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Wearable Metamaterial Inspired Antenna for ISM, WiMax, WLAN, Wi-Fi 6E(6 GHz), Aeronautical Radio Navigation and Radio-Location Applications

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ABSTRACT: A compact, spectacle-shaped, tri-band, metamaterial inspired antenna is designed for ISM, WiMax, WLAN, Wi-Fi 6E 6 GHz, Aeronautical Radio navigation, and Radio-Location Applications. The radiating electrical length is modified by two successive CSRR structures to mitigate the current and create a band notch at 3.9 GHz as well as 5.5 GHz. The proposed prototype is designed on low cost FR-4 material. Antenna performance parameters are investigated on a four-layered phantom model. The results obtained reveal that the antenna works well on free space as well as at the close proximity to human tissues.

1. INTRODUCTION

Metamaterial inspired antennas have a unique property of miniaturization, where lower bands can be achieved with compact size of antenna. This is particularly useful when the antenna has to be embedded on a small sized wearable device, which has a limited dimension. Wearable devices are more relevant to astronomers that have embedded antennas on the space suite. Radio navigation and radio location has emerged as the most prominent field of communication where an astronomer or astronomical equipment is dependent on the number of channels to precisely locate himself, other astronauts, and spacecraft in outer space. Radio navigation provides intelligence to the pilot for enhancing and maintaining flight safety. Transponder antennas are vital for satellite communications. Antennas attached to satellites are used for transmitting and receiving the signals from satellite to earth stations (uplink and downlink).

Therefore, the antenna designed for aeronautical radio navigation and radio location need not have high gain, but the antenna has to be compact enough, so that it can be affixed on the space suite or devices.

Several designs are based on split ring resonator (SRR) and complementary SRR (CSRR) which are published where it is used for eliminating unwanted bands by creating a notch. In [1], multiple SRR rings are responsible for multiband on a coplanar waveguide (CPW)-fed antenna. In [2], SRR with tapered ground and L-shaped feed is utilized for operation at ISM band. In [3], an array, composed of an SRR is used on a saw tooth shaped defected ground, thereby improving antenna bandwidth. In [4], a radiating stub on the opposite side of a feedline is connected to SRR, where a CSRR in the ground enhances the metamaterial properties. In [5], a fractal antenna with the shape of diamond based on an edge-coupled SRR is accountable for multiple bands. In [6], a hybrid fractal shaped antenna with tapered ground is realized for multiple bands. In [7], a polygon shaped radiator with a square shaped SRR is responsible for three radiating bands and two notches. In [8], a hexagonal antenna with a circular SRR is used for biomedical applications. In [9], an arc shaped structure in the radiator agitates the surface current and is the reason for CP in ISM band. In [10], an E-shaped ground with step feed and parasitic strips are used as radiator, whereas two SRRs at the ground plane along with partial ground are utilized for 5G applications. In [11], a reconfigurable antenna is designed for 5G and other sub-6 GHz applications, where a parasitic patch is switched "ON" and "OFF", with radiating elements for switching between two different frequency bands. In [12], a four-port CPW multiple-input multiple-output (MIMO) antenna element is imbibed with a circular CSRR to generate Wi-Fi and WLAN notch. In the proposed antenna design, four SRRs and two CSRRs are employed on the antenna structure to generate tri-bands that exist at 3.14 GHz to 3.68 GHz, 4.19 GHz to 5.30 GHz, and 5.75 GHz to 6.05 GHz. The operations performed at these bands are given in Table 1. The notch band exists from 3.67 GHz to 4.13 GHz as well as from 5.30 GHz to 5.75 GHz. The antenna is positioned over a quad-layered phantom model, where its characteristics are simulated and presented in Section 3 of the article.

The novelty of the proposed design includes the points as given below

1. The antenna has compact size that guarantees simple integration into wearable devices with a small effective area.
2. Antenna is intended on low cost, easily available FR4 substrate.

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TABLE 1. Operating frequency of antenna and its applications.

Sl. No	Operating Frequency	Applications	Operating Band
1	3.14 GHz to 3.68 GHz	5G	3.3 GHz
		WiMax 3500	3.5 GHz
2.	4.19 GHz to 5.30 GHz	C-Band	4.5 GHz
		Fixed Satellite	4.5 GHz–4.8 GHz
		Radio Astronomy	4.99 GHz–5.00 GHz
		Aeronautical Radio Engineering	5.00 GHz–5.15 GHz
		Radio-Location	5.25 GHz–5.30 GHz
3	5.75 GHz to 6.05 GHz	ISM, Wi-Fi 6E(6 GHz)	5.8 GHz

