Implantable Slot Antenna for Biomedical Application

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Abstract. A compact implantable coplanar waveguide (CPW) fed slot antenna for biomedical application is presented in this paper. Biocompatible material Poly (methylmethacrylate) (PMMA) is coated on the proposed antenna to make it suitable for implantation. The performance parameters of the antenna are measured in terms of the reflection coefficient by immersing the fabricated antenna in a liquid phantom. The proposed antenna covers the complete ISM band (2.4 GHz – 2.5 GHz). In addition, specific absorption rate (SAR) is also estimated which indicates the antenna meets the required safety regulations.

Keywords: CPW, CPW fed antenna, implantable antenna, SAR

1. Introduction

The demand for implantable and wearable antennas has increased for biomedical applications. These antennas can be placed inside or outside of the patient's body. These antennas are used to transfer signal in and out of the body. The major challenge associated with the implantable antenna is to make it compatible with implanted devices by keeping the gain as high as possible. Various types of compact antennas have been presented for such systems including planar inverted F antennas [1]-[2], Helical antenna [3], microstrip patch antenna [4] and spiral antenna [5]. In addition to size and gain it is necessary to consider other constraints, such as biocompatibility [6-7] and effect of tissues in which antenna is to be implanted [5]. Electrical properties of biological tissues severely affect antenna impedance and efficiencies [8-9].

In this paper, a compact CPW fed implantable antenna operating in the ISM band (2.4GHz-2.5 GHz) for biomedical application is presented. To make the proposed antenna suitable for implantation, it is coated with Poly (methymethacrylate) (PMMA) biocompatible material. Further, the antenna is immersed into liquid phantom to measure the antenna performance. Simulations and measurements results demonstrate that the antenna covers the complete ISM band. Simulation study of SAR is carried out to evaluate the performance and safety issues related to implanted antennas compared with the FCC and ICNIRP guidelines [10-11].

2. Characterization of liquid phantom

Since the implantable antennas are operated through muscle in vitro measurements therefore characterization of liquid phantom is required. The liquid phantom is prepared with mixture of deionized water, sugar, and salt in appropriate quantity. The deionized water having high dielectric permittivity and low conductivity. Precise quantity (as mentioned in Table 1) of sugar and salt is added to reduce permittivity and increase conductivity, respectively. The electrical properties of phantom is measured using Agilent's 85070E dielectric probe kit and an Agilent Technology N5230A network analyser as shown in Fig. 1. An open-ended coaxial cable was inserted into the liquid; the probe is connected to a network analyzer and the calibration, using short-open-water, was carried out at 22◦ C. Next the reflection coefficient values are processed to evaluate the electrical properties of the solution.

To formulate an appropriate recipe for liquid muscle phantom for the ISM bands, the effects of sugar and salt on relative permittivity and conductivity was studied. Figure 2 and Figure 3 show the changes in the relative permittivity and conductivity with respect to sugar concentration in a 100-mL mixture. As seen from figure 2, relative permittivity decreases significantly as sugar concentration increases in the mixture. However, there is only a slight increase in conductivity with the increase in sugar concentration.

The lowering of the dielectric constant is due to the dissolved non-polar particles or ions in water. The non-polar particles or ions orient the water molecules around them, thereby reducing their ability to orient in applied field, so reducing the dielectric constant by local high-field effect [12].

We carried out a similar study to determine the effect of salt concentration on relative permittivity and conductivity.

Fig. 1. Experimental setup for measurement of electrical properties of liquid phantom.

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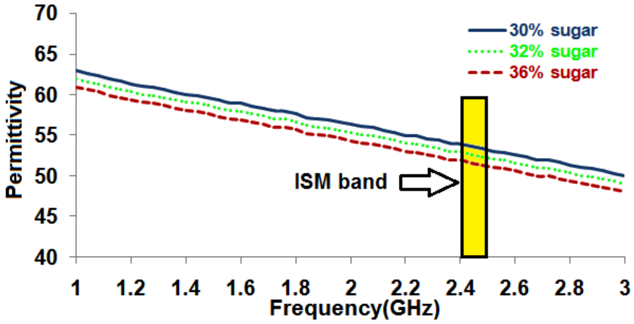

Fig. 2. Relative permittivity as a function of frequency for various sugar concentrations

