ELECTROMAGNETIC MATERIALS MEASUREMENTS FOR RF AND MICROWAVE METROLOGY

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ABSTRACT

In this paper we will review some of the recent RF and Microwave (RF & MW) measurement studies at NPL concerned with dielectric and magnetic materials. The paper concentrates on materials measurements that were aimed at supporting other RF & MW metrological activities and these are mainly measurements on high loss dielectric and magnetic materials. The work is prompted by the requirements of new technologies and new international standard test methods. Measurements on both solid and liquid dielectric materials are required and are illustrated respectively by characterisation of RAM (Radiation Absorbing Material) and of reference and tissue-equivalent dielectric liquids. The latter have a role to play in the accurate measurement of cell phone SAR (Specific Absorption Rate).

INTRODUCTION

Dielectric and magnetic materials measurements play an essential role in the development of all RF and MW systems. There are requirements at RF and microwave frequencies for characterisation of high and low *permittivity* dielectrics and high and low *loss* dielectrics. Magnetic materials, apart from their use in components such as isolators and cores, are chiefly used in bulk in Radiation Absorbing Materials (RAM). This paper describes the recent dielectric/magnetic material measurement work at NPL that has been stimulated by new requirements in RF & MW technology. A number of papers have been published which describe our recent work on low loss dielectrics, e.g. [1] - [3], the present paper concentrates rather upon the measurement of high loss dielectrics: i.e. those with a loss tangent, tan δ, greater than 0.03 or with a substantial magnetic loss. Development of new measurement techniques and enhancement of established techniques has been undertaken both to meet the demands of new technology and to facilitate the implementation of international standards. In the latter case, new standard methods for EMC measurement (e.g. [4]) and mobile telecommunications metrology (e.g. [5]) have given rise to new requirements for electromagnetic materials measurements. Such measurements must be traceable to international standards and in many cases require measurement uncertainties to be reduced below levels that were previously readily available.

Measurements on both *solid* and *liquid* dielectrics are required to support this work and examples of measurements performed on both classes of material are presented in this paper.

MEASUREMENTS UPON SOLID DIELECTRICS

Such measurements are typically performed for three reasons:

(i) to evaluate new materials,
(ii) to provide data for modelling and optimisation of component design,
(iii) to ensure that materials meet their specifications in production quality control.

The wide variety of applications for high loss dielectrics requires a correspondingly wide range of measurement techniques to be developed to minimise uncertainties in their characterisation. Even for the evaluation of one class of material, specifically RAM, four different techniques have been employed at NPL in recent years. Effective RAM is required in many different telecommunications and defence applications. Its main use in metrology is for lining the anechoic chambers in which antennas are tested and calibrated. The RAM materials studied at NPL are used for this purpose.

1. Measurement of the Electromagnetic Properties of RAM.

Effective RAM with a reflectivity of 30dB or better is readily available commercially at microwave frequencies, but RAM for RF, 30 MHz – 300 MHz, generally performs less well, often having reflectivity in the range 5 – 20 dB, and it is typically more expensive. This has led to various schemes for improving RF RAM performance and reducing cost. One example studied at NPL and previously reported elsewhere [6] is the use of multilayer RAM (optionally including one or more magnetic ferrite layers) optimised in its design by use of a Genetic Algorithm [7]. Such numerical optimisation presupposes knowledge of the complex dielectric relative permittivity, $\varepsilon^* = \varepsilon' - j\varepsilon''$, and magnetic permeability, $\mu^* = \mu' - j\mu''$, of each layer (where $j = \sqrt{-1}$). Four techniques suitable for such evaluations are described below.

1. Measurement of Ferrite RAM Specimens in a Transmission Line

Ferrite RAM is a key component of effective RF RAM. It is applied to the metal walls of anechoic chambers and when used as part of 'hybrid' or multilayer RAM it usually forms the base layer with other dielectric layers, of e.g foam RAM, placed above it. Sintered ferrite is a hard material which can be machined very precisely by grinding and, as it is a magnetic material, it must be measured by a technique which determines both ε^* and μ^*. The transmission line method [8] proves to be one of the most effective, though care must be taken over the treatment of air-gaps around the specimens. Either waveguide or coaxial cells can be used, with the latter being best suited for RF. The method requires the S-parameters of the sample to be measured in the transmission line, typically by an Automatic Network Analyser (ANA). It readily allows one to inspect the effect of stray static magnetic fields upon μ^*. This effect can be substantial – one does need to consider the presence of such fields in the vicinity of anechoic chambers!

