Using Electromagnetic Modeling to Evaluate Uncertainty in a Millimeter-wave Cross-guide Verification Standard

Hui Huang\(^1\)* N M Ridler\(^2\) and M J Salter\(^2\)

\(^1\)National Institute of Metrology, China; \(^2\)National Physical Laboratory, UK;

*Visiting researcher - National Physical Laboratory, UK;

Abstract — This paper describes some investigations, made using electromagnetic modeling, into the uncertainty for a cross-guide verification standard of transmission loss for waveguide Vector Network Analyzers (VNAs) operating at millimeter-wave frequencies. The cross-guide is calculable and can be made traceable to the International System of units (SI) via precision dimensional measurements of the waveguide aperture and flange. The measurement errors due to dimensional tolerances of the cross-guide line (including waveguide aperture height, width, corner radii and waveguide line length) and the mechanical discontinuity between the cross-guide and the VNA test ports (including the connection angle) can be predicted from electromagnetic theory. The measurement uncertainty due to these errors can be calculated according to the Law of Propagation of Uncertainty. The paper describes these details, and compares experimental results, obtained using a VNA operating in the 140 GHz to 220 GHz band, with simulated values evaluated by electromagnetic modeling software.

Index Terms — Uncertainty, Traceability, Cross-guide, Transmission loss measurements, Verification standard, Electromagnetic modeling, Millimeter-wave measurements.

I. INTRODUCTION

In recent years, there has been a significant increase in the availability of millimeter-wave rectangular waveguide Vector Network Analyzers (VNAs). With this increase comes a need for verifying the performance of these VNAs at these operational frequencies. Traditionally, this has been done in waveguide at lower frequencies using VNA waveguide verification kits containing devices such as sections of precision waveguide (with close to zero reflection and transmission loss) and sections of reduced-height waveguide (with significant reflection and transmission loss). However, to further reduce the height of such waveguide becomes difficult to manufacture, and ensuring the accuracy is mechanically challenging in the extreme at high millimeter-wave frequencies. At the present time, NMIs do not provide attenuation standards at frequencies above 110 GHz, and the transmission loss is still not traceable to the SI. During 2013, a new form of ‘calculable’ device was introduced as a candidate for primary standards applications. This verification standard is simply a section of precision waveguide that is connected so that the waveguide aperture is at right-angles to the usual connection orientation of the waveguide. A diagram illustrating this connection strategy for the waveguide apertures is shown in Fig. 1. We call this type of device a ‘cross-guide’ standard [1]-[3].

Fig. 1 Diagram to illustrate a section of cross-guide inserted between two conventionally-oriented waveguides [1]-[3]

The performance of a cross-guide device as a verification standard is calculated from its waveguide aperture and flange sizes. Hence, it can be made traceable to the SI via precision dimensional measurements. This paper analyzes the impact on the measurement performance of the cross-guide device due to the imperfection in the interface between the cross-guide and the VNA test ports, including the tolerance of the aperture height and width, corner radii, line length and connection angle. These measurement errors are predicted from electromagnetic theory according to the values suggested in the IEEE std 1785.1-2012 standard [4], using electromagnetic simulation software – in particular, CST Microwave Studio [5]. The measurement uncertainty due to these errors is calculated according to the Law of Propagation of Uncertainty [6].

This paper presents experimental results obtained for a cross-guide line in the WR-05 waveguide size at frequencies from 140 GHz to 220 GHz, this being the conventional operating band for this waveguide size. These results are compared with the electrical performance predicted using electromagnetic modeling software.

II. DIMENSIONAL MEASUREMENTS ON CROSS-GUIDE

Traceability for S-parameter measurements is established via precision dimensional measurements of the waveguide aperture and flange. The measurements of the cross-guide
waveguide aperture size, e.g., width and height, are made using a coordinate measuring machine (CMM) with a 0.3 mm diameter ball tip micro-stylus. This process is used to characterize WR-05 line standards [7] [8]. The length of the cross-guide is measured by micrometer. The connection angle between the cross-guide and the VNA test ports is predicted based on a conventional UG-387 flange [9]. The nominal values for the aperture width and height are 1.295 mm and 0.6475 mm. The measured values can be summarized in terms of the maximum observed deviation from the nominal dimensions of the cross-guide. The summary values are shown in TABLE I.

