ISSN: 2449 – 0539
BAYERO JOURNAL OF ENGINEERING AND TECHNOLOGY (BJET) VOL.17 No.1, JAN, 2022 PP 60-68

DESIGN AND ANALYSIS OF FLEXIBLE MICROSTRIP PATCH ANTENNA AT 2.45GHz ISM BAND

[1]Gajo S. I., [2]Babale S. A., [3]Lawan S. H. and [4]Danbatta K.

[1] Department of Networking and System Security, Katsina State Institute of Technology and Management, Katsina, Nigeria
[2,3] Department of Electrical Engineering, Bayero University Kano, Kano, Nigeria
[4]Nigerian Communications Commission (NCC), Abuja, Nigeria.

Corresponding author Email: shehugajo2004@gmail.com

ABSTRACT

The paper presents a design and performance analysis of an in-set feed rectangular wearable patch antenna at 2.45GHz for ISM band. The antenna is made of polydimethylsiloxane (PDMS) flexible substrate with dielectric constant of 2.7, loss tangent of 0.02 and thickness of 2.5mm which is conformal and robust solution to wearable applications. Zelt, a nylon-based material, with surface resistivity of 0.01 ohm/sq and thickness of 0.063mm was used for radiating planes. The proposed antenna was studied and analysed using CST Microwave Studio, where different parameters such as Return Loss, Gain and Efficiency were observed. As the antenna is expected to be worn in close proximity to human tissue, the Specific Absorption Rate (SAR) was investigated on a three layered body model of Skin, Fat and Muscle. The proposed antenna achieved a 100MHz impedance bandwidth (4.08%), Gain of 3.11dB and Efficiency of 51%. The proposed antenna on flat body phantom gives acceptable SAR of 0.615W/Kg and 0.281W/Kg over 1gram and 10gram of tissue which are below the SAR threshold limits of 1.6W/kg and 2W/kg respectively. The proposed antenna can be incorporated in to various wearable devices.

Key words: Microstrip patch antenna, Flexible substrate, SAR.

1. INTRODUCTION

For efficient and reliable radio links, low cost, lightweight, and miniaturized antennas are desired devices for wireless communications [1]. Microstrip Patch Antennas (MPA) can be the most appropriate candidate in this regard. These antennas are low profile, conformable in nature to different surfaces, easy and less production cost. They were first presented in the 1950s however came to practice after the innovation of a printed circuit board (PCB) in the 1970s. The antennas consist of a dielectric substrate etched with radiating patch and ground plane above and below it respectively. The radiating patch may be of various shapes such as rectangular, square, circular, triangular, dipole, etc [2, 3]

The main element of the patch antenna is a dielectric substrate. Thus, in choosing the dielectric substrate, it important to consider distinctive design parameters such as dielectric constant, loss-tangent, and substrate's thickness. Many substrates utilised in producing microstrip antennas are available and their dielectric constants are usually in the range of 2.2 to 12. In a rare case, the dielectric constant can be less than 2.2. The dielectric constant value affects surface wave and bandwidth of an antenna. Loss tangent quantify the amount of power converted to heat in the material. Losses will be high for higher value of loss-tangent there by affecting radiation efficiency of an antenna. Substrate thickness is a trade-off between good antenna performance and circuit design. To limit undesired radiation and mutual coupling in microwave circuit design, thin substrates with higher dielectric constants are preferred to achieve smaller component size. But this is at the expense of less efficiency and bandwidth. On the other hand, thick substrates with lower dielectric constant give better efficiency, larger bandwidth but to the detriment of a bigger component size [2, 4].

