Abstract: Currently, the UK’s national standards for impedance measurements are only available for frequencies up to 50 GHz in a coaxial line and 110 GHz in a metallic rectangular waveguide. No standards exist above these frequencies. A need to provide measurement standards and measurement assurance above these frequencies has led to research into a new form of impedance standard for precision metrology applications across the entire millimetre-wave band and perhaps beyond (i.e. extending to at least 300 GHz). We report the development of the new standards and other devices that utilise a dielectric waveguide as the transmission medium, and we show how these standards can be used to calibrate measuring instruments, such as vector network analysers (VNAs), and to provide traceability to national standards.

1 Introduction

The millimetre-wave part of the electromagnetic spectrum, extending from 30 to 300 GHz, forms a vital resource, both scientific and commercial, for a wide range of applications. These applications include active radar (used for both military and civil applications), radiometry (i.e. passive radar or imaging) and communications (e.g. short-range wireless links etc.), see, for example, [1–3]. As these applications become more mature, precise measurement reference standards become essential to ensure meaningful interpretation of specifications and performance figures for these technologies.

Conventional RF and microwave transmission lines (i.e. coaxial lines and metallic rectangular waveguides) are not well suited for measurement standards applications across this frequency band. For example, precision coaxial connector technology has only been developed, to date, up to 110 GHz [4], and existing metallic rectangular waveguides are unlikely to be suitable for high-precision metrology applications above 110 GHz [5]. This is owing primarily to the physical size of these standards (needed to ensure monomode propagation) becoming too small to be manufactured reliably and the necessary dimensional accuracy not being easy to achieve. The conductor losses and connection reliability of these standards also create severe difficulties for precision metrology applications. This has opened up demands for new forms of impedance standards at these frequencies [6].

An alternative transmission line suitable for use at millimetre wavelengths is the dielectric waveguide. This form of transmission line has several advantages over the existing transmission lines used for standards applications. First, the necessary mechanical sizes and tolerances of the dielectric waveguide dimensions are easier to maintain. Also, as these dimensions correspond to the external boundaries of the waveguide, they are easy to verify using simple mechanical measurement techniques. Secondly, owing to the absence of metallic conductors, the transmission losses are much smaller than those in metallic transmission lines. Finally, the connection between a pair of dielectric waveguides is less dependent on accurate alignment of the conductors and therefore provides more reliable connections.

There are several tasks necessary to the design of new forms of impedance standards using dielectric waveguides. First, it is necessary to choose a suitable material to form the dielectric waveguide transmission lines. Secondly, transitions from metallic rectangular waveguides to dielectric waveguides must be designed to enable suitable test port reference planes for the measuring instrument (i.e. either commercially available vector network analysers (VNAs) or some other form of reflection/transmission measuring instrument; see, for example, [7]) to be formed. Finally, a range of ‘known’ standards must be fabricated suitable for performing high-accuracy calibrations of the measuring instrument.

This paper describes the work undertaken on all these tasks to date. This work has concentrated on the frequency band from 75 to 110 GHz, so that developed measurement capabilities can be compared directly with existing national standards in metallic rectangular waveguides at these frequencies [8]. If this comparison is favourable, the longer-term goal is to extend these methods to encompass the entire millimetre-wave region (to 300 GHz) and probably beyond.

2 Selection of dielectric material

For precision metrology applications, the selection criteria for the dielectric material are: low dielectric loss at the
frequencies of interest; suitable mechanical properties (in terms of rigidity and mechanical machining capabilities); and low coefficient of thermal expansion, thus ensuring the stability of any assumed mechanical dimensions. Many materials were considered during the initial selection process, leading to the following six materials being studied in detail: polyetheretherketone (PEEK), polytetrafluoroethylene (PTFE), polypropylene (PP), cross-link polystyrene (Rexolite), high density polyethylene (HDPE) and polymethylpentene (TPX).

Figure 1 shows loss measurements (in terms of $S_{21}$) for four of these materials. In this simple comparative study, the measurements were performed using an uncalibrated system, which, in this case, consisted of an HP8510 VNA. Therefore the resonances, or ripples, seen in the measurement results could be caused by errors, imperfections, or mismatches in the system, which could all be removed if the system were fully calibrated, i.e. the reference plane being established at the end of the measurement port. PEEK was found to have very high loss at these frequencies, i.e. typically up to 20 dB even for short lengths of line (e.g. 100 mm). Both PTFE and HDPE exhibit very low dielectric loss. However, PTFE is not sufficiently mechanically rigid to be used to fabricate impedance standards reliably. Although HDPE is sufficiently rigid, it has a high thermal coefficient of expansion and can change shape easily with external force, and thus it is not robust enough against accidental pressing or bending when a connection is made.

