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INTERLABORATORY COMPARISON OF S-PARAMETER MEASUREMENTS IN WM-570 WAVEGUIDE AT FREQUENCIES FROM 325 GHz TO 500 GHz

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ABSTRACT

A recent measurement comparison exercise involving four participating laboratories was undertaken to establish understanding of the current state of the art of WM-570 rectangular metallic waveguide S-parameter measurement capabilities. This report details the comparison in which each participant measured five WM-570 waveguide devices operating from 325 GHz to 500 GHz. A summary of the results obtained is given, in addition to some observations and analysis.

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CONTENTS

GLOSSARY/ABBREVIATIONS

WM-570	Rectangular waveguide with broad wall dimension of 570 μm supporting frequencies from 325 GHz to 500 GHz
S-parameters	Scattering parameters of a device or component
SOLT	Short-Offset short-Load-Through method of VNA calibration
TRL	Through-Reflect-Line method of VNA calibration
IF	Intermediate frequency
VNA	Vector Network Analyser
S_{11}	Reflection S-parameter measured at port 1
S_{22}	Reflection S-parameter measured at port 2
S_{21}	Transmission S-parameter measured between ports 1 and 2 with stimulus applied at port 1
S_{12}	Transmission S-parameter measured between ports 1 and 2 with stimulus applied at port 2

1 INTRODUCTION

The TEMMT[1] European metrology project [1], which ran from 2019 to 2022, involved the development of state-of-the-art high frequency S-parameter measurement facilities. One of these developments was based around the WM-570 waveguide band, which operates at frequencies from 325 GHz to 500 GHz. Following the development of these new facilities, an intercomparison of measurements was undertaken to establish the level of equivalence between these measurement facilities. The participants in the intercomparison were the four institutes involved in developing the new measurement facilities: University of Birmingham, UK; Virginia Diodes, Inc (VDI), USA; Anritsu, USA; National Physical Laboratory, UK.

This report provides details about this intercomparison in which the participants each measured five WM-570 devices. The devices were selected to provide a broad range of responses which would indicate the extent of the performance of each measurement facility. The results from the four participants are presented in an anonymised fashion, using labels A, B, C and D. This is so that the results can be judged independently from the knowledge of who contributed them.

2 PARTICIPANT DETAILS

Table 1 lists the participants' details, i.e. the dates of the measurements, the method used for calibrating the VNA, and other related information. In terms of hardware, three participants used Keysight PNA-X Vector Network Analysers (VNAs) and one used an Anritsu MS4647B VNA, each in conjunction with VDI frequency extender heads, to achieve the WM-570 setup.

Table 1. Details of the Comparison Participants

Participant	Date of measurements	Calibration technique used	Other information
A	April 2021 October 2021	SOLT	IF bandwidth: 30 Hz Measured every 1 GHz
B	June 2021	SOLT	IF bandwidth: 100 Hz Measured every 1 GHz
C	August 2021	TRL, SSLT, MSSS	IF bandwidth: 100 Hz Measured every 1 GHz
D	October 2021	¾-wave TRL	IF bandwidth: 50 Hz Measured every 1 GHz

2.1. NOTES ON PARTICIPANTS

- Participant A measured the items twice: first, at the beginning of the comparison, and again at the end of the comparison. The two sets of measurements were used to determine whether the characteristics of the devices had changed significantly during the comparison exercise. It was found that the differences between these two sets of measurements were insignificant when compared with the differences seen between the participants' results in the comparison, and therefore the devices are expected to have remained stable throughout the duration of the comparison.

[1] TEMMT – "Traceability for Electrical Measurements at Millimetre-wave and Terahertz frequencies for communications and electronics technologies".

- Participant C utilised three different calibration techniques, and so there are three sets of results for Participant C in this report. The comparison therefore produced a total of six participant results (three from Participant C and one each from Participants A, B and D) for each device at each frequency.

- For this comparison exercise, Participant D used Participant A's VNA measurement facility. This is because Participant D does not currently own a WM-570 VNA measurement facility. However, Participant D does own WM-570 calibration standards and so these standards (used to implement the ¾-wave TRL calibration technique) were used in conjunction with the Participant A measurement facility (comprised of a Keysight PNA-X VNA with VDI extender heads) to provide the measurement results for Participant D in this comparison.

3 COMPARISON DEVICES

Table 2 lists the comparison device details along with the measurement parameters being compared in this comparison.

Table 2. Comparison Device Details

Type	**Model Number**	**Serial Number**	**Parameters**
10 dB attenuator	WM570SWGMD2R7	2-20	S_{11}, S_{22}, S_{21}, S_{12}
¼-wave cross-guide	WR2.2QW	-	S_{21}, S_{12}
Offset short-circuit	WR2.2 QD R3	2-15	S_{11}
Termination	WM570SWGMD1R7	1-39	S_{11}
1" straight waveguide	WM570SWGMD1R7	1-01	S_{11}, S_{22}, S_{21}, S_{12}, Magnitude reciprocity, Phase reciprocity

4 MEASUREMENT CONDITIONS

The comparison exercise involved comparing the measurement results from each participant at frequencies from 325 GHz to 500 GHz in 1 GHz steps. The results at the extra frequencies (i.e. down to 320 GHz and up to 505 GHz) that were included to avoid any problems that might occur at the beginning or end of the measurement sweep were not compared.

The measurands were the complex-valued S-parameters listed in Table 2 together with 'magnitude reciprocity' and 'phase reciprocity' of the 1" straight waveguide, i.e. the difference between a participant's S_{21} and S_{12} magnitude and phase results at each frequency. Results are presented in logarithmic magnitude (dB) and phase format with phase in the range -180° to +180°.

Separate S-parameter measurements were made in order to account for the four possible orientations of each device:

1) Device port 1 connected to VNA port 1—DUT in "up" position
2) Device port 1 connected to VNA port 1—DUT in "down" position
3) Device port 1 connected to VNA port 2—DUT in "up" position
4) Device port 1 connected to VNA port 2—DUT in "down" position

The serial number on the flange of each device was used to identify the device orientation (i.e. "up" is when the serial number is facing upwards during connection).

5 ANALYSIS TECHNIQUES

Statistics summarising the S-parameter measurements made in the comparison in terms of logarithmic magnitude (dB) and phase (degrees) are plotted in figures 1 to 12. Figure 13 summarises the magnitude and phase reciprocity measurements for the 1” straight waveguide. Table 3 lists the contents of the figures.

Table 3. Figures summarising the measurements made in the comparison

Figure	Section	Device	Parameter
1	6.1	10 dB Attenuator	S_{11}
2			S_{22}
3			S_{21}
4			S_{12}
5	6.2	¼-wave cross-guide	S_{21}
6			S_{12}
7	6.3	Offset short-circuit	S_{11}
8	6.4	Termination	S_{11}
9	6.5	1” Straight Waveguide	S_{11}
10			S_{22}
11			S_{21}
12			S_{12}
13			Reciprocity

For S-parameters with a small magnitude (i.e. with a linear magnitude close to zero), the phase of the S-parameter is not well defined since a small change in the complex-valued S-parameter (such as that caused by noise in the VNA or lack of repeatability in the device connection) can result in a very large change in its phase. In addition, the phases of S_{21} and S_{12} of the cross-guide are not considered to be of primary interest. Therefore, phase is only presented for the S-parameters listed in Table 4 which are considered to have a sufficiently large magnitude to ensure that the phase is well defined, in addition to the phase being a direct characteristic of the device’s performance.

Table 4. S-parameters for which phase was considered

Device	S-parameter phase included in the comparison
10 dB attenuator	None
Cross-guide	None
Offset short-circuit	S_{11}
Termination	None
1” Straight waveguide	S_{12} and S_{21}

The participants made up to four repeat measurements of each device with the device in a different orientation for each repeat measurement, with the four orientations as defined in Section 4.

For each S-parameter of interest, $S = |S|\angle\phi$, the following summary statistics are plotted as functions of frequency:

- The mean S-parameter magnitude (dB) for participant result i (where $i = 1, \ldots, 6$ for the six participant results), $\overline{|S|}_i(\mathrm{dB})$. This is an average of the repeat measurements made for participant result i.
- The mean S-parameter magnitude (dB) for all six participant results, $\overline{|S|}(\mathrm{dB})$. This is an average of the mean of all six participant results.
- The standard deviation in S-parameter magnitude (dB) for participant result i (where $i = 1, \ldots, 6$ for the six participant results), $\mathrm{SD}(|S|_i)(\mathrm{dB})$. This measures the amount of variability between the repeat measurements made for participant result i.
- The standard deviation in S-parameter magnitude (dB) for all six participant results, $\mathrm{SD}(|S|)(\mathrm{dB})$. This measures the amount of variability between the mean measurements made for each of the participant results.

In addition, for those S-parameters for which phase is being considered, the following summary statistics are also plotted:

- The mean S-parameter phase for participant result i (where $i = 1, \ldots, 6$ for the six participant results), $\bar{\phi}_i$.
- The mean S-parameter phase for all six participant results, $\bar{\phi}$.
- The standard deviation in S-parameter phase for participant result i (where $i = 1, \ldots, 6$ for the six participant results), $\mathrm{SD}(\phi_i)$.
- The standard deviation in S-parameter phase for the six participant results, $\mathrm{SD}(\phi)$.

Finally, for the 1” straight waveguide, the following additional parameters are also plotted:

- Magnitude (dB) reciprocity for participant result i (where $i = 1, \ldots, 6$ for the six participant results), $R_i(\mathrm{dB})$. This is the difference between the mean S_{21} (dB) and the mean S_{12} (dB) for participant result i.
- Phase reciprocity for participant result i (where $i = 1, \ldots, 6$ for the six participant results), ψ_i. This is the difference between the mean S_{21} phase and the mean S_{12} phase for participant result i.

The calculation of these summary statistics is now described.

5.1. CALCULATION OF SUMMARY STATISTICS

Let M be the number of participant results in the comparison ($M = 6$), let S be a complex-valued S-parameter of interest and let N_i be the number of repeat measurements of S made for the *i*th participant result. Let the jth repeat measurement of S made for the ith participant result at a particular frequency be

$$S_{ij} = |S|_{ij}\angle\phi_{ij}$$

for $i = 1, \cdots, M$ and $j = 1, \cdots, N_i$ where $|S|_{ij}$ is the measured linear magnitude and ϕ_{ij} is the measured phase. The following summary statistics are calculated at each frequency.

5.1.1. Summary statistics for magnitude values

5.1.1.1. Summary of repeat magnitude measurements made for the ith participant result

The mean S-parameter magnitude (expressed in dB) for participant result i, $\overline{|S|}_i(\mathrm{dB})$, is given by equation (1):

$$\overline{|S|}_i(\mathrm{dB}) = 20\log_{10}\left(\frac{1}{N_i}\sum_{j=1}^{N_i}|S|_{ij}\right). \tag{1}$$

The standard deviation in S-parameter magnitude for participant result i (expressed in dB), $\mathrm{SD}(|S|_i)(\mathrm{dB})$, is given by equation (2) [2]:

$$\mathrm{SD}(|S|_i)(\mathrm{dB}) = \frac{8.686}{\overline{|S|}_i}\sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{N_i}\left(|S|_{ij} - \overline{|S|}_i\right)^2} \tag{2}$$

where $\overline{|S|}_i = \frac{1}{N_i}\sum_{j=1}^{N_i}|S|_{ij}$.

5.1.1.2. Summary of magnitude measurements made for all six participant results

The mean S-parameter magnitude (expressed in dB) for all six participant results, $\overline{|S|}(\mathrm{dB})$, is given by equation (3) (with $M = 6$):

$$\overline{|S|}(\mathrm{dB}) = 20\log_{10}\left(\frac{1}{M}\sum_{i=1}^{M}\overline{|S|}_i\right) \tag{3}$$

The standard deviation in S-parameter magnitude (expressed in dB) for all six participant results, $u(|S|)(\mathrm{dB})$, is given by equation (4) (with $M = 6$) [2]:

$$\mathrm{SD}(|S|)(\mathrm{dB}) = \frac{8.686}{\overline{|S|}}\sqrt{\frac{1}{M - 1}\sum_{i=1}^{M}\left(\overline{|S|}_i - \overline{|S|}\right)^2} \tag{4}$$

where $\overline{|S|} = \frac{1}{M}\sum_{i=1}^{M}\overline{|S|}_i$.

5.1.2. Summary statistics for phase values

In order to avoid difficulties arising from phase wrapping, measured phase values are ‘unwrapped’ (i.e. numerical discontinuities at +180° and -180° are removed by subtracting multiples of 360°) prior to the calculation of mean and standard deviation phase statistics.

5.1.2.1. Summary of repeat phase measurements made for the ith participant result

The mean S-parameter phase for participant result i, $\bar{\phi}_i$, is given by equation (5):

$$\bar{\phi}_i = \frac{1}{N_i}\sum_{j=1}^{N_i}\phi_{ij}. \tag{5}$$

The standard deviation in S-parameter phase for participant result i, SD(ϕ_i), is given by equation (6):

$$\text{SD}(\phi_i) = \sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{N_i}\left(\phi_{ij} - \bar{\phi}_i\right)^2} \tag{6}$$

5.1.2.2. Summary of phase measurements made for all six participant results

The mean S-parameter phase for all six participant results, $\bar{\phi}$, is given by equation (7):

$$\bar{\phi} = \frac{1}{M}\sum_{i=1}^{M}\bar{\phi}_i. \tag{7}$$

The standard deviation in S-parameter phase for all six participant results, SD(ϕ), is given by equation (8):

$$\text{SD}(\phi) = \sqrt{\frac{1}{M - 1}\sum_{i=1}^{M}(\bar{\phi}_i - \bar{\phi})^2} \tag{8}$$

5.1.2.3. Summary of normalised phase measurements made for all six participant results

The normalised mean S-parameter phase for participant result *I*, $Norm(\bar{\phi}_\iota)$, is given by equation (9):

$$Norm(\bar{\phi}_\iota) = \bar{\phi}_\iota - \bar{\phi} \tag{9}$$

i.e. it is the difference between the mean S-parameter phase for participant result *i* and the mean S-parameter phase for all six participant results. The normalised mean phase for S_{12} and S_{21} of the straight waveguide section is plotted in figures 11d and 12d respectively. The standard deviation in the normalised mean phase for S_{12} and S_{21} is plotted in figures 11e and 12e respectively.

