

Improvements in national standard S-parameter measurements in rectangular waveguide at millimetre-wave frequencies

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1. Abstract

The UK's National Physical Laboratory has recently introduced a primary national standard system for S-parameter impedance measurement in the millimetre wave region. The system consists of a vector network analyser used in conjunction with a desktop PC. The PC runs in-house written software for VNA control, data collection and processing. The system is used to perform measurements in metallic waveguide sizes WG23, WG25, and WG27, covering a frequency range from 33 GHz to 110 GHz. This paper describes the measurement system, the method of measurement and outlines the dominant uncertainty contributions along with typical measurement uncertainties obtained with the system.

2. Introduction

The use of millimetre frequencies is growing rapidly in many areas, including communications, automotive applications and astronomy. As a result there is a growing requirement for high measurement accuracy and traceability.

This paper describes a newly commissioned national standard impedance measurement capability for rectangular metallic waveguide in sizes WG23, WG25 and WG27, covering the frequency ranges 33 GHz to 50 GHz, 50 GHz to 75 GHz and 75 GHz to 110 GHz respectively. Altogether the system provides measurement capability across the whole millimetre band from 33 GHz to 110 GHz.

The system is based around NPL's Primary Impedance Measurement System (PIMMS) [1] and uses a vector network analyser (VNA) under the control of an external PC. The system can provide full Sparameter measurements for both one-port and two-port devices. The measurements made are directly traceable to the SI base unit of length.

3. System

The VNA's internal test set will provide frequencies up to 50 GHz, allowing WG23 measurements to be made without extra hardware. For WG25 and WG27 (50 GHz to 110 GHz), the mixers and couplers required are housed externally. Two 'pods' are connected to the front of the VNA, each is supplied with an IF and RF by the VNA and contains the appropriate equipment to form a full one-port reflection analyser. Used in conjunction, the two 'pods' form a full two-port test set.

As the 'pods' are external to the VNA and individually mounted with six (restricted) degrees of freedom, it is possible, with a little effort, to configure the system to measure devices of any design, provided that there is sufficient clearance around the device's test ports.

4. Measurements

The PIMMS software is the cornerstone of the measurement system. It allows pre-definition of the measurement configuration, including line size, calibration technique and the specifics of the calibration artefacts. It also requires entry of the devices under test (DUTs). All the information regarding any specific measurement is stored locally and can be recalled at any time to reproduce a measurement environment. This permanent

electronic record forms a ‘soft’-notebook and ensures that no measurements can be made without the appropriate laboratory notes being recorded.

Once all the required information is entered into the software, the control of the process is handed over to the computer, which provides on-screen prompts for the operator and controls every aspect of the operation of the VNA. The operator’s task becomes one of ensuring good connections of the correct devices as they are requested by the software.

4.1 Calibration

As a VNA is not an inherently accurate device, it is necessary to correct for the errors introduced by such properties as detector non-linearity and test port mismatch. To do this the system must be calibrated before measurements are made using impedance standards with well known properties.

This system implements either an LRL (Line – Reflect – Line) type calibration algorithm, or a TRL (Thru – Reflect – Line) method. The LRL scheme is, in effect, a generalised form of the more common TRL scheme.

The TRL scheme [2] requires that a Thru connection be made. This is just a matter of connecting the two test ports together to effectively form a theoretical well matched line with an electrical path length of zero. The Line connection requires a short piece of waveguide line to be inserted between the two test ports. The TRL calibration scheme makes the assumption that the match of the line is perfect, so that

$$S_{11} = S_{22} = 0 \quad (1)$$

It is a requirement of the algorithm used to calculate the error coefficients that the phase shift introduced by the Line standard should not be a multiple of $\pm 180^\circ$. If this is the case then the algorithm becomes unstable and, therefore, unreliable.

Because of this, the length of the line is chosen to provide a nominal 90° phase shift at mid band. This length, l , can be calculated using the expression

$$l = \frac{c}{4\sqrt{f_m^2 - f_c^2}} \quad (2)$$

where c is the velocity of propagation of the wave (the speed of light), f_m is the mid band frequency and f_c is the cut-off frequency for the TE_{10} mode for the waveguide size [3].

The generalization of this method to produce an LRL scheme [4] requires the replacement of the Thru standard with a second Line standard such that the difference in length between the two lines is equal to the length of the line used in the TRL scheme as calculated using equation (2). This enables an effectively very short TRL line to be constructed using the LRL algorithm for millimetre wave frequencies. This is advantageous as very short lines are inherently fragile and difficult to handle.

Below is a table detailing the line lengths used to make up NPL’s capability for the different calibration schemes discussed here.