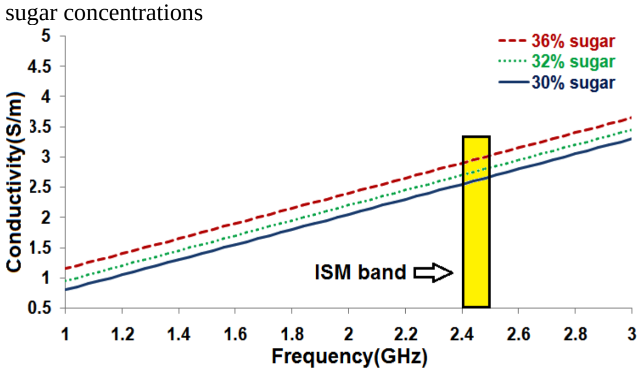

Fig. 3. Conductivity as a function of frequency for various sugar concentrations.

First, a reference 32% sugar solution is prepared and then 1–3 g of salt is added. As seen in Figure 4 and Figure 5, relative permittivity decreases and conductivity increases, as expected, when more salt is added to the mixture. Since salt particles separate into ions ($Na^{+}$and cl^{-}) while dissolving, the solution becomes more conductive. Thus, a water solution, which has relative permittivity and conductivity equivalent to that of muscle tissues at given frequency, can be obtained by mixing proper ratio of sugar and salt in the water. From the experimentally generated graph it can be seen that solution obtained with 32% and 2% of sugar and salt respectively, gives electrical property similar to muscles. Table 1 depicts the weight ratio of the sugar-salt-water solution for the tissue-equivalent phantom. The measured quantity of permittivity and conductivity values of the human muscle tissue and the liquid muscle phantom at different frequencies are shown in Table 2. It is observed that solution prepared with 32% and 2% of sugar and salt respectively, gives electrical property like muscles.

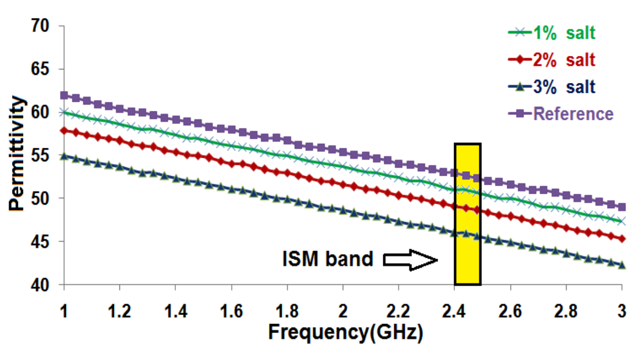

Fig. 4. Permittivity as a function of frequency for various salt concentrations

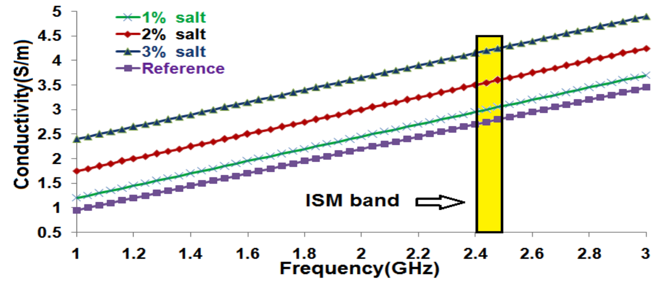

Fig. 5. Conductivity as a function of frequency for various salt concentrations

Table 1: Content for liquid muscle phantom at ISM band

Ingredient	Percentage contribution (%)
Deionized water	66.00
sugar	32.00
Salt	2.00

Table 2: Electrical properties of human muscle tissue

Frequency (GHz)	Human Muscle Tissue [13]-[15]		Liquid Phantom (measured)	
	ε_r	σ (S/m)	ε_r	σ (S/m)
2.0	53.29	1.45	55.37	2.2
2.25	52.98	1.61	53.94	2.51
2.45	52.73	1.74	52.79	2.79
2.65	52.46	1.87	51.32	3.01
3.0	52.05	2.14	49.02	3.45

3. Formation and characterization of biocompatible material

To make the antenna suitable for implantation, low-cost biocompatible material poly(methylmethacrylate) or (PMMA) is used. *PMMA*, is a non-biodegradable polymer which possesses a good degree of compatibility with human tissues [15]. It has therefore found applications specifically in perm- anent structures, such as bone tissue regeneration and bone structural enhancement. It manifests low toxicity and is used as scaffolding to deliver mechanical stability following its implantation.