5.1.3. Reciprocity for the 1” straight waveguide section

Let *A* and *B* represent S_{21} and S_{12} of the 1” waveguide, respectively, where

$$A = S_{21} = |A|\angle\alpha$$

And

$$B = S_{12} = |B|\angle\beta.$$

Let the mean magnitude and phase quantities measured by participant i be $|\bar{A}|_i$, $|\bar{B}|_i$, $\bar{\alpha}_i$ and $\bar{\beta}_i$. The magnitude reciprocity for participant i (expressed in dB), $R_i(\text{dB})$, is given by equation (10):

$$R_i(\text{dB}) = 20\log_{10}\left(\frac{|\bar{A}|_i}{|\bar{B}|_i}\right) = 20\log_{10}|\bar{A}|_i - 20\log_{10}|\bar{B}|_i \tag{10}$$

The phase reciprocity for participant i, ψ_i, is given by equation (11):

$$\psi_i = \bar{\alpha}_i - \bar{\beta}_i. \tag{11}$$

6 RESULTS

For all figures, the participant results are presented as coloured traces as described in Table 5, where the three sets of results for Participant C are shown as C_1, C_2, C_3.

Table 5. Legend for Participant Results

Participant Result	**Colour of Trace**
A	Orange
B	Yellow
C_1	Grey
C_2	Purple
C_3	Dark Blue
D	Light Blue
All Participant Results	Green

6.1. 10 DB ATTENUATOR

6.1.1. Reflection coefficients (S_{11} and S_{22})

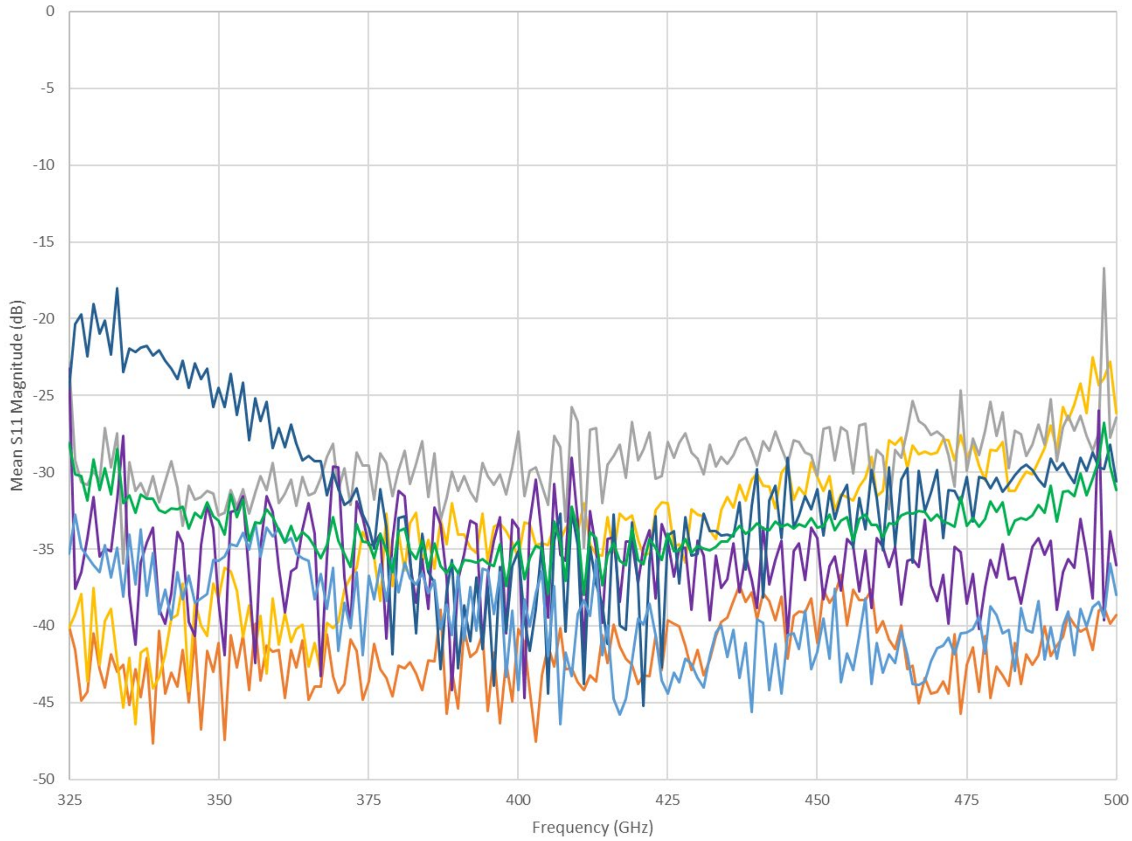

Figure 1a. 10 dB attenuator - S_{11} mean magnitude (dB)

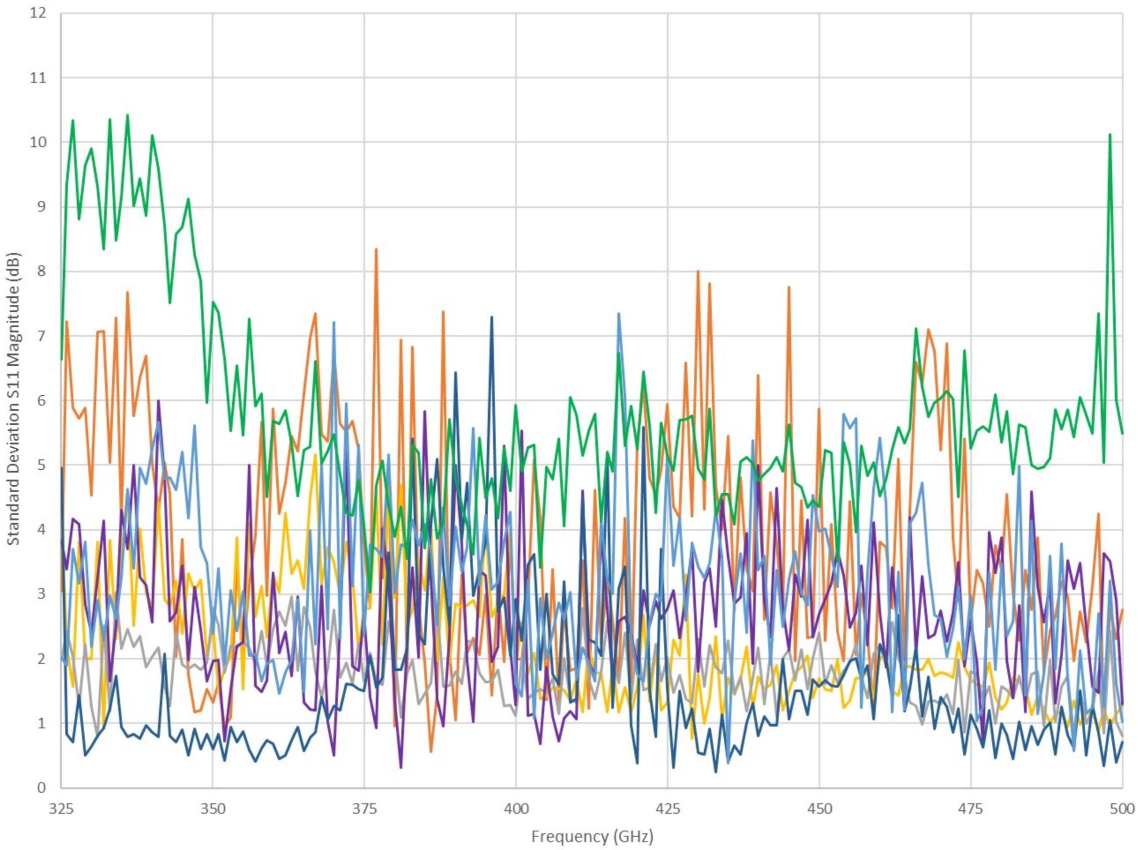

Figure 1b. 10 dB attenuator - S_{11} standard deviation magnitude (dB)

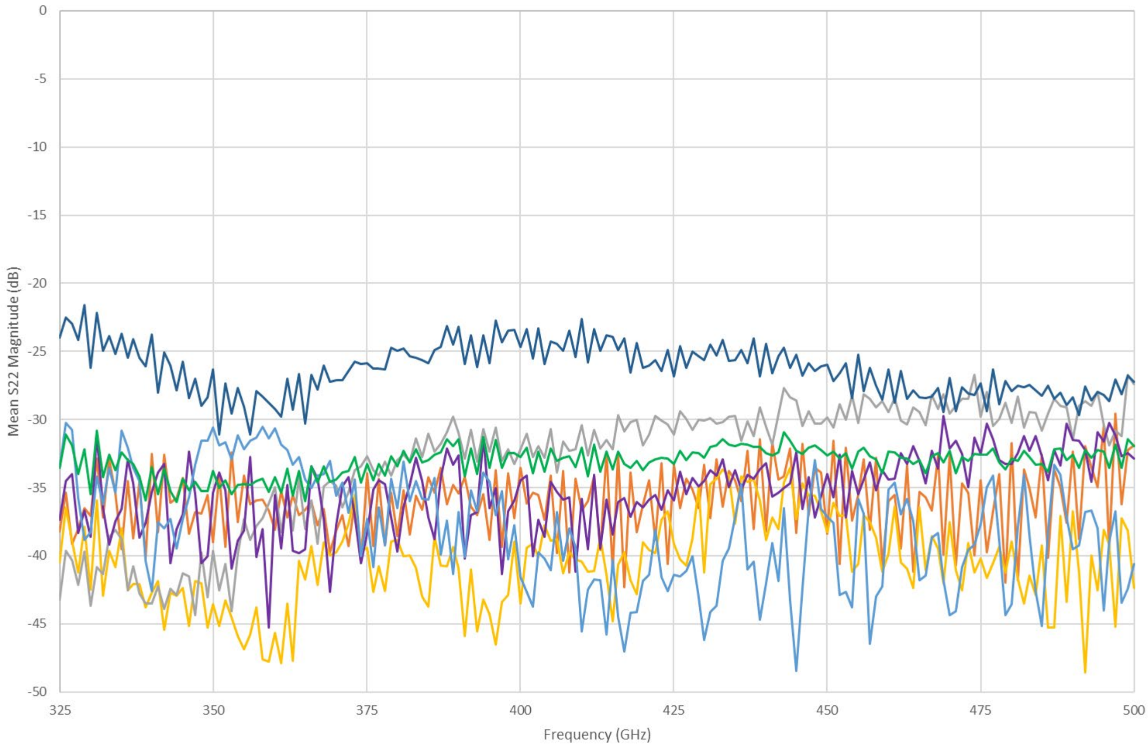

Figure 2a. 10 dB Attenuator - S_{22} Mean Magnitude (dB)

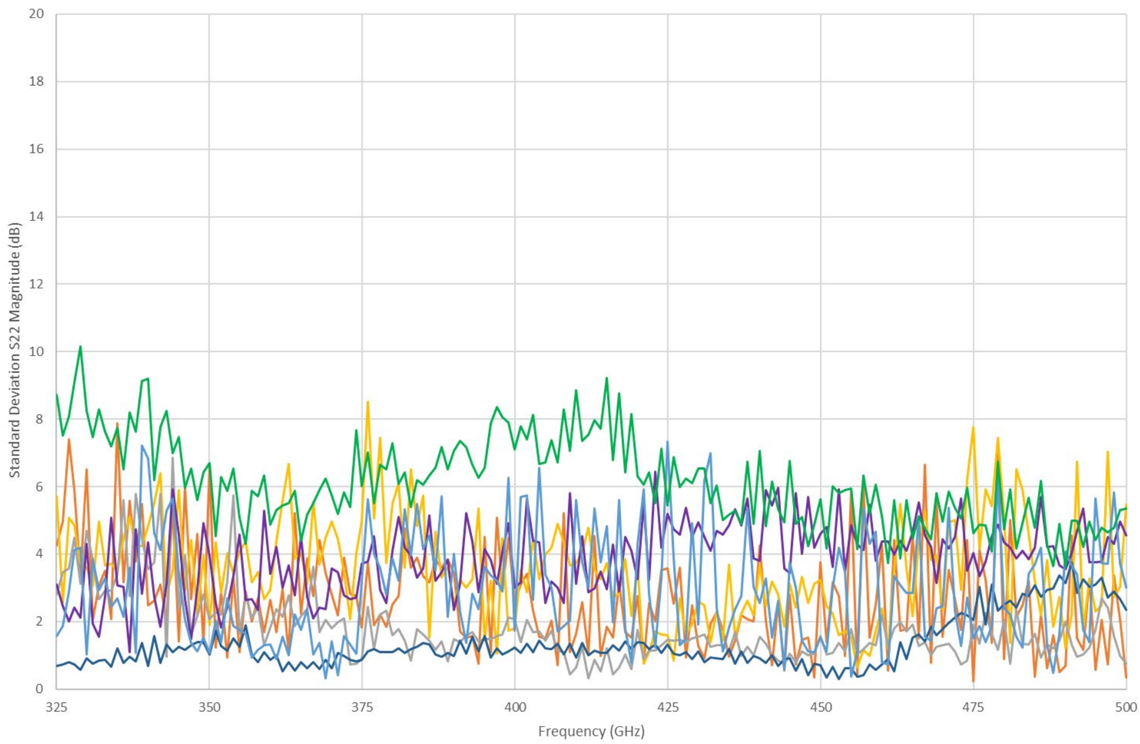

Figure 2b. 10 dB Attenuator - S_{22} Standard Deviation Magnitude (dB)