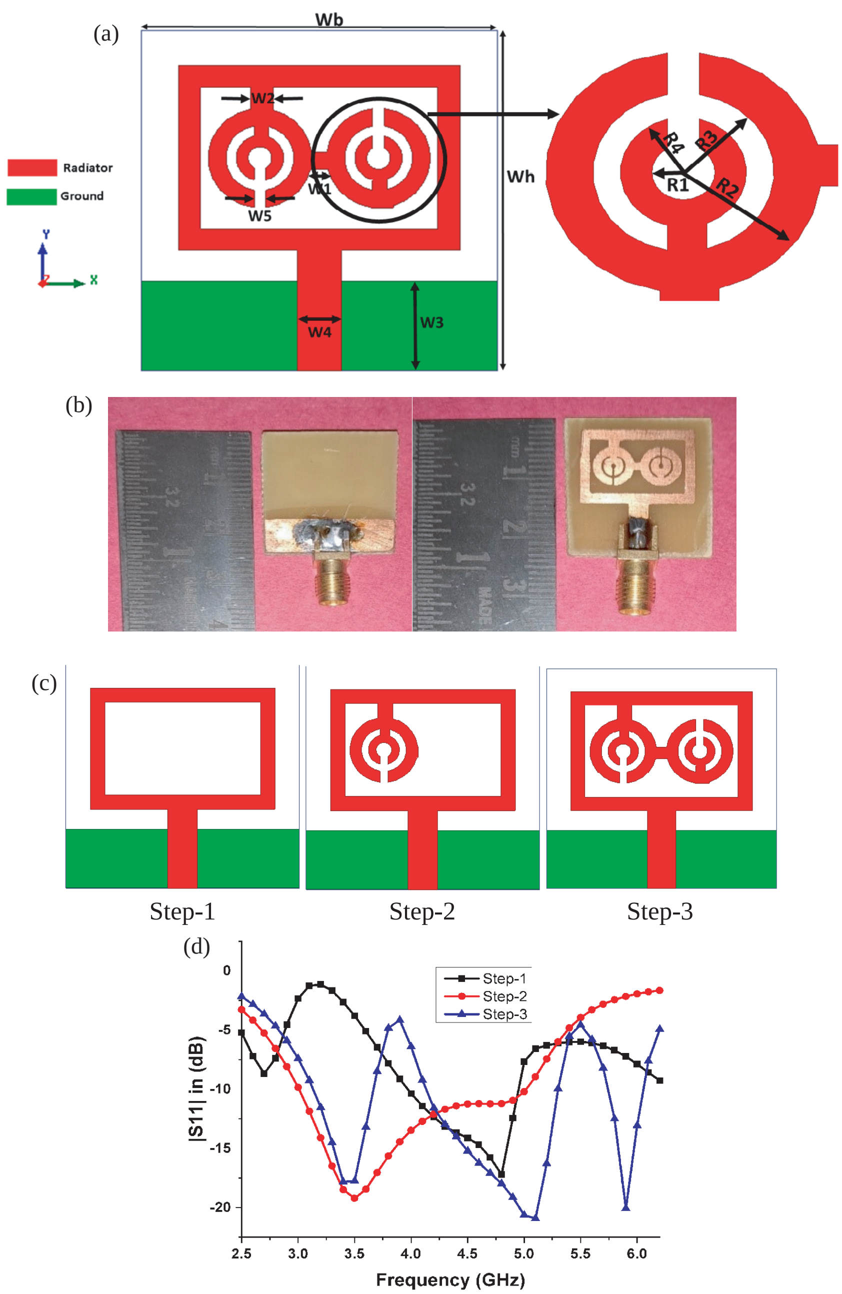

FIGURE 1. (a) Proposed antenna, (b) Fabricated Prototype, (c) Steps (evolution), (d) Return loss parameters (Steps).

