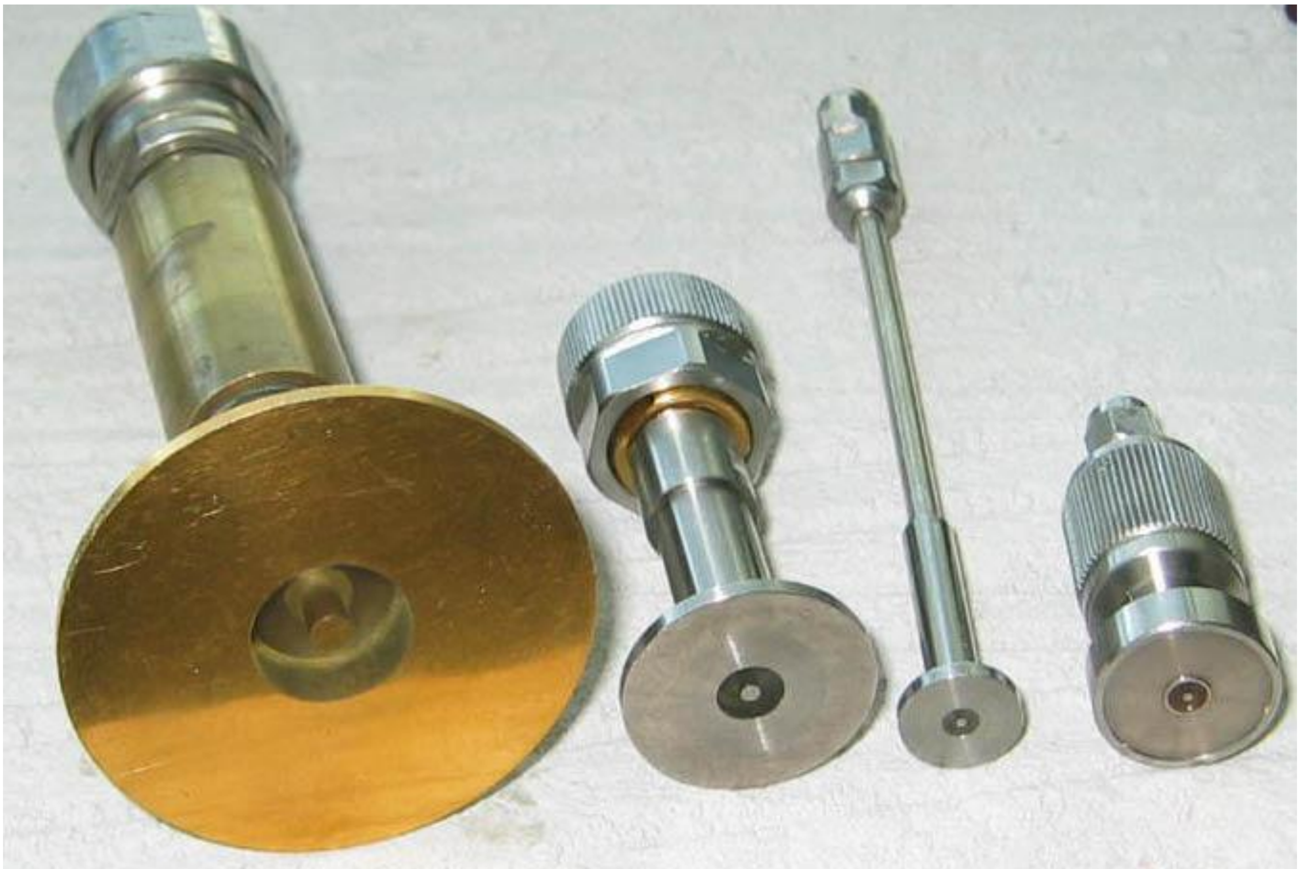
Coaxial sensors for measurement of complex permittivity in the frequency range 50 MHz to 50 GHz



Coaxial sensors are used for measurement of the complex permittivity of liquids and malleable solid materials at RF and microwave frequencies. They can be used to measure liquid and solid tissue-equivalent materials (tissue phantoms), foodstuffs, biomedical materials, soils, radar absorbent material, rubber etc. They are particularly useful for measuring high-loss materials. NPL possesses a range of sensors, including open-ended coaxial probes with diameters from 0.66 mm to 44 mm, and sensors in which specimens are contained within a metal cylindrical cell. Traceable measurements with quantified uncertainties can be offered.

