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Performance and design Analysis of an Implantable Antenna for Biotelemetry

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Abstract- An implantable patch antenna is designed to work in ISM band (2.4-2.5 GHz) for biomedical applications. The effect of human body on the different performance parameters of antenna is studied. To examine the effect of human body on antenna output characteristics, the patch antenna is tested by implanting in three layered body phantoms consisting of skin, fat and muscle and their performance is analysed by using different substrates for the same phantoms.

Index Terms- Biocompatibility, human tissues, implantable, patch antenna, embedded.

I. Introduction

In recent years flexible and portable electronics have received increasing attention due to their wide variety of applications [1] and applicability. They are particularly interested in bio-medical applications, in which they now are being widely deployed. Implantable antennas are widely being used in biomedical applications. Antenna is crucial component in implantable biomedical telemetry, because antenna plays the important role for the communication link between the implanted device inside the body and the receiver out of the body. So implantable antennas are specifically designed keeping in view of the various physical as well as biological constraints inside the human body and the FCC regulations of radiation for implanted devices [2].

Human body is electrically lossy and consists of different tissues of variable values of permittivity and conductivity. Different implantable antennas are designed for different sites of implantations in the human body [2], some are designed to work beneath the skin [3], some in muscles [4] and few in bones [5].The ITU-R recommendation SA.1346 [6], which outlined the use of the 402-405 MHz frequency band for Medical Implant Communication Systems (MICS). The MICS band is regulated by the FCC (Federal Commission for Communication) [7] and the ERC (European Radio-communication Commission) [8]. The ISM band (2.40 - 2.5 GHz) is also used for implantable medical devices in some countries [9]. Patch antenna designs have received considerable attention for implanting applications as they are highly flexible in design, small in shape and easily conformable [10 - 12], thus allowing for relatively easy miniaturization and integration with implantable medical device. For optimum performance, it is necessary to design the implantable antenna in the environment in which it is expected to operate with optimum performance. So the dielectric properties of the biological tissues such as skin, fat and muscles must be considered [13]. In this paper an implantable patch antenna with inset type feed is designed with PDMS (Poly Dimethyl Siloxane) as a superstrate and it is tested by implanting in 3 layered body phantoms. Its various performance parameters are studied and analysed using HFSS simulator.

II. ANTENNA DESIGN

To design a patch antenna, all the dimensional parameters for simple patch antenna are initially calculated using the conventional formulaes given below [14].

Width of patch, $W_{p,}$ can be calculated as

$$W_p = \frac{V_f}{2\times\frac{f\times\sqrt{\epsilon+1}}{\sqrt{2}}} \quad (1)$$

where, V_f is velocity of light, f is resonant frequency and ϵ is dielectric constant.

Due to the air-dielectric interface, effective dielectric constant can be calculated as the combination of dielectric constant of substrate and dielectric constant of air above it at the edges of the patch given by [14].

$$\epsilon_e = \frac{\frac{\epsilon+1}{2}+\frac{\epsilon-1}{2}}{\sqrt{[1+12\times\frac{h}{W_p}]}} \qquad (2)$$

Due to effect of fringing length of patch looks electrically wider than its physical length. Now actual length of patch can be calculated as the function of effective dielectric constant as [11]

$$L_p = \left\{\left[\frac{V_f}{2\times f\times\sqrt{\epsilon_e}}\right] - 2\left[0.412\times h\times\frac{(\epsilon_e+0.3)\times\left(\frac{W_p}{h}-0.264\right)}{(\epsilon_e-0.258)\times\left(\frac{W_p}{h}-0.8\right)}\right]\right\} \qquad (3)$$

So using equations (1), (2) and (3) all the required parameters for a three layer simple patch antenna with inset type of feed with lowermost layer as ground plane of PEC material with thickness approximately equal to thickness of patch is evaluated. Above the ground plane there is substrate of material Rogers 3210 and the uppermost layer is patch of PEC and biocompatible rectangular capsule. The calculated parameters are tabulated in table 1.