Microstrip antennas found application in different fields such as mobile devices, radio frequency identification (RFID), location findings, satellite communications, medical imaging, surveillance system, remote sensing, and so on [3]. Despite these advantages, microstrip antennas suffer from an inherent disadvantage of low gain, narrow bandwidth, multiple resonances, less efficiency, and low power handling capability [5, 6].
Body-centric wireless communication became interested area of research in the present era. Wearable antennas designed to operate in 2.40GHz ISM (Industrial, Scientific, and Medical) band were found useable in wearable devices, such as healthcare monitoring system, military communications, portable gadgets, and implantable medical tools. For body-worn applications, the antennas ought to be of small size, light, ease of fabrication, and less power consumption. These make microstrip patch antenna a suitable candidate for wearable applications. However the size reduction degrades the performance of the antenna as stated above. Thus the design of a wearable antenna is usually challenging task [7, 8].

Due to the conformal nature of the human body, flexible substrates are replacing the rigid one in microstrip patch antennas fabrication. As stated in [9], materials made from textiles such as felt, cotton, fabric, polyester, Velcro, and polycot were used as substrate materials for wearable antennas design. Polydimethylsiloxane (PDMS) introduced in [10, 11] is a good candidate for wearable antenna designs due to its low cost, high flexibility, and easy realization. On the other hand, the radiating planes for wearable antenna should have high conductivity, flexible in nature, and less resistivity among others [9]. As such conductive fabrics (e-textiles) are used as conductive planes in wearable antennas design and fabrication. The e-textiles materials were made to behave as a metal such as copper mostly used in patch antenna designs [12]. Performance characteristics of different e-textile materials such as Zelt, Shieldit, and Flectron were studied [13] with zelt having the best performance. Zelt is made from copper and tin as a nylon-based conducting material with a low surface resistivity (<0.01 ohm/sq.) and high conductivity of 10^6 S/m [9].
Wearable antennas usually operate near the human body having a higher permittivity and conductivity which leads to frequency detuning from resonant point. This affects other parameters such as gain, bandwidth, and efficiency. Also, the side and back lobe radiations are usually absorbed into the human body. As such it is important to study the effect of these radiations into human body tissues. Thus three layered body model consisting of muscle, fat and skin was proposed in this paper.

2. GEOMETRY AND DESIGN OF PROPOSED ANTENNA

The antenna proposed in this paper is designed for a resonant frequency (f_r) of 2.4GHz ISM band application. PDMS, a polymer based material with high flexibility and low loss factor is used as a substrate with a dielectric constant (ε_r) of 2.7, loss-tangent of 0.02 and thickness (h) of 2.5mm. Zelt which is is durable, tear and water resistant, is used as a conducting material for patch, ground and microstrip feeding line. It is plated with copper and tin with a conductivity of 10^6 S/m, thickness of 0.063 mm with a manufacturer's surface resistivity specification lower than 0.01 ohm/square, which is excellent for creating efficient antennas at wireless frequencies [19]. The dimensions of the patch and substrate were obtained using the design equations (1-8) [2] as illustrated in the appendix. The proposed antenna is designed and simulated using CST microwave studio.

$$\mathrm{Wp} = \frac{c_o}{2f_r}\sqrt{\frac{2}{1+\varepsilon_r}} \quad \ldots \quad (1)$$

$$\varepsilon_{eff} = \frac{1+\varepsilon_r}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{\mathrm{Wp}}\right]^{-1/2} \quad \ldots \quad (2)$$

$$L_{eff} = \frac{c_o}{2f_r\sqrt{\varepsilon_{eff}}} \quad \ldots \quad (3)$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)(\frac{\mathrm{Wp}}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{\mathrm{Wp}}{h} + 0.8)} \quad \ldots \quad (4)$$

$$\mathrm{Lp} = L_{eff} - 2\Delta L \quad \ldots \quad (5)$$

$$\mathrm{Ls} = 2 * \mathrm{Lp} \quad \ldots \quad (6)$$

$$\mathrm{Ws} = 2 * \mathrm{Wp} \quad \ldots \quad (7)$$

Where Wp and Ws are the width of patch and substrate respectively, Lp and Ls are length of patch and substrate respectively, L_{eff} is an effective length of the patch, ΔL is the change in patch's length due to fringing effect, ε_{eff} is an effective dielectric constant and c_o is the velocity of light.

