A Review of Measurement Capabilities at Millimetre and Submillimetre Wavelengths at the UK's National Physical Laboratory

Xiaobang Shang[1], Nick Ridler[1], Roland Clarke[2], and Mira Naftaly[1]

[1]National Physical Laboratory, UK, xiaobang.shang@npl.co.uk
[2]University of Leeds, UK

***Abstract*—This paper gives an overview of capabilities available at the UK's National Physical Laboratory (NPL) for measuring the scattering parameters (i.e. *S*-parameters) and material properties of devices operating at millimetre-wave and submillimetre-wave frequencies. The paper also reports on some current research activities aimed at extending these capabilities and addressing major measurement challenges at these high frequencies.**

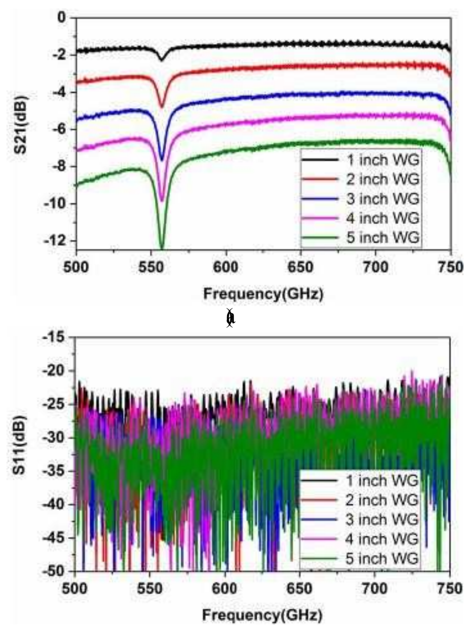
***Index Terms* – Millimetre-wave measurements, Submillimetrewave measurements, Waveguide measurements, On-wafer measurements, Material measurements**

I. INTRODUCTION

There is a rapid increase in exploitation of the millimetre-wave and submillimetre-wave spectrum, driven by the demands from diverse applications such as 5G, Internet of Things (IoT), Connected Autonomous Vehicles (CAV), planetary and Earth observations, and security imaging, etc. Advancement in these applications has led to an increased demand for accurate and traceable electrical measurements for devices and integrated circuits operating at these high frequencies.

The measurement capabilities for *S*-parameters, at NPL, are currently concentrated on two types of techniques, i.e. in rectangular metallic waveguides, to 1.1 THz (which includes equipment based at the University of Leeds), and on-wafer, to 750 GHz. Time-Domain Spectrometry (TDS) [1] has been the predominant technique utilised at NPL for characterising material properties at THz frequencies. This is a free-space technique capable of measuring complex permittivity over a wide frequency range, from around 200 GHz to several THz. NPL also makes material measurements using Vector Network Analyzers (VNAs). Such techniques complement the TDS, allowing measurement of material properties at the lower limit of the operational range of the TDS.

This paper will discuss the abovementioned topics in detail and present some recent measurement results. Note that these topics represent only a part of the work at NPL, there are also other active research activities, such as VNA-based free-space measurement for characterisation of quasi-optical components fabricated using 3-D printing [2].



(a)

Fig. 1. Measured transmission coefficients (a) and reflection coefficients (b) for five WM-380 waveguide sections (manufactured by VDI). There is a strong water line at around 557 GHz.

II. WAVEGUIDE MEASUREMENT

Rectangular metallic waveguides are used extensively at millimetre-wave and submillimetre-wave frequencies, mainly due to their low loss characteristic. Although waveguide is a well-established transmission medium, measurement in waveguide above 100 GHz is not straightforward. This is mainly due to the small size of the waveguide features that results in poor connection repeatability and measurement traceability. To address such problems, NPL has proposed techniques to establish traceability to the International System of units (SI) for *S*-parameter measurement [3], and contributed to the development of new international standards for these waveguides, i.e. for waveguide apertures [4], flanges [5], and performance indication of combination of waveguide apertures and flanges [6]. These standards include waveguide loss obtained from modelling and calculations, however no measured values of loss are provided.

Fig. 1 shows the test results of several WM-380 (500-750 GHz) straight sections of commercial waveguides with different lengths (from 1″ to 5″). Detailed discussion about the results including uncertainly analysis can be found in [7]. The measurement was performed on a Keysight N5247A PNA-X fitted with VDI WM-380 Extender Heads, and was subject to a two-port SOLT (Short/Offset-short/Load/Thru) calibration. The SOLT calibration was verified using TRL technique that is based on custom designed 3/4-wave Line Standards [3]. These standards are the UK's primary national reference standards, which are traceable to basic quantities of the SI system, i.e. the meter, second, kelvin, etc.

For future work, it is anticipated that further research is still required to provide traceable waveguide measurements across the whole of the millimetre-wave and submillimetre-wave regions. The challenges to provide measurement accuracy as well as verification techniques at these frequencies also need to be addressed.

