Permittivity Measurements on Human Skin in the Millimetre Wave Band

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Abstract

The complex permittivity of a sample of human skin is measured across the band 57 to 100GHz using a free space technique. This data is used to fit a single term Cole-Cole function. The measured data is used in conjunction with a thermal model to determine the temperature rise on the skin surface exposed to millimetre wave signals of 100 Watts/m^2. This indicates a maximum temperature increase of 0.25^{0}C from a 30 second exposure.

1. INTRODUCTION

This paper describes the measurement of the complex permittivity of a single sample of excised human skin across the millimetre wave (MMW) band using a free space technique. The measured data has been used to set the parameters of a Cole-Cole function to describe the frequency dependence of the permittivity of human skin. A thermal model utilising the measured data has also been applied to determine the temperature rise on the skin surface when exposed to millimetre wave signals of incident power density of 100 Watts/m^2.

Data on the dielectric characteristics of biological tissue is very sparse in the MMW band. Hitherto, the permittivity of tissues has been extrapolated from models of permittivity as functions of frequency based on relaxation phenomena such as Debye and Cole-Cole functions, as in [1][2]. However, the model parameters have been based on data measured at centimetric wave frequencies and exhibit a large degree of variation. Consequently, the predicted permittivity for human skin in the MMW band varies over a wide range. Increasing use is being made of the MMW band for sensor and communications applications which inevitably raises concerns over the potential hazards of exposure to MMW. Since it is anticipated that the skin will be highly lossy at MMW frequencies most of the power will be absorbed by the skin which, baring the brunt of any exposure, shields deeper lying tissues. A direct measurement of the permittivity of the skin is therefore deemed necessary in order to validate an appropriate model and to evaluate the heating of skin exposed to MMW radiation.

Most methods of permittivity measurement are awkward to scale to the MMW band. A free space method was chosen here as it is conveniently applied to make wideband measurements of lossy, planar dielectrics and because it captures data from a sample averaged over several square centimetres. Initial results for human skin have been published by the author [3]. However, this study is more comprehensive in its repeated tests and temperature modelling. Recently, some permittivity results for human skin in the MMW band have been published using different techniques [4] – [7]. However, this data has highlighted the inconsistency of skin from differing sites and subjects. Notwithstanding this, data is still sought and this study aims to furnish new data measured using a free space method.

The next section of this paper describes the theoretical aspects of the measurement and also presents the Cole-Cole function and the thermal model. Subsequent sections describe the measurement method, present and discuss the results and draw some conclusions.

2. THEORY

2.1. Measurement 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 and are given respectively by:

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

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

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 ($= \varepsilon_r^{/} - j\varepsilon_r^{//}$), of the sample given by:

$$r_1 = -\frac{\sqrt{\varepsilon_r} - \sqrt{\varepsilon_O}}{\sqrt{\varepsilon_r} + \sqrt{\varepsilon_O}} \quad (3)$$

and
$$k_s = k_o\sqrt{\varepsilon_r} \quad (4)$$

where k_O and ε_0 are the propagation constant and permittivity of 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:

$$R_m = 20\log_{10}|r|\,dB \text{ and } T_m = 20\log_{10}|t|\,dB \quad (5)$$

2.2. Relaxation Models

It is anticipated that the permittivity of tissues in the MMW band will be dominated by the relaxation characteristics of its free "bulk" water and bound water content. Bulk water has a relaxation frequency centred at around 25GHz at 37^{0}C (human arterial blood temperature) [8]. Other relaxations exist at lower frequencies and several models account for multiple overlapping relaxation phenomena [8]. One of the most commonly applied is the Cole-Cole function which may be expressed as:

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \left(j\, f/f_c\right)^{1-\alpha}} - j\frac{\sigma_s}{\omega\varepsilon_o} \quad (6)$$

where f_c is the relaxation frequency, ε_s and ε_∞ refer to the permittivity well below and well above f_c, respectively, ω is the (angular) frequency, σ_s denotes the static conductivity, α (= 0 to 1) is indicative of the spread of relaxation frequencies and $j = \sqrt{-1}$. When α = 0 equation (6) reduces to a Debye function. Multi-term variants of equation (6) have also been proposed for biological tissue e.g. [1][8].

