Publishable Summary for 14IND02 PlanarCal
Microwave measurements for planar circuits and components

Overview

The overall aim of this project was to enable the traceable measurement and electrical characterisation of scattering parameters (S-parameters) of integrated planar circuits and components from radio-frequency (RF) to sub-mm frequencies. This project developed an extensive set of measurement capabilities ranging from nanodevice characterisation and dedicated calibration software to traceable planar S-parameter measurements for frequencies up to 110 GHz. A calibration service for traceable on-wafer measurements is currently put in place at PTB, and first steps towards an Institute of Electrical and Electronics Engineers (IEEE) standard for on-wafer microwave measurements have been made. The results of this project enable manufacturers of planar microwave circuits and components to offer assured products with defensible specifications which are supported for the first time through on-wafer measurement traceability chains.

Need

Although on-wafer high-frequency measurements already had an economic impact on chip fabrication costs, industrial assurance and traceability were not established before this project. Boundary conditions of the measurement system setup and parasitic modes were often not sufficiently considered, leading to inconsistent results. This project has used the most advanced vector network analysers (VNAs) that are currently available together with state-of-the-art numerical simulation techniques to fully capture all relevant effects. At the end of this project, industry has been provided with methods to perform reliable on-wafer scattering-parameter (S-parameter - an electrical description of the transmission/reflection behaviour of a device at higher frequencies) measurements down to mm wavelengths.

Using a certain transmission-line system for calibration purposes in planar circuits requires adequate knowledge of its high-frequency properties. Until recently, relatively simple line models have been used describing these properties with sufficient accuracy for circuit designs in the frequency range of some tens of GHz. With increasing frequency and with the ongoing developments in semiconductor technologies more and more parasitic effects need to be taken into account. This includes, particularly, crosstalk due to field coupling and substrate modes, radiation into the environment, and increased losses due to the microscopic structure of the conductor surfaces.

High-frequency on-wafer science, engineering and metrology are underpinning technologies for almost all applications that employ micro- and nano-electronics. Integrated circuits operated in the microwave and mm wave frequency range are in widespread use, in applications ranging from mobile communications to sensors. The ubiquitous presence of wireless data transmission that we are used to would not be possible without them. However, the demands for higher data rates, the growing number of services to be covered, and the development of high-resolution (radar) imaging have been continuously pushing up the frequency of operation. 60 GHz short-range high-data rate communications and automotive radar at 77 GHz are examples of important applications at higher frequencies which have recently been deployed. Beyond this, various applications for imaging, material testing, and ultra-broadband wireless links are envisaged above 100 GHz. These needs will be intensified by the Internet of Things (IoT) initiative of the European Commission (EC), which strongly relies on wireless networks and wireless sensor functions.

Objectives

The aim of the project was to enable industry to characterise integrated planar circuits and components for ultimate use in high-speed and microwave applications with known measurement uncertainties.

The specific scientific and technical objectives of the project were to:

- Establish traceability of planar scattering parameter measurements on reference calibration substrates. The aim was to provide the lowest possible uncertainties for scattering parameter measurements of devices embedded on the same wafer, and to quantify the uncertainties. Candidates for these calibrations, such as airline-like interconnects in membrane technology and substrates such as GaAs which allow for comparisons to electro-optic waveform metrology, have been evaluated.
- Transfer uncertainties to calibration standards in conventional technology to be used in industry. This addressed the difficulty of moving between different substrate materials and different planar waveguide types. Residual errors of the calibration have been quantified with regard to the selected calibration algorithms and the influences of probe geometry and technology.
- Improve planar transmission lines models accounting for surface roughness and radiation losses. This not only helped develop reliable uncertainty budgets for planar S-parameter measurements but is of fundamental importance to the entire microwave design and circuit community.
- Develop calibration substrates and algorithms for planar scattering parameter measurements up to at least 325 GHz. This was achieved by fully characterising calibration standards built in selected substrate materials through dimensional measurements, wideband substrate permittivity extraction and numerical simulation. Guidelines have been developed to suppress the excitation of unwanted parasitic modes.
- Develop suitable calibration standards and methods for measurements of RF nano-devices. These addressed issues such as the impedance mismatch problem for calibrated S-parameter measurements of nano-devices and also the challenge of probing at nanoscale dimensions.
- Engage with manufacturers of planar microwave circuits and components to facilitate the take up of the technology and measurement infrastructure developed by the project. This has been achieved by actively engaging such manufacturers in technical work packages and by developing best measurement practice guidelines, which serve the entire on-wafer measurement community.

