Recent and Future Developments in Millimetre and Sub-millimetre Wavelength Measurement Standards at NPL[1]

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1. INTRODUCTION

With the rapidly growing interest in millimetre-wave and sub-millimetre-wave systems, the lack of traceability for measurements at these wavelengths is becoming ever more of a problem. Making comparable measurements of fundamental parameters, such as power, is very difficult and no proper calibrations traceable to SI realisations are available. At NPL, work undertaken in the 1980s led to the development of the photo-acoustic power meter by QMC, London (now marketed commercially by Thomas Keating) but this does not easily address measurements of power in waveguide. NPL also has comprehensive standards (power, *S*-parameters, noise and attenuation) in waveguide up to 110 GHz but nothing (until recently) at higher frequencies.

There is a clear need to provide standards of measurement for higher frequencies. Members of the UK Millimetre-wave Users Group (www.npl.co.uk/mm-wave) have stated that standards for power and complex-valued *S*-parameters are the most important and should be developed first, followed by noise.

1.1. Complex-valued S-parameters

NPL are working on standards for complex-valued *S*-parameters in the following bands:

- WR-06 – 110 GHz to 170 GHz;
- WR-05 – 140 GHz to 220 GHz;

and plans are in place to extend this to 325 GHz, then 500 GHz (and perhaps above) in metallic rectangular waveguide.

However, *S*-parameter standards based on conventional waveguide are less than ideal, and our work also includes the development of more suitable primary standards while recognising that many practical measurements will take place in waveguide. Significant work has been undertaken to investigate the use of dielectric waveguides as calculable standards with the intention that the use of them will meet industry needs.

NPL is also leading an IEEE initiative to standardise waveguide sizes and flanges for the sub-millimetre-wave region – it is expected that this will form a new IEEE standard (see http://grouper.ieee.org/groups/1785 for more details).

Finally, in the area of *S*-parameter measurements, NPL is leading a round-robin measurement comparison programme in metallic rectangular waveguide at frequencies from 110 GHz to 170 GHz. This exercise currently has nine participants from Europe and the USA - more participants are welcome. This comparison will provide a valuable indication of the current state-of-the-art for these measurements.

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1.2. Power Standards

Power standards in many of the world's National Metrology Institutes (NMIs) have historically been based on thermistor power sensors, which are not commercially available at present (except for low frequencies). Nonetheless, NPL has recently built a new primary standard system based on thermistor power sensors for the band 75 GHz to 110 GHz and this project has enhanced NPL's millimetre-wave capability. It is our intention to develop these systems (using alternative sensors) initially to 170 GHz and eventually to 325 GHz and we expect the first of these capabilities to be in place before 2012. It is likely that the uncertainties will be higher than for lower frequencies but it is hoped that the increase in uncertainty will be reasonably in line with the increases in uncertainties that occur at lower frequencies.

1.3. Noise Standards

Noise standards are required for measurement of receiver noise temperatures and NPL also plans to develop noise standards and radiometers, initially in the 90 GHz to 140 GHz band.

2. COMPLEX-VALUED *S*-PARAMETERS

2.1. Traceability for Complex-valued *S*-parameters to 220 GHz

NPL has established traceability for complex-valued *S*-parameters up to 170 GHz with work underway to extend this. A full uncertainty treatment for the system up to 170 GHz has been developed and is given in [1] and the measurements made on the system are fully traceable to SI base units. The system makes use of hardware belonging to the University of Leeds and software and traceability provided by NPL. Work is underway to cover frequencies up to 220 GHz and plans are in place to extend the work – first, up to 325 GHz, then, up to 500 GHz.

The calibration scheme used is a TRL scheme using two different line lengths [2]. At high frequencies, choosing a line length that provides suitable phase changes across the waveguide band, while being large enough to be mechanically robust, becomes impossible since a line of length $\lambda/4$ at the mid-band frequency is too short to be robust. The use of an LRL scheme would avoid this difficulty but would introduce problems of its own – in particular, the dimensional tolerances on the waveguide size mean that the *S*-parameters of the first "line" are not truly known which is an essential pre-requisite for the calibration scheme. The NPL scheme circumvents these difficulties by using two lines, one for the lower half of the waveguide band and the other for the upper half. In each case the length is chosen to be approximately $3\lambda/4$ for the mid-point of the waveguide sub-band for which that standard is used.

