PIER Letters

(Received 28 October 2023, Accepted 11 December 2023, Scheduled 25 December 2023)

A Red Cross Bag MPA with a Very Low SAR and High F/B Ratio for Bio-Medical Applications

Anwer Sabah Mekki[1,*], Siba Monther Yousif[2], and Saif Mohammed Baraa[3]

[1]*Department of Medical Devices Techniques Engineering, Al-Turath University College, Iraq*
[2]*Department of Electronic and Communications Engineering, College of Engineering Al-Nahrain University, Jadriya, Baghdad, Iraq*
[3]*Department of Medical Instruments Techniques Engineering, Technical College of Engineering, Albayan University, Baghdad, Iraq*

ABSTRACT: A microstrip patch antenna of red cross bag shape is designed, simulated, and fabricated. The antenna is designed to work at 5.8 GHz for on-body applications. Small size, low specific absorption rate, and high front to back ratio with a low-profile design are achieved. The measured frequency is 5.878 GHz with 25 mm as the largest dimension used, and the matching impedance is -47.06 dB. Other parameters are recorded from the simulator such as front-to-back ratio which is 37.37 dB and a specific absorption rate of 0.0984 W/kg in 10 gm. Finally, this work is compared with a compact dual-band antenna with paired L-shape slots, a watchstrap integrated wideband antenna, and a dual-band AMC-based MIMO antenna. The proposed red cross bag antenna overcomes the mentioned works in terms of small size, high front-to-back ratio, and low specific absorption rate.

1. INTRODUCTION

Wearable devices have grown widely through new techniques such as artificial intelligence technologies [1–3]. The free movement of the patient is significant especially when the medical case is recommended to keep the patient under monitoring for a long time. Therefore, a wireless solution is the optimum technique to be used.

One of the most essential parts of wireless communication circuits is the antenna. An antenna with a small size and low Specific Absorption Rate (SAR) is required in wearable devices. Moreover, a high Front-to-Back (F/B) ratio is one of the most critical parameters that effectively protects the human body from reflected microwave signals [4–6].

Most wearable devices are based on flexible substrates to make humans more comfortable during human movement. These substrates may be textile or bendable materials that can be used safely for on-body application [7, 8]. However, there are some disadvantages such as changes in the center frequency, low gain, and unstable values of antenna parameters due to the changes in dimensions depending on the bending angle. Moreover, the receiving antenna should be designed with a wide range of frequencies to communicate with the transmitter antenna [9–11]. A Wireless Body Area Network (WBAN) is the solution to avoid the changes in the center frequency far away from the Industrial, Scientific, and Medical Band (ISM). Due to the uncertainty of the frequency value during the antenna's bending, the wide frequency range is specified to occupy the variable frequency range (3 GHz to 10 GHz) [12–14].

Some researchers have used rigid and compact size antennas in wearable devices because size is a crucial parameter, and small sizes can be used instead of large and flexible antennas [15–17]. Internet of Things (IoT) is a new significant technique that enhances workability and increases the demand for communications among different devices. Medical devices use IoT in many applications to make data transfer more accessible and accurate [18–20].

In this work, a new Microstrip Patch Antenna (MPA) is designed, simulated, and measured. The simulation uses Computer Simulation Technology — Microwave Studio (CST-MW). The MPA dimension is calculated using the conventional square patch antenna equations. Then, an optimization technique is employed to achieve a center frequency of 5.8 GHz with an impedance of $49.93 + j0.028\,\Omega$, a matching impedance of -63.53 dB with F/B of 37.4, and a gain of 6.57 dBi. The antenna is optimized according to the fixed location at the upper part of the arm, and the voxel model is Gustave. After fabrication, the fabricated results are compared with the simulated ones, and the comparison shows good matching between them. Finally, the fabricated antenna is compared with three recently published works which are a compact dual-band antenna with paired L-shape slots [21], a watchstrap integrated wideband antenna [22], and a dual-band AMC-based MIMO antenna [23].

2. ANTENNA DESIGN

An antenna of low SAR, small size, high F/B, good gain, low profile, wide band, and flexible substrate is required. Sometimes, the compact size antenna with a rigid substrate can be used rather than the large size one with a flexible substrate.

