Propagation Characteristics of Ultra-Wideband Pulse in Multilayered Human Chest Tissue

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***Abstract*—In this paper two major propagation characteristics such as reflection and absorption of Ultra-wideband (UWB) pulse in a human body have been analysed. A simplified multi-layered non-homogenous model of human tissue is considered here. S-parameters and path loss due to transmission of UWB pulse in the multi-layered tissue model are evaluated. Frequency dependent Electromagnetic properties of three layers (skin, fat and muscle) such as permittivity and conductivity of human tissues based on Cole-Cole model are used for the simulations. Specific Absorption rate (SAR), which is directly related to the internal electric field and the conductivity, is computed at a wide band of frequency ranging between 1-5 GHz.**

***Keywords*—Ultra-wideband, Multilayered Human Tissue, Reflection, Absorption, Path loss, Specific Absorption Rate**

I. INTRODUCTION

The ultra-wide band (UWB) using the frequency range from 3.1 to 10.6 GHz is a new promising technology suitable for high rate communications in small distances [1]. UWB is a very promising technology for in-body to on-body communication in medical applications. Two major properties in case of transmission of UWB pulse are reflection and absorption. A good amount of work to study the interaction of electromagnetic waves in human tissues has been done in [2-6]. But most of the work did not consider the frequency dependence of conductivity and relative permittivity. In [7] frequency dependence on EM properties were considered but thickness of skin layer was considered 10mm. Thickness for skin layer generally lies between 1-3mm. So, considering 10mm skin thickness is not realistic. In [7] no air gap between the antennas and model was mentioned. Again, in [8] frequency dependent properties were used and proper tissue modelling was done. But frequencies at which simulations were done were at frequencies 3GHz, 6 GHz and 8 GHz which are spaced far apart. Change in EM properties occurs significantly in short range of frequencies. In [3] only fat-muscle layer was considered and muscle layer was assumed very thick. In [9] S-parameters and SAR were estimated for separate layers but not as a multilayered model. From [2-8] Path loss due to transmission of EM waves was not analysed. In this paper frequency dependent - real and imaginary part of relative permittivity are calculated using Cole-Cole model. Tissue has been modelled anatomically. Realistic air gap between transmitter and tissue has been considered.

Section II describes the EM properties and propagation characteristics. Modelling of human tissue and simulation parameters are given in section III. Simulation results are presented with brief discussion in section IV. The section V concludes this paper.

II. PROPAGATION CHARACTERISTICS OF EM WAVES

In case of transmission of EM waves, both the dielectric property and the conductivity of a medium depend significantly on the frequency of the EM wave [7]. In all the tissues, these properties changes with frequency because of their difference in water content [7]. In a lossy medium:

$$\varepsilon_r = \varepsilon_r' - i(\frac{\sigma}{\varepsilon_o w}) \quad (1)$$

Where, σ is the conductivity of the medium. ε_r' is the real part of the permittivity. Conductivity changes with frequency with following equation:

$$\sigma = |\varepsilon_o \varepsilon_r''| \times \omega \quad (2)$$

Where, ω=angular frequency of the incident signal, ε_r''=complex permittivity in lossy medium and ε_0= permittivity of free space.

Dispersive characteristics of biological tissues like dielectric constant variation with frequency can be expressed by well-known Cole-Cole model as [10]:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+(i\omega\tau)^{1-\alpha}} \quad (3)$$

Where, ε_∞ and ε_s are the relative permittivity of material at infinite and zero frequencies respectively. And, α is actually a distribution parameter in the interval $0 \leq \alpha < 1$ [10].