2.2. Alternative realisations of primary standards for Vector Network Analyzer (VNA) calibrations

It is important to note that, although TRL (and LRL) calibration schemes using metallic waveguides are an acceptable calibration scheme, other techniques are possible and may offer advantages at higher frequencies. NPL has carried out significant work looking at dielectric waveguides to provide the actual calculable calibration artefacts for use with VNAs. This work has been previously reported, for example in [3]. The most important benefit offered by dielectric waveguide standards is that the sensitivity to small dimensional errors is a great deal less than in metallic waveguides [4], [5]. For a more complete description of this aspect of NPL's work, the interested reader is referred to the references.

NPL's plans include further work in dielectric waveguides and in other types of wave guiding structures.

2.3. Standard waveguide sizes above 325 GHz

For any sub-millimetre wavelength application, it is necessary to have agreed, standardised sizes for the metallic waveguides used. Agreed standards exist up to 325 GHz [6], [7]. Two proposals to define waveguide sizes above 325 GHz exist, each having their own advantages and disadvantages. The proposal by Hesler [8], is a straightforward extension of the existing schemes but it is not based on SI units. The proposal by Ward [9], is based on SI units but is not a simple extension of existing schemes. NPL chairs a recently formed IEEE Working Group (P1785 [10]) and the scope of this group includes both the waveguide sizes and the flanges (i.e. interfaces) of those waveguides. Reference [11] describes a proposal which utilises SI units, has a naming convention derived from existing naming conventions and which produces waveguide sizes which are compatible with existing definitions. The scope of this proposed definition extends from 325 GHz to 3.3 THz. Recognising that waveguides following the Hesler definitions are already in use (for example, [12]), the mismatch between the proposed waveguide sizes and the Hesler sizes has been calculated and found to be better than -30 dB return loss.

3. POWER STANDARDS

The present state-of-the-art in power metrology is that, at NMI level, power standards only exist up to 110 GHz until the infra-red and optical regions are reached. One type of power meter recognized as being traceable was developed at Queen Mary College, University of London, in the 1980s under a contract from NPL and is now available commercially from Thomas Keating Instruments Limited [13]. Comparisons of its performance against more conventional power standards were carried out at 94 GHz [14]. This power meter has two main disadvantages in practical use, it is relatively insensitive and it is not suited to making measurements of power in waveguides.

Standards for power metrology at frequencies up to 110 GHz in waveguide (and coaxial line) are based on calorimeters in several NMIs around the world. The NPL systems are well described in [15]. NPL's systems are based on the use of thermistor power sensors, originally manufactured by Hughes and subsequently by Millitech. These sensors were designed to be compatible with an HP (now Agilent) 432A power meter and they are very well suited to use as primary standards, in particular, they operate in a self-balancing DC bridge that allows reference to DC power and they feature excellent linearity. Unfortunately, it is many years since Millitech ceased production of these sensors. Sensors up to 110 GHz can be obtained (with some difficulty) on the second-hand market but sensors above that frequency are extremely rare (very few, if any, were made).

3.1. Transfer instruments

Once calibrated thermistor sensors are obtained using the calorimeter (a slow process due to the thermal mass of the sensors) it is normal to use a transfer instrument to calibrate a customer's sensor (which can be based on any technology) in terms of the known efficiency of the calibrated thermistor sensor. In order to determine the calibration factor, the reflection coefficient must also be measured. At NPL this is done using a multistate reflectometer [16], which can be considered a one-port network analyser. This instrument is easy to implement (it requires only couplers, a movable short-circuit and two linear power sensors), easy to calibrate (three short-circuits with different offsets and a 'perfect' load, synthesised by using an imperfect load with three different offsets) and, since the circuit includes an output coupler which provides a measure of forward going power, it is easy to take ratios of the power indicated at the measurement port (by the calibrated thermistor sensor) and the power indicated on the output coupler which means that the instrument is excellently suited to use as a transfer instrument.

3.2. Recent power metrology systems at NPL

Recently, NPL undertook the construction of a new calorimeter and a new multistate reflectometer transfer instrument, on behalf of a third party, operating in the 75 GHz to 110 GHz band. New design features were incorporated in the calorimeter and its performance exceeds the performance of the NPL system. The new calorimeter uses Millitech sensors as the sensing element and the multistate reflectometer transfer instrument uses the same type of sensor for the two linear sensors required.