The mechanical properties, in terms of rigidity and machining capabilities, of TPX and Rexolite are very good, but their dielectric loss increases with frequency, and so they are unlikely to be suitable as standards above 110 GHz. This reduces the choice of material to just PP, which has low loss and reasonable rigidity and possesses an acceptable coefficient of thermal expansion. Polypropylene was therefore chosen as the material to be used to form the dielectric transmission lines and standards. Table 1 summarises the properties of the materials that were studied in detail.

### 3 Rectangular waveguide to dielectric waveguide transition

A transition has been designed to optimise the energy coupling between metallic rectangular waveguide ports, which are usually found on measuring instruments at these and higher frequencies, and the required dielectric waveguide reference planes. There are two parts to the transition: first, there is a dielectric taper inside a uniform section of rectangular waveguide that improves matching between air-filled and dielectric-filled rectangular waveguides; secondly, there is a standard, off-the-shelf, waveguide horn that helps to shape the field from a dielectric-filled metallic waveguide to a pure dielectric waveguide. Figure 2 shows the different types of dielectric taper that have been studied.

The performance of these designs was assessed using 3D electromagnetic simulation (CST Microwave Studio). As an example, Fig. 3 shows the predicted return loss for each taper design. In each design, the cross-sectional dimensions of the dielectric waveguide have been chosen to be the same as the dimensions of the metallic rectangular waveguide (Known, as either WG27, R900, WR10 or W-band waveguide), i.e. $2.54 \text{mm} \times 1.27 \text{mm}$, and the relative permittivity of the dielectric material (of PP in this case) was set to be 2.3. The losses in the dielectric material and in the metal were assumed to be zero.

These simulations show that the H-plane asymmetric taper gives the best overall performance, because it does not bend the E-field in the dominant waveguide TE_{01} mode and it has the minimum number of dielectric interfaces, which could otherwise cause multiple entries of the wave as it propagates in and out of the dielectric, thus causing multiple reflections and refractions. Therefore tapers of this design have since been constructed and used as the VNA reference planes.

### 4 Calibration standards and calibration schemes

For a measuring instrument to be reliable, it must first be calibrated using standards with known properties. In the case of a VNA (or similar impedance-measuring instrument), these standards provide known, or partially known, values of reflection and/or transmission and are attached to the VNA measurement reference planes so that the system error terms (e.g. directivity, tracking, test port match etc.)

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**Table 1: Materials that were considered for use as dielectric waveguide transmission lines**

<table>
<thead>
<tr>
<th>Name</th>
<th>Dissipation factor $\tan \delta$ (published values at RF)</th>
<th>Coefficient of thermal expansion ($\times 10^{-6} \text{K}^{-1}$)</th>
<th>Rigidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyetheretherketone (PEEK)</td>
<td>0.003 at 1 MHz</td>
<td>47–108</td>
<td>good</td>
</tr>
<tr>
<td>Polytetrafluoroethylene (PTFE)</td>
<td>0.0003–0.0007 at 1 MHz</td>
<td>100–160</td>
<td>poor</td>
</tr>
<tr>
<td>Cross-link polystyrene (Rexolite)</td>
<td>0.0002 at 1 MHz</td>
<td>70–90</td>
<td>very good</td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>0.0003–0.0005 at 1 MHz</td>
<td>100–180</td>
<td>fair</td>
</tr>
<tr>
<td>High density polyethylene (HDPE)</td>
<td>0.0001–0.0001 at 1 MHz</td>
<td>100–200</td>
<td>poor</td>
</tr>
<tr>
<td>Polymethylpentene (TPX)</td>
<td>0.0002 at 1 kHz</td>
<td>117</td>
<td>very good</td>
</tr>
</tbody>
</table>

Data are obtained from [9]
can be determined [10]. In principle, all the popular VNA calibration techniques used for coaxial lines, rectangular waveguides and other transmission media (see, for example, [11, 12]) can be implemented in dielectric waveguides. In the simplest case, three standards with known reflection coefficient are attached to each of the VNA’s measurement reference planes that requires calibration.

