Coaxial Dielectric Probe

Introduction

The coaxial dielectric probe is a system for making wideband measurements of the dielectric properties of materials, specifically the complex relative permittivity over the band 500MHz to 40GHz. The system comprises:

- Coaxial probe,
- Short circuit plate and
- Software.

The coaxial dielectric probe system interfaces with the user's own vector network analyser (VNA) to make a *time gated frequency domain* measurement of S_{11} (input reflection coefficient) at the interface between the probe tip and material under test. The VNA can convert the S_{11} measurement to the admittance at the probe/material interface. This admittance is recorded at each frequency of interest and input into a Matlab program that returns the complex relative permittivity of the material under test at the desired frequency.

The system is quick and easy to set up and accurate results are returned within seconds.

A measurement of complex relative permittivity (or simply *permittivity*) readily yields data on:

- dielectric constant (i.e. the real part of the complex relative permittivity),
- loss factor (i.e. the imaginary part of the complex relative permittivity),
- loss tangent (i.e. the ratio of the imaginary to real parts of the complex relative permittivity) and,
- conductivity.

The accuracy of the coaxial dielectric probe system depends on the accuracy of the model to relate probe admittance to material permittivity and on the accuracy of the calibration of the probe. White Horse Radar's coaxial dielectric probe system employs a highly accurate electro-magnetic model of the probe and sample and yet it provides solutions quickly. Many other systems on the market have to solve approximate models in the interest of processing speed. These approximate models must be calibrated using reference dielectrics. White Horse Radar's coaxial dielectric probe system relies only on a short-circuit reference that is quick and easy to use and gives consistent results. This gives White Horse Radar's coaxial dielectric probe system the speed and accuracy that scientists and engineers require.

For further technical information on WHR's coaxial dielectric probe system, follow the links at the bottom of this webpage.

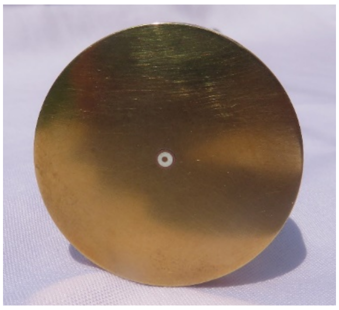
Components

The coaxial probe (pictured - *right*) is a 30cm length of semi-rigid coaxial cable with a brass flange at its base that rests in contact with the material under test and has a 2.92mm RF connector (female) at its top end for connection to your vector network analyser.

The short circuit plate is a metallic disc that provides a short-circuit reference when pressed against the under-side of the coaxial probe flange.

The software is currently supplied in Matlab and comprises (i) a data table, (ii) a look-up and interpolation program and (iii) a user interface. Supplied on a memory stick.

The components are accommodated in a handsome oak box.



Pictured (*left*): Under-side of flange at base of probe. This surface must be in good all-round contact with the sample

Options

Bandwidth The full system bandwidth is 500MHz to 40GHz. Reduced bandwidth options are available and can be specified using the following notation:

B(start freq in GHz)-(stop freq in GHz)

e.g.:	**B0.5-40**	The full bandwidth of 500MHz to 40GHz,
	B0.5-12	500MHz to 12GHz,
	B1-4	1GHz to 4GHz.

Length The default probe length is 30cm. Shorter probes may be specified using the following notation:

L(length in cm)

e.g.:	**L30**	The full length of 30cm,
	L15	15cm.

The length and bandwidth cannot be chosen independently from each other since the admittance at the probe tip is measured from the reflection coefficient between the flange surface and the material under test. The reflection coefficient at the probe/material interface must be resolvable from reflections at the 2.92mm connector at the top end of the probe. The resolution limit, δd, is given by:

$$\delta d = \frac{3 \times 10^8}{2 \times 0.77 \times B} = \frac{194.8 \times 10^6}{B}$$

where *B* is the bandwidth.

The length of the probe must *exceed* the resolution limit for the two reflections to be resolvable, otherwise the admittance measurement at the probe tip will be corrupted by the reflection from the connector.

For example, for option **B1-4** the bandwidth *B* = 3GHz and so $\delta d = 65mm$. WHR recommends using a probe which is at least twice this distance, i.e. > 130mm. In this case, probe length option **L15**, or longer, is recommended.

Software The software can be downloaded from our website if the user would prefer not to use a memory stick.

