Defence Science Journal, Vol. 74, No. 4, July 2024, pp. 546-551, DOI : 10.14429/dsj.74.19018

Elliptical Multi-Orbital Truncated Flexible Patch Antenna Using PDMS Substrate for Sub-6 GHz Applications

Tilakdhari Singh[#,*], Pooja Sharma[#], Shivesh Tripathi[$] and Vijay Shanker Tripathi[#]

[#]Motilal Nehru National Institute of Technology Allahabad, Prayagraj - 211 004, India
[$]G.L. Bajaj Institute of Technology and Management, Greater Noida - 201 306, India
[*]E-mail: tilakdhari.2020rel08@mnnit.ac.in

ABSTRACT

This paper presents an elliptical-shaped multi-orbital truncated patch antenna applicable forsub-6 GHz bands. The sub-6 GHz bands cover 5.8 GHz high-speed wireless communication. The antenna is designed on a Poly Dimethylsiloxane (PDMS) substrate. PDMS is used for designing the proposed antenna. It is a flexible substrate with a dielectric constant εr value of 2.7 and a loss tangent tan δ value of 0.022. The substrate dimension is 20×15×1.6 mm3in which a patch is created with the size of 12.5×13 mm2. The proposed antenna resonates at 6.2 GHz showing a reflection coefficient (s11) value of -37 dB. The impedance bandwidth of the antenna is 1.225 GHz in the range of 5.5-6.725 GHz frequency, and the maximum peak gain is about 3.5 dB. The proposed antenna is simulated, fabricated, and experimentally tested.

Keywords: Flexible antenna; PDMS substrate; Bandwidth; Polarization; Wideband; Wearable military WBAN

1. INTRODUCTION

In recent years, Wireless Body Area Network (WBAN) has shown a growing interest and huge demand for research in the field of military applications for remote health monitoring of vital signs, faster rescue operations, and remote data telemetry services[1]. When WBAN is used for on-body communication, it requires low-profile and compact-size antennas having monopole radiation characteristics in the near field of the body surface[2]. Military personnel require a large number of sensors and electronic equipment to be integrated with their suites. So, there is a need for flexible, lightweight electronics and antennas in WBAN that can be easily integrated with their suite[3,19].

Flexible antennas are becoming very popular in the market of making wearable devices for military personnel suites. Current trends in flexible and wearable electronics have boosted the development of miniaturized and flexible materials. With the advancement and high demand for flexible electronics and antennas, the researcher is inspired to explore new innovative flexible materials to provide unique characteristics as flexible substrates[4].

In the literature, various antennas are discussed. Most of the antennas in the literature are developed with the help of flexible substrates. Even those aforementioned antennas have to face some limitations because of the properties of substrate materials. For example, a fabric substrate is currently becoming more popular in making flexible antenna design. But such substrate is sensitive to environmental effects. In fact, the radiation characteristics change sharply with temperature variation, moisture absorption, etc. Polymers have attracted a high demand as substrate materials for developing flexible antennas. Polymers have numerous advantages over rigid and fabric substrates. The polymers show unique characteristics of flexibility and stretch ability. It also shows the ability for performing in conformal conditions. Polymers have become a point of attraction for antenna design due to their low level of dielectric losses, high thermal conductivity, and high transition temperature.

Some of the most commercially used polymer substrates in the market are Polyamide (PI), Liquid Crystal Polymers (LCP), composite laminate, and rubber-based composite. These polymers provide antenna designs having poor flexibility. The performance of these antennas is also altered at high temperatures[5]. Hence, researchers are looking for other suitable materials. In such situations, silicon-based PDMS as a substrate can be considered a good choice for designing flexible antennas[6]. PDMS is a type of silicon polymer[7]. For the preparation of PDMS, the base of silicon elastomer can be mixed with an agent of silicon curing in the ratio of 10:1.[8] It has all desirable properties including transparency, flexibility, resistance properties against water, thermal stability, isotropic nature, and characteristics of homogeneity confirming its usability for flexible antenna substrate[9]. Nowadays PDMS is used for various specific purposes with an example of thin membranes as well as a hydrophobic coating for antenna design, sensors, and microchips. By changing the dielectric constant of PDMS, researchers have achieved advanced characteristics of antenna parameters[10]. Poly Dimethylsiloxane (PDMS) can be prepared for a particular specification in the lab for antenna designs, sensor designs, etc.

