Conference Digest

Sixth British Electromagnetic Measurements Conference

2 - 4 November 1993

National Physical Laboratory
Teddington, Middlesex

The cover design depicts the microwave planar near-field scanner being developed at NPL.

© Crown copyright 1993

National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW

ISBN 0 946754 15 2

Extracts from this digest may be
reproduced provided that the source is aknowledged

Additional copies of this digest are available
from the above address, price £50.00.

The c

Improvements in design, measurement and calibration techniques for open-ended coaxial dielectric sensors.

A P Gregory and R N Clarke, Division of Electrical Science, National Physical Laboratory, Teddington, Middx., TW11 0LW

1. Introduction

There has been much metrological interest in recent years in using coaxial open-ended sensors for dielectric measurements at RF and microwave frequencies [1-14]. In this technique, the open end of a coaxial line is placed in contact with the dielectric to be measured and its other end is attached to a reflectometer, typically an Automatic Network Analyser (ANA). Provided that the dielectric is in good contact with the sensor, its complex permittivity, $\epsilon^* = \epsilon' - j\epsilon''$ (where $j = \sqrt{-1}$), may be computed from the reflection coefficient, Γ, measured at the end of the sensor. There are a number of implicit assumptions in this short description which lie at the basis of many of the existing theoretical treatments of the technique. It is effectively assumed, for example, that the dielectric is homogeneous as well as being in direct contact with the sensor. Another theoretical assumption is that the specimen has sufficient loss or bulk to render the electromagnetic fields at its other boundaries negligible. These assumptions are often seen as limiting the utility of the the sensor method. However, the technique need not be so limited if suitable numerical modelling software is used.

In low-loss measurements, a model which takes account of all specimen boundaries is essential for accurate measurements. This can be effected by containing the specimen in a cylindrical metal cell. The assumptions of perfect specimen contact and dielectric homogeneity can be overcome for a broad class of specimens by using a multilayer treatment. This is particularly useful for measurements on substrates, radomes and biological tissues since they are often stratified or laminated. With rigid solid specimens, small specimen/sensor air gaps of ill-defined thickness are difficult to avoid. They can cause errors as large as 50% in ϵ' for specimens a few millimetres thick if conventional treatments are used. They can be avoided, however, by 'fluid immersion' techniques in which a multilayer treatment is used with a well-defined thickness of fluid as the first layer.

Another aspect of coaxial sensor metrology which often limits its utility and/or accuracy is calibration. Artefact (impedance) standards can be used with some sensors [2] which should ensure traceability for the measurements, but they can be inconvenient to use. Use of 'known' reference dielectric liquids is more convenient, but can cause large errors unless care is taken to ensure that the complex permittivity of the reference liquids is indeed 'known' accurately enough.

In recent years, workers at NPL [9] and elsewhere [10-14] have turned their attention to overcoming such limitations, thereby extending the range of application of coaxial sensors. This paper describes further work at NPL using 14-mm and 7-mm coaxial sensors to measure laminar, multilayer, rigid solid and low loss specimens whilst ensuring traceability for the measurements.

2. Software Developments

Three independent computer programs, 'RCAV', 'TEH2/3' and 'MIC2' have been developed by our co-workers which are described in detail in an NPL Report [5]. They handle coaxial sensor measurements upon dielectrics having one or more parallel layers of arbitrary thickness and complex permittivity (Figure 1). Two of these programs assume a cylindrical geometry (Figure 2), with the layers entirely filling the cross-section of a metal cylinder, the third assumes an effectively 'infinite' cross-section, which is suitable mainly for lossy specimens. The programs are all based

upon analytic techniques using modal decompositions of the fields. Where traceable measurements are dependent upon sophisticated software, as here, it is essential to crosscheck computations from the programs by intercomparisons [8]. Table 1 gives an example of such a software intercomparison. Comparison with actual measurements is discussed in the next section.

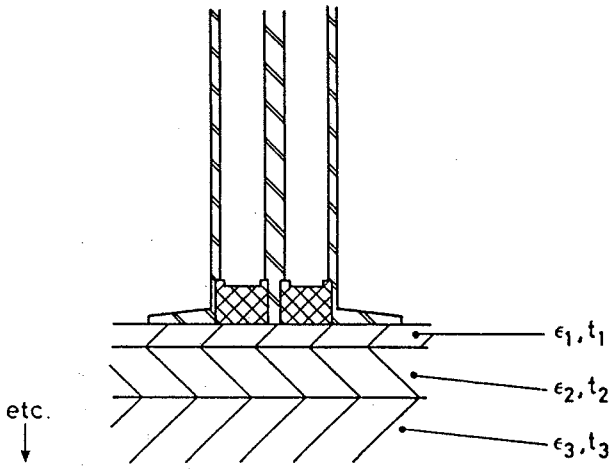


Figure 1: Sensor geometry for measuring a multilayer lamina.

