Progress In Electromagnetics Research C, Vol. 122, 165–181, 2022

An Metamaterial Inspired Antenna with CSRR and Rectangular SRR Based Flexible Antenna with Jeans Gap Filled for Wireless Body Area Network

Siddhant Goswami* and Deepak C. Karia

Abstract—In this paper, a flexible compact Jeans gap filled metamaterial inspired antenna is proposed to operate at 2.4 GHz in the Industrial Scientific and Medical (ISM) band. This designed antenna is flexible having size of about $27 \times 23\,\text{mm}^2$ with substrate of thickness 0.3 mm. The proposed antenna comprises two complementary split ring resonators at ground plane and one circular ring and complementary rectangular split ring resonator. The top patch consists of two rectangular split ring resonators etched inside the rectangular patch. The use of SRR and CSRR on top and bottom of patch has helped to reduce the size of antenna along with maintaining performance of antenna. Further enhancements are done to make it jeans gap filled antenna with jeans filled between main patch and superstrate. The superstrate top patch consists of a square EBG structure. The simulation results have shown an increase in return loss due to the use of square EBG structure on superstrate. The simulated directivity obtained on antenna is 2.0775 dB. The measured and simulated results are in a good agreement. The motivation of this work is to design a compact metamaterial based antenna for wireless body area network with gap coupled jeans material to nullify effects of human body. Effects of air gap coupled and jeans gap coupled are analyzed in terms of performance. While the final antenna (Antenna-4) is designed, several iterations are tried to optimize and maintain good performance. Step 1 (Antenna-1) consists of two complementary split ring resonators along with a circular ring placed in ground plane with thickness of polyamide substrate as 0.3 mm. Step 2 (Antenna-2) consists of two split ring resonators along with a circular ring placed in ground plane. An air gap coupled superstrate is designed having gap between main patch and superstrate as 1 mm. Step 3 (Antenna-3) has the same configuration as Antenna-2, and the only difference is the air gap between main patch and superstrate which is replaced by jeans material. Step 4 (Antenna-4) is the final designed antenna with miniaturized size of $27 \times 23\,\text{mm}^2$ as compared with previous antenna configurations. This research work has identified the challenges involved for designing an antenna in a wireless body area network. Practical aspect of design needs to consider: a) Bending effect on performance as movement and physiological changes might affect the performance. b) Performance degrades when antenna comes in contact with human body. Bending Effect: This work has also analyzed the effect of bending on return loss. For the final designed antenna (Antenna-4), maximum bending up to bend 30° is possible. Further bending would break the substrate. After maximum bending, the measured return loss is about −16.7071 dB at 2.28 GHz. Body area network: The designed final antenna (Antenna-4) is tested on different parts of human body such as human-arm and leg. No major difference is seen on return loss when it is tested on different parts of body. The designed final antenna (Antenna-4) is tested on direct contact with human-arm as well as with different cloths (cotton jeans, cotton, curtain cloth, floor cloth, polyester and Turkish cloth) having different permittivities with the distance between cloth and antenna as 0 cm and 1 cm. Wearable antennas should be carefully constructed to avoid causing harm to the human body when being worn. The Low Specific Absorption Rate is one of the criteria that should be considered while developing a wearable antenna. The maximum allowable SAR limit is 1.6 W/kg. The specific absorption rate for Antenna-4 is 0.2 W/kg when input power is 1 watt and is 0.036 W/kg when input power is 100 milli watt.

Received 2 February 2022, Accepted 17 June 2022, Scheduled 9 August 2022

* Corresponding author: Siddhant Goswami (siddhantgoswami23@gmail.com).
The authors are with the Sardar Patel Institute Of Technology, Mumbai, India.

The results obtained show that the proposed antenna is both safe and acceptable for use in compliance with the World Health Organization's ICNIRP requirements.

1. INTRODUCTION

Wireless Body Area Network in brief:

WBAN offers potential of improvement in both medical and non-medical fields. In medical fields, WBAN technology can be used to monitor patient health, measuring changes in patient vital signs, and also medical applications including rehabilitation after surgeries. It allows distant doctors to have real time opinions in diagnosis (remote health patient monitoring system) and tracking human movement in home based rehabilitation scheme. This has been used in placing sensors inside body (Implantable) or on body or around body. Wearable antenna technology is mostly used for heart rate monitoring, temperature monitoring, respiration rate monitoring, mobile communication, and military applications. A significant interest is seen for flexible/semi-flexible devices to be worn for biomedical telemetry applications. Bio-telemetry is used for remote monitoring of biomedical parameters of patient [1, 2].

In non-medical fields, WBAN is used in entertainment, security (fire-alarm), fitness monitoring applications, monitoring aeroplane pilot's and truck driver's tiredness [3, 4].

The demand for on-body flexible antenna has been increasing with a large requirement in sports (Non-medical field), health-monitoring, and post checkups (Medical field).

In the present market, the key considerations for electronic wearable devices are that they should work in robust environment [5], compact size, low profile [6], flexible in design [7] and should have minimal SAR (Specific Absorption Rate) so as to meet the market needs.

This promising work of designing antenna for wireless body area network has led many researchers to focus on realization of antennas. Several antennas such as planar inverted-F antenna (PIFA) operating at ISM and MICS band [8], cylindrical dielectric resonator antenna for wearable biomedical devices [9], single input single output (SISO), and multiple input and multiple output (MIMO) antennas are proposed in literature [10].

In the literature, several efforts have been carefully made to reduce the size of antenna [4, 11], such as metamaterial SRR [12, 13], metamaterial cpw-fed CSRR, rectangular complementary split ring resonator [14], adding rectangular slots in conventional rectangular patch [2], complementary triangular electromagnetic resonator [15], and complementary split ring resonator [16]. Along with compact size maintaining minimal SAR values is an important factor in designing on body antenna as per ICNIRP (International Commission on Non-Ionizing Radiation Protection) standards of World Health Organization. Literature suggests several methods to reduce SAR as capacitive grating AMC structures [17], using meandering the monopole [18], using electromagnetic bandgap (EBG) structure [19], loading antenna with high impedance surfaces [20], using electro conductive cloth [21], and using metamaterials [22, 23].

The new trend is to support the lives of elderly people remotely. Technology is required to enhance the feeling of protection for old-age assistance, such as breathing issues, routine acts, body temperature, and sleep or limb activity to assist in the spontaneous well-being monitoring. The sensors used in wireless body area network could monitor that the exercises performed are not very hard and ought to be in permitted limits. The wireless communication technology is enhanced due to rapid innovation in antenna technology. As per present demand in information-oriented society, wearable systems requires flexibility to be incorporated in order to provide wireless connectivity operating in specific bands [24–26].

Wearable antennas have been recently studied due to ease of integration and flexibility in design [27]. Flexible textile antennas play a major role in wireless body area network [28, 29].

Due to their flexibility and simplicity of integration with textile materials, flexible textile antennas are attractive candidates for WBAN systems. The integration of antenna with textile material such as jeans, measuring performance on various parts of body, provides the practical aspect to the design.

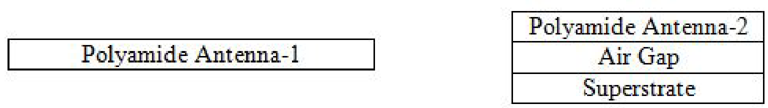
2. CHALLENGES INVOLVED

1. Performance degrades when antenna comes in contact with human body. This body effect on antenna performance should be reduced [30, 31].

2. Bending effect degrades the performance. This degradation should be reduced [2, 32].
3. Current healthcare needs a solution for remote monitoring with good performance.
4. Movement and physiological changes might affect devices that need to be attached to different parts of human body.

