Publishable Summary for 18SIB09 TEMMT
Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies

Overview

This project aims to establish traceability to the SI for 3 electrical measurement quantities; (i) S-parameters, (ii) power and (iii) complex permittivity of dielectric materials, at millimetre-wave and terahertz (THz) frequencies. Such traceability is important for many emerging applications, exploiting communications and electronics technologies – e.g. 5th Generation mobile networks (5G), the Internet of Things (IoT), Connected and Autonomous Vehicles (CAVs), space-borne radiometers for Earth remote sensing, security imaging, etc. The goal of this project is to support such emerging applications and enable European NMIs to provide traceability to the SI for these 3 parameters in the millimetre-wave and THz part of the spectrum, which will be beneficial to end-users.

Need

The rollout of 5G networks and large-scale deployments of cellular IoT will lead to fundamental changes to our society, impacting not only consumer services but also industries embarking on digital transformations. CAVs are progressing rapidly and are expected to improve traffic flow, safety and convenience significantly. Space deployed radiometers are used for passive remote sensing of atmospheric constituents which are related to climate change and play a critical role in environmental protection. All these applications require the use of the millimetre-wave and THz regions of the electromagnetic spectrum, and demand devices and integrated circuits operating at these high frequencies.

However, the development of devices and systems to underpin these applications is currently hampered by the lack of traceability for electrical measurements at millimetre-wave and THz frequencies. For example, although power meters working at frequencies up to at least 750 GHz are commercially available, there is no established calibration hierarchy, accessible to industrial and other end-users, to allow traceability to the SI for these measurements. In addition, current commercially available frequency extender heads and calibration kits for vector network analysers (VNAs) enable these systems to measure S-parameters at frequencies up to 1.5 THz. These VNA systems can also be adapted to measure materials properties (e.g. complex permittivity) using commercially available Material Characterisation Kits (MCK) at frequencies up to at least 750 GHz. However, again, there is no traceability to the SI to benchmark this measurement capability. NMI-level metrology research is therefore, urgently needed to address this lack of traceability so that the capabilities of these high frequency measurement systems can be fully exploited.

This is important to ensure product quality and end user confidence, and ultimately to improve the competitiveness of European Industry. The work in this project also aligns with broader European visions, as outlined in the Europe Commission Strategy i.e. “Digital Single Market”.

Objectives

The overall objective of this project is to achieve accurate and traceable electrical measurements for users of the millimetre-wave and THz regions of the electromagnetic spectrum, particularly for electronics applications impacting future communications technologies – so-called 5G communications and beyond.

The specific objectives of the project are:

1. To develop metrological traceability and verification techniques for S-parameters (that measure the loss and phase change for transmitted and reflected signals) in both coaxial line (using the 1.35 mm E-band connector to 90 GHz) and rectangular metallic waveguide (using waveguides covering frequencies from 330 GHz to 1.5 THz). Three waveguide bands within this frequency range will be covered and these are 330 GHz to 500 GHz, 500 GHz to 750 GHz, and 1.1 THz to 1.5 THz.

2. To develop metrological traceability and verification techniques for S-parameter measurements on planar substrates from 110 GHz to 1.1 THz. Three waveguide bands within this frequency range will be covered and these are 110 GHz to 170 GHz, 500 GHz to 750 GHz, and 750 GHz to 1.1 THz.
3. To develop metrological traceability for power measurements in waveguide to 750 GHz. Two waveguide bands within this frequency range will be covered and these are 110 GHz to 170 GHz, and 500 GHz to 750 GHz.
4. To develop metrological traceability for complex permittivity of dielectric materials to 750 GHz. Two waveguide bands will be covered and these are 140 GHz to 220 GHz, and 500 GHz to 750 GHz.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by other NMIs with the view of forming a coordinated network of NMIs that provide a comprehensive measurement capability as well as by the measurement supply chain (research institutes, calibration laboratories), standards developing organisations (e.g. IEEE P287 and IEEE P1785) and end users (i.e. manufacturers of telecom equipment, measuring instruments, absorber materials, etc).

Progress beyond the state of the art

Currently, metrological traceability for electrical measurements in the frequency range from 50 GHz to 1.5 THz is poorly served by the global NMI community. This global lack of traceability at these frequencies is demonstrated by the fact that there are no Calibration and Measurement Capability (CMC) entries in the BIPM key comparison database at any frequency above 200 GHz. Given the current rapid increase in use of this part of the electromagnetic spectrum (particularly for communications and electronics applications), this situation represents a serious gap in the services provided by the NMI community to stakeholders i.e. end-users in industry and academia.