When the transmitted power propagates through tissue medium, part of it is lost because of absorption. And some portion of it is available to the receiver. If S-parameter representation is used, for the two-port system, S_{11} is the input port voltage reflection coefficient. S_{11} is simply the reflection co-efficient of the two port network. However transmission coefficients and hence transmitted power can be estimated from using this also. The amount of power that is reflected back can be calculated from this. Now, reflected power:

$$R = Input\ power\ \times |S_{11}|^2 \quad (4)$$

Path loss is defined by the ratio of transmitted power to received power. It is often expressed in decibels.

$$|\frac{1}{S_{21}}|^2 = \frac{P_{tx}}{P_{rx}} \quad (5)$$

The equation illustrates the path loss of the tissue model. But more realistic value for path loss can be obtained by the equation:

$$PL = \frac{1-|S_{11}|^2}{|S_{21}|} \quad (6)$$

Values from equation (5) and (6) will be substantially different when S_{11} will be close to unity. Equation (5) gives uncompensated path loss and equation (6) gives compensated values for path loss [11].

Specific absorption rate (SAR) is a measure of the rate at which energy is absorbed by the human body when it gets interacted with electromagnetic field. It is defined as the power absorbed per mass of tissue and has units of watts per kilogram (W/kg) [12]. Simplified formula for calculating SAR is:

$$SAR = \frac{\sigma \times |E|^2}{\rho} \quad (7)$$

Where σ is the conductivity of the medium, E is the RMS electric field and ρ is the density of the medium [12]. So SAR depends both on electric field and conductivity of the medium.

III. Modelling and simulation

In order to inspect the propagation characteristics of model of human tissues, proper parameters are needed to be known. Three layers of human tissues: skin, fat and muscle have been modelled here. There is no gap between any two layers of the following model. Values of different parameters for modelling in Simulation tool, for the 3 layers of human tissue, were taken from CST Voxel family data. Thickness of different layers is not same. In this work the thickness has been set assuming that the tissues are from chest tissue of an adult male and thickness of the skin layer is 2mm, fat layer is 10mm and muscle layer is 28 mm which are anatomically right [13]. All the tissues are of equal surface of 20mm×15mm but different thicknesses. All the tissue samples have been modelled as brick shaped cubic box. So the multi-layered human tissue model is ready and looks like this in the simulation 3D view:

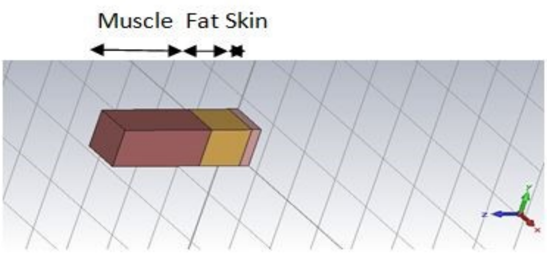

Fig.1: Rectangular box shaped tissue model for simulation.

To simulate the above model, CST microwave studio (CST MWS) has been used. It is mainly based on FDTD (Finite Difference Time Domain) method. Again in some manual it is written as FIT (Finite Integral Technique). But after looking closely the two methods are somehow similar. FIT is actually a Finite difference method based on a small scale interpretation of Maxwell's equations. It is a powerful tool for the 3D electromagnetic (EM) simulation of high frequency components. After properly modelling the multi-layered tissues, it is necessary to set simulation parameters. The simulation of the model has been done from 1GHz to 5 GHz. Gaussian pulse of 2nd order has been used as excitation signal from the transmitter end. Distance between the transmitter and the tissue model was 4mm. Input power from the implanted UWB slot antenna (transmitter) is 0.5 Watts. Mesh type is hexahedral and accuracy is set as -30 decibels. EM wave propagates through negative Z direction. Since the transmitter is implanted, so it meets the muscle layers first, then fat layer and lastly the skin layer. The receiver is also 4mm away from the model.

IV. Results and discussion

From FDTD simulation we get several graphs and distribution of 3D fields on 2D plane at different frequencies. These graphs show all S parameters of the two port network. Real and imaginary parts of relative permittivity, which is a strong function of frequency, were estimated using Cole-Cole model as well.3D SAR distribution on 2D plane at 1GHz-5GHz on a difference of 1GHz are found. Lastly 3D SARs on 2D plane from the simulation post processing at 1 GHz interval are given with reference values.