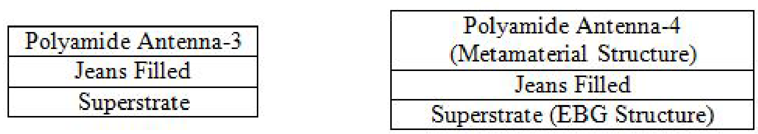
3. ANTENNA DESIGN METHODOLOGY

The configuration of proposed antenna is shown in Fig. 1(a), Fig. 1(b), Fig. 2(a), and Fig. 2(b). Four steps are described to get the final design of antenna (Antenna-4). The results obtained show minimum human body effect on antenna return loss. Further, Antenna-2, Antenna-3, and Antenna-4 are tested on human hand as well as in the vicinity of different cloths.



(a) (b)

Figure 1. (a) Step 1-(Antenna-I Model). (b) Step 2-(Antenna-II Model).



(a) (b)

Figure 2. (a) Step 3-(Antenna-3 Model). (b) Antenna-4 Model.

4. STEPWISE DESIGN ANALYSIS

Several iterations are tried to optimize the antenna and maintain good performance.

4.1. Step 1 (Antenna-1)

In this step, antenna has two complementary split ring resonators along with a circular ring placed in ground plane. A simple rectangular patch is designed on top view as shown in Fig. 3(a) and Fig. 3(b). The fabricated antenna is shown in Fig. 4(a) and Fig. 4(b). The thickness of antenna substrate is 0.3 mm with polyamide material. This designed antenna is flexible and adds a robustness to design.

Table 1 shows the parameter dimensions of Antenna-1. Antenna-1 shows good simulated return loss of −23.4260 dB at 2.4 GHz, and measured return loss is about −20 dB as shown in Fig. 5(a). The measured and simulated results are in good agreement. The VSWR is below 3 in frequency range of 2.4 GHz as shown in Fig. 5(b). The obtained bandwidth of Antenna-1 is 120 MHz as shown in Fig. 5(a). The antenna has directivity of 2.7085 dB, as shown in Fig. 6(a). The impedance of antenna is around 44.43 dB at 2.4 GHz as shown in Fig. 6(b). The radiation patterns in E plane and H plane are shown in Fig. 7(a) and Fig. 7(b).

4.2. Step 2 (Antenna-2)

In this step, the antenna has two split ring resonators along with a circular ring placed in ground plane. An air gap coupled superstrate has been designed. The gap between the main patch and superstrate is 1 mm. The simulated-gap coupled antenna is shown in Fig. 8(a). The fabricated antenna is shown in Fig. 8(b).

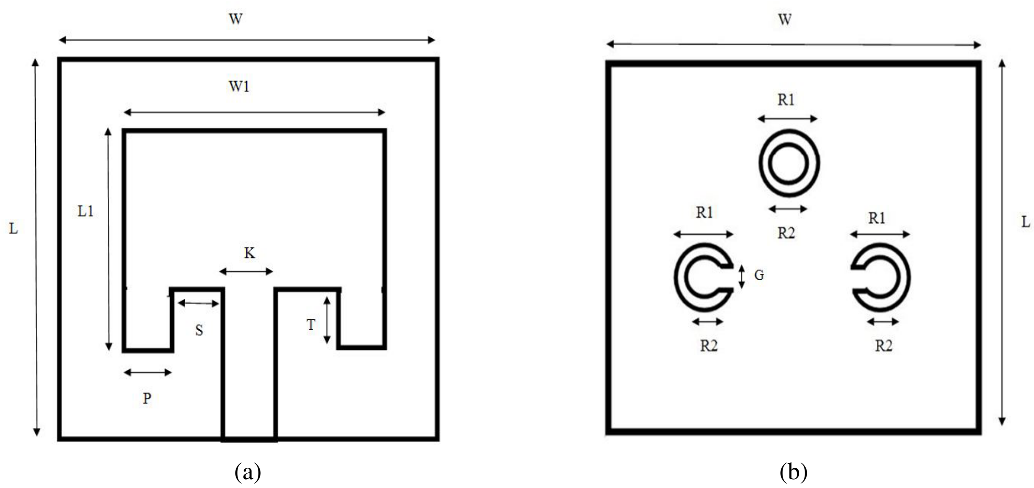


Figure 3. HFSS Model for Antenna-1. (a) Step 1: Top View of Antenna. (b) Step 1: Bottom View of Antenna.

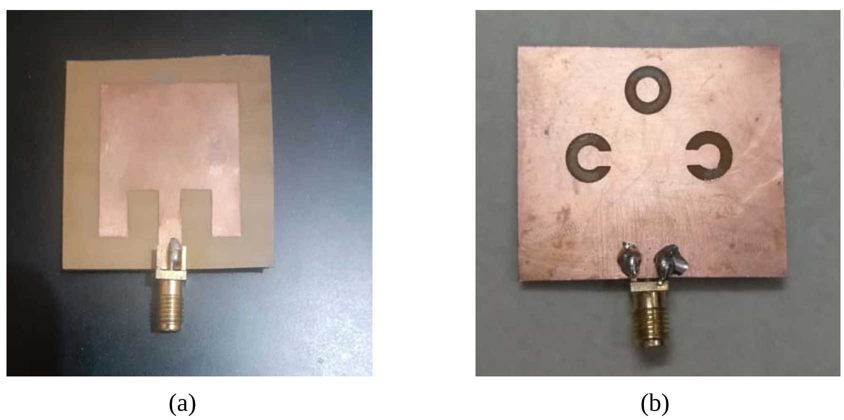


Figure 4. Step 1: (a) Top view of Antenna-1; (b) Bottom view of Antenna-1.

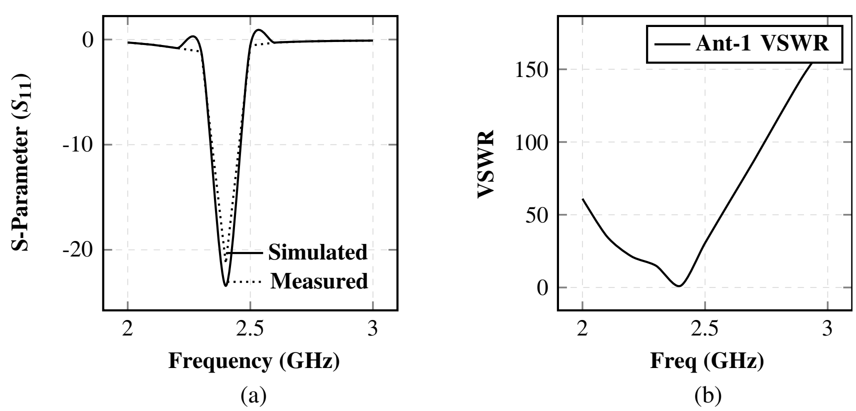


Figure 5. (a) Antenna-1-Measured and simulated return loss. (b) Antenna-1-VSWR.

The measured as well as simulated return loss is shown in Fig. 9(a). Antenna-2 is tested in the vicinity of human hand. It has been observed that the return loss of Antenna-2 has been reduced from −21.42 dB to −10 dB at 2.4 GHz as shown in the red line in Fig. 9(a). Fig. 9(b) shows the VSWR result which is about 1.18. The directivity is 2.8946 dBi as shown in Fig. 10(a). There is slight improvement

Table 1. Dimensions of Antenna-1.