Traceable S-parameter measurements in waveguides to 1.5 THz and in E-band coaxial lines to 90 GHz

The current state of the art for metrological traceability for measurements in coaxial lines is up to 116.5 GHz within Europe. The NMI of Japan is capable of providing traceability in waveguide up to 170 GHz, representing the highest frequency in the BIPM database. This project is extending the state of the art by putting in place traceability in waveguides up to 1.5 THz. This will complement the work carried out in the previous EMRP project SIB62 HFCircuits that included a preliminary study on the steps needed to establish traceability for waveguides up to 1.1 THz.

The E-band 1.35 mm coaxial connector has been recently introduced to support applications like 5G and 77 GHz automotive radar sensors. However, there is currently no traceability established for E-band connector measurements. This project is going beyond the state of the art by establishing both dimensional traceability and electrical traceability for E-band connector measurements, allowing industry to perform traceable measurements with known uncertainty.

Traceable planar S-parameter measurements to 1.1 THz

Currently there is no traceability established for on-wafer S-parameter measurements above 110 GHz. Another EMPIR project 14IND02 PlanarCal established traceability up to 110 GHz. This project is continuing the work of 14IND02 and developing traceability and verification techniques for S-parameters to 1.1 THz. This will enable industry to characterise integrated circuits with confidence at these very high frequencies.

Traceable power measurements to 750 GHz

The current state of the art for power measurement is up to 110 GHz in waveguides. This project is putting in place traceability for power measurement up to 750 GHz. Micro-calorimeter and transfer standards are being developed for the 110 GHz to 170 GHz band and novel approaches using a combination of quasi-optical (pyroelectric detection) and guided wave power measurement are also being explored. In addition, evaluation of the traceability of a commercial power meter will be carried out up to 750 GHz.

Traceable material measurements to 750 GHz

For materials measurement (i.e. complex permittivity) existing traceability services extend only to 110 GHz and currently this is only available at a few NMIs. This project is putting in place traceability mechanisms to establish the quality of material measurements to 750 GHz and will expand the number of NMIs offering such services to those in this consortium. This will unlock the potential for using dielectric materials in applications demanding accurate knowledge of material properties, e.g. for space applications.

Results

1. *To develop metrological traceability and verification techniques for S-parameters (that measure the loss and phase change for transmitted and reflected signals) in both coaxial line (using the 1.35 mm E-band connector to 90 GHz) and rectangular metallic waveguide (using waveguides covering frequencies from 330 GHz to 1.5 THz). Three waveguide bands within this frequency range will be covered and these are 330 GHz to 500 GHz, 500 GHz to 750 GHz, and 1.1 THz to 1.5 THz.*

The project has extended the laser micrometer and air-gauging measurement systems to enable dimensional measurements to be made in the 1.35 mm coaxial line size. Such dimensional information allows accurate calculation of characteristic impedance of coaxial lines used to form standards for calibrating VNAs operating in the 1.35 mm coaxial line size to 90 GHz. This frequency range to 90 GHz is becoming of great interest to new and emerging applications in the telecommunications industries (e.g. mobile communications backhaul, connected and autonomous vehicles, etc). European component manufacturers have also introduced a new coaxial connector (the E-connector) specifically for these applications.

Additionally, the project is working on new measurement systems to enable measurements to be made in three waveguide bands within the frequency range, 330 GHz to 1.5 THz. New calibration and uncertainty techniques have also been developed for these three waveguide bands and detailed comparisons of these new calibration and uncertainty techniques in the three waveguide bands (i.e. 330 GHz to 500 GHz, 500 GHz to 750 GHz, and 1.1 THz to 1.5 THz) will subsequently be undertaken.

2. *To develop metrological traceability and verification techniques for S-parameter measurements on planar substrates from 110 GHz to 1.1 THz. Three waveguide bands within this frequency range will be covered and these are 110 GHz to 170 GHz, 500 GHz to 750 GHz, and 750 GHz to 1.1 THz.*

Design of the reference substrate incorporating co-planar waveguide (CPW) calibration standards for S-parameter measurements up to 1.1 THz is nearly complete and will be ready for fabrication shortly. Electromagnetic full wave simulations have been carried out to optimise the dimensions and the layout of the silicon-based calibration substrate which is formed of standards including matched and mismatched lines, shorts, offset shorts, opens and loads.