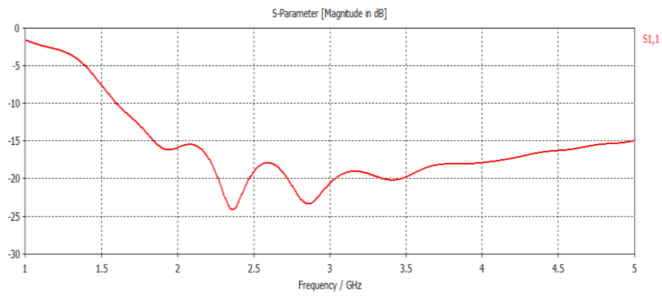

Fig.2: S_{11} vs frequency.

Figure 2 shows S_{11}. -10dB occurs at 1.6GHz which is like UWB slot antenna used in [1]. Impedance bandwidth is here about 68% in this 1-5GHz range. The large available bandwidth covers UTMS (1.9 GHz and 2.1 GHz), WLAN (2.45 GHz) and some parts of UWB (3.1-10.6 GHz) [14]. In [14] only low UWB band ranging from 3.1-5GHz was investigated.

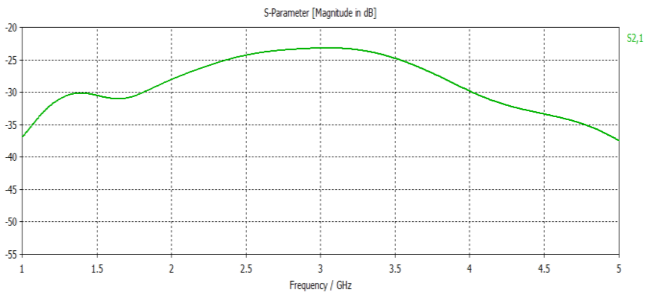

Fig.3: S_{21} vs frequency.

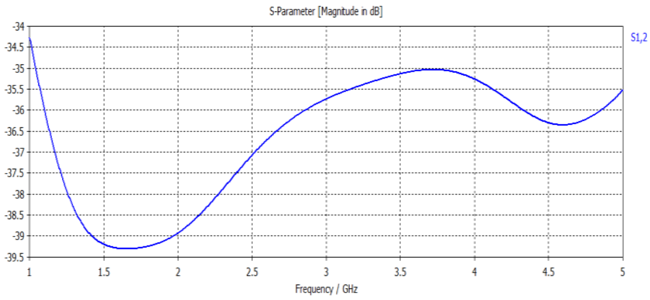

Fig. 4: S_{12} vs frequency.

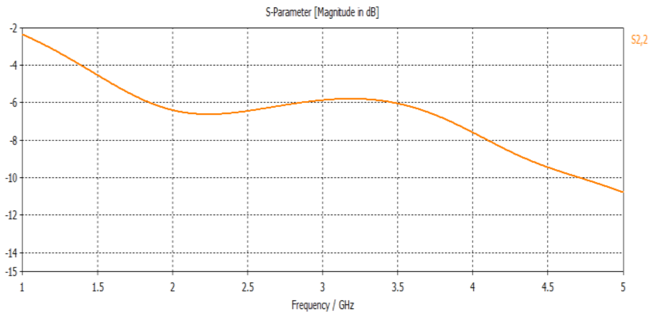

Fig.5: S_{22} vs frequency.