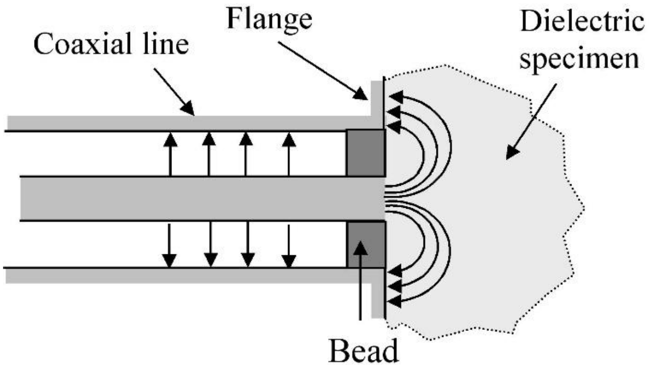


Figure 1 and cover image: Open-ended coaxial probes for measurement of the complex permittivity of liquids and malleable solids.

Coaxial sensors [1] are used for broadband measurement of complex permittivity ($\varepsilon' - j\varepsilon''$) [2] of liquids and malleable solids. The technique requires measurements of complex reflection coefficient with a Vector Network Analyser (VNA), from which complex permittivity is calculated. The most widely used type of sensor, the open-ended coaxial probe (Figure 1), enables non-destructive measurements on malleable solid materials, as well as liquids. Sensors with related geometries are available at NPL [3], including one in which specimens are placed in a conducting cylindrical cell. This can be used to measure the complex permittivity of one layer of a two-layer specimen [4]. Coaxial sensors are usually calibrated by the reference liquid method. This requires measurements on air, a short-circuit, and a chemically pure liquid for which traceable data is available. A measurement on another reference liquid is used to check that an accurate calibration has been obtained.

Through its research [1-9] NPL has improved the accuracy of measurements with coaxial sensors and made them traceable to VNA measurements and sensor dimensions via validated modal-analysis software that is used for deriving complex permittivity from reflection measurements. A notable early development (1989) was a comparison of modal analysis software written independently by three mathematicians [5]. These were shown to produce consistent results. Tables of reference data for organic liquids [6] (complex permittivity as a function of frequency and temperature) are available from NPL that can be used for the calibrating coaxial sensors. A Monte-Carlo technique [1] that allows a comprehensive approach to the evaluation of uncertainty has been developed. NPL used coaxial sensors to characterise tissue-equivalent materials (liquid phantoms [7]) as part of a wider project to establish traceability for measurements of the Specific Absorption Rate (SAR) of radiated power from devices such as mobile phones. A large sensor (44-mm) [7] was developed to enable measurements of complex permittivity at the frequencies used by Magnetic Resonance Imaging (MRI) systems (64 MHz and 128 MHz).