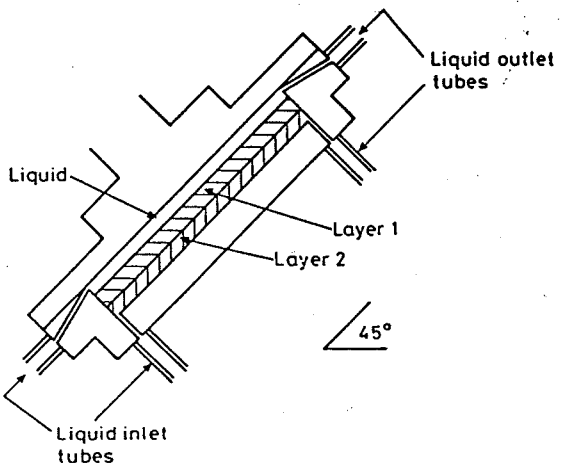


Figure 2: Typical measurement upon a multilayer system in a coaxial cell.

Table 1 Values of Γ from 'RCAV3' and 'TEH2' for a two layer structure in a 70-mm-diameter cell attached to a 14-mm diameter coaxial sensor (see Figure 2). *Layer 1* (in contact with the sensor): thickness 0.514mm, is ethanol, for which ϵ^* changes with frequency as shown. *Layer 2* (backed by a conducting plane): thickness 1.003mm, is the polymer 'Delrin', $\epsilon^* = 2.96 - 0.0j$ at all frequencies.

Frequency τ (GHz)	Γ from 'RCAV3'		Γ from 'TEH2'		ϵ^*-ethanol	
	$\lvert\Gamma\rvert$	θ	$\lvert\Gamma\rvert$	θ	ϵ'	ϵ''
0.3	0.9707	-12.50	0.9707	-12.48	22.85	6.69
0.5	0.9332	-19.58	0.9332	-19.55	19.69	9.23
0.8	0.8790	-28.50	0.8790	-28.46	15.19	10.41
1.0	0.8493	-33.91	0.8493	-33.85	12.89	10.23
1.5	0.7589	-49.85	0.7590	-49.76	9.29	8.81
2.0	0.7711	-49.69	0.7711	-49.58	7.48	7.35
2.5	0.7628	-63.38	0.7628	-63.27	6.49	6.21
3.0	0.7483	-76.02	0.7482	-75.89	5.91	5.33

Even this software models a sensor which has in various ways been idealised to give calculable boundary conditions. For example, the sensor is assumed to have a perfectly coplanar measuring face. Estimates of the uncertainties arising from the shortcomings of an actual (non-ideal) sensor can be obtained [4].

3. Hardware Developments and Measurements

Measurements up to 3GHz on low-loss specimens ($\tan\delta < 0.1$) have been performed within a liquid-tight cylindrical cell which is clamped to a 14-mm sensor (Figure 2). Solid specimens must have the same diameter as the cell, but this does not reduce the flexibility of the technique too greatly since the cells of any diameter can be machined cheaply and easily. Solids can be

measured in a multilayer geometry (Section 2) to reduce uncertainties. Typically, this is achieved by supporting them with non-metallic spacers and filling the remainder of the cell with a reference liquid. The spacers are placed near the periphery of the cell where they have little disturbing effect on the measurement. High-loss specimens can also be measured within a cell, but this is not necessary because the fields are absorbed before reaching the specimen boundaries, so the need for precise sizing can be avoided.

Figure 3 demonstrates how closely the reflection from a single layer of liquid (methanol) can be modelled by the software. It shows a polar plot of Γ from 300 MHz to 3 GHz with a 14-mm diameter sensor. As the frequency increases, the value of Γ moves clockwise around the chart to give the trace shown. The software correctly predicts the behaviour of resonances within the dielectric which show up in this case as reductions in $|\Gamma|$. Where losses are low, such plots are not very informative because the trace always remains on the edge of the chart, corresponding to $|\Gamma| \approx 1.0$. In these circumstances it is better to plot the phase of Γ against frequency, as in Figure 4. This demonstrates how a third dielectric layer can be sensed through two others which are each about a millimetre thick. The figure also shows the level of agreement with the software prediction from program 'TEH3'. Such agreement permits the possibility of measuring absolute changes, say, in the permittivity of a liquid through a solid dielectric window.

