Material Characterisation Kits for measurement of complex permittivity in the frequency range 50 GHz to 750 GHz

Material Characterisation Kits (MCKs) are used for measurement of the permittivity and loss angle of planar specimens at room temperature. Powders can also be measured. The MCKs are available cover the frequency range 50 GHz to 750 GHz. They are used in conjunction with a millimetre-wave Vector Network Analyser (Keysight PNA-X). Using algorithms developed at NPL, the permittivity and loss angle are calculated from swept frequency measurements of complex transmission coefficient. The minimum loss angle that can be resolved depends on the specimen thickness and the frequency, but is typically of the order of 3 milliradians.

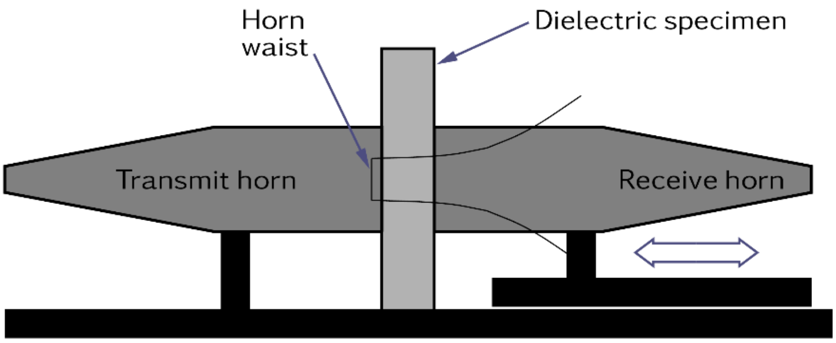

Figure 1 and cover image: Material Characterisation Kit for measurement of the permittivity and loss of planar specimens. These quantities are determined from S-parameters measured by using a Vector Network Analyser.

Material Characterisation Kits (MCKs) [1] are systems for broadband measurement of complex permittivity. They consist of a pair of corrugated horns that are aligned on a linear track (Figure 1). Materials to be measured must be prepared by machining them into laminar specimens (usually discs) with parallel faces. These are placed between the horns for measurement. Powders contained between sheets of material can also be measured. Complex permittivity is determined iteratively from measurements of complex transmission coefficient that are made with a Vector Network Analyser. MCKs use corrugated horns that emit high-purity Gaussian beams to improve the accuracy of calculated results. The MCKs available at NPL, and the required specimen dimensions, are given in Table 1. Specimens can also be measured by time-domain spectroscopy (THz-TDS) in free-space over an extended frequency range (up to 5 THz for some low loss materials).

The theory for measurement of dielectric properties by transmission is well known [3], but unaccounted-for mismatch, coupling and scattering effects which occur in free space systems add apparent noise and ripple to the measurements. The permittivity and loss change slowly with frequency, so these measurement errors are normally reduced by smoothing the data, e.g. with a moving window (adjacent averaging) filter. Example measurements are shown in Figures 2 & 3. The mismatch, coupling and scattering effects make it more difficult to evaluate measurement uncertainty. A model for uncertainty, based on measurements on reference materials [2, 4], has been developed. This allows estimates of the measurement uncertainty for arbitrary specimens to be obtained.

Measurements are normally reported as the real part of permittivity (ε'), and the *loss angle* (δ) [2] in milliradians (mrad). For specimens that have $\delta<0.2$, loss angle is related to loss tangent by $\delta \approx \tan\delta \times 10^3$ mrad. If preferred, data can be reported as refractive index (n) and absorption coefficient (α).

[1] Manufactured by SwissTo12, https://mck.swissto12.ch/
[2] 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/
[3] J. Baker-Jarvis, "Transmission /reflection and short-circuit line permittivity measurements", NIST Technical Note 1341, 1990, https://dx.doi.org/10.6028/NIST.TN.1341
[4] M. Naftaly and A. P. Gregory, "Terahertz and microwave optical properties of single-crystal quartz and vitreous silica and the behavior of the boson peak", *Applied Sciences*, Vol. 11, 2021. https://doi.org/10.3390/app11156733

Table 1: Material Characterisation Kits available at NPL

Range (GHz)	Band	WG size	Minimum specimen diameter (mm)	Preferred specimen length (mm)*
50 – 75	V	WG25/WR15	42	10 – 30
75 – 110	W	WG27/WR10	42	7 – 20
140 – 220	G	WG30/WR05	30	4 – 12
500 – 750	–	WM380	20	1.5 – 7

*Consult NPL if ε′ > 4, as thinner specimens may be preferred.