Pyrax rapid prepare kit was used to prepare PMMA. Electrical properties of the PMMA was obtained from the resonant cavity method. A typical measurement system consists of a network analyzer, and 85071E Split post dielectric resonators (SPDR). The electrical property of the PMMA is obtained from the resonant cavity method [16]. The permittivity and loss tangent of the material can then be determined from the change in resonant frequency and Q-factor using Eq (1) and (2).

$$\varepsilon_r{}' = 1 + \frac{V_c\,(f_c - f_s\,)}{2\,V_s f_s} \quad (1)$$

$$\varepsilon_r{}'' = \frac{V_c}{4V_s}\left(\frac{1}{Q_s} - \frac{1}{Q_c}\right) \quad (2)$$

where,
f_c= Resonant frequency of empty cavity
f_s= Resonant frequency of filled cavity
Q_c=Q of empty cavity
Q_s= Q of filled cavity

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V_s=Volume of empty cavity
V_c= Volume of sample

The measurement setup is shown in the Figure 6. The cylinder shape solid sample is placed along the centre of the cavity. Using the above mentioned method, the calculated value of permittivity and loss tangent of the PMMA is found to be ε_r=2.23 and tan δ = 0.035 respectively.

4. Antenna characterization and measurements

4.1. Antenna characterization in liquid phantom

Figure 7 shows the proposed slot antenna configuration and its prototypes. The antenna is designed using full wave EM solver IE3D on alumina substrate ($\varepsilon_r = 9.6$, $\tan\delta = 3.0\times 10^{-5}$). Rigorous simulation study is carried out to optimize the antenna shape parameters in vitro after making it biocompatible. Figure 8 shows the effect of the thickness of the PMMA when antenna is immersed into liquid phantom. It is observed that 0.5 mm-thick PMMA ($\varepsilon_r = 2.23, \tan\delta = 0.035$) superstrate covers the entire ISM band. It is noted that 0.5 mm is the fundamental practical lower limit. Due to brevity, the reflection coefficient characteristics of the proposed antenna for various shape parameters are not shown here. The optimized dimensions of the slot antenna are given in Table 3.

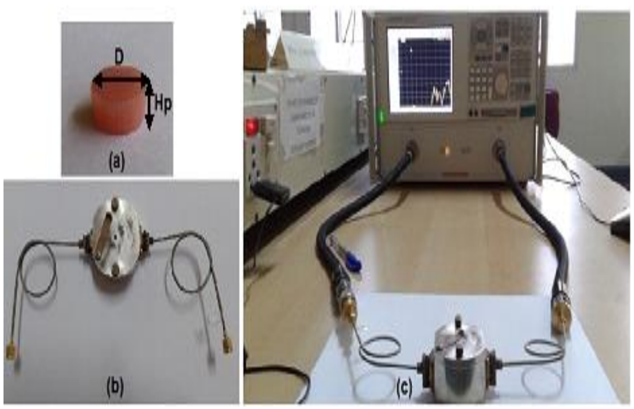
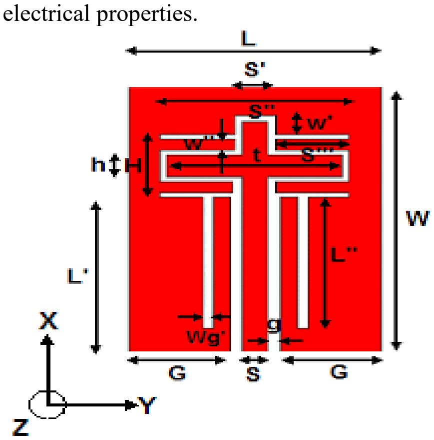
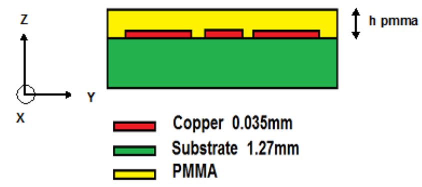


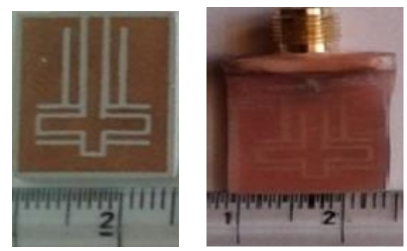
Fig. 6. (a) Cylinder shape PMMA sample (b) Split post dielectric resonators (SPDR), and (c)Measurement setup used for measuring the PMMA electrical properties.



