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MODELLING OF ELECTROMAGNETIC WAVE PROPAGATION AT FREE SPACE-HUMAN SKIN INTERFACE

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Abstract
The proliferation of the ambient environment with many wireless communication infrastructures has constituted a source of concern, at least from health point of view. Hence, there is a need for the investigation of electromagnetic wave interaction with human tissue. This paper models electromagnetic wave propagation at the free-space-human tissue interface, in an attempt to understand how electromagnetic waves interact with the human skin. Maxwell's equations were used to derive the governing equations of propagating electromagnetic waves in free space while the solution of the boundary-value problem arising from the incident electromagnetic wave at the free space-human tissue interface was found through the use of appropriate boundary conditions. The solution led to the emergence of four Fresnel equations, a pair each for perpendicular and parallel polarizations of the incident wave, at the boundary. Through the use of the Fresnel equations obtained, components of the incident electromagnetic wave power at the boundary can be quantified. Typical profiles of the normalized reflected and absorbed powers at the free space-human skin interface at 28, 60, and 73 GHz were computed, using measured values of permittivity of human tissue. It is found that the total absorption of the power of the incident wave by the human skin occurs when the angle of incidence is between 69^0 and 77^0 for the three frequencies used. This is irrespective of the polarization of the incident wave. Information on such distinct angles of incidence for total absorption of power does not appear to exist in the literature as they represent new, previously unreported facts in the existing body of research. Furthermore, computed profiles of reflected power versus incidence angle displayed here, for perpendicular polarization, demonstrate strong alignments with established literature, thus reinforcing the credibility of the results presented in this paper.

1.0 INTRODUCTION
Bio-electromagnetism refers to the study of interactions of biological organisms with electromagnetic (EM) fields. The investigation is mainly carried out via the method of electrophysiology. By the late 18th century, the discovery of static electricity by Luigi Galvani, muscular activation was regarded as a result of an electrical fluid or substance existing in the nerves. Electrical events of short durations, known as action potentials, occur in a variety of animal cells described as exciting cells [1]. Muscle cells, neurons, and endocrine cells are all examples of exciting cells. Employed in intra-cellular communications as well as in activation of intra-cellular potentials is what is known as activation potential. Voltage-gated ion channels, which allow the resolution of membrane

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resting potential, make possible the physiological phenomena of action potentials.

It is known that several organisms (animals and birds) possess the ability to detect EM fields. For instance, many aquatic animals with mechanisms capable of sensing changes in voltage resulting from varying magnetic fields [2], while migratory birds are believed to employ the magneto-reception phenomenon for navigation [3]. Exposure to magnetic fields has been linked to numerous behavioral consequences at various EM field intensities, particularly those connected to pulsed magnetic fields [4]. An important factor in determining the behavioral effects appears to be the particular pulse shape used. For example, it has been discovered that standing balance and pain perception are affected when a full body is exposed to a pulsed magnetic field [5]. A powerful varying magnetic field has the potential to induce electric pulses in conductive tissue such as the brain. Because of the magnetic field's ability to penetrate tissue, it may be generated outside the head to induce current flow within, resulting in transcranial magnetic stimulation. Such pulses going into the skull depolarize neurons in a specific area of the brain and alter neural activity patterns [6].

Wireless communication devices have turned out to be extremely effective in linking people everywhere, anywhere, anyplace, and anytime, the world over. However, they constitute today's major source of EM radiation. The ability of the human body to absorb these radiations could harmfully cause neural effects and cancerous growth in the body [7]. Dopamine reduction is caused by exposing the brain to RF-EM radiation [8 – 11]. The pioneering work reported in [12] signaled the inquiry into the effects of voltage gradients on biological systems. Results from coordinated efforts by many researchers established that stable voltage gradients were associated with several drastic changes in the organism, which include growth and localized impairment [13]. Findings from studies further explicated that these effects were the results of variations in the spatial distribution of ions within the biological systems [5], which may be due to exposure to EM radiations. Furthermore, it is widely believed that what is described as the "colony collapse" (disappearance of bees), in Europe and the US had a link with EM radiations [2], [3]. The EM fields have also been reported to interfere with the migration of birds [3].

