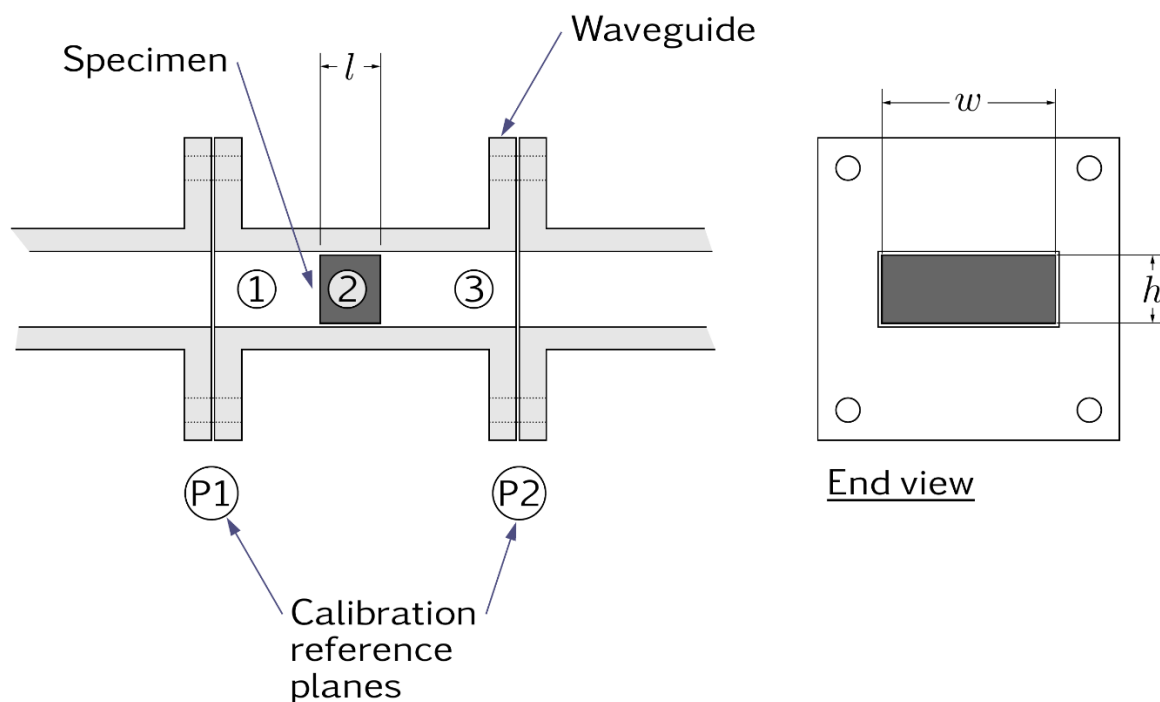


# Measurement of complex permittivity and complex permeability by the transmission-reflection method in the range 100 MHz to 18 GHz



Coaxial-lines and waveguides can be used for measurement of the complex permittivity of solid materials, grains, soils and powders at RF and microwave frequencies. They are used with Vector Network Analysers that measure S-parameters. For non-magnetic materials, the complex permittivity is usually obtained from transmission-coefficients, while for magnetic materials, simultaneous solution of complex permeability and complex permittivity is possible, using both transmission and reflection coefficients. Traceable measurements with estimates of uncertainty can be offered.



**Figure 1:** Measurements on a granular material in waveguide size WG8 (1.7 GHz to 2.6 GHz). The top waveguide adaptor has been disconnected for the photo.

The Transmission/Reflection method enables the dielectric and magnetic properties [1] of a specimen placed inside a transmission-line (waveguide or coaxial line) to be determined from S-parameters measured with a Vector Network Analyser (VNA) over a broad band of frequencies. The method is best suited to materials that have permittivity below 10. It can be used to measure high loss materials, but loss tangents smaller than approximately 0.01 cannot be resolved. The real part of permittivity of low-loss materials can, however, be measured. Uncertainties are estimated from uncertainty contributions associated with measured S-parameters and dimensions of specimens and transmission lines. Figure 1 shows a measurement on a granular material.