III. On-Wafer Measurement

On-wafer measurement and calibration above 100 GHz is currently another area of active research. A European project entitled "PlanarCal" [8], includes research into on-wafer measurements above 100 GHz. One of the objectives of this project is to establish traceability for *S*-parameter measurements on reference impedance standard substrates (ISS). Two ISS devices are utilised and they are: GGB Industries CS-15 and Cascade Microtech 138-356.

NPL is involved in this project and has investigated the reproducibility of on-wafer measurement [9], using a modified in-house probe station (see Fig. 2). Fig. 3 shows the test results of a 900 µm CPW line on Cascade Microtech 138-356. Measurements were made from 140 GHz to 220 GHz using 75 µm pitch ground-signal-ground (GSG) probes (GGB Industries Picprobe Model 220-BT-M). A single tier, two-port SOLT calibration was carried out twice, using the two ISSs mentioned above. The GGB ISS provided "Off-wafer" calibration and the Cascade ISS delivered "On-wafer" calibration. Four repeatable measurements were taken for each calibration. This offers insight into the contact-repeatability and positioning-repeatability. It can be observed from Fig. 3 (a) that the measured reflection coefficients show some residual mismatch between the reference impedance established by the calibrations and the line impedance for both on-wafer and off-wafer calibrations. The measured transmission coefficients in Fig. 3 (b) show considerable difference for the two calibrations; they are also greater than predicated (e.g. the predicted loss was -0.45 dB at 220 GHz). The measured transmission phases depicted in Fig. 3 (c) suggest good agreement for two calibrations, however they deviate from the expected values by up to 15°. More discussions about the results are given in [9].

Another dimension to the on-wafer work at NPL is the development of new calibration methods that provide better measurement accuracy, e.g. the new SOLT calibration method using a 10-term error model [10].

Fig. 2 Photograph of the modified manual probe station at NPL. Currently on-wafer measurement up to 750 GHz can be performed.

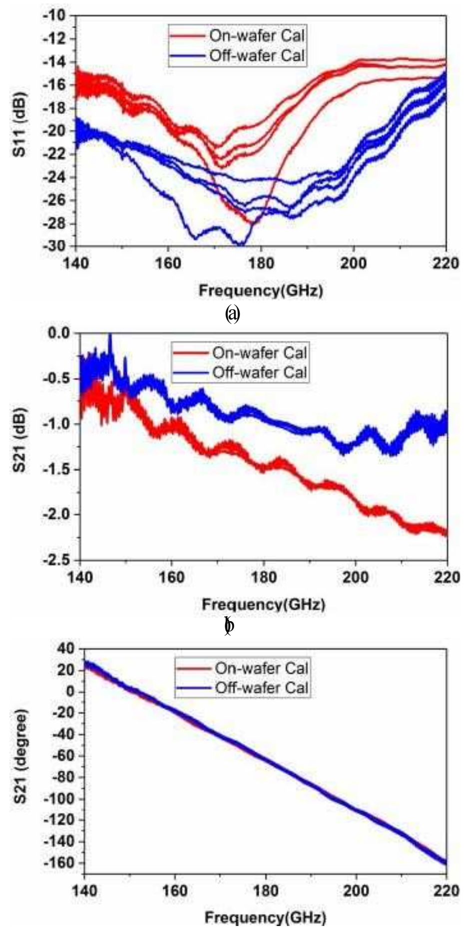


Fig. 3. Measured results for the 900 µm CPW line on Cascade Microtech 138-356. (a) Reflection coefficients magnitude; (b) Transmission coefficients magnitude; (c) Transmission coefficients phase.

IV. Material Measurement

Since its invention in the early 1990s terahertz time domain spectroscopy (THz TDS) has gained wide acceptance for determining dielectric properties of materials at THz frequencies. It is a technique in the long and illustrious tradition of optical spectroscopy and operates in free space, with the sample placed in the THz beam and its optical properties measured in transmission or reflection. A crucial advantage of THz TDS is that it measures field amplitude and phase, allowing both real and imaginary permittivity to be determined directly and unambiguously. To date, almost every type of material has been studied using THz TDS, including semiconductors, ceramics, polymers, conductive films, glasses, pharmaceuticals, bio-molecules, gases, composites, foams, oils, and many others. In recent years the importance of robust metrology in THz TDS measurements has gained prominence. NPL has pioneered and championed several key developments in this area; in particular, testing for linearity of amplitude measurements [11], and frequency calibration using FabryPerot etalon [12].

NPL has three THz TDS systems. The main research instrument is a laboratory built system using a standard configuration [13]. It employs a Ti-sapphire femtosecond laser as an optical pump, a biased photoconductive GaAs THz emitter, ZnTe electro-optic detection, and four off-axis parabolic mirrors to guide the THz beam. The bandwidth of this instrument is 0.2-4 THz and its maximum frequency resolution is 1.5 GHz. We also have a commercial pulsed THz TDS instrument: Menlo Tera K15. This is a fiber-coupled system using a mode-locked 1.56 um pump laser and a photoconductive emitter and detector. Its bandwidth is 5 THz and its frequency resolution is 1.2 GHz. This system is used whenever configuration flexibility is required, and where fast signal acquisition is necessary, e.g. imaging. In addition we have a continuous-wave frequency domain instrument: Toptica TeraBeam. This is also a fiber-coupled system, using 3 telecoms-type 1.55 µm DFB lasers with a photoconductive emitter and detector. Its bandwidth is 0.05-2 THz and its maximum frequency resolution is 0.05 GHz. This system is used for high-resolution spectroscopy, and for measurements at frequencies below 1 THz, especially on highly absorbing materials [14].