The proposed antenna is designed to work in free space with a distance of 2 mm from the arm. The voxel model (Gustave) is used with a finite element software CST-MW for simulation. The primary dimensions are calculated from the conventional

* Corresponding author: Anwer Sabah Mekki (asmekki68@yahoo.com).

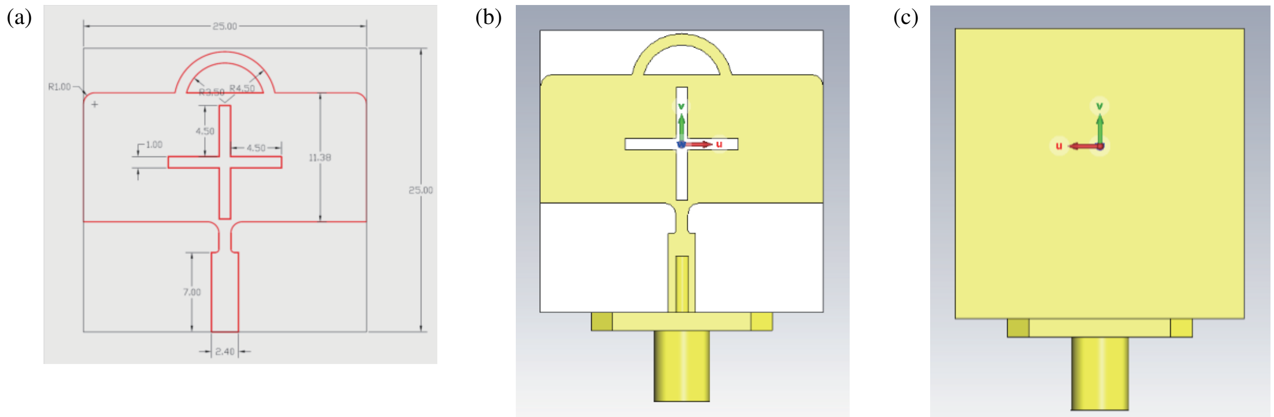

FIGURE 1. Proposed antenna design: (a) antenna dimensions in mm (b) patch layer, and (c) GND layer.

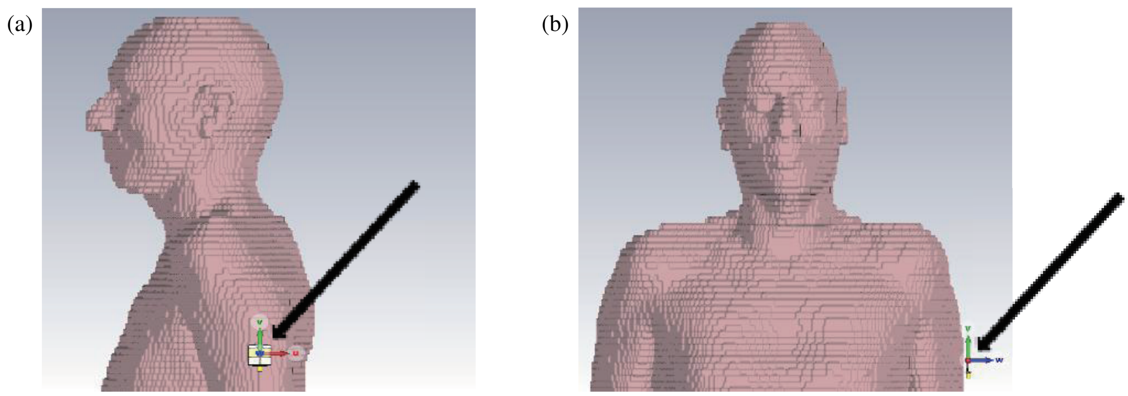

FIGURE 2. Proposed antenna position indicated by black arrow (a) front view (b) side view.