The proposed antenna is designed for sub 6GHz applications to cover 5.8 GHz high-speed Wi-max and WBAN

Received : 31 March 2023, Revised : 20 January 2024
Accepted : 30 January 2024, Online published : 24 July 2024

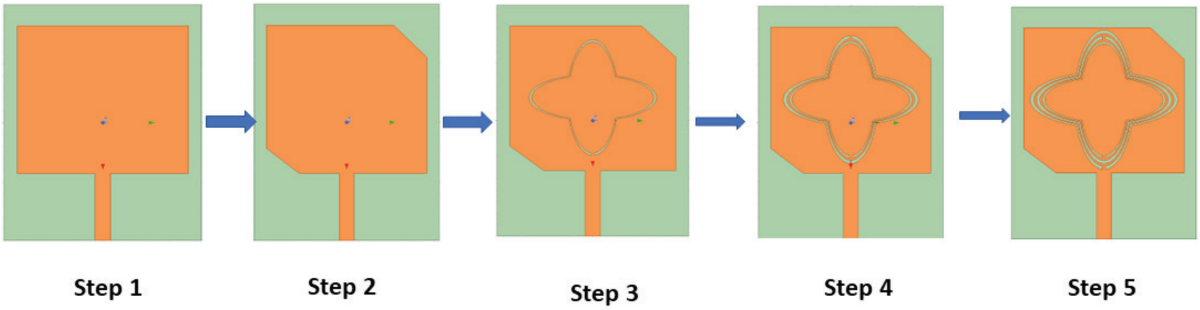

Figure 1. Design step for desired antenna.

applications[11]. In the next section its design steps, specification, simulated and measured results, comparison with other existing works, and conclusion are explained respectively.

2. ANTENNA DESIGN AND SPECIFICATION

2.1 Antenna Design

Antenna design starts with the design of a simple microstrip patch antenna as shown in step 1which is considered a parallel combination of resistance (R), capacitance (C), and inductance (L). If the dimension of a rectangular patch is assumed as length (L_p), width (W_p), and substrate height h then[12]

$$R = \frac{Qr}{\omega c}$$

$$L = 1/(\omega^2 C), \ \omega = 2\pi f_r$$

$$C = \frac{\varepsilon_0 \varepsilon_{eff}}{2h} L_p W_p \cos^{-2}\left(\frac{\pi d}{L_p}\right)$$

$$Qr = \frac{c\sqrt{\varepsilon_{eff}}}{4 f h}$$

For $\frac{Wp}{h} > 1$,

$$e_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W_p}\right]^{-1/2}$$

Here, c is the velocity of light, f_r is the resonance frequency, Qr is the radiation quality factor, $and\ \varepsilon_{eff}$ is the effective permittivity of the medium.

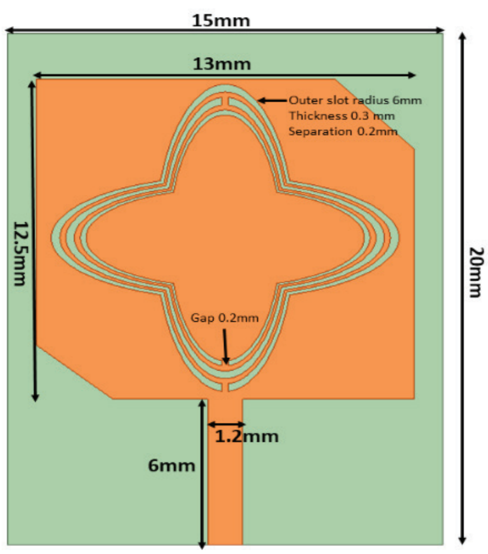

Figure 2. Dimension of final antenna design.

He designed antenna in step 5 is the final design which is an elliptical-shaped multi-orbital truncated patch antenna. The antenna is designed on a PDMS based flexible substrate having ε_r value of 2.7 and tan δ value of 0.022 as shown in Fig. 2. The size of the substrate is 20×15 mm^2, the upper side of the substrate has a patch of the size 12.5 ×13 mm^2 and on the bottom side, the ground plane is made with equal size to the substrate. The opposite corner of the patch is truncated with a length of 4 mm having three orbital-shaped slot perpendicular to each other to form a complementary split ring resonator. The radius of an outer ellipse is 6 mm with a thickness of 0.3 mm. The separation between two ellipses is about 0.2 mm, and the ratio of the major to minor axis is 1:0.4 to form an ellipse.

The gap is about 0.2 mm in the ellipse to form a split ring resonator. Microstrip feed line has a size of 6×1.2 mm^2. The designed antenna has a miniaturized shape of 20×15×1.6 mm^3.

