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‘Mind the Gap’ . . . Establishing Measurement Capability in the Terahertz Gap Region – from 0.1 THz to 1.1 THz

N M Ridler[1], R G Clarke[2] and M J Salter[1]

[1]National Physical Laboratory, UK; [2]University of Leeds, UK

Abstract

This paper reviews the current state-of-the-art of measurements made using vector network analysers operating in the 0.1 THz to 1.1 THz frequency range. The paper concentrates on the development of three types of measurement capability: (i) in rectangular metallic waveguides; (ii) on-wafer planar circuits; (iii) bulk material characterisations. The paper describes progress to date with establishing this measurement capability and reviews the remaining challenges facing this measurement community.

1. INTRODUCTION

In recent years, there has been a significant increase in the availability of test and measurement equipment operating in the 0.1 THz to 1.1 THz region. This region has traditionally been referred to as the “Terahertz Gap” because it corresponds to a gap, in the electromagnetic spectrum, between the use of electronics capabilities (operating at RF and microwave frequencies) and photonics capabilities (operating at optical frequencies). The extension, into the terahertz gap region, of electronics capabilities based around Vector Network Analysers (VNA) has been mainly responsible for this increase in measurement capability. Photonics-based capabilities – e.g. Time-Domain Spectrometers (TDS) and Fourier Transform Infrared Spectrometers (FTIR) – can also be used in this frequency region. However, they will not be discussed in this paper.

The development of VNA capabilities operating in the Terahertz Gap region has been enabled by the use of external frequency ‘extender heads’ that attach to the base unit VNA; see Fig. 1. The extender heads contain harmonic multipliers for generating the stimulus signals, sub-harmonic mixers used for down-converting the measurement signals, and, signal separation devices (directional couplers). The base unit VNA continues to operate with signals in the 10 GHz to 20 GHz range and provides further stages of frequency down-conversion as required.

The VNA extender heads provide waveguide test ports of the correct size for the frequency range of interest. These waveguide test ports can be used to make measurements in rectangular metallic waveguide or can be used to attach on-wafer probes to enable measurements to be made of devices on planar substrates. A recently new accessory that can be used with these waveguide extender heads is a Materials Characterisation Kit (MCK) that provides an interface between the waveguide test ports and an insertion plane where bulk material samples can be inserted so their materials properties (complex permittivity, etc) can be measured.

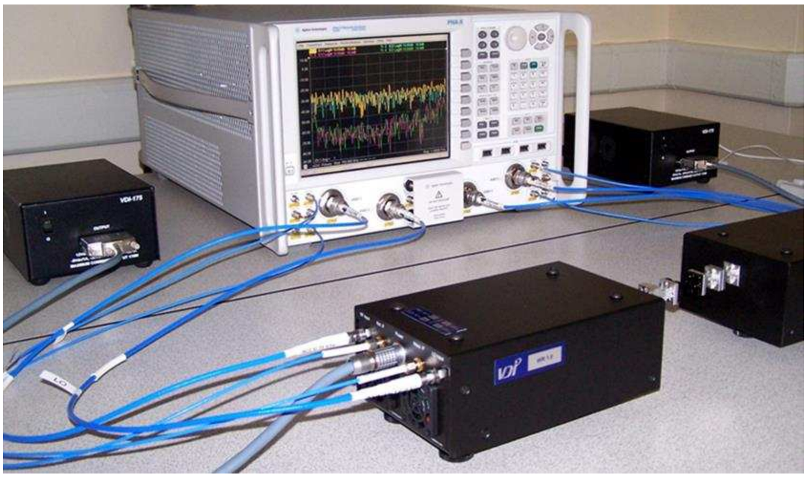

Fig. 1. 1.1 THz VNA located at the University of Leeds. The two "black boxes" in the foreground are the extender heads, shown interconnected with sections of waveguide. The coaxial cables carry lower frequency signals to and from the base unit VNA in the background

This paper reviews measurement capabilities in the above three architectures: (i) rectangular metallic waveguides; (ii) on-wafer planar circuits; (iii) bulk material characterisations. The paper concentrates on primary national standard measurement capability that is currently available at the National Physical Laboratory (NPL) and the University of Leeds. In recent years, NPL and the University of Leeds have established a partnership to provide traceable, accurate, *S*-parameter measurements in the 0.1 THz to 1.1 THz frequency range.

