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Ridler, N, Clarke, R, Huang, H et al. (1 more author) (2016) Evaluation of Cross-Connected Waveguides as Transfer Standards of Transmission at High Millimetre-wave Frequencies. Metrologia, 53 (4). 1069. ISSN 0026-1394

https://doi.org/10.1088/0026-1394/53/4/1069

Evaluation of Cross-Connected Waveguides as Transfer Standards of Transmission at High Millimetre-wave Frequencies

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Abstract

At the present time, transfer and verification standards of transmission coefficient (or, equivalently, transmission loss) are not readily available at high millimetre-wave frequencies (i.e. at frequencies ranging typically from 100 GHz to 300 GHz). In recent years, cross-connected waveguide devices have been proposed to provide calculable standards of transmission loss at these frequencies. This paper investigates the viability of these cross-connected waveguides as transfer standards of transmission for inter-laboratory measurement comparison exercises. This relates to their potential use in activities such as international key comparison exercises and measurement audit programmes. A trial inter-laboratory comparison involving four laboratories using two cross-connected waveguides in the WR-05 waveguide size (covering frequencies from 140 GHz to 220 GHz) is described and includes an analysis of the measurement results obtained during the comparison exercise.

Key words

Inter-laboratory comparison; Key Comparisons; Millimetre-waves; Verification Devices; Vector Network Analysis; Waveguides

1. INTRODUCTION

In recent years, there has been a growing interest in the use of frequencies in the higher millimetre-wave region of the electromagnetic spectrum (i.e., typically, from 100 GHz to 300 GHz). This interest is being driven by many new developments that are opening up this area of the electromagnetic spectrum for new end-user applications, for example in electronics [1], communications [2] and security [3].

With these new applications comes the need for reliable test and measurement of devices and products operating at these frequencies. For high-frequency test and measurement, the Vector

Network Analyser (VNA) is one of the most versatile and widely used measuring instruments for electronic component and circuit analysis. The upper operating frequency of commercially available VNAs has increased significantly during the past decade or so. VNAs are now available that operate at all frequencies across the millimetre-wave region (i.e., from 30 GHz to 300 GHz) and into the submillimetre-wave region (i.e., at frequencies above 300 GHz). For frequencies above 100 GHz, rectangular metallic waveguide is usually chosen to provide the VNA test ports. The recommended frequency range for each waveguide size is given in numerous international standards [4-6]. To provide a VNA for a given waveguide size, a pair of waveguide Extender Heads is needed to enable the VNA to operate over the required range of frequencies [7, 8]. One pair of extender heads is used for each waveguide band that is needed for making the measurements.

With this increase in frequency comes a need for validating the quality of measurements made using VNAs operating at these frequencies. One method that is often used to validate measurement systems at different locations is through the use of measurement Inter-Laboratory Comparison (ILC) exercises. These exercises usually involve circulating a series of pre-determined devices to laboratories wishing to participate in the exercise and comparing and analysing the results obtained by the participating laboratories. However, this pre-supposes the availability of suitable test devices for the ILC. In general, devices used in ILCs need to be physically robust – i.e. they must be able to withstand transportation between the various laboratories participating in the ILC. These participants may be situated in different parts of the world. The devices must also exhibit stable performance – i.e. the electrical characteristics that will be measured during the ILC must remain essentially the same for the duration of the ILC. This is so that the analysis of the measurement results obtained by the participants in the ILC is relatively straight-forward (i.e. that each participant has measured essentially the same measurands). Finally, the devices need to exhibit measured values that are of interest to the participants and within the measuring capabilities (i.e. dynamic ranges) of the measurement systems used by the participants. In other words, the measured values should be within the range of values that are usually measured by the measurement systems, and, are representative of values of interest to the participants.

One such candidate device for ILCs at these high millimetre-wave frequencies is the so-called cross-connected waveguide [9]. These devices have been used previously at these frequencies as verification standards, to verify calibrations of individual VNA systems [10]. This paper examines the use of cross-connected waveguides as candidate transfer standards in ILC exercises involving transmission measurements made by multiple VNA systems situated at different locations. Two cross-connected waveguides are used in this comparison, both in the WR-05 waveguide size (which operates from 140 GHz to 220 GHz). In this ILC, the devices are each measured separately, then measured ‘cascaded’ (i.e. joined together to form a single, combined, device). These ‘three’ devices-under-test (DUT) have been measured by four laboratories – two in the United Kingdom (UK), one in Germany, and one in China. The magnitude of the transmission coefficient (i.e. $|S_{21}|$ or $|S_{12}|$) of these cross-connected waveguides, measured at a series of frequencies across the waveguide band, is used as the measurands for the ILC. The paper presents an analysis of the results from the ILC in order to demonstrate the suitability of these cross-connected waveguides as transfer standards of transmission for ILC exercises, including Key Comparisons organised by regional and international metrology organisations (e.g. BIPM, EURAMET, APMP, etc).