2.2 Parametric Analysis of Designed Antenna

The parametric study of the proposed antenna from a regular patch antenna to achieve the final design has been shown in Fig. 3. The regular shape rectangular micro strip patch antenna is shown in step 1. The reflection coefficient of step 1 is shown in Fig. 3. Step 1 has narrow bandwidth at a higher frequency obtained from regular mathematical analysis in Eqn.[1-5]. Our motto is to obtain 6 GHz bands with higher bandwidth for sub 6 GHz bands applications. Hence, there is a need for changes in frequency to the lower side with increasing the bandwidth.

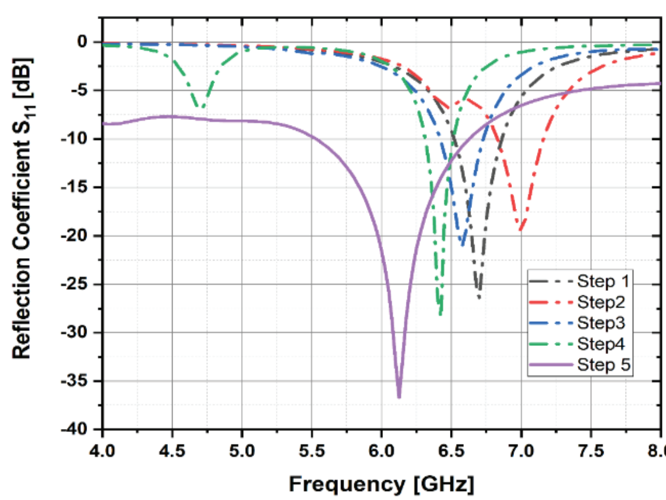

Figure 3. Parametric analysis of different development stages of antenna design.

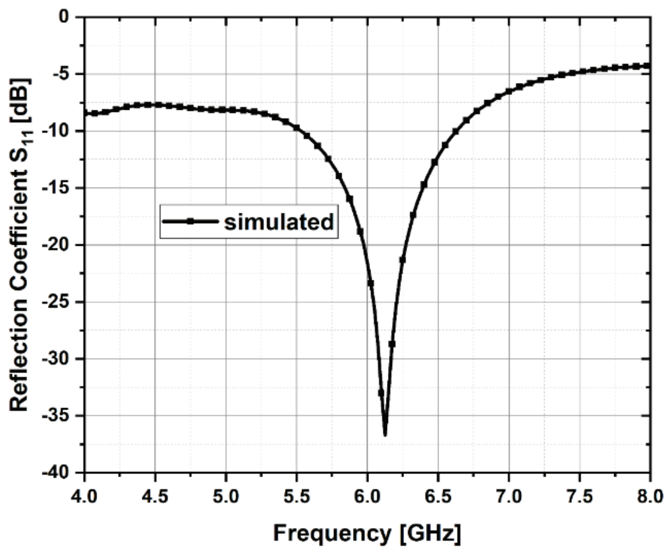

Figure 4. S_{11} versus frequency graph for the proposed antenna.

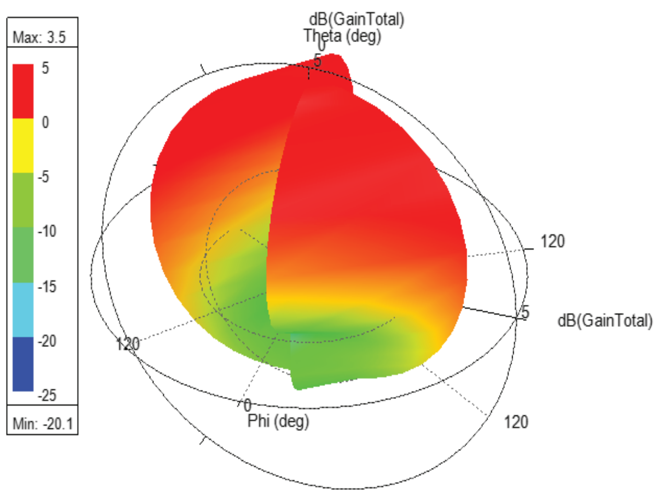

Figure 5. 3D polar plot of peak gain [dB] of the proposed antenna.