The development of verification and calibration methods for S-parameter measurements on planar substrates from 110 GHz to 1.1 THz is progressing well. Reliability studies have been conducted using both manual and automated probing techniques through repeated measurements of devices on commercial calibration substrates, and these results have shown reasonable stability of probe planarisation and device contacting. This has then been used to provide input to the development of verification and calibration methods, to be undertaken in the coming months.

Regarding measurement uncertainty, the comprehensive uncertainty budget developed in the preceding EMPIR project 14IND02 PlanarCal (for operation up to 110 GHz) has been reviewed, along with recent published results in open literature. These will be considered during the development of an uncertainty framework for planar measurements up to 1.1 THz. Further investigation into sources of measurement uncertainty will be performed after the design of the reference calibration substrate has been finalised, as parasitic effects depend on layout dimensions and material permittivity of the subtract, and these can play an important role in the uncertainty.

3. *To develop metrological traceability for power measurements in waveguide to 750 GHz. Two waveguide bands within this frequency range will be covered and these are 110 GHz to 170 GHz, and 500 GHz to 750GHz.*

Different types of waveguide calorimeters, in terms of thermal insulation line and thermopile, are being developed by LNE, NPL and PTB for use in the 110 GHz to 170 GHz band. Up to three different types of calorimeter designs will be developed and then produced (one per partner). Electromagnetic and thermal simulations have been performed to optimise the designs of these calorimeters in order to achieve low loss and superior thermal isolation.

Two types of power sensors, one based on thin film bolometric and the other one based on thermoelectric, were designed to be used with the waveguide calorimeters. For the two types of power sensors; the bolometric power sensor is currently being fabricated and the thermoelectric power sensor has been fabricated and is currently awaiting characterisation.

Free-space power measurement setups based on pyroelectric detectors have also been developed for use in the 500 GHz to 750 GHz band and installed at METAS and PTB. Initial measurements of S11 and waveform have been made and further analysis will be performed to verify the free-space power measurement setups.

4. *To develop metrological traceability for complex permittivity of dielectric materials to 750 GHz. Two waveguide bands will be covered and these are 140 GHz to 220 GHz, and 500 GHz to 750 GHz.*

This work focused on three measurement methods: (i) VNA-based systems, (ii) optical systems based on Time-Domain Spectrometer (TDS) and Frequency-Domain Spectrometer (FDS), and (iii) resonator-based systems.

Dielectric material specimens have been measured on the VNA-based systems (installed at METAS and NPL) operating at 140-220 GHz and 500-750 GHz, using the project’s newly developed TRL-based calibration techniques and extraction methods for calculation of material permittivity from S-parameters.

For the optical systems, the first version of an instruction guide to unify the calibration and evaluation of measurement parameters for complex permittivity of dielectric materials has been created and will be used in future measurements.

For the resonator-based systems, fixed length and variable length methods have been developed for dielectric material parameter extraction.

Comparison of the dielectric material properties measured by these three systems will subsequently be undertaken, to investigate and determine the consistency between their measurement results. A set of low to medium loss dielectric reference materials, e.g. ultra-high-molecular-weight polyethylene (UHMW) Polythene, fused silica, yttrium-aluminum-garnet (YAG), have been selected by NPL for this measurement comparison and will be attained in the coming months.

Impact

The project has created a website for end users at http://projects.lne.eu/jrp-temmt/. It has also produced three open access peer-reviewed papers, that are published or accepted and awaiting publication. The project has also been presented 6 times at conferences such as the 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), the 21st International Conference on Electromagnetics in Advanced Applications (ICEAA), the 2019 Asia-Pacific Microwave Conference (APMC) and the 12th UK/Europe-China Workshop on Millimetre-Waves and Terahertz Technologies (UCMMT).

A proposal for a one-day workshop has been accepted by the European Microwave Week 2020 (Europe's premier conference on microwave, millimetre-wave and terahertz devices, systems and technologies). The workshop will be devoted to the outputs from the project, with all 14 confirmed speakers from the consortium and its collaborators.

Impact on industrial and other user communities

This project will enable accurate and traceable measurements of three key electrical quantities at millimetre-wave and THz frequencies. This will have a direct impact on communications and electronics industries exploiting this part of spectrum. Notable examples include point-to-point backhaul for 5G communications, the IoT, radar sensors for CAVs, space-borne radiometers for Earth monitoring, and security imaging. Improvement of measurement accuracy and establishment of measurement traceability will enable manufacturers to provide confidence in their measurements and specifications. This project will also significantly extend the measurement capabilities of the participating NMIs, to over 1 THz for S-parameter measurement and to 750 GHz for power and material measurement. This will lead to greatly improved access to, and dissemination of, measurement traceability for European accredited testing and calibration laboratories and manufacturers of test instrumentation. This will be beneficial for all end-users, including customers and suppliers of millimetre-wave and THz devices and systems.

