

A primary national impedance standard from 75 GHz to 110 GHz in metallic waveguide

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Abstract

A primary national standard facility to provide complex scattering parameter measurements in W-band waveguide is presented. The system utilises an automatic network analyser in conjunction with in-house developed control, calibration and uncertainty analysis algorithms. In this paper the system is described and the dominant uncertainty contributions are discussed. Typical uncertainties that can be obtained using this system for a range of one-port and two-port devices are also given.

1. Introduction

The use of millimetre-wave frequencies is growing at a rapid rate and can be found in numerous commercial and research developments such as automotive cruise control, communications and radio astronomy. However, the rapid exploitation of these higher frequency bands means there is also a need for traceable standards in millimetre-wave parameters to ensure measurement accuracy and assurance.

This paper describes a new national standard impedance measurement facility for rectangular waveguide operating at W-band frequencies, from 75 GHz to 110 GHz. The facility is an extension of NPL's Primary IMpedance Measurement System (PIMMS) [1] and utilises an automatic network analyser (ANA) controlled externally using a PC. The system can provide *S*-parameter measurements for both one-port and two-port devices, at the highest levels of accuracy with direct traceability to the S.I. base quantities.

All aspects of the system are discussed, from the measurement hardware, to the calibration procedure and data processing. The uncertainty analysis is described and the range of uncertainties that can be obtained using the system on a variety of devices is given.

2. The measurement system

The PIMMS measurement cycle comprises of three key stages which are outlined below:

2.1 Instrument calibration

To correct for the inherent non-ideal properties of an ANA, the instrument is calibrated using impedance standards whose properties are well known. For the system described here, an externally encoded 'line-reflect-line' (LRL) two-port calibration scheme [2] is employed. This is a generalisation of the 'thru-reflect-line' (TRL) calibration algorithm [3]. In the TRL case, the 'thru' standard is realised by connecting the two measurement planes together. The 'line' standard consists of a waveguide spacer of known thickness inserted between the test-ports, with the 'reflect' standard being a repeatable, but not necessarily known, reflection standard. The latter is normally a short-circuit applied to both test-ports. The TRL algorithm makes two assumptions about the line standard. Firstly, it assumes that the waveguide spacer is a perfectly matched transmission line such that

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

Secondly, for the TRL solution not to become ill-conditioned, the phase shift induced by the line must not be multiples of 180°. For rectangular waveguide, the phase shift in degrees through a transmission line can be written as

$$\Delta\phi = 360 \cdot \frac{l\sqrt{f^2 - f_c^2}}{c}, \quad (2)$$

where f is the frequency in free space, l is the physical length, f_c is the waveguide cut-off frequency for the TE_{10} mode and c is the velocity of light.

By choosing an optimal phase shift of 90° at the centre frequency, f_m , for the waveguide band, (2) can be rewritten to give a suitable length of line:

$$l = \frac{c}{4\sqrt{f_m^2 - f_c^2}}. \quad (3)$$

For the WG-27 (W-band) waveguide size, eqn. (3) gives a length for the 'line' standard of 1.05 mm. The LRL scheme employed in the system described here, replaces the 'thru' connection with a shorter line of length l_{thru} , such that the difference in length between the 'line' standard and l_{thru} is 1.05 mm.

The LRL calibration is performed externally on a PC running in-house developed software that controls the ANA via the GPIB interface. The calibration constants calculated by the external LRL algorithm are stored both on the PC and used to provide a calibrated display on the ANA to aid the operator in assessing the validity of the measurements being made.

2.2 Data collection

Having performed an LRL calibration, the device under test (DUT) is measured. The uncorrected complex scattering parameters of the DUT are transferred from the ANA to the external software. This data is corrected using the calibration constants stored on the PC, which have been determined from the LRL calibration. The external software subsequently resets the ANA and the calibration-measurement cycle is repeated.

2.3 Uncertainty evaluation

To estimate the uncertainty in measurements, both type A and type B contributions [4] are assessed. Type A uncertainties are those which are determined using statistical techniques and normally evaluate random error effects caused by connector repeatability, noise and environmental variations. Repeating the process of calibration and DUT measurement n times allows for the estimation of type A uncertainties associated with both the connection of the calibration standards and the DUT. Typically between 6 and 10 repeat measurements are made. By re-calibrating before each measurement of the DUT, the effects of instrument drift and any instabilities present are implicitly included in the type A uncertainty contribution.

Statistical techniques based on the mean and standard deviation are used to calculate the real and imaginary components of each S-parameter measured and their associated standard deviations. From these values a mean magnitude and phase can be determined.

To complete the uncertainty analysis, the type B contributions are analysed. The dominant contribution arises from the uncertainty in waveguide aperture sizes of the line standards used in the LRL calibration. These uncertainties cause systematic errors in defining zero reflection during calibration, as assumed by (1). Subsequently, these systematic errors manifest themselves as type B uncertainties in measuring S_{11} and S_{22} of the device under test. Figure 1 illustrates the type of misalignment that can occur at the interface between the test-port and the device under test [5].