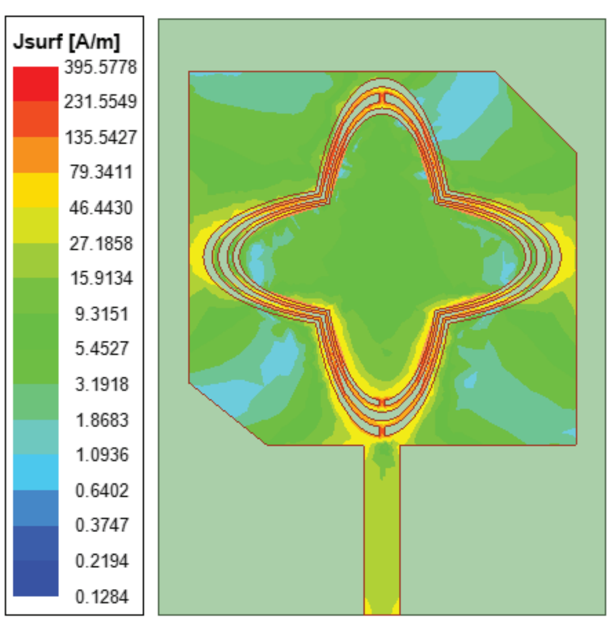

Figure 6. Current distribution of the designed antenna.

Step 2 design has a truncated structure at the opposite corner of the patch, the additional truncated structure provides little improvement in bandwidth but at a higher frequency. The parametric analysis has been done for various lengths of truncation but it has achieved a better shape for increased bandwidth at a 4 mm length. Slots cut in the patch provide extra electrical length to change frequency and additional capacitive and inductive effects to change the bandwidth which is shown in step 3. Step 3 results in a lower shift of frequency but it has no major effect on bandwidth. To increase the bandwidth and change the resonance frequency split ring resonator structure has been developed in step 4. Step 5 has developed as the final antenna design to resonate at 6 GHz with increased bandwidth. The step-wise analysis of the reflection coefficient is shown in Fig. 3.

3. RESULTS & DISCUSSION

3.1 Simulated Results

ANSYSHFSS simulation software ver. 2021R1 is used in simulation of proposed antenna. The reflection coefficient S_{11} is

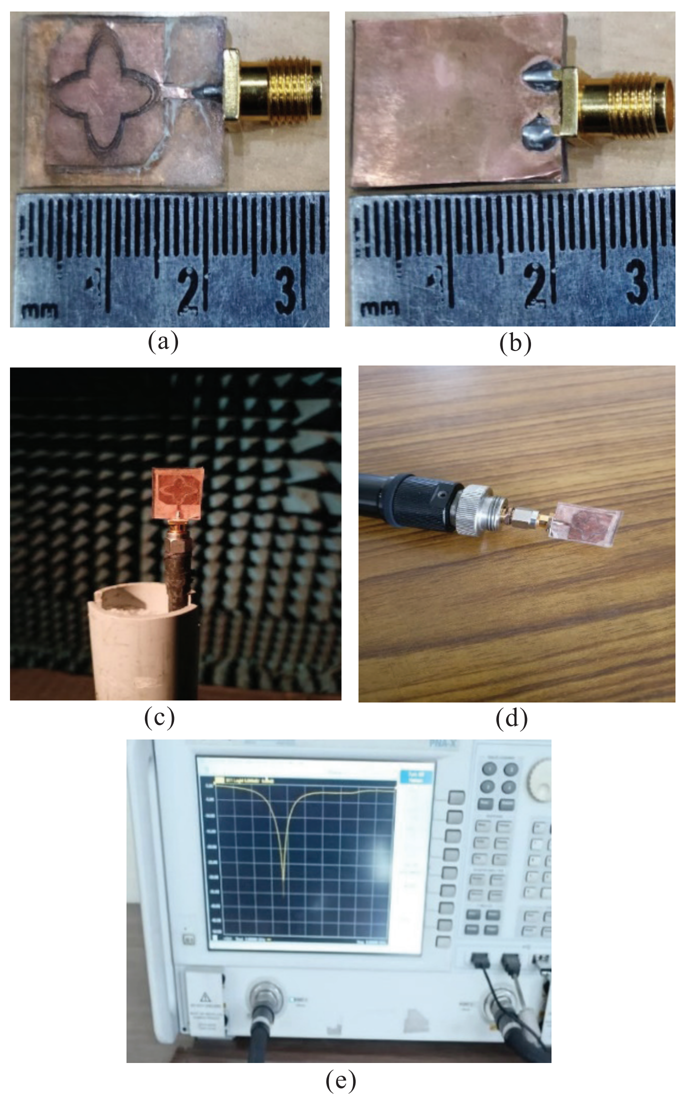

Figure 7. Fabricated antenna: (a) Front side, (b) Opposite side, (c) Antenna under test in an anechoic chamber, (d) Antenna connected to probe with VNA, and (e) Vector Network Analyzer (VNA).