Example measurements

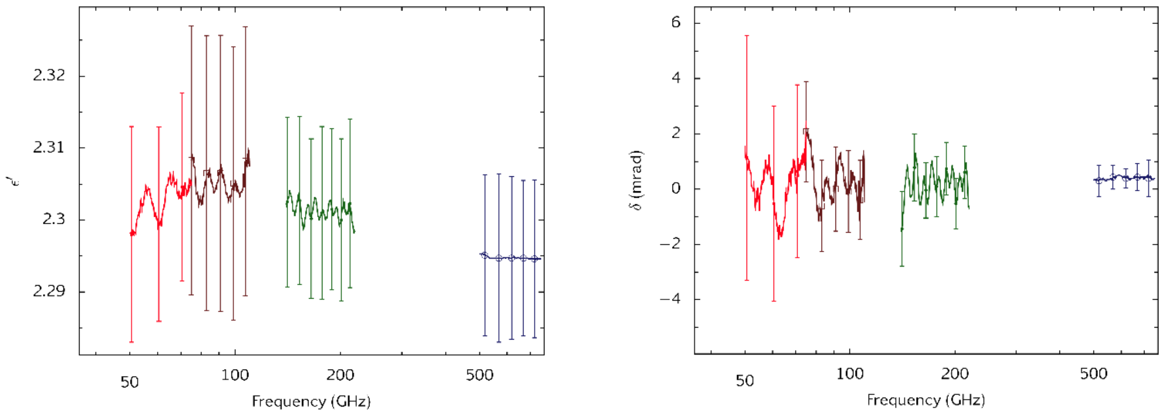

Figure 2: Measurement of the permittivity and loss angle of a specimen on LDPE (thickness 11.4 mm) using all four MCKs available at NPL. The data has been smoothed. The uncertainty bars show the standard uncertainty multiplied by a coverage factor *k* = 2 (equivalent to 95% Confidence Level).

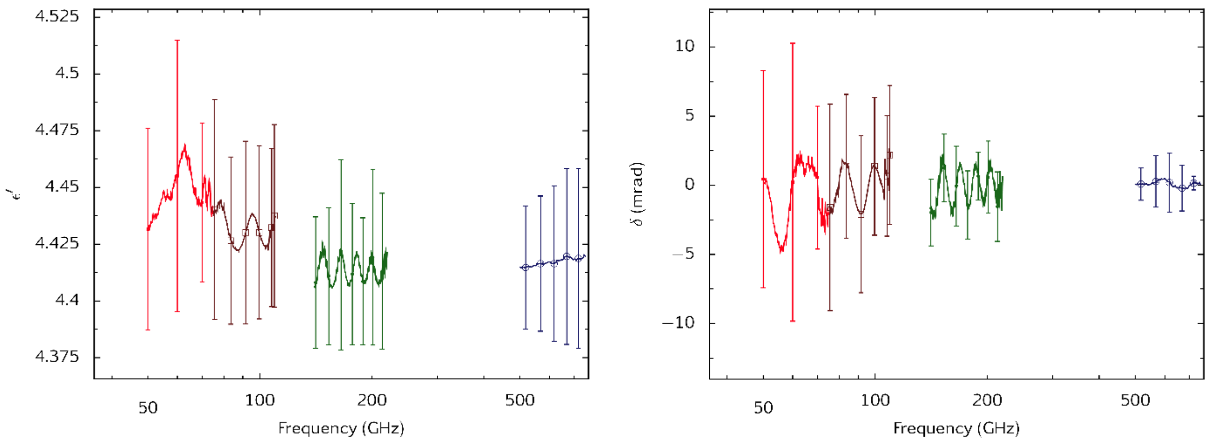

Figure 3: Measurement of the permittivity and loss angle of a specimen of Z-cut single-crystal quartz (thickness 4.118 mm) using all four MCKs available at NPL. The data has been smoothed. By resonant methods [4] it is found that *ε'*= 4.435 and *δ*=0.04 mrad (at 36 GHz). The uncertainty bars show the standard uncertainty multiplied by a coverage factor *k* = 2 (equivalent to 95% Confidence Level).

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Version 1. November 2021