Radiofrequency (RF), which includes the frequency band between 100 kHz and 300 GHz of the EM spectrum, is the most widely used EM radiation field globally [14], [15]. Main applications include mobile phones, radio, and TV broadcasting, as well as medical and industrial uses. Because of their versatility of usage, RF sources can be further sub-grouped into three: sources that are used close to the human body, sources that are used at a far distance away from the human body, and sources that are employed for medical diagnostics and therapeutic purposes. A typical RF source that operates near the human body is the mobile phone. In addition, other wireless application devices such as cordless phones are equally common appearance in our environment. The maximum peak power level of a typical cordless phone is 250mW while that of a wireless local area network system is 200mW [13]. Fixed installed transmitters for broadcasting stations as well as radio base stations for mobile communication networks, are routine examples of sources of RF that are at a far distance from the human body during operation. Therapeutic applications like soft tissue healing devices, hyperthermia for treatment of malignant growth and cancer, diathermy, etc. involve exposing the patient to a controlled amount and well above the stipulated standard EM wave exposure limit to achieve the intended biological effects [1], [7], [14].

One thing is obvious from the three categories of RF sources, the human body does interact with EM radiation from them, directly or indirectly. This interaction is taking place at the free space-human skin boundary. An attempt to understand the interaction of EM fields at the free space-human skin boundary motivates this research, which is concerned with the modelling of EM wave propagation at the free space-human skin boundary. Specifically, governing equations for different scenarios of EM wave incidence are considered with corresponding computed curves obtained to describe EM wave characteristics at the boundary. It should be noted that the needed constitutive parameters of the human skin employed in the analysis were those experimentally determined by other investigators and made available in the literature.

The rest of the paper is organized as follows: Section 2 describes the analytical procedures while in Section 3, results and discussion are presented. Section 4 treats the conclusion as well as the major novel contributions of the investigation.

2.0 ANALYTICAL PROCEDURE

The engineering problem tackled in this paper borders on the general area of bio-electromagnetics. Specifically, consideration is given to how electromagnetic waves propagate and interact with the human skin. In free space, where an EM wave travels at a constant speed without acceleration, the attenuation is zero and the propagation constant has a value equivalent to that of the propagating wave phase constant, which is non-zero. When the propagating EM wave strikes the human skin (just like in any other medium), the incident EM wave hitting the human skin splits into two; part of the wave is reflected into the homogenous free space medium while the remaining part is transmitted (absorbed) into the inhomogeneous human tissue.

To determine the proportion of incident EM wave that is absorbed by the human tissue, it is required to derive the governing equations at the free space-human tissue interface. For this purpose, use is made of appropriate boundary conditions. At the point where the EM wave slams the human skin, applicable boundary conditions are: the tangential component of both the electric field, symbolized by $\boldsymbol{E}$, and the magnetic field, represented by $\boldsymbol{H}$ are continuous across the boundary.

The aforementioned conditions lead to the equations we had to solve through which the four Fresnel equations can emerge. Those four equations are the perpendicular polarized reflection and transmission coefficients and the parallel polarized reflection and transmission coefficients. Those four equations were used to quantify the relative amount of components of the incident wave at the free space-human skin boundary.

2.1 Governing Equations of EM Field at Free Space-Human Skin Interface

Consider a free space region, which is an isotropic, homogeneous, and source-free medium, which is defined by the constitutive parameters $(\sigma = 0, \varepsilon = \varepsilon_0, \mu = \mu_0)$. Applicable Maxwell's equations are expressible in forms given as:

$$\nabla \times \boldsymbol{H} = \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} \tag{1}$$

$$\nabla \times \boldsymbol{E} = \mu_0 \frac{\partial \boldsymbol{H}}{\partial t} \tag{2}$$

$$\nabla \cdot \boldsymbol{H} = 0 \tag{3}$$

$$\nabla \cdot \boldsymbol{E} = 0 \tag{4}$$

where $(\boldsymbol{E}\ and\ \boldsymbol{H})$ are the electric and magnetic fields, respectively, while $(\mu_0 \varepsilon_0)$ are the permeability and permittivity of free space, respectively. Manipulations of equations (1) - (4) yields;

$$\nabla^2 \boldsymbol{E} - \mu_0 \varepsilon_0 \frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0 \tag{5}$$

as the governing wave equation for the electric field vector and

$$\nabla^2 \boldsymbol{H} - \mu_0 \varepsilon_0 \frac{\partial^2 \boldsymbol{H}}{\partial t^2} = 0 \tag{6}$$

as that of the associated magnetic field vector wave equation.