2. ILC DETAILS

2.1 Cross-guide Realisation

A cross-connected waveguide consists of a short section of waveguide that is orientated during connection such that the waveguide aperture is at right-angles to the waveguide apertures on the VNA test ports. The cross-connected waveguide (or ‘cross-guide’, for short) forms a section of waveguide that is effectively below cut-off and so its loss can be predicted from electromagnetic theory, e.g. using 3-D electromagnetic simulation software. Figure 1 illustrates the concept of a cross-guide. For a given waveguide size, different lengths of cross-guide give different values of transmission coefficient.

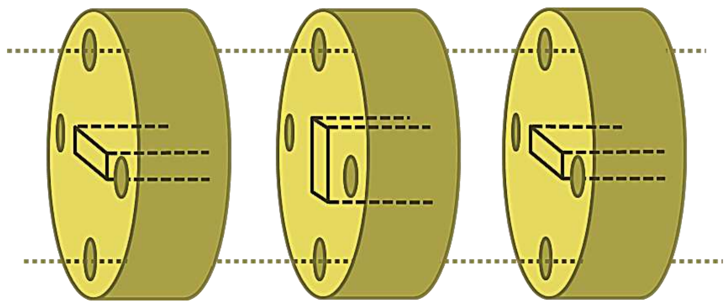

Figure 1. Illustration showing the concept of a ‘cross-guide’. Three sections of waveguide are shown: the two outer sections represent the VNA test ports; the inner section is a section of waveguide connected a right-angles to the two VNA test ports.

2.2 Waveguide Interfaces

Many waveguides used at millimetre-wave frequencies are fitted with so-called UG-387 type interfaces [11], as shown in Figure 2a. However, these interfaces do not perform well, in terms of their ability to align waveguides accurately and repeatedly, at frequencies above 100 GHz. This is because the dimensions of the waveguide aperture (i.e. the aperture width and height) are very small at these frequencies. This has led to modified versions of this interface being developed to improve the alignment of these waveguides so they can be used reliably at frequencies above 100 GHz. One modified version – sometimes called the 'precision' UG-387 interface [12] – contains two additional alignment holes situated immediately above and below the waveguide aperture, as shown in Figure 2b. The method of aligning waveguides fitted with precision UG-387 interfaces is to insert precision dowel pins into these two inner holes before making a connection to another precision UG-387 interface.

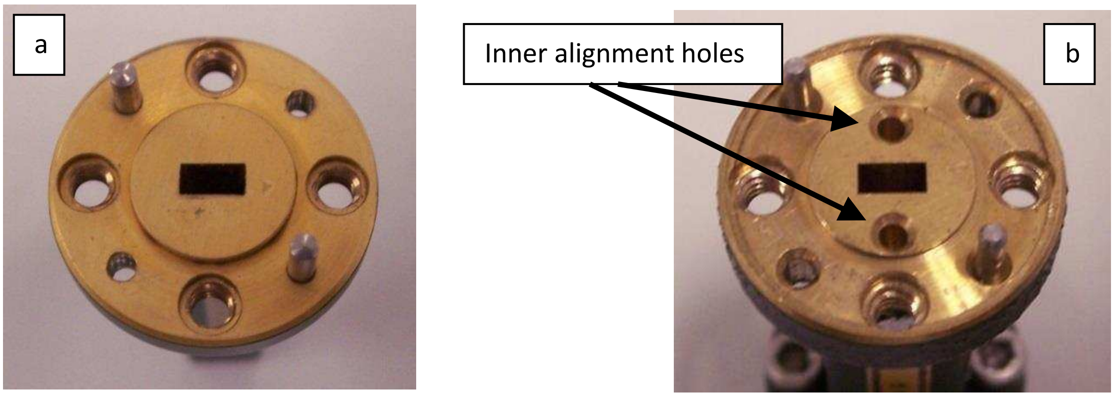

Figure 2. Waveguide interfaces: (a) conventional UG-387; (b) 'precision' UG-387 containing two additional inner alignment dowel holes, as indicated.

2.3 Test Devices

Figure 3 shows a photograph of the two WR-05 cross-guides used for this ILC. Note that, for these devices, the waveguide interface includes two additional inner alignment holes situated on either side of the waveguide aperture.   This is so that two precision dowel pins can be inserted into these holes along with the inner alignment holes on the VNA test port interfaces (assuming they are also precision UG-387 interfaces). This provides improved alignment of the lines to the VNA test ports, when the lines are connected in the cross-guide configuration.

In addition to measuring each cross-guide as a separate DUT, the two cross-guides were connected at the same time (i.e. in 'cascade') to form effectively a 'third' DUT. This combination produces a decrease in transmission when compared with the transmission produced when each line is measured on its own. When cascading two cross-guide sections, the correct orientation of each cross-guide is maintained by inserting dowel pins into the two additional inner alignment holes in each of the cross-guide sections, as shown in Figure 3.

Therefore three cross-guide DUTs were measured during this exercise, with lengths: (i) 0.62 mm, (ii) 1.36 mm, and (iii) 1.98 mm (i.e. 0.62 mm + 1.36 mm). The transmission magnitude (i.e. the average of $|S_{21}|$ and $|S_{12}|$), expressed in dB, for each DUT was measured from 140 GHz to 220 GHz at 101 regularly-spaced frequency points – i.e. at intervals of 800 MHz. (Some of the participants measured at additional frequencies but these have not been analysed as part of this ILC.)

