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## **Publishable Summary for 19SIP02 PlanarMeT**

### **Knowledge transfer of planar calibration and measurement techniques at millimetre-wave frequencies**

#### **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).

#### **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).

#### **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.

## Results

*Publication of an industrial User Guide for end users that demonstrated industry-level methods to perform reliable and precise on-wafer calibration and measurement at millimetre-wave frequencies (Objective 1)*

The User Guide has now been written and published on the coordinator's website at <http://eprintspublications.npl.co.uk/9001/1/PlanarMeT%20Guide.pdf>. 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.

The first objective has been achieved successfully.

*Having worked with the user community so they are aware of, and able to use, the User Guide and to promote its uptake (Objective 2)*

Two specific outputs are planned in relation to the objective:

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

Training activities involving NPL and the Primary Supporter (Filtronic Broadband Ltd) took place at NPL during August 2021. The measurement comparison was undertaken at D-band (110-170 GHz) by following the User Guide produced in Objective 1. The measured results from the two participants showed a very good agreement, and this demonstrated that the User Guide could help end-users to achieve accurate and consistent results at these very high frequencies. This measurement comparison was summarised in an article titled "Reliable mmWave On-wafer Measurement from Lab to Factory Floor" and published in *Microwaves & RF Magazine*.

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 featured eight technical presentations from international experts in the on-wafer measurement field, and two open-discussion sessions. NPL and Filtronic jointly 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 Automatic RF Techniques Group (ARFTG) On-wafer Users Forum, held together with the IMS, and interacted with the participants (most were industrial end users).

The second objective has been achieved successfully.

## 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.

### 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>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

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1. NPL, UK	-	2. Filtronic Broadband Ltd, UK