(a)



(b)



(c) (d)

Fig. 7. (a) Schematic top view, (b) Cross section view, (c) Prototype without PMMA, and (d) Prototype with PMMA coating

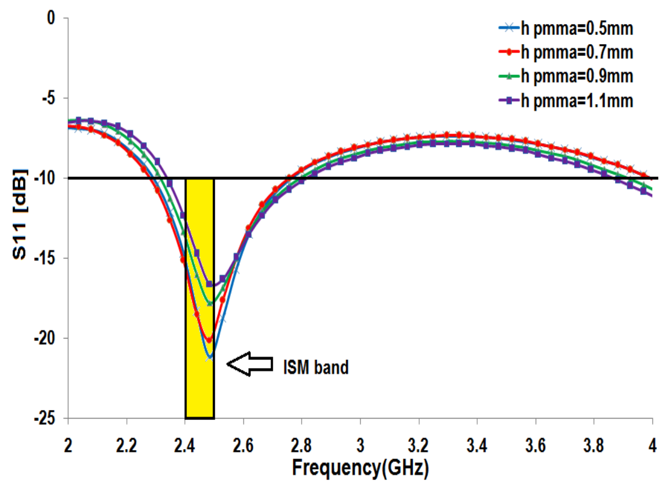


Fig. 8. Varaiation of reflection coefficient due to different insulation thickness of PMMA .

Table 3. Dimensions of the slot antenna

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
L	15.0	S'	2.5	W'	1.0
W	20.0	S"	11.25	W"	0.875
S	1.5	L"	9.8	g	0.75
G	6.0	S"'	4.3	Wg'	0.635
t	10.5	h	1.75		
L'	11.25	H	5.0		

4.2. Antenna simulation and measurements in Vitro

In order to verify the performance of the proposed antenna, simulation and measurement study is carried out in vitro. For simulation study in vitro, one layer muscle tissue is considered as shown in Figure 9. The measurement set-up

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with liquid phantom representing the dielectric characteristics of human muscle tissue at 2.45 GHz is shown in Figure 10.

Figure 11 shows the measured and simulated reflection coefficient of the antenna in muscle tissue liquid phantom with biocompatible superstrate layer. Measured bandwidth is 480 MHz (2.26–2.74GHz) and the fractional bandwidth at the centre frequency (2.45 GHz) approximately 19.28% is obtained. The measured and simulated results are found in good agreement.

5. Radiation characteristics

The IE3D simulation software is used to calculate the radiation patterns and gain of the antenna inside the liquid phantom. The computed radiation patterns in the ϕ-plane and the θ-plane are shown in Figure 12. The patterns are computed at 2.45 GHz, at a reference distance of 1 m, and using an input power of 1 W.

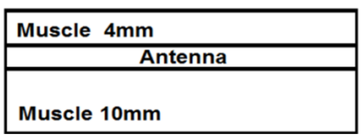


Fig.9. Antenna placed in one layers muscle tissue.

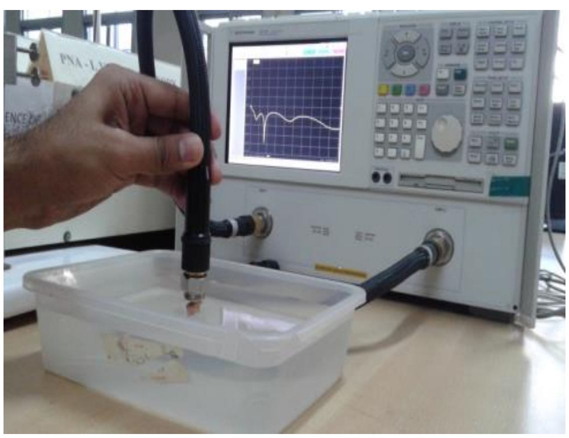


Fig. 10. Measurement setup with human muscle tissue liquid for implantable antennas.