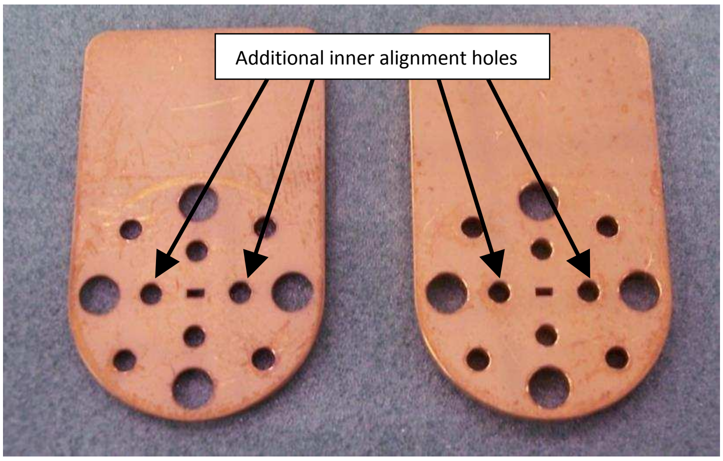

Figure 3. Photograph showing the two cross-guides used for the ILC exercise. Also indicated are the additional inner alignment holes for aligning the waveguide when it is cross-connected to other waveguide.

2.4. Participants

Four organisations participated in the ILC: (i) National Institute of Metrology (NIM), China; (ii) National Physical Laboratory (NPL), UK; (iii) Physikalisch-Technische Bundesanstalt (PTB), Germany; (iv) University of Leeds, UK. Details of the measurement systems used by each participant are described below.

(i) The system used by NIM was an Agilent Technologies PNA-X VNA fitted with Virginia Diodes Inc WR-05 waveguide Extender Heads. The Intermediate Frequency (IF) bandwidth was set to 30 Hz. No numerical signal averaging (or smoothing) was used. The VNA was calibrated using a TRL calibration scheme [13]. Two precision sections of waveguide manufactured by OML, Inc, were used to establish the VNA test port reference planes.

(ii) The type of system and set-up used by NPL was similar to that used by NIM. The only difference was that the NPL set-up used two precision sections of waveguide manufactured by Flann Microwave Ltd to form the VNA test port reference planes.

(iii) The system used by PTB was an Agilent Technologies PNA VNA fitted with Rohde & Schwarz ZVA-Z220 WR-05 waveguide Extender Heads. The Intermediate Frequency (IF) bandwidth was set to 10 Hz. No numerical signal averaging (or smoothing) was used. The VNA was calibrated using a TRL calibration scheme [14].

(iv) The system used by the University of Leeds was an Agilent Technologies 8510C VNA fitted with OML Inc WR-05 waveguide Extender Heads. A point Averaging Factor of 1024 was used and no trace smoothing was applied. The VNA was calibrated using an LRL calibration scheme [15] with the isolation step omitted. The test ports comprised sections of waveguide manufactured by OML Inc.

3. RESULTS

The results obtained for the three cross-guide DUTs (0.62 mm, 1.36 mm and 1.98 mm) are shown in Figures 4, 5 and 6. The results are shown as the logarithmic magnitude of the transmission coefficient (in dB) as a function of frequency. These Figures show that the transmission for each cross-guide increases smoothly as a function of frequency, across the full operating bandwidth of the waveguide. This is summarised in Table 1, which shows that, when taken together, these cross-guides provide transmission magnitude values that range from -10 dB to -70 dB. To some extent, this corresponds approximately to the typical range of transmission measurements for passive devices using these types of VNA.

Table 1. Approximate ranges of values of transmission produced by the three cross-guides.

Cross-guide nominal length / mm	Approximate transmission magnitude / dB	
	140 GHz	220 GHz
0.62	-25	-10
1.36	-50	-20
1.98	-70	-25

Figures 4, 5 and 6, show that, at any given frequency, the measured transmission due to the 1.98 mm cross-guide is not equal to the sum of the measured transmission due to the 0.62 mm and 1.36 mm cross-guides. In fact, the measured transmission of the 1.98 mm cross-guide is always greater than the sum of the measured transmission magnitudes of the 0.62 mm and 1.36 mm cross-guides. This is most likely due to the mechanisms that give rise to the loss in transmission for any given cross-guide device. The overall loss for a cross-guide is caused by a combination of loss due to reflection (at the interfaces between the cross-guide and the VNA test port reference planes) and loss due to transmission (as the electromagnetic wave decays evanescently through the cross-guide section which is below cut-off). The loss due to reflection will be similar for any given cross-guide device. Therefore, a cross-guide that has been constructed by joining together two separate sections of cross-guide will exhibit the same loss due to reflection as any single cross-guide device. So, whereas two single cross-guides will each exhibit a similar amount of loss due to reflection, a cross-guide that is formed by joining together two single cross-guides will still only produce the same loss due to reflection as any other single section of cross-guide. In addition, the inevitable misalignment of the two cascaded sections of cross-guide will contribute to the overall loss produced by the cross-guide sections.

