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MICROWAVE CHARACTERIZATION OF HUMAN SKIN IN VIVO FOR FREQUENCY RANGES 8-12.5 GHz AND 18-26 GHz

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ABSTRACT

In this paper, the dielectric properties of human skin in vivo were measured in the frequency range 8 – 12.5 GHz and 18 - 26 GHz. The work involved testing of several human subjects by pressing an area of the human body against a waveguide sensor. The measurement system consists of a Vector Network Analyzer (VNA) Wiltron 37269B and open-ended waveguide sensor. The waveguide sensor consists of coaxial cables, coaxial-to-rectangular waveguide transition,and Teflon™ impedance transformer. Complex reflection coefficients (S_{11}) were measured and complex permittivities (ε^*) are calculated by implementing a formulation of a rectangular waveguide radiating in to the half-space of lossy dielectric material. Results are reported for the mean value of 20 (male and female) subjects for the palm region of human skin in vivo. Also, complex permittivities of the sole region of human skin in vivo are reported for the mean value of 5 male subjects.

INTRODUCTION

In the last ten years, high-frequency microwaves (10 – 30 GHz) and millimeter-waves (30 – 100 GHz) are increasingly being used in applications such as local multipoint distribution services (LMDS), hand-held traffic radar and automotive anti-collision radars. LMDS systems (operating in frequency range 27 – 30 GHz) will offer interactive video on demand, voice and data services via radio networks. Also, hand-held traffic radars and automotive anti-collision radars are operating at frequencies above 20 GHz. So, with the increasing use of microwave and millimeter-wave radiation in communications and radar, it is necessary to know dielectric properties of various human tissues for evaluation of potential hazards to humans. At millimeter-wave frequencies, the absorption of electromagnetic radiation is mostly restricted to the skin because of the submillimeter depths of penetration. Therefore, the knowledge of dielectric properties of human skin in vivo is of prime importance for quantifying hazardous effects of microwave and millimeter-wave radiation.

The dielectric properties of human skin in vivo were measured in the frequency ranges of 8 - 12.5 GHz and 18 - 26 GHz. This dielectric data is very useful for evaluation of potential hazards to human beings due of microwave and millimeter-wave radiations. An open-ended rectangular waveguide (WR-90 waveguide 8 –12.5 GHz and WR-42 waveguide operating in 17 – 28 GHz) is used as a microwave sensor for nondestructive evaluation. An area of the human body is pressed against the waveguide flange for measurement of complex reflection coefficients. A quarter-wavelength impedance transformer of Teflon™ is used to reduce reflectivity of human skin. The complex permittivity of human skin in vivo is estimated by solving

the radiation problem of a rectangular waveguide with semi-infinite flange terminated by a semi-infinite half-space of lossy dielectric material. The paper involved a testing of several human subjects by using a microwave non-destructive testing techniques. The technique used is a waveguide technique that makes it possible for the measurement of live human skin.

The measurement system consists of a Vector Network Analyzer (VNA) Wiltron 37269B and an open-ended waveguide sensor. The sensor has coaxial cables, a coaxial-to-rectangular waveguide transition and Teflon™ impedance transformer. The measurement system was calibrated up to the rectangular waveguide end of the coaxial-to-waveguide adapter by implementing LRL (line, reflect line) calibration technique. In LRL calibration, first line is a through connection, the second line is a precision waveguide of length equal to quarter wavelength at mid-band. The reflect standard is a waveguide shorting plate. A computer program was implemented to calculate the complex permittivity of human skin in vivo from the measured and calculated values of complex reflection coefficients.

In addition, this technique that has been done can be extended to image fat, bone and muscle layers in human body using microwave radiations. The objective of this paper is to mesure the dielectric properties of human skin in vivo (measurements on live human skin) in the frequency ranges 8 – 12.5 GHz and 18 to 26 GHz bands for palm and sole region of the human body.

Advantages of the research are as follows: -

(i) It may lead to the development of a new product for finding complex permittivities and imaging human skin in vivo using microwaves radiations.
(ii) It is possible that the healthcare industry may have an interest in this project since it is very useful in measuring moisture content, complex permittivities, attenuation coefficients and emissivity of human skin in vivo.