Table 1: Design parameters for patch antenna

Operating frequency	(2.4-2.5 GHz)
Substrate length and width	(47.5×59.65) mm
Length and width of patch	(25.35×18.75)mm
Substrate thickness	62 mil
Inset feed	6.727mm
Inset distance	0.739mm
Feed length	19.12mm
Feed width	1.477mm
Substrate thickness	62 mil
Biomaterial dimensions	(48×60)mm

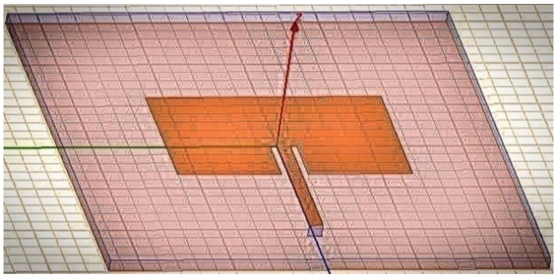


Fig.1: Proposed antenna design

To consider the effectiveness of antenna in human body, three layer body phantoms of rectangular and cylindrical shapes are modelled. These body phantoms consists of muscle, skin and fat layers [15-17] with the parameters as detailed in Table 2.

Table 2: Dielectric parameters of the human body tissues at 2.45 GHz

Tissue	€$_r$	σ (S/m)	Density (kg/m^3)	Thermal conductivity
Skin	38.01	1.46	1100	.53
Fat	5.28	0.10	909.4	201
Muscle	52.73	1.73	1040	.293

Further medical wireless applications such as implanted devices and on-body sensors require an antenna to transmit and receive signals from the human body. In this paper a patch antenna at 2450 MHz is designed for implantable purpose.

A. ***Biocompatibility***

Implantable antennas must be biocompatible in order to ensure patient safety and prevent rejection of the implanted device. Further human tissues are electrically conductive and would short circuit the metallization of the antenna. Biocompatibility and prevention of unwanted short circuits are crucial for long term implantation. The most widely used approach for preserving the biocompatibility of the antenna is to separate the metal radiator from human tissue by encasing the structure in a superstrate [18] which is a biocompatible material called Poly Dimethyl Siloxane (ε_r= 2.8 ,tan δ= 0.005) [19].

B. ***Miniaturisation***

For miniaturization purpose high permittivity dielectric material is used for substrate because they shorten the effective wavelength and resulting to lower the resonance, thus assisting in antenna miniaturization [15]. The proposed antenna is simulated using Rogers 3210 (ε_r=10.2, tan δ = 0.003) as substrate.

III. MATHEMATICAL ANALYSIS

When a microstrip line feed antenna is covered by a dielectric layer the characteristic impedance, phase velocity, losses, Q-factor varies as a function of the dielectric constant [20].The resonant frequency of a microstrip antenna covered with a dielectric layer can be determined when the effective dielectric constant of the structure is known which is shown as example by the Fig.2 for a microstrip antenna [20-21]. This concept is used to find the resonant frequency at which the proposed antenna design will resonate in air.

With reference to Fig.2 the fractional change in the resonant frequency is evaluated using equation (4) given below [20]

$$\frac{\Delta f_r}{f_r} = \frac{f_r(d=0) - f_r(d)}{f_r} \qquad (4)$$

$$\frac{\Delta f_r}{f_r} = \frac{1}{2} \times \frac{\Delta\epsilon_e/\epsilon_{eo}}{1+0.5(\frac{\Delta\epsilon_e}{\epsilon_{eo}})} \qquad (4a)$$

where,
f_r = resonating frequency
d = thickness of the dielectric
Δf_r = change in the resonating frequency
$f_r(d=0)$ = resonating frequency when no dielectric is loaded
$f_r(d)$=resonating frequency when thickness of dielectric "d" is loaded, here dielectric refers to the biomaterial encapsulation.
ϵ_{eo} = effective dielectric constant without encapsulation which is fixed for any material.
ϵ_e = effective dielectric constant with biomaterial encapsulation which can be calculated using equation (2).

Using equations (4) and (4a) we obtain equation (5) as,

$$\frac{f_r}{f_{rd}} = \frac{2(\epsilon_{eo} + 0.5\epsilon_e)}{(2\epsilon_{eo} - \Delta\epsilon_e)} \qquad (5)$$

$$\Delta\epsilon_e = \epsilon_e - \epsilon_{eo} \quad (5a)$$

where,
f_r = resonating frequency
f_{rd} = when thickness of dielectric "d" is loaded ,here dielectric refers to the biomaterial encapsulation
ϵ_{eo} = effective dielectric constant without encapsulation which is fixed for any material.
ϵ_e = effective dielectric constant with biomaterial encapsulation which can be calculated using equation (2).