Other Requirements

Vector Network Analyser (VNA) The coaxial dielectric probe interfaces with the users own VNA (a VNA is *not* supplied with the coaxial dielectric probe system, although WHR can advise on this). A single port VNA only is required supporting S_{11} measurements. The coaxial dielectric probe system is supported by a wide range of VNAs from all the major manufacturers provided the VNA has the following features:

- The VNA must cover the bandwidth of the coaxial dielectric probe system.
- The VNA must have the *Time Domain* option so that *time gated frequency domain* measurements of S_{11} are possible.

The precise user instructions vary with the specific VNA used but all operate in a similar manner.

Please note that a network analyser or scalar network analyser is inadequate as the complex S_{11} (complex admittance) must be measured.

Software This is currently only available as Matlab files. The user must therefore have a licence to run Matlab on their own computer (a Matlab licence is *not* supplied with the coaxial dielectric probe system). Please get in touch with us if this is a problem.

Limitations

Any coaxial dielectric probe system, including that from WHR, is best suited to the wideband measurement of (complex relative) permittivity of lossy dielectrics that are liquids, gels, soft solids or solids that can be prepared with a flat surface. Coaxial probes are not best suited to the accurate measurement of the loss factor (loss tangent) of very low-loss dielectrics. Coaxial probes cannot measure the dielectric properties of granular solids or materials at temperature extremes due to the necessity for the probe tip to be in good all-round contact with the sample. Sample volumes of several cubic centimetres are typically required.

Sales & Services

Please contact Clive at clive@whradar.com for all enquiries.

The coaxial dielectric probe system is offered for sale. Please contact Clive to discuss your requirement and obtain a quotation.

We understand that purchase of a coaxial dielectric probe system may not suit everyone's requirements. Perhaps you don't have a VNA or Matlab licence or perhaps you only need to make a limited number of tests that don't warrant a great deal of expense. Alternatively, WHR can offer consultancy services to perform measurements of permittivity using the coaxial dielectric probe system on samples provided by you.

WHR has considerable experience in the measurement of permittivity in other frequency bands and using other methods. In particular, WHR can offer consultancy services in the fields of:

- measurement of permittivity at millimetric wave frequencies,
- measurement of permittivity using the perturbation of a resonant cavity technique (suitable for highly accurate measurement at a single frequency in the centimetric wave band and for small sample sizes),
- measurement of permittivity using transmission and/or reflection coefficient data (suitable for planar dielectric samples),
- analysis and measurement of planar, multi-layered dielectrics,
- dielectric characteristics of biological tissues,
- dielectric properties of soils.

Complex Relative Permittivity

Here, we try to explain the characteristics of materials, concentrating on the *relative permittivity* of dielectric materials.

Conductors & Insulators

Naturally occurring materials tend to be divided into *conductors* and *insulators*. Good conductors include most metals with gold having a particularly high conductivity, or conversely, a very low resistance. No metal, however, is a perfect conductor having zero resistance, although *superconductors* do achieve this characteristic below a critical temperature. The opposite of a conductor is an insulator, or *dielectric*, that has very high resistance and very low conductivity, ideally zero conductivity. Most practical insulators do support a tiny degree of conductivity and so cannot be considered as pure dielectrics, although *free-space* supports no conductivity and so can be considered a pure dielectric. Indeed, the dielectric properties of free-space become the reference for all other dielectrics. Most naturally occurring materials at everyday temperatures tend to sit somewhere between a pure conductor and a pure dielectric. As remarked earlier, most metals are good conductors and doped semi-conductors are also good conductors, whereas intrinsic semi-conductors support very little conductivity and may be considered as dielectrics. Low-loss dielectrics have very low conductivity and include many polymers (plastics), hydrocarbons, glasses, silicates and many other minerals including diamond. Lossy dielectrics support a small degree of conductivity such as water and anything containing water, e.g. animal and plant tissues, wood, concrete, foods and soils. Indeed, the permittivity of many materials is highly dependent on its water content and so dielectric analysis can be used as a means of determining water content.

Permittivity

The *permittivity* of a dielectric describes its ability to support an electric field and the *permeability* of a material describes its ability to support a magnetic field. For non-magnetic materials, their permeability is equal to that of free-space (μ_0), and these are not considered any further here. Permittivity (and permeability) may vary with frequency and are also typically dependent on temperature.