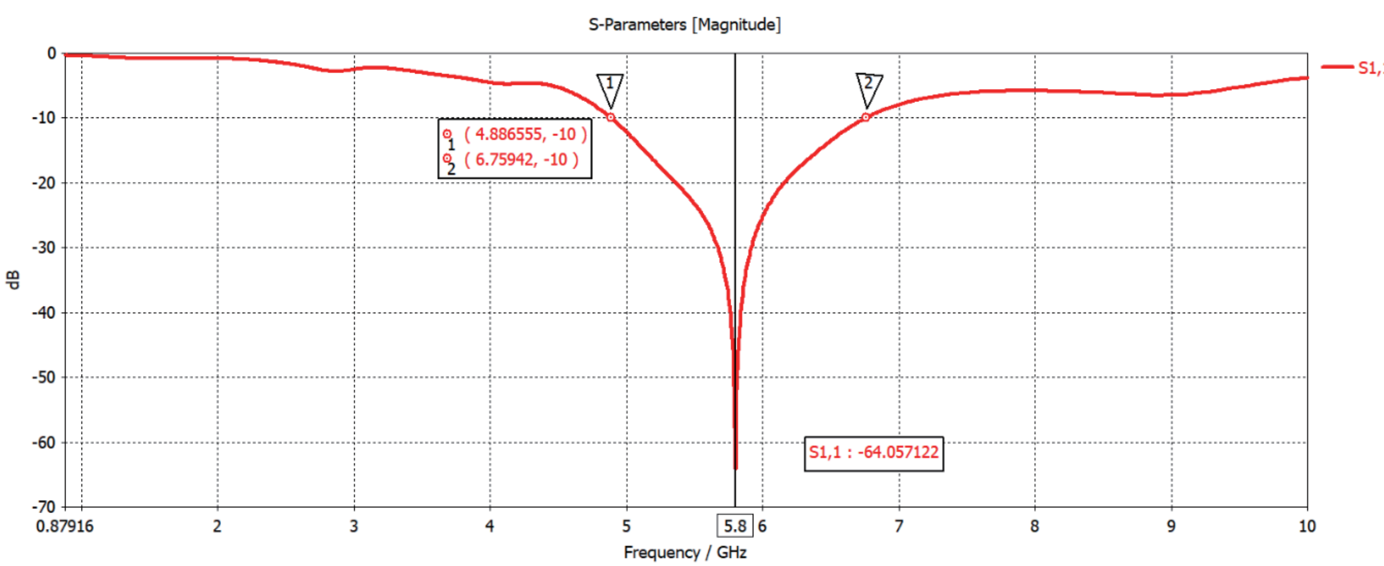

FIGURE 3. Proposed antenna S_{11} vs. Frequency.

square patch antenna equations, and then the design is optimized to achieve the desired requirements. The fringing plays an essential role regarding the patch antenna's dimensions [24]. The width of the patch is identical to the width of the substrate, which leads to the enhancement of the electrical length of the fringe field distributions. According to that, the gain is raised, and the VSWR is 1.008, which is almost ideal, meaning that the antenna has more radiated power.

TABLE 1. Simulated results of the proposed antenna.

Parameter	Value	Unit
Center frequency	5.8	GHz
Bandwidth	1.872	GHz
Matching impedance	-64.057	dB
Directivity	6.83	dBi
Gain	6.572	dB
Front to Back ratio	37.37	dB
Total linear efficiency	0.9432	—
Linear radiation efficiency	0.9279	—
Dimensions $(L \times W \times H)$	$25 \times 25 \times 1.6$	mm^3
SAR in 10 g	0.0984	W/Kg
SAR in 1 g	0.235	W/Kg
Radiation efficiency	0.9432	–

