FREE SPACE MEASUREMENT OF PERMITTIVITY

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ABSTRACT

This paper presents a free space technique for the measurement of the complex permittivity of a slice of dielectric sample. The experimental set up is described and the technique validated by measurements on well characterised dielectrics at J band whereupon it is concluded that the method would be suitable for use in the millimetre wave band. Measured data on a variety of plastics, glass, building materials and biological tissues samples at 60GHz is then given and includes new data for the permittivity of skin at this frequency.

INTRODUCTION

This paper presents a free space technique of measuring the complex permittivity of dielectrics which has been developed in the J band and subsequently employed at 60GHz to characterise a variety of materials.

There is a growing interest in the characteristics of dielectric materials in the millimetre wave (MMW) band as an ever increasing number of radar and communications systems seek to exploit these frequencies. Different materials are relevant for different applications and yet there is a paucity of permittivity data available in the published literature. Many of the measurement methods in use at centimetric wave frequencies do not scale well to the MMW band. Those methods which have been applied successfully are either based on measurements of the transmission and/or reflection coefficients arising from samples inserted within waveguide (or terminating a waveguide) Alekseev and Ziskin (1), or made in free space, Kadaba (2), or by the perturbation of the resonant frequency (or electrical length) and quality factor of an open resonator, Afsar and Ding (3). A free space method was preferred for this study since it is deemed the most suitable for wideband measurements on lossy dielectrics and requires minimal sample preparation. Furthermore, the method used here is similar to that of Ma and Okamura (4) and is based on a measurement of only the amplitudes of transmission and reflection coefficients, and not their phases, and so relaxes the requirement for mechanical precision implicit in other techniques.

The next section of this paper describes the theory of the technique. Further sections then describe the experimental set up and calibration of both the J band and 60GHz systems. The results are then presented and discussed; these include permittivity data for plastics, glass, building materials and biological tissues at 60GHz. There follows a brief section outlining further work planned in this area, then finally the conclusions are summarised.

THEORY

A plane wave normally incident on a slab of dielectric sample of thickness t_S is partially reflected, transmitted and absorbed by the dielectric. The reflected and transmitted signals are comprised of an infinite number of components due to the multiple reflections between the air/dielectric interfaces. Thus the total reflected and transmitted signals are given respectively by:

$$r = \frac{r_1 - r_1 \exp(-2k_s t_s)}{1 - r_1^2 \exp(-2k_s t_s)} \tag{1}$$

and

$$t = \frac{(1 - r_1^2)\exp(-k_s t_s)}{1 - r_1^2 \exp(-2k_s t_s)} \tag{2}$$

where k_S is the propagation constant in the sample and r_1 is the reflection coefficient of the sample/air interface. Both are functions of the relative complex permittivity, ε_r, of the sample given by.

$$r_1 = -\frac{\sqrt{\varepsilon_r} - \sqrt{\varepsilon_O}}{\sqrt{\varepsilon_r} + \sqrt{\varepsilon_O}} \tag{3}$$

and

$$k_S = k_O \sqrt{\varepsilon_r} \tag{4}$$

where k_O and ε_r are the propagation constant and permittivity in free space, respectively.

The measured values of the reflection and transmission coefficients are R_m and T_m respectively and relate to r and t by the equation pair:

$$R_m = 20\log_{10}|r| \quad dB \tag{5a}$$

and

$$T_m = 20\log_{10}|t| \quad dB \tag{5b}$$

Wideband solutions of R_m and T_m indicate cyclical variations with frequency due to the multiple reflections between interfaces beating in and out of phase. The frequencies of peaks and troughs occur when the sample thickness is a multiple of a quarter wavelength and may be used to provide an initial estimate of ε_r. For very lossy samples, equations (1) and (2) simplify to:

$$r = r_1 \tag{6}$$

and

$$t = \left(1 - r_1^2\right)\exp\left(-k_s t_s\right) \tag{7}$$

EXPERIMENTAL SET UP

A slice of sample was held in place on a rigid frame placed mid-way between a pair of standard gain horns connected to a vector network analyser (VNA). T_m and R_m were measured via the VNA $|S_{21}|$ and $|S_{11}|$ paths respectively. The horns were aligned for vertical polarisation, parallel with each other and for normal incidence on the sample. Lähteenmäki and Karttaavi (5) conclude that misalignment errors of up to 3^0 have minimal effects on the results. Furthermore, the authors own experience suggests that T_m and R_m are relatively insensitive to small alignment errors. The sample was positioned just beyond the far field threshold of each horn ($= 2D^2/\lambda$, where D = the horn aperture and λ = the longest wavelength) to ensure plane wave incidence. The sample was sufficiently large to subtend an angle of twice the 3dB beamwidth of the horns; thus it intercepted the entire main beam and approximates to an infinitely large sample.