6.1.2. Transmission coefficients (S_{21} and S_{12})

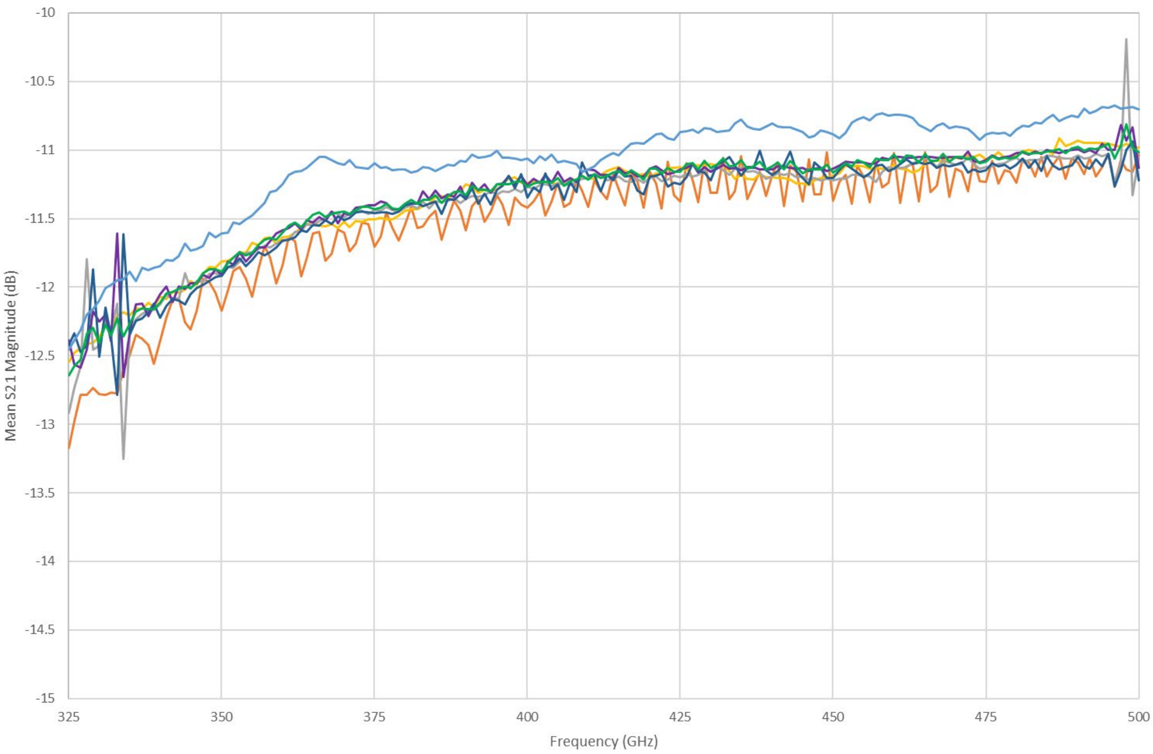

Figure 3a. 10 dB Attenuator - S_{21} Mean Magnitude (dB)

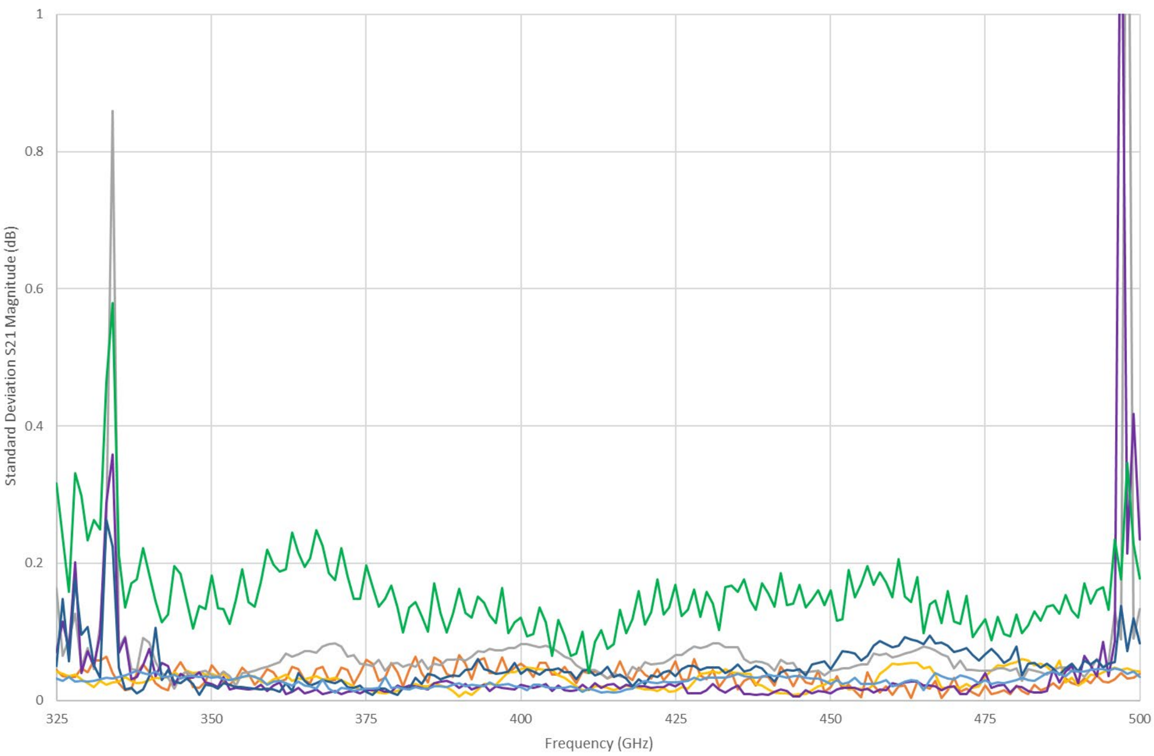

Figure 3b. 10 dB Attenuator - S_{21} Standard Deviation Magnitude (dB)

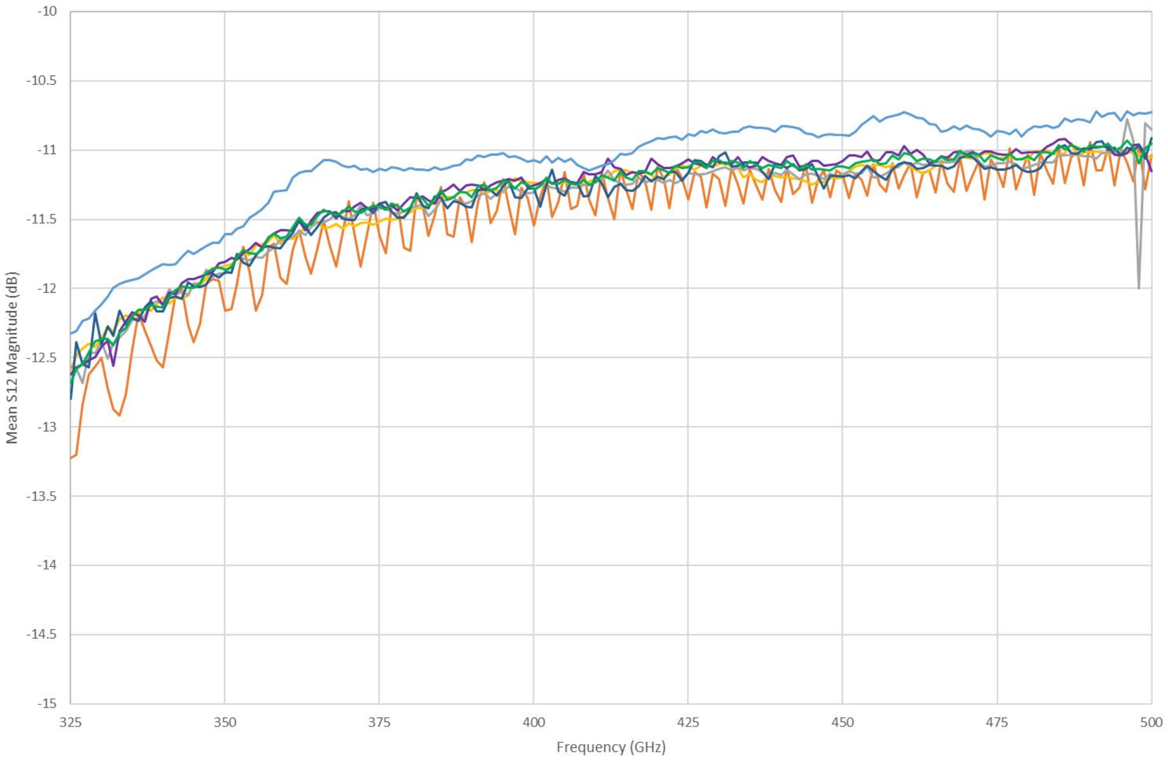

Figure 4a. 10 dB Attenuator – S_{12} Mean Magnitude (dB)

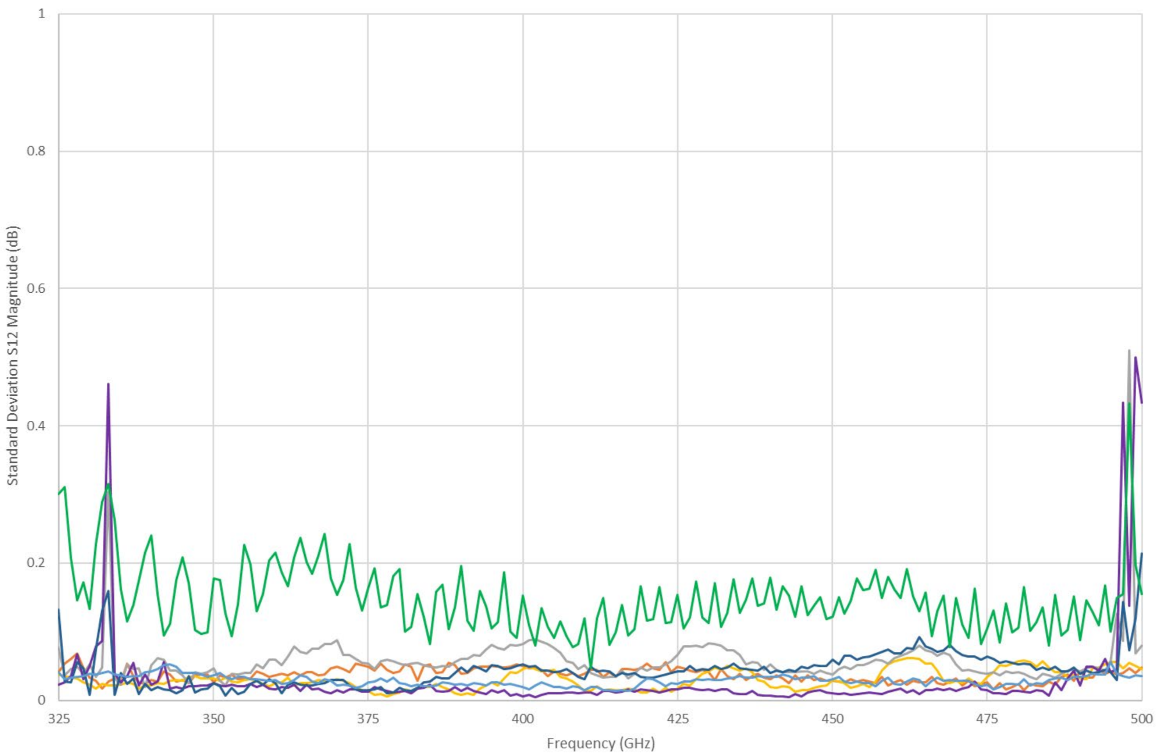

Figure 4b. 10 dB Attenuator - S_{12} Standard Deviation Magnitude (dB)

6.2. ¼-WAVE CROSS-GUIDE

6.2.1. Transmission coefficients (S_{21} and S_{12})

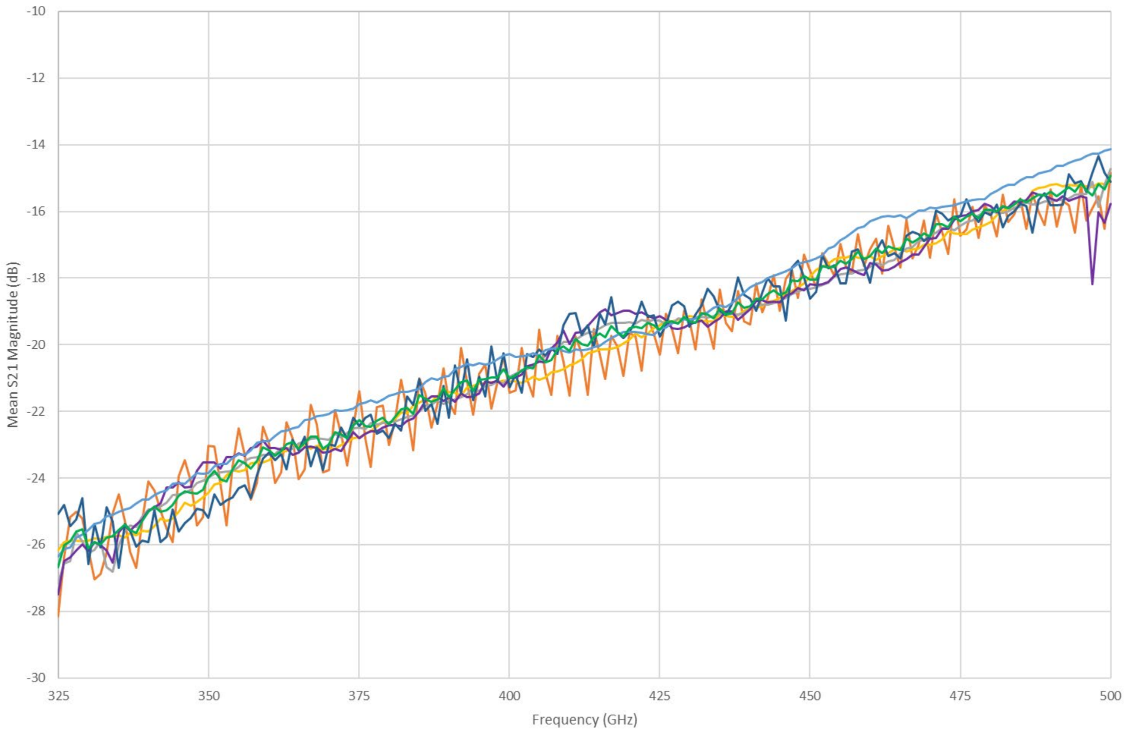

Figure 5a. 1/4-Wave Cross-Guide Line – S_{21} Mean Magnitude (dB)