To test this approach, a series of six standards have been designed and built using different lengths of dielectric waveguide (0.000, 2.435, 3.632, 4.561, 5.100 and 5.590 mm), each terminated with a precision short circuit (formed using a flat sheet of high-conductivity metal placed across the end of the waveguide). The lengths of these dielectric waveguide ‘offset short circuits’ are chosen to provide different phase separations in the complex reflection coefficient plane. To illustrate this, Figs. 4a and b show the achieved phase separation for these six standards at 75 GHz and 110 GHz, respectively. This enables different ‘known’ values of reflection to be available at each frequency so that the calibration can be performed. The selection process for choosing the standards can be an ‘adaptive’ approach [13] whereby the calibration algorithm chooses the best three standards at each given frequency. (The term ‘best three standards’ is used here to describe the collection of three standards that provides phase separations between each pair of standards closest to the optimum value of 120°.) For example, from Fig. 4a, a good choice of standards is likely to be the 2.435, 5.100 and 5.590 mm offsets, whereas the 0.000 and 3.632 mm standards would not be used, as their values in the complex plane at 75 GHz are almost identical. This ‘problem’ is not present in the position of the standards in Fig. 4b, where there is good spacing between all six standards. Alternatively, a method that uses all standards simultaneously and employs regression techniques to improve the overall accuracy of the determination of the calibration coefficients can be used [14].

The six standards that have been constructed are attached to the VNA measurement reference plane in a computer-driven rotating wheel arrangement, as shown in Fig. 5. This arrangement allows the standards to be connected very easily and without the need for accurate alignment of the standards each time they are connected: this alignment is performed once-and-for-all during the initial setting up and positioning of the standards. The arrangement also allows a form of ‘automatic calibration’ to be achieved, whereby the standards attached to the wheel can be connected and measured automatically by the VNA during calibration. This means that calibrations can be performed very quickly (and, hence, very cost-effectively), are highly repeatable, and do not require the operator to make manual connections and alignments of the standards.
Tables and figures

Table 2: Expected size of errors in reflection coefficient for standards in dielectric waveguide at 75 GHz and values for the equivalent rectangular metallic waveguide, for comparison

<table>
<thead>
<tr>
<th>Transmission medium</th>
<th>Random errors due to connection repeatability</th>
<th>Systematic errors due to connection misalignment</th>
<th>Combined standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric waveguide</td>
<td>0.003</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>Rectangular metallic waveguide</td>
<td>0.007</td>
<td>0.006</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Fig. 5 Photograph showing the rotating wheel arrangement used to connect to standards to the VNA’s measurement reference plane

The reference plane extends beyond the waveguide horn used as part of the transition

(as is usually the case during conventional calibration techniques in other transmission media).

In addition to the above standards, self-calibration schemes, such as thru-reflect-line (TRL) [13], line-reflect-line (LRL) [16], thru-reflect-match (TRM) and line-reflect-match (LRM) [17, 18], are also currently under consideration with the above system. For such calibration schemes, either a length (or several lengths) of dielectric waveguide and/or a matched load are used as the impedance references for the calibration. This may provide a further reduction in the overall uncertainty of the measurement system.

5 Predicting instrument performance

The performance of a VNA (or similar measuring instrument) is primarily dependent on the quality of the standards used during the calibration process. In particular, errors in the calibration standards translate into errors in the achieved measurements made by the calibrated VNA.

To assess the performance of a VNA calibrated using the above standards, it is first necessary to provide estimates for the errors in the calibration standards. These errors will be both random and systematic in nature. Random errors result from effects such as the connection repeatability of the standards to the VNA test ports, and systematic errors occur owing to the less-than-perfect dimensions and misalignment of the standards.

Table 2 gives estimates for these errors in terms of the linear reflection coefficient at 75 GHz for the dielectric waveguide standards discussed in this paper. Values for the equivalent metallic rectangular waveguide standards are also given for comparison purposes. In both cases the estimates for the random errors, expressed as standard deviations in the mean (i.e. standard uncertainties), are based on experiments performed in the laboratory. The

estimates for the systematic errors are based on experience and published data [19, 20] for misalignment errors (i.e. taken here to be 50 μm displacements in both the E- and H-planes of the waveguides) for the standards with respect to the measuring instrument test port.

Table 2 also gives an estimate of the combined standard uncertainty, for each standard in both types of waveguide, resulting from these errors. These uncertainty estimates have been established following accepted methods [21], i.e.

(i) convert the systematic error estimate to the equivalent standard uncertainty, by dividing by \( \sqrt{3} \) (i.e. assuming that a uniform distribution, with upper and lower limits equal to the size of the error estimate, characterises the error estimate)

(ii) combine, in quadrature, the standard uncertainty due to the systematic error estimate with the (standard uncertainty) estimate due to the random errors.