In the general case, equations (1) to (5) are solved using an iterative technique to find solution(s) for ε_r. Solutions for ε_r are sought over a user defined search space and resolution which result in computed values of transmission and reflection coefficients (T_c and R_c respectively) which most closely match the measured values T_m and R_m. However, due to the multiple reflections present in all but very lossy samples, multiple solutions of ε_r may be found. This ambiguity can easily be overcome based on an initial estimate from the peak and trough frequencies or by fitting data at several nearby frequencies. (4) applied this technique to lossy samples within a container at 9.4GHz and ignored the multiple reflections in order to minimise the ambiguities.

The presence of the dielectric provides a degree of focusing of the signals onto the receiver of the transmitted path. A small correction must therefore be made to T_m in accordance with Shimabukuro et al (6). This correction requires an estimate of the permittivity of the sample which can be calculated from processing the uncorrected T_m data. The correction is typically very small and so the initial estimate is valid.

Initial measurements were made at J band with the intention of assessing the suitability of this technique for use in the MMW band. The calibration procedure resulted in valid data over the band 11 to 12GHz. This necessitated a sample size of 500mm x 500mm, which was large enough to intercept the first five Fresnel zones and a distance between the horn apertures of just over 1 metre. Clearly, this is becoming unfeasibly large at centimetric wavelengths.

The measurements at 60 ± 3GHz required a distance between horns of 305mm and a sample of 105mm diameter. This intercepts the first 7 Fresnel zones and was large enough to avoid total internal reflection (and multiple modes within the sample) at all points across its surface for samples whose $\varepsilon_r < 9.2$. Solutions for ε_r were computed for which the rms percentage error between computed and measured transmission and reflection coefficients at 57, 60 and 63GHz was a minimum.

Calibration

The transmission measurement was calibrated by normalising the VNA $|S_{21}|$ measurement with the sample in place to one in which no sample was present. Multiple reflections between the horns and sample gave rise to ripple on the measurement. This was overcome using the trace smoothing function at J band and by using the time gating feature to isolate the main through path in the 60GHz measurements. The latter is the preferable technique but was not available on the VNA used at J band.

The $|S_{11}|$ measurement was calibrated in free space in the plane of the forward surface of the sample. This was accomplished via a one port reflection calibration of the VNA; the short circuit being provided by an inflexible metal plate fitted on the sample frame, an open circuit being provided by the same metal plate displaced $\lambda/4$ back from its short position using metal shims and a matched load being provided by free space. Multiple reflections between sample and horn were overcome using the trace smoothing or time gating as with the $|S_{21}|$ measurements. This method of $|S_{11}|$ calibration restricts the band of measurements to ±5% of the centre frequency as defined by the $\lambda/4$ shims. The bandwidth could be extended by offsetting several calibrations using shims of the appropriate thickness up to the limitation of the horn bandwidth.

Preparation of Biological Samples

Both tissue samples were excised from a freshly butchered animal, stitched onto a metal supporting frame and chemically fixed in formaldehyde. Prior to measurement they were rinsed in water, dried with tissue paper and allowed to stand for several minutes to further dry. The pericardium sample was measured whilst still damp but without any film of surface moisture whereas the skin sample was only slightly damp at the time of measurement. The samples were then secured to the sample frame; the outer surface being exposed to the illuminating horn. Sample thickness was measured by averaging micrometer readings taken at 10 locations (pericardium) or 7 locations (skin) on the periphery of the sample.

Applications

Measurements were made on a number of building materials since this is of interest in the modelling of indoor propagation of wireless local area network (LAN) signals at 60GHz. There is very little data published for biological tissues in the MMW band. Data on skin is required in order to assess the health and safety implications of exposure to MMW signals. As far as the authors are aware, these measurements of permittivity are the first on skin in the MMW band.

RESULTS & DISCUSSION

J Band

Table 1 presents results over 11 to 12 GHz. These coincide quite closely with previously published data also listed in Table 1. Multiple solutions were obtained for the chipboard and medium density fibre (MDF) board but were readily resolved by fitting the data across the measurement band.