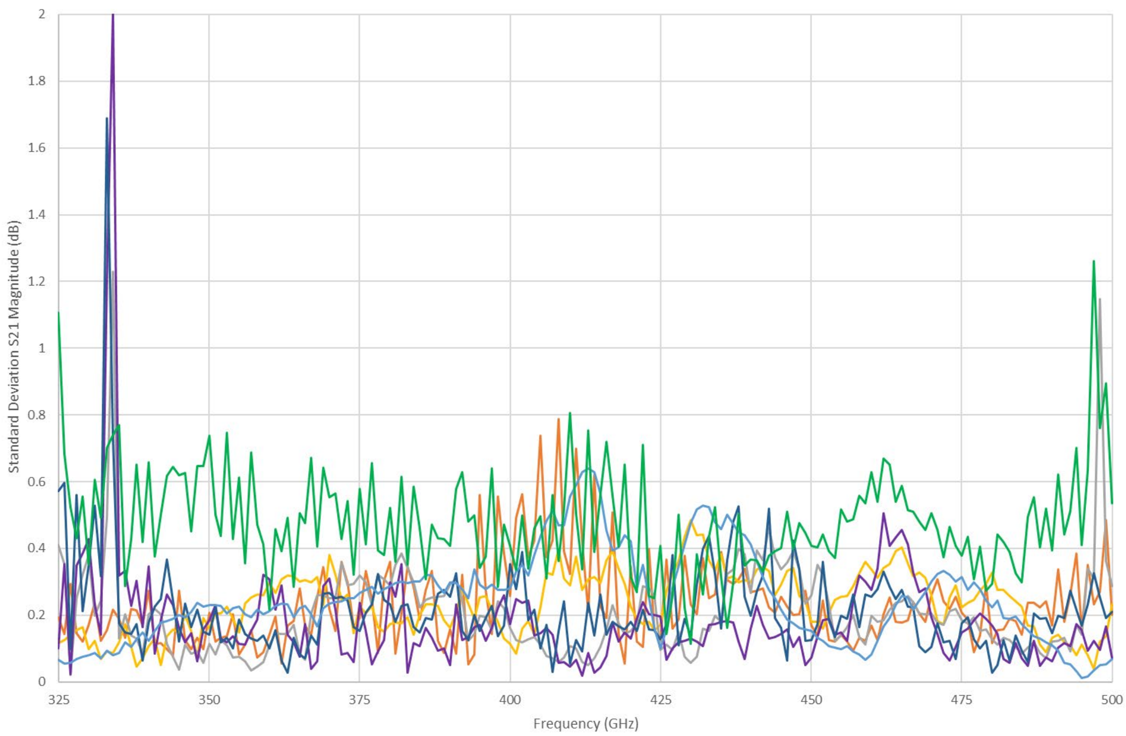

Figure 5b. 1/4-Wave Cross-Guide Line - S_{21} Standard Deviation Magnitude (dB)

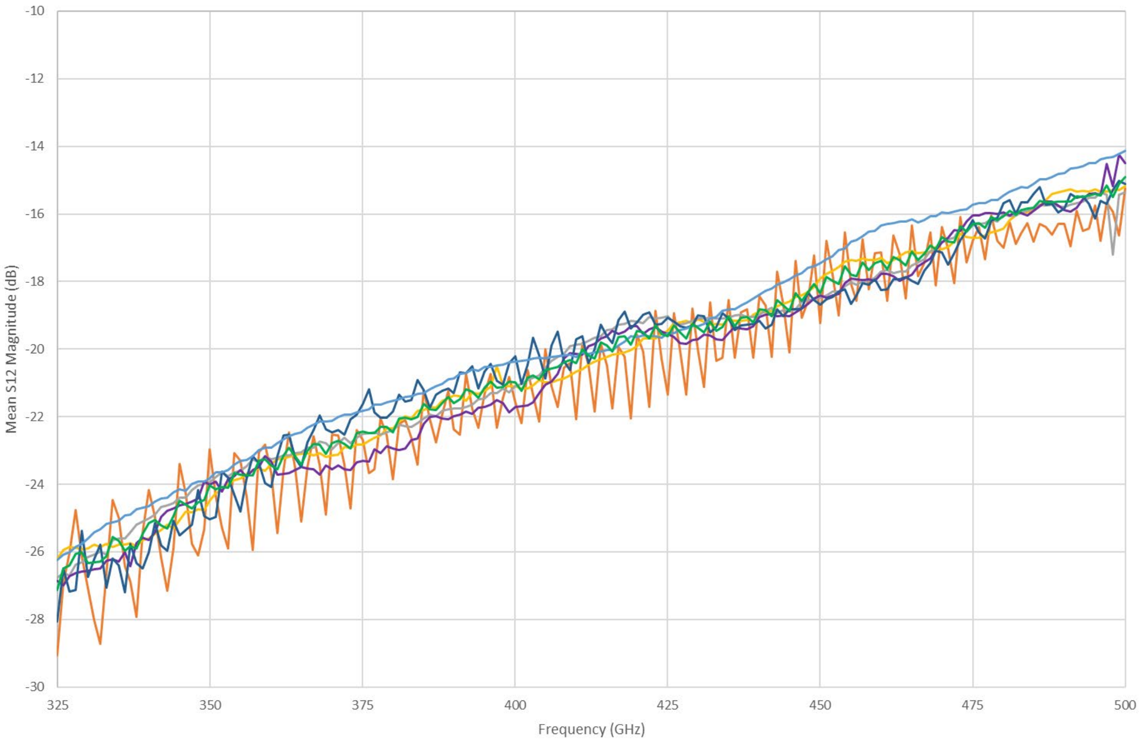

Figure 6a. 1/4 -Wave Cross-Guide Line - S_{12} Mean Magnitude (dB)

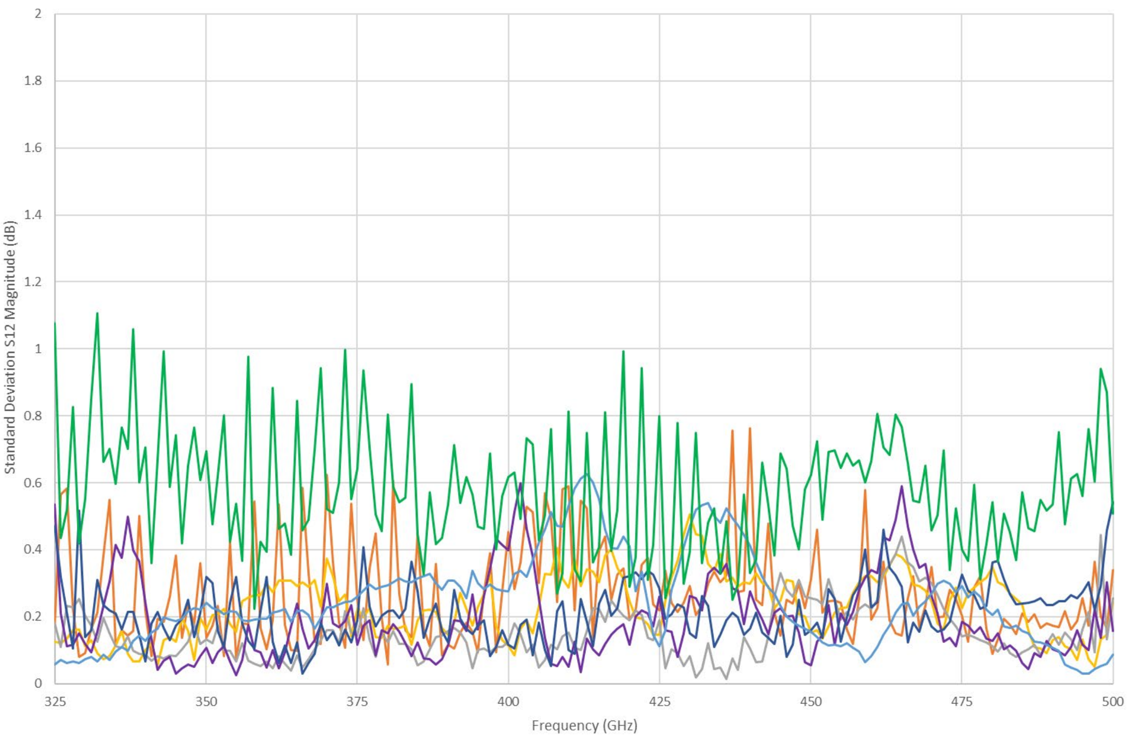

Figure 6b. ¼-Wave Cross-Guide Line - S_{12} Standard Deviation Magnitude (dB)

6.3. OFFSET SHORT-CIRCUIT

6.3.1. Reflection coefficient (S_{11})

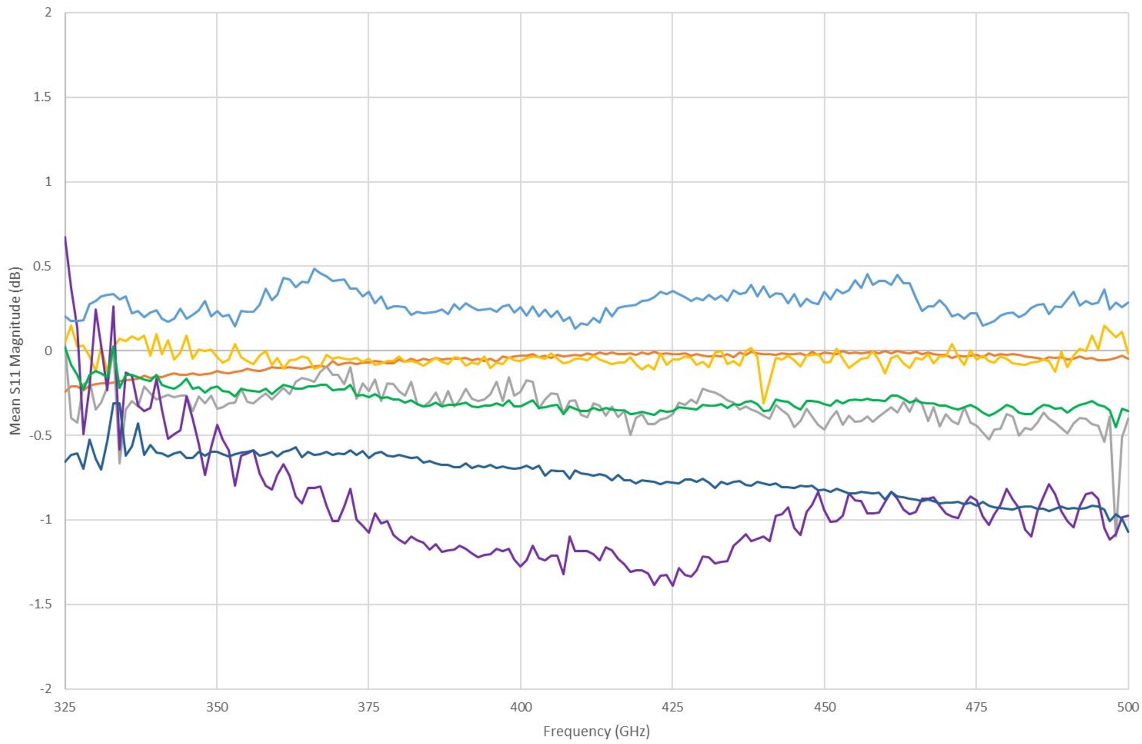

Figure 7a. Offset Short-Circuit - S_{11} Mean Magnitude (dB)

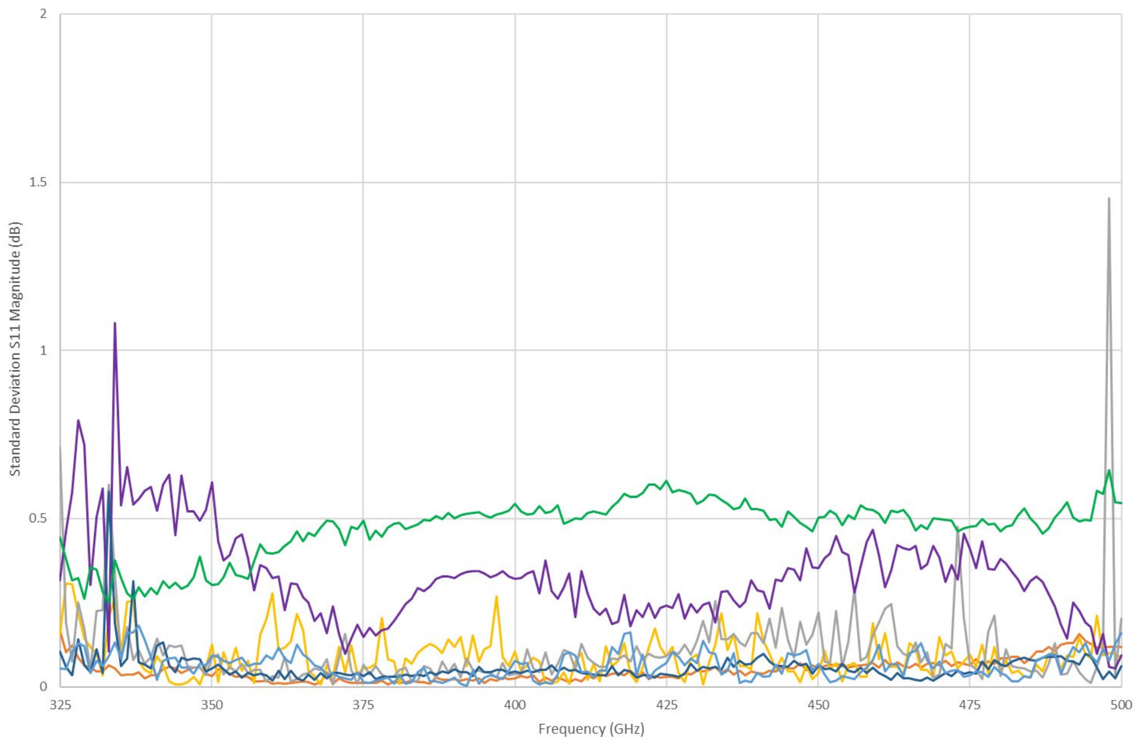

Figure 7b. Offset Short-Circuit - S_{11} Standard Deviation Magnitude (dB)