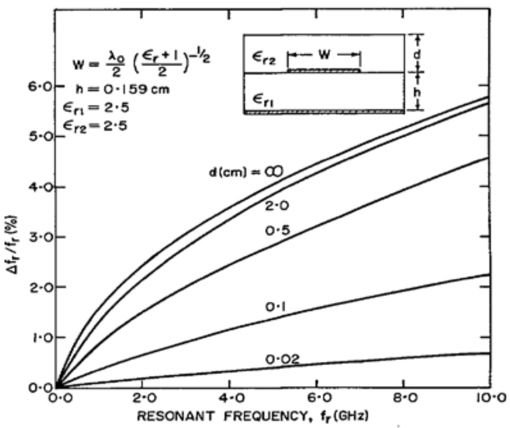


Fig.2: Fractional change in resonant frequency versus resonant frequency for polystyrene (ϵ_r=2.5) when dielectric thickness is varied.

Using equation (5), we can calculate the resonant frequencies of the antenna when dielectric is loaded or not by using the values of the relative and effective dielectric permittivities of the used substrate. The equation (5) is important to determine the resonant frequency of the antenna in air. Using the equations (2) and (5) and Fig.2 [20], it is depicted that the fractional change in resonant frequency for polystyrene has been observed by varying the thickness '*d*' of the dielectric loaded, ranging from 0 to infinity. It is also observed that the decrease in the resonant frequency for thin dielectric layers is less than 1 per cent for frequencies below 3 GHz and maximum is 5.8 % for antennas resonating below 10 GHz [20].

IV. SIMULATION AND RESULTS

The patch antenna is designed for bio-telemetry applications like health monitoring system to work in range of (2.4 - 2.5 GHz) ISM band for wireless communication networking. For performance evaluation of the antenna parameters viz; resonant frequency, return loss, gain, directivity and radiation pattern are essential characteristics for patch antenna in free space and then after implanting the patch antenna encased inside the superstrate (PDMS) inside the human body phantoms of various types.

A.Antenna inside rectangular phantom.

The characteristics of the antenna; dielectric constant and conductivity are affected by the depth of the antenna inside the different layers; of skin, fat and muscle, of body phantoms. In simulation for human body model, rectangular phantom is first used. For the rectangular model we have the antenna embedded into muscle layer at a depth of 13.5 mm from the top of the skin layer, the rectangular phantom represents implantation under the human torso [13]. For simulation purposes we have used standard dielectric parameters of skin, fat and muscle at 2.45 GHz as shown in Table 2

The antenna is designed with Rogers 3210 as substrate as per the dimensions given in Table 1. The antenna has been simulated without biomedical encasing and surrounded with air medium. The S_{11} parameter characteristics of the antenna have been shown in Fig. 3. In the next instance the antenna is covered with biomaterial encasing and simulation results of the S_{11} parameters are shown in Fig.3. The detailed dimensions used to design the rectangular phantom is shown in Table 7 and the detailed representative figure of the rectangular phantom used is shown in Fig.4. For instance I, the designed antenna has a return loss of -9.9 dB in air at resonant frequency of 2.52 GHz. In instance II, the same antenna when encapsulated with the biomaterial encasing, S_{11} of the antenna is -10.2 dB at resonant frequency of 2.5 GHz. In both I and II instances the -10 dB bandwidth of the antenna has been observed very sharp. In instance III, the antenna developed in instance II is placed inside a rectangular phantom mimicking human body tissues and simulated.

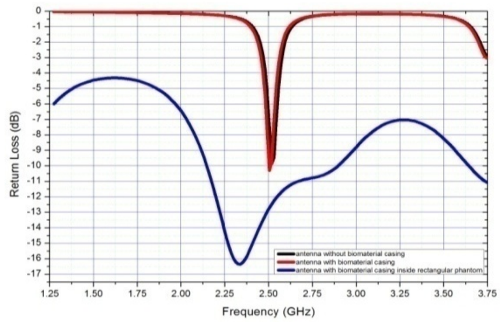


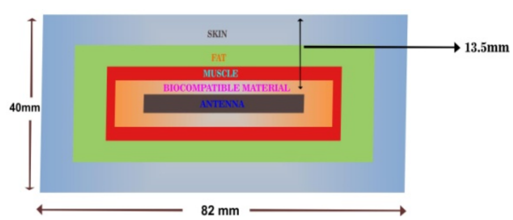
Fig.3: Comparison of S_{11} parameters for the three types of mediums for the proposed antenna for rectangular phantom

In instance Ⅲ, when antenna is placed inside the phantom, as shown in Fig. 3,S_{11} is observed at -16.6 dB at resonant frequency of 2.36 GHz. The resonant frequency shift Δf for the antenna is less than 1 per cent for the resonance frequency is below 3 GHz, when antenna covered with the thin layer of dielectric encasing [20], which is 0.793 % as per analysis of instances I and II. Since the rectangular phantom again acts as another dielectric loading to the antenna because the antenna gets loaded with dielectric, its resonance frequency decreases and return loss changes depending on the electrical properties of the loaded dielectric. The comparative fractional resonant frequency change observed is tabulated in Table 3 and the performance analysis of section-A is tabulated in Table 4.