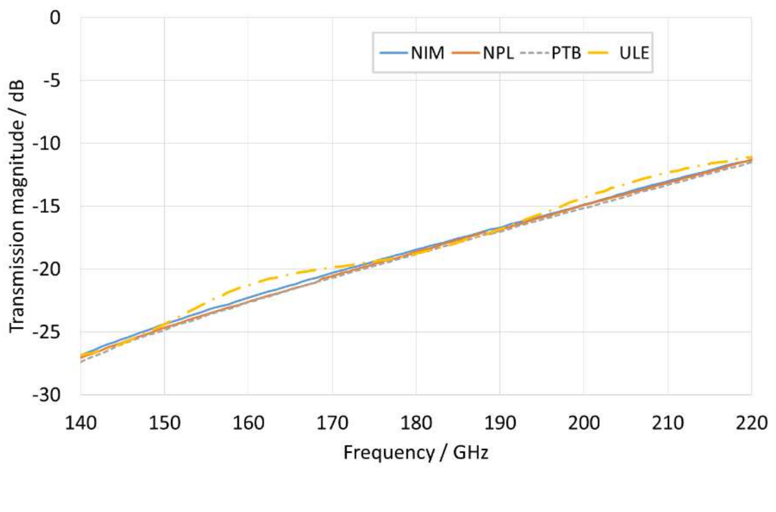

Figure 4. Participants' measurement results for the 0.62 mm cross-guide.

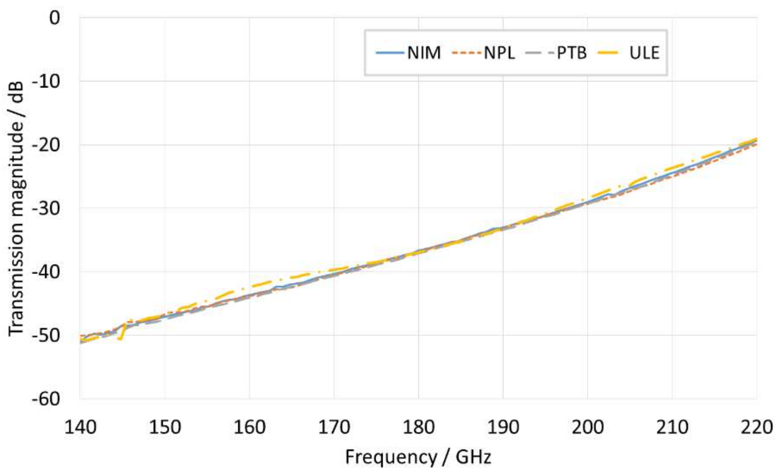

Figure 5. Participants' measurement results for the 1.36 mm cross-guide.

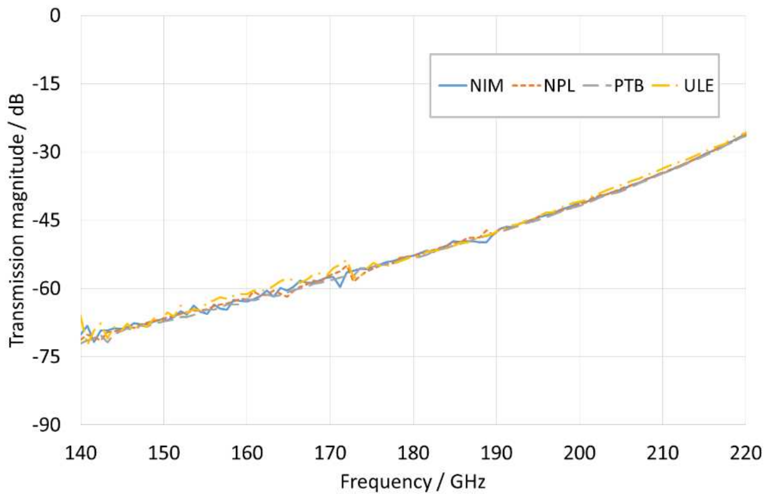

Figure 6. Participants' measurement results for the 1.98 mm cross-guide.

For the 1.98 mm cross-guide, the transmission magnitude at frequencies below 180 GHz is approaching the typical noise floor of the measurement systems. This is evident in the increased trace noise in the results obtained from each participant. Also, at some frequencies, a small systematic discontinuity can be seen in the measured transmission. In Figure 6, this effect is visible at approximately 190 GHz in the measurements from at least two participants. It is believed that this is caused by a cavity resonance, since the guide wavelength at around 190 GHz corresponds to the length of the cross-guide.

The guide wavelength, λ_g, is given by:

$$\lambda_g = \frac{\lambda}{\sqrt{1-(\lambda/\lambda_0)^2}} \tag{1}$$

where λ is the free space wavelength and λ_0 is the waveguide cut-off wavelength, which is defined as:

$$\lambda_0 = 2a \tag{2}$$

where *a* is the broad wall dimension of the waveguide.