The inset feed point (y_o) was determined from equation (8) for the required input impedance of 50ohms.

$$R_{y_0} = R_{in} \mathrm{Cos}^2\left(\pi \frac{y_0}{Lp}\right) \quad \ldots \quad (8)$$

The calculated and optimised parameters of the proposed antenna are summarized in table 1, and figure 1 depicts the geometry of the proposed antenna.

Table 1: Calculated and optimized values of the proposed antenna dimensions

Parameters	Calculated Values (mm)	Optimized Values (mm)
Patch Length (Lp)	36.16	35.8
Patch Width (Wp)	45.01	44.7
Inset feed (y_o)	12.81	10.8
Feedline Width (W_f)	6.7	6.5
Feedline spacing (gf)	1	1
Substrate Length Ls	72.32	71
Substrate Width Ws	90.02	90

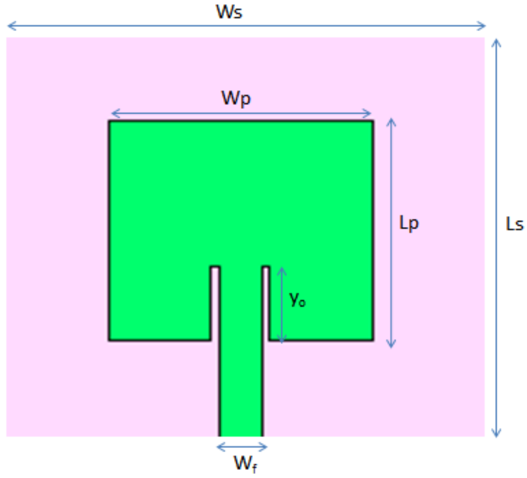


Figure 1: Geometry of proposed patch antenna

3. SIMULATION RESULTS AND DISCUSSIONS

3.1 Reflection Coefficient (S1,1)

The proposed antenna was analysed through the frequency range of 2.0 to 3.0GHz in free space to cover the 2.45GHz ISM frequency band. The S1,1 plot is presented in figure 2. The antenna resonates at 2.45 GHz with a return loss of -30.6dB. The antenna gives an acceptable bandwidth (100 MHz) from 2.40 to 2.50GHz which is suitable for ISM band applications.

3.2 Radiation Pattern

The antenna's radiation pattern plays an important role in its performance analysis. The copolarization pattern of the proposed antenna in both H-Plan ($\varphi=0^0$) and E-plan ($\varphi=90^0$) is depicted in Figure 3. The antenna has a directivity of 7.0dBi, and beam width of 88.9^0 in E-plan.