The product $(\mu_0 \varepsilon_0)$ in each of (5) and (6) is linked to the free-space EM wave's phase velocity v_p, which is expressible as:

$$v_p = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \tag{7}$$

Each of (5) and (6) is a second-order homogeneous partial differential equation that has a single possible solution. In addition, one needs only to solve either (5) or (6), as the solution of the other, is readily determined via the use of Maxwell's equations.

Assuming the usual $\exp(j\omega t)$ time variation such that the propagating electric field vector of the EM wave, described by (5), has its solution given by:

$$\boldsymbol{E}(x, y, z, t) = \boldsymbol{E}(x, y, z)e^{j\omega t} \tag{8}$$

If the electric field in (8) is a wave propagating in the positive z-direction, and the field is constant everywhere in the (x, y) plane, then (8) reduces to:

$$\boldsymbol{E}(z, t) = \boldsymbol{E}_0 e^{j(\omega t - \beta z)} \tag{9}$$

provided $\boldsymbol{E}_0$ is a complex constant vector, β is the wave phase constant and ω is the angular frequency, in radians. Expanding (9) and taking the real part, one obtains

$$\boldsymbol{E}(z, t) = Re\{\boldsymbol{E}(z, t)\} = \boldsymbol{E}_0 cos(\omega t - \beta z) \tag{10}$$

From (10), the corresponding magnetic field $\boldsymbol{H}$ can be found using Ohm's law such that

$$\boldsymbol{H} = \frac{\boldsymbol{E}}{\eta_0} = \boldsymbol{H}_0 cos(\omega t - \beta z) \tag{11}$$

where η_0 is the intrinsic impedance of free space, and

$$\boldsymbol{E}_0 = \eta_0 \boldsymbol{H}_0 \tag{12}$$

It ought to be borne in mind that $\boldsymbol{E}$ and $\boldsymbol{H}$ are mutually perpendicular to each other and they are the propagating waves that strike the free space-skin interface.

The expression stated in (10) is an oscillating EM wave propagating in a free space where there are no sources. The EM wave travels at a constant speed of light, with no acceleration. This radiating wave hits any subject that can be found within the region of free space including human beings. It may not be amiss to ask, what happens when the propagating wave strikes the human skin (the free space-human body interface). The scheme presents a boundary value problem that needs to be solved taking cognizance of appropriate boundary conditions. This is pursued in the next section.

As remarked earlier, when the wave described by (10) is incident on the human skin, part of the wave is reflected into the free space region while the remaining part is absorbed into the skin layers (in the form of the transmitted wave). Depending on the polarization (perpendicular or parallel) of the incident EM wave, different sequences of events occur at the boundary between the free space and human skin such as depicted in Figure 1.

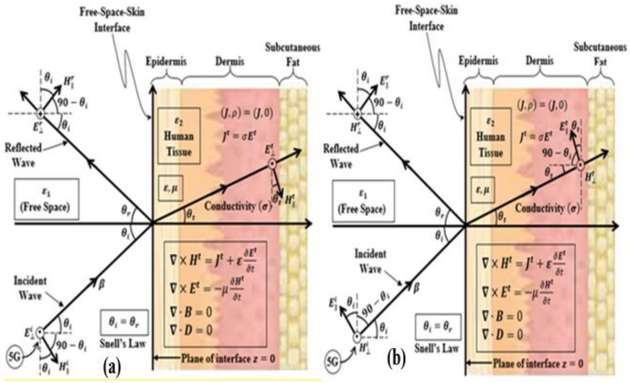

Figure 1: Incident wave polarization at the interface (a) perpendicular (b) parallel

Appropriate use of the boundary conditions enables the solution of the boundary value problem arising for each of the perpendicular and parallel polarizations of the incident EM wave. The solutions lead to what are known as Fresnel equations expressed in the forms given as:

$$\Gamma_{\perp} = \frac{\boldsymbol{E}_r}{\boldsymbol{E}_i} = \frac{cos\theta_i - \sqrt{\varepsilon_r - sin^2\theta_i}}{cos\theta_i + \sqrt{\varepsilon_r - sin^2\theta_i}} \quad (13)$$

$$\tau_{\perp} = \frac{\boldsymbol{E}_t}{\boldsymbol{E}_i} = \frac{2cos\theta_i}{cos\theta_i + \sqrt{\varepsilon_r - sin^2\theta_i}} \quad (14)$$