For WR-05 waveguide, the nominal broad wall dimension is 1.295 mm and so, according to equation (2), $\lambda_0 = 2 \times 1.295 = 1.590$ mm. The free space wavelength, λ, is given by:

$$\lambda = \frac{c}{f} \tag{3}$$

where *c* is the speed of light (299 792 458 ms^{-1}) and *f* is the frequency. According to equation (3), at 190 GHz, λ = 1.578 mm. Substituting the values of λ_0 and λ into equation (1) gives λ_g = 1.989 mm, which is close to the nominal length of the 1.98 mm cross-guide line.

In order to summarise these results and investigate differences between the participants' measured values, an average (i.e. mean) value is calculated for each DUT at each frequency. Figures 7, 8 and 9 show plots of the differences, at each frequency, between each participant's value and the calculated mean value.

All differences for the 0.62 mm and 1.36 mm cross-guides (shown in Figures 7 and 8) are within 2 dB of the mean values at all frequencies. All differences for the 1.98 mm cross-guide (shown in Figure 9) are within 4 dB of the mean values at all frequencies.

4. ANALYSIS

4.1 Comparing participants' differences

The results shown in the previous section can be further summarised by presenting absolute differences (between each participant's value and the mean value) at selected frequencies (i.e. every 20 GHz) across the band. These values are presented in Tables 2 to 4, along with the mean values derived from the participants' measured values.

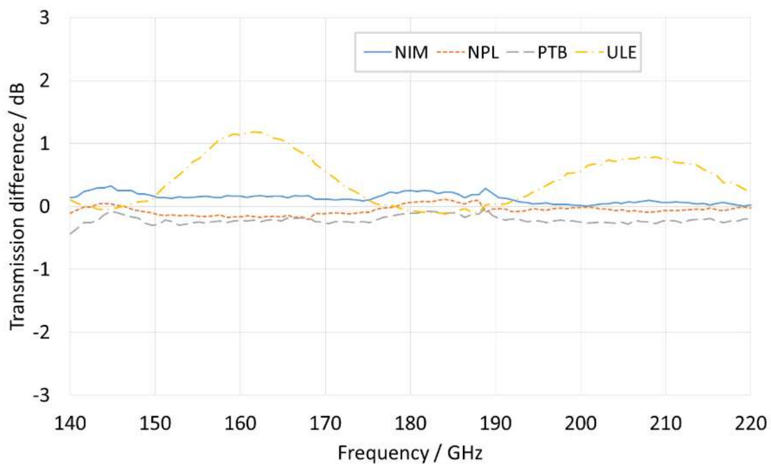

Figure 7. Difference between the participants' values and the mean value, for the 0.62 mm cross-guide.

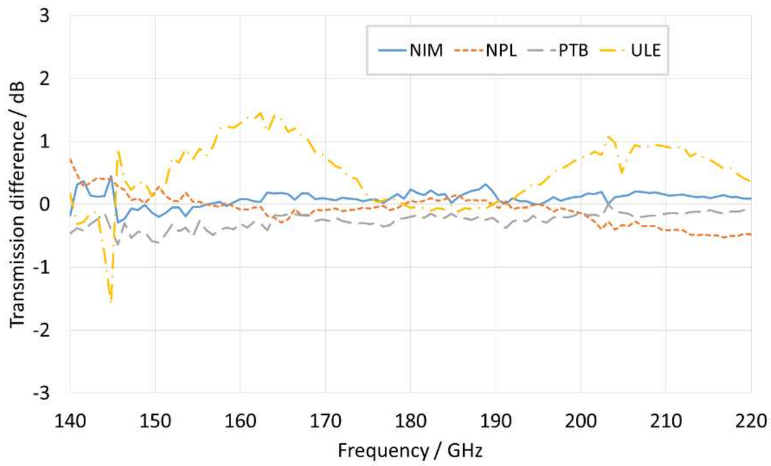

Figure 8. Difference between the participants' values and the mean value for the 1.36 mm cross-guide.

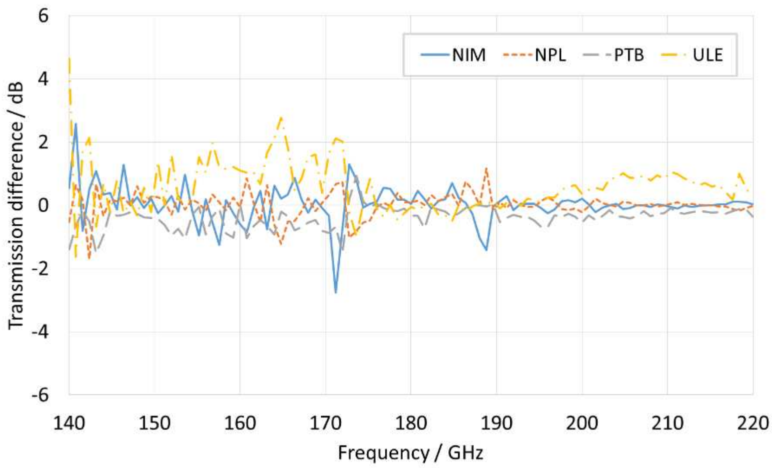

Figure 9. Difference between the participants' values and the mean value for the 1.98 mm cross-guide.