Parameters	Dimensions obtained
W	45 mm
$W1$	30 mm
L	38 mm
$L1$	27 mm
P	6.16 mm
S	6.405 mm
K	4.87 mm
T	7.8 mm
$R1$	14.5 mm
$R2$	2.8 mm
G	2.4 mm

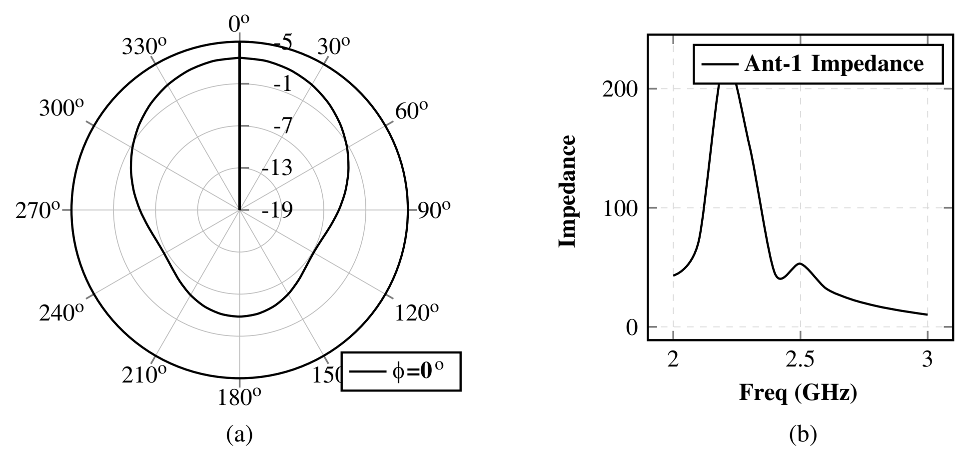


Figure 6. (a) Antenna-1-Directivity. (b) Antenna-I-Impedance.

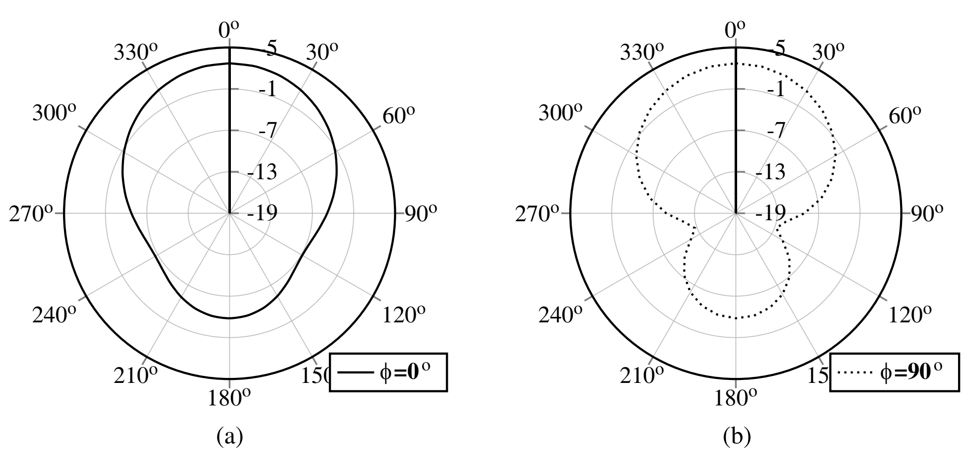
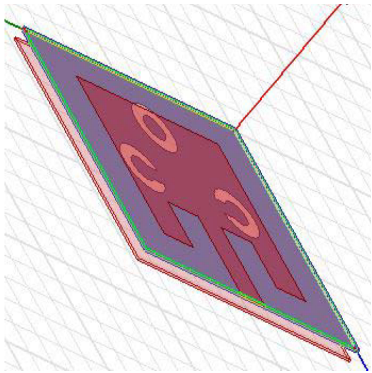


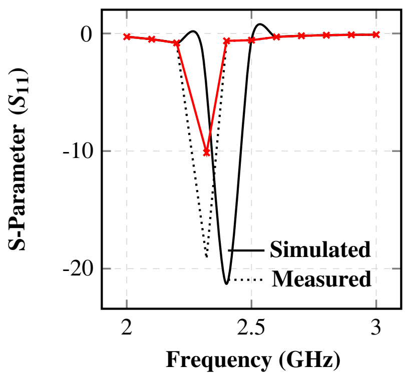
Figure 7. (a) E-Plane Radiation Pattern of Antenna-1. (b) H-Plane Radiation Pattern of Antenna-1.



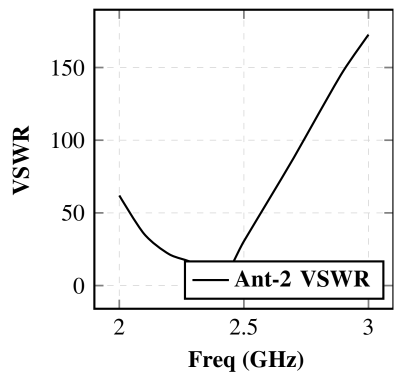
(a)

(b)

Figure 8. Step 2: Air gap coupled Antenna-2. (a) HFSS design Model. (b) Fabricated design Model.

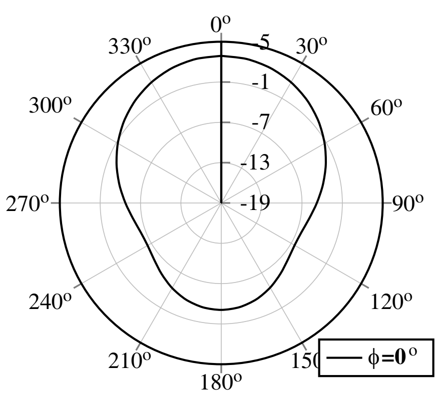


(a)

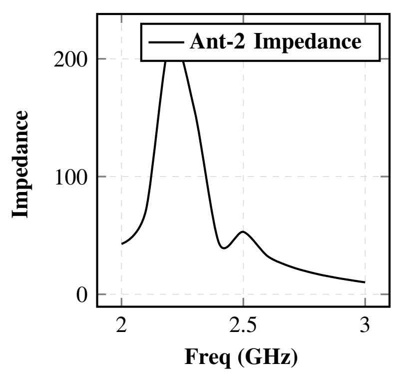


(b)

Figure 9. (a) Antenna-2-Experimental and simulated return loss (Red Line shows on hand measured). (b) Antenna-2-VSWR.



(a)



(b)

Figure 10. (a) Antenna-2-Directivity. (b) Antenna-2-Impedance.

in directivity as compared to Antenna-1 due to the use of air gap coupled model. The designed antenna is flexible, but making it gap coupled reduces its flexibility. The magnitude impedance obtained is 43.48 dB at 2.4 GHz as shown in Fig. 10(b). The antenna performance has been drastically reduced after keeping antenna in the vicinity of human body as shown in Fig. 9(a).

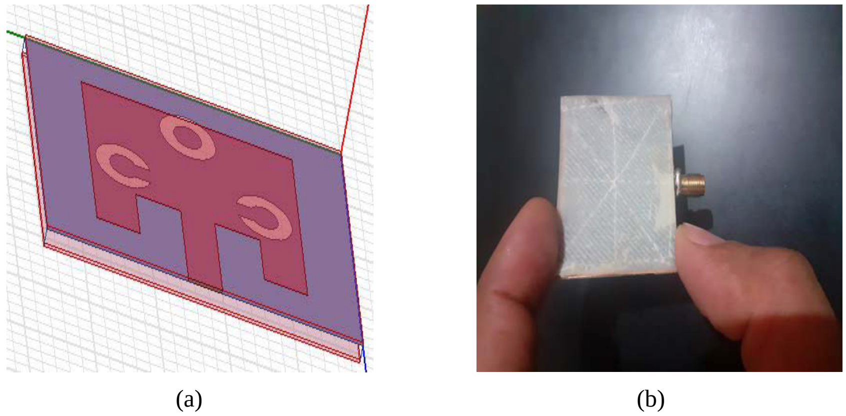


Figure 11. Step 3: Textile gap coupled antenna. (a) HFSS design Model. (b) Fabricated design Model.