Progress beyond the state of the art

Prior to the start of this project there were no reference calibration substrates available for on-wafer S-parameter measurements, and there was no traceability established. Therefore, this project investigated two approaches to achieve traceability up to 110 GHz, airline-like interconnects built in membrane-technology and electro-optic time-domain waveform measurements. The investigations on airline-like interconnects enabled traceable S-parameter measurements of planar circuits and components for the first time.

Commercially available calibration substrates known as impedance standard substrates (ISSs) are commonly used by industry, despite the fact that calibration methods suffer from parasitic effects in the impedance standards at higher frequencies. Therefore, to address these problems, this project investigated whether the low uncertainties achievable on dedicated reference substrates can be transferred to device measurements on substrates built using conventional technology. One approach proved being feasible and was demonstrated successfully on an industrial alumina substrate.

Accurate transmission-line models form the basis for the design of calibration standards and for the corresponding algorithms, since most of the calibration standards are basically transmission lines. Before this project, these models did not, or only to a limited extent, include the high frequency phenomena related to conductor loss and radiation. Therefore, this project performed a thorough study of the surface roughness and radiation effects in the higher GHz frequency range and found a simplified description which could be implemented in the existing models.

On-wafer measurement set-ups are currently available to at least 325 GHz and beyond. A major problem at these frequencies is the presence of parasitic electromagnetic modes which contaminate the measurement integrity. This project went beyond the state-of-the-art by addressing these issues. In particular, guidelines for the design of calibration substrates were developed, including the suppression of parasitic modes for frequencies up to and including 325 GHz.

The development of dedicated high impedance calibration standards and calibration methods addressed the high impedance mismatch problem associated with nano-device measurements. Furthermore, new access structures were developed to transfer the measurement reference plane to nanoscale dimensions, leading to the accurate RF characterisation of nano-devices and resolving the probing problem experienced with nano-device measurements.

Results

Objective 1 – Establish traceability of planar scattering parameter measurements on reference calibration substrates

Traceability forms the basis for credible measurement results and their associated uncertainties. It is driven by today's global economy needs and usually achieved by an unbroken chain of comparisons to stated references.

As a world-wide first, this project demonstrated traceability to dimensional measurements for on-wafer S-parameter measurements from 1 to 110 GHz for devices built on fused silica and membrane technology substrates. A comprehensive uncertainty budget including instrumentation errors, connector repeatability and calibration standard uncertainties has been successfully established. In contrast to the membrane technology case, the influence of the fused silica substrate material had to be taken fully into account. This necessitated the wideband extraction of the complex permittivity in the entire frequency range under consideration. To achieve highest precision in the dimensional characterisation of the calibration standards, atomic-force microscopy (AFM) was used. Besides the dimensional uncertainties in the calibration standard, the measurement result depends on the environment as well as on the specific combination of substrate material, planar waveguide type, and probes. Only for such fully specified combinations, and only when single-mode propagation is ensured, reliable uncertainties and traceability for on-wafer S-parameters can be stated.

An alternative candidate for traceable on-wafer VNA measurements, electro-optical sampling (EOS) has also been under consideration. To this end, specialised structures addressing the needs of both measurement techniques (EOS and conventional) were implemented on a low-temperature-grown gallium arsenide (LT-GaAs) substrate. For a high-frequency interconnect structure consisting of coplanar and coaxial elements, both measurement methods were compared for the first time in the frequency range from 10 GHz to 110 GHz and good agreement was found. For comparison measurements on purely planar devices, however, unexpected artefacts showed up in the frequency domain results of the EOS measurements. This rendered the EOS approach as currently unsuitable for providing traceability.