Table 2. Summary results for the 0.62 mm cross-guide.

Frequency / GHz	Transmission magnitude / dB				
	Mean	Absolute difference from mean			
		NIM	NPL	PTB	ULE
140	-27.03	0.21	0.03	0.36	0.18
160	-22.21	0.06	0.39	0.45	0.91
180	-18.65	0.22	0.03	0.15	0.10
200	-14.81	0.06	0.10	0.32	0.48
220	-11.29	0.02	0.03	0.20	0.21

Table 3. Summary results for the 1.36 mm cross-guide.

Frequency (GHz)	Transmission magnitude / dB				
	Mean	Absolute difference from mean			
		NIM	NPL	PTB	ULE
140	-50.70	0.23	0.65	0.52	0.11
160	-43.50	0.16	0.33	0.55	1.05
180	-36.89	0.23	0.05	0.21	0.07
200	-28.98	0.03	0.29	0.28	0.59
220	-19.43	0.12	0.45	0.06	0.39

Table 4. Summary results for the 1.98 mm cross-guide.

Frequency / GHz	Transmission magnitude / dB				
	Mean	Absolute difference from mean			
		NIM	NPL	PTB	ULE
140	-69.91	0.28	1.35	2.21	3.83
160	-62.17	0.72	0.18	0.07	0.97
180	-52.95	0.11	0.16	0.27	0.01
200	-41.34	0.26	0.17	0.50	0.41
220	-26.08	0.05	0.01	0.34	0.30

The likely uncertainty in measurements of cross-guides in WR-05 due to practical, and hence imperfect, realisation of the cross-guides (e.g. due to tolerances on critical dimensions) has been established elsewhere [16]. In addition, investigations in the connection repeatability of cross-guides in WR-05 have been presented in [17]. The work in [16] and [17] has shown that, for cross-guides in WR-05 fitted with ‘precision’ UG-387 interfaces (as used in this investigation), errors due to connection repeatability are likely to be small compared to systematic errors due to the practical realisation of a cross-guide device. These systematic errors will affect all measurements of cross-guide devices and so will be present, to the same extent, in all the measurements made by the participants in this ILC. Therefore, uncertainty estimates derived from assessments of these systematic errors can be used as generic uncertainty estimates for the measurements made by all the participants in the ILC. However, this pre-supposes that other sources of error that are local to each participant’s measurement system are relatively small compared to these systematic errors. Such additional sources of uncertainty include imperfect VNA calibration, imperfect VNA linearity, and spectral purity of the VNA test frequency. It is difficult to fully quantify these potential additional sources of uncertainty, but these uncertainty sources should be taken into consideration if the outcome from an ILC demonstrates a lack of equivalence between participants' measurement results.

According to [16], the main contributions to the uncertainty in the realisation of a cross-guide device are due to: (i) errors in the assumed height of the waveguide aperture, Δb; (ii) errors in the assumed length of the cross-guide, Δl; and (iii) errors in the assumed 90° connection angle for the cross-guide with respect to the VNA test ports, $\Delta\phi$. (Symbols used here are the same as used in [16].)

Following the methods given in [16], the worst-case size of these errors for each of the three cross-guides used in this ILC are: (i) for Δb, a value of 6.5 μm is used, as this is considered an achievable tolerance for this waveguide aperture dimension in this waveguide size [4]; (ii) for Δl, a value of 3 μm is used, as this degree of accuracy is easily achievable for a routine length measurement (e.g. using a digital micrometer) of a short section of waveguide; (iii) for $\Delta\phi$, a value of 0.4° is used, as this tolerance is suggested in [11] for a standard UG-387 flange type and so this is easily achievable using the inner dowel pins and holes on the cross-guides used in this comparison.

The above worst-case errors (Δb, Δl and $\Delta\phi$) are converted into worst-case errors in the associated transmission magnitude ($T(\Delta b)$, $T(\Delta l)$, $T(\Delta\phi)$) using electromagnetic simulation software – in particular, CST Microwave Studio [18]. The simulation employs the time-domain solver in CST and uses a hexahedral mesh with a steady state limit of -40 dB. The simulation is first run using nominal values for the waveguide dimensions. These nominal values are: a broad wall dimension of 1.295 mm, a narrow wall dimension of 0.647 5 mm, a cross-connection angle of 90°, and cross-guide lengths of 0.62 mm, 1.36 mm and 1.98 mm. Values produced by the simulation using these nominal values are shown in Tables 5, 6 and 7, in the column labelled T, at the same selected frequencies used in Tables 2 to 4. The effect due to each error, Δb, Δl and $\Delta\phi$, is then assessed, in turn, by running the simulation using nominal values for all parameters except the parameter being assessed, which takes on a value which is perturbed by the assumed error (i.e. perturbed by 0.65 μm for Δb, 3 μm for Δl, and 0.4° for $\Delta\phi$). Each set of values produced by the simulation under these perturbed conditions is compared with the original values produced using all nominal values for the waveguide dimensions. The difference between the two sets of values – perturbed and nominal – is taken as representing the size of the error in transmission magnitude ($T(\Delta b)$, $T(\Delta l)$, $T(\Delta\phi)$) due to the error in the waveguide nominal values (Δb, Δl, $\Delta\phi$, respectively). Values of $T(\Delta b)$, $T(\Delta l)$ and $T(\Delta\phi)$ for each of the three cross-guides used in this ILC are shown in Tables 5, 6 and 7.