$$\Gamma_{\parallel} = \frac{\boldsymbol{E}_r}{\boldsymbol{E}_i} = \frac{-\varepsilon_r cos\theta_i + \sqrt{\varepsilon_r - sin^2\theta_i}}{\varepsilon_r cos\theta_i + \sqrt{\varepsilon_r - sin^2\theta_i}} \quad (15)$$

$$\tau_{\parallel} = \frac{\boldsymbol{E}_t}{\boldsymbol{E}_i} = \frac{2cos\theta_i}{\varepsilon_r cos\theta_i + \sqrt{\varepsilon_r - sin^2\theta_i}} \quad (16)$$

where $(\Gamma_{\perp}, \tau_{\perp})$ are the reflection and transmission coefficients for perpendicular polarization, respectively, while $(\Gamma_{\parallel}, \tau_{\parallel})$ are the reflection and transmission coefficients of parallel polarization, respectively; $\boldsymbol{E}_i$, $\boldsymbol{E}_r$, and $\boldsymbol{E}_t$ represent incident, reflected, and transmitted electric field vectors, respectively; ε_r is the relative permittivity of the human skin and θ_i is the angle of incidence of the wave at the boundary.

Using (13)-(16), the reflected component of the incident wave at the boundary is given by

$$\boldsymbol{E}_r = \Gamma^* \boldsymbol{E}_i \quad (17)$$

while the transmitted component is expressible as:

$$\boldsymbol{E}_t = \tau^* \boldsymbol{E}_i \quad (18)$$

provided Γ^* assumes expression in (13) and (15) for perpendicular and parallel polarized incident waves, respectively, and τ^* takes the form of (14) and (16) for perpendicular and parallel polarized incident waves, respectively.

The instantaneous power radiated by an EM wave is generally given by:

$$P = \boldsymbol{E} \times \boldsymbol{H} = \frac{\boldsymbol{E}^2}{\eta} \quad (19)$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are the instantaneous electric and magnetic field vectors, respectively and η is the intrinsic impedance of the medium. It, therefore, follows that the normalized power associated with each of the reflected and transmitted waves at the boundary can be written in a form expressed as:

$$P_n = (\Gamma^*)^2 \quad (20)$$

for reflected waves and

$$P_n = (\tau^*)^2 \quad (21)$$

for transmitted wave, where Γ^* and τ^* assume earlier definitions.

The transmitted component of the incident EM wave is absorbed by the human tissue. It proves necessary to know the values of constitutive parameters of human tissue before the amount of EM energy absorbed can be estimated. This is discussed in what follows.

2.2 Electrical Properties of Human Tissue

To elucidate the outcome of the analysis carried out in this research, the results of experimental measurements of complex permittivity of certain parts of the human body through exposure to EM radiation at certain frequencies, and which have been reported in the literature by other investigators, are utilized. Table 1 presents *in vivo* measurements of the permittivity of certain parts of human skin at three different frequencies of 28, 60, and 73 GHz, as reported in [16].

Table 1: Values of the complex permittivity at 28, 60 and 73 GHz [16]

Skin Parts	Complex Permittivity ε^* at different frequencies (GHz)		
	28	60	73
Alekseev (palm)	15.0 – j14.2	8.0 – j9.5	7.0 – j8.2
Chahat (palm)	11.0 – j5.7	8.7 – j4.3	8.2 – j3.9
Gandhi	19.3 – j19.5	9.9 – j13.1	7.4 – j11.2

Since the complex intrinsic impedance of any medium generally admits a form given as:

$$\eta^* = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} = \sqrt{\frac{j\omega\mu}{j\omega\varepsilon\left[1 - j\left(\frac{\sigma}{\omega\varepsilon}\right)\right]}} = \sqrt{\frac{\mu}{\varepsilon\left[1 - j\left(\frac{\sigma}{\omega\varepsilon}\right)\right]}} \quad (22)$$

provided ε, μ, and σ are the permittivity, permeability, and coefficient of conductivity of the medium, respectively, while ω is the angular frequency in radians. It follows from (22) that the complex permittivity of the medium assumes a form expressible as:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{23}$$

where

$$\varepsilon' = \varepsilon_r \tag{23a}$$

is the relative permittivity of the medium and

$$\varepsilon'' = \sigma/\omega\varepsilon \tag{23b}$$

represents the loss tangent. It is clear from (22)-(23b) that the real parts of the entries of Table 1 are what are required as values of the relative permittivity of human skin at the respective frequency of measurements.