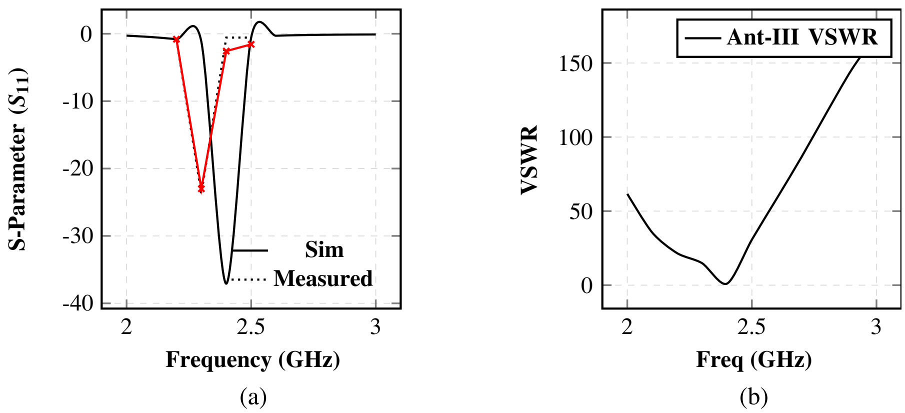


Figure 12. (a) Antenna-3-Experimental and simulated return loss (Red colour shows on hand measured). (b) Antenna-3-VSWR.

4.3. Step 3 (Antenna-3)

In this step, the antenna has two split ring resonators along with a circular ring which is placed in ground plane. An air gap coupled superstrate has been replaced with jeans material. Simulated-jeans coupled antenna is shown in Fig. 11(a). The fabricated antenna is shown in Fig. 11(b).

The simulated and measured return losses of Antenna-3 are −37.0799 dB and −23.01 dB respectively as shown in Fig. 12(a) and Fig. 12(b). The simulated directivity of Antenna-3 is 2.75 dB, and impedance at 2.4 GHz is about 51.4168 dB as shown in Fig. 13(a) and Fig. 13(b). The antenna performance is almost the same after keeping antenna in the vicinity of human hand due tothe effect of jeans inside bottom plane and superstrate. The obtained return loss on measuring on human hand is about −23.95 dB. The flexibility of jeans coupled model is more than air gap coupled antenna. The antenna shows the return loss of −23.75 dB at 2.324 GHz, and the same return loss is obtained in the vicinity of human hand at 2.321 GHz of around −23.95 dB as shown in Fig. 14(a) and Fig. 14(b). The external body effect has been drastically reduced due to gap coupled jeans.

4.4. Step 4 (Antenna-4)

This is the final designed antenna, and the size of antenna is about $27 \times 23\,\text{mm}^2$ with substrate of thickness 0.3 mm. The proposed antenna comprises two complementary split ring resonators at ground plane and one circular ring and complementary rectangular split ring resonator. The top patch consists of two rectangular split ring resonators etched inside the rectangular patch. The use of metamaterial on top and bottom of patch has helped to reduce the size of antenna along with maintaining performance of

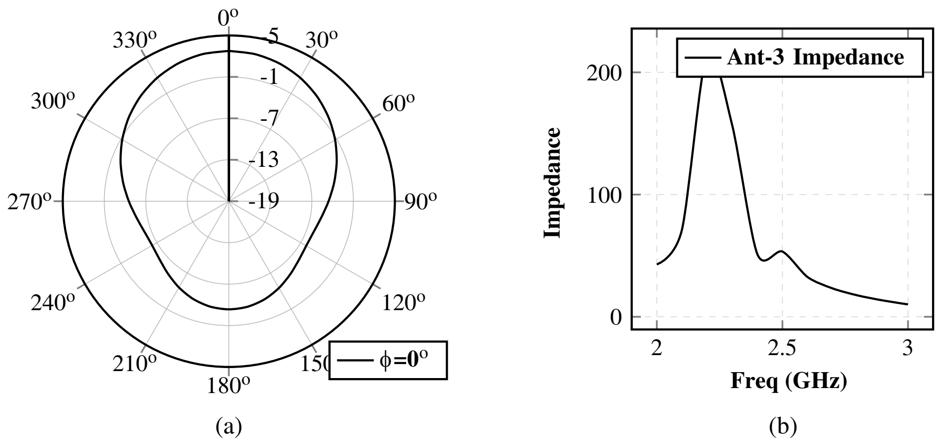


Figure 13. (a) Antenna-3-Directivity. (b) Antenna-3-Impedance.

Figure 14. Textile gap coupled antenna. (a) Measured Return Loss. (b) Measured Return loss in vicinity of human hand.

the antenna. Further enhancements are done in order to make jeans gap filled antenna with jeans filled between main patch and superstrate. The superstrate top patch consists of a square EBG structure that has helped to improve the performance of antenna-4.

Table 2 shows the parameter dimensions of Antenna-4. Antenna-4 HFSS designed model is as shown in Fig. 15(a) and Fig. 15(b).

Figure 16(a) shows the design of the EBG structure used at top of the superstrate. Fig. 16(b) shows the fabricated antenna-4 top view.

Figure 17(a) shows the fabricated antenna bottom view, and Fig. 17(b) shows the EBG structure and Jeans used during fabrication.

Antenna-4 shows good simulation return loss of −41.53 dB at 2.42 GHz, and measured return loss is about −35 dB at 2.3 GHz as shown in Fig. 18(a). The antenna is further tested on human hand and human leg which have shown measured results of about −32 dB and −31 dB, respectively. The measured and simulated results are in good agreement. The VSWR is 1.56 and is close to 1 in frequency range of 2.4 GHz as shown in Fig. 18(b). The simulated directivity of Antenna-4 is 2.08 dB as shown in Fig. 19(a), and the impedance at 2.42 GHz is 50.18 as shown in Fig. 19(b). The antenna performance is same after keeping the antenna in the vicinity of human hand and human leg due to the effect of jeans in the bottom plane and superstrate. The external body effect has been drastically reduced due to gap coupled jeans structure.

Table 2. Dimensions of Antenna-4.

Parameters	Dimensions obtained	Parameters	Dimensions obtained
$W1$	23.74 mm	W	23.74 mm
$L1$	27.136 mm	L	27.136 mm
$X1$	20.1 mm	T	19.16 mm
C	25.1 mm	U	23.4 mm
B	13.05 mm	X	13.97 mm
A	13.2 mm	Y	13.22 mm
K	10 mm	R	4 mm
O	1.5 mm	$R2$	2 mm
E	1.69 mm	K	10 mm
I	10.26 mm	P	3.43 mm
$X1$	20.1 mm	$X2$	4 mm

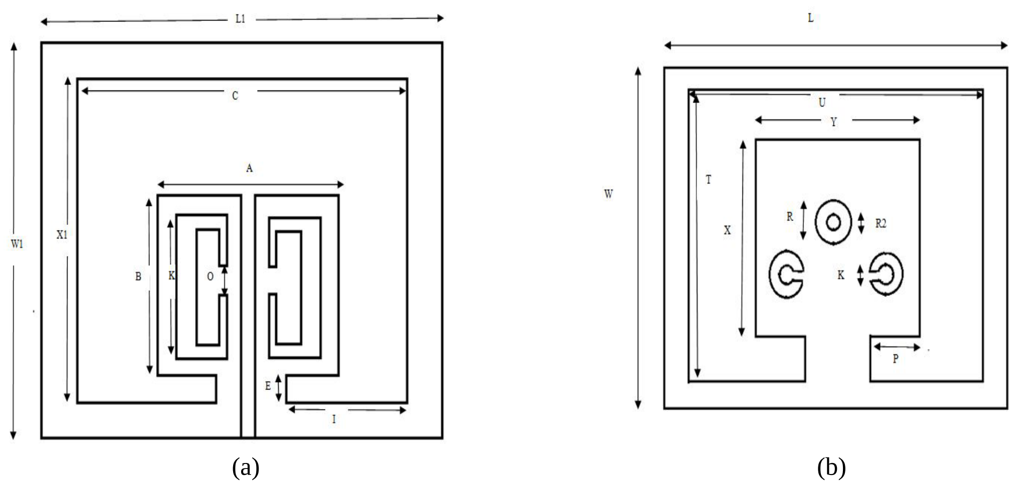


Figure 15. Step 4: Textile gap coupled antenna. (a) HFSS design Model top view. (b) HFSS design Model bottom view.