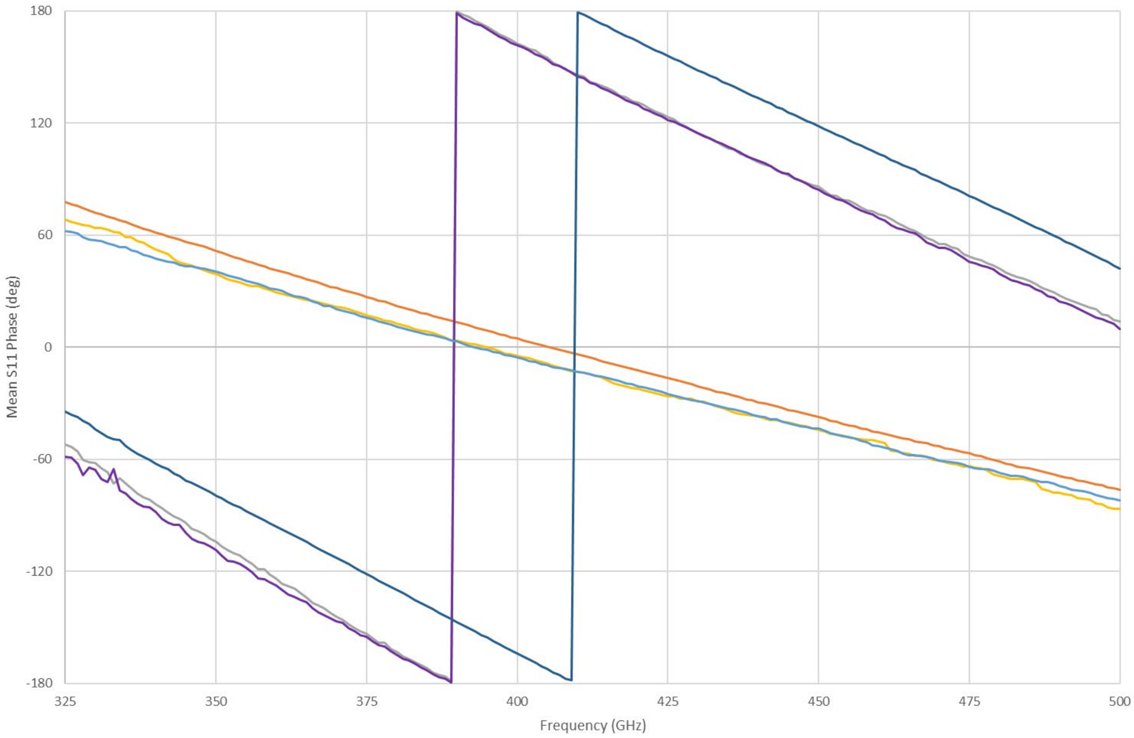

Figure 7c. Offset Short-Circuit - S_{11} Mean Phase

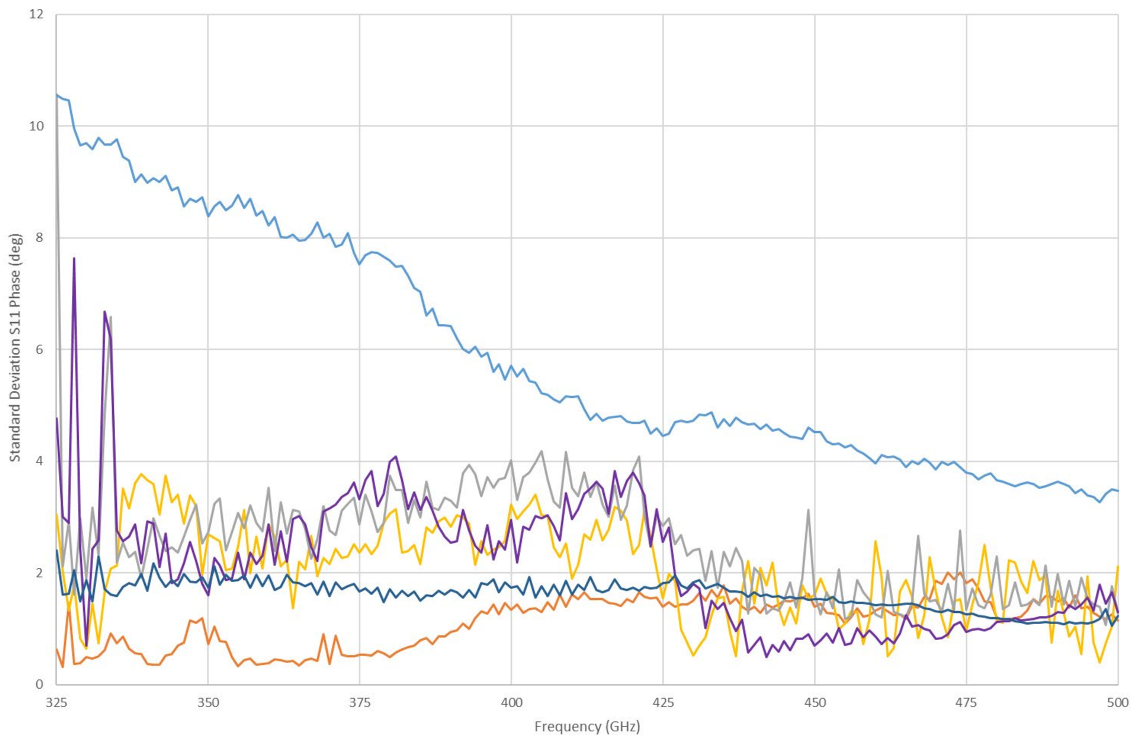

Figure 7d. Offset Short-Circuit - S_{11} Standard Deviation Phase

6.4. TERMINATION

6.4.1. Reflection coefficient (S_{11})

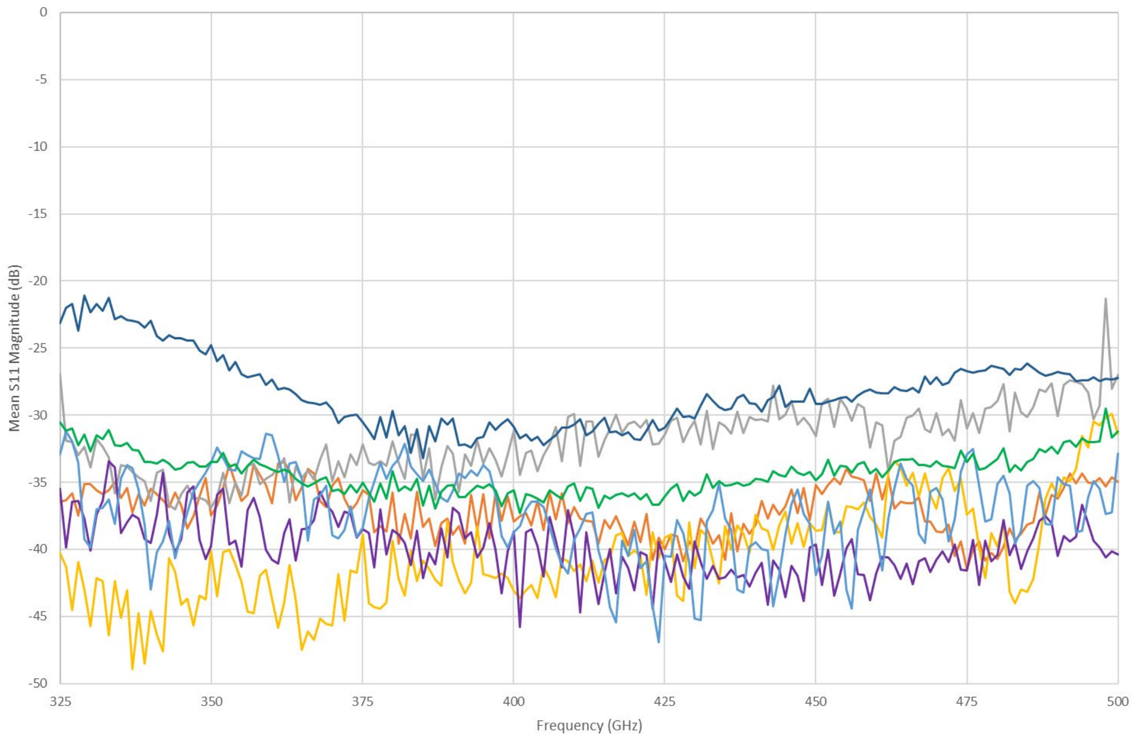

Figure 8a. Termination - S_{11} Mean Magnitude (dB)

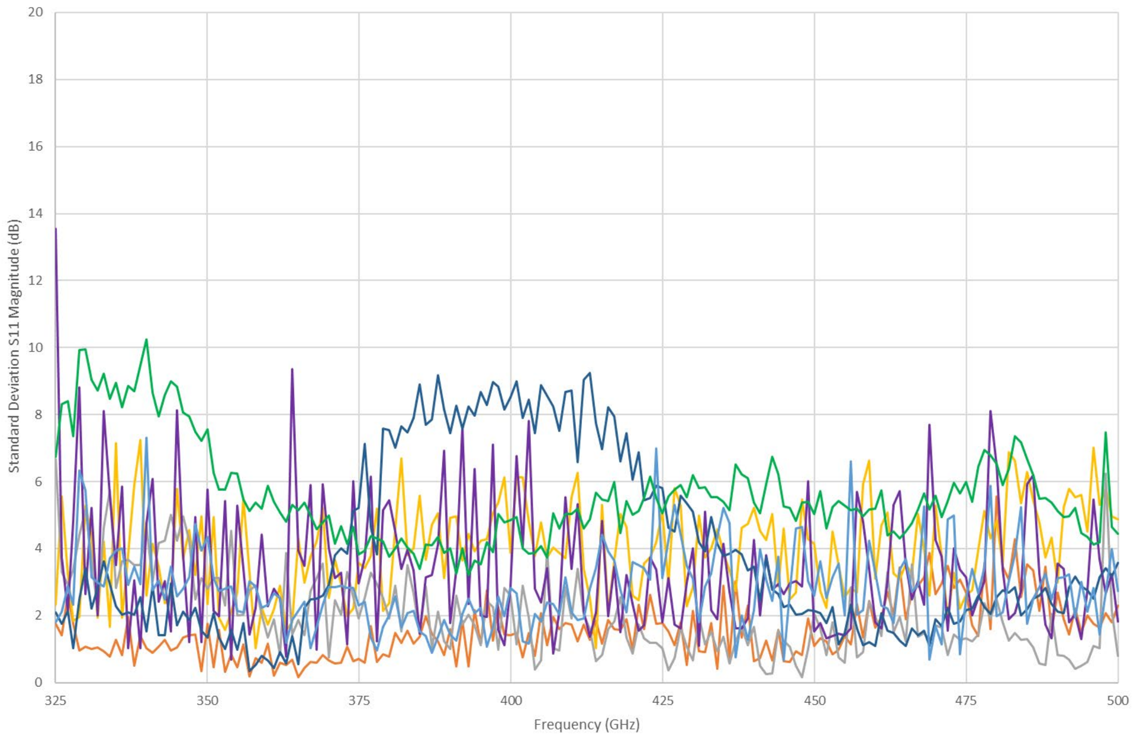

Figure 8b. Termination - S_{11} Standard Deviation Magnitude (dB)

6.5. 1” STRAIGHT WAVEGUIDE SECTION

6.5.1. Reflection coefficients (S_{11} and S_{22})

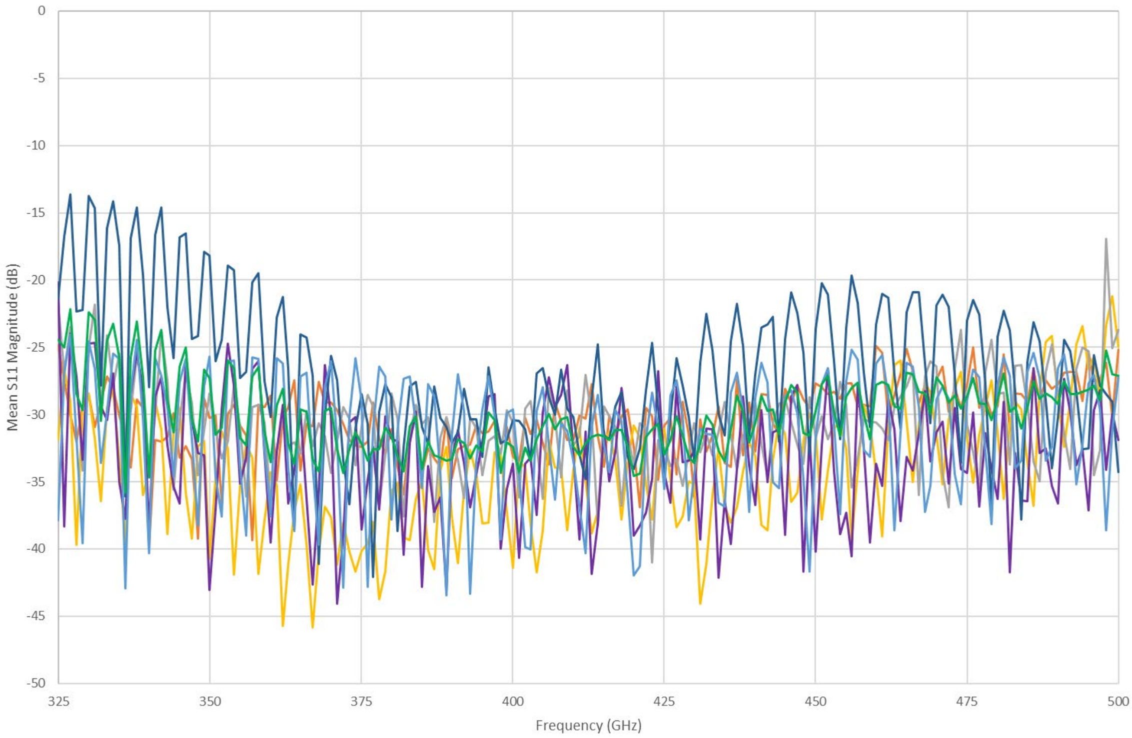

Figure 9a. 1” Straight Waveguide - S_{11} Mean Magnitude (dB)