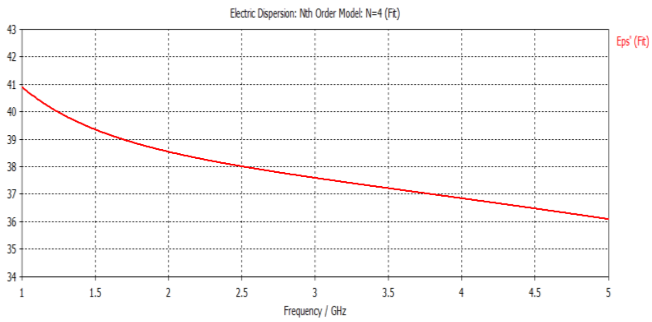

Fig.6: Real part of relative permittivity(at skin layer) vs frequency

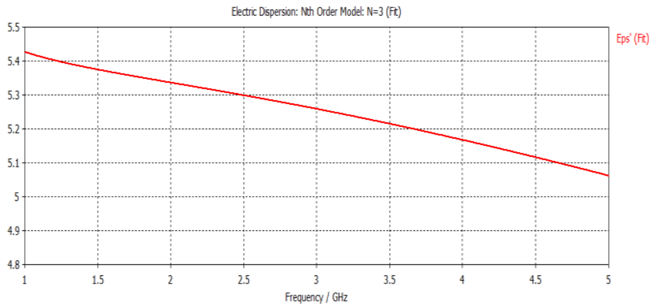

Fig.7: Real part of relative permittivity(at Fat layer) vs frequency.

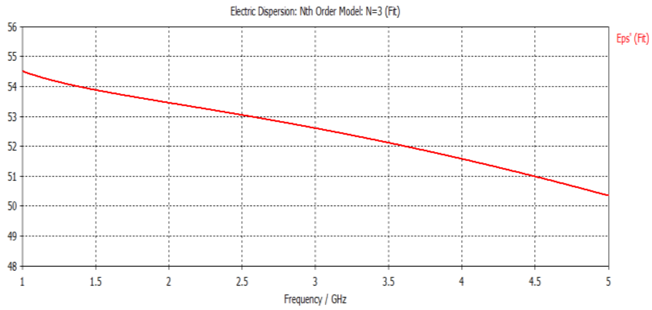

Fig.8: Real part of relative permittivity(at muscle layer) vs frequency.

Change in real part of permittivity is not so significant in all layers but considering this change with frequency ensures best results. In muscle layer the real permittivity is 54.5, 52.7 and 50.3 at 1 GHz, 3 GHz and 5 GHz respectively.

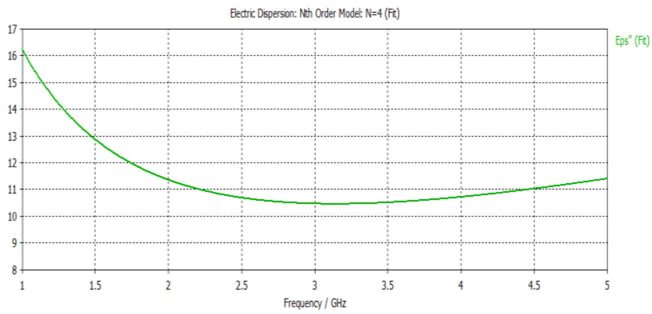

Fig.9: Imaginary part of relative permittivity (at Skin layer) vs frequency.

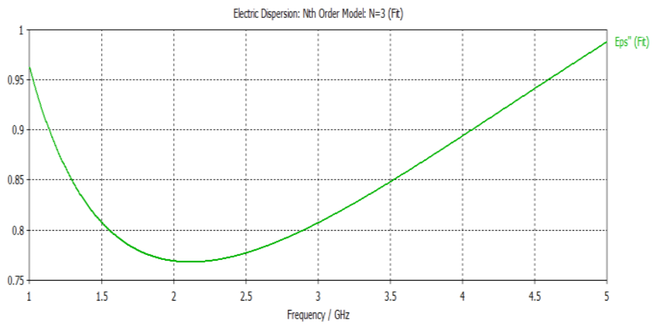

Fig.10: Imaginary part of relative permittivity (at Fat layer) vs frequency

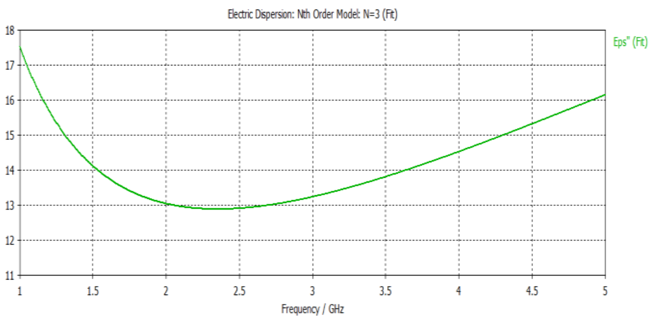

Fig.11: Imaginary part of relative permittivity (at muscle layer) vs frequency

Conductivity of tissues significantly changes with frequency. Using equation (1) conductivity in muscle layer at 1 GHz, 3GHz and 5GHz were 0.97S/m, 2.19S/m and 4.46S/m respectively.