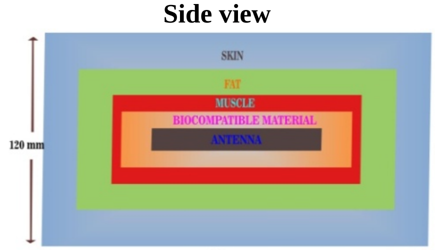
Table 3: Comparison of three different types of mediums

	Fractional change in resonant frequency	Percentage fractional change
Instance II with comparing instance I	0.00793	0.793 %
Instance III with comparing instance II	0.052	5.2%

a) Instance I-antenna without biomaterial encasing
b) Instance II-antenna encased in biomaterial encasing
c) Instance III-antenna encased in biomaterial encasing inside rectangular phantom



Side view



Top view

Fig 4: Antenna encased in the three layered rectangular phantom used for testing.

Table 4: Performance parameters of the designed antennas in various mediums

Type of medium	Resonant frequency (GHz)	3D gain	Directivity (dB)
Antenna in air	2.52	5.8694	3.8632
Antenna encased in biomaterial	2.5	4.9393	5.8308
Antenna encased in biomaterial inside rectangular phantom	2.36	4.3005	3.4943

A.Antenna inside Cylindrical phantom.

Now the antenna is implanted into cylindrically shaped multi-layered phantom at a depth of 40 mm inside the muscle layer from the top of skin layer, all other parameters are kept same as used in Section-A. the cylindrical phantom is used for simulations to mimick the human arm [13] Again for simulation purposes we have used standard dielectric parameters of skin, fat and muscle at 2.45 GHz as shown in Table 2. As mentioned in Section-A the antenna is designed with Rogers 3210 as substrate as per the dimensions given in Table 1, by simulating the antenna without biomedical encasing and surrounded by air medium. The S_{11} characteristics of the antenna is shown in Fig. 5. In the next instance the antenna is covered with biomaterial encasing and simulation results of the S_{11} parameter is shown in Fig.5. The detailed dimensions used to design the cylindrical phantom is shown in Table 7 and the detailed representative figure for the designed cylindrical phantom used is shown in Fig.6.

As mention in Section-A, in instance I designed antenna have a return loss of -9.9 dB in air at resonant frequency of 2.52 GHz. In instance II, the same antenna when encapsulated with the biomaterial encasing, S_{11} of the antenna is -10.2 dB at resonant frequency of 2.5 GHz. In both I and II instances the -10 dB bandwidth of the antenna has been observed very sharp. In instance III, the antenna developed in section A, is covered with biomedical encasing and placed inside a cylindrical phantom mimicking human body tissues and simulated.

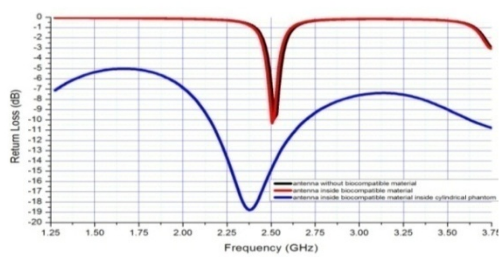


Fig 5: Comparison of S_{11} parameters for the three types of mediums for the proposed antenna for cylindrical phantom

As we know for instance Ⅲ, antenna is placed inside the cylindrical phantom as shown in Fig. 4, the S_{11} is recorded at -19.0 dB at resonant frequency of 2.375 GHz. The resonant frequency shift Δf for the antenna when antenna covered with thin layer of dielectric encasing is less than 1% for 3 GHz [20] as observed as same in Section-B, thus the cylindrical phantom again acts as another dielectric loading to the antenna because the antenna gets loaded with dielectric, its resonance frequency decreases and return loss changes depending upon the electrical properties of the loaded dielectric. The detailed performance analysis of Section-B is tabulated in Table 6. And the comparative analysis for the fractional change of resonant frequencies is tabulated in Table 5.