2.3. Thermal Model

The rise in skin surface temperature is solved using the method of Walters et al [9]. A one-dimensional thermal model is used in which it is assumed that a plane surface of skin is illuminated by a plane wave and that heat diffusion along the surface of the skin and cooling due to blood perfusion and surface heat losses to the air above are negligibly small. Assuming insulated boundary conditions, the surface temperature rise, T_{sur} is given by:

$$T_{sur} = C_1\sqrt{t} - C_2\left(1 - e^{t/\tau}erfc\left(\sqrt{\frac{t}{\tau}}\right)\right) \quad (7)$$

where $C_1 = \frac{2I_0T}{\sqrt{\pi k\rho C}}$ and $C_2 = \frac{I_0T\delta}{k}$

and *erfc* denotes the complimentary error function. T is the coefficient of surface transmission ($=1-|r_1|^2$), t is time, I_0 is the incident power density, δ is the skin depth, C is the specific heat (of skin), k is the thermal conductivity (of skin), ρ is the density of the skin and τ is the thermal time constant i.e. the time for the thermal energy to diffuse a distance equal to the energy penetration depth (= δ). Walters et al [9] quote values of ρkC = 1.7 x 10^6 W^2 s/m^4 $^0C^2$ (thermal inertia of skin) and k = 0.3 Wm^{-1} $^0K^{-1}$ (thermal conductivity of skin). An incident power density, I_0 = 100 W/m^2 was assumed as this is the National Radiological Protection Board (NRPB, a UK regulatory body) basic restriction in the 10 to 300GHz band [10].

3. METHOD

A method similar to that of Ma and Okamura [11] was employed. Circular samples were clamped on to an annular sample frame placed mid-way between a pair of standard gain waveguide 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 and for normal incidence on the sample. The sample was positioned just beyond the far field threshold of each horn ($=2D^2/\lambda$, where D = the horn aperture and λ = wavelength) to ensure an approximate plane wave incidence. Samples of 105mm diameter were sufficiently large to subtend an angle of greater than twice the -3dB beamwidth of the horns; thus they approximate to an infinitely large sample intercepting 7 to 15 Fresnel zones. The VNA was operated in a time gated mode in order to reject multiple reflections between the horns and/or sample. Equations (1) to (5) are solved using an iterative technique to find solution(s) for ε_r.

A sample of human skin was obtained from National Disease Research Interchange (NDRI), Philadelphia and was fixed in a 10% formaldehyde solution. A circular skin sample was cleaned and stitched onto a stainless steel frame which in turn can be clamped to the sample frame so as to present a circular skin sample of 105mm diameter and nominal thickness 1.5mm with the outer surface of the skin in the measurement plane facing towards the illuminating horn. Prior to each measurement the sample was removed from the formaldehyde, rinsed in tap water, dabbed dry and then left to stand for four hours in order to further dry. Slight differences in sample drying may have arisen from variations in the ambient temperature and humidity. This drying protocol was used consistently for all tests.

Thirty repeated tests were made over the band 57 to 63GHz and five repeated tests were made over the 76 to 100GHz band. The effect of the formaldehyde fixing was ascertained on a sample of porcine skin through a comparison of measurements conducted on the fresh, unfixed sample and then repeat measurements made after a week in a 10% formaldehyde fixing solution. Furthermore, the results taken at the ambient lab temperature may be projected to 37^{0}C. A literature survey of the temperature gradients of the permittivity of water in the MMW band yielded the following data: gradient for $\varepsilon_r^{/}$: + 2.35% / ^{0}C (± 0.65% / ^{0}C), gradient for $\varepsilon_r^{//}$: + 1.05% / ^{0}C (+0.67/-0.46 % / ^{0}C).

The measurement method was validated by measurements made on a PTFE sample whose properties are well established in the MMW band.

4. RESULTS & DISCUSSION

The measured result for the PTFE sample was ε_r = 2.02 (±0.10) – j 0.007 (±0.007) across the band 76 to 100GHz. This is in close agreement with the published result of ε_r = 2.0271 – j0.0007 at 70-115GHz [12].

The measurements on the porcine skin before and after fixing suggested that the "fresh" skin value of $\varepsilon_r^{/}$ is 0.954 (+0.046/-0.05) times that of the "fixed" skin value and the "fresh" skin value of $\varepsilon_r^{//}$ is 1.72 (+0.44/-0.073) times that of the "fixed" skin value.

The permittivity results for the human skin are given in Figs. 1 and 2. Experimental errors result from tolerances on the calibration and references, variation in sample placements, noise modulations of the VNA results, the tolerance to which the skin thickness is measured, and the dynamic range of the measurement. However, experimental repeatability is dominated by the consistency to which the skin is dried. The variation of the repeated tests captures all sources of error and is a fair reflection of the total experimental tolerance. The tolerance of the fixed, ambient temperature results is given as 2σ_n of the statistical spread and is depicted by the dotted lines in Figs. 1 and 2. Variations due to skin orientation where found to be within the limits of experimental repeatability and so it is concluded that skin behaves isotropically in the MMW band. Fig. 1 presents the permittivity values as measured at the ambient temperature (18 to 23^{0}C) for the fixed skin sample. Fig. 2 gives the permittivity results projected to 37^{0}C unfixed (i.e. fresh) values. Total errors of approximately ±18% apply to the fixed skin at ambient temperatures and approximately ±24% to the corrected fresh skin at 37^{0}C across the band.