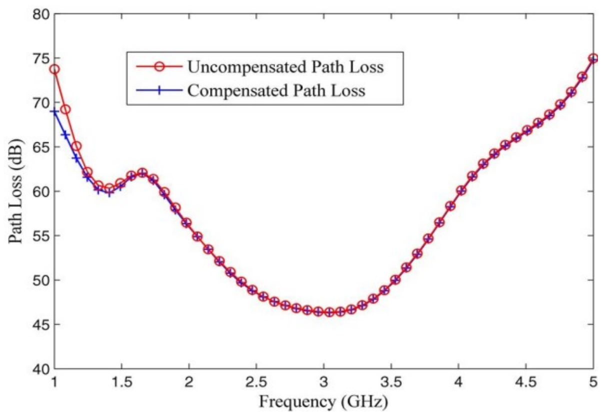

Fig.12: Uncompensated and compensated path loss by the tissue model vs frequency

Figure 6 shows the path loss. The large path loss of the UWB pulses is the main obstructing factor for wireless communication in the tissue medium [10]. In an experiment it was demonstrated that 1 Mbit/s link is possible with a BER of 10^{-2} at a maximum depth of 12 cm to on body receiver from implanted transmitter [15]. Here, the path loss is decreasing from 1-1.5 GHz then it again increases. From 1.7 to 3.1 GHz it decreases. Path loss around 2.7-3.2 GHz is minimum, around 46-47dB. After 4.5 GHz path loss is so enormous, after 5.5 GHz the path loss was more than 80dB.

The path loss values at 5cm depth and changes of path loss support the experimental results found in [10] which is claimed to be the first in body to on body path loss model. The simulation was restricted to 5GHz because since after that point the electric field is so large and conductivity is also huge that almost all transmitted power is absorbed by human tissue. Also the propagation losses of low-band UWB were also evaluated. In WBAN scenarios, low-band UWB is more advantageous than high-band UWB from the viewpoint of reducing propagation losses [16].

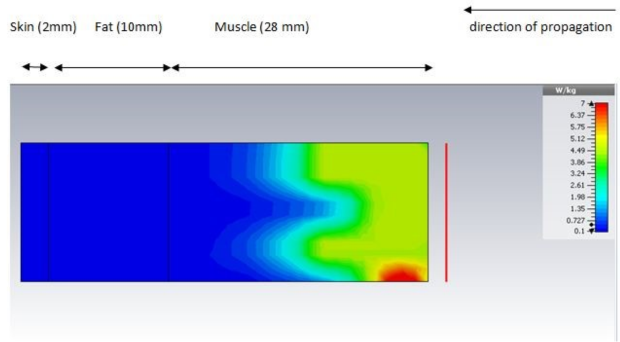

Fig.13: 3D SAR distribution on 2D plane at f= 1GHz.

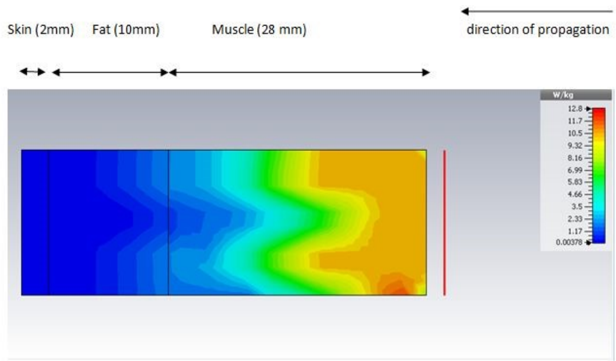

Fig.14: 3D SAR distribution on 2D plane at f= 2GHz.