3.0 RESULTS AND DISCUSSION

The amount of power absorbed by the human tissue is determined at those three frequencies where values of measured permittivity of human skin are available. Use is made of expressions derived in Section 2 as well as the entries of Table 1 to arrive at appropriate results at varying angles of incidence. Figure 2 depicts variations, with angle of incidence, of normalized power reflected at the free space-skin interface when the incident EM wave exhibits parallel polarization. Figure 3 is the zoom-out version of Figure 2 while Table 2 presents records of Brewster angles at which the value of reflected power is identically equal to zero at each of the three frequencies considered.

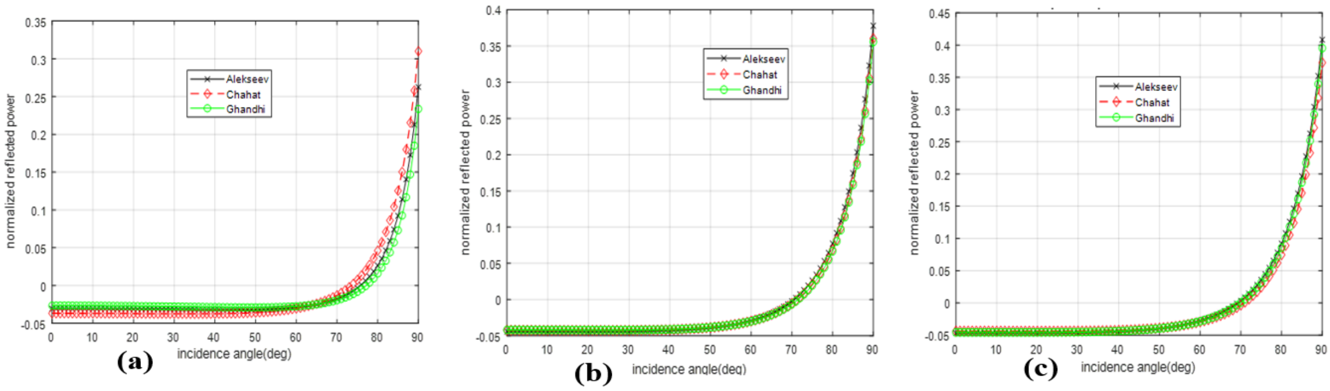

Figure 2: Variations of normalized reflected power for parallel polarized incident EM wave with the angle of incidence at different frequencies (a) 28 GHz (b) 60 GHz (c) 73 GHz

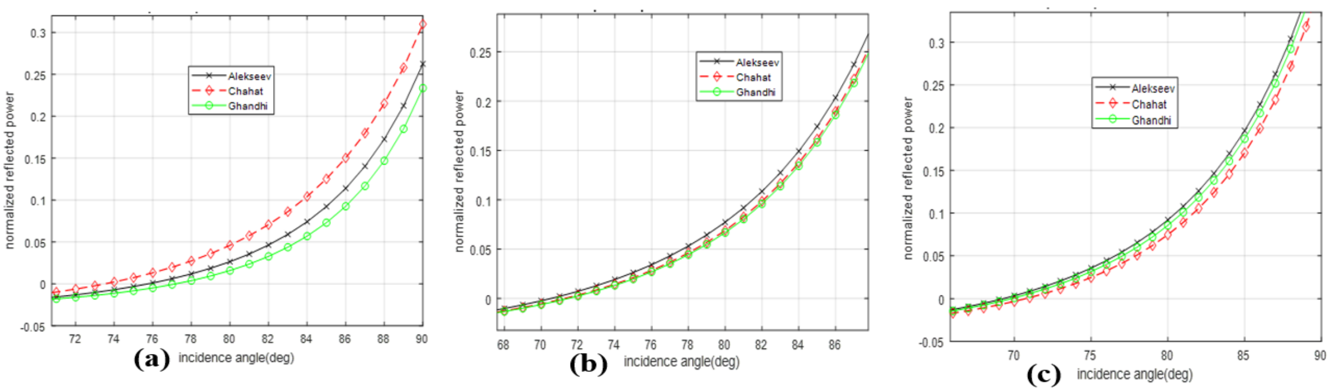

Figure 3: Zoomed-out versions of Figure 2 to show Brewster angles at different frequencies (a) 28 GHz (b) 60 GHz (c) 73 GHz

It can be observed from Figures 2 and 3 that the values of the reflected power assume a positive exponential rise with increasing angles of incidence for each of the three frequencies employed and for the three values of relative permittivity of the skin utilized for computations. In addition, it is evident from the zoomed-out versions (Figure 3) that, the Brewster angle decreases with an increase in the value of the operating frequency of the striking EM wave. Furthermore, none of the frequencies yields a value of Brewster angle that is less than 69^0 approximately, as can be inferred from the entries of Table 2. The implication of this is that a parallelly polarized EM wave that is incident on human skin at an angle of at least 69^0 may give rise to total absorption, depending on the operating frequency of the incident EM wave.