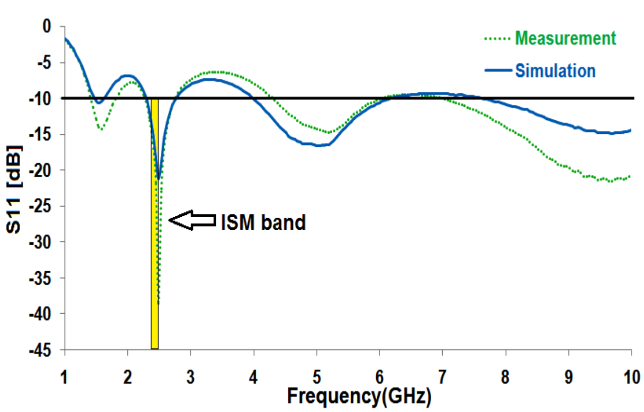
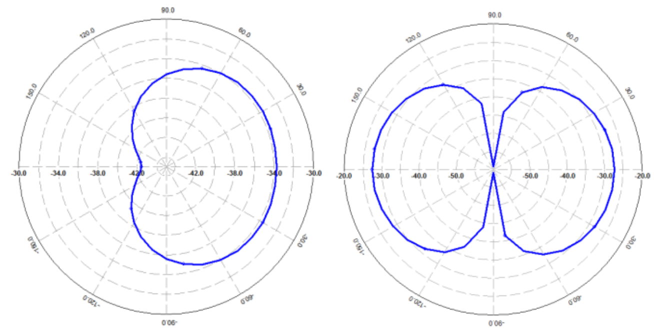


Fig. 11. Simulated and measured results in muscle tissue liquid phantom with biocompatible superstrate layer.

Figure 13 shows the simulated antenna gain in vitro. The gain values are lies between -25.92 dBi to -27.12 dBi. These values are comparable to results presented in literature [9]. Since the antenna is embedded inside the human body which is lossy in nature hence gain is very low.

Figure 14 shows the simulated SAR distribution over 1-g of average tissues for the proposed antenna implanted into the muscle. It is considered that the antenna delivered 1 W of power inside the muscle tissue, the maximum SAR value (148 W/kg) is obtained. To satisfy SAR regulation (1.6 W/kg) of ANSI [10]-[11]; the delivered power must be decreased to the suitable level (10.8mW).



(a) (b)

Fig. 12. Far-field patterns at 2.45 GHz in the (a) ϕ -plane, xy- plane and (b) ϴ- plane, yz- plane.

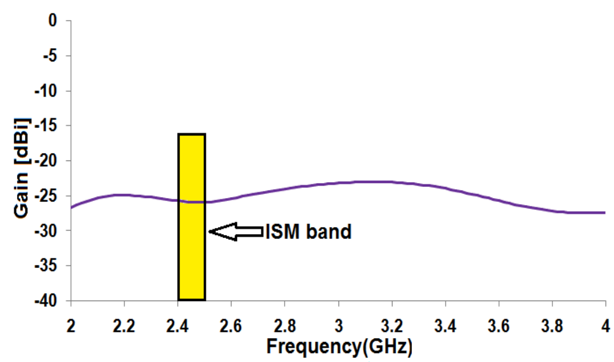


Fig. 13. Simulated gain pattern in vitro.

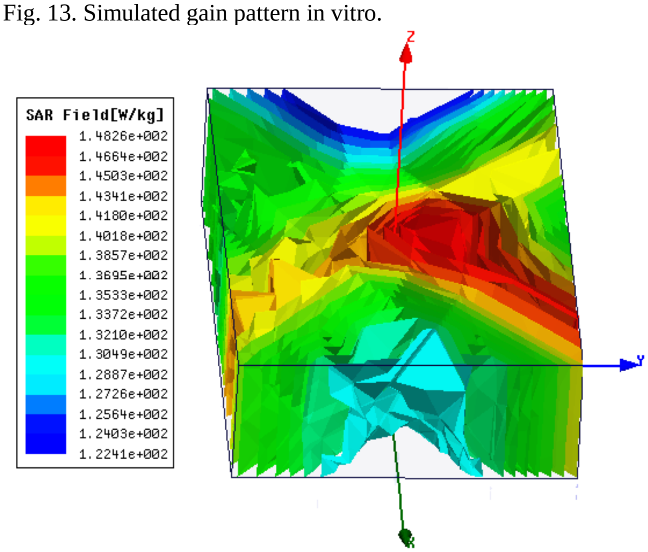


Fig. 14. Simulated SAR distribution over 1-g of tissue (delivered power = 1 W).