2. Reflectometric Coaxial Probe Measurements

A very popular small-scale measurement device is the reflectometric coaxial probe [9-11]. It has an effective measurement diameter in the range 3 to 15 mm, depending on probe size, measuring at points close to the dielectric surface only. It can readily be used to measure the properties of foam RAM, which typically consists of a polymer foam matrix with carbon particles dispersed throughout it. Being malleable, such RAM compresses easily, so the most accurate measurements should take account of the force applied by the probe. A correction can be made by extrapolating this force to zero. Such measurements, though relatively easy to perform, show that the dispersion of carbon in the foam is often very uneven – a large number of measurements may be needed to obtain an average value of ε^*. This fact may prompt one to prefer a larger-scale cell for RAM evaluation. As described next, this averages such inhomogeneities automatically.

3. Measurement in a TEM (Transmission Line TEM-mode) Cell.

In the RF region, typically up to 300 MHz, measurements on a much larger scale in a TEM cell can be used to provide information on the average properties of RAM. Measurement on a larger scale is in any case essential for a structured (e.g. pyramid) RAM because the structure must be adequately sampled in the measurement. This has been achieved at NPL in a 1.2 metre-square cross-section TEM cell, Figure 1, and also in a smaller TEM cell, as used for the measurements in Figure 2. It has been found that calibration of ANA measurements *within* the TEM cell transmission line can be achieved by means of a movable short circuit placed inside it. This allows normal-incidence reflectivities to be measured down to approx. 25dB. Figure 2 shows a comparison of the measured reflection coefficient from a composite ferrite/rubber sheet. Predicted values are computed from measurements on small annular specimens of the same material in a coaxial line. This measurement was undertaken to help to evaluate the TEM cell method for RAM.

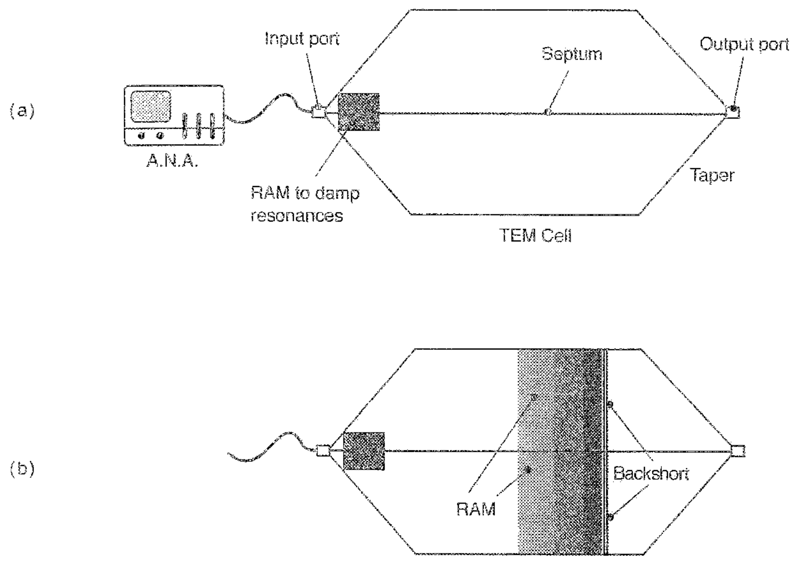

Figure 1. Measurement of multilayer RAM in a TEM Cell: (a) the TEM Cell with additional RAM to reduce resonances, (b) the TEM-Cell with RAM in place against the back-short.