2. RECTANGULAR METALLIC WAVEGUIDES

The use of metallic waveguides for commercial applications goes back to the early/middle part of the 20th century. The first 'popular' waveguide operated from approximately 8 GHz to 12 GHz and corresponded to what is nowadays known as X-band waveguide. The size of the rectangular aperture of this waveguide is 23 mm x 10 mm (0.9″ x 0.4″). As the operating frequency of waveguide is increased, the size of the waveguide aperture decreases. For example, at 200 GHz (i.e. millimetre-wave frequencies), the waveguide aperture size is 1.30 mm x 0.65 mm, and at 1 THz (i.e. submillimetre-wave frequencies), the aperture size is 250 μm x 125 μm – i.e. approximately one hundred times smaller than traditional X-band waveguide.

During the mid-2000s, it was realised that no international standards existed for waveguides, and waveguide flanges, operating in this 'terahertz gap' region – i.e. from 0.1 THz and above. This led to an international effort (sponsored by IEEE) to establish a series of standards for waveguide apertures [1], flanges [2] and performance indications for the combination of waveguide aperture and flange [3]. Commercial companies can now manufacture and specify waveguides for any frequency above 0.1 THz (i.e. 100 GHz) for these types of waveguide.

In parallel with the development of these new international standards, research groups around the world began to develop measurement system capabilities that operated in the terahertz gap region. In the UK, this was achieved through a partnership between the National Physical Laboratory (NPL) and the University of Leeds to provide scattering parameter measurements that were state-of-the-art (in terms of achievable accuracy) and traceable to the International System of units (i.e. the SI). The first such capability operated in the WR-06 waveguide band (from 110 GHz to 170 GHz) [4]. This was followed by capabilities in WR-05 waveguide (from 140 GHz to 220 GHz) [5] and WR-03 waveguide (from 220 GHz to 330 GHz) [6]. The most recent capability established by this partnership covers the WM-250 waveguide band (which covers 750 GHz to 1.1 THz) [7]. This WM-250 facility achieves a dynamic range of typically 60 dB (see Fig. 2(a)) with a measurement uncertainty of approximately 3 dB for a measured attenuation of 30 dB (see Fig. 2(b)). This represents the current state-of-the-art for VNA measurement capabilities at these frequencies.

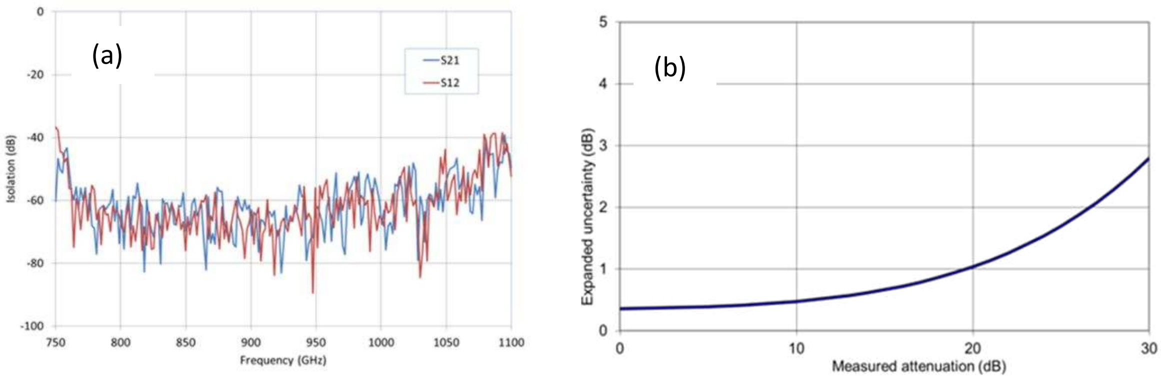

Fig. 2. (a) typical dynamic range for a VNA operating from 750 GHz to 1.1 THz; (b) uncertainty in transmission measurement as a function of measured attenuation

Current challenges with measurements in waveguide in the terahertz gap region include (i) the need to provide traceable measurements for the complete frequency range from 0.1 THz to 1.1 THz; (ii) to provide measurement accuracy / verification techniques for users of VNAs at these frequencies; and (iii) to implement the requirements given in the new IEEE standards [1-3]. Finally, the very latest VNA systems being developed enable measurements to be made at the next higher waveguide band (WM-164) – i.e. from 1.1 THz to 1.7 THz. As the number of users of this waveguide band increases, there will become a need to provide traceable measurements for this waveguide band – e.g. to underpin developments planned with the next generation of radio telescope [8].