PTB is currently preparing calibration and measurements capabilities (CMCs) entries for traceable 2-port S-parameter measurements of fused silica and membrane technology devices. The methodology developed can be extended to other substrate materials used in industry such as e.g. alumina or GaAs. PTB will be the first NMI worldwide able to offer calibration services for planar S-parameter measurements to industry.

Objective 1 was fully achieved, as traceability was established not only on a reference substrate built in in membrane technology, but also on a more common fused silica substrate.

Objective 2 – Transfer uncertainties to calibration standards in conventional technology to be used in industry

Methods to transfer uncertainties from reference calibration substrates to working calibration substrates are essential for industrial applications. The aim is to preserve the low uncertainties in S-parameter measurements achieved on custom-made reference calibration substrates even when using low-cost working calibration substrates, such as e.g. ISSs, which can be purchased from several on-wafer vendors. Two approaches have been initially under investigation which can potentially transfer uncertainties from a reference calibration substrate to a working calibration substrate: permittivity compensation and residual error estimation. Work on both approaches on a range of devices has shown that the frequency ranges where the methods offer improvements are quite limited.

As a third option for transferring uncertainties to industrial applications where commercial ISSs and simple calibration algorithms have to be used, one has to first characterise the standards in a manner which is adequate for the target application. This requires building custom calibration standards on the target DUT wafer, which serve for characterising the ISS calibration standards appropriately. The feasibility of this approach was demonstrated for the case of alumina substrates. The results of a reference calibration using custom standards were in essence duplicated with the aid of characterised ISS standards and a much simpler, industrial calibration. The uncertainties of the industrial calibration only slightly increased compared to the uncertainties of the reference calibration.

Objective 2 was fully achieved, as the uncertainties obtained from a reference calibration could be transferred to calibration standards in conventional technology to be used in industry.

Objective 3 – Improve planar transmission lines models accounting for surface roughness and radiation losses

Accurate planar transmission lines models are of fundamental importance to the design of calibration standards and to the traceability of on-wafer scattering parameters. They form the basis for comparison, should be accurate and include all phenomena as good as possible. However, there is a combination of different physical effects which compromise the accuracy of the present models as well as of on-wafer measurements in general. On the one hand, these effects are linked to the Device under Test (DUT) itself, which are mainly dispersion, radiation and surface roughness. On the other hand, there are external factors related to the non-ideality of layouts and microwave probes. With this motivation, an in-depth investigation of surface roughness, dispersion and radiation in the higher GHz frequency range has been performed and the existing transmission line model for coplanar waveguides (CPW) was improved accordingly. The description of dispersion and radiation was updated, based on full-wave electromagnetic simulations for various geometries and material constellations. The impact of surface roughness was modelled by effective material parameters which were derived from a physics-based surface roughness formulation and used to modify the respective parameters of the CPW model. The surface roughness model is physics-based, as it comprehensively utilises the physical properties of conductor material and surface.

Though the external influences cannot be included in the existing model, their impact has also been studied thoroughly. Different layouts of calibration substrates were fabricated and characterised. The influence of microwave probes on the on-wafer measurements were not only identified, but also clarified for the most common planar transmission lines, CPW and thin film microstrip lines (TFMSL), up to 110 GHz. For the first time, comprehensive data is available that details the influence of probe size and geometry, needle length, and the coaxial opening of the probe. Based on these results, design guidelines verified by measurements were provided.

By improving planar transmission lines models accounting for surface roughness and radiation losses Objective 3 was fully achieved.