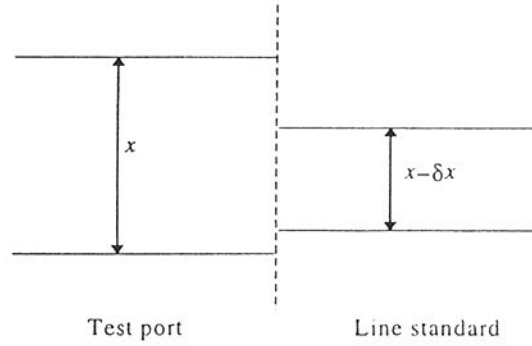


Figure 1 - Aperture size error at a waveguide junction between test-port and DUT. x is the aperture dimension of the ideal test-port and δx is the aperture tolerance of the line standard.

The uncertainty in defining zero reflection magnitude $|\Gamma|$, due to the tolerance in aperture width is given by [5]

$$\delta|\Gamma|_w \approx \frac{1}{8} \left(\frac{\lambda_{gt}}{a_t} \right)^2 \cdot \frac{|\delta a|}{a_t}, \quad (4)$$

where a_t is the width of the test port aperture (for WG27, $a_t = 2.54$ mm), λ_{gt} is the guide wavelength of the TE₁₀ mode propagating through the test port and δa is the aperture tolerance of the line standard. Similarly, the uncertainty in reflection due to the tolerance in aperture height is given by

$$\delta|\Gamma|_H \approx \frac{|\delta b|}{2b_t}, \quad (5)$$

where b_t is the height of the test-port aperture (for WG27, $b_t = 1.27$ mm), and δb is the aperture height tolerance of the line standard.

The overall uncertainty, $\Delta|\Gamma|$, as a result of both height and width tolerances is the root-sum-square of the expressions (4) and (5). It occurs at the minimum working frequency and is approximately 0.001 in $|\Gamma|$ for an aperture tolerance of $\pm 2 \mu\text{m}$ in the calibration line standards.

The dominant type B uncertainties in transmission measurements are from the effects of mismatch, which is a function of $\Delta|\Gamma|$, at the two test-ports. Isolation also becomes significant when measuring high levels of attenuation, typically >50 dB. For this system, the isolation is better than 85 dB.

At millimetric wavelengths, connection repeatability becomes a significant contribution to the overall uncertainty and, as such, the quality of the waveguide flanges on the DUT will impact on the uncertainties that can be achieved. Phase uncertainties have not been discussed here but are calculated on the assumption that the distribution of data in the complex plane about a mean vector is circular, and hence the phase uncertainty can be estimated by

$$U(\phi) = \sin^{-1} \frac{U(|S_{ij}|)}{|S_{ij}|}, \quad (6)$$

where $U(|S_{ij}|)$ is the expanded uncertainty in the mean magnitude of the scattering parameter S_{ij} . In some instances where the uncertainty is greater than the magnitude of a particular S-parameter, a phase uncertainty of $\pm 180^\circ$ is assigned. This occurs frequently when measuring devices that are well matched.

3. Results

Table 1 gives a summary of the typical magnitude uncertainties that can be obtained with this system. They are quoted as expanded uncertainties giving a confidence level of 95% and are a combination of the type A and type B uncertainties described earlier.

Typical device	Magnitude Uncertainty (Linear units)	
	Reflection	Transmission
Matched load, $ \Gamma \approx 0$	≤ 0.005	-
VSWR 1.5 mismatch, $ \Gamma \approx 0.2$	≤ 0.008	-
20 dB attenuator ($ S_{21} $ nominally 0.1)	≤ 0.005	≤ 0.002
40 dB attenuator ($ S_{21} $ nominally 0.01)	≤ 0.005	≤ 0.0002

Table 1 - Expanded uncertainties for a range of typical devices

4. Summary

A W-band primary national standard impedance measurement facility has been developed, that provides traceable *S*-parameter measurements via the physical dimensions of the primary LRL line standards. The instrumentation and measurement processes have been discussed together with the evaluation of the uncertainties associated with the magnitude and phase of a particular scattering parameter. The principal type B uncertainty contribution arises from the dimensional tolerances of the calibration line aperture causing a small error in defining zero reflection. The type A uncertainty contribution takes into account the variability of both the calibration and the repeatability of the device under test and all other random effects. Magnitude uncertainties have been presented for a range of one-port and two-port devices.

Not discussed here are the effects of surface roughness, oxidation and other surface irregularities on measured values of attenuation at millimetre wavelengths. These effects are known collectively as the anomalous skin effect [6] and can cause measured attenuation levels to be higher than would otherwise be predicted. Further investigations are in progress to assess the significance of such effects for this waveguide size in comparison to other uncertainty contributions.

Acknowledgements

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