ISSN: 2449 – 0539
BAYERO JOURNAL OF ENGINEERING AND TECHNOLOGY (BJET) VOL.17 No.1, JAN, 2022 PP 60-68

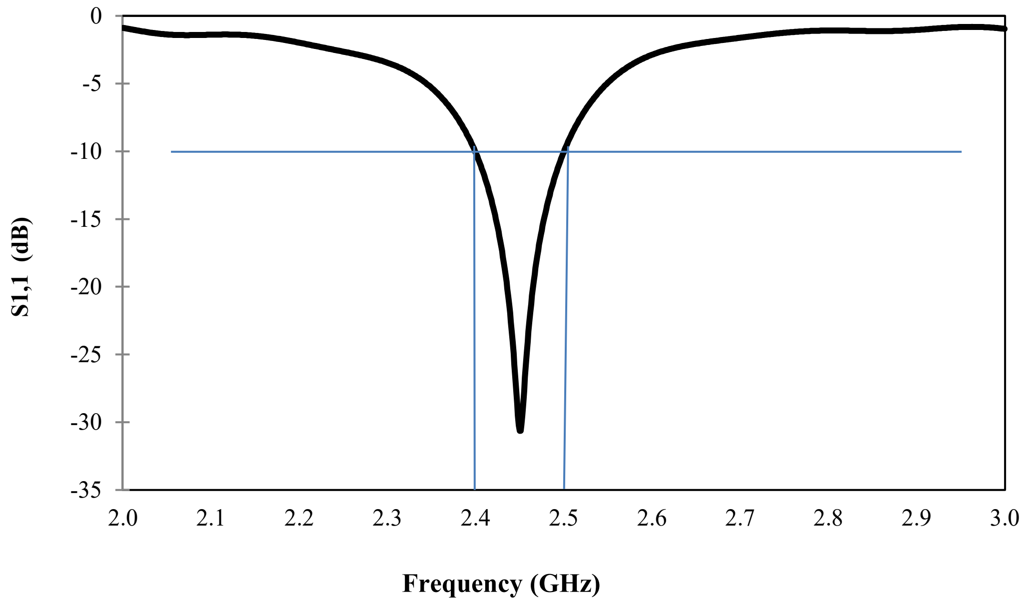


Figure 2: Reflection coefficient (S1,1)

3.3 Gain and Efficiency

Antenna Gain describes the ability of the antenna to emanate power toward a path of greatest radiation. Radiation efficiency quantifies the power losses in the antenna and relates the radiated power (P_r) and the input power (P_{in}) to the antenna. Figure 4 illustrates the antenna gain and efficiency at ISM band frequencies where the gain of 4.64dB remained constant over the ISM frequency band and maximum radiation efficiency of 58% is at 2.45GHz.

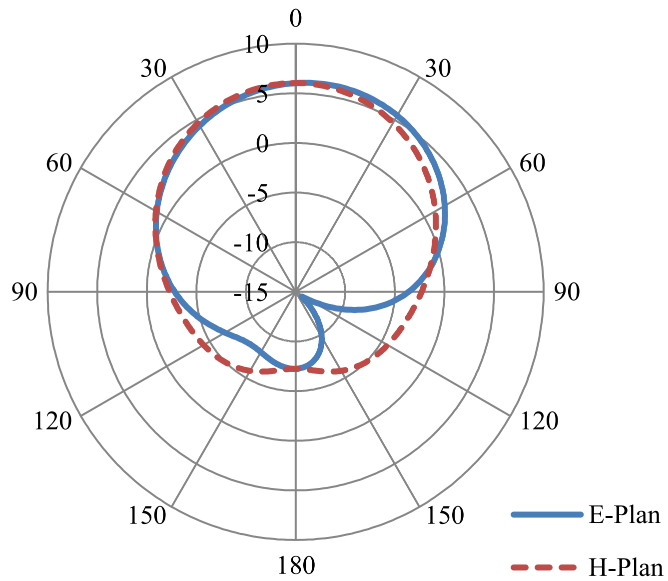


Figure 3: Radiation pattern (copolarization)