The uncertainty in phase will vary as a function of the measured magnitude of the reflection coefficient. As a rule of thumb, it can be estimated by \( u(\phi) = 2u(\Gamma)|\Gamma| \) where \( u(\phi) \) is the uncertainty in phase, \( |\Gamma| \) is the measured magnitude of the reflection coefficient, and \( u(\Gamma) \) is the uncertainty in the magnitude of the reflection coefficient. For example, \( u(|\Gamma|) \) of a dielectric waveguide short circuit (with \( |\Gamma| = 1 \)) is approximately 0.003 at 75 GHz, and so \( u(\phi) \) will be approximately 0.17°.

From the values given in Table 2, it is clear that both random and systematic errors are smaller for dielectric waveguide standards compared with equivalent standards in metallic rectangular waveguides. It is also clear that this leads to uncertainties in the dielectric waveguide standards that are smaller by almost a factor of three compared with equivalent standards in metallic rectangular waveguides.

The values for the uncertainty in the calibration standards, given in Table 2, can be used to predict the subsequent uncertainty of measurement for a measurement system calibrated using these standards [22]. This leads to an uncertainty profile over the complex reflection coefficient measurement plane, as shown in Fig. 6. This figure shows that, for standards that are nominally separated by 120°, the range of (standard) uncertainty for a VNA calibrated using the dielectric waveguide standards described in this paper will be from 0.003 to 0.005 in terms of the measured linear magnitude reflection coefficient. An uncertainty of 0.003 is achieved at the points in the complex plane defined by the position of the calibration standards and for a broad surrounding region of the plane that includes the origin (i.e. the ‘matched’ condition). The uncertainty rises as the measured reflection coefficient moves away from the positions of the calibration standards around the circumference of the unit disc. The maximum uncertainty of 0.005 occurs at 60° away from the calibration points.

\[ u(\phi) = \sin^{-1}\left(\frac{u(|\Gamma|)}{|\Gamma|}\right) \]
Although the uncertainties given in Table 2 have not been established using a full uncertainty budget, the resulting uncertainty values (for the metallic rectangular waveguide) compare favourably with values published elsewhere [8] for a (national standard) measurement system calibrated using metallic rectangular waveguide standards. (The uncertainties quoted in [8] refer to measurements of relatively low-reflecting devices, whereas the uncertainties referred to in Table 2 refer to high values of reflection (i.e. short circuits). In general, uncertainties have a tendency to increase as the measured value of reflection increases. This needs to be taken into account when uncertainties from different sources are compared.) This is likely to be owing to over-estimation (i.e. exaggeration) of the likely error due to misalignment of the standards, and thus compensation for the neglect of other components from the uncertainty budget (e.g. a component of uncertainty needed to take into account the less-than-perfect dimensions of the standards).

Finally, it is expected that the performance of the dielectric waveguide standards, when compared with equivalent standards in metallic rectangular waveguides, will improve as the frequency extends beyond 110 GHz. This indicates that standards realised from dielectric waveguides should be the preferred choice for the calibration of VNAs and other similar measuring instruments operating over the entire millimetre-wave region.

6 Conclusions

This paper has presented work undertaken to realise new impedance measurement capabilities, based on a dielectric waveguide as the transmission medium, suitable for use across the entire millimetre-wave band (i.e. to 300 GHz and beyond). This work has involved: choosing suitable material for the manufacture of dielectric waveguide components for these frequencies; designing and fabricating transitions to act as test port reference planes for impedance measuring instruments (such as VNAs etc.); designing and realising measurement standards and calibration schemes for these measuring instruments; and predicting post-calibration uncertainty profile for reflection coefficient measurement plane based on calibration using three offset standards

Fig. 6 Uncertainty profile for reflection coefficient measurement plane based on calibration using three offset standards

instrument performance (in terms of the uncertainty of measurement).

The work has concentrated on providing measurements at frequencies up to 110 GHz, where other measurement instrumentation is currently available, based on metallic rectangular waveguide transmission lines. This has enabled performance comparisons to be made between the two types of measurement system. These comparisons have shown that the dielectric waveguide systems are superior in that they are likely to be up to three times more accurate than the existing primary national standard measurement systems using metallic rectangular waveguide standards [8]. It is also expected that the performance of the dielectric waveguide standards will further improve (when compared with the equivalent metallic rectangular waveguide standards) as the frequency extends above 110 GHz, and so this indicates that the dielectric waveguide standards should be the preferred choice for primary national impedance standards for the entire millimetre-wave region to 300 GHz and perhaps beyond.

To reduce the uncertainty of measurement, more work is required to gain a better understanding of the whole system and the characteristics of the dielectric waveguide, such as propagation constant and characteristic impedance etc. This work can be extended to the measurement of other forms of dielectric waveguide, such as integrated dielectric waveguides, non-radiation dielectric waveguides and photonic bandgap structures etc.

7 Acknowledgment

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8 References

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