Iterative algorithms developed at NPL are used for extracting the material properties. The relative complex permittivity ( $\epsilon' - j\epsilon''$ ) of non-magnetic materials can be obtained from each of the four S-parameters (although the transmission-coefficient data,  $S_{21}$  and  $S_{12}$ , is generally used preferentially as it usually has smaller uncertainties than the reflection data). For magnetic materials, the relative complex permittivity and permeability ( $\mu' - j\mu''$ ) can be obtained from measured transmission- and reflection-coefficient data S-parameters (the pair  $S_{21}$  and  $S_{11}$ , and also the pair  $S_{12}$  and  $S_{22}$ ).

Measurements can be made in waveguide or coaxial line in a range of sizes (Table 1). Currently, measurements are only offered at room temperature.

**Waveguides:** Rectangular solid specimens must be machined to fit a section of waveguide (Figure 2). Measurements on thin specimens can be unreliable because it is difficult to position them perpendicular to the waveguide but, as a multilayer analysis is used, they can sometimes be supported against another block of material, which must be characterised separately. Powdered and granular materials can be measured by orientating the waveguide vertically (a dielectric window is used to contain them). Large waveguides can be used to obtain the effective permittivity of materials with large-scale granularity. The weave of woven materials should be orientated parallel to the long side or the short side of the waveguide, respectively perpendicular to and parallel to the E-field. Specimens cut in both orientations allow anisotropy to be studied. An example measurement on a non-magnetic material is shown in Figure 4. The same specimens may also be suitable for measurement at low frequency (e.g. 1 MHz) by using admittance cell methods.

**Coaxial lines:** Line sizes 7-mm and 14-mm are available at NPL – Figure 2 shows a 14-mm coaxial line. If the maximum frequency required does not exceed 6 GHz, the 14-mm line size is to be preferred as measurement uncertainties are usually smaller. Solid specimens are cylinders with a concentric hole that must fit the line closely (dimensions shown in Table 2). The machining of specimens can be challenging for hard materials because of the tight tolerance of the hole. For high permittivity materials, air gaps between the coaxial line and the specimen (Figure 3) have a large effect, and are often the largest uncertainty contributions. Measurement of specimen and conductor diameters enables corrections to be applied [1]. NPL possesses air-gauging equipment [2] that allows the bore diameter of specimen and coaxial lines to be measured. The maximum frequency of measurement for high-permittivity materials is limited by high-order-mode propagation effects and resonances [1]. Such effects are increased if specimens are not concentric with the coaxial line (this can occur if they are undersized), or if they are non-uniform or have chipped corners. An example measurement on a magnetic material made in coaxial line is shown in Figure 5.

Typical specimen thicknesses for 14-mm coaxial line are 5 – 8 mm. For 7-mm line they are 3 – 7 mm. For measuring high-permittivity specimens (e.g.  $\epsilon' \approx 10$ ) thickness should be reduced to e.g. 2 mm for 7-mm line to increase the frequency at which high-order mode propagation effects onset [1, Figure 40]. Longer specimens can be used at the lower frequencies to reduce uncertainty and improve the resolution of loss measurements. If specimens are thin, it is sometimes advantageous to place a number of them in series.

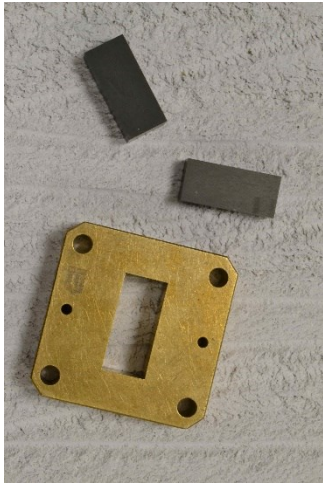
The permittivity of coaxial specimens can also be obtained at low frequency (e.g. 1 MHz) from measurement of the capacitance between the conductors of the coaxial line. These measurements are made by using an LCR meter with a coaxial adaptor.

**Table 1:** Transmission line sizes. If additional waveguide sizes are required, please enquire. The apertures of rectangular waveguides can be found here: <https://www.everythingrf.com/tech-resources/waveguides-sizes>.