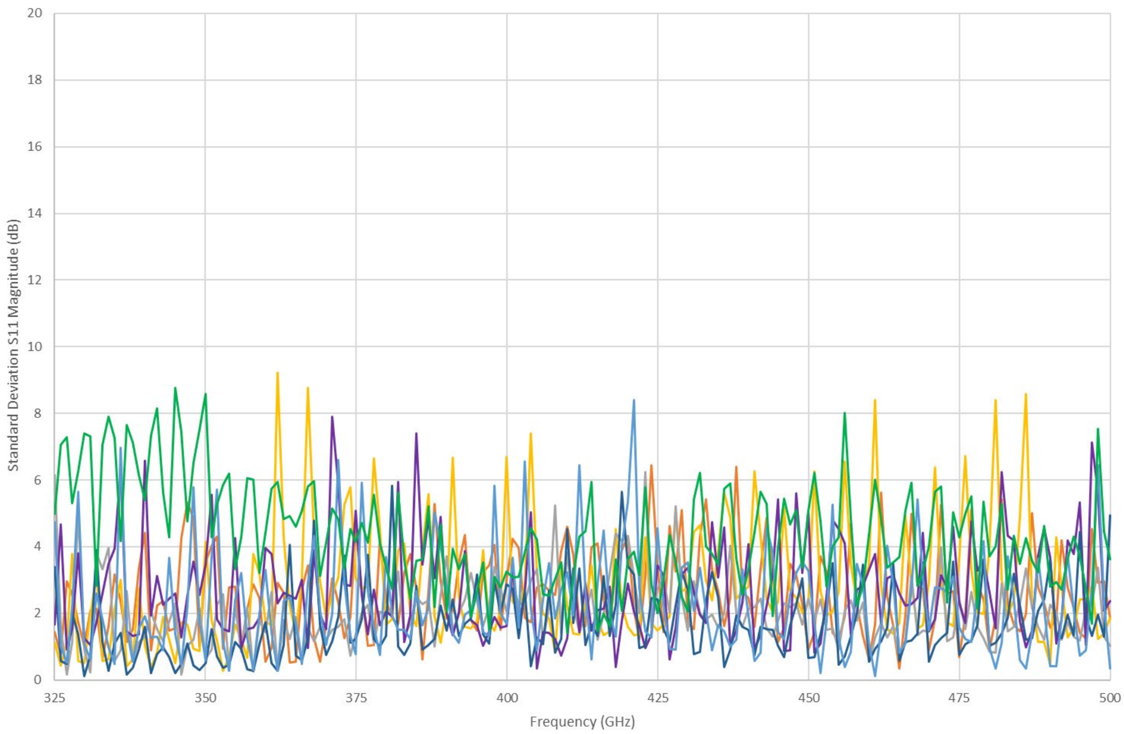

Figure 9b. 1” Straight Waveguide - S_{11} Standard Deviation Magnitude (dB)

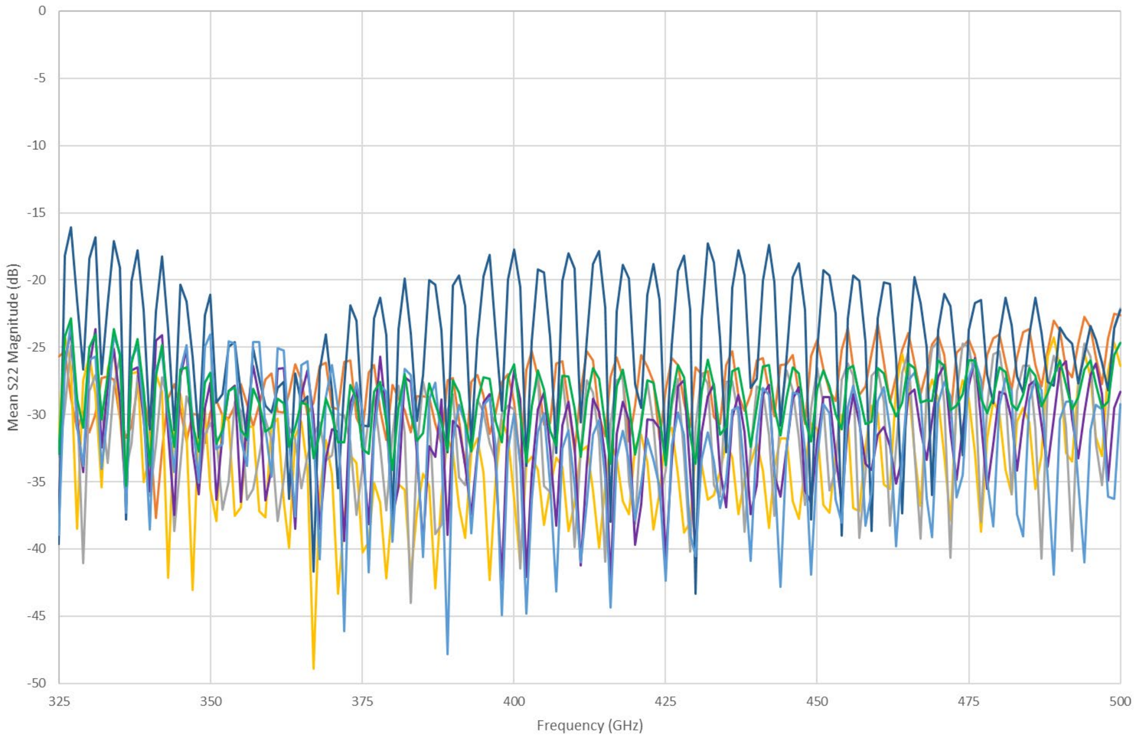

Figure 10a. 1” Straight Waveguide - S_{22} Mean Magnitude (dB)

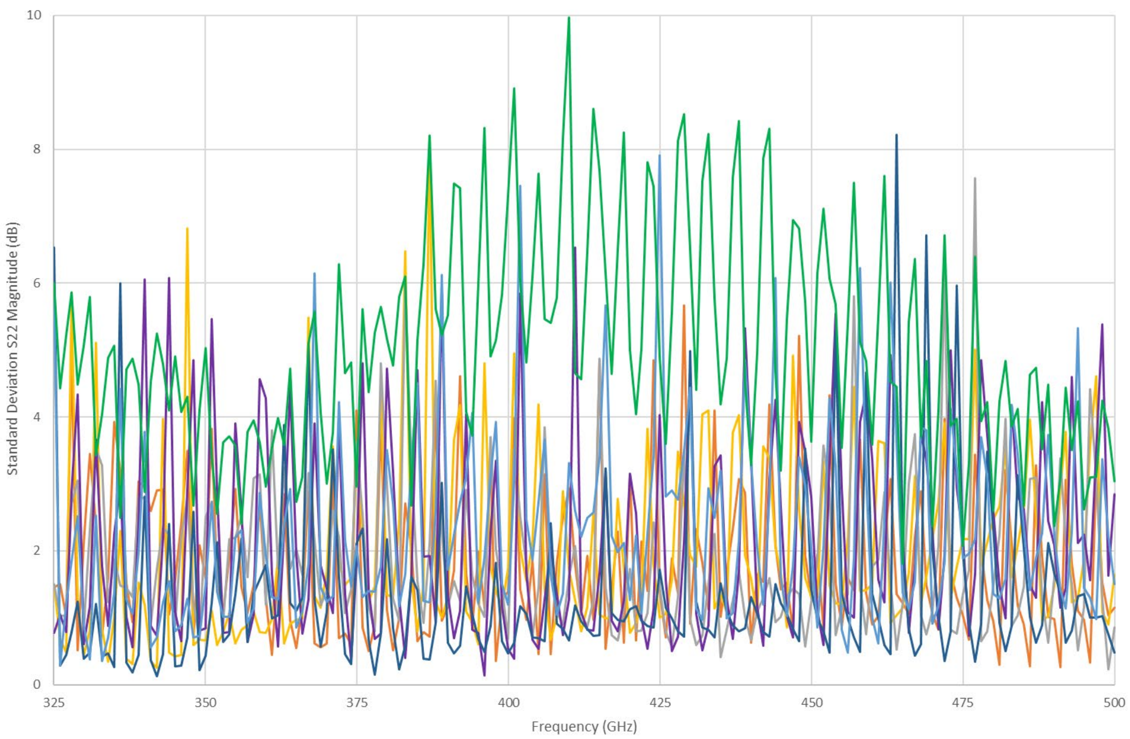

Figure 10b. 1” Straight Waveguide - S_{22} Standard Deviation Magnitude (dB)

6.5.2. Transmission coefficients (S_{21} and S_{12})

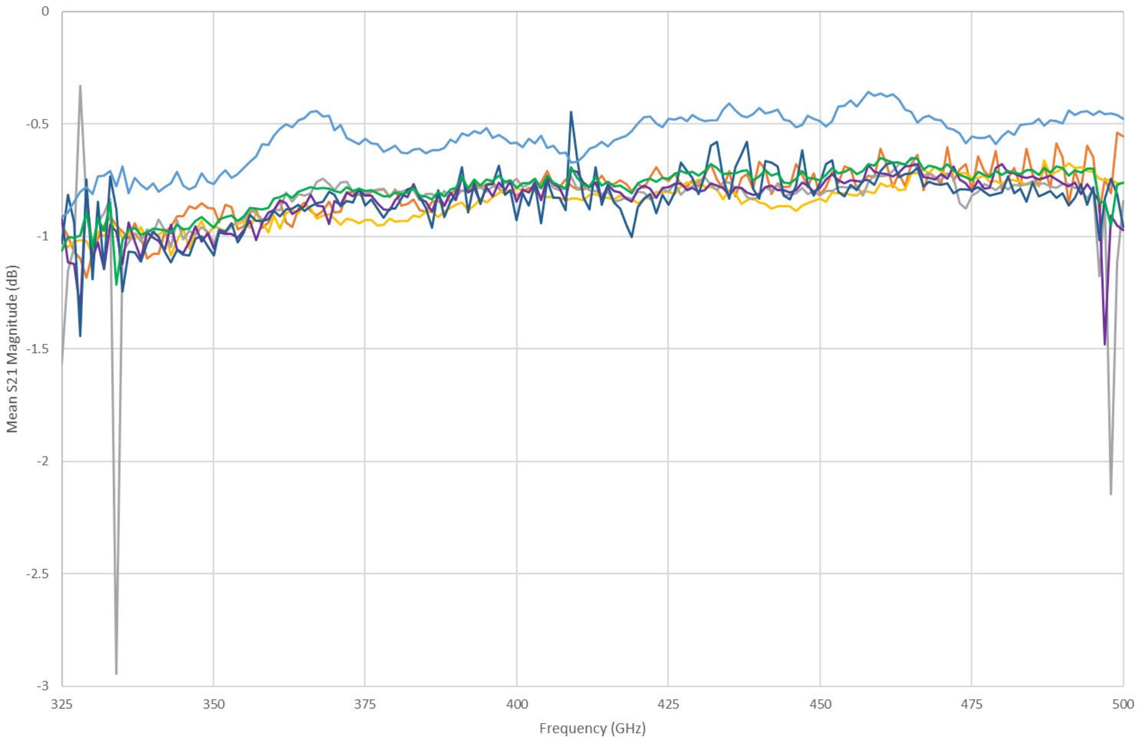

Figure 11a. 1” Straight Waveguide - S_{21} Mean Magnitude (dB)

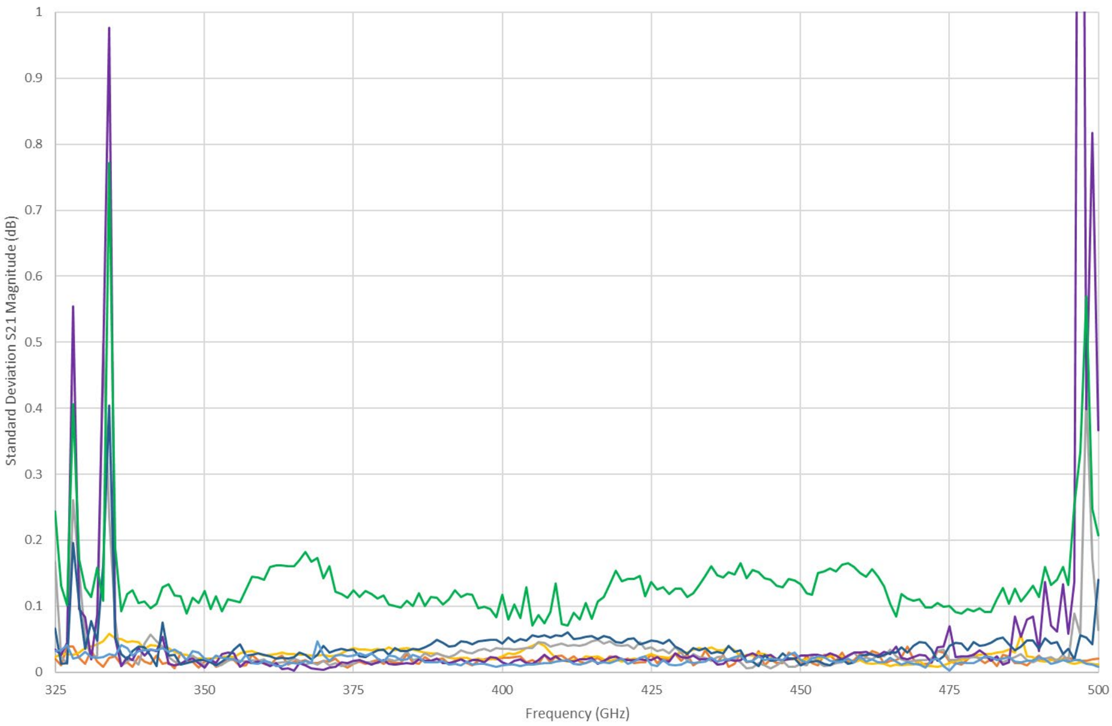

Figure 11b. 1” Straight Waveguide - S_{21} Standard Deviation Magnitude (dB)