Skin Depth, δ

Skin depth represents the depth of penetration. Skin depth is a measure of the degree to which an electromagnetic field penetrates a certain material. This skin effect is a function of frequency, the depth of penetration decreasing with increasing frequency. The skin depth also known as a distance required to reduce the radiant power flux by a factor of "e" = 2.7 or the depth at which electric field reduces to 1/e = 37 % of its original value. To calculate the skin depth, we should get the propagation constant first;

$$\gamma = (2\pi / \lambda_o) (-\varepsilon^*)^{1/2} \quad (1)$$

where, γ = Propagation constant
ε^* = Complex permittivity of the material
λ_o = Wavelength in the free space

and,
$$\gamma = \alpha + j\beta \quad (2)$$

where, α = Attenuation constant (Nepers/meter)

β = Phase constant

therefore, the skin depth, $\delta = 1 / \alpha$ (3)

Experimental Work

By using a microwave non-destructive testing, it is possible to know the dielectric properties of human skin in vivo which are required in a variety applications. The dielectric properties of human skin in vivo were measured in the frequency ranges of 8 – 12.5 GHz and 18–26 GHz. Twenty subjects of live human skin in the palm region and five subjects in the sole region.

In this project for LRL calibration, first line is a through connection, the second line is a precision waveguide of length equal to quarter wavelength at mid-band. The reflect standard is a waveguide shorting plate. The smoothing function of Vector Network Analyzer (VNA) can further reduce the residual post-calibration errors.

The measurement system [3] is as shown in Figure 1.1. It consists of a Vector Network Analyzer (VNA) Wiltron 37269B which is the main equipment of the measurement system and an open-ended waveguide sensor. The sensor has coaxial cables, a coaxial-to-rectangular waveguide transition and Teflon™ impedance transformer as shown in Fig. 1.1. Complex reflection coefficients (S_{11}) measurements were measured in the frequency range of 8 – 12.5 GHz and 18 – 26 GHz by pressing the waveguide sensor against an area of the human body. The measurement system was calibrated up to the rectangular waveguide end of the coaxial-to-waveguide adapter by implementing LRL (line, reflect line) calibration technique. In LRL calibration, first line is a through connection, the second line is a precision waveguide of length equal to quarter wavelength at mid-band. The reflect standard is a waveguide shorting plate. The smoothing function of VNA can further reduce the residual post-calibration errors.

In this paper, an open-ended rectangular waveguide is used as a microwave sensor for nondestructive evaluation. The open-ended waveguide is terminated in a cover flange. Figure 1.2 shows an arrangement for complex permittivity ($\varepsilon^* = \varepsilon' - j\,\varepsilon''$) measurement of human skin in vivo. A quarter-wavelength impedance transformer of Teflon™ is used to reduce reflectivity of human skin. An area of the human body is pressed against the waveguide flange for measurement of complex reflection coefficients (S_{11}). The complex permittivity of human skin in vivo is estimated by solving the radiation problem of a rectangular waveguide with semi-infinite flange terminated by a semi-infinite half-space of lossy dielectric material.

The calculation of complex permittivity consists of three steps, namely, calculation of input admittance, admittance transformation for Teflon™ impedance transformer and calculation of new ε^* guess by zero finding technique [1].

The human skin consists of two layers: (a) the epidermis and (b) the dermis. The range of thickness of the epidermis and dermis for adult males and females are 0.03-1.4 mm and 0.86-3 mm, respectively [4]. For the palm region, the approximate thickness of the epidermis and dermis are 0.6 mm

and 3 mm, respectively [4, 5]. The palm region of the human body will be chosen for measurements because the skin is thick in this area and has a relatively smooth surface. For the calculation of complex permittivities from measured reflection coefficient, it is necessary to make the two assumptions regarding human skin in vivo: -

(1) It can be modeled as a homogeneous lossy dielectric layer.
(2) Reflections from the muscle and fat layers can be neglected.