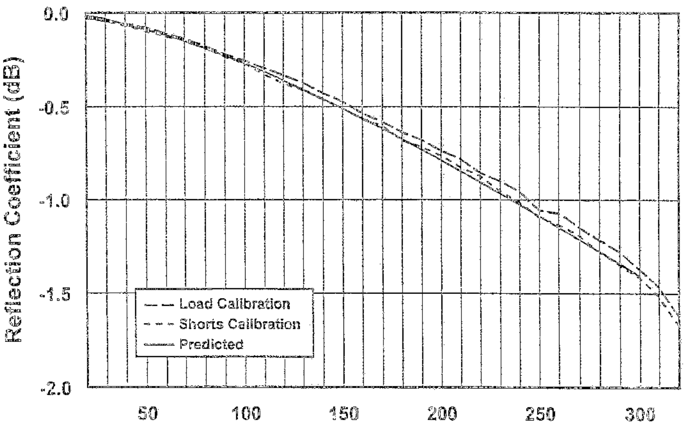

Figure 2. The measured and predicted reflection from MnZn/NR ferrite/rubber composite RAM in a TEM cell.

4. Use of an Optically Modulated Scatterer (OMS) for Free-Field Evaluation of RAM in the Near Field.

RAM is intended for use in the free-field and so must ultimately be evaluated by free-field measurements. A number of methods based on far-field techniques, such as the 'arch method', are available for just such evaluations. In recent years a number of improved RF RAM materials have been developed which rely upon their lateral (e.g. waffle) structure to achieve their physical performance and there is some advantage to be gained by studying the fields above their surfaces in the near field, i.e. close to their surfaces. At NPL an OMS [12, 13] is used as a minimally invasive electric-field probe to perform such measurements. It is scanned above the RAM surface to measure the patterning of the field above the RAM structure [14]. The OMS technique has also been used for measuring the dielectric properties of much simpler dielectric sheets. It has also proved to be an effective tool for characterising surface waves above dielectrics [15].

2. MEASUREMENTS ON LIQUID DIELECTRICS.

As stated above, the dielectric properties of solid materials are usually measured because the materials themselves are intended for end-use applications. Liquid dielectrics, by contrast, are more typically used as *substitutes* for other materials, e.g. biological tissues, either because they can usually be measured more easily and accurately than solid dielectrics or because health and safety concerns preclude direct use of humans in testing. The latter concern arises, for example, whenever high levels of electromagnetic field are present. Two major applications of dielectric liquids are therefore as *reference materials* for checking and calibrating measurements, and as *tissue equivalent materials* (t.e.m.s) in biomedical and health and safety testing.

1. Characterisation of Dielectric Reference Liquids.

These are chemically pure liquids whose dielectric properties have been well established at specified frequencies and temperatures. Typical liquids are ethanol and other n-alcohols, and distilled water and acetone. For ease of later use, the properties of the liquids can be parameterised and tabulated using dielectric relaxation models. One such is the Debye Relaxation model, which has just three constant parameters at any given temperature. These are the 'static' (low frequency) real permittivity, ε_s, the high frequency permittivity limit, ε_i, and the relaxation frequency f_r. At any frequency f one has:

$$\varepsilon^*(f) = \varepsilon' - j\varepsilon'' = \varepsilon_i + (\varepsilon_s - \varepsilon_i)/(1 + jf/f_r)$$

More complex relaxation models must be used where necessary (e.g. Double Debye, Cole-Cole). Once characterised, the liquids can be used both to check dielectric measurement systems and to calibrate them, thereby providing measurement traceability, as required by international standards. NPL has undertaken two study programmes to characterise suitable reference liquids [16, 17]. Further papers on the most recent work, from 'DC' to 5 GHz and 10 to 50 °C, are currently being prepared for publication. Three techniques have been used and intercompared in order to cover this frequency range and to promote confidence in the results. A parallel-electrode shielded two-terminal micrometer-driven admittance cell was used to determine the static permittivity of the liquids, ε_s, directly. This enables the microwave measurements to be checked by extrapolating ε' results down to zero frequency with the appropriate relaxation model. The ε_s measurements were actually performed between 100 kHz and 1 MHz, rather than at DC, to avoid electrode polarisation effects - even for lossy liquids, ε' differs insignificantly from its static value over this frequency range. At microwave frequencies two types of 14-mm diameter coaxial cell were used for these measurements: transmission cells, see Figure 3, and a reflection cell. In fact, two transmission cells of different length were employed.