NPL's activities in the area of THz TDS measurements fall primarily into two areas: metrology [15], and dielectric spectroscopy of materials, e.g. ceramics, glasses, textiles, liquid crystals, and nonlinear crystals. In addition to the THz TDS technique, Vector Network Analyzer (VNA) based techniques are being developed for relatively lower frequencies (i.e. from 75 to 750 GHz). Work in progress includes the study on Swissto12 Material Characterisation Kit (MCK), with some preliminary results reported in [16].

V. Conclusions

This paper has summarised the research and development at the UK's National Physical Laboratory for measurements of *S*-parameter and material permittivity at millimetre-wave and submillimetre-wave frequencies. Some latest measurement results have been presented and discussed. Much of this work is undertaken in collaboration with other universities with interest in this area. NPL welcomes such collaborations.

Acknowledgment

The authors would like to acknowledge support by the European Metrology Programme for Innovation and Research (EMPIR) project 14IND02 “Microwave measurements for planar circuits and components”. The EMPIR program is co-financed by the participating countries and the European Union's Horizon 2020 research and innovation program. This work was also supported by the National Measurement System Programme of the UK government's Department for Business, Energy & Industrial Strategy (BEIS).

References

[1] M. Naftaly, R. G. Clarke, D. A. Humphreys and N. M. Ridler, "Metrology state-of-the-Art and challenges in broadband phase-sensitive terahertz measurements", Proceedings of the IEEE, vol. 105, no. 6, pp. 1151-1165, June 2017.

[2] S. Lucyszyn, X. Shang, W. J. Otter, C. W. Myant, R. Cheng, N. M. Ridler, "Polymer-based 3D printed millimeter-wave components for spacecraft payloads," in IEEE MTT-s International Microwave Workshop Series on Advanced Materials and Processes (IMWS-AMP), Ann Arbor, Michigan, USA, July 2018.

[3] N. M. Ridler and R. G. Clarke, “Establishing Traceability to the International System of Units for Scattering Parameter Measurements from 750 GHz to 1.1 THz”, IEEE Trans Terahertz Science & Technology, vol. 6, no 1, pp 2-11, January 2016.

[4] IEEE Std 1785.1-2012: “IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—Part 1: Frequency Bands and Waveguide Dimensions”.

[5] IEEE Std 1785.2-2016: “IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—Part 2: Waveguide Interfaces”.

[6] IEEE Std 1785.3-2016: “IEEE Recommended Practice for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—Part 3: Recommendations for Performance and Uncertainty Specifications”.

[7] N. Ridler, C. Li, “Benchmarking electrical loss in rectangular metallic waveguide at submillimeter wavelengths,” in 10th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies (UCMMT), Liverpool, UK, 2017, pp. 1-4.

[8] Microwave measurements for planar circuits and components (PlanarCal), https://planarcal.ptb.de/.

[9] R. G. Clarke, C. Li and N. M. Ridler, "An intra-laboratory investigation of on-wafer measurement reproducibility at millimeter-wave frequencies," 90th ARFTG Microwave Measurement Symposium (ARFTG), Boulder, CO, 2017, pp. 1-6.

[10] C. Liu, A. Wu, C. Li, 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, *early access*.

[11] M. Naftaly, R. Dudley, “Linearity calibration of amplitude and power measurements in terahertz systems and detectors”, Opt. Lett., vol. 34, no.5, pp. 674-676, 2009.

[12] M. Naftaly, R. Dudley, J. Fletcher, “An etalon-based method for frequency calibration of terahertz time-domain spectrometers (THz TDS)”, Opt. Commun., vol. 283, pp.1849-1853, 2010.

[13] J. Molloy, M. Naftaly, R. Dudley, “Characterization of terahertz beam profile and propagation”, IEEE J. Select. Topics Quantum Electron, vol. 19, no.1, pp. 8401508, Jan-Feb 2013.

[14] A. Afsharinejad, A. Davy and M. Naftaly, "Variability of terahertz transmission measured in live plant leaves," IEEE Geoscience and Remote Sensing Letters, vol.14, no.5, pp. 636-638, April 2017.

[15] M. Naftaly, ed., Terahertz Metrology, Artech House 2015.

[16] A. Khalid, D. Cumming, R. Clarke, C. Li and N. Ridler, "Evaluation of a VNA-based material characterization kit at frequencies from 0.75 THz to 1.1 THz," in 9th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies (UCMMT), Qingdao, 2016, pp. 31-34.