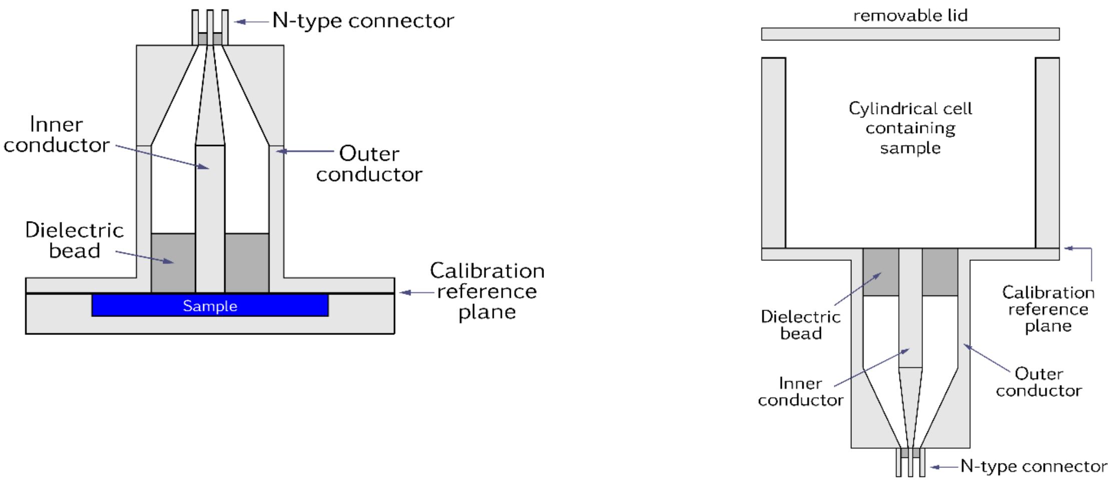


Figure 2: NPL 44-mm coaxial sensor for measurements in the frequency range 50 to 350 MHz with cylindrical cells for measuring liquids (left) and powders and soils (right). This sensor was originally developed for measurements on liquids at MRI frequencies. For more details see reference [7].

Coaxial sensor measurements are possible because the fringing fields between outer and inner-conductors of the sensor interact with samples, which changes the reflection coefficient measured by the VNA. The method requires that samples have good uniformity, especially near the end of the truncated inner-conductor as this is where the fringing fields are most concentrated. Even small air gaps at the sensor face can cause significant measurement error.

The penetration depth of the fringing fields varies considerably with the frequency, the size of the sensor, and the complex permittivity of samples. Reference [8] defines the histological sensing depth and shows that it is approximately 1/6th of the aperture of an open-ended coaxial probe at microwave frequencies for measurements on tissue. The limited depth of penetration must be carefully considered when planning measurements on inhomogeneous materials. Measurements are obtained on the assumption that samples are uniform and isotropic.

Limitations of the technique

Coaxial sensors are not normally used to measure hard materials because even small air gaps between the sensor and samples cause significant measurement error. The effect of air gaps is increased for high-permittivity materials. Low-loss hard materials can be measured by resonant methods. Special techniques that enable high-loss hard materials to be measured in a multilayer geometry have been developed [4].

Materials that contain a high proportion of carbon powder, fibres or nanotubes are generally not measurable because of practical difficulties establishing reliable contact with probes. A further problem is that such materials may be highly non-uniform because of random conduction paths. As a guide, if the resistance of a carbon-loaded material can be measured with a digital multimeter, the percolation threshold has been exceeded, and satisfactory measurements will not be possible.

Coaxial sensors cannot be used to measure magnetic materials.

Measurements on ionic liquids are affected by electrode polarisation effects [7]. These cause an apparent increase in the real part of permittivity that diminishes as the frequency is increased. For highly-ionic samples, the minimum frequency for reliable measurement may exceed 1 GHz.

Large open-ended coaxial probes can show flange and volumetric resonances [1] if high permittivity materials with $\tan\delta < 0.3$ are measured. Measurements on deionised water with the 7-mm probe show resonances at frequencies below approximately 3 GHz. This probe is calibrated by using alcohols to ensure that the calibration is not affected by such resonances.

The measurement temperature of liquid samples

The complex permittivity of liquid is a function of temperature. Polar liquids, such as water, have a high temperature coefficient. Temperature control systems are available at NPL, and measurement temperatures in the range 12 °C to 50 °C can be specified if required. The measurement temperatures of liquid samples are always recorded. Note that the open-ended coaxial probe technique requires samples to be placed in an open-top container. In consequence, the temperature of volatile liquids is affected by evaporative cooling. Some liquids that react with moisture in the air, causing an increase in temperature.

Probe sizes, sensitivity and uncertainty

Table 1 shows the coaxial sensors available at NPL, and their frequency ranges. Some example measurements are shown in Table 2. The sensitivity of measurements depends on the size of the sensor, the frequency and the complex permittivity of samples [1]. Uncertainties tend to be lowest in the middle part of the specified frequency ranges. Measurements with open-ended coaxial probes on polar liquids have been compared to reference data [1].

Table 1: NPL Coaxial sensors.