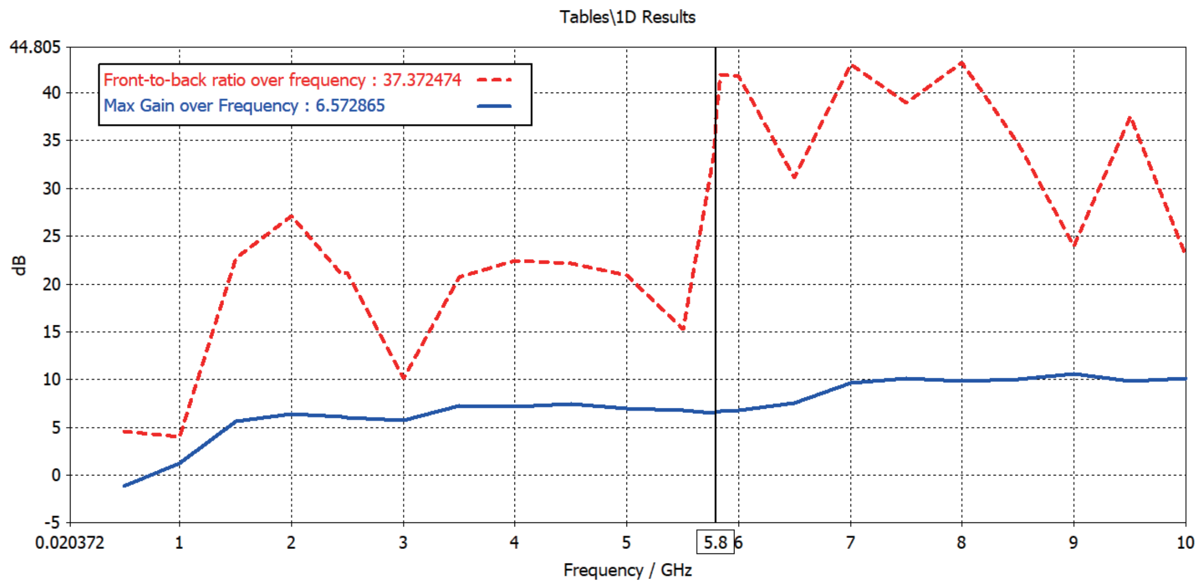

FIGURE 4. Proposed antenna gain and F/B ratio.

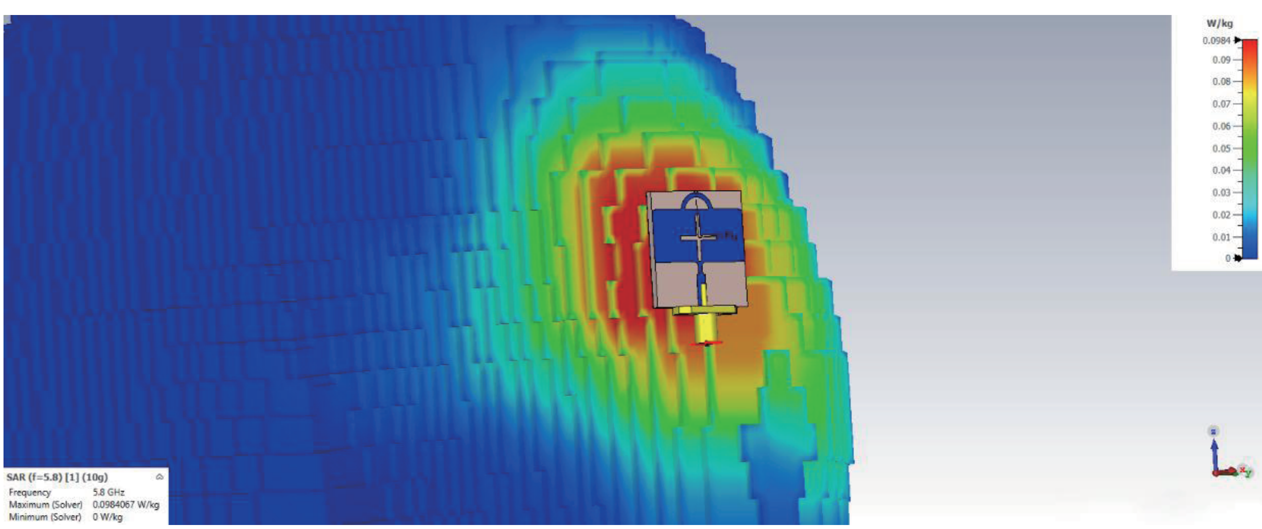

FIGURE 5. SAR values and its distribution on the human body.

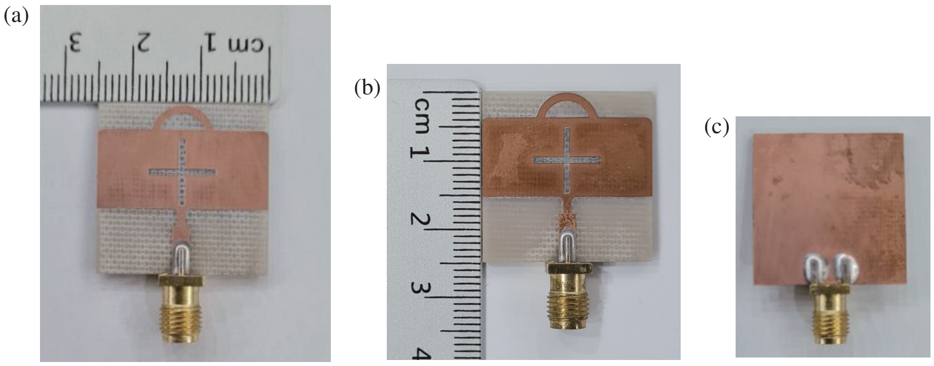

FIGURE 6. Fabricated antenna (a) width dimension, (b) height dimension, and (c) ground layer.