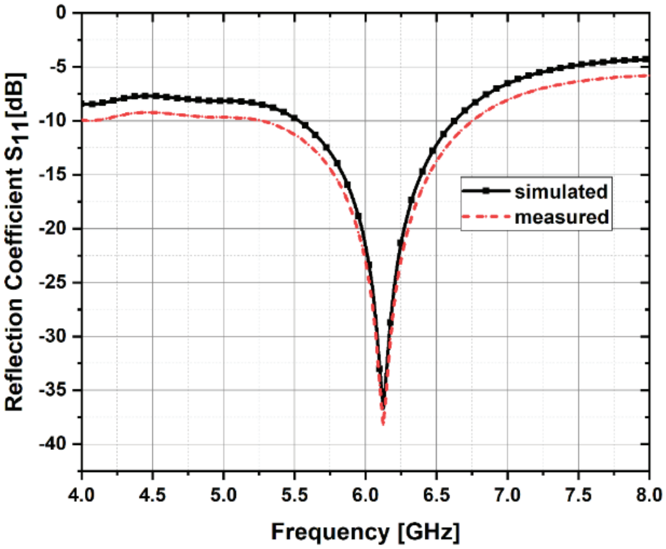

Figure 8. Comparison of simulated and measured results for reflection coefficient S_{11}.

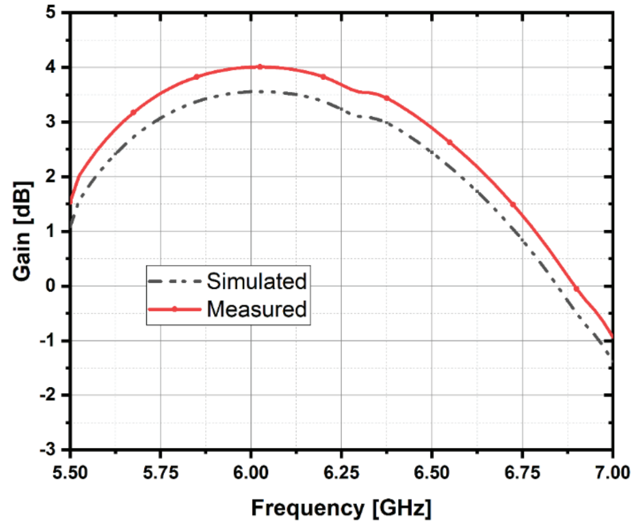

Figure 9. Comparison of simulated and measured peak gain of fabricated antenna.