Because of the first assumption, the measured dielectric data will correspond to average properties of epidermis and dermis. At frequencies above 10 GHz, human skin in vivo will have submillimeter depths of penetration [7]. So, the second assumption is justified for the regions of human body (e.g., palm, sole, etc.) where the total (epidermis and dermis) thickness of skin is greater than 3 mm (i.e. total thickness ≥ 3-4 depths of penetration).

The method for calculation of complex reflection coefficient for the arrangement shown in Fig. 1.2 has been implemented which is similar to a formulation given by Galejs [2]. It calculates input admittance of a smaller waveguide radiating into a larger waveguide containing lossy dielectric material. Increasing the size of larger waveguide to a value where converged results are obtained for input admittance simulates the half-space of specimen material. The input admittance in the smaller waveguide is calculated by considering large number of all possible TE_{mn} and TM_{mn} modes in the smaller and larger waveguides. Then, calculated S_{11} value is obtained. The cover flange terminating the open-ended waveguide is a good approximation for semi-infinite flange, especially for lossy dielectric materials [8].

The measured value of S_{11} is modified by using transmission line equations for TE_{10} mode to account for the effect of impedance transformer. It should be noted that only TE_{10} mode is propagating in Teflon™ and TE_{30} is nonpropagating [1]. The objective function F (F= |modified measured S_{11} – calculated S_{11} |) is calculated. If F is not less than 10^{-3}, then Muller Method with deflation is used to predict a new guess ε^*. This new guess is used to calculate another value of F. It is found that the function F is unimodal and converges rapidly (in few tens of iterations) to the actual value of ε^* [1].

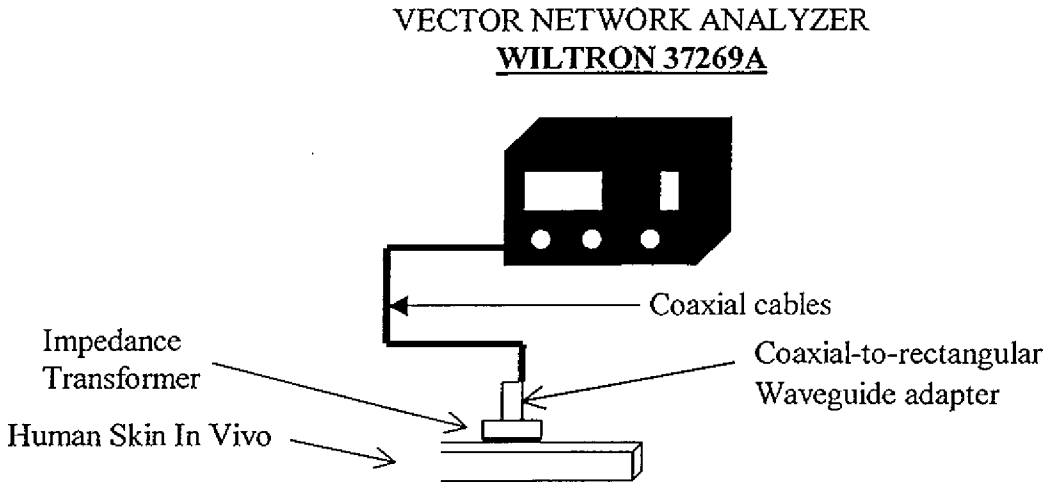


Fig. 1.1: Measurement system for S_{11} measurement of open-ended waveguide radiating into lossy dielectric material such as human skin in vivo.

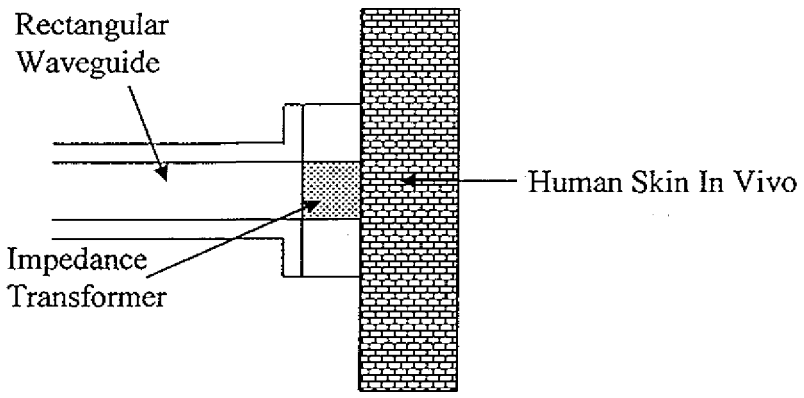


Fig. 1.2: Specimen arrangement for calculation of S_{11} of waveguide radiating into half- space of lossy dielectric material.