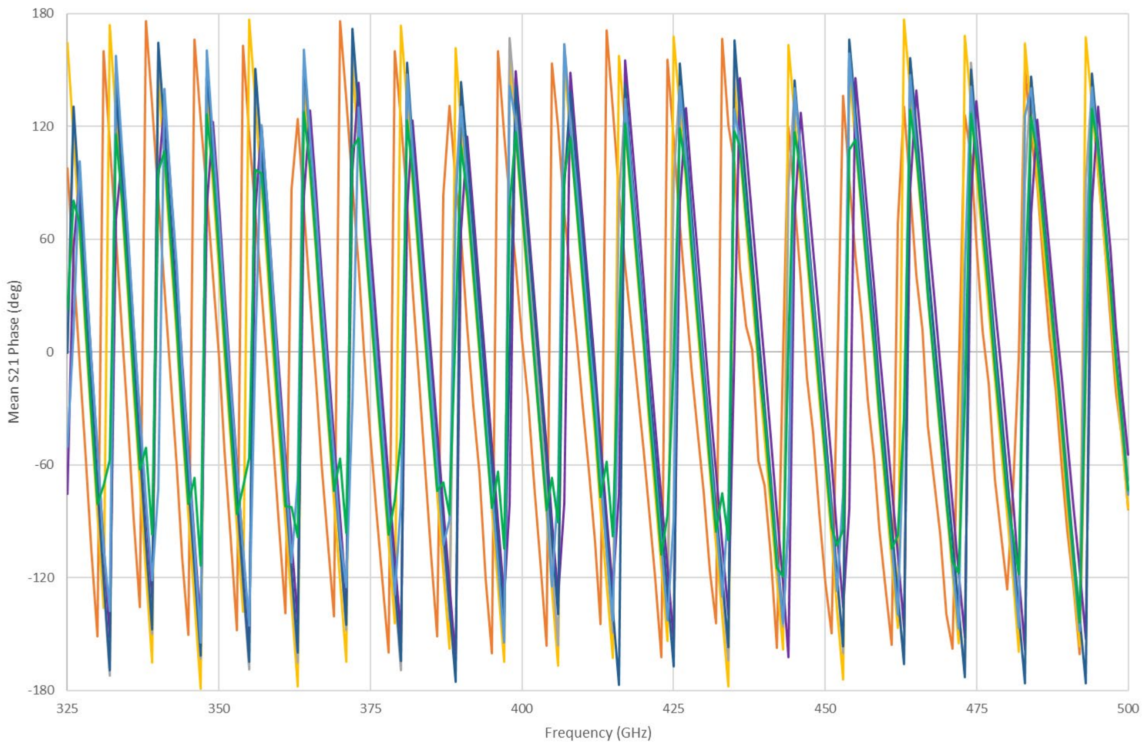

Figure 11c. 1" Straight Waveguide - S_{21} Mean Phase

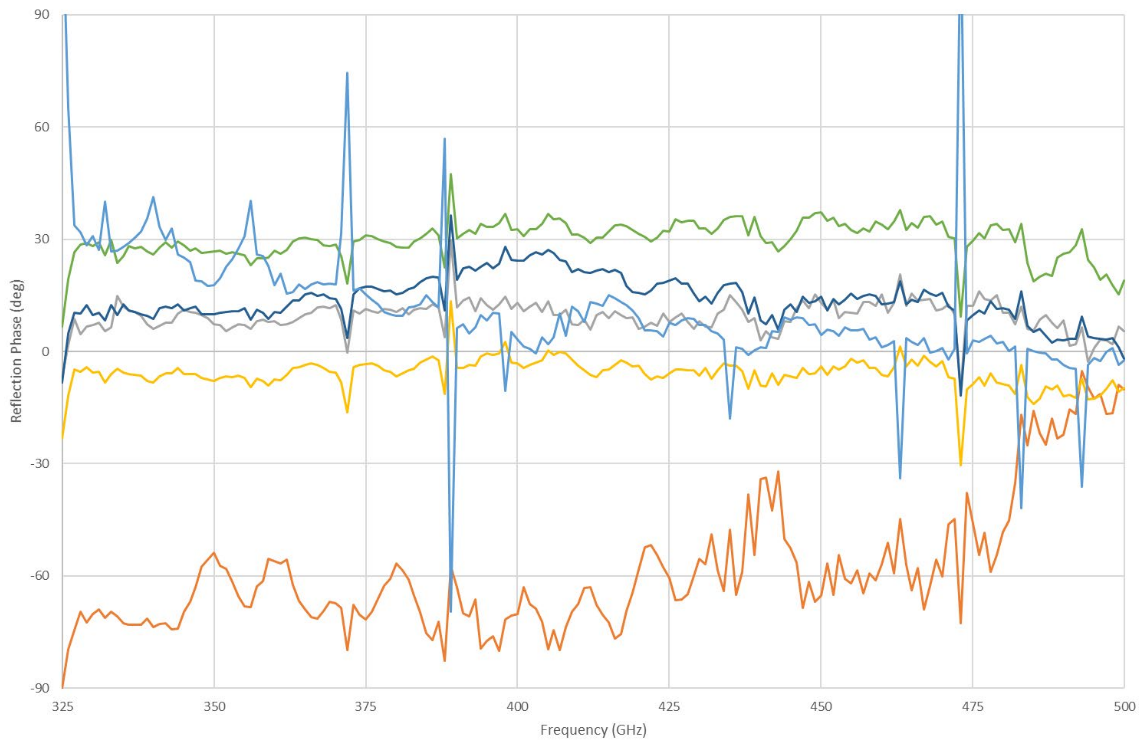

Figure 11d. 1" Straight Waveguide - S_{21} Mean Phase (Normalised)

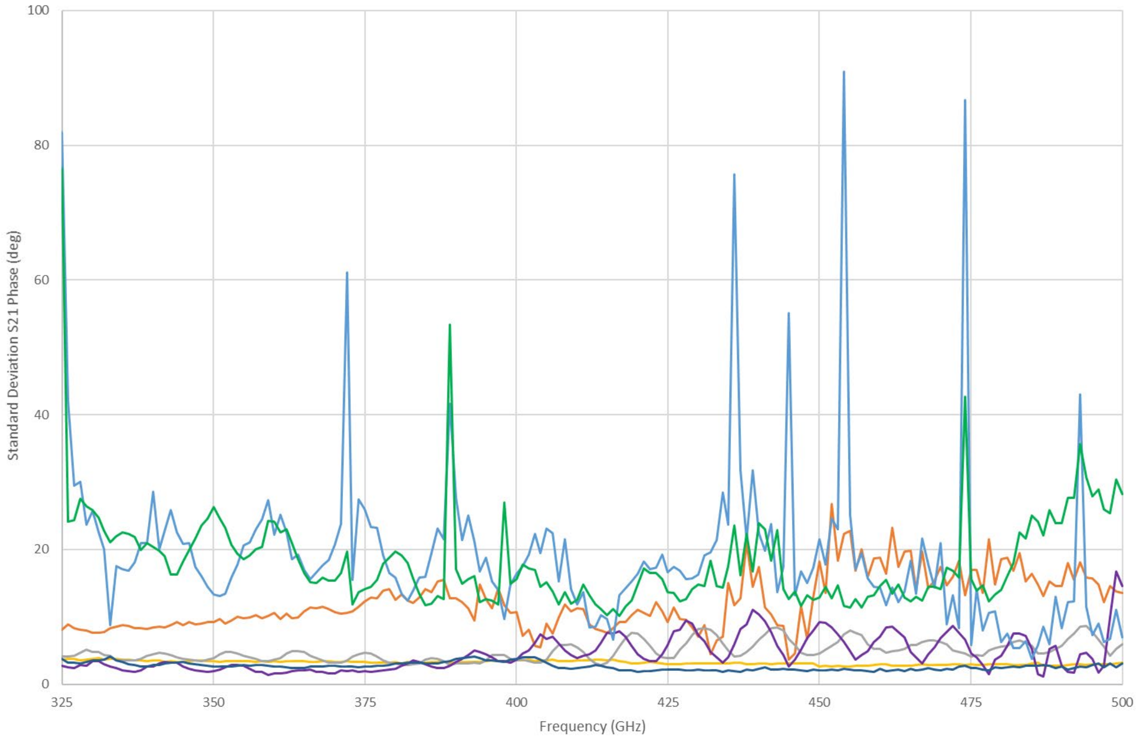

Figure 11e. 1" Straight Waveguide - S_{21} Standard Deviation Phase

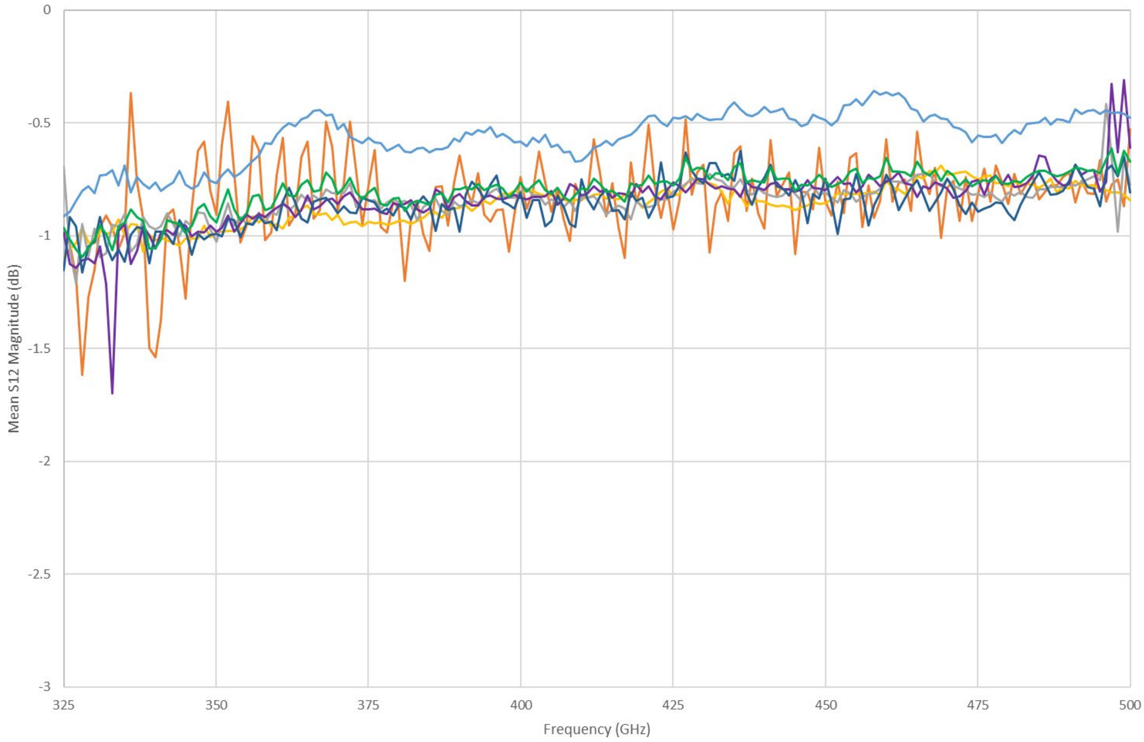

Figure 12a. 1" Straight Waveguide - S_{12} Mean Magnitude (dB)

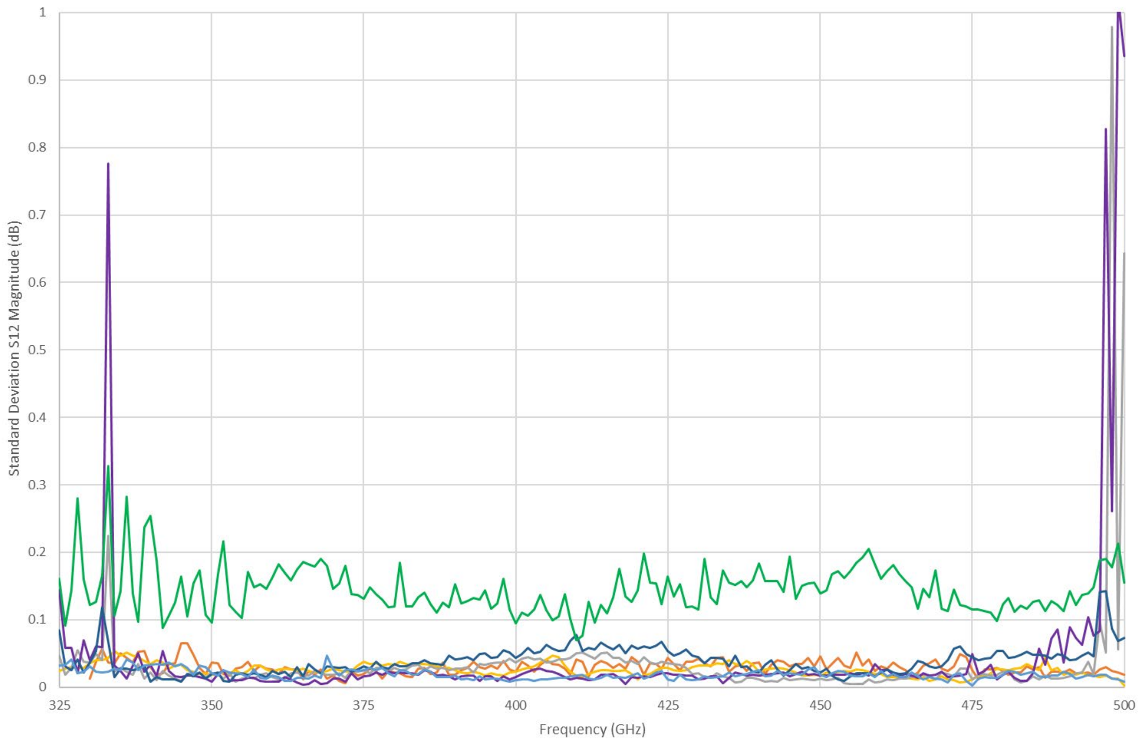

Figure 12b. 1" Straight Waveguide - S_{12} Standard Deviation Magnitude (dB)