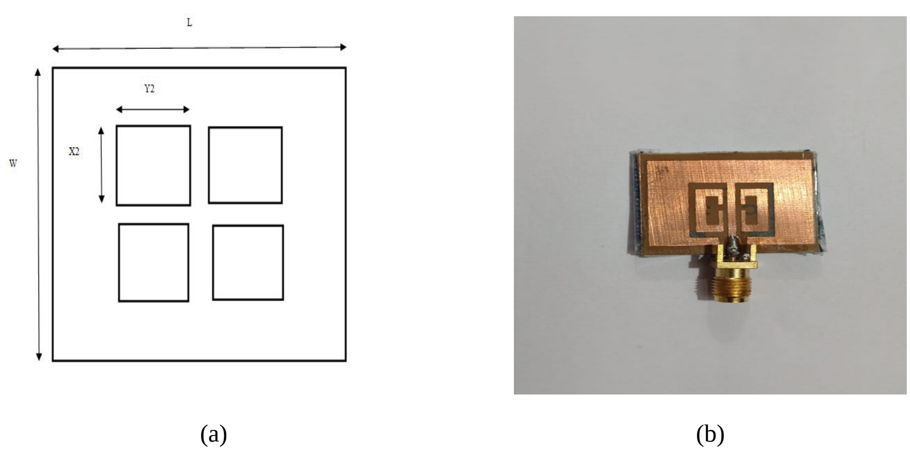
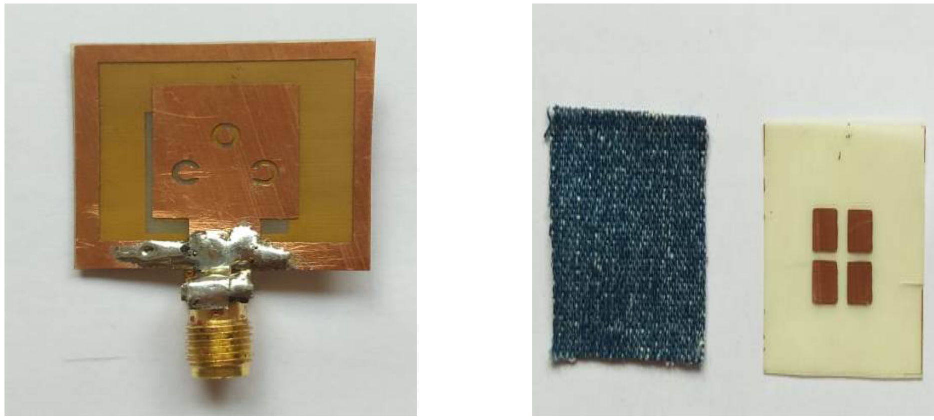
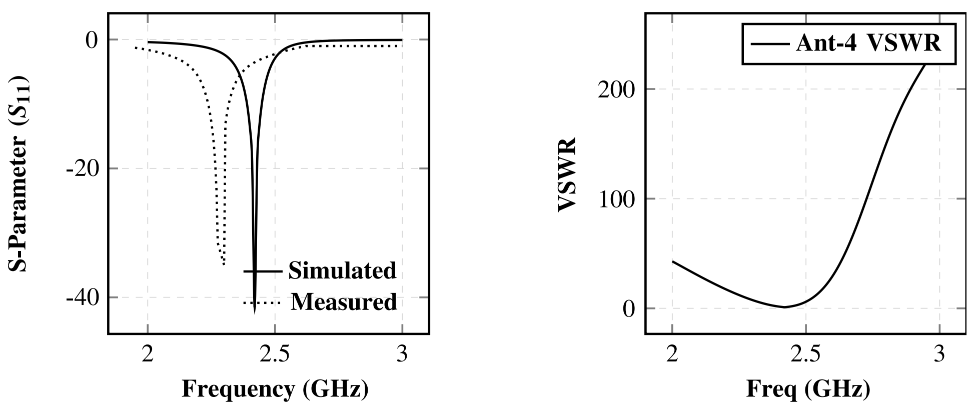


Figure 16. Step 4: Textile gap coupled antenna. (a) HFSS design Model EBG (Superstrate). (b) Fabricated Antenna-4 Top view.



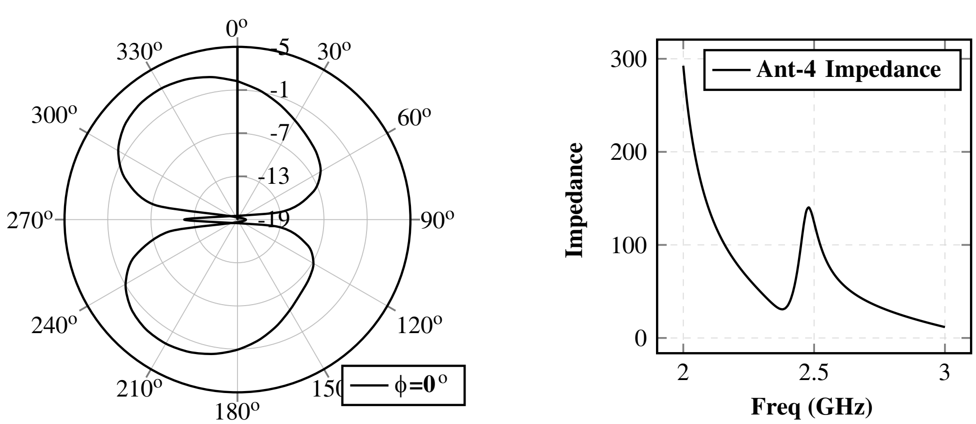
(a) (b)

Figure 17. Step 4: Textile gap coupled antenna. (a) Fabricated Antenna-4 Bottom view. (b) Fabricated Antenna-4 EBG and Jeans Used.



(a) (b)

Figure 18. (a) Antenna-4-Measured and simulated return loss. (b) Antenna-4-VSWR.



(a) (b)

Figure 19. (a) Antenna-4-Directivity. (b) Antenna-4-Impedance.

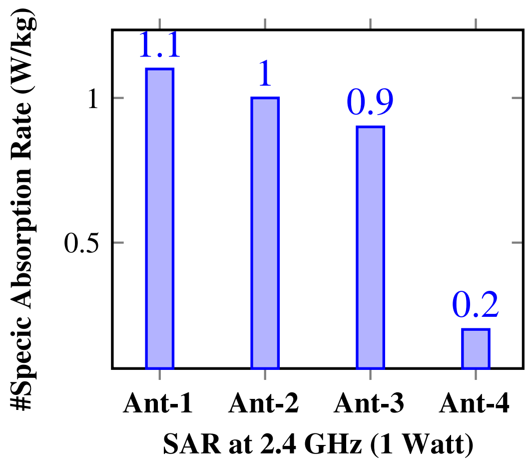
5. SPECIFIC ABSORPTION RATE INVESTIGATION

According to government agencies around the world, there is a restriction in amount of radio frequency energy consumed by body for wireless devices. The SAR value is calculated in watts per kilogram (W/kg). SAR is a critical parameter in antenna design and should be at lower end to avoid hazardous effects on human body. The maximum allowable SAR limit is 1.6 Watts per kilogram. To analyze the SAR value, a three layer human body model is used. The three layer model consists of skin, fat, and muscle. The properties of a three-layer human model is shown in Table 3.