Nominal bore diameter	Maximum frequency range	Geometry	Notes
44 mm	50 MHz to 350 MHz	Open-ended and with cylindrical cell (see Figure 2)	Liquids are normally measured with the cylindrical-cell geometry to reduce the required volume of samples. The sensor can be upturned to enable powders and soils to be measured. NPL design.
7 mm	100 MHz to 10 GHz	Open-ended	NPL design.
3.5 mm	*200 MHz to 18 GHz	Open-ended	Hewlett-Packard HP85070A.
1.6 mm	*500 MHz to 50 GHz	Open-ended	Keysight performance probe.
0.66 mm	*1 GHz to 50 GHz	Open-ended	Experimental probe based on truncated UT-034 cable. For measurement on very small samples. Measurements have low precision and are not traceable.

* At frequencies below 10 GHz there are several characterised reference liquids that can be used for calibrating and checking sensor calibration [7], but at frequencies above 10 GHz, there is only one (water). This is used to calibrate the asterisked probes. The maximum frequency for `check' measurements with an alternative reference liquid is therefore 10 GHz. Full traceability at frequencies above 10 GHz cannot be provided.

Table 2: Measurements on Tween-based “head” phantoms made with a 7-mm open-ended coaxial probe. Traceable measurement of the Specific Absorption Rate (SAR) of power radiated from devices such as mobile phones requires phantoms to be measured to ensure that they are within specification. Target data, published in standards, is summarised in reference [7]. Estimates of the expanded uncertainty are shown in brackets. These are based on a standard uncertainty multiplied by a coverage factor k = 2 (equivalent to 95% Confidence Level). The quantity σ is the conductivity, given by $\sigma = \omega \varepsilon_o \varepsilon''$, where ε_o is the permittivity of free space.

Frquency (GHz)	Temperature °C	ε'	ε''	σ (S/m)
0.9	21.0 (0.2)	42.6 (0.5)	18.6 (0.3)	0.93 (0.01)
2.45	21.0 (0.2)	38.4 (0.6)	14.1 (0.3)	1.92 (0.04)
5.8	21.0 (0.2)	36.1 (0.6)	18.4 (0.5)	5.9 (0.2)

Sending chemical samples to NPL

When sending chemicals to NPL, ensure that the appropriate GHS warning symbols are attached to the outside of the packaging. Safety Data Sheets (SDS) must also be provided so that NPL can ensure the safety of its staff. Chemicals should be supplied in appropriate leakproof bottles. NPL will provide advice on the suitability of chemicals for measurement, and the required volumes of samples.

NPL reports and papers

[1] A. P. Gregory and R. N. Clarke, "Dielectric coaxial sensor metrology”, *Meas. Sci. Tech*., 2007. http://eprintspublications.npl.co.uk/id/eprint/9065

[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] A. P. Gregory and R. N. Clarke, “A review of RF and microwave techniques for dielectric measurements on polar liquids”, *IEEE Trans. Dielectr. Electr. Insul*., 2007. http://eprintspublications.npl.co.uk/id/eprint/3590

[4] NPL Report MAT 13, "Measurements on layered materials", A. P. Gregory, R. N. Clarke, T. E. Hodgetts and G. T. Symm, 2008. http://eprintspublications.npl.co.uk/4075/

[5] S. Jenkins, T. E. Hodgetts, G. T. Symm, A. G. P. Warham, R. N. Clarke and A. W. Preece, "Comparison of three numerical treatments for the open-ended coaxial line sensor", *Electr. Lett*., 1990. http://dx.doi.org/10.1049/el:19900158

[6] NPL Report MAT 23, "Tables of the complex permittivity of dielectric reference liquids at frequencies up to 5 GHz", A. P. Gregory and R. N. Clarke, 2012. http://eprintspublications.npl.co.uk/4347/

[7] NPL Report TQE 9, "Formulation and properties of liquid phantoms", 1 MHz to 10 GHz, B. G. Loader, A. P. Gregory and R. Mouthaan, 2018. http://eprintspublications.npl.co.uk/7946/

[8] P. M. Meaney, A, P. Gregory, J. Seppala, T. Lahtinen, “Open-ended coaxial dielectric probe effective penetration depth determination", *IEEE Microw. Theor. Tech*., 2016. http://eprintspublications.npl.co.uk/id/eprint/7001

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