FIGURE 7. Proposed antenna during measurement.

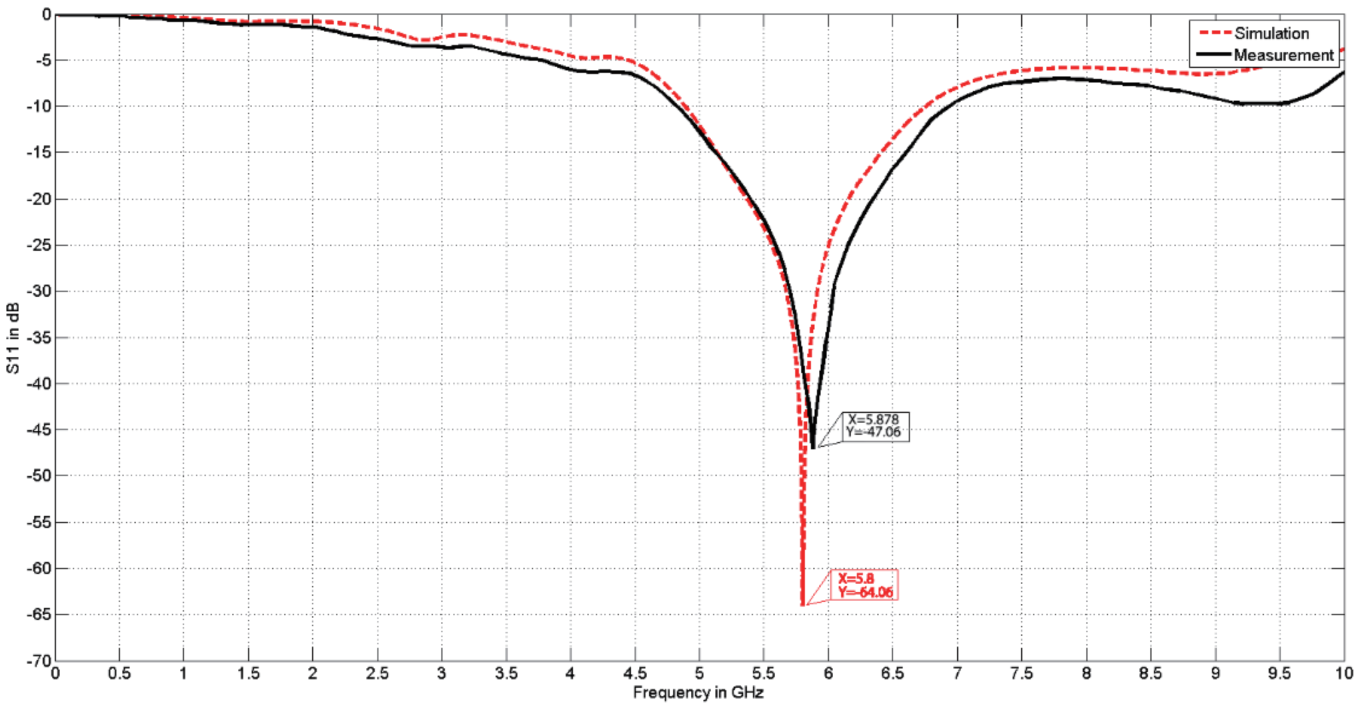

FIGURE 8. Comparison of S_{11} between simulation and measurement results.

TABLE 2. Comparison between simulation and measurement results of the proposed antenna.

Parameter	Simulation	Measurement	Unit
Center frequency	5.8	5.878	GHz
Bandwidth	1.872	2.07	GHz
Matching Impedance	-64.057	-47.06	dB
Gain	6.572	6.7	dB
Dimensions ($L \times W \times H$)	$25 \times 25 \times 1.6$	$25 \times 25 \times 1.6$	mm^3

The proposed antenna is designed to resonate at 5.8 GHz with a substrate of Flame Retardant (FR-4) with a relative permittivity of 4.3 and thickness of 1.53 mm. The overall dimensions are (25 mm $\times$ 25 mm $\times$ 1.6 mm) as ($W \times L \times H$). The proposed antenna design with its dimensions is shown in Figure 1, and it is essential to clarify that the patch layer is made from annealed copper, and the ground layer (GND) is fully annealed copper.