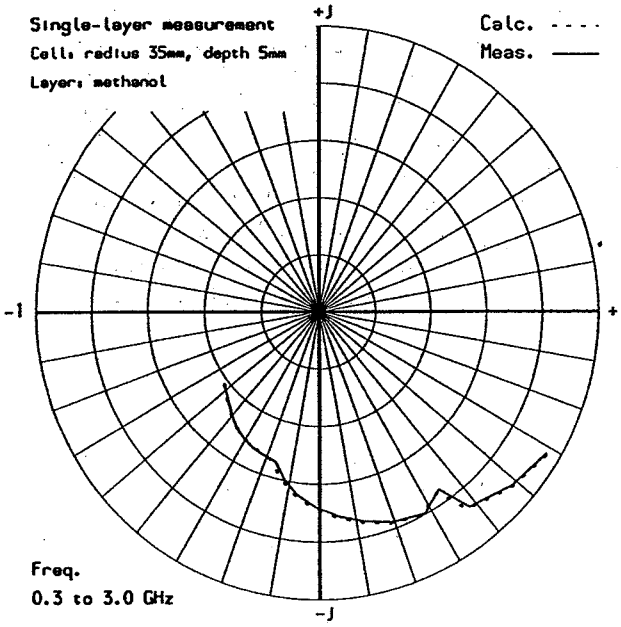


Figure 3: Polar plot showing measured and calculated reflection coefficients Γ, 300 MHz-3 GHz, of a cylindrical cell filled with methanol.

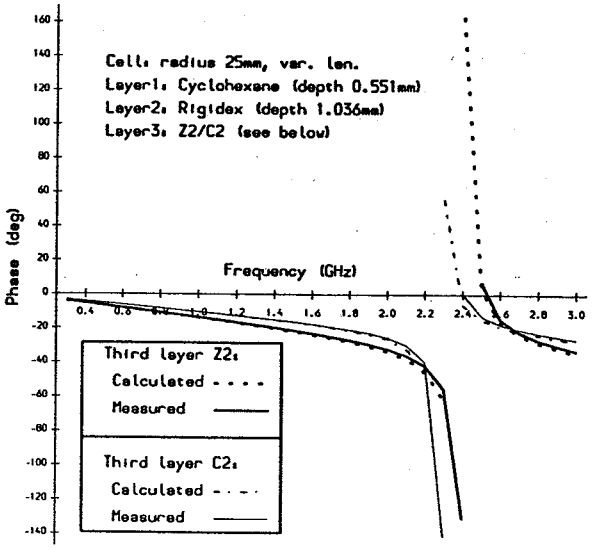


Figure 4: Measured and calculated phases for two composite specimens of three layers. The first layer (closest to the sensor) is cyclohexane. The second layer is polyethylene. The third layer is either zirconate (marked Z2) or cordierite (C2).

Permittivity measurements require 'inverse' versions of the computer programs to be written. These compute ϵ^* from the measured Γ. The inverse version of 'TEH3' allows the permittivity of any layer in a three-layer system to be computed when the permittivities of the other layers are known and all of the layer thicknesses are known. This is illustrated in Table 2, where the permittivity ϵ_2 of the central layer of a three layer specimen is measured from both sides. From independent measurements the permittivity of the glass is expected to fall from 7.0 in the RF range down to 6.75 at higher microwave frequencies. The measurement at 2 GHz (in italics) is *expected* to be in error because a cell resonance occurs at that frequency, greatly increasing the uncertainties. The values of ϵ'' show no significant trend. They are indicative of the uncertainties of the method: the glass actually has a loss which is below the threshold of measurability by this technique.

Table 2 Permittivity measurements upon upon the inaccessible central glass layer of a three-layer composite specimen: Delrin/glass/polystyrene. The specimen was measured from both sides: (a) PTFE in contact with sensor (b) polystyrene in contact with sensor. The layer properties are: Delrin: $\epsilon' = 2.90$, thickness 1.003mm; glass: thickness 2.078mm; polystyrene: ϵ' 2.57, thickness 1.007mm.