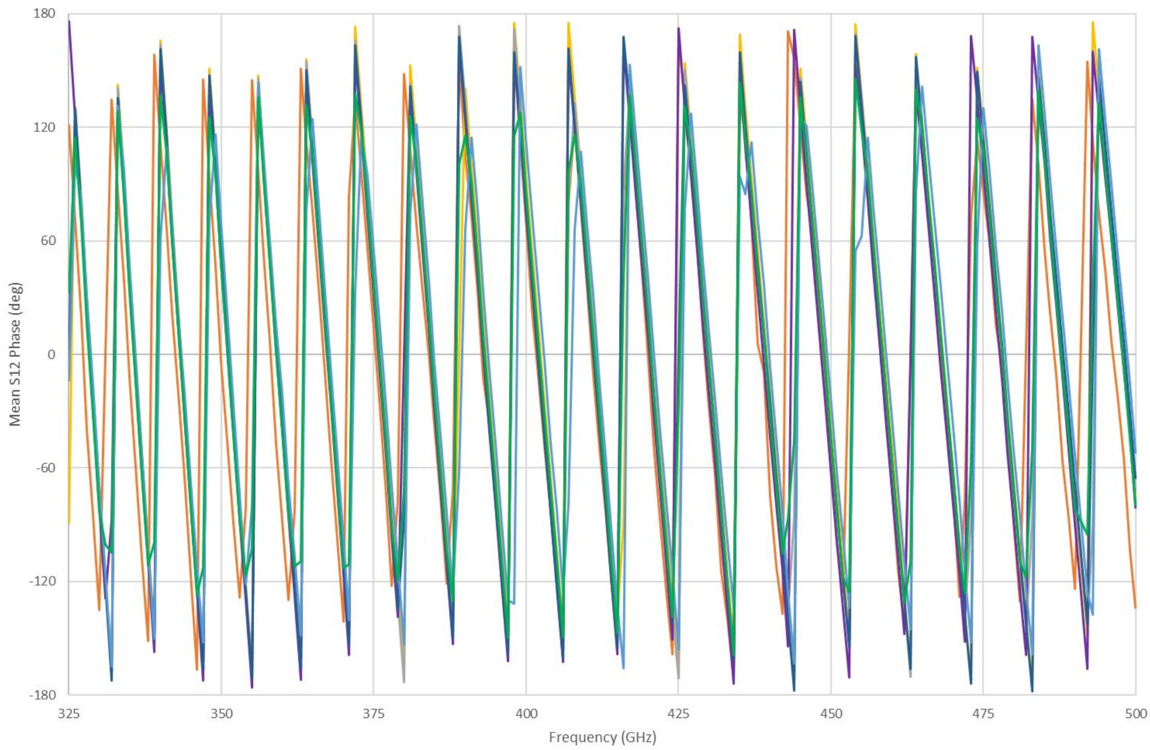

Figure 12c. 1" Straight Waveguide - S_{12} Mean Phase

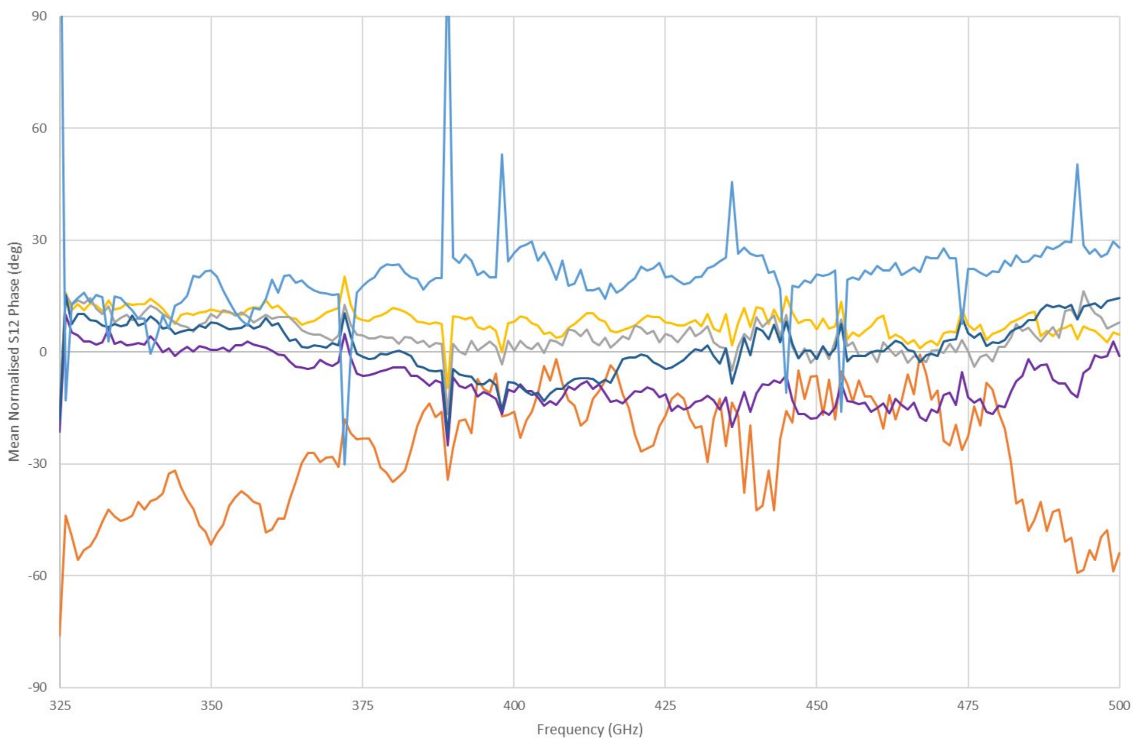

Figure 12d. 1" Straight Waveguide - S_{12} Mean Phase (Normalised)

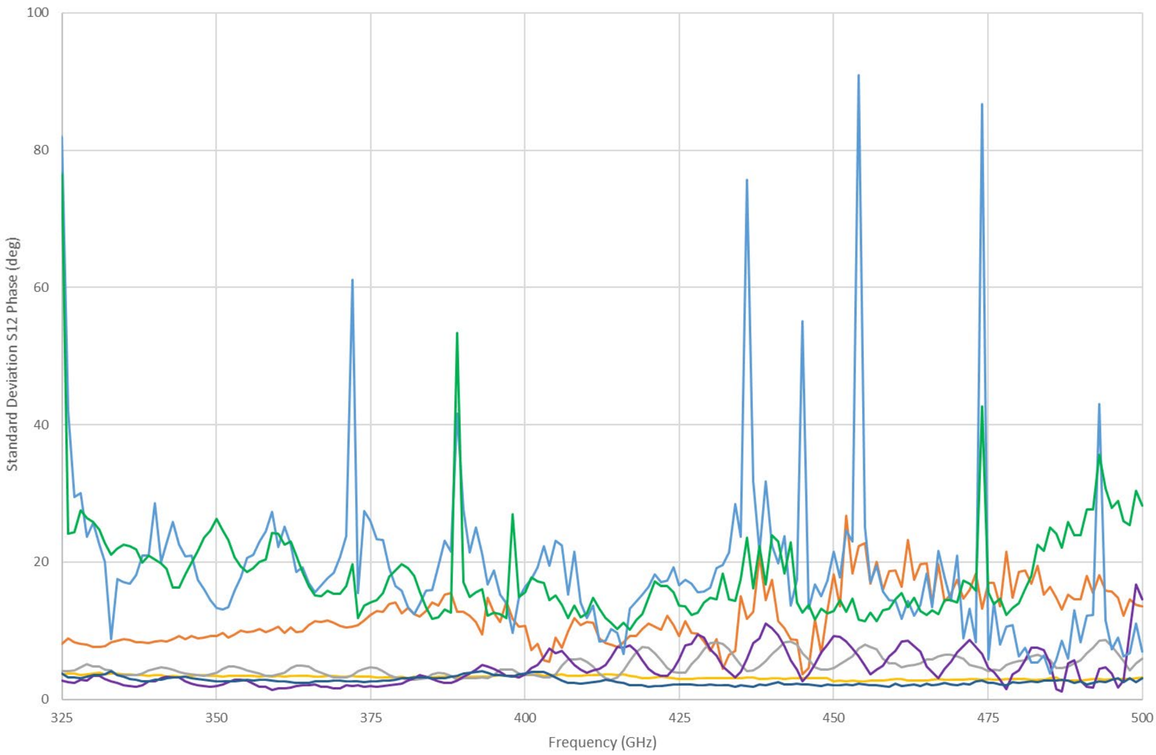

Figure 12e. 1" Straight Waveguide - S_{12} Standard Deviation Phase

6.5.3. Reciprocity

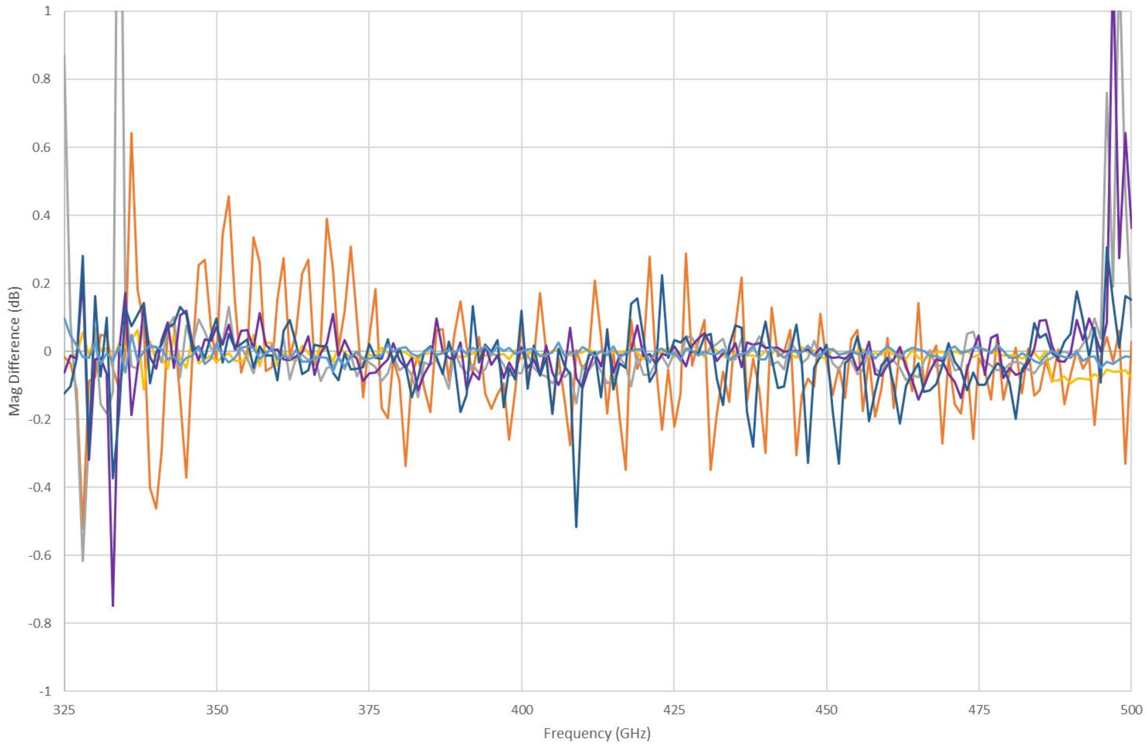

Figure 13a. 1” Straight Waveguide - Magnitude Reciprocity

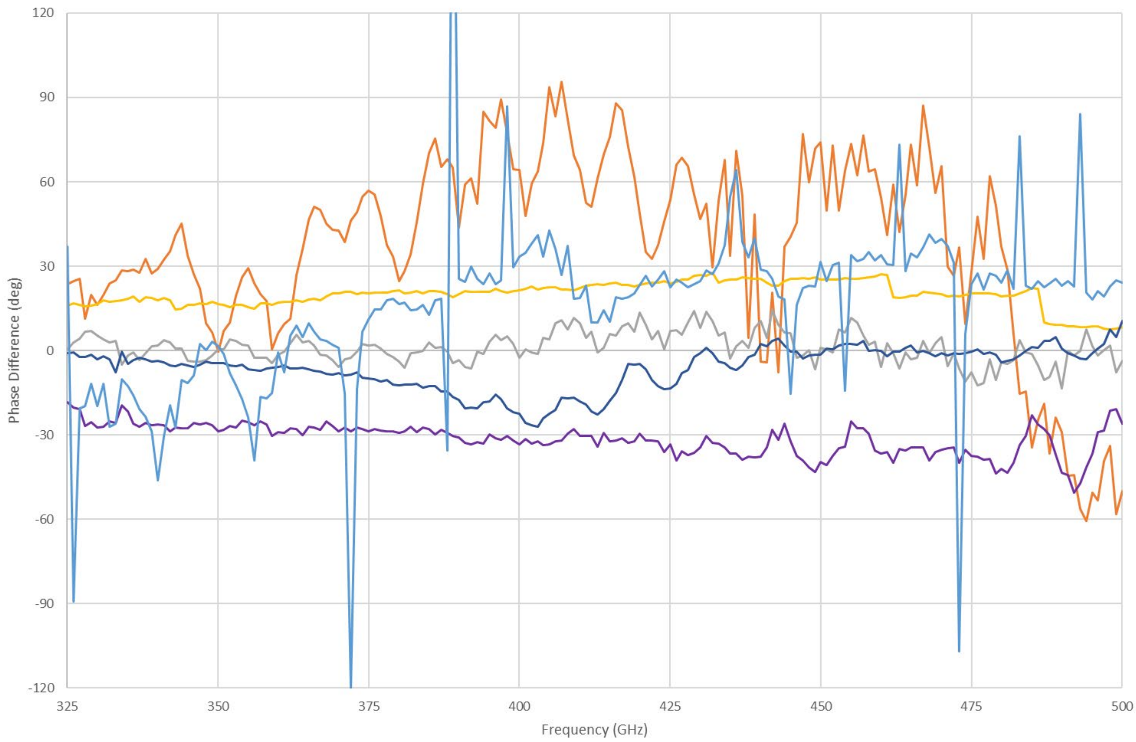

Figure 13b. 1” Straight Waveguide - Phase Reciprocity

7 OBSERVATIONS

- The participants' ability to achieve repeatable S-parameter results varied from device to device and from S-parameter to S-parameter.
- No single participant achieved the lowest standard deviation amongst the four participants for the measurement of all S-parameters. In other words, no one participant consistently showed better repeatability in their measurements than the other participants.
- It is assumed that the 1" straight waveguide is reciprocal, and so ideally the transmission magnitude and phase reciprocity plotted in figures 13a and 13b should be zero. Any observed deviations of these quantities from zero are indicative of errors in the S-parameter measurements.
- For a given S-parameter, the standard deviation for a single participant indicates the measurement repeatability achieved by the participant. The standard deviation for all participants indicates the measurement reproducibility between all participants. In most cases, the standard deviations for the individual participants are smaller than the standard deviation for all participants (with some exceptions due to outliers). This indicates that, in general, the measurement repeatability of the individual participants is significantly better than the overall between participant reproducibility.[2]
- Large spikes can be observed in figures 3b, 4b, 5b, 7b, 11b and 12b where some participants struggled to achieve repeatable results, most often at points near the band edges.
- It can be observed in figures 3a, 4a, 7a, 11a and 12a that participant D achieved outlying results. In the case of figure 7a these results are non-physical (S_{11} magnitude >0 dB across the full waveguide band). This is suggestive of a significant systematic error present in the results.
- In figure 7c, participant C's three results are very different from the results for the other three participants. This constitutes significant disagreement. For this reason, an 'All Participants' trace has not been added to this figure.
- Figures 11e and 12e show spikes in standard deviation at a number of points for Participant D. This suggests that Participant D struggled to achieve repeatable phase results at these points. This is reflected in the reciprocity results shown in figure 13b.

8 SUMMARY

This report has presented an analysis of the results obtained from a recent S-parameter measurement comparison exercise in WM-570 waveguide. In general, the results obtained by individual participants have shown good agreement.

9 ACKNOWLEDGEMENTS

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[2] This situation is common for many high frequency measurements. It indicates that the size of random errors (e.g. due to connection repeatability) is significantly less than systematic errors (e.g. due to different participants' measurement systems).

10 REFERENCES

[1] European Metrology Programme for Innovation and Research (EMPIR) Project 18SIB09 “Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies (TEMMT)”. Project website: https://projects.lne.eu/jrp-temmt/. Published 2022. Accessed July 14, 2022.

[2] N M Ridler, “Converting between logarithmic and linear formats for reflection and transmission coefficients”, ANA Tips No. 4, October 2000.