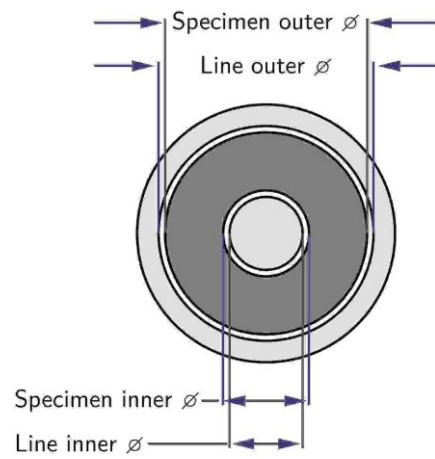
Transmission line	Frequency Range
<b>WG4</b>	750 MHz to 1.15 GHz
<b>WG8</b>	1.7 GHz to 2.6 GHz
<b>WG16</b>	8.2 GHz to 12.4 GHz
<b>14-mm coax</b>	100 MHz to 6 GHz
<b>7-mm coax</b>	200 MHz to 18 GHz

**Table 2:** Coaxial line and typical specimen outer and inner diameters (mm).

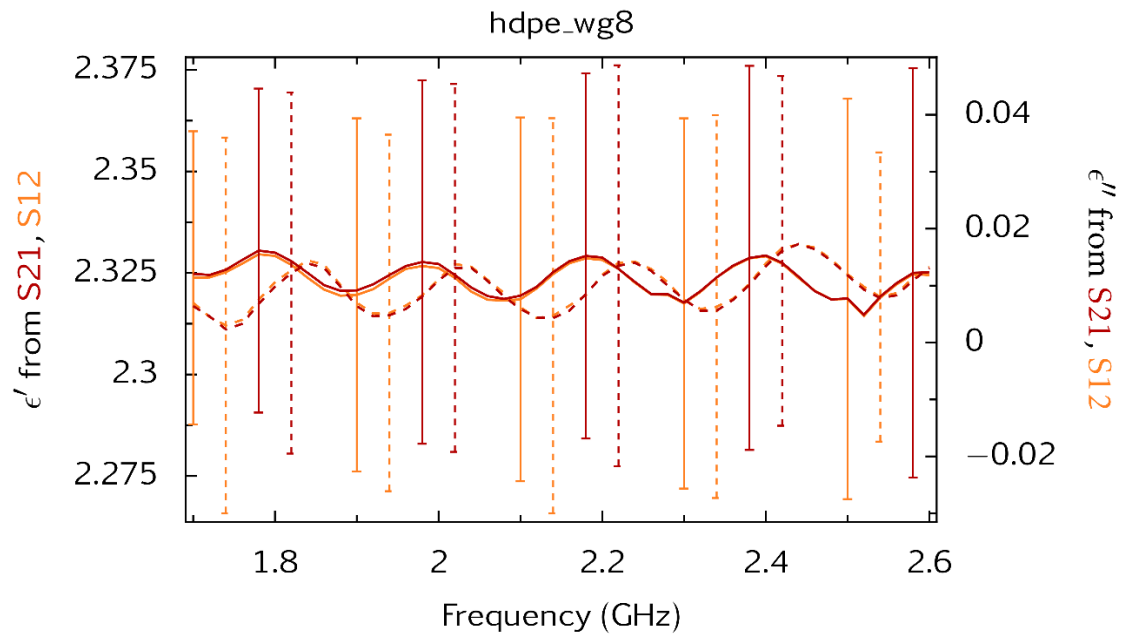
Specimen Size	O.D.	I.D.	Flatness of ends
<b>7-mm</b>	6.990 ±0.005	3.045 <sup>+0.008</sup> <sub>-0.000</sub>	± 0.01
<b>14-mm</b>	14.280 ±0.005	6.208 <sup>+0.005</sup> <sub>-0.000</sub>	± 0.01
Line size	Nominal O.D.	Nominal I.D.	
<b>7-mm</b>	7.000	3.040	
<b>14-mm</b>	14.288	6.204	