Frequency (GHz)	ϵ_2, geometry (a)	ϵ_2, geometry (b)
0.3	$7.12 - 0.38j$	$7.11 + 0.61j$
0.5	$7.29 - 0.13j$	$7.15 + 0.24j$
1.0	$7.10 - 0.25j$	$7.06 - 0.03j$
1.5	$6.74 - 0.45j$	$6.83 - 0.53j$
2.0	$6.93 - 1.12j$	$6.77 - 1.58j$
2.5	$6.78 - 0.37j$	$6.77 - 0.24j$
3.0	$6.67 - 0.35j$	$6.73 - 0.26j$

The above work employed two types of 14-mm sensor of similar design. The sensor used with the cylindrical cell has a more substantial earth-plane flange than that shown in Figure 1. It has a diameter of 100mm and the cell is clamped onto it, Figure 2. These 14-mm sensors were designed to work in the RF frequency range but, in fact, with many dielectrics, they work well up to 3, or even 5GHz. To cover higher frequencies, smaller sensors must be used and a 7-mm sensor (Figure 5), has been developed [3] for this purpose and tested up to 6GHz. Components fitted with conventional APC7 connectors may be attached to the front face of this sensor by means of a special adaptor which is screwed on when required. This enables the sensor to be calibrated (see Section 4) with 7-mm coaxial standards. Continuation of the inner conductor (F) through the adaptor is provided by exchanging it for one of greater length (G). In measurements on reference liquids, the new 7-mm sensor was found to provide measurement uncertainties as low as ±1–2% after calibration with coaxial standards. This is comparable with the accuracy of reference liquid calibration techniques, yet provides more direct traceability of measurements to national impedance standards.

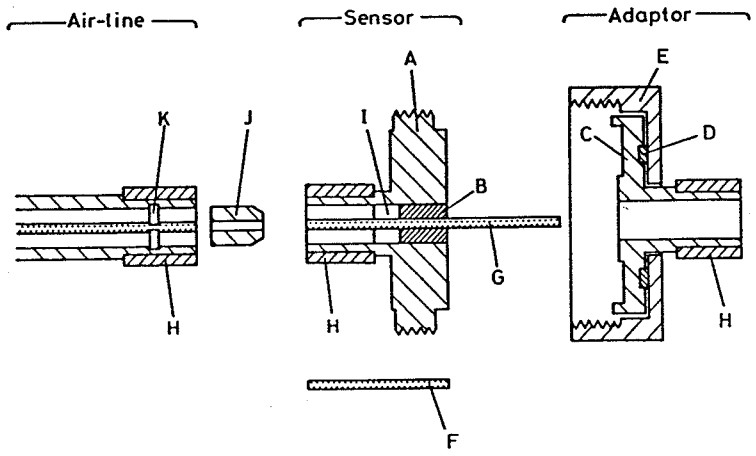


Figure 5: Schematic of the new 7-mm sensor. Key: A sensor body, B sensor bead, C PTFE washer, E Nut, F short inner-conductor, G long inner-conductor, H coupling nut of APC7 connector, I, J Perspex sleeves, K bead within APC7 connector of air-line.

4. Calibration Methods

Prior to measurements on dielectric materials, a coaxial sensor must be calibrated to establish a reference plane for the measurements (which would otherwise be quite arbitrary) and to account for the effects of mismatches. The method is essentially the same as that for calibrating any reflectometer, requiring measurements on at least three reflection-coefficient standards, but since connectors cannot be attached directly to the sensor specialised procedures are required. A least-squares calibration program, which allows use of more than three standards, has been found to be a valuable aid to producing reliable calibrations.

Two "natural" standards are available at the face of the sensor, open-circuit (sensor radiating into free-space) and short-circuit (the inner and outer conductors shorted with metal foil). The commonest method of obtaining a third standard is by immersion of the sensor in a liquid which has known dielectric properties (a high-purity *reference liquid* at a known temperature). The lack of reliable reference-liquid permittivity data can be a problem in precise coaxial-sensor work so a programme of measurements on the lower n-alcohols (which are particularly suitable for use as calibration standards) was also recently conducted at NPL [1, 6, 7].

A sensor may be calibrated with coaxial impedance-standards if a suitable method of attaching them is provided. This can be achieved by either (1) replacing the head of the sensor with a connector of electrically similar design [2, 4], to which the standards may be attached, or (2) attaching them to the face of the sensor by means of an adaptor. After removal of the connector or adaptor, measurements on one or both of the two "natural" standards are needed for a "secondary" calibration [4].