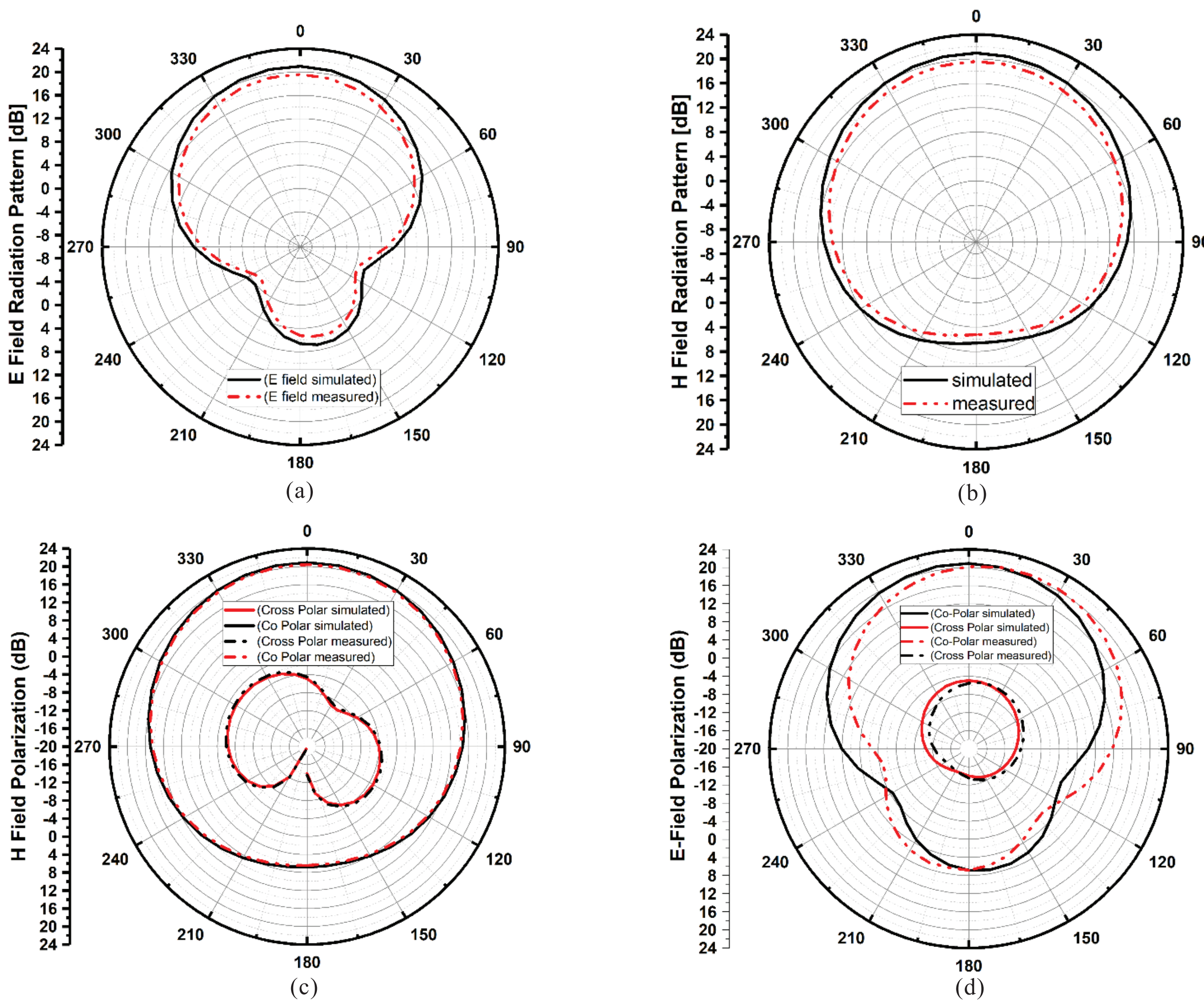

Figure 10. (a) Graph of E-field radiation pattern for measurement and simulation; (b) Graph of H-field radiation pattern for measurement and simulation; (c) Co and Cross polarization of H-field for measurement and simulation results and (d) Co and Cross polarization of E-field for measurement and simulation results.

Table1. Comparison table of the proposed antenna with existing standard work

References	Substrate flexible	Dimensions mm^3	Resonance frequency [GHz]	Bandwidth (MHz)	Gain (dB)
[13]	Kapton polyimide	70×70×0.11	3.4	470	2.1
[14]	Rogers 5880	39×39×0.508	2.45	220	2
[15]	PDMS	50×40×2	5	---	3.2
[16]	Textile	200×200×50	5.8	242	3.66
[17]	LCP	38×32×0.1	5.8	---	---
[18]	PDMS	50×40×1	5.8	640	4.2
Proposed antenna	PDMS	20×15×1.6	6.2	1225	3.5

shown in Fig. 4. In Fig. 4, the reflection coefficient (S_{11}) is -37 dB at a particular resonant frequency of 6.2 GHz. The achieved impedance bandwidth for resonant frequency is about 1.225 GHz in the range of 5.5-6.725 GHz. The impedance bandwidth is calculated at a -10 dB reference line.

In Fig. 5, a 3D polar plot of the antenna has been shown. The proposed antenna hasa maximum gain of approximately 3.5 dB. Figure 6 shows the surface current distribution for the designed antenna. In the figure, the maximum current is observed distributed at the boundaries of the elliptical-shaped slot. The value of maximum current is found to be 395.5 A/m.

3.2 Fabrication and Measured Results

Figure 7 shows the fabricated antenna along withthe measurement setup in the presence of the Vector Network Analyzer (VNA) model Agilent N 5247A. The fabricated antenna is tested under an anechoic chamber to avoid environmental fluctuations. Figure (a) and (b) shows the front and the opposite side of the fabricated antenna. Figure (c) shows the testing of an antenna in an anechoic chamber, in figures (d) and (e) antenna connection with probe and VNA has been shown. Figure 8 shows the comparison of simulated results with measured ones.

Measured results have good matching with the results of simulated ones. Measured results show additional bandwidth of 250 MHz in comparison to simulated results. There is little variation in the reflection coefficient of simulated as well as in measured results.

In Fig. 9, a comparison of simulated and measured peak gain has been shown. Measured gain has some variation to simulated peak gain. The measured gain has achieved a maximum value of 4 dB at 6 GHz frequency. The plot of gain has a positive value in the range of frequency 5.5 to 6.75 GHz.