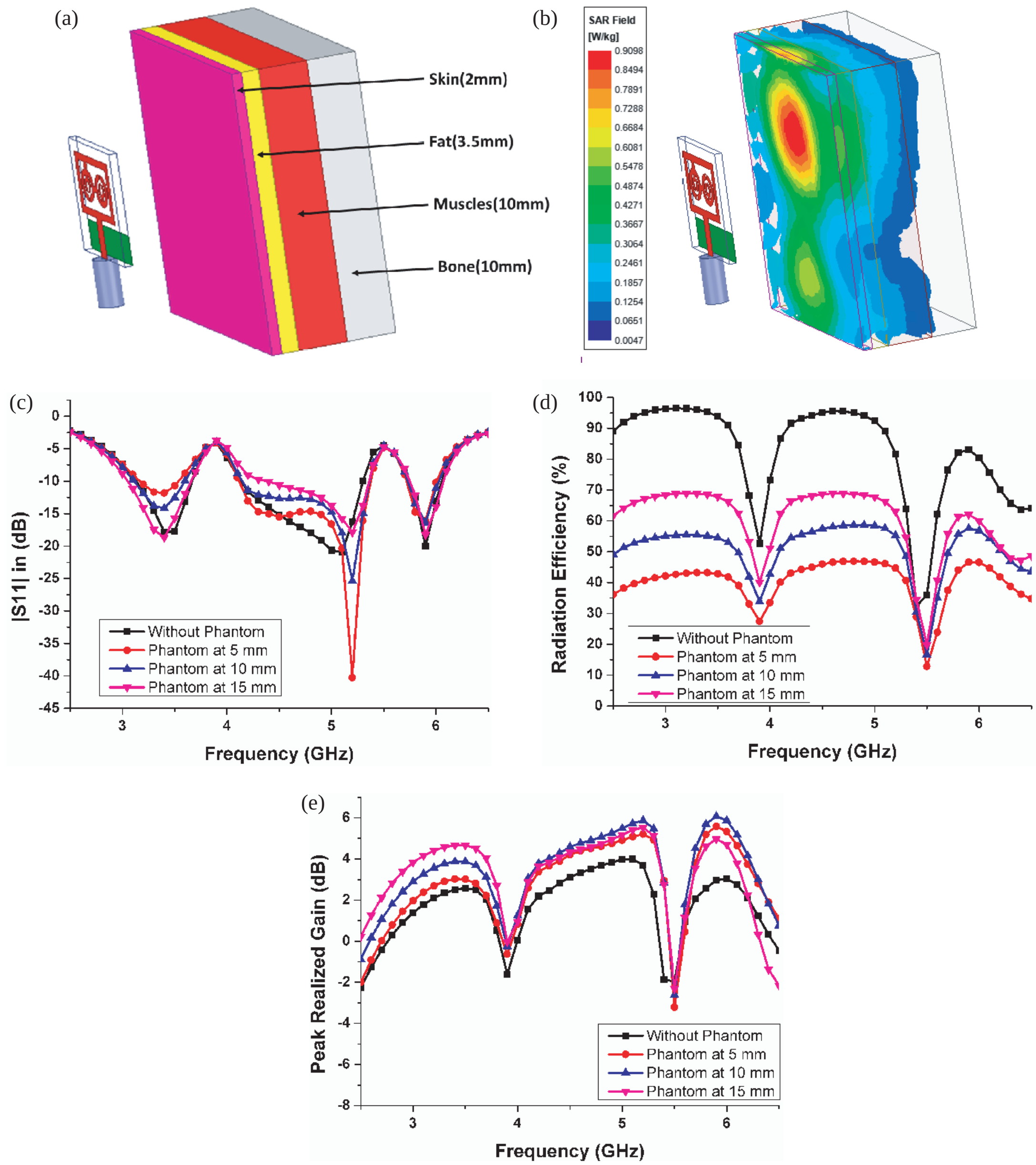

FIGURE 2. Analysis on phantom model, (a) Positioning antenna on phantom model, (b) SAR Analysis (c) $|S_{11}|$, (d) Radiation Efficiency, (e) Peak Realized Gain.

3. The compact size works well in a 4 layered phantom model, where the specific absorption rate (SAR) is low; therefore it can be used for wearable device.
4. A single antenna is utilized for Biomedical (ISM), Wi-Max, W-LAN, Aeronautical Radio Navigation and Radio-Location applications.
5. The antenna is highly compact and has low SAR, which makes it most suitable for wearable devices.
6. Metamaterial structure such as CSRR is utilized for notch bands to eliminate 3.9 GHz and 5.5 GHz bands.

2. ANTENNA DESIGN AND EVOLUTION ANALYSIS

The optimized antenna is fabricated on FR4 material ($\varepsilon_r = 4.4$) of 1.6 mm thickness. The antenna geometry is depicted in Fig. 1(a). The dimensions in mm are $W_b = W_h = 24$, $W1 = 1.2$, $W2 = 1$, $W3 = 6.3$, $W4 = 3$, $W5 = 0.8$, $R1 = 0.8$, $R2 = 3.4$, $R3 = 2.3$, $R4 = 1.6$.

Antenna is evolved in three consecutive steps.

Step-1: An approximated $\lambda/4$ rectangular radiator 19 mm $\times$ 13 mm with a 1.5 mm peripheral strip is used, where 10 dB impedance bandwidth (IBW) exists from 3.9 GHz to 4.9 GHz. Feed width is 3 mm for 50 Ω impedance as depicted in Fig. 1(a).

Step-2: Dual circular SRRs are inserted in the cavity with CSRR. The 10 dB IBW is extended that exists from 3.10 GHz to 5.00 GHz as shown in Fig. 1(c).

Step-3: A similar structure (but 180° flipped) is extended to the radiating surface. In this step, $|S_{11}|$ in dB extends