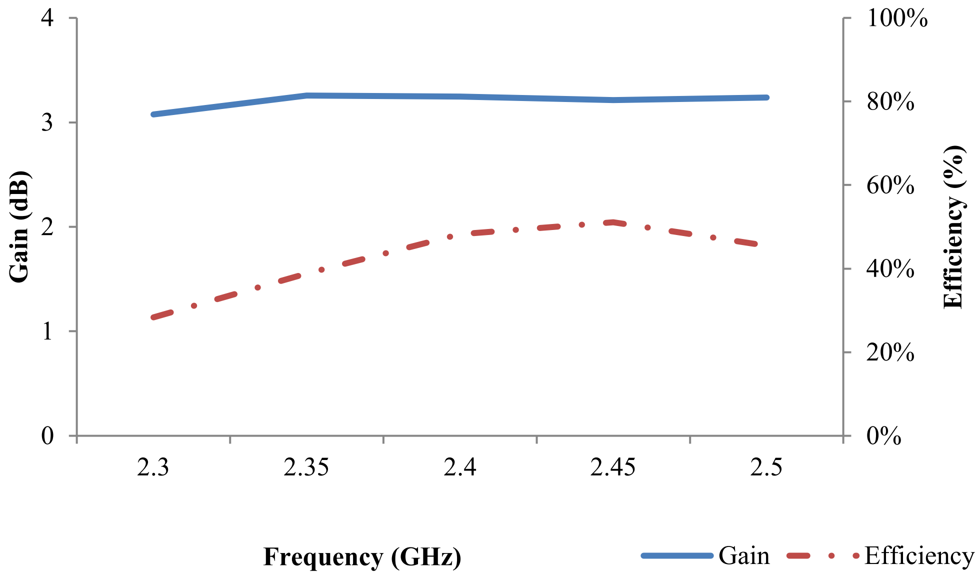


Figure 4: Gain and Radiation efficiency

4. ON-BODY ANALYSIS

Wearable antennas are usually placed in or near human body tissues. This affects the antenna performance due to the lossy nature of the human body [14]. For this reason, it is necessary to analyse the performance of the wearable antenna in both free space (Off-body) and then on-body tissues.

4.1 Human Tissue Model and Tissue Properties

A three-layered human body phantom consisting of muscle, fat and skin as depicted in figure 7 was designed using CST microwave studio. The proposed antenna is placed on the body phantom to create an on-body simulation environment. The relative permittivity (ε_r) and conductivity (σ) of the three layers at 2.45 GHz are stated in table 2 [15]. The thickness of the three layers, muscle, fat and skin is 23mm, 8mm, and 2mm respectively [9]. To simplify the simulation process, the amount of water content in the tissues is not considered.

4.2 Antenna Performance on Human Tissue

The resonant frequency of the antenna near a flat human phantom increased slightly above 2.45GHz with a return loss (S11) of -12.6dB. For copolarization radiation pattern, the directivity and gain changed to 7.59dBi and 4.44dB respectively. These variations are due to the conductivity and higher permittivity of human body tissues. Most of the radiated signals is been absorbed by the body tissues thereby affecting the antenna performance. Figure 5 compare the reflection coefficient of the antenna in free space and on-body analysis. Table 3 summarized the results of the proposed antenna for free space and on-body analysis.

4.3 Specific Absorption Rate (SAR)

As stated earlier, wearable antennas working near the human body are detuned due to impedance mismatches. Some amount of the available power is reflected and absorbed by the human body. This absorption results in a higher estimation of SAR values. SAR explains how much the human tissues absorbed the reflected power. It is express as:

$$SAR = \sigma E^2/\rho \quad (W/Kg) \qquad . . . \qquad (9)$$

Where:

σ represents conductivity of the human tissue (S/m),
E represents the root mean square amplitude of an incident electric field (V/m) and
ρ is the density of human tissue (Kg/m^3) [16].