Figure 10 explains about radiation pattern and level of cross-polarization for the designed antenna. In Fig. 10(a) graph of the E-field radiation pattern for measurement and simulation results has been shown. From the figure, it is observed it has a good agreement between simulation results along with measured radiation patterns in which radiation occurs unidirectionally at a plane having phi equal to zero degrees. Maximum radiation occurs at theta equal to zero degrees. Figure 10(b) shows a comparison of simulation results with measured radiation patterns for the H-field at a plane having phi equal to 90°. H field also radiates maximum at theta equals to 0°. Figure 10(c) shows a comparison of measured results with simulated results for H field Co and cross-polarization. From Fig. 10(c) it is clear that there is approx. 28 dB difference between Co and cross-polarization level. It has observed a good agreement between simulation results with measured results. Figure 10(d) reveals the comparison of simulated results with measured results for E-field Co and cross-polarization. From Fig. 10(d), it is clear that the level of cross-polarization is approx. 28 dB lower than the Co-polarization level.

4. COMPARISON

The table of comparison for the proposed antenna with existing standard work has been shown in Table 1.

Based on a comparison table with other existing work in Table 1, it is found that the designed antenna is compact having better performance in terms of bandwidth and gain in comparison to other work.

5. CONCLUSION

An elliptical-shaped multi-orbital truncated patch antenna has been introduced in this paper. The proposed antenna is applicable for sub-6 GHz bands. Sub 6 GHz bands are widely known and acceptable for high-speed Wi-max, and WBAN applications. The resonance frequency of the antenna is 6.2 GHz. It is designed on the flexible PDMS substrate with a compact size of 20×15×1.6 mm^3. The proposed antenna is simulated as well as fabricated and experimentally tested by using a vector network analyzer (VNA)Agilent N 5247A in an anechoic chamber. The measured results indicate a maximum gain of 4 dB with an impedance bandwidth of 1.5 GHz from the frequency 5.25 GHz to 6.75 GHz.

REFERENCES

1. Chaturvedi, D. & Raghavan, S. A triangular shaped quarter-mode substrate integrated waveguide based antenna for WBAN applications. *Def. Sci. J.,* 2018*,* **68**(2), 190-196. doi:10.14429/dsj.68.11833.
2. Kang, D.G.; Tak, J. & Choi, J. Low-profile dipole antenna with parasitic elements for WBAN applications. *Microw. Opt. Technol. Lett.,* 2016*,* **58**(5), 1093-97. doi: 10.1002/mop.29749.
3. Sharma P.K. & Gupta N. A CPW-fed circular SRR-inspired flexible antenna using Polydimethylsiloxane (PDMS) substrate for WLAN and WBAN applications. *IEEE J. Flex. Elect.*, 2022, **1**(1), 39-46. doi: 10.1109/JFLEX.2022.3153240.