Sources of error. For the low-loss materials the values of T_m are less than 1dB and so great accuracy is required in its measurement. Repeated readings of the reflection and transmission coefficients suggest an experimental repeatability of ±0.11dB in R_m and ±0.18dB in T_m. This renders the determination of the imaginary part of ε_r subject to large percentage errors for the low loss materials. Similar problems were experienced with the 60GHz data. A significant source of error is the variation of sample thickness and the unaccounted roughness of the surface. It is not possible to predict the consequence of the tolerances of the measured data on the result for ε_r due to the iterative search technique employed. However, for the PTFE sample the measured values of T_m and R_m were within the ranges of values computed from equations (1) to (5) based on the published permittivity data and the measured thickness of 12.6mm ± 0.4mm over the band 11 to 12GHz. Furthermore, the peak in T_m at 8.2GHz affords an initial estimate of $\varepsilon_r \sim 2.1$.

TABLE 1 – Permittivity Results at J Band

Sample	11.0GHz	12.0GHz	Published result
PTFE	2.095 – j0.0007	2.07 – j0.0012	2.08 – j0.00077 at 10GHz (7)
Polystyrene	2.47 – j0.014	2.49 – j0.006	2.48 – j0.003 at 3GHz (7)
Borosilicate glass (80% SiO_2)	4.79 – j0	4.61 – j0	4.6 at 1MHz (as quoted by manufacturers)
MDF board	2.23 – j0.138	2.29 – j0.130	
Chipboard	2.34 – j0.197	2.38 – j0.178	

60GHz

Table 2 presents data for the best fit solution across the measurement band of 57 to 63GHz, together with previously published data where available. The measured data coincides quite closely with previously published values. As at J band multiple solutions of ε_r were obtained for the building materials which are all moderately lossy. Solutions for the very lossy biological tissues were unique.

TABLE 2 – Permittivity Results at 60GHz

Sample	Measured ε_r	Published result
PTFE	2.04 – j0.0007	2.063 – j0.0006 (3)
Polystyrene (3 samples)	2.48 – j0	
Fused Quartz (3 samples)	3.78 – j0	3.793 – j0.001 (3)
MDF board	3.48 – j0.170	
Chipboard	3.14 – j0.161	2.78/3.15 – j0.136/0.180 (8) 2.95 – j0.19 (5)
Plasterboard	2.95 – j0.035	2.60/3.08 – j0.036/0.055 (8) 2.58 – j0.021 (5)
Concrete	6.03 – j0.795	6.78 ± 0.7 – j0.75 at 51.3GHz (9)
Bovine Pericardium	5.43 – j14.33	
Porcine skin	5.79 – j6.36	

Tissue characteristics. The similarity in the results for the real part of the permittivity of the two tissue samples is perhaps unsurprising since both are composed predominantly of collagen. The variation in their imaginary parts is probably due to their differing moisture contents. The transmission and reflection coefficients of the tissue samples were measured three times for random sample orientations. Very little variability in the readings was observed and so the results tabulated above were based on averaged readings.

FUTURE WORK

Future work aims to extend the characterisation of tissues to include human skin and measurements in the 77 and 94GHz bands. It is also planned to characterise road materials at 77GHz since this band is used by automobile radar.

A significant application of the techniques described in this paper is to use a measurement of the permittivity of laminated composite materials to non-invasively detect and locate faults arising during the curing of these materials. Such faults would seriously undermine the strength of the materials and could go undetected until they fail. In this application the superior spatial resolution of high frequency MMW (94GHz) is desirable.

CONCLUSIONS

The free space measurement of the amplitudes of reflection and transmission coefficients is a reliable and accurate means of determining the complex permittivity over a 10% bandwidth. This bandwidth could be extended by offsetting the frequencies of several calibrations. The technique developed at J band scales successfully to MMW frequencies and is indeed conveniently applied at 60GHz and would be suitable for use at yet higher frequencies. It has been used successfully to measure a variety of dielectric materials which can be prepared in slices of known thickness. However, it is not best suited to the accurate determination of the imaginary part of permittivity of very low loss materials. The complex permittivity of a variety of building materials has been measured and is in close agreement with previously published data. The method has also provided new data on the complex permittivity of porcine skin and bovine pericardium tissues at 60GHz.

Multiple solutions arise in low and medium lossy dielectrics. Resolution of the ambiguities may be accomplished by fitting measured and computed data over the measurement bandwidth and/or by making initial estimates based on frequencies of peaks or troughs.

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