Objective 4 – Develop calibration substrates and algorithms for planar scattering parameter measurements up to at least 325 GHz

To establish and demonstrate the quality of on-wafer measurements at higher millimetre wave frequencies (in particular in the frequency band 140 GHz to 220 GHz), a round-robin measurement comparison exercise has been carried out. To this end, ISSs manufactured by two leading on-wafer equipment suppliers have been examined with regard to their suitability at frequencies ranging from 140 GHz to 220 GHz. The measurement data for this comparison has been collected and analysed. Generally, there was a relatively good agreement between results obtained from participating organisations. The deviations on some devices were considerable, which are believed to be attributed to factors including different probes, different calibration techniques, different manufacturers' ISSs, different artefact standards, and different hardware (VNA, probe station etc.). Additionally, a comparison between well-established waveguide calibrations and an equivalent on-wafer calibration has been performed at D-band (110-170 GHz). This work concerned S-parameter measurements of electronic components on planar substrates performed with a waveguide module and in a conventional on-wafer probing environment. Second-tier calibration was applied to the waveguide modules to achieve the same reference planes for the waveguide measurements as used for the on-wafer probing measurements. An algorithm-based crosstalk correction and a shielded probe-to-pad transition have been utilised, to compensate for crosstalk and higher order modes influencing the on-wafer S-parameter measurements. Both techniques have been proved to be efficient in terms of improving on-wafer S-parameter measurements at high frequencies.

Simulation work to link the substrate electrical and mechanical parameters to the generation of unwanted propagation modes has been carried out, and eight guidelines on the design of calibration substrates have been produced and given in the Final Publishable Report. Objective 4 was fully achieved.

Objective 5 – Develop suitable calibration standards and methods for measurements of RF nano-devices

To extend S-parameter measurement to nano-scale dimensions, next-generation ultra-small-sized Micro-Electro-Mechanical System (MEMS) based probes have been designed and manufactured, together with conventional access structures which allow for testing with conventional probe dimensions. Additionally, an active interferometer-based 2-port VNA measurement system was designed, which demonstrated first low-noise and broadband measurement for devices presenting highly mismatched conditions. Furthermore, a high-precision probing station has been developed with emphasis on retaining system stability and enhancing measurement accuracy for nano-device characterization. The system utilises a two-microscope-based fixture for visualisation of the DUT and offers the capability to move each probe with 20 nm resolution along each axis. To improve calibration uncertainty for extreme impedance measurements, a number of impedance standards have been designed and measured. Measurements were conducted using a conventional 50 Ω on-wafer station on a single non-intentionally doped silicon nanowire embedded in a two-port CPW 2µm gap structure; few µS of conductivity were measurable in transmission. In addition, CPW gaps with and without resistances were realised on a new wafer, and capacitances <50aF and corresponding to a gap of 14µm were accurately measured in transmission. Scanning microwave microscope (SMM) measurements were used to detect broken lines, however this approach was found to be inadequate as the probe tip displaced the nano-wires.

The measurement challenges presented by extension of high precision S-parameter measurements in the GHz range to nanoscale dimensions with device visualisation, probing, noise suppression and calibration have been addressed collectively. These findings have been included in a measurement capability report on the development of techniques supporting the extension of state-of-the-art S-parameter measurements in the GHz range to nano-scale dimensions. Objective 5 was fully achieved.

Impact

Key results of this project have been communicated to the end-users in industry and academia via training courses, workshops and publications at leading international microwave conferences. First standardisation efforts for on-wafer S-parameter measurements have been initiated at the recently founded On-Wafer Measurement User Forum, sponsored by the Automatic RF Techniques Group (ARFTG).

In particular, the following dissemination activities by the project have helped to strengthen the links to the end-user community:

- Two training courses, for end users: (i) “1st PlanarCal Training Course”, at TU Delft, The Netherlands, in June 2016; (ii) “2nd PlanarCal Training Course”, at METAS, Switzerland, in December 2017. All two courses involved project’s partners as instructors and offered practical laboratory demonstrations.
- Two workshops at major international conferences, on: (i) “New developments in microwave measurements for planar circuits and components” at the International Microwave Symposium IMS2017, June 2017, (ii) “Modelling, Identification and Suppression of Parasitic Modes in On-Wafer Measurements” at the European Microwave Week EuMW2017, October 2017.
- 56 presentations at international scientific conferences and the publishing of 26 scientific papers, including three contributions to trade journals and professional press.
- Regular nine-monthly teleconferences with the Project’s Advisory Board (PAB); a group of 6 international experts in the project’s scientific areas.
- A project website (https://planarcal.ptb.de/) for end-users, and a LinkedIn Discussion Group.