### TABLE I
**DIMENSIONAL MEASUREMENTS FOR CROSS-GUIDES**

<table>
<thead>
<tr>
<th>Cross-guide Dimension</th>
<th>Results</th>
<th>Max Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, ( a )</td>
<td>1.295 mm</td>
<td>13.8 ( \mu )m</td>
</tr>
<tr>
<td>Height, ( b )</td>
<td>0.6475 mm</td>
<td>3.5 ( \mu )m</td>
</tr>
<tr>
<td>Length, ( l )</td>
<td>1.478 mm</td>
<td>5 ( \mu )m</td>
</tr>
<tr>
<td>Angle, ( \Phi )</td>
<td>90°</td>
<td>0.4°</td>
</tr>
</tbody>
</table>

III. ELECTROMAGNETIC SIMULATION OF CROSS-GUIDE

The electromagnetic characteristics of the cross-guide as a verification standard are calculated from its waveguide aperture and flange sizes. Hence, it can be traceable to the SI via precision dimensional measurements. These dimensions are: aperture height, width and corner radii, line length, and the mechanical discontinuity between the cross-guide and the VNA test ports due to the connection angle. For a cross-connected waveguide, the width and corner radii of the aperture are assumed to have no significant influence for transmission loss measurements and so are not included in the simulation. The other dimensions will affect the electromagnetic measurements. The summary tolerance values of the cross-guide are shown in TABLE II. In TABLE II, tolerances of height are suggested in the IEEE std 1785.1-2012 standard, tolerances of length are due to the likely dimensional measurements errors, and tolerances of angle are derived from the specification for a standard UG-387 waveguide flange.

### TABLE II
**TOLERANCES OF CROSS-GUIDE DIMENSIONS**

<table>
<thead>
<tr>
<th>Par.</th>
<th>Tolerance in simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )</td>
<td>( \pm 2.6 \mu )m ( \pm 6.5 \mu )m ( \pm 13 \mu )m ( \pm 26 \mu )m</td>
</tr>
<tr>
<td>( l )</td>
<td>( \pm 1 \mu )m ( \pm 2 \mu )m ( \pm 3 \mu )m ( \pm 4 \mu )m ( \pm 5 \mu )m</td>
</tr>
<tr>
<td>( \Phi )</td>
<td>( \pm 0.2° ) ( \pm 0.4° ) ( \pm 0.6° ) ( \pm 0.8° ) ( \pm 1.0° )</td>
</tr>
</tbody>
</table>

The transmission loss errors of cross-guide due to these dimensional errors are calculated from electromagnetic theory, using electromagnetic simulation software – in particular, CST Microwave Studio.

In Fig. 2, errors due to the tolerances of the cross-guide aperture height are shown, and values at selected frequencies are summarized in TABLE III. In Fig. 3, errors due to the tolerances of the cross-guide line length are shown, and values at selected frequencies are summarized in TABLE IV. In Fig. 4, errors due to the tolerances of the angle of connection are shown, and values at selected frequencies are summarized in TABLE V. From these simulation results, it can be seen that the influence on the transmission loss of the cross-guide due to the aperture height tolerance is the most significant, and the influence due to angle tolerance is the second most significant.

The influence due to length errors is much smaller than the influences due to height and angle tolerance. The simulation results also show that the effect on the achieved transmission loss due to a positive error within the tolerance interval is larger than the influence due to a negative error within the tolerance interval (assuming the positive and negative errors are of the same magnitude).

### TABLE III
**LOSS ERRORS DUE TO HEIGHT TOLERANCES AT SELECTED FREQUENCIES**

<table>
<thead>
<tr>
<th>Freq. (GHz)</th>
<th>( S21 ) (dB)</th>
<th>( \Delta S21 ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \pm 2.6 \mu )m</td>
<td>( \pm 6.5 \mu )m</td>
</tr>
<tr>
<td>140</td>
<td>57.61</td>
<td>1.17</td>
</tr>
<tr>
<td>160</td>
<td>50.43</td>
<td>0.41</td>
</tr>
<tr>
<td>180</td>
<td>43.02</td>
<td>0.49</td>
</tr>
<tr>
<td>200</td>
<td>34.62</td>
<td>0.51</td>
</tr>
<tr>
<td>220</td>
<td>24.05</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Fig. 2 Loss errors due to height tolerances
IV. UNCERTAINTY ESTIMATES

In order to specify the performance of the cross-guide as a transmission loss verification standard, uncertainty budgets are constructed showing the likely size of uncertainty contributions due to errors derived from cross-guide aperture, flange and line length tolerances. The approach used to establish the uncertainty in the measurements follows the procedures given in [6]. For a cross-guide transmission loss verification standard, the three uncertainty components are:

(i) Worst-case errors due to height tolerance;
(ii) Worst-case errors due to angle tolerance;
(iii) Worst-case errors due to length tolerance.