WG Size	TRL Line Length (mm)	LRL Line 1 Length (mm)	LRL Line 2 Length (mm)	LRL Effective Line Length (mm)
23	2.4	2.0	4.4	2.4
25	1.6	2.0	3.6	1.6
27	1.1	2.0	3.1	1.1

Table 1: Line lengths forming NPL’s millimetre wave capability.

4.2 Data collection and correction

Once the calibration is completed, the DUTs are connected and the uncorrected data is sent to the PC. The calibration coefficients are sent to the VNA. This allows a calibrated trace to be displayed, enabling the operator to use experienced judgement in making good connections. All calibration corrections for the final data are carried out in the PIMMS software.

Once the cycle of calibration and DUT measurement is completed the software prompts the operator to perform another set of measurements. Typically, between five and eight complete calibration/measurement cycles are completed, allowing PIMMS to evaluate the effects of random errors in the measurement process by applying statistical uncertainty calculations to the data.

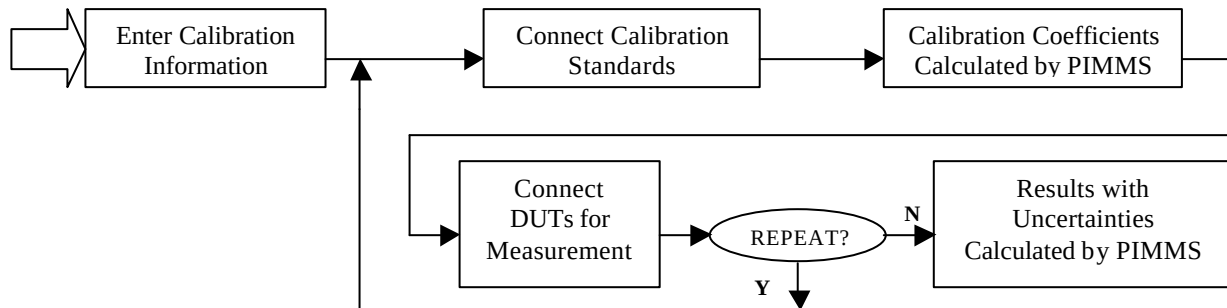


Figure 1: Flow chart of PIMMS measurement sequence.

4.3 Uncertainty contributions

For the calculation of uncertainties, both random and systematic errors are considered. Random errors are evaluated statistically from the repeat measurements and are the result of effects such as electrical noise and connector repeatability. By performing repeat measurements of the DUTs, these effects can be statistically evaluated. Also, as the VNA is re-calibrated before every measurement run, the effects of random error and variation in the calibration are included in the statistical evaluation.

Systematic errors are introduced into the system by many factors, but the most significant of these is the mismatch introduced by the uncertainty in the dimension of the waveguide aperture. This produces a systematic error in the calibration, as equation (1) requires the reflected signal from both ports to be equal and zero. The misalignment caused by mismatched ports can produce significant reflections. The mismatch can occur in several ways, either through bad alignment of the aperture within the flange, or through the dimensions of the aperture being incorrect. For example, typical values for a dimensional uncertainty of $\pm 5 \mu\text{m}$ [5] are tabulated below.

WG size	Maximum linear reflection coefficient uncertainty due to $\pm 5 \mu\text{m}$ error in aperture width	Maximum linear reflection coefficient uncertainty due to $\pm 5 \mu\text{m}$ error in aperture height
23	0.0008	0.0009
25	0.0012	0.0013
27	0.0016	0.0020

Table 2: Worst case errors due to dimensional tolerances

5. Results

Below is tabulated a typical set of uncertainties as might be obtained using this system when measuring a nominal 20 dB attenuator.

WG size	Transmission Uncertainty for 20 dB Attenuator.	Reflection Uncertainty for Nominal Low Reflection Coefficient Device.
23	0.001 – 0.002	0.003 – 0.009
25	0.001 – 0.002	0.005 – 0.006
27	0.003 – 0.007	0.006 – 0.009

Table 3: Typical measurement uncertainties

This demonstrates excellent measurement accuracy even up to 110 GHz.

6. Conclusions

The UK National Physical Laboratory's millimetre wave S-parameter impedance measurement capability has been extended to provide measurements of the highest accuracy over a continuous frequency range from 33 GHz to 110 GHz.

The construction of the system allows easily recreatable measurements to be made and creates a comprehensive record of the measurement for later reference. Both TRL and LRL calibration schemes are supported and full four S-parameter measurements have been made. Random error effects were evaluated statistically using data collected over several measurement runs, correcting not only for effects such as electrical noise and connector repeatability, but also for random errors in the calibration. Systematic errors were also evaluated fully.

7. Acknowledgements

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8. References

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