Impact on industrial and other user communities

On-wafer microwave measurements play a key role in lowering the enormous costs of developing new products, because they enable industry to measure the true performance of RF components at the wafer level. Reliability and traceability of on-wafer measurements are vital for the entire RF and microwave industry, because they provide confidence in measurements and specifications. This is very important for customer/supplier relationships and where products need to be demonstrated as compliant to specifications or directives, regardless of who is doing the testing, or where the test is being done. The outcomes of this project will benefit all sectors of the electrical and electronics industries involved in characterisation and modelling of high-frequency devices and systems.

In particular, there have been four major achievements from which industry and the academic community can draw benefits.

As a world-wide first, this project demonstrated traceability for on-wafer S-parameter measurements of devices fabricated on fused silica and membrane technology substrates by establishing a comprehensive uncertainty budget. This traceability path can be applied to other configurations of measurement hardware, substrate materials and probes, as long as single-mode propagation is ensured.

Second, the specialised VNA measurement and uncertainty calculation software VNATools, developed by METAS, has been extended for on-wafer measurements and calibrations. The software package VNA Tools is available at no cost and can be downloaded from the METAS website (www.metas.ch/vnatools).

Third, guidelines for the design of calibration substrates have been developed, including the suppression of parasitic modes. They provide an overall framework on how to avoid effects such as parasitic modes and crosstalk through the substrate and between the microwave probes at millimetre wavelengths and beyond by formulating easy-to-follow design rules. Evidence of the efficacy of the design rules has been given through validated examples of calibration substrates fabricated during the lifetime of this project, and through measurements.

Fourth, Univ-Lille1 and VSL have developed a new generation of instrumentation aimed to address on-wafer measurement of nano-devices in the microwave regime. Future plans concern the RF test of high impedance CMOS devices from the silicon industry with targeted objectives such as improvement of the measurement accuracy and reduction of the wafer area dedicated to test and calibration.

Impact on the metrology and scientific communities

By the end of the project, new measurement capabilities have been established. These new measurement services are being provided subsequently to the stakeholder community and other industrial end-users in general. In the short-term, PTB will propose changes to the CMCs statements recorded in the BIPM key comparison database (KCDB) regarding planar S-parameter measurements up to 110 GHz. In the medium-term, the other NMIs participating in this project are also expected to propose changes to their CMCs statements. All these changes will account for the traceability routes for planar S-parameter measurements that have been newly developed within this project.

The extensions of the CPW model regarding high-frequency effects represent an indispensable tool for those working on advancing the state of the art, i.e. the metrological and scientific communities. Accurate modelling is not only essential for pushing the limits in circuit design but also to set up high-precision calibration routines and standardised measurements. The extended descriptions for transmission lines will also be communicated to the respective stakeholders providing circuit design CAD software.

The Best Practice Guide developed in this project represents a summary of state-of-the-art recommendations for performing on-wafer measurements together with a selection of the latest research results obtained over a period of three years during the PlanarCal project. Some of the uncertainties shown in the examples of this Guide can be significantly reduced by improving on the measurements of the wideband frequency-dependent material properties, which is a subject of future research.

As a result of this project the scientific communities in Europe will be enabled to expand their field of expertise compared to the international community and thus increase the chance of high level research and funded projects. Concerning the wider impact of the project, this can push technology development by accurate measurement results. These precise results will give new insight into technology processes and how to best optimise them.

Impact on relevant standards

Up to now, no documentary standards existed for on-wafer calibrations and measurements. To change this situation, during this project, the consortium has engaged with the ARFTG Board of Directors, and an On-wafer Users' Forum has been set up. This Forum has met during several major international conferences. Also, a pre-standardisation Special Interest Group (SIG) for on-wafer measurements has been set up. This SIG has developed a draft Project Authorisation Request (PAR) which is required as part of the process for initiating an IEEE standards-making activity. The draft PAR has been submitted to the IEEE Standards Association shortly after the end of the project.