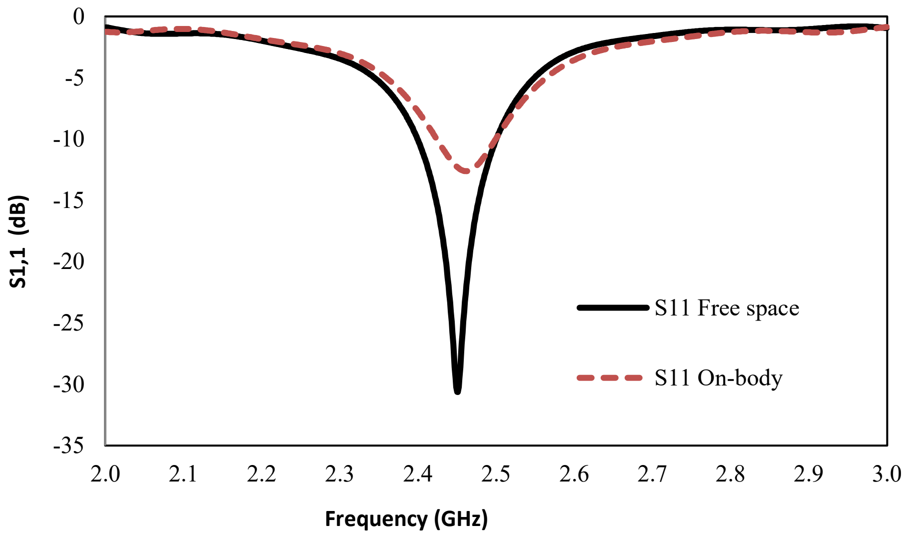


Figure 5: Reflection coefficient (S1,1) comparison for Off-body and On-body analysis

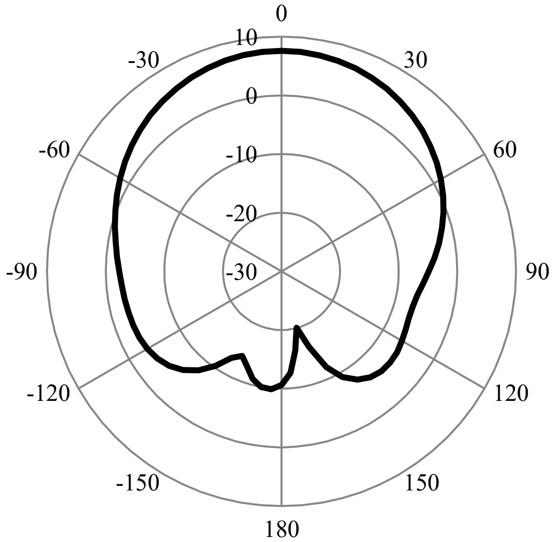
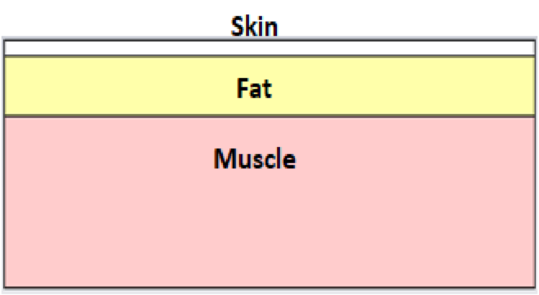
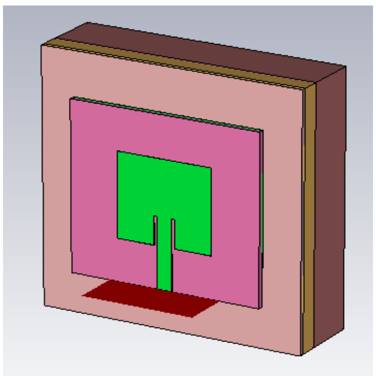


Figure 6: Copolarization radiation pattern for On-body analysis (Directivity)



(a)



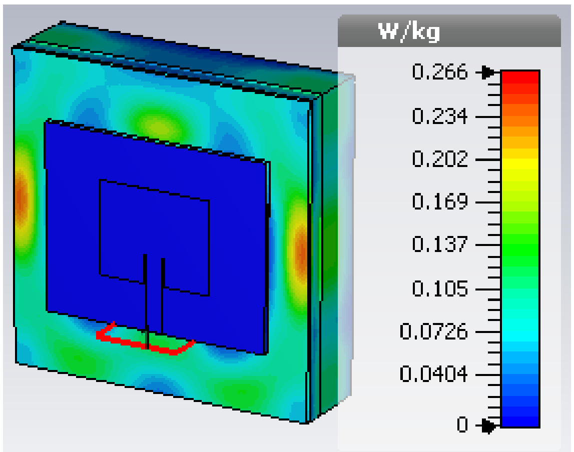
(b)

Figure 7: Three-layered body tissues; (a) side view, (b) 3D view with the proposed antenna on top.