5. Conclusions

All of the work summarised above has been aimed at extending the range of applicability of coaxial sensors and with improving the accuracy of measurement whilst ensuring that traceable dielectric measurements can be performed and that realistic uncertainties can be assigned. It has been demonstrated that the permittivity of the first layer of a specimen can often be measured to better than 3%, while second and third layers have been measured to significantly better than $\pm 10\%$ when the permittivity and thickness of the intervening layer(s) was known. Such multilayer measurements will work typically down to a depth of a few millimetres, provided the surface layers do not present too great a mismatch (for example by being too conductive). Where homogeneous lossy material is available in bulk, measurements with uncertainties as low as $\pm 1\%$ are possible [2]. The resolution for $\tan\delta$ is limited to approximately 0.05 at present.

The computer programs and models which have been developed are not specific to NPL-designed sensors. They can be used to characterise a wide range of dielectric measurements with coaxial sensors. Flat-faced sensors of any size can be characterised at any required frequency and the programs can also be used to predict the performance and uncertainties to be expected from sensors having related geometries.

5. Acknowledgements

The authors gratefully ackowledge The National Measurement System Policy Unit (NMSPU) of the Department of Trade and Industry (DTI) for supporting this work. We thank G T Symm and T E Hodgetts for developing the computer programs.

6. References

[1] Clarke, R.N., Improving measurement confidence and achieving traceability in dielectric measurements through the use of reference materials. *This conference.*

[2] Grant, J.P., Clarke, R.N., Symm, G.T. and Spyrou, N.M., A critical study of the open-ended coaxial line sensor technique for RF and microwave complex permittivity measurement, *J. Phys. E: Sci. Instrum.*, **22**, 1989, 757 - 770.

[3] Gregory A.P. and Clarke, R.N., A new design of coaxial sensor with a beadless adaptor for the attachment of calibration standards, *in preparation.*

[4] Gregory, A.P. and Clarke, R.N., On the design, calibration and accuracy of a coaxial sensor for permittivity measurement, *in preparation.*

[5] Gregory, A.P.,Clarke, R.N., Hodgetts, T.E. and Symm, G.T., RF and microwave dielectric measurements upon layered materials using a reflectometric sensor, NPL Report DES 125 *in preparation.*

[6] Jenkins, S. and Clarke R.N., Measured values and uncertainties for the complex permittivity of selected organic reference liquids at 20° to 30° and frequencies up to 3 GHz, *NPL Report in preparation.*

[7] Jenkins, S., Hodgetts, T.E., Clarke , R.N. and Preece, A.W., Dielectric measurements on reference liquids using automatic network analysers and calculable geometries, *Measure. Sci. Technol.*, **1**, 1990, 691 - 702.

[8] Jenkins, S., Hodgetts, T.E., Symm, G.T., Warham, A.G.P., Clarke , R.N. and Preece, A.W., Comparison of three numerical treatments for the open-ended coaxial line sensor, *Electron. Lett.*, **26**, No. 4, 1990, 234 - 236.

[9] Jenkins, S., Warham, A.G.P. and Clarke, R.N., Use of an open-ended coaxial line sensor with a laminar or liquid dielectric backed by a conducting plane, *Proc. IEE, Pt. H*, **139**, 1992, 179-182.

[10] Li, L.L., Ismail, N.H., Taylor, L.S. and Davis, C.C., Flanged coaxial probes for measuring thin moisture layers, *Trans. IEEE, Biomed. Eng.*, **39**, 49 - 57, 1992.

[11] Nishikata, A. and Shimizu, Y., Analysis for reflection from coaxial end attached to lossy sheet and its application to nondestructive measurement, *Electron. Commun. Jpn. 2*, **71**, 1988, 95 - 101.

[12] Nishikata, A. and Shimizu, Y., Effectiveness of gaps for lossy dielectric sheet measurements by coaxial electrode, *Electron. Commun. Jpn. 2*, **73**, 1990, 14 - 22.

[13] Xu., Y, and Bosisio, R.G., On the measurement of resistive thin films and dielectric slabs using an open-ended coaxial line, *J. Electromagn. Waves and Appl.*, **6**, 1992, 1247 - 1258.

[14] Xu., Y and Bosisio, R.G., Nondestructive measurements of the resistivity of thin conductive films and the dielectric constant of thin substrates using an open-ended coaxial line. *IEE Procedings-H*, **139**, 1992, 500 - 506.