Table 5. Modelled worst-case errors, $T(\Delta b)$, $T(\Delta l)$, $T(\Delta \Phi)$, and expanded uncertainty, $U(T)$, for a 0.62 mm length of WR-05 cross-guide.

Frequency / GHz	T / dB	$T(\Delta b)$ / dB	$T(\Delta l)$ / dB	$T(\Delta \Phi)$ / dB	$U(T)$ / dB
140	-28.38	0.59	0.13	0.12	0.71
160	-23.74	0.61	0.12	0.04	0.72
180	-19.83	0.61	0.10	0.05	0.72
200	-16.04	0.60	0.08	0.02	0.70
220	-12.22	0.56	0.05	0.02	0.65

Table 6. Modelled worst-case errors, $T(\Delta b)$, $T(\Delta l)$, $T(\Delta \Phi)$, and expanded uncertainty, $U(T)$, for a 1.36 mm length of WR-05 cross-guide.

Frequency / GHz	T / dB	$T(\Delta b)$ / dB	$T(\Delta l)$ / dB	$T(\Delta \Phi)$ / dB	$U(T)$ / dB
140	-53.54	1.21	0.13	0.46	1.50
160	-46.82	1.01	0.11	0.19	1.19
180	-39.86	1.11	0.08	0.11	1.29
200	-32.10	1.21	0.07	0.12	1.41
220	-22.53	1.46	0.04	0.08	1.69

Table 7. Modelled worst-case errors, $T(\Delta b)$, $T(\Delta l)$, $T(\Delta \Phi)$, and expanded uncertainty, $U(T)$, for a 1.98 mm length of WR-05 cross-guide.

Frequency / GHz	T / dB	$T(\Delta b)$ / dB	$T(\Delta l)$ / dB	$T(\Delta \Phi)$ / dB	$U(T)$ / dB
140	-62.53	4.85	1.49	2.71	6.64
160	-67.41	0.42	0.93	5.81	6.81
180	-55.90	1.80	0.04	0.88	2.31
200	-45.68	1.53	0.12	0.21	1.79
220	-29.89	2.53	0.01	0.09	2.92

Following guidance given in [16], these worst-case errors in magnitude transmission ($T(\Delta b)$, $T(\Delta l)$, $T(\Delta\phi)$) are converted to equivalent standard uncertainties using equations (4) to (6):

$$u_1(T) = \frac{T(\Delta b)}{\sqrt{3}} \tag{4}$$

$$u_2(T) = \frac{T(\Delta l)}{\sqrt{3}} \tag{5}$$

$$u_3(T) = \frac{T(\Delta \phi)}{\sqrt{3}} \tag{6}$$

The combined standard uncertainty in transmission magnitude, $u(T)$, due to the uncertainty contributions determined by equations (4) to (6), is given by [19]:

$$u(T) = \sqrt{u_1^2(T) + u_2^2(T) + u_3^2(T)} \tag{7}$$

and the expanded uncertainty in transmission magnitude, $U(T)$, is given by:

$$U(T) = ku(T) \tag{8}$$

where k is a coverage factor. Values of $U(T)$ (using $k = 2$) for each cross-guide are also shown in Tables 5, 6 and 7. A value of $k = 2$ is chosen to provide a coverage interval at a coverage probability of approximately 95%. (Note: the terms “standard uncertainty”, “expanded uncertainty”, “coverage factor”, “coverage interval” and “coverage probability” are as defined in [20].)

The values of $U(T)$ given in Tables 5, 6 and 7 can be used to assess the significance of the absolute differences between the participants’ values and the mean values reported in Tables 2, 3 and 4. In particular, if, for a given cross-guide at a given frequency, a participant’s difference from the mean is less than the associated value of $U(T)$, then the difference is not considered to be significant – i.e. the participant’s value and the mean value are therefore considered to be equivalent (with respect to the associated expanded uncertainty). If, however, the participant’s difference is greater than the associated value of $U(T)$, then the difference is considered significant and so the participant’s value and the mean value are not considered to be equivalent. Under these circumstances, the cause for the observed difference should be investigated further. This concept of equivalence is in line with methods given elsewhere [21] for evaluating key comparison measurement data.

Comparing the participants’ differences at each frequency in Table 2 with the value of $U(T)$ for the same frequency in Table 5, it is clear that the differences in the participants’ measured values for the 0.62 mm cross-guide are not significant at these selected frequencies – i.e. the participants’ measurements can be considered to be equivalent. Similarly, by comparing the participants’ differences at each frequency in Table 3 with the value of $U(T)$ for the same frequency in Table 6, the participants’ measured values for the 1.36 mm cross-guide are also considered to be equivalent at these selected frequencies. Finally, comparing the participants’ differences at each frequency in Table 4 with the value of $U(T)$ for the same frequency in Table 7, the participants’ measured values for the 1.98 mm cross-guide are also considered to be equivalent at these selected frequencies. This demonstrates that the measurements made by the participants in this ILC can be considered equivalent with each other at these selected frequencies. However, it should be noted that, at frequencies away from these selected frequencies, some of the differences in the participants’ values are likely to be greater than the associated uncertainty in the measurements. Such differences would need to be investigated, on a case by case basis.