Longer-term economic, social and environmental impacts

The results of this project will enable manufacturers of planar microwave circuits and components to offer assured products with defensible specifications which are supported for the first time through on-wafer measurement traceability chains. By fulfilling cost and quality assurance requirements more easily, this project will help products in different areas to become market leaders. These markets include consumer electronics, security and detection systems, medical diagnostics, climate change monitoring, and the entire telecommunications and automotive industry. The outcomes of this project will benefit all sectors of the electrical and electronics industries involved in characterisation and modelling of high-frequency devices and systems. Increasing technological innovation will help secure existing jobs and create future jobs in Europe as a location for business.

As wireless data communications are becoming more and more commonplace, the average electromagnetic radiation intensity is steadily increasing. It is therefore very important to decrease the transmitted power of radio-communication systems. The development of characterisation and measurement methods for planar circuits and components as carried out in this project will help to increase the efficiency of mobile communication systems, and thus to reduce the overall electromagnetic radiation.

List of publications

[1] F. Mubarak, R. Romano, and M. Spirito, "Evaluation and modeling of measurement resolution of a vector network analyzer for extreme impedance measurements," in 86th ARFTG Microwave Measurement Conference, 2015. [Online]. Available: http://ieeexplore.ieee.org/document/7381475/?arnumber=7381475&tag=1

[2] M. Bieler and U. Arz, "Characterization of high-frequency interconnects: Comparison between time- and frequency-domain methods," in 20th IEEE Workshop on Signal and Power Integrity (SPI), 2016. [Online]. Available: https://oar.ptb.de/resources/show/10.7795/EMPIR.14IND02.CA.20190403D

[3] K. Daffé, G. Dambrine, F. von Kleist-Retzow, and K. Haddadi, "RF wafer probing with improved contact repeatability using nanometer positioning," in 87th ARFTG Microwave Measurement Conference, 2016. [Online]. Available: https://hal.archives-ouvertes.fr/hal-02083251

[4] M. Bieler and U. Arz, "Comparison between time- and frequency-domain high-frequency device characterizations," in Conference on Precision Electromagnetic Measurements (CPEM), 2016. [Online]. Available: https://oar.ptb.de/resources/show/10.7795/EMPIR.14IND02.CA.20190403E

[5] G. Gold and K. Helmreich, "Modeling of transmission lines with multiple coated conductors," in 46th European Microwave Conference (EuMC), 2016, pp. 635–638. [Online]. Available: http://dx.doi.org/10.1109/EuMC.2016.7824423

[6] H. Votsi et al., "Development of a reference wafer for on-wafer testing of extreme impedance devices," in 88th ARFTG Microwave Measurement Conference, 2016. [Online]. Available: http://dx.doi.org/10.1109/ARFTG.2016.7839719

[7] L. Galatro and M. Spirito, "Millimeter-Wave On-Wafer TRL Calibration Employing 3-D EM Simulation-Based Characteristic Impedance Extraction," IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 4, pp. 1315–1323, Apr. 2017. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7837598

[8] F. J. Schmückle, T. Probst, U. Arz, G. N. Phung, R. Doerner, and W. Heinrich, "Mutual interference in calibration line configurations," in 89th ARFTG Microwave Measurement Conference, 2017. [Online]. Available: https://www.fbh-berlin.com/publications-patents/publications/title/mutual-interference-in-calibration-line-configurations

[9] M. Wollensack, J. Hoffmann, D. Stalder, J. Ruefenacht, and M. Zeier, "VNA tools II: Calibrations involving eigenvalue problems," in 89th ARFTG Microwave Measurement Conference, 2017. [Online]. Available: https://oar.ptb.de/resources/show/10.7795/EMPIR.14IND02.CA.20190404