Table 2: Brewster angles when the incident EM wave exhibits parallel polarization at different frequencies

Relative Permittivity Source	Brewster Angles at Different Frequencies		
	28 GHz	60 GHz	73 GHz
Alekseev	75.7^0	70.5^0	69.3^0
Chahat	73.5^0	71.3^0	70.6^0

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Ghandi	77.2^0	71.4^0	69.8^0

Figure 4 depicts variations of normalized reflected power with angle of incidence when the incident wave is perpendicularly polarized. It can be observed from Figure 4 that, irrespective of the value of the relative permittivity of human skin used in the computation, values of Brewster angle obtained for perpendicularly polarized EM wave are approximately 75^0, $74^{0,}$ and 72^0, respectively, when the operating frequencies are 28, 60 and 73 GHz, respectively. This observation concerns normalized power reflected at the interface when the incident EM wave is perpendicularly polarized and it agrees with what is observed in the case of an incident wave of parallel polarization, where the observed values of Brewster angle are at least 69^0.

Figures 5 and 6 display profiles of normalized power absorbed by human skin from striking EM waves at the interface at the three specified frequencies, for parallel and perpendicular polarized waves, respectively. One common thing is the nose-diving characteristics of each of the profiles from relatively high values to zero where the angle of incidence is 90^0.

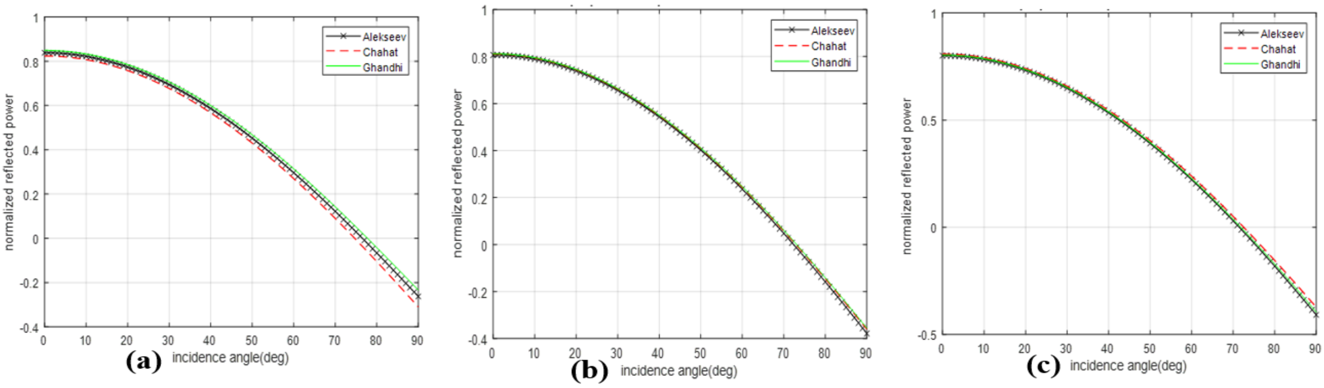

Figure 4: Variations of normalized reflected power for perpendicularly polarized incident EM wave with angle of incidence at different frequencies (a) 28 GHz (b) 60 GHz (c) 73 GHz

