millimetre-wave Wavelengths", EMPIR 19SIP02 PlanarMeT, 2021. https://doi.org/10.47120/npl.9001

[2] Xiaobang Shang, Andrew Tucker, Tudor Williams, Nick Ridler, "Reliable mmWave On-Wafer Measurement from Lab to Factory Floor", Microwaves & RF Journal, pp. 1-5, 1st April 2022, https://www.mwrf.com/technologies/test-measurement/document/21237918/reliable-mmwave-onwafer-measurement-from-lab-to-factory-floor-download

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