[10] G. N. Phung, F. J. Schmückle, R. Doerner, T. Fritzsch, and W. Heinrich, "Impact of parasitic coupling on multiline TRL calibration," in 47th European Microwave Conference (EuMC), 2017, pp. 835–838. [Online]. Available: https://www.fbh-berlin.com/publications-patents/publications/title/impact-of-parasitic-coupling-on-multiline-trl-calibration-1

[11] K. Daffé et al., "Nano-probing station incorporating MEMS probes for 1D device RF on-wafer characterization," in 47th European Microwave Conference (EuMC), 2017, pp. 831–834. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01726555

[12] N. Ridler, R. Clarke, and M. Salter, "Mind the Gap".Establishing Measurement Capability in the Terahertz Gap Region - from 0.1 THz to 1.1 THz," ARMMS Conference Digest. ARMMS, Nov. 2017. [Online]. Available: http://eprints.whiterose.ac.uk/125335/

[13] R. Clarke, C. Li, and N. Ridler, “An Intra-Laboratory Investigation of On-wafer Measurement Reproducibility at Millimeter-wave Frequencies,” 90th ARFTG Microwave Measurement Conference, 2017. [Online]. Available: http://eprints.whiterose.ac.uk/125336/

[14] T. Probst, R. Dörner, M. Ohlrogge, R. Lozar, and U. Arz, “110 GHz On-Wafer Measurement Comparison on Alumina Substrate,” in 90th ARFTG Microwave Measurement Conference, 2017. [Online]. Available: https://oar.ptb.de/resources/show/10.7795/EMPIR.14IND02.CA.20190403A

[15] U. Arz, S. Zinal, T. Probst, G. Hechtfischer, F.-J. Schmückle, and W. Heinrich, “Establishing Traceability for On-Wafer S-Parameter Measurements of Membrane Technology Devices up to 110 GHz,” 90th ARFTG Microwave Measurement Conference, 2017. [Online]. Available: https://oar.ptb.de/resources/show/10.7795/EMPIR.14IND02.CA.20190403 *(Best Paper Award)*

[16] G. N. Phung, F.-J. Schmückle, R. Doerner, W. Heinrich, T. Probst, U. Arz, "Effects degrading accuracy of CPW mTRL calibration at W-band," Proceedings of International Microwave Symposium (IMS), 2018, pp. 1296-1299. [Online]. Available: https://www.fbh-berlin.com/publications-patents/publications/title/effects-degrading-accuracy-of-cpw-mtrl-calibration-at-w-band

[17] T. Probst, S. Zinal, R. Doerner, and U. Arz, “On the Importance of Calibration Standards Definitions for On-Wafer Measurements up to 110 GHz,” in 91st ARFTG Microwave Measurement Conference, 2018. [Online]. Available: https://oar.ptb.de/resources/show/10.7795/EMPIR.14IND02.CA.20190403C

[18] F. Mubarak, V. Mascolo, G. Rietveld, M. Spirito, K. Daffe, and K Haddadi, "Parameterization Models for Traceable Characterization of Planar CPW SOL Calibration Standards," Conference on Precision Electromagnetic Measurements (CPEM), 2018. [Online]. Available: https://hal.archives-ouvertes.fr/hal-02085776

[19] K. Haddadi, P. Polodolov, D. Theron, and G. Dambrine, "Quantitative error analysis in near-field scanning microwave microscopy," in 3rd International Conference on Manipulation, Automation and Robotics at Small Scales, MARSS 2018, Nagoya, Japan, 2018. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01913677

[20] K. Haddadi et al, “On-Wafer Series-Through Broadband Measurement of Sub-fF55-nm MOS RF Voltage-Tunable Capacitors," IEEE Microwave and Wireless Components Letters, 2018, vol 28, no 9, p. 831-833. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01873048

[21] C. Liu, A. Wu, C. Li, and N. Ridler, “A New SOLT Calibration Method for Leaky On-Wafer Measurements Using a 10-Term Error Model,” IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 8, pp. 3894–3900, Aug. 2018. [Online]. Available: http://dx.doi.org/10.1109/TMTT.2018.2832052