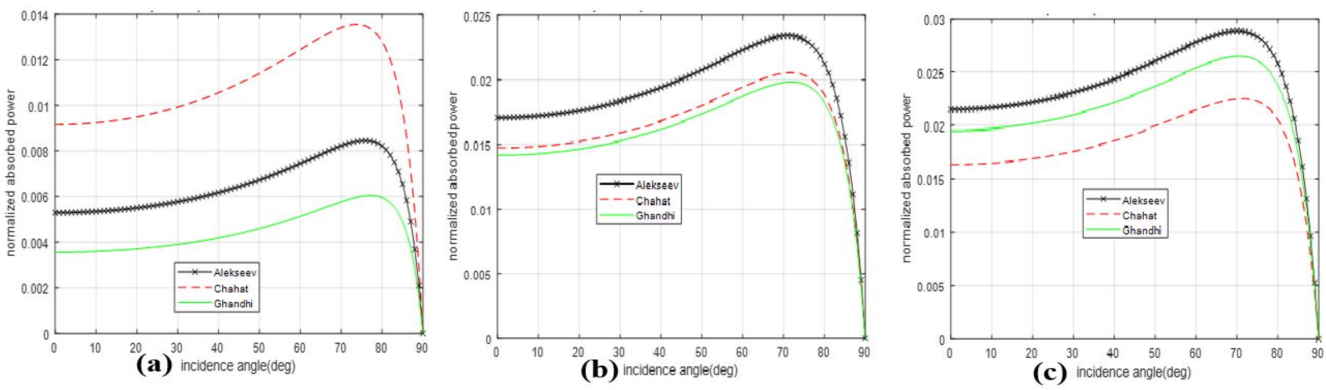

Figure 5: Variations of normalized absorbed power with the angle of incidence at different frequencies, for incident EM wave of parallel polarization (a) 28 GHz (b) 60 GHz (c) 73 GHz

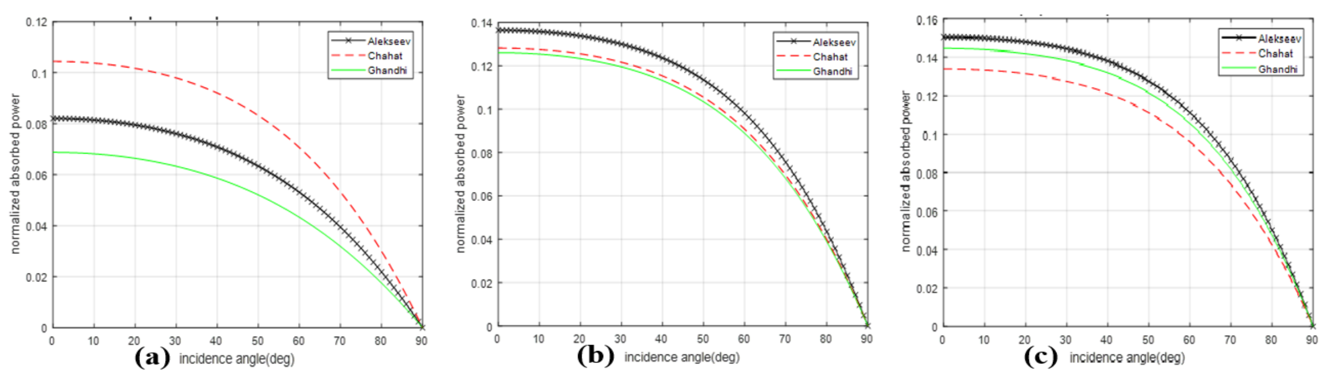

Figure 6: Variations of normalized absorbed power for perpendicularly polarized incident EM wave with angles of incidence at different frequencies (a) 28 GHz (b) 60 GHz (c) 73 GHz

For parallel polarization (Figure 5), the peak value of power absorbed, at different frequencies, occurs when the angle of incidence is about 75^0 whereas in the case of perpendicular polarization (Figure 6), peak power is absorbed by the human skin from the striking EM wave when the incident angle is 0^0. These observations point to the fact that polarization of striking EM waves plays a significant role in the determination of the amount of power that is transmitted into human skin across the free space-human skin interface.

4.0 CONCLUSION

Developed in this paper are the model equations describing EM wave propagation at the free space-human skin interface. Simulation results arising from the use of the model equations derived, and values of human skin permittivity measured by other investigators, reveal that total absorption of propagating EM wave can occur at an angle of incidence from 69^0, depending on the polarization of the striking EM wave, especially for parallel polarized EM wave. The import of this is that a parallelly polarized EM wave that is incident on human skin at an angle of at least 69^0 may result in total absorption, depending on the operating frequency of the incident EM wave. Indeed, it has been shown that the angle of incidence varies between 69^0 and 77^0 for the three frequencies employed here when the incident plane wave enjoys parallel polarization. These observations attest to the fact that polarization of striking EM waves is crucial in determining the amount of power that is transmitted into human skin across the free space-human skin interface. These facts have not been reported before in the literature.

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