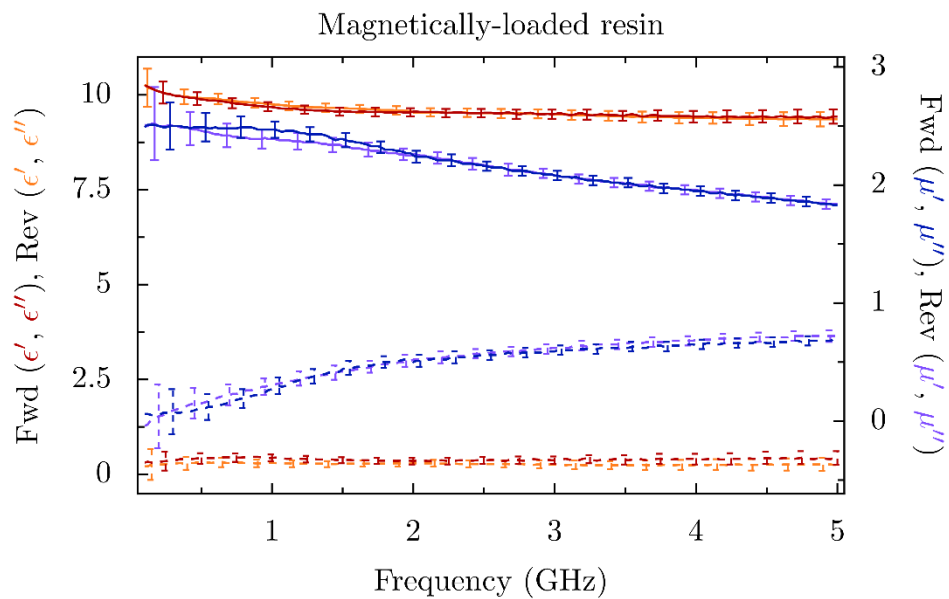
**Figure 2:** Left: WG16 waveguide spacer and specimens. Right: 14-mm coaxial line and specimens.



**Figure 3:** Air gaps for coaxial specimens.



**Figure 4:** A measurement on a non-magnetic material (HDPE thickness 28 mm) in waveguide WG8.  $S_{21}$  and  $S_{12}$  are results shown in red and orange respectively. Solid lines represent  $\epsilon'$  (refer to left-hand axis), and dashed lines represent  $\epsilon''$  (refer to right-hand axis). Uncertainty bars are shown for a coverage factor of  $k=2$ . The ripple observed is an artefact of the measurement, but is well within the estimates of uncertainty.



**Figure 5:** Measurement on a magnetic-loaded resin (length 4-mm) in 7-mm coaxial line.  $S_{21}/S_{11}$  results: red ( $\epsilon' - j\epsilon''$ ) and dark blue ( $\mu' - j\mu''$ ).  $S_{12}/S_{22}$  results: orange ( $\epsilon' - j\epsilon''$ ) and light blue ( $\mu' - j\mu''$ ). Solid lines represent real parts, and dashed lines represent imaginary parts. Uncertainty bars are shown for a coverage factor of  $k=2$ .

**Specimen preparation:** Specimens can be machined by the machine workshop at NPL to the high tolerances required. Material Safety Data must be provided.

## **NPL reports and papers**

- [1] R. N. Clarke (Ed.) "Guide to the characterisation of dielectric materials at RF and microwave Frequencies", The Institute of Measurement, Control, and The National Physical Laboratory, London, 2003. <http://eprintspublications.npl.co.uk/2905/>
- [2] J. P. Ide, "Traceability for Radio Frequency Coaxial Line Standards", National Physical Laboratory Report DES 114, July 1992.

For further information please contact Customer Services

email: [measurement\\_services@npl.co.uk](mailto:measurement_services@npl.co.uk)

call: **+44 20 8943 7070**

contact form: [www.npl.co.uk/products-services/products-services-contact-form](http://www.npl.co.uk/products-services/products-services-contact-form)

National Physical Laboratory  
Hampton Road  
Teddington  
Middlesex  
United Kingdom  
TW11 0LW

Switchboard: **+44 20 8977 3222**

Website: [www.npl.co.uk](http://www.npl.co.uk)

Version 1. August 2022

Disclaimer. Although every effort is made to ensure that the information contained in this brochure is accurate and up-to-date, NPL does not make any representations or warranties, whether express, implied by law or by statute, as to its accuracy, completeness or reliability. NPL excludes all liabilities arising from the use of this brochure to the fullest extent permissible by law. NPL reserves the right at any time to make changes to the material, or discontinue the brochure, without notice. The NPL name and logo are owned by NPL Management Limited. Any use of any logos must be authorised in writing.

© NPL Management Ltd, 2022.