4. Abbasi, Q.H.; Rehman, M.U.; Yang, X.; Alomainy, A.; Qaraqe, K. & Serpedin, E. Ultra wideband band-notched flexible antenna for wearable applications. *IEEE Ante. Wire. Propag. Lett*., 2013, **12**, 1606–1609. doi:10.1109/LAWP. 2013. 2294 -214.
5. Al-Sehemi, A.; Al-Ghamdi, A.; Dishovsky, N.; Atanasova, G. & Atanasov, N. Flexible polymer/fabric fractal monopole antenna for wideband applications. *IET Microw., Antennas Propag*., 2021, **15**(1), 80–92. doi: 10.1049/mia2.12016.
6. Bakar, A.A.; Hasnan, F.; Razali, A.R.; Rahim, A.F.A.; Osman, M.S.; Ali, T. & Radzali, R. Polydimethylsiloxane as a potential antenna substrate. *Acta Phys. Polonica A*, 2019, **135**(5), 938–941. doi: 10.12693/APhysPolA.135.938.
7. Abbas, S.M.; Desai, S.C.; Esselle, K.P.; Volakis, J.L. & Hashmi, R.M. Design and characterization of a flexible wideband antenna using polydimethylsiloxane composite substrate. *Int. J. Antennas Propag.*, 2018, 1–6. doi: 10.1155/2018/4095765.
8. Li, N. Design and investigation on wideband antenna based on polydimethylsiloxane (PDMS) for medical imaging application. *Przegl¸ad Elektrotechniczny*, 2020, **1**(3), 91–94. doi:10.15199/48.2020.03.21.
9. Sharma, P.K.; Gupta, N. & Dankov, P.I. Characterization of polydimethylsiloxane (PDMS) as a wearable antenna substrate using resonance and planar structure methods. *AEU Int. J. Electron. Commun*., 2020, 127. doi: 10.1016/j.aeue.2020.153455.
10. Sharma, P.K.; Gupta, N. & Dankov, P.I. Analysis of dielectric properties of polydimethylsiloxane (PDMS) as a flexible substrate for sensors and antenna applications. *IEEE Sensors J*., 2021, **21**(17), 19492–19504. doi: 10.1109/JSEN.2021.3089827.
11. Qas Elias, B.B.; Soh, P.J.; Al-Hadi, A.A. & Vandenbosch, G.A.E. Design of a compact, wideband, and flexible rhombic antenna using CMA for WBAN/WLAN and 5G applications. *Int. J. Numer. Model., Electron. Netw., Devices Fields*, 2021, **34**(5). doi: 10.1002/jnm.2841.
12. Dhanabalan, S.S.; Sitharthan, R.; Karthikeyan, M.; Thirumurugan, A.; Rajesh, M.; Avaninathan, S.R. & Carrasco, M.F. Flexible compact system for wearable health monitoring applications. *Comp. Electri. Eng.*, 2022, **102**. doi: 10.1016/j.compeleceng.2022.108130.
13. Ahmed, S.F.; Tahir, A; Shamim, A. & Cheema, H.M. A compact kapton-based inkjet-printed multiband antenna for flexible wireless devices. *IEEE Ant. Wire. Propa. Lett.,* 2015*,* **14**, 1802-1805. doi: 10.1109/LAWP.2015.2424681.
14. Arif, A; Zubair, M.; Ali, M.; Khan, M.U. & Mehmood, M.Q. A compact, low-profile fractal antenna for wearable on-body WBAN applications. *IEEE Ante. Wire. Prop. Lett.*, 2019, **18**(5), 981-985. doi: 10.1109/LAWP.2019.2906829.
15. Elmobarak Elobaid, H. Abdul Rahim, A.S.K; Himdi, M. Castel, X. & Abedian Kasgari, M. A transparent and flexible polymer-fabric tissue UWB antenna for future wireless networks. *IEEE Ante. Wire. Propa. Lett.*, 2017, **16**, 1333-1336. doi: 10.1109/LAWP.2016. 2633790.
16. Simorangkir, R.B.V.B.; Yang, Y.; Matekovits, L. & Esselle, K.P. Dual-band dual-mode textile antenna on PDMS substrate for body-centric communications. *IEEE Ant. Wire. Propag. Lett.*, 2016, **16**, 677-680. doi: 10.1109/LAWP.2016.2598729.
17. Rao, Venkateswara Manikonda. Circularly polarized flexible antenna on liquid crystal polymer substrate material with meta material loading. *Micro. and Opti. Techn. Letters,* 2020*,* **62**(2), 866-874.
18. Sharma, P.K. & Gupta. N. A CPW-fed circular SRR-inspired flexible antenna using Polydimethylsiloxane (PDMS) substrate for WLAN and WBAN applications. *IEEE J. Fle. Elec.*, 2022, **1**(1), 39-46. doi: 10.1109/JFLEX.2022.3153240.
19. Dalal, P; Rafique, Abbas, U.S.M.N.C: Pradhan, S. & Karthikeyan, S. Dual-band wearable antenna for wireless body area networks on a flexible substrate. *In* IEEE Wireless Antenna and Microwave Symposium (WAMS), Rourkela, India, 2022, pp. 1-5, doi: 10.1109/WAMS54719.2022.9944978.

CONTRIBUTORS

Mr Tilakdhari Singh is pursuing PhD from MNNIT Allahabad in Department of Electronics and Communication Engineering. His research interests include: Flexible microwave sensors for health monitoring applications.
In this paper, he has contributed simulation and fabrication of a novel design of an antenna for sub 6 GHz applications along with simulated and measured results analysis.

Ms Pooja Sharma obtained her MTech in Electronics Engineering from Sundardeep Engineering college, Ghaziabad, India. Her research interests include: Wearable antenna for MIOT applications. In the present paper, she has contributed to the introduction part of the literature survey on wearable antenna.

Dr Shivesh Tripathi is currently working as an Associate Professor in the Department of Electronics and Communication Engineering, G. L. Bajaj Institute of Technology and Management, Greater Noida, India. He obtained his PhD from IIT, Roorkee, India. His current areas of research are Reconfigurable multiband and multifunctional radio-frequency integrated circuits, active and passive RF/Microwave/Millimetre waves circuits.
In this paper, he has contributed to the measurement part of the antenna design in current research article.

Mr Vijay Shanker Tripathi is currently Professor in Department of Electronics and Communication Engineering, Motilal Nehru National Institute of Technology Allahabad, Prayagraj. His research interests include: RF circuits and systems, Antenna, SDR and non-invasive RF sensors.
In this paper, he has contributed technical inputs and improved the grammar part of this research article.