Table 5: Comparison of three different types of mediums

	Fractional change in resonant frequency	Percentage fractional change
Instance II with comparing instance I	0.00793	0.793 %
Instance III with comparing instance II	0.05	5%

d) *Instance I-antenna without biomaterial encasing*
e) *Instance II-antenna encased in biomaterial encasing*
f) *Instance III-antenna encased in biomaterial encasing inside cylindrical phantom*

Table 6: Performance parameters of the designed antennas in various mediums

Type of medium	Resonant frequency (GHz)	3D gain	Directivity (dB)
Antenna in air	2.52	5.8694	3.8632
Antenna encased in biomaterial	2.5	4.9393	5.8308
Antenna encased in biomaterial inside cylindrical phantom	2.375	7.514	1.3728

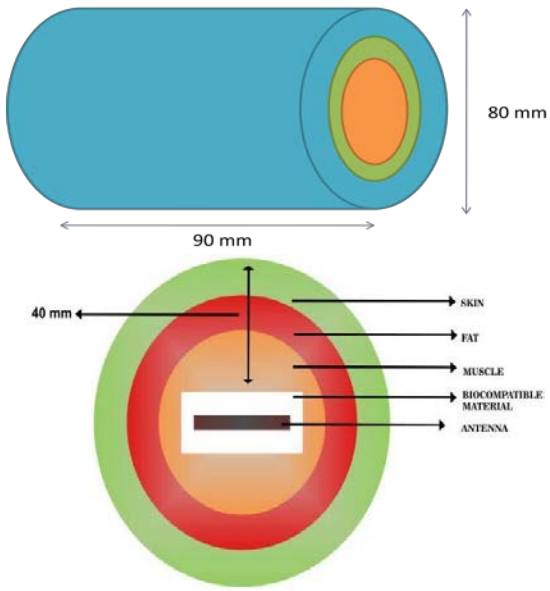


Fig.6: Three layered cylindrical phantom used in the testing of the antenna

Table 7: Human phantom models dimensions used in the testing of the proposed antenna

Model type	Size[mm]
Rectangular	82× 120 × 40
Cylindrical	R=40,H=90

` ***D.Performance observation of the designed antenna by using different Substrates by placing inside phantoms***

Table 9: Dielectric values of the substrates used

Name of substrate	Relative permittivity	Tangent loss	Mass density (kg/m^3)
Rogers 6002	2.94	0.0012	0
Rogers 3003	3	0.0013	0
Fr_4 epoxy	4.4	0.02	1900
Bakelite	4.8	0.002	1300
Tmm 10	9.2	0.0022	0
96%	9.4	0.066	3800

alumina			
Rogers 3210	10.2	0.003	0

By using the dielectric values as given in Table 9. And keeping all the parameters for designing rectangular and cylindrical phantoms same as given in Section A and B respectively, the antenna is tested for six different types of substrates and their return losses graphs is plotted for rectangular and cylindrical in Figures' 9 and 10 repectively. The detailed performance parameters are tabulated for both types of phantoms in Tables' 10 and 11.

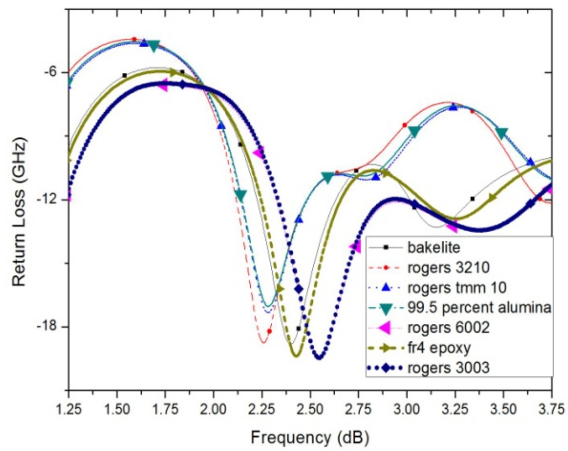


Fig. 8: Comparison of return loss for the rectangular phantoms testing by varying different types of substrates at their respective resonant frequencies

Table 10: Performance comparison of rectangular phantom by testing various types of substrates when antenna is implanted at a depth of 13.5 mm keeping the dimensions of biomaterial encapsulation same as in Table 1.