The dimensions of the substrate are specified to get a center frequency of 5.8 GHz, highlighting that the substrate is FR-4. The cross shape is used to enhance the F/B ratio and optimize the center frequency by redistributing the surface current to in-

TABLE 3. Comparison of measurement parameters between this work and compact dual-band antenna with paired L-shape slots, watchstrap integrated wideband, and dual band-AMC based MIMO.

Reference	Center Frequency in GHz	Bandwidth in GHz	Substrate	Matching Impedance in dB	Gain in dB	Front to Back ratio in dB (Simulation)	Dimensions ($L \times W \times H$) in mm^3	SAR in 1 g in W/kg	SAR in 10 g in W/kg	Polarization
[21]	5.8	3.44	FR-4	-25	5.25	——	$45 \times 30 \times 1.6$	1.18	——	——
[22]	5.46	0.69	FR-4	-34	8.49	——	$45 \times 15 \times 1.6$	0.521	0.171	Linear
[23]	5.8	1.23	FR-4	-36	7.48	26.77	$79.5 \times 79.5 \times 0.8$	——	0.16	——
This work	5.878	2.07	FR-4	-47.06	6.7	37.37	$25 \times 25 \times 1.6$	0.235	0.0984	Linear

crease the radiated power and reduce the sustained power on the patch surface. Moreover, the fully grounded layer of proposed antenna was used as a reflector to reduce the back and side lobes of the EM field propagation outside the human body. Consequently, the SAR and skin depth will be reduced [25, 26]. The fully ground antenna means narrow bandwidth in a square patch antenna. In this work, the added half-circular shape at the top of the patch (handle of the cross bag) leads to an increase in the bandwidth of the resonate frequency by approximately 2 GHz. Finally, the feeder transformer is calculated to increase the matching impedance (S_{11}). The antenna is connected to the port of 50 Ω using a SubMiniature version A (SMA) connector. The complicated antenna shape gives a good optimization facility due to many parameters in shape that can be changed to get the desired results.

3. SIMULATION RESULTS

Using CST-MW software, the proposed antenna is positioned at a distance of 2 mm from the arm and simulated with a high mesh setting as shown in Figure 2, and the simulated results are listed in Table 1.

From Table 1, it can be realized that the proposed antenna is capable of working for biomedical applications. The designed antenna resonates at the ISM band with high S_{11} value as shown in Figure 3 and a good gain with a high F/B ratio as shown in Figure 4. Finally, the SAR values in 10 g and 1 g are lower than the standard values [27]. SAR is the main parameter that indicates how microwave frequency affects human tissues. Figure 5 shows the SAR values distributed on the human body.

4. MEASUREMENT

The proposed antenna is fabricated after the final process of optimization. An FR-4 substrate of 1.53 mm thickness is used with dimensions illustrated in Figure 1(a). The proposed antenna is connected to a 50 Ω port through an SMA connector and measured using a Power Network Analyzer (PNA) which is Agilent model E5071C and two horn antennas. The fabricated antenna is shown in Figure 6. The proposed antenna is examined on the upper part of the hand as shown in Figure 7.

5. COMPARISON

Figure 8 shows a comparison between simulation and measurement results of S_{11}. From Figure 8, the proposed antenna indicates an excellent matching between them. The differences between these results are due to the limited number of variables taken into account during the simulation process. A comparison between simulation and measurement results is listed in Table 2.

From Table 2, it can be shown that the fabricated antenna has a good matching impedance which is -47.06 dB as compared to the simulated one. This matching is achieved due to the use of high mesh numbers during the simulation process and the use of actual data given by the manufacturer such as ε_r of the substrate as well as the thickness. Moreover, the optimization techniques are considered more flexible when dealing with a complicated design than a simple design. It means that whenever multi-geometrical shapes are proposed in the design, good optimization results will be achieved even though a lot of time is consumed.

