Permittivity of Human Skin in the Millimetre Wave Band

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Abstract: The complex permittivity of a human skin sample is measured over the band 60 to 100GHz using a quasi-optical method. The results are presented and compared with predictions from standard models. There is a wide range of modelled results; each model providing a partial fit with the measured data.

Introduction: Currently, very little measured data is available for the permittivity of biological tissues in the millimetre wave (MMW) band. This Letter presents the first measured permittivity data for human skin in the MMW band. Hitherto, the permittivity of biological tissues in the MMW band has been extrapolated from models of permittivity as functions of frequency such as Debye and Cole-Cole type equations. Model parameters have been based on measured data at lower, centimetric, frequencies. With the increasing use made of the MMW band for communications, radar and other passive sensor applications it becomes important to have measured data available. Since it is anticipated that human skin will be very lossy within the MMW band it may be assumed that MMW radiation incident on the human body will be almost entirely absorbed (or reflected) by the skin layer. Consequently, it is particularly important to have reliable data on the characteristics of human skin. Such data can verify or adjust the standard models and be used as a basis for determining the heat deposition and propagation of MMW signals in the body. This Letter describes the quasi-optical experimental method and theory used and presents the measured results for a single, ex-vivo sample of human skin fixed in formaldehyde together with a comparison of data from standard permittivity extrapolation models.

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 (*r*) and transmitted (*t*) 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_o are the propagation constant and permittivity in free space, respectively.

Experimental Method: A slice of sample was held in place on a rigid circular frame placed between and just beyond the far-field threshold of a pair of standard gain horns connected to a vector network analyser (VNA), similar to the method of [1]. The amplitudes of the transmission and reflection coefficients 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. The sample was sufficiently large to subtend an angle of twice the 3dB beamwidth (at least the first 7

Fresnel zones) of the horns; thus it intercepted the entire main beam and approximates to an infinitely large sample. The VNA was used in a time gated mode to isolate the reflection from the sample or the main through signal for the reflection and transmission measurements, respectively. The reflection measurement was calibrated with respect to a metal short circuiting plate placed in the sample frame whereas the transmission measurement was calibrated with respect to the path loss with no sample in place.

Equations (1) to (4) 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 which most closely match the measured values. 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 caused by the multiple reflections beating in and out of phase or by fitting data at several nearby frequencies [2].

The skin sample was obtained from a white, 50 year old, female donor. Its fat was removed and it was scrapped to a near uniform thickness (~ 1.5mm) and fixed in 10% formalin soon after excision. The skin was lightly stretched over an annular stainless steel frame and stitched into location around the frame periphery. Prior to measurement, the sample was rinsed in water and allowed to dry for 4 hours. A 105mm diameter of the sample was exposed to the measurement.

A PTFE sample, whose properties are well established, was measured in the same way in order to verify the method.

Results & Discussion: The permittivity of the PTFE sample was determined to be: ε_r = 2.04 – j0.0007 and 2.00 – j0.0023 at 60GHz and 94GHz, respectively, which are in close agreement with previously published data. The results for the skin sample are given in Table 1. Table 1 quotes the permittivity values which represent the best solutions over given bands and at certain spot frequencies of interest. The results are quoted at both the measurement temperature and extrapolated to 37^0C. The following temperature gradients have been applied as they represent the mean of those reported in the literature based on data for water in the MMW band: real part of ε_r: $+2.35\%/^0$C, imaginary part of ε_r: $+1.05\%/^0$C [3], [4], [5] and [6].

Table 2 quotes the values for dry human skin at 37^0C predicted from standard models used to extrapolate the permittivity of biological material.

The results of Table 1 indicate that both real and imaginary parts of the permittivity show a reduction with increasing frequency, as is to be expected from relaxation phenomena. The sample was slightly moist at the time of measurement. An increase in the permittivity was observed when measured wet and is in line with expectations. Indeed, significant variation in the permittivity of skin is also anticipated on a sample by sample basis. The effects of the formaldehyde fixing were undetermined. The effects of measurement error are not possible to quantify due to the iterative search technique used. Repeated measurements indicate possible errors of up to ±15%. It is also worth noting that extrapolations of the permittivity data to new temperatures may be unreliable as there is a wide variety in the temperature gradients reported in the literature.

The measured values show a consistently higher real part of permittivity than the predicted values, whereas the imaginary parts are in reasonable agreement. No one model provides the most consistent fit to the measured data. The likely reasons for the discrepancies in the two sets of data include: (i) the unknown moisture content of the sample used here and also those used in measurements to set the model parameters, (ii) the effects of fixing in formaldehyde and (iii) natural tissue variations.

Acknowledgments

The author wishes to thank the following:
Prof. J. Dahele of Cranfield University, my PhD supervisor, for his help and advice.
Dr P. Zioupos and Mrs V. Wise of Cranfield University for the preparation of the skin sample.
The National Disease Research Interchange, Philadelphia, PA. for the provision of the human skin sample.
Anritsu Corporation and Birmingham University for the use of their VNAs.

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Automated calculations based on this model also available at: http://niremf.iroe.fi.cnr.it/tissprop/

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Table captions:

Table 1 Measured Permittivity Data for Human Skin

Table 2 Predicted Permittivity Data for Human Skin (37^0C)

Table 1

Frequency (GHz)	Measured Permittivity T (^{0}C)		Permittivity (Extrapolated to37^{0}C)
57 - 63	23	9.9 – j9.1	13.2 – j10.4
60	23	9.9 – j9.0	13.2 – j10.3
76 – 78	30	10.4 – j3.3	12.1 – j3.5
77	30	10.4 – j3.2	12.1 – j3.4
84	30	9.5 – j3.5	11.1 – j3.8
90 – 100	30	7.9 – j3.0	9.2 – j3.2
90	30	7.9 – j3.0	9.2 – j3.2
94	30	7.5 – j2.9	8.7 – j3.1

Table 2

Frequency (GHz)	Ref [7] Single term Debye	Ref [7] Two term Debye	Ref [8] Four term Cole-Cole
60	8.7 – j14.6	5.8 – j5.0	7.98 – j10.90
75	7.27 – j11.0	5.2 – j4.1	6.69 – j9.11
77			6.56 – j8.91
94			5.79 – j7.49
100	5.9 – j8.6	4.7 – j3.2	5.60 – j7.09