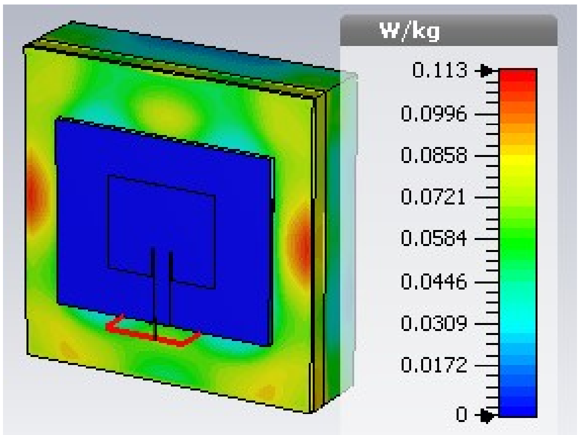
Two international standard commissions, the American Federal Communication Commission (FCC) [17] and the European International Commission of Non-Ionization Radiation Protection (ICNIRP) [18] set a maximum safe level of SAR as 1.6 W/Kg for 1 gram and 2 W/kg for 10 grams of body tissue respectively. The SAR values were obtained using the IEEE C95.3 averaging method over 1gram and 10 grams of tissue volume with reference power level of 500mW. The results of the simulation are depicted in figure 8.

Table 2: Relative permittivity and conductivity of human tissues

Human Tissue	Relative permittivity ε_r	Conductivity σ (S/m)	Thickness (mm)
Skin	38	1.46	2
Fat	5.28	0.105	8
Muscle	52.7	1.74	23



(a)



(b)

Figure 8: SAR distributions on flat phantom: (a) 1gram, (b) 10grams.

Table 3: Result Summaries

Parameter	Off-Body analysis	On-Body analysis
Resonant frequency (GHz)	2.45	2.46
Return loss (dB)	-30.6	-12.6
Bandwidth(MHz)	100	80
Directivity (dBi)	7.0	7.59
Gain (dBi)	4.64	4.44
Efficiency (%)	58	48.4
SAR (W/Kg)	-	1gram: 0.266 10grams: 0.113

5. CONCLUSION

This paper proposed a wearable microstrip patch antenna at 2.4GHz ISM band. For flexibility purposes, PDMS and Zelt have been proposed in the design. The overall dimension of the antenna is 90 x 71 x 2.5 mm^3 (Ws x Ls x hs). The proposed antenna was designed and analysed in CST Microwave software. The antenna has a gain of 4.64dB, bandwidth of 100MHz and radiation efficiency of 58%. The antenna was also analysed near the human body phantom and the results show the decrease in gain and efficiency due to the conductivity of the human body. The SAR values for both 1gram and 10grams standards are both below the threshold limits (0.266W/kg for 1gram and 0.113W/kg for 10grams). The proposed antenna can be used in many wearable electronic devices operating at 2.4GHz ISM band.

REFERENCE

[1] K. N. Lal and A. K. Singh, "Modified design of microstrip patch antenna for WiMAX communication system," *Proceedings of the 2014 IEEE Students Technology Symposium*, 2014.

[2] C. A. Balanis, *Antenna Theory - Analysis and Design (3rd Edition)*. John Wiley & Sons.

[3] Adamu, S. A., Masri, T., Abidin, W. Z., Ping, K. H., & Babale, S. A. (2018). High gain modified antipodal vivaldi antenna for ultra-wideband applications. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, vol. *10 no.*1-12, pp55-59, 2018.

[4] "Analysis of Different Performance Parameters of ..." [Online]. Available: https://www.ripublication.com/awmc17/awmcv10n4_21.pdf. [Accessed: 22-Jan-2020].