6. DISCUSSION AND CONTRIBUTION

In this work, an on-body antenna is designed to resonate at 5.8 GHz with a low profile, small size of 1000 mm^3, and impedance of $49.93 + j0.012$ which leads to semi-ideal VSWR. The proposed antenna is fabricated on a rigid substrate rather than a flexible substrate since it can be considered a longstanding substrate. Moreover, the resonant frequency and all the antenna parameters will not be affected by bending as compared to a flexible substrate. Furthermore, the rigid antenna should be designed with a small size to maintain patient comfortability rather than the large size of a flexible antenna. From Table 3, it can be shown that the proposed antenna is smaller in size than [21] by 1,160 mm^3, [22] by 80 mm^3, and [23] by 4,056 mm^3.

The gain is another parameter that is considered a challenge due to the small antenna size. The proposed antenna gain is higher than [21] by 1.45 dB but lower than [22] by 1.79 dB and [23] by 0.78 dB. These results are considered comparable due to the small size of the proposed antenna since the antenna is fabricated on the same substrate which is FR-4.

The main significant point is that the F/B of proposed antenna reaches 37.37, which is considered as a very high value since no reflector layer is used. This value indicates that the skin depth is very low, and the whole propagation field is directed outside the human body. Consequently, the high F/B reduced SAR value which is one of the main contributions in this work. The SAR value of the proposed antenna has lower value than [21] by 0.945 W/kg in 1 g, [22] by 0.286 W/kg in 1 g, and [23] by 0.0616 W/kg in 10 g. This means that the proposed antenna is more applicable in bio-medical applications than the mentioned works since it has the lowest SAR value.

Therefore, the proposed antenna shows important features as compared to the compact dual-band antenna with paired L-shape slots, watchstrap integrated wideband antenna, and dual band-AMC based MIMO in terms of small size and high F/B with very low SAR.

REFERENCES

[1] Dimitropoulos, N., T. Togias, N. Zacharaki, G. Michalos, and S. Makris, "Seamless human-robot collaborative assembly using artificial intelligence and wearable devices," *Applied Sciences*, Vol. 11, No. 12, Jun. 2021.

[2] Sabry, F., T. Eltaras, W. Labda, K. Alzoubi, and Q. Malluhi, "Machine learning for healthcare wearable devices: The big picture," *Journal of Healthcare Engineering*, Vol. 2022, Apr. 2022.

[3] Yousif, S. M., A. S. Mekki, and A. J. Lafta, "Compact low profile 5.8 GHz MPA for on-body applications," *Bulletin of Electrical Engineering and Informatics*, Vol. 12, No. 3, 1495–1501, 2023.

[4] Gupta, A. and V. Kumar, "DGS-based wideband MIMO antenna for on-off body communication with port isolation enhancement operating at 2.45 GHz industrial scientific and medical band," *Journal of Electromagnetic Waves and Applications*, Vol. 35, No. 7, 888–901, May 2021.

[5] Kiani, S., P. Rezaei, and M. Fakhr, "A CPW-fed wearable antenna at ISM band for biomedical and WBAN applications," *Wireless Networks*, Vol. 27, No. 1, 735–745, Jan. 2021.

[6] AL-Sabti, S. M. B. and D. C. Atilla, "A novel vision for mathematical model between electromagnetic radiation and thermodynamic parameters in biochemistry frame," *Applied Nanoscience*, Aug. 2021.

[7] Corchia, L., G. Monti, E. D. Benedetto, A. Cataldo, L. Angrisani, P. Arpaia, and L. Tarricone, "Fully-textile, wearable chipless tags for identification and tracking applications," *Sensors*, Vol. 20, No. 2, Jan. 2020.

[8] Mandal, D. and S. S. Pattnaik, "Quad-band wearable slot antenna with low SAR values for 1.8 GHz DCS, 2.4 GHz WLAN and 3.6/5.5 GHz WiMAX applications," *Progress In Electromagnetics Research B*, Vol. 81, 163–182, 2018.

[9] Liu, Q., C. Yi, J. Chen, M. Xia, Y. Lu, Y. Wang, X. Liu, M. Li, K. Liu, and D. Wang, "Flexible, breathable, and highly environmental-stable Ni/PPy/PET conductive fabrics for efficient electromagnetic interference shielding and wearable textile antennas," *Composites Part B-Engineering*, Vol. 215, Jun. 2021.