Previous NPL waveguide calorimeters have been single-load calorimeters with the sensor under test mounted on a measurement flange, which is surrounded by an annular reference ring. A thermopile between the measurement flange and the reference ring detects temperature changes on the measurement flange. The thermal paths from the outside of the calorimeter to each of the measurement flange and the reference ring are intended to be approximately equal so that ambient fluctuations reach both equally and therefore give rise to no temperature difference. In practice, it has always proved difficult to properly achieve this thermal balance and, instead, the new design utilises two loads (i.e. two identical sensors on identical measurement flanges) with a thermopile between them.

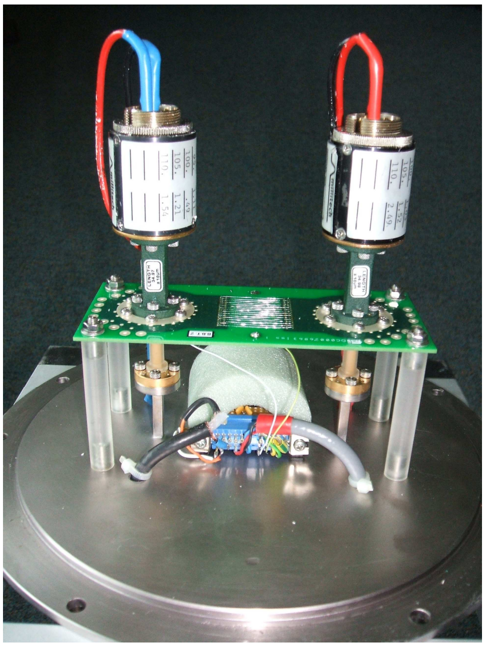

Fig. 1. Photograph of twin-load calorimeter

The new calorimeter design shows improved performance, particularly in terms of the measurement time. It is straightforward to build and to use and it is anticipated that developing similar systems in higher bands will be possible. The new design requires a sensor based on a thermistor mount operating in a self-balancing bridge. Since these are no longer available commercially, for high frequencies, NPL plans to develop new sensors of this type and this work is described in the next section.

3.3. New sensors

NPL is investigating new thermistor based sensors with the intention of developing sensors suitable for metrology for frequencies up to 325 GHz and potentially beyond. The expectation is that the thermistor based sensors will be linear and capable of operation in a similar manner to those used at lower frequencies. Good linearity will allow them to be used in a multistate reflectometer transfer instrument as well as sensing elements in a calorimeter which will allow NPL to develop a complete calibration system. Initially, the 110 GHz to 170 GHz band will be targeted, with plans to go above this frequency as demand becomes demonstrable.

4. NOISE STANDARDS

Most noise measurement systems at NMIs use a thermal noise standard as the primary reference. These can be hot or cold and historically, most such devices at NPL have been hot, operating at about 400 °C (673 K) although cold standards operating under liquid nitrogen have also been used at lower frequencies. NPL worked with ESOC to perform accurate measurements of complex amplifier noise for LNAs operating at liquid helium temperatures and cold standards were used for this work. At higher frequencies, accurate characterisation of a noise standard becomes very dependent on the accurate measurement of the loss of the interconnecting waveguide and this means that the uncertainty increases for small waveguide sizes. Partly to address this, standards utilising a horn antenna were developed at NIST [17]. More recently, similar designs have been developed commercially [18]. In standards of this type, the absorber is cooled to liquid nitrogen temperature and the "connection" between the absorber and the waveguide output port is achieved through free-space using a calibrated horn antenna. NPL intends developing a standard of this sort, starting with the 90 GHz to 140 GHz band which will allow comparison with the existing 75 GHz to 110 GHz system.

5. CONCLUSION

This paper has given a brief overview of existing work above 110 GHz, recent work up to 110 GHz which serves as a foundation for extension above 110 GHz and future plans for work up to 500 GHz. NPL's work is supported and funded largely as a consequence of demonstrable needs in industry and it is therefore important that we are able to obtain support from industry for our plans. NPL therefore welcomes feedback on these plans and collaboration in our work so as to ensure that the standards of measurement that are developed provide a real benefit to users and industry.

6. ACKNOWLEDGEMENTS

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