[5] K. Mondal, K. Pandey, S. K. Singh, and T. Pal, "Effect of feeding locations on bandwidth, gain and resonance frequency of the patch antenna," *2015 International Conference on Microwave and Photonics (ICMAP)*, 2015.

[6] P. K. Mishra, V. Sachdeva, D. Sharma, and S. D. Gupta, "Multiband Microstrip Antenna for 4G Mobile Application," *2015 Fifth International Conference on Communication Systems and Network Technologies*, 2015.

[7] G. Gao, S. Wang, R. Zhang, C. Yang, and B. Hu, "Flexible EBG-backed PIFA based on conductive textile and PDMS for wearable applications," *Microwave and Optical Technology Letters*, vol. 62, no. 4, pp. 1733–1741, 2019.

[8] V. Kumar and B. Gupta, "On-body measurements of SS-UWB patch antenna for WBAN applications," *AEU - International Journal of Electronics and Communications*, vol. 70, no. 5, pp. 668–675, 2016.

[9] U. Ali, S. Ullah, J. Khan, M. Shafi, B. Kamal, A. Basir, J. A. Flint, and R. D. Seager, "Design and SAR Analysis of Wearable Antenna on Various Parts of Human Body, Using Conventional and Artificial Ground Planes," *Journal of Electrical Engineering and Technology*, vol. 12, no. 1, pp. 317–328, 2017.

[10] S. A. Babale, S. K. A. Rahim, K. N. Paracha, and S. I. Orakwue, "3 dB Branch-Line Coupler with Improved Bandwidth Using PDMS and Zoflex Conductor," *Advanced Science Letters*, Vol. 23, no 11, pp11378-11381, 2017.

[11] G.-P. Gao, B. Hu, S.-F. Wang, and C. Yang, "Wearable Circular Ring Slot Antenna With EBG Structure for Wireless Body Area Network," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 3, pp. 434–437, 2018.

[12] S. K. Mishra, S. Shukla, and V. Mishra, "Design of dual band textile antenna for ISM bands using fractal geometry," *2015 International Conference on Signal Processing and Communication (ICSC)*, 2015.

[13] S. Sankaralingam and B. Gupta, "Use Of Electro-Textiles For Development Of Wibro Antennas," *Progress In Electromagnetics Research C*, vol. 16, pp. 183–193, 2010.

[14] S. Sankaralingam, S. Dhar, B. Gupta, L. Osman, K. Zeouga, and A. Gharsallah, "Performance of Electro-Textile Wearable Circular Patch Antennas in the Vicinity of Human Body at 2.45 GHz," *Procedia Engineering*, vol. 64, pp. 179–184, 2013.

[15] M. M. U. Rashid, A. K. Sarkar, L. C. Paul, A. Bouazizi, R. Sen, and B. Podder, "An investigation of SAR inside human heart for antenna directivity, surface current variations and effect on antenna frequency in presence of heart," *2016 2nd International Conference on Electrical, Computer & Telecommunication Engineering (ICECTE)*, 2016.

[16] S. I. Kwak, D.-U. Sim, and J. H. Kwon, "SAR reduction on a mobile phone antenna using the EBG structures," *2008 38th European Microwave Conference*, 2008.

[17] W. U. R. Khan, S. M. Umar, F. Ahmad, and S. Ullah, "Specific Absorption Rate Analysis of a WLAN antenna using Slotted I-type electromagnetic bandgap (EBG) structure," *2016 International Conference on Intelligent Systems Engineering (ICISE)*, 2016.

[18] A. Afridi, S. Ullah, S. Khan, A. Ahmed, A. H. Khalil, and M. A. Tarar, "Design of Dual Band Wearable Antenna Using Metamaterials," *Journal of Microwave Power and Electromagnetic Energy*, vol. 47, no. 2, pp. 126–137, 2013.

[19] S. Zhu and R. Langley, "Dual-Band wearable TEXTILE antenna on An EBG Substrate," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 926–935, 2009.