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6. conclusion

In this paper, simulation and experimental study of implantable compact biocompatible slot antenna was carried out in vitro. The simulation and measurement study of a biocompatible slot antenna immersed into the liquid phantom was performed. Measurements and simulations of the reflection coefficient in the 2.45 GHz ISM band demonstrated a very large bandwidth which covers the entire ISM band. A good agreement was found between simulation and measurement results. The PMMA layer not only make antenna biocompatible but also helps in improving gain. The proposed antenna also satisfies SAR regulation for the power up to 10.8 mW. The simulated results shows that the designed antenna can be used for biomedical applications.

References

[1] H. Li, Y.-X. Guo, C. Liu, S. Xiao, and L. Li, A miniature-implantable antenna for medradio-band biomedical telemetry, *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1176–1179, 2015.

[2] C. M. Lee, T. C. Yo, F. J. Huang, and C. H. Luo, Bandwidth enhancement of planar inverted-f antenna for implantable biotelemetry, *Microwave and Optical Technology Letters*, vol. 51, no. 3, pp. 749–752, 2009.

[3] C. Liu, Y.-X. Guo, R. Jegadeesan, and S. Xiao, In Vivo Testing of Circularly Polarized Implantable Antennas in Rats, *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 783–786, 2015.

[4] C. Liu, Y.-X. Guo, and S. Xiao, Capacitively loaded circularly polarized implantable patch antenna for ISM band biomedical applications, *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 5, pp. 2407–2417, 2014.

[5] J. Kim and Y. Rahmat-Samii, Implanted antennas inside a human body: Simulations, designs, and characterizations, *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 8 II, pp. 1934–1943, 2004.

[6] M. L. Scarpello et al., Design of an implantable slot dipole conformal flexible antenna for biomedical applications, *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 10, pp. 3556–3564, 2011.

[7] A. Kiourti, J. R. Costa, C. A. Fernandes, and K. S. Nikita, A broadband implantable and a dual-band on-body repeater antenna: Design and transmission performance, *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 6, pp. 2899–2908, 2014.

[8] A. J. Johansson, Wireless Communication with Medical Implants: Antennas and Propagation, Ph.D. dissertation, Lund University, Lund, June 2004.

[9] T. Karacolak, A. Z. Hood, and E. Topsakal, Design of a dual-band implantable antenna and development of skin mimicking gels for continuous glucose monitoring, *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 4, pp. 1001–1008, 2008.

[10] Evaluating Compliance with FCC Guidelines for Human Exposure to Radio Frequency Electromagnetic Fields, Federal Communication Commission (FCC) Std. Supplement C, OET Bulletin 65, Edition 97-01, 2001.

[11] IEEE Standard for Safety Levels With Respect to Human Exposure to Radiofrequency Electromagnetic Fields, 3 kHz to 300 GHz, IEEE Standard C95.1-2005, 2005.

[12] J. Hasted, *Aqueous Dielectrics*. London: Chapman and Hall, 1973.

[13] C. Gabriel, S. Gabriel, and E. Corthout, The dielectric properties of biological tissues: I. Literature survey, *Physics and Medical Biology*, vol. 41, pp. 2231–2249, 1996.

[14] S. Gabriel, R. W. Lau, and C. Gabriel, The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz, *Physics and Medical Biology*, vol. 41, pp. 2251–2269, 1996.

[15] V. Mittal, *Polymer nanocomposite foams*. Boca Raton: CRC Press, 2013

[16] A. Von Hippel, *Dielectric materials and applications*. Boston: Artech House, 1995.

Biography of the authors

Rahul Dubey received the M.Tech. Degree in Electronics Engineering from the Birla Institute of Technology, Mesra, India, in 2016. He is currently pursuing the Ph.D. Degree in Electronic Engineering in the area of implantable antennas, at Indian Institute of Technology (BHU), Varanasi, India. His research interests include design and characterization of implantable antennas for biomedical applications, including wireless power transfer, RF biomedical applications, and textile antennas.

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