Table 3. Properties of three Layer human Model.

Layer	Thickness mm	ϵ_r
Skin	2	38
Fat	5	5.28
Muscle	20	52.7

In HFSS, for simulating specific absorption rate, we have given input power as 1 Watt [33]. Also, while calculating SAR the gap between antenna and body model is 5 mm. The SAR value of Ant-1 is 1.1 W/Kg, and Ant-2 is 1 W/Kg obtained with gap coupled antenna model. The SAR value of Ant-3 is further reduced to 0.9 W/K. For Ant-4 the value is further reduced to 0.2 W/k. The Bar Chart below shows the specific absorption rate at 2.4 GHz for input power as 1 watt.



Further, we have tested with input power as 100 milli Watt [34]. Also, while calculating SAR the gap between antenna and body model was 5 mm. The SAR value of Ant-1 is 0.368 W/Kg, and Ant-2 is 0.285 W/Kg obtained with gap coupled antenna model. The SAR value of Ant-3 is further reduced to 0.09 W/K. For Ant-4 the value is further reduced to 0.036 W/k. The Bar Chart below shows the specific absorption rate at 2.4 GHz for input power as 100 milli watt.

Comprehensive comparison of the performance parameters has been done with the existing antennas and summarized in Table 4.

The output description of the designed antenna is shown in Table 5.

6. BODY AREA NETWORK

Antenna-2, Antenna-3, and Antenna-4 are tested on different cloths in combination with hand. Table 6 shows the different cloth materials and their permittivity used during the experiment.

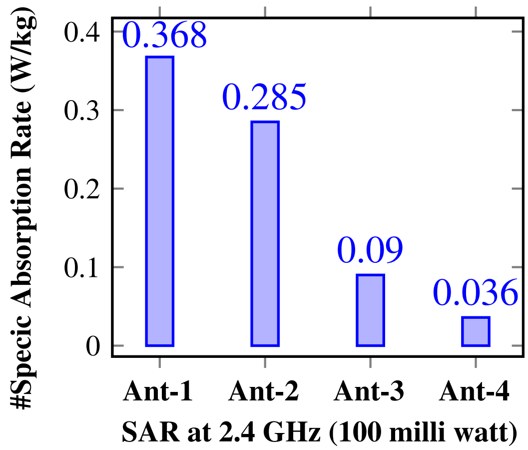


Table 4. Comparison of proposed antenna with the previous literature.

Parameters	Ref. [5]	Ref. [13]	Ref. [15]	Ref. [22]	Ref. [23]	Ref. [24]	Current Work
Area (mm^2)	1750	1296	1444	2500	6699	10000	644
Freq (GHz)	2.45	2.45	2.4	2.4	2.3–3/ 4–5.3	2.4–2.5	2.4
Substrate	Felt (Flexible)	FR4 (Rigid)	FR4 (Rigid)	Latex (Flexible)	Felt (Flexible)	Felt (Flexible)	polyamide (Flexible)
Gain (dBi)	1.47	4.87	Not Verified	4.12	7.3	2.42	2.08
ϵ_r	1.2	4.4	4.4	-	1.33	1.335	2.8

Table 5. Summary of performance for designed antennas.

Parameters	Antenna-1	Antenna-2	Antenna-3	Antenna-4
Simulated Freq (GHz)	2.4	2.4	2.4	2.42
Measured Freq (GHz)	2.4	2.32	2.3	2.3
Simulated Return Loss (dB)	−23.426	−21.292	−37.09	−41
Measured Return Loss (dB)	−21.292	−19.14	−23.75	−35
Measured On hand Return Loss (dB)	−10.292	−10.00	−23.00	−29.35
Simulated VSWR	1.44	1.18	1.02	1.56
Simulated Bandwidth (MHz)	117	70	140	60
Simulated Directivity (dB)	2.7085	2.8946	2.7596	2.08

6.1. Antenna-2

The obtained return loss for Antenna-2, when it is tested with distance of 1 cm in cloth and antenna is about −14.5 dB. No major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester, and Turkish cloth.

The obtained return loss for Antenna-2, when it is tested with distance of 0 cm in cloth and antenna is about −12.5 dB. As compared with testing return loss with 1 cm gap, −2 dB loss is observed. No

Table 6. Cloth materials and permittivity.

Cloth Materials	Permittivity
Jeans (Cotton)	1.67
Cotton	1.51
Curtain cloth	1.47
Floor Cloth	1.46
Polyester	1.44
Turkish cloth	1.1

major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester, and Turkish cloth.

The obtained return loss for Antenna-2, when it is tested with distance of 0 cm in cloth and antenna and human hand is about −13.0 dB. No major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester, and Turkish cloth.

6.2. Antenna-3

The obtained return loss for Antenna-3, when it is tested with distance of 1 cm in cloth and antenna is about −21.5 dB. As compared with Antenna-2, return loss is improved. No major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester, and Turkish cloth. Minor difference is seen with Turkish cloth, and the obtained return loss is about −22.5 dB.

The obtained return loss for Antenna-3, when it is tested with distance of 0 cm in cloth and antenna is about −19 dB. As compared with testing return loss with 1 cm gap, −2.5 dB loss is observed. No major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester, and Turkish cloth.

The obtained return loss for Antenna-3, when it is tested with distance of 0 cm in cloth and antenna and human hand is about −19.8 dB. No major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester and Turkish cloth.

6.3. Antenna-4

The obtained return loss for Antenna-4, when it is tested with distance of 1 cm in cloth and antenna is about −29 dB. As compared with Antenna-3, return loss is improved. No major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester and Turkish cloth. Minor difference is seen with Turkish cloth, and the obtained return loss is about −30 dB.

The obtained return loss for Antenna-4, when it is tested with distance of 0 cm in cloth and antenna is about −27 dB. As compared with testing return loss with 1 cm gap, −2 dB loss is observed. No major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester, and Turkish cloth.

The obtained return loss for Antenna-4, when it is tested with distance of 0 cm in cloth and antenna and human hand is about −29.8 dB. No major change in return loss is seen when it is tested with different cloths as cotton jeans, cotton, curtain cloth, Floor cloth, polyester, and Turkish cloth.

Figure 20(a) shows comparison for return loss of on hand measurement, on leg measurement, and in free space measurement. Fig. 20(b) shows the comparison of return loss of Antenna-2, Antenna-3, and Antenna-4.

Figure 21(a) shows the measured and simulated E plane pattern and H plane pattern.

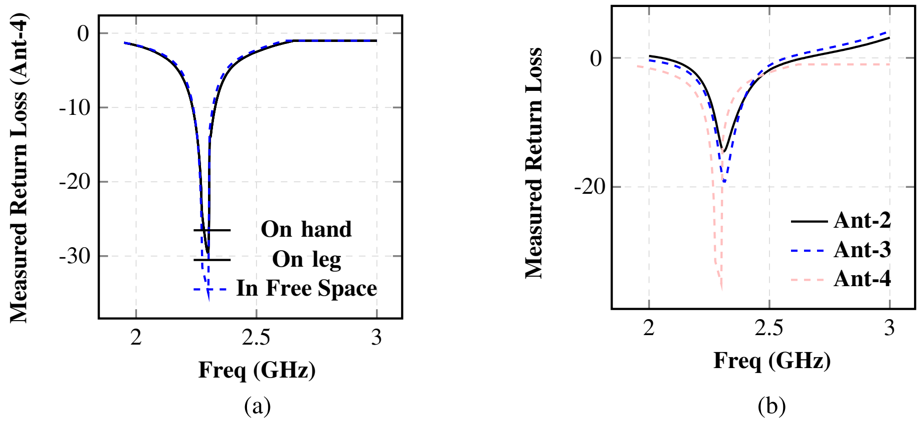


Figure 20. (a) Antenna 4-Comparison for return loss of hand measurement and free space. (b) Comparison of return loss of Antenna-2, Antenna-3 and Antenna-4.