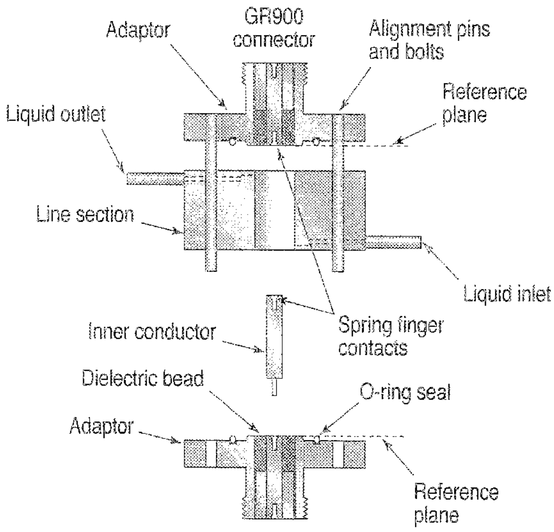

Figure 3. The 14-mm coaxial transmission cell for microwave reference liquid measurements, shown disassembled.

The three microwave cells were optimised for different frequency ranges but results obtained with them can be intercompared at 1 GHz, where all three work effectively, see Table 1. It is intended that the data obtained in the latest studies should eventually contribute to an international agreement on the dielectric properties of these reference liquids.

	Reflection cell †				14-mm transmission cell				40-mm transmission cell			
	ε'	±*	ε''	±*	ε'	±*	ε''	±*	ε'	±*	ε''	±*
Methanol	30.40	0.18	8.78	0.18	30.46	0.36	8.71	0.35	30.47	0.18	8.81	0.15
Ethanol	12.98	0.07	10.17	0.07	12.97	0.14	10.13	0.14	12.95	0.09	10.16	0.09
Propan-1-ol	6.21	0.03	6.06	0.03	6.20	0.07	6.03	0.07	6.20	0.05	6.03	0.05
Butan-1-ol	4.43	0.02	3.66	0.02	4.39	0.05	3.62	0.05	4.41	0.04	3.63	0.04
DMSO	46.15	0.35	5.09	0.34	46.46	0.79	4.91	0.80	46.37	0.19	5.23	0.09
Ethanediol	25.82	0.19	16.96	0.19	25.55	0.45	17.14	0.43	25.79	0.23	17.33	0.22

† Discontinuous-inner cell geometry

Table 1: Measured complex permittivities at 1.0 GHz and 20 ± 0.1°C.
A comparison of measurements in three different coaxial cells.
* Uncertainties are tabulated for a coverage factor of $k = 2$

2. Measurement of Liquid Tissue Equivalent Materials (t.e.m.s)

Well-characterised composite liquid t.e.m.s, mixed to a defined recipe, are used for the measurement of the Specific Absorption Rate (SAR) of power from hand-held mobile telecommunications devices (e.g. cell-phones) in human head phantoms. Liquid phantoms are required because the field-strength probes employed for the SAR measurements must be scanned inside the phantom to determine the position of highest SAR. The use of such liquids is, in any case, required by international SAR measurement and test standards, e.g. [5]. The liquids specified by the standards must mimic the highly absorbing dielectric properties of the human head but it has not proved possible to find one single liquid that can achieve this across the full frequency range of most interest, currently 300 MHz – 2.5 GHz. Typically three different liquid recipes have to be employed. Coaxial reflectometric dielectric probes (see above, and [9-11]) are widely employed for checking t.e.m. liquid permittivities prior to SAR determinations and the *reference* liquids discussed above prove invaluable in checking such measurements. However, NPL has also employed the transmission and reflection cells described above for direct measurements upon the SAR t.e.m. liquids as these cells offer better uncertainties than the coaxial probe method. One recommended liquid for 1.8 GHz has thereby been shown to have a high temperature coefficient which is far from ideal. The liquids have other undesirable properties too - they can evaporate easily and some possess components that have a degree of toxicity. It is therefore likely that many more liquid recipes will have to be examined and they too will need to have their dielectric properties determined.

OVERVIEW

The range of dielectric measurement techniques discussed in this paper illustrates the importance of choosing the optimum method for any given material sample: each technique needs to be matched to sample size, geometry, permittivity, permeability (where relevant) and to its intended application. Measurement uncertainties can be significantly reduced when this is done. The importance of traceability for providing confidence in measurements must also be emphasised. It has been illustrated here by the use of reference liquids for checking dielectric measurements and for providing traceable measurement calibrations.

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