Permittivity (ε) is a complex quantity, i.e. it has real and imaginary parts:

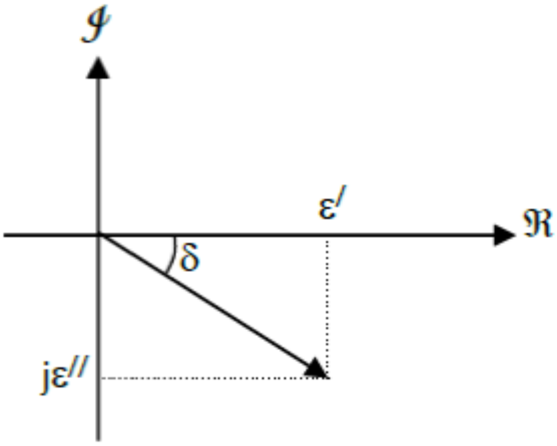
$$\varepsilon = \varepsilon' - j\varepsilon''$$

where $j = \sqrt{-1}$, ε' is the real part of the permittivity and ε'' is the complex part of the permittivity.

The permittivity of free-space is denoted ε_0 and is numerically equal to:

$$\varepsilon_0 = 8.854191 \times 10^{-12} \;\; F/m$$

The real part of the permittivity, ε', is known as the dielectric constant, whereas the imaginary part of permittivity, ε'', is the dielectric loss factor. The real and imaginary parts of permittivity may be depicted on a set of orthogonal axes as illustrated in the Figure below.



A pure dielectric is loss-less and so $\varepsilon'' = 0$. In practice, most dielectrics are not ideal since they support some degree of conductivity and so $\varepsilon'' > 0$. It is worth noting that the imaginary part of permittivity is usually written as a negative quantity and so $\varepsilon'' > 0$ implies dielectric *loss*.

Dielectric losses are also quantified using the loss tangent term i.e.

$$tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon'}$$

where σ is the conductivity and ω is the angular frequency.

It is usual to refer to the *relative* permittivity as being the permittivity relative to that of free-space. Relative permittivity, ε_r , is defined as the factor by which the capacitance of a capacitor increases when the volume between and around its plates is filled with the dielectric as compared with free space. Therefore:

$$\varepsilon = \varepsilon_r\,.\,\varepsilon_0$$

The relative permittivity can also be broken down into relative real and imaginary parts as:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

and it is common to measure these *relative* parts of the complex permittivity. In truth, the capacitance of a capacitor increases by a factor ε_r' when the volume between and around its plates is filled with the dielectric as compared with free space but for loss-less dielectrics, $\varepsilon_r'' = 0$ and so $\varepsilon_r = \varepsilon_r'$ and the relative permittivity and relative dielectric constant become synonymous with each other.

Note that naturally occurring dielectrics have $\varepsilon'' > 0$ and $\varepsilon_r' \geq 1$.

Since the (relative) dielectric constant ε_r' is often a function of frequency, temperature and several other parameters one may indeed wonder at its name and question *with what is it constant*? The answer is that the dielectric constant is independent of the strength of the applied electric field. This is true for field potentials below the breakdown point; the field strength sufficient to cause arcing and is an important consideration for determining the maximum power handling of RF transmission lines and the insulation of high-tension supplies.

Meta-materials are man-made structures comprising a repeating pattern of conductors and dielectrics that repeat over a distance considerably smaller than the wavelength. These materials have bulk dielectric properties that are not normally found in natural materials, i.e. $\varepsilon'' < 0$ and $\varepsilon_r' < 1$, and open the door to many innovative and fascinating applications.

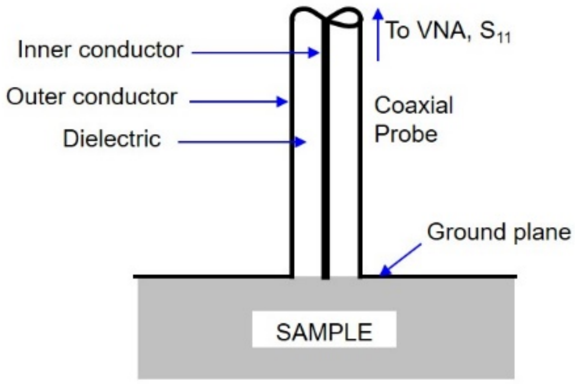
Measurement of Permittivity

From the definition of permittivity given above, a direct measurement can be made by observing the factor by which the capacitance of a capacitor increases when the volume between and around its plates is filled with the dielectric as compared with free space. This is practical at low frequencies but not into the microwave band. Many different methods of measuring permittivity have been pursued with differing techniques being best suited to certain frequency bands, the state and physical characteristics of the sample, the expected result (some techniques are well-suited to low-loss dielectrics, others to high-loss dielectrics) and the degree of accuracy and bandwidth (spot frequency or wideband result) required. Some example techniques used in the microwave band include:

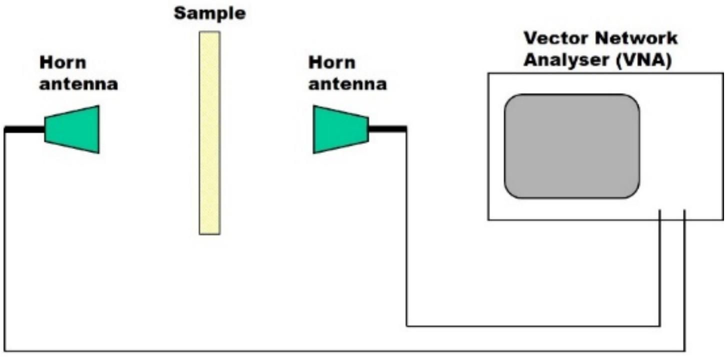
- coaxial probe,
- free-space measurement of transmission and/or reflection coefficients,
- perturbation of a resonant structure (waveguide cavity, microstrip patch, resonator),
- dielectric loaded waveguide,
- open waveguide terminated in dielectric.

This list is not exhaustive.

WHR has experience with a wide variety of measurement techniques and dielectric materials and can offer consultancy in this field.

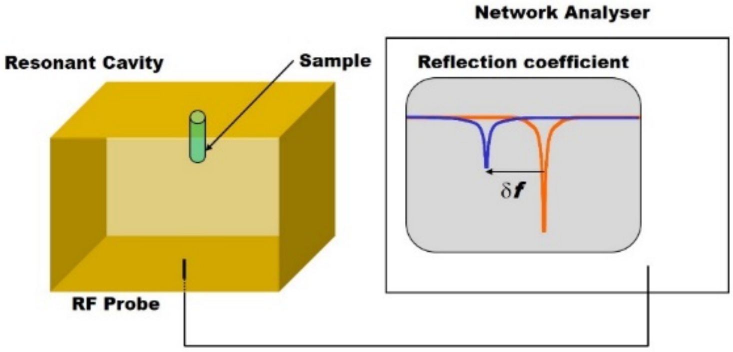


Coaxial Dielectric Probe



Complex ε_r can be found from $|S_{11}|$ and $|S_{21}|$

Free-Space measurement of Transmission and/or Reflection Coefficient



ε_r' is a function of δf and ε_r'' is a function of the reduced Q-factor.

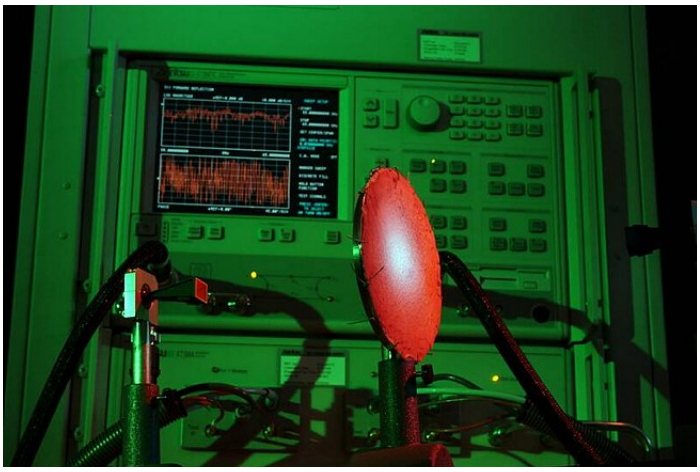
Perturbation of a Resonant Waveguide Cavity

Applications

The permittivity of a material reveals a great deal about its content and its electromagnetic performance and so its measurement is exceedingly useful in very many applications. Here are a few (*the list is far from exhaustive*):

- Determining the rate of heating of dielectrics. This is useful in industrial microwave heating and curing processing and in determining safety levels of human exposure to name but two.
- Characterising substrate materials used in RF engineering.
- Modelling the radar cross section of radar targets.
- Design of coatings and loads to minimise radar cross-section (stealth).
- Modelling radar clutter from surfaces and weather effects.
- Quantifying radar data for remote-sensing applications.
- Modelling RF propagation in poor weather, within an urban environment or within a vehicle or building.
- Modelling the RF propagation in complex natural (biological) structures such as the human body (breast cancer detection, RF hyperthermia) and structures for ground penetrating radar applications.
- RF antenna design.
- Characterising the water content of materials. This has applications in the analysis of soils, foods and drying processes and in controlling the contamination of other chemicals by water e.g. fuels.

Accurate determination of permittivity opens the door to many applications of RF sensing, communications and processing.



The free-space measurement of transmission and reflection at 75-110GHz.