The project has setup a Technical Advisory Group, formed of members from end-user industry and metrology communities. Such direct interaction with industry ensures the project aligns with industrial needs and fosters knowledge transfer. The Technical Advisory Group currently comprises 11 end-users from the electronic, instrumentation, semiconductor sectors and 2 NMIs outside of Europe (AIST; Japan and KRISS; Korea). A teleconference with the Technical Advisory Group members was held in January 2020 at LNE (France) alongside with the M9 project meeting.

Impact on the metrology and scientific communities

No single NMI currently has the capability to deliver this project, therefore, this project involves eight of Europe’s NMIs and will synergise their national research programmes. During the project, preparatory tasks are being undertaken to subsequently establish a coordinated network of NMIs, including the NMI of Argentina (INTI), in order to provide a comprehensive measurement capability based on the outcomes of this project, and the previous EMRP project SIB62. This project will also foster the development of three relatively small NMIs (CMI, GUM and TUBITAK) whose metrology programmes are at an early stage of development in the field of electrical measurements. This will be done through their working collaborations with the five experienced European NMIs (i.e. METAS, LNE, NPL, PTB and VSL) in this consortium.

Impact on relevant standards

This project has so far provided inputs to two standardisation bodies, IEEE MTT/SCC (Standards Coordinating Committee) P287 - Standard for Precision Coaxial Connectors (DC-110 GHZ) Sub-committee and IEEE On-wafer Measurements Pre-standardisation Special Interest Group. Additionally, this project expects to make contributions to other standardisation bodies including IEEE MTT/SCC P1785 - A new standard for waveguide above 110 GHz, IEC/TC 46 Cables, wires, waveguides, RF connectors, RF and microwave passive components and accessories SC46F RF and microwave passive components, the BIPM Key Comparison Database, the BIPM database of CMCs, and EURAMET guidance documents on power calibrations and measurements, materials properties measurements, in the range from 110 GHz to 750 GHz.

Longer-term economic, social and environmental impacts

The measurement science generated by this project will pave the way for development of emerging applications including future telecommunications, autonomous vehicles, the IoT, and security imaging. This will enable European businesses to move into these areas and will support a strong competitive advantage. For established applications, e.g. measurement instruments and space radiometers, state of the art performance will ensure a commercial edge and allow European industry in these sectors to continue progress with key technologies and to attract business from global markets.

The social benefits of this project will be to retain a competitive advantage in Europe over worldwide competition on technology and thereby keep and grow expertise and much needed highly skilled electronic engineering and support staff jobs. This project also has wider social impact on quality of life enabled by greater data transport in mobile networks, medical diagnostics using THz imaging, easier and safer mobility using CAV and security scanning in public places such as airports.

Space radiometers play a key role in Earth monitoring, which provides information about global climate change and weather forecasting. This project will facilitate more accurate and traceable measurements at millimetre-wave and THz frequencies, yielding radiometers with better performance. Improved energy efficiency of components and systems will also be supported by more accurate measurements, which will in turn support a reduction in energy consumption and should lead to a more sustainable environment.

List of publications

[1]. R. Judaschke, M. Kehrt, and A. Steiger, Comparison of Waveguide and Free-Space Power Measurement in the Millimeter-Wave Range, 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)
https://doi.org/10.1109/IRMMW-THz.2019.8874235

Project start date and duration:	01 May 2019, for 3 years	
Coordinator: Xiaobang Shang, NPL Tel: 020 8943 6643 E-mail: xiaobang.shang@npl.co.uk Project website address: http://projects.lne.eu/jrp-temmt/		
Internal Funded Partners: 1. NPL, United Kingdom 2. CMI, Czech Republic 3. GUM, Poland 4. LNE, France 5. METAS, Switzerland 6. PTB, Germany 7. TUBITAK, Turkey 8. VSL, Netherlands	External Funded Partners: 9. BHAM, United Kingdom 10. Chalmers, Sweden 11. FVB, Germany 12. ULILLE, France 13. WAT, Poland	Unfunded Partners: 14. Anritsu, United Kingdom 15. FormFactor, Germany 16. INTI, Argentina 17. Keysight BE, Belgium 18. R&S, Germany 19. VDI, United States
RMG -		