Types of substrate	Return Loss (dB)	Resonant frequency (GHz)	Directivity (dB)	Band Width (GHz)	Dielectric
Rogers 6002	-19.4	2.55	6.3836	1.86	2.94
Rogers 3003	-19.6	2.51	6.3933	1.74	3
Epoxy	-19.4	2.42	6.2286	1.61	4.4
Bakelite	-19	2.4	6.1846	1.73	4.8
Tmm 10	-17.15	2.25	6.3836	0.86	9.2
96% Alumina	-16.10	2.28	4.7604	0.8	9.4
Rogers 3210	-18.8	2.25	4.4839	0.77	10.2

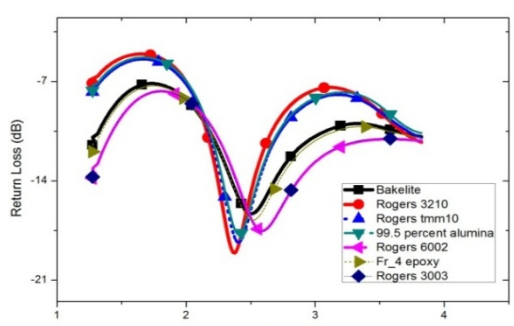


Fig.9: Comparison of return loss for the cylindrical phantoms used by varying different types of substrates at their respective resonant frequencies

Table 11: Performance comparison of cylindrical phantom by testing various types of substrates when antenna is implanted at a depth of 40 mm keeping the dimensions of biomaterial encapsulation same as in table 1.

Type of substrate	Return loss (dB)	Resonant frequency (GHz)	Directivity (dB)	Band Width (GHz)	Dielectric
Rogers 6002	-17.1	2.59	2.2428	7.8	2.94
Rogers 3003	-17.5	2.58	2.2602	7.81	3
Epoxy	-16.7	2.51	3.2244	9	4.4
Bakelite	-16.3	2.5	1.8022	1.1783	4.8
Tmm 10	-18.4	2.39	2.2428	0.615	9.2
96% alumina	-17.8	2.41	1.8363	0.588	9.4
Rogers 3210	-19.2	2.39	1.3382	0.551	10.2

From Table 10, it is clear by observation that as the dielectric values of the substrate increases the bandwidth of the antenna decreases, it is also clear by observation from Table 10 that as the values of dielectric increases the resonant frequency gradually decreases, also it is clear that the variation in S_{11} is not much since it ranges from -16.10 dB to -19.6 dB. Also by observation from table 10 we can choose to decide which type of substrate suits best for better bandwidth for the proposed antenna which is rogers 6002 it is also clear that for return loss performance the best substrate is again rogers 6002,the trade off in choosing rogers 6002 is that its resonant frequency skids off the unlicensed ISM band limitations of 2.4-2.5 GHz.

From Table 11, it is clear by observation that as the dielectric value increases the bandwidth of the antenna initially increases then decreases rapidly again, also it is clear that as the values of dielectric increases the resonant frequency decreases this is in par with the observation of Table 10. From table 11, the S_{11} variation is from -16.3 to -18.4 dB. It is clear that the substrate with the best return loss from Table 10 for rectangular type of phantom is shown by Rogers 3003,again in observation from table 11 the best bandwidth is observed in epoxy,where as the best return loss is shown by rogers 3210.so each parameter has its own superior performance and its trade off ,as rogers 3210 has best S11 however its bandwidth is very low.

It is also observed that the overall directivity is better when the antenna is tested in the rectangular phantom compared to cylindrical phantom by comparing Tables 10 and 11, From Tables 10 and 11 again it is also clear that the best bandwidth performance for testing the rectangular type of phantom is given by Rogers 6002 and the best bandwidth performance for the cylindrical type of phantom testing is shown by Epoxy.lastly from the analysis done we can now decide which type of substrate to choose as per the required designed parameter and upto what extent we can compromised the trade off of each substrate ‘s performance parameters..

V. CONCLUSION

This paper proposed an implantable antenna for biotelemetry applications. Miniaturisation and biocompatibility are two important aspects of antenna designing. So for miniaturization a high dielectric material is used and for biocompatibility the antenna was encased in a biocompatible material. So an antenna is designed at 2.5 GHz which falls within the ISM band inside the human phantom model. The antenna was designed using Rogers 3210 as substrate. The performance of the antenna was observed in two types of human phantom models by implanting the antenna in three layered phantoms , using different types of substrates and compared. This mode of analysis can be further used to determine the choice of a substrate for various types of implantation of biomedical implants. Further work can be done to reduce the size of the antenna and to exhibit mutli band frequencies.

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