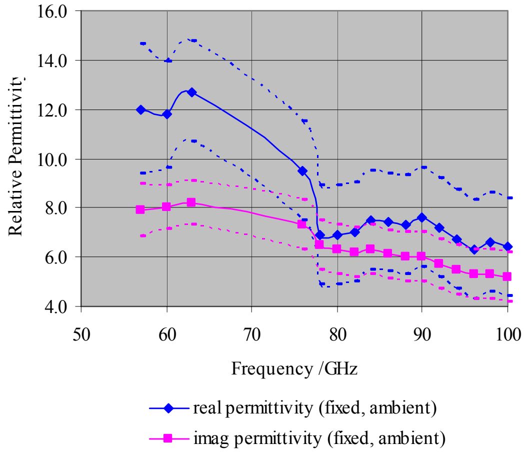

Fig. 1. Relative permittivity of human skin (ambient lab temp, fixed)

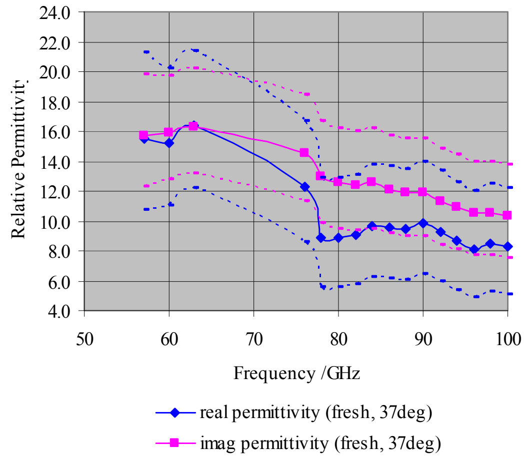

Fig. 2. Relative permittivity of human skin (37^{0}C, fresh)

These results coincide most closely with the 4 term Cole-Cole function for wet skin of Gabriel and Gabriel [1]. The results presented here are in reasonable agreement with those of Boric-Lubecke et al [5][6] for the permittivity of skin on the back of the hand at 40GHz (= 16 – j17).

The permittivity data for the fresh skin at 37^{0}C has been used to establish the parameters of a Cole-Cole function which best fits the measured data. The parameters were found to be; ε_s = 48, ε_∞ = 7, f_c = 26GHz, σ_s = 0 and α = 0. It is interesting to note that the best fit was obtained for α = 0 i.e. a simple Debye function suggesting that the permittivity of skin is dominated by its free water content. However, these model parameters result in an rms percentage error between modelled and measured permittivity values of 12.9%. This discrepancy may well be due in part to differing characteristics between the three distinct layers comprising skin:

the epidermis, the dermis and the subcutaneous layer. This is supported by the results of Hwang et al [7] whose data for the *epidermis* alone in the MMW band differs from the result presented here which pertain to the whole of the skin.

The permittivity data for the fresh skin at 37^0C has been applied in the thermal model to determine the temperature rise on the skin surface resulting from a 30 second exposure of 100 W/m^2 at 60 - 100GHz. The heating rate increases slightly with frequency and results in a maximum rise of 0.25^0C at 100GHz. The increasing surface temperature rise with frequency is to be expected since the skin depth decreases with frequency and the RF power is absorbed by an increasingly thin surface layer as frequency increases. It is worth noting that these temperature increases have been calculated under the simplifying assumptions of no heat loss mechanisms and so represent a worst case.

5. CONCLUSIONS

New data on the permittivity of human skin in the MMW band has been measured and projected to fresh skin values at body temperature, albeit on the basis of a single sample. This data plus previously published measured data made by other methods plus data extrapolated from various models all exhibit wide degrees of variation which is consistent with observations made at lower frequencies. It is concluded that skin naturally exhibits a wide degree of variation across the human body and from one subject to another and that this is likely to be due to its varying water content.

The permittivity of skin adheres somewhat loosely to a Debye function and is in accordance with expectations since its permittivity in the MMW band is dominated by its water content. The discrepancies with a Debye model are believed to be due to differing characteristics of the three discrete layers forming skin. Models based on measured data well below the MMW band do not yield results which accord accurately with measured values within the MMW band.

The temperature increase on the surface of human skin exposed to MMW radiation at the NRPB basic restriction of 100 Watts/m^2 does not exceed 0.25^0C over a 30 second exposure. This suggests that current UK limits are sufficient to avoid a burn hazard.

6. REFERENCES

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