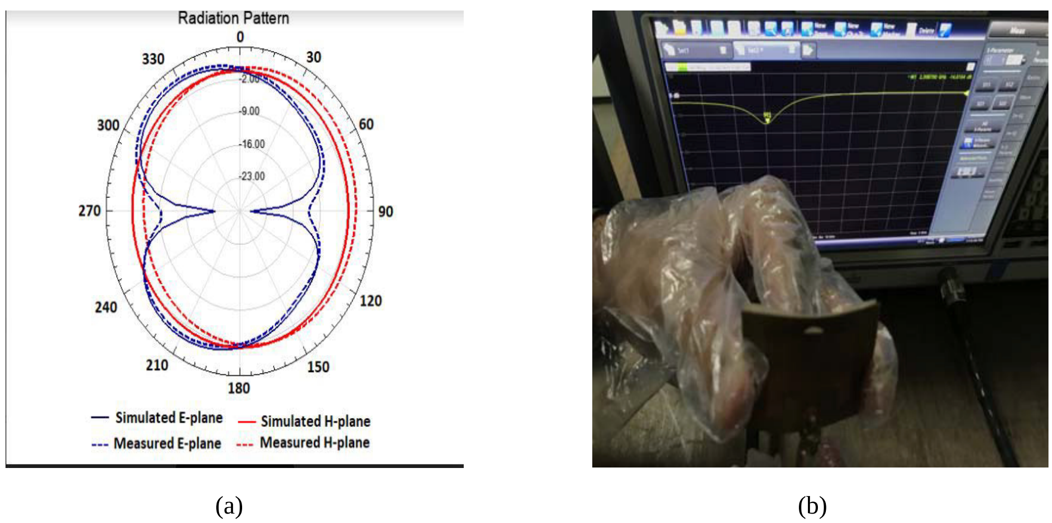


Figure 21. (a) Antenna 4-Measured and Simulated E plane and H plane pattern. (b) Antenna-2-Measured Return loss of folded Flexible Antenna.

7. FLEXIBLE ANTENNA READINGS

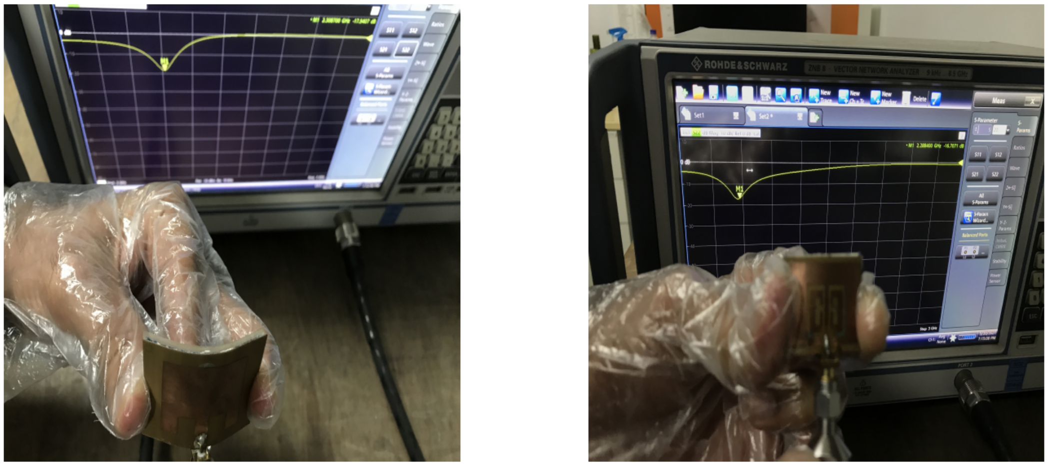
Antenna-2, Antenna-3, and Antenna-4 are made with a polyamide substrate having a thickness as 0.3 mm.

Antenna-2 is able to bend up to 20° maximum, due to the use of air gap between main patch and superstrate. Further bending of Antenna-2 would have broken the substrate. Fig. 21(b) shows that the measured return loss of Folded Flexible Antenna is about −14.614 dB at 2.3 GHz.

Antenna-3 is able to bend up to 30° maximum, due to the use of jeans gap between main patch and superstrate. Further bending of Antenna-3 would break the substrate. Fig. 22(a) shows that the measured return loss of Folded Flexible Antenna is about −17.91 dB at 2.3 GHz.

Antenna-4 is able to bend up to 30° maximum, due to the use of jeans gap between main patch and superstrate. Further bending of Antenna-4 would break the substrate. Fig. 22(b) shows that the measured return loss of Folded Flexible Antenna is about −16.7071 dB at 2.28 GHz.

In multi-layer configuration, Antenna-3 and Antenna-4 are more bendable than Antenna-2, due to the use of jeans in superstrate and main patch.



(a) (b)

Figure 22. (a) Antenna 3-Measured Return loss of folded Flexible Antenna. (b) Antenna-4- Measured Return loss of folded Flexible Antenna.

8. CONCLUSION

In this paper, a compact metamaterial based antenna is designed to work in Industrial, Scientific and Medical band. Metamaterial property of antenna has been proved with the help of Nicolson Ross Method. The use of Jeans material inside main substrate and superstrate has reduced the human body effect on antenna. The proposed antenna is compact and flexible, making it suitable for wireless body area network. The final designed antenna is compact in size and flexible, and the use of metamaterial helped to reduce the size of antenna. Practical measurements in the vicinity of direct hand contact and different cloth materials are taken. Further, the bending effects of different antennas are analyzed thoroughly.

9. CONFLICT OF INTEREST

The authors declare that the publishing of this article does not have any conflict of interest.

REFERENCES

1. Iqbal, A., A. Smida, A. J. Alazemi, M. I. Waly, N. Khaddaj Mallat, and S. Kim, "Wideband circularly polarized MIMO antenna for high datawearable biotelemetric devices," *IEEE Access*, Vol. 8, 17935–17944, 2020, doi: 10.1109/ACCESS.2020.2967397, http://dx.doi.org/10.1109/ACCESS.2020.2967397.
2. Smida, A., A. Iqbal, A. J. Alazemi, M. I. Waly, R. Ghayoula, and S. Kim, "Wideband wearable antenna for biomedical telemetry applications," *IEEE Access*, Vol. 8, 15687–15694, 2020, doi: 10.1109/ACCESS.2020.2967413, http://dx.doi.org/10.1109/ACCESS.2020.2967413.
3. Chaturvedi, D. and S. Raghavan, "A compact metamaterial-inspired antenna for WBAN application," *Wirel. Pers. Commun.*, Vol. 105, No. 4, 1449–1460, 2019, doi: 10.1007/s11277-019-06153-z, http://dx.doi.org/10.1007/s11277-019-06153-z.
4. Goswami, S. and D. C. Karia, "A metamaterial-inspired circularly polarized antenna for implantable applications," *Engineering Reports*, Vol. 2, No. 10, e12251, doi: 10.1002/eng2.12251, http://dx.doi.org/10.1002/eng2.12251.
5. Soh, P. J., G. A. Vandenbosch, S. L. Ooi, and N. H. M. Rais, "Design of a broadband all-textile slotted PIFA," *IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 1, 379–384, 2011.