4.2 Comparing measured with modelled values

As well as the participants' differences and the uncertainties in the transmission values for the cross-guides, a comparison can also be made between the measured and the modelled transmission magnitude values. This will indicate whether these modelled values for these cross-guides could be useful as reference (i.e. benchmark) values for assessing the quality of the measurements of these devices. The mean measured values, for each cross-guide device, at selected frequencies, are shown in Tables 2, 3 and 4. The modelled values, *T*, for a realisation of the same cross-guide devices using nominal dimensional values, at the same frequencies, are given in Tables 5, 6 and 7. The differences between these measured and modelled values are shown in Table 8.

Table 8. Differences between the mean measured values and the modelled values for each cross-guide.

Frequency / GHz	Differences (mean – model) for each cross-guide / dB		
	0.62 mm	1.36 mm	1.98 mm
140	1.35	2.84	-7.38
160	1.53	3.32	5.24
180	1.18	2.97	2.95
200	1.23	3.12	4.34
220	0.93	3.10	3.81

For all three cross-guides, at all selected frequencies, these differences are larger than the differences between each participant's value and the mean measured value (shown in Tables 2, 3 and 4). This shows that the difference between the measured performance of a cross-guide and modelled performance, using nominal values for the dimensions, is significant. Therefore, under these circumstances, transmission coefficient values derived from these models are unlikely to be useful as reference values for benchmarking measurements (e.g. in ILC exercises and other validation/verification activities). The reason for the significant discrepancy between measured and modelled values for these cross-guides is likely due to dimensional differences between a physically realised cross-guide and a cross-guide with nominal waveguide dimensions. These dimensional differences will impact the electrical performance of the cross-guide so that the behaviour of the realised cross-guide will be significantly different from the modelled cross-guide. Under these circumstances, in order to establish reference values for these cross-guides, it would be recommended to use either consensus values established by a series of measured values (e.g. as obtained during an ILC) or values supplied by a laboratory with metrological traceability to the international system of units (SI) [22].

5. SUMMARY

This paper has described an investigation into the suitability of cross-guides as transfer standards of transmission at high millimetre-wave frequencies. The investigation has concentrated on the WR-05 waveguide size (i.e. at frequencies from 140 GHz to 220 GHz) and involved undertaking an ILC involving four measurement laboratories – NIM (China), NPL (UK), PTB (Germany), and University of Leeds (UK).

Some conclusions can be drawn from the results of this exercise:

i. The cross-guides used in the ILC behaved well throughout the ILC – there was no obvious change in the electrical characteristics of the cross-guides (e.g. due to damage during transit between the participants' sites or during measurement);
ii. The cross-guides chosen for the exercise provided a range of transmission values that were useful for assessing the dynamic ranges of the participants' VNAs. The cross-guide device that exhibited the lowest transmission (i.e. the 1.96 mm cross-guide) provided transmission values that were likely to be close to the instrument noise floors, at the lower part of the waveguide band, for these VNAs;
iii. The measurements made by the participants generally showed good agreement, with differences between participants generally being less than the expected expanded uncertainty in the values of transmission generated by the cross-guides at selected frequencies. However, some discrepancies were observed in the results, at some frequencies, and these would require further investigation in a formal ILC exercise;
iv. The cross-guide configuration that exhibited the lowest transmission was realised by joining two separate cross-guide devices together (i.e. by joining the 0.62 mm and 1.36 mm cross-guide to form a cross-guide of 1.98 mm length). This technique proved successful and meant that three values of transmission were realisable from just two cross-guide devices. This technique could be useful for ILCs in the future that employ cross-guide devices as DUTs;
v. It was found that the values of transmission measured by the participants were significantly different from values predicted using electromagnetic modelling software derived from models using nominal values for the waveguide dimensions. This suggests that it is not realistic to use modelled values based on nominal values for the waveguide dimensions for benchmarking measured values when these types of device are used at these high millimetre-wave

frequencies. This is likely due to dimensional differences between a manufactured cross-guide and a cross-guide modelled using nominal dimensions.

In summary, the investigation has shown that cross-guides are suitable for use as transfer standards and verification devices for transmission at high millimetre-wave frequencies. This property demonstrates that cross-guides will be useful for validating the performance of any VNA operating at these frequencies and that cross-guides could be used as transfer standards in formal measurement comparison exercises, as organised by regional and international metrology organisations (e.g. BIPM, EURAMET, APMP, etc).

ACKNOWLEDGEMENT

This work was funded through the European Metrology Research Programme (EMRP) Project SIB62 'Metrology for New Electrical Measurement Quantities in High-frequency Circuits'. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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