[10] Van Baelen, D., N. Macoir, Q. Van Den Brande, E. De Poorter, S. Lemey, J. Verhaevert, and H. Rogier, "Fully flexible textile antenna-backed sensor node for body-worn UWB localization," *Sensors*, Vol. 21, No. 5, Mar. 2021.

[11] Jameel, M. S., Y. S. Mezaal, and D. C. Atilla, "Miniaturized coplanar waveguide-fed UWB antenna for wireless applications," *Symmetry*, Vol. 15, No. 3, 633, 2023.

[12] Jayakumar, S. and G. Mohanbabu, "A wearable low profile asymmetrical slotted ultra-wide band antenna for WBAN applications," *Eurasip Journal on Wireless Communications and Networking*, Vol. 2022, No. 1, Oct. 2022.

[13] Taleb, H., A. Nasser, G. Andrieux, N. Charara, and E. M. Cruz, "Wireless technologies, medical applications and future challenges in WBAN: A survey," *Wireless Networks*, Vol. 27, No. 8, 5271–5295, Nov. 2021.

[14] Ahmad, N., B. Shahzad, M. Arif, D. Izdrui, I. Ungurean, and O. Geman, "An energy-efficient framework for WBAN in health care domain," *Journal of Sensors*, Vol. 2022, Feb. 2022.

[15] Singh, S. and S. Verma, "Compact wideband circularly polarized bowtie slot antenna for WBAN applications," *AEU-International Journal of Electronics and Communications*, Vol. 136, Jul. 2021.

[16] Dash, R. K., P. B. Saha, D. Ghoshal, and G. Palai, "Fractal slot loaded compact wearable button antenna for IOT and X-band applications," *Wireless Networks*, Vol. 29, No. 2, 589–605, Feb. 2023.

[17] Ashar, D., M. Sharma *et al.*, "SAR evaluation of flexible UWB antenna for wearable applications," in *Journal of Physics: Conference Series*, Vol. 2312, No. 1, 012051, 2022.

[18] Varma, S., S. Sharma, M. John, R. Bharadwaj, A. Dhawan, and S. K. Koul, "Design and performance analysis of compact wearable textile antennas for IOT and body-centric communication applications," *International Journal of Antennas and Propagation*, Vol. 2021, Aug. 2021.

[19] Atanasova, G. L., B. N. Atanasov, and N. T. Atanasov, "Fully textile dual-band logo antenna for IOT wearable devices," *Sensors*, Vol. 22, No. 12, Jun. 2022.

[20] Ali Khan, M. U., R. Raad, F. Tubbal, P. I. Theoharis, S. Liu, and J. Foroughi, "Bending analysis of polymer-based flexible antennas for wearable, general IOT applications: A review," *Polymers*, Vol. 13, No. 3, Feb. 2021.

[21] Ahmad, S., A. Ghaffar, N. Hussain, and N. Kim, "Compact dual-band antenna with paired L-shape slots for on- and off-body wireless communication," *Sensors*, Vol. 21, No. 23, Dec. 2021.

[22] Rabhi, R., S. Gahgouh, and A. Gharsallah, "Watchstrap integrated wideband circularly polarized antenna design for smartwatch applications," *IET Microwaves Antennas & Propagation*, Vol. 16, No. 9, 587–601, Jul. 2022.

[23] Du, C., L.-R. Pei, J. Zhang, and C.-X. Shi, "A gain enhanced dual-band low SAR AMC-based MIMO antenna for WBAN and WLAN applications," *Progress In Electromagnetics Research M*, Vol. 115, 21–34, 2023.

[24] Elrashidi, A., K. Elleithy, and H. Bajwa, "Performance analysis of a microstrip printed antenna conformed on cylindrical body at resonance frequency 4.6 GHz for TM_{01} mode," in *Procedia Comput. Sci.*, Vol. 10, 775–784, Aug. 2012.

[25] Pozar, D. M., *Microwave Engineering*, John Wiley & Sons, 2011.

[26] Balanis, C. A., *Antenna Theory: Analysis and Design*, John Wiley & Sons, 2016.

[27] Lu, B., B. Pang, W. Hu, and W. Jiang, "Low-SAR antenna design and implementation for mobile phone applications," *IEEE Access*, Vol. 9, 96 444–96 452, 2021.