If $\Delta b$ is the worst-case errors due to the aperture height tolerance, the equivalent standard uncertainty, $u(\Delta b)$, can be established using:

$$u(\Delta b) = \frac{\Delta b}{\sqrt{3}} \tag{1}$$

If $\Delta \phi$ is the worst-case errors due to angle, the equivalent standard uncertainty, $u(\Delta \phi)$, can be established using:

$$u(\Delta \phi) = \frac{\Delta \phi}{\sqrt{3}} \tag{2}$$

If $\Delta l$ is the worst-case errors due to length, the equivalent standard uncertainty, $u(\Delta l)$, can be established using:

$$u(\Delta l) = \frac{\Delta l}{\sqrt{3}} \tag{3}$$

Equation (1), (2) and (3) are used to determine the overall uncertainty for transmission loss measurements, expressed in dB. The combined standard uncertainty for transmission loss measurements, $u(A)$, is given by:

$$u(A) = \sqrt{[u(\Delta b)]^2 + [u(\Delta \phi)]^2 + [u(\Delta l)]^2} \tag{4}$$

Therefore, the expanded uncertainty, $U(A)$, is given by:

$$U(A) = 2 \times u(A) \tag{5}$$

In practice, the calculation of uncertainty is performed at each frequency. For selected frequencies across the band, this leads to the values of uncertainty shown in TABLE VI.

In TABLE VI, the height tolerance is chosen to be $\pm 6.5 \, \mu m$ from TABLE II, which is the tolerance for Grade 0.5 (-34 dB reflection coefficient) waveguide given in [4] and is slightly larger than the maximum observed deviation for the height of the cross-guide given in TABLE I. The length tolerance is chosen to be $\pm 3 \, \mu m$ from TABLE I, which is the estimated
measurement uncertainty of the micrometer used to measure the length of the cross-guide line and is within the manufacturing tolerance for length given in TABLE I. The angle tolerance is chosen to be ±0.4° from TABLE II, which is the value suggested by [9] for a standard UG-387 waveguide flange.

\[ \Delta_{D\text{ut}} \text{, the last column in TABLE VI, is given by:} \]

\[ \Delta_{D\text{ut}} = \text{Mea.}_{D\text{ut}} - \text{Mod.}_{D\text{ut}} \]  

(6)

where, \( \text{Mea.}_{D\text{ut}} \) is the measured attenuation of the cross-guide in dB (see Section V) and \( \text{Mod.}_{D\text{ut}} \) is the corresponding modeled value.

### TABLE VI

<table>
<thead>
<tr>
<th>Freq. (GHz)</th>
<th>S21 (dB)</th>
<th>( \Delta b = 6.5 \mu m )</th>
<th>( \Delta l = 3 \mu m )</th>
<th>( \Delta \Phi = 0.4° )</th>
<th>( \text{U} = (k^{-2}) )</th>
<th>( \Delta_{D\text{ut}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>57.61</td>
<td>2.71</td>
<td>0.97</td>
<td>0.68</td>
<td>3.42</td>
<td>1.78</td>
</tr>
<tr>
<td>160</td>
<td>50.43</td>
<td>1.12</td>
<td>0.17</td>
<td>0.18</td>
<td>1.32</td>
<td>0.09</td>
</tr>
<tr>
<td>180</td>
<td>43.02</td>
<td>1.22</td>
<td>0.10</td>
<td>0.25</td>
<td>1.44</td>
<td>0.65</td>
</tr>
<tr>
<td>200</td>
<td>34.62</td>
<td>1.31</td>
<td>0.08</td>
<td>0.09</td>
<td>1.52</td>
<td>0.91</td>
</tr>
<tr>
<td>220</td>
<td>24.05</td>
<td>1.66</td>
<td>0.04</td>
<td>0.10</td>
<td>1.92</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

V. COMPARISON OF MEASURED AND MODELED VALUES

A measurement was made on one candidate cross-guide line using NPL’s Primary Impedance Measurement System (PIMMS) [10]. A millimeter-wave VNA was configured with WR-05 waveguide test ports. These test ports were established as reference planes by performing a ‘Thru-Reflect-Line’ (TRL) calibration using: two “¾-wave” lines (as the Line standard); a flush short-circuit connected, in turn, to both test ports (as the Reflect standard); and, joining the test ports together (as the Thru standard) [11] [12]. A relatively short waveguide line, of approximate length of 1.478 mm, was connected as the cross-guide line to the VNA test port reference planes, as shown in Fig. 5.

Fig. 6 show plots of the measured transmission magnitude, as a function of frequency, for the cross-guide line. Also shown in Fig. 6 are the values predicted by the electromagnetic model. The uncertainty intervals for the modeled values can be used to verify the measured values – i.e. the measured values are verified when they fall within the range of values established by the uncertainty intervals for the modeled values.

VI. CONCLUSION

This paper has presented an analysis of the uncertainties in a cross-guide verification line used as a standard of attenuation. The analysis used electromagnetic modeling to predict the effect due to tolerances in the dimensions of the cross-guide line and the subsequent impact on the electromagnetic behavior of the line. These model-based uncertainties have been used subsequently to verify a VNA by comparing measurements of a cross-guide line with these modeled values, with uncertainties. By using a range of different cross-guide lengths, the performance of a VNA can be verified over a wide range of operating conditions. This is analogous to the use of commercial coaxial verification kits to verify VNAs that operate at frequencies below 110 GHz.
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REFERENCES