6. Hazarika B. and B. Basu, "Multi-layered low-profile monopole antenna using metamaterial for wireless body area networks," *2019 International Conference on Automation, Computational and Technology Management (ICACTM)*, 431–435, 2019.
7. Hu, B., G. P. Gao, L. L. He, X. D. Cong, and J. N. Zhao, "Bending and on-arm effects on a wearable antenna for 2.45 GHz body area network," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 378–381, 2015.
8. Bouazizi, A., G. Zaibi, A. Iqbal, A. Basir, M. Samet, and A. A. Kachouri, "Dual-band caseprinted planar inverted-F antenna design with independent resonance control for wearable short range telemetric systems," *International Journal of RF and Microwave Computer-Aided Engineering*, Vol. 29, No. 8, e21781, 2019.
9. Iqbal, A., A. J. Alazemi, and N. Khaddaj Mallat, "Slot-DRA-based independent dual-band hybrid antenna for wearable biomedical devices," *IEEE Access*, Vol. 7, 184029–184037, 2019, doi: 10.1109/ACCESS.2019.2960443, http://dx.doi.org/10.1109/ACCESS.2019.2960443.
10. Elfergani, I., A. Iqbal, C. Zebiri, et al., "Low-profile and closely spaced four-element MIMO antenna for wireless body area networks," *Electronics*, Vol. 9, No. 2, 258, 2020, doi: 10.3390/electronics9020258, http://dx.doi.org/10.3390/electronics9020258.
11. Aziz Ul Haq, M. and S. Koziel, "On topology modifications for wideband antenna miniaturization," *AEU — International Journal of Electronics and Communications*, Vol. 94, 215–220, 2018, doi: https://doi.org/10.1016/j.aeue.2018.07.006, http://dx.doi.org/https://doi.org/10.1016/j.aeue.2018.07.006.
12. Ali, T. and R. C. Biradar, "A compact multiband antenna using $\lambda/4$ rectangular stub loaded with metamaterial for IEEE 802.11N and IEEE 802.16E," *Microwave and Optical Technology Letters*, Vol. 59, No. 5, 1000–1006, 2017, doi: 10.1002/mop.30454, http://dx.doi.org/10.1002/mop.30454.
13. Ajetrao, K. and A. Dhande, "Study of metamaterials and analysis of split ring resonators to design multiband and UWB antennas," *GRENZE International Journal of Engineering and Technology*, 2, 2016, doi: 10.21647/gijet/2016/v2/i2/48895, http://dx.doi.org/10.21647/gijet/2016/v2/i2/48895.
14. Ali, T., A. Mohammad Saadh, R. Biradar, J. Anguera, and A. Andújar, "A miniaturized metamaterial slot antenna for wireless applications," *AEU — International Journal of Electronics and Communications*, Vol. 82, 368–382, 2017, doi: https://doi.org/10.1016/j.aeue.2017.10.005, http://dx.doi.org/https://doi.org/10.1016/j.aeue.2017.10.005.
15. Zhu, C., T. Li, K. Li, et al., "Electrically small metamaterial-inspired tri-band antenna with metamode," *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, 1738–1741, 2015.
16. Raval, F., Y. Kosta, and H. Joshi, "Reduced size patch antenna using complementary split ring resonator as defected ground plane," *AEU — International Journal of Electronics and Communications*, Vol. 69, No. 8, 1126–1133, 2015, doi: https://doi.org/10.1016/j.aeue.2015.04.013, http://dx.doi.org/https://doi.org/10.1016/j.aeue.2015.04.013.
17. Lee, J. G. and J. H. Lee, "SAR reduction using integration of PIFA and AMC structure for pentaband mobile terminals," *International Journal of Antennas and Propagation*, Vol. 2017, Article ID 6196721, 2017.
18. Kim, S., K. Kwon, and J. Choi, "A compact circularly-polarized antenna with enhanced bandwidth for Wban applications," *Microwave and Optical Technology Letters*, Vol. 55, No. 8, 1738–1741, 2013.
19. Sultan, K. S., H. H. Abdullah, and E. A. F. Abdallah, "Low-SAR miniaturized handset antenna using EBG," *Microstrip Antennas: Trends in Research on*, Vol. 1, 127, 2017.
20. Chen, Y. S. and T. Y. Ku, "A low-profile wearable antenna using a miniature high impedance surface for smartwatch applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 1144–1147, 2015.
21. Igarashi, A. and Y. Okano, "Basic research of reduction technique for the microwave exposure with conductive cloth," *2010 Asia-Pacific Microwave Conference*, 1364–1367, 2010.
22. Sultan, K. S., H. H. Abdullah, E. A. Abdallah, and E. A. Hashish, "Low-SAR, miniaturized printed antenna for mobile, ISM, and WLAN services," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, 1106–1109, 2013.

23. Gómez-Villanueva, R., H. Jardón-Aguilar, and R. L. Y. Miranda, "State of the art methods for low SAR antenna implementation," *Proceedings of the Fourth European Conference on Antennas and Propagation*, 1–4, 2010.
24. Wang, M., Z. Yang, J. Wu, et al., "Investigation of SAR reduction using flexible antenna with metamaterial structure in wireless body area network," *IEEE Transactions on Antennas and Propagation*, Vol. 66, No. 6, 3076–3086, 2018.
25. Lakshmanan, R. and S. K. Sukumaran, "Flexible ultra wide band antenna for WBAN applications," *Procedia Technology*, Vol. 24, 880–887, Part of Special Issue: International Conference on Emerging Trends in Engineering, Science and Technology (ICETEST — 2015), 2016, doi: https://doi.org/10.1016/j.protcy.2016.05.149, http://dx.doi.org/https://doi.org/10.1016/j.protcy.2016.05.149.
26. Al-Sehemi, A. G., A. A. Al-Ghamdi, N. T. Dishovsky, N. T. Atanasov, and G. L. Atanasova, "Flexible and small wearable antenna for wireless body area network applications," *Journal of Electromagnetic Waves and Applications*, Vol. 31, Nos. 11–12, 1063–1082, 2017.
27. Agarwal, K., Y. X. Guo, and B. Salam, "Wearable AMC backed near-endfire antenna for onbody communications on latex substrate," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 6, No. 3, 346–358, 2016.
28. Mantash, M., A. C. Tarot, S. Collardey, and K. Mahdjoubi, "Investigation of flexible textile antennas and AMC reflectors," *International Journal of Antennas and Propagation*, Vol. 2012, Article ID 236505, 2012.
29. Lago, H., P. J. Soh, M. F. Jamlos, N. Shohaimi, S. Yan, and G. A. Vandenbosch, "Textile antenna integrated with compact AMC and parasitic elements for WLAN/WBAN applications," *Applied Physics A*, Vol. 122, No. 12, 1–6, 2016.
30. Zhang, K., P J. Soh, and S. Yan, "Meta-wearable antennas — A review of metamaterial based antennas in wireless body area networks," *Materials*, Vol. 14, No. 1, 149, 2021.
31. Alhawari, A. R., A. Almawgani, A. T. Hindi, H. Alghamdi, and T. Saeidi, "Metamaterial-based wearable flexible elliptical UWB antenna for WBAN and breast imaging applications," *AIP Advances*, Vol. 11, No. 1, 015128, 2021.
32. Iqbal, A., A. Basir, A. Smida, et al., "Electromagnetic bandgap backed millimeter-wave MIMO antenna for wearable applications," *IEEE Access*, Vol. 7, 111135–111144, 2019, doi: 10.1109/ACCESS.2019.2933913, http://dx.doi.org/10.1109/ACCESS.2019.2933913.
33. Keshwani, V. R., P. P. Bhavarthe, and S. S. Rathod, "Eight shape electromagnetic band gap structure for bandwidth improvement of wearable antenna," *Progress In Electromagnetics Research C*, Vol. 116, 37–49, 2021.
34. Verma, A., R. K. Arya, R. Bhattacharya, and S. N. Raghava, "Compact PIFA antenna with high gain and low SAR using AMC for WLAN/C-band/5G applications," *IETE Journal of Research*, 1–11, 2021.