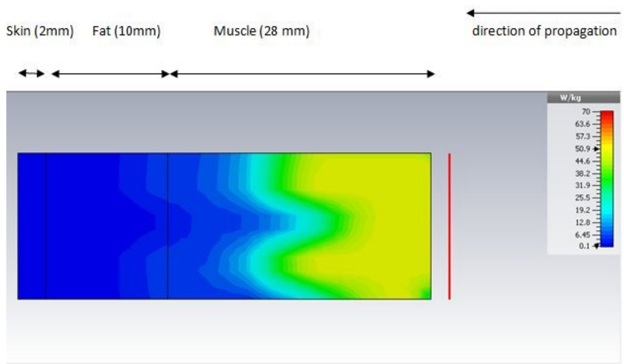

Fig.15: 3D SAR distribution on 2D plane at f= 3GHz.

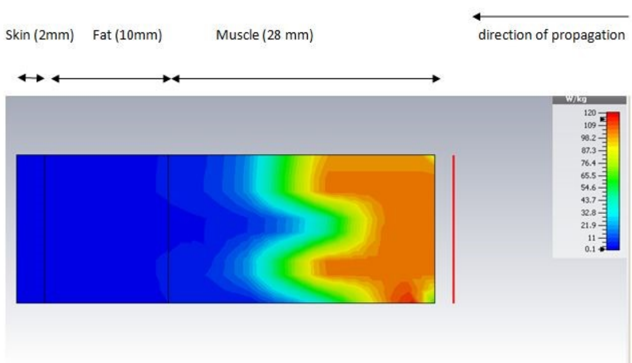

Fig.16: 3D SAR distribution on 2D plane at f= 4GHz.

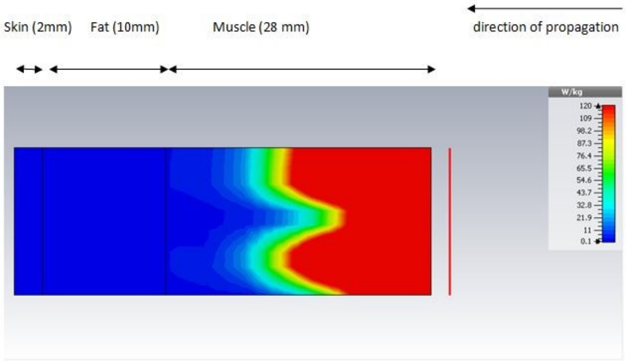

Fig.17: 3D SAR distribution on 2D plane at f= 5GHz.

Figures 13-17 show SAR distribution in tissue layers. SAR is significantly increasing with the increase of frequency. For the muscle layer closest to the transmitter, SAR values are 4.5 W/kg, 9.75 W/kg, 44 W/kg, 89 W/kg and 120 W/ kg at 1 GHz, 2 GHz, 3 GHz, 4 GHz and 5 GHz respectively. The SAR distributions are presented. SAR of Fat layer also increases but less significantly. Meanwhile, SAR for skin layer remains almost constant with frequency (almost 0.1 W/kg) since this layer is farthest of the three layers from transmitter.

V. CONCLUSIONS

S-parameters of the human tissue model, path loss and SAR distribution was presented at frequency range 1-5 GHz. Using S-parameter values we can estimate reflected power. Using path loss we can also estimate received power. Path loss was found to be around 47-65 dB at 3.1-4.5 UWB band. This is low UWB. In this range high speed rate transmission for implants is possible. After that range path loss increases significantly. So this low UWB (3.1-4.5) can be useful for in-body to on-body communication.

Specific absorption rate (SAR) distribution of different layers in human body in frequency range 1-5GHz was found. With the increase of frequency, SAR increases so fast due to increase of E-field value and conductivity increase. In 5 GHz in muscle interface SAR is even more than 120 W/kg which is too dangerous for health. Safety limit of SAR according to FCC regulations in that frequency range lies between 8-20 W/kg for per 10 gm of tissue in human body. Also that SAR decreases so rapidly with depth of penetration of the E-field, was also found from the 3D distribution on 2D plane. As the frequency increases SAR values and E-field magnitudes increase so strongly at the closest part of the transmitter which is muscle in this work.

ACKNOWLEDGEMENT

The author acknowledges the department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, for constant support and help throughout the research work.

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