Discussion and Conclusion

Tables 1 shows the mean value of complex permittivity ($\varepsilon^* = \varepsilon' - j\,\varepsilon''$) values for 20 different subjects of live human skin in the palm region for frequency range 18 –26 GHz. Meanwhile, Table 2 showed the mean value of complex permittivity values for 5 male subjects of live human skin in the sole region in 18 – 26 GHz range. Tables 3 shows the mean value of complex permittivity ($\varepsilon^* = \varepsilon' - j\,\varepsilon''$) values for 20 different subjects of live human skin in the palm region for frequency range 10 –12.5 GHz. Meanwhile, Table 4 showed the mean value of complex permittivity values for 5 male subjects of live human skin in the sole region in the 10-12.5 GHz range. The values below 10 GHz are not reported because the total thickness of the human skin (epidermis and dermis) is expected to be less than 3 skin depths. The choice of the palm and sole region of the human body are chosen because skin is thick and smooth.

In Tables 1 to 4, it is observed that the dielectric properties of human skin in decreases with frequency. The ε' represents the relative permittivity values for human skin in vivo, which is also known as a dielectric constants for the human skin. Meanwhile, ε'' represents the loss factor for the human skin. From the tables, it is observed that the dielectric properties of human skin in vivo in the palm and sole regions are somewhat different. In conclusion, the dielectric properties of human skin in vivo are expected to vary in the various regions of the human body depending on the thickness of the skin layer (epidermis and dermis).

The calculated values of skin depths for the palm region varies from 1.34 mm at 16 GHz to 0.86 mm at 25 GHz. For the sole region of the human body, the depth of penetration varies from 1.62 mm at 16 GHz to 1.24 mm at 25 GHz.

Table 1 Mean value of ε^* (all twenty subjects) for human skin (palm) in vivo in the frequency range 18-26GHz

Frequency (GHz)	Real part, ε'	Imaginary part, ε''
16	9.9	17.2
17	9.3	16.8
18	9.2	16.2
19	9.1	16.0
20	8.4	15.6
21	7.8	15.5
22	7.0	15.4
23	6.3	15.3
24	5.8	14.9
25	5.3	14.3

Table 2 Mean value of ε* (all five subjects) for human skin (sole) in vivo in the frequency range 18-26GHz

Frequency (GHz)	Real part, ε'	Imaginary part, ε"
16	6.2	11.1
17	5.9	10.2
18	5.8	9.8
19	5.7	9.4
20	5.5	8.9
21	5.4	8.6
22	5.2	8.2
23	4.9	7.9
24	4.8	7.4
25	4.4	6.9

Table 3 Means values of Complex Permittivity for 20 subjects (palm region) for 10.0 –12.5 GHz range.

Frequency In (GHz)	Real part, ε'	Imaginary part, ε"
10.03	22.90	22.33
10.36	21.97	19.73
11.24	26.76	25.22
11.46	26.24	24.18
11.79	25.69	23.40
11.90	25.45	21.74
12.12	25.01	21.43
12.23	24.88	22.17
12.34	24.60	22.38
12.45	24.39	22.03

Table 4 Mean values of complex permittivity for sole region for 10.0 –12.5 GHz range.

Frequency In (GHz)	Real part, ε'	Imaginary part, ε"
10.00	7.08	9.05
10.25	10.40	12.94
10.50	10.13	12.88
10.80	10.19	12.80
11.00	10.26	12.72
11.33	9.19	12.76
11.70	8.48	12.75
12.00	8.28	11.14

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