[22] G. N. Phung, F.-J. Schmückle, R. Doerner, W. Heinrich, T. Probst, U. Arz, "Impact of Substrate Modes on mTRL-Calibrated CPW Measurements in G Band," 48th European Microwave Conference (EuMC), 2018. [Online]. Available: https://www.fbh-berlin.com/fileadmin/downloads/Publications/2018/2018_06_04_EuMC_2018_Mode_Suppression_final_03.pdf

[23] K. Daffé, F. Mubarak, V. Mascolo, H. Votsi, N. Ridler, G. Dambrine, I. Roch, K. Haddadi, "On-wafer broadband microwave measurement of high impedance devices - CPW test structures with integrated metallic nano-resistances," 48th European Microwave Conference (EuMC), 2018.[Online]. Available: https://hal.archives-ouvertes.fr/hal-02056825

[24] U. Arz, A. Savin, "On-wafer residual error correction through adaptive filtering of verification line measurements," CEMi’18 International Workshop on Computing, Electromagnetics, and Machine Intelligence, 2018. [Online]. Available: https://oar.ptb.de/resources/show/10.7795/EMPIR.14IND02.CA.20190403F

[25] F. A. Mubarak, R. Romano, L. Galatro, V. Mascolo, G. Rietveld, and M. Spirito, “Noise Behavior and Implementation of Interferometer Based Broadband VNA,” IEEE Transactions on Microwave Theory and Techniques, vol. 67, nr. 1, pp. 249-260, Jan. 2019. http://dx.doi.org/10.1109/TMTT.2018.2874667 [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8566175

[26] G.N. Phung, F.-J. Schmückle, R. Doerner, T. Fritzsch, S. Schulz and W. Heinrich, "Crosstalk Effects of Differential Thin-Film Microstrip Lines in Multilayer Motherboards", Proc. of the 12th German Microwave Conference, pp. 178-181, Mar. 2019. [Online]. Available: https://www.fbh-berlin.com/fileadmin/downloads/Publications/2019/2019_02_20_GeMiC_GNP_repository.pdf

[27] G.N. Phung, F.-J. Schmückle, R. Doerner, B. Kähne, T. Fritzsch, U. Arz and W. Heinrich, "Influence of Microwave Probes on Calibrated On-Wafer Measurements," IEEE Transactions on Microwave Theory and Techniques, vol. 67, nr. 5, pp. 1892-1900, May 2019. [Online]. Available: https://www.fbh-berlin.de/fileadmin/downloads/Publications/2019/FINAL_VERSION_repository.pdf

[28] U. Arz, K. Kuhlmann, T. Dziomba, G. Hechtfischer, G.N. Phung, F.J. Schmückle and W. Heinrich, "Traceable Coplanar Waveguide Calibrations on Fused Silica Substrates up to 110 GHz," accepted for publication in IEEE Transactions on Microwave Theory and Techniques, 2019. [Online]. Available: http://dx.doi.org/10.1109/TMTT.2019.2908857

[29] 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," [Online]. Available: https://oar.ptb.de/resources/show/10.7795/530.20190424B

[30] M. Spirito, U. Arz, G. N. Phung, F. J. Schmückle, W. Heinrich, R. Lozar "Guidelines for the design of calibration substrates, including the suppression of parasitic modes for frequencies up to and including 325 GHz," [Online]. Available: https://oar.ptb.de/resources/show/10.7795/530.20190424A

Project start date and duration:	01 October 2015, 36 months	
Coordinator: Dr. Uwe Arz, PTB	Tel: +49 531 592 2297	E-mail: uwe.arz@ptb.de
Project website address: https://planarcal.ptb.de/		
Internal Funded Partners: 1 PTB, Germany 2 NPL, United Kingdom 3 VSL, Netherlands	External Funded Partners: 4 FAU, Germany 5 FhG, Germany 6 FVB, Germany 7 TU Delft, Netherlands 8 ULE, United Kingdom 9 Univ-Lille1, France	Unfunded Partners: 10 RF360, Germany 11 METAS, Switzerland 12 R&S, Germany
RMG: -		