3. ON-WAFER PLANAR CIRCUITS

Having established reliable measurements at the waveguide reference planes of the extender heads used with these VNAs, the next step is to use adaptors to transform from the waveguide reference planes to other transmission media. Most electronic components and circuits at these frequencies are fabricated on planar substrates. A probe station and on-wafer probes are needed to do these measurements. A range of on-wafer probes, with waveguide inputs, are now available (from companies such as Cascade Microtech (www.cascademicrotech.com), GGB (www.ggb.com) and Dominion MicroProbes (www.dmprobes.com)) covering all frequencies from 0.1 THz to 1.1 THz; see Fig. 3. However, for on-wafer measurements, it is usually best to calibrate the VNA at the probe tips to remove unwanted errors due to the transition from waveguide to the on-wafer environment. This requires the use of reliable on-wafer reference standards on calibration substrates. At the present time, such standards are not readily available commercially at all frequencies in the terahertz gap region. Some standards are available to 220 GHz. For frequencies above 220 GHz, many end-users are currently faced with developing their own on-wafer reference standards for these types of measurement – see, for example, Fig. 4.

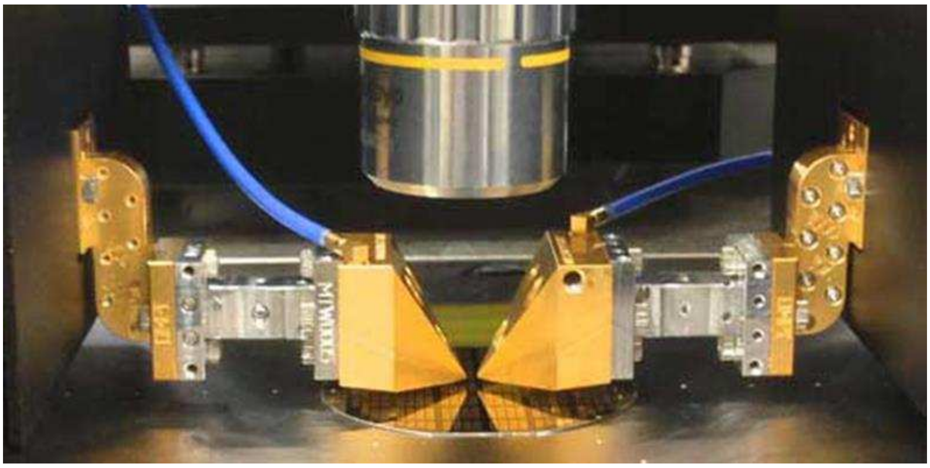

Fig. 3. THz on-wafer probes, available from Dominion MicroProbes Inc

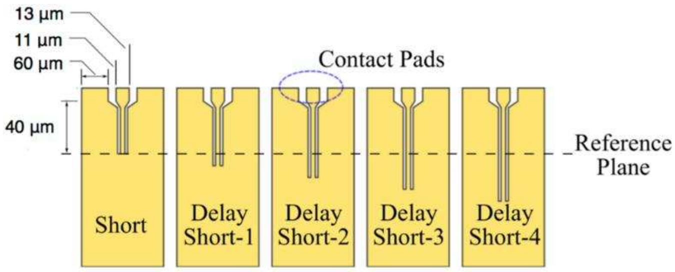

Fig. 4. Custom-made calibration standards, comprising offset short-circuits for use up to 1 THz

On-wafer measurement and calibration above 110 GHz is currently an area of active research. For example, there is a European project, called "Microwave Measurements for Planar Circuits and Components" (called PlanarCal, for short) [9] which includes research topics for measurements above 110 GHz. Both the University of Leeds and NPL are key partners in this project, along with several other European research groups and National Measurement Institutes (NMIs). The contribution to the project from the University of Leeds and NPL includes a comparison of measurements made on-wafer and using split-block waveguides (to 170 GHz), and, a comparison of on-wafer measurements to 220 GHz using commercial calibration substrates. Evaluating the uncertainty in the measurements is a critical aspect of this work.

Current challenges for on-wafer measurements in the terahertz gap region relate primarily to the complete lack of traceability (to SI) for these on-wafer measurements. In addition, there is only limited availability of commercial calibration substrates to cover the full bandwidth to 1.1 THz. As with waveguide measurements at these frequencies, there is a need to provide measurement assurance / verification techniques for users at these frequencies. Finally, research is needed in order to understand electromagnetic phenomena (such as parasitic and other unwanted modes) that is often present in on-wafer measurement set-ups at these frequencies.

4. BULK MATERIAL CHARACTERISATIONS

As well as being able to attach on-wafer probes to the waveguide reference planes of the extender heads used with these VNAs, other accessories can be used to transform the reference planes for other applications. One recent new development is the availability of material characterisation kits (MCK) that attach to the waveguide reference planes on the VNA extender heads. An MCK is needed for each waveguide band to enable complex permittivity measurements to be made at all frequencies in the terahertz gap region. MCKs manufactured by SWISSto12 [10] can measure bulk material samples of thicknesses ranging from 4 mm to 18 mm.

The MCKs utilise low-loss waveguide transitions to transform from the rectangular waveguides of the VNA test ports to enlarged circular corrugated waveguide apertures that are used to form the reference planes for the material samples – see Fig. 5. The MCKs are commercially available, easy to operate, and do not suffer from alignment problems that often compromise the quality of waveguide measurements at these frequencies (since no waveguide flanges are used to connect to the material under test). This relatively new technique is showing much promise and some performance tests have recently been published [11].

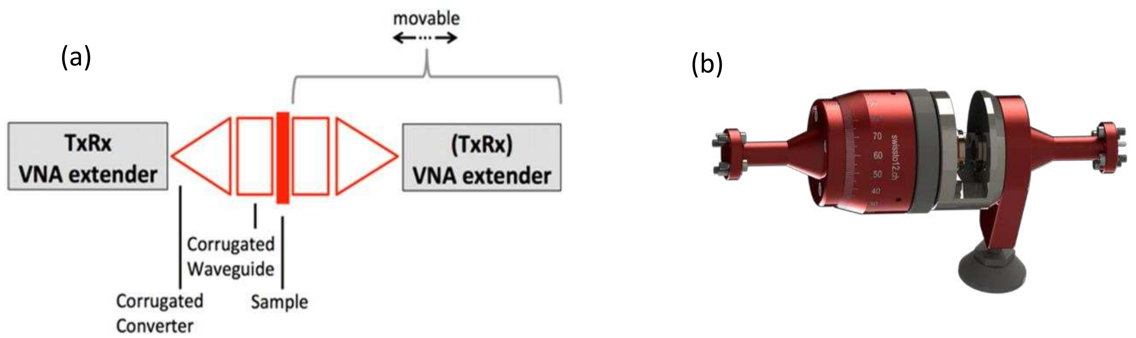

Fig. 5. (a) Schematic diagram of an MCK, shown connected between two VNA extender heads; (b) a typical MCK with waveguide connectors

Current challenges for materials measurements using MCKs include the need to demonstrate reliability of the technique over the complete terahertz gap region. This will include validating these measurements using independent measurement techniques (e.g. using TDS and FTIR), evaluating the measurement uncertainty, and, establishing traceability to SI for the measurements.

5. SUMMARY

Measurements in waveguide, on-wafer and of bulk materials can now be made relatively easily, using commercially available VNAs, at all frequencies in the terahertz gap region (i.e. from 0.1 THz to 1.1 THz). A VNA connected to extender heads forms the basic system and enables measurements to be made in waveguide. Adding on-wafer probes to the extender heads enable the VNA to measure devices on planar substrates. Adding MCKs to the extender heads enable the VNA to measure material properties (complex permittivity, etc) of bulk material samples. Although there are still many measurement challenges to address before this technology becomes routine within our industry, none of these challenges are considered insurmountable and so the future looks bright for reliable, accurate and robust measurements in the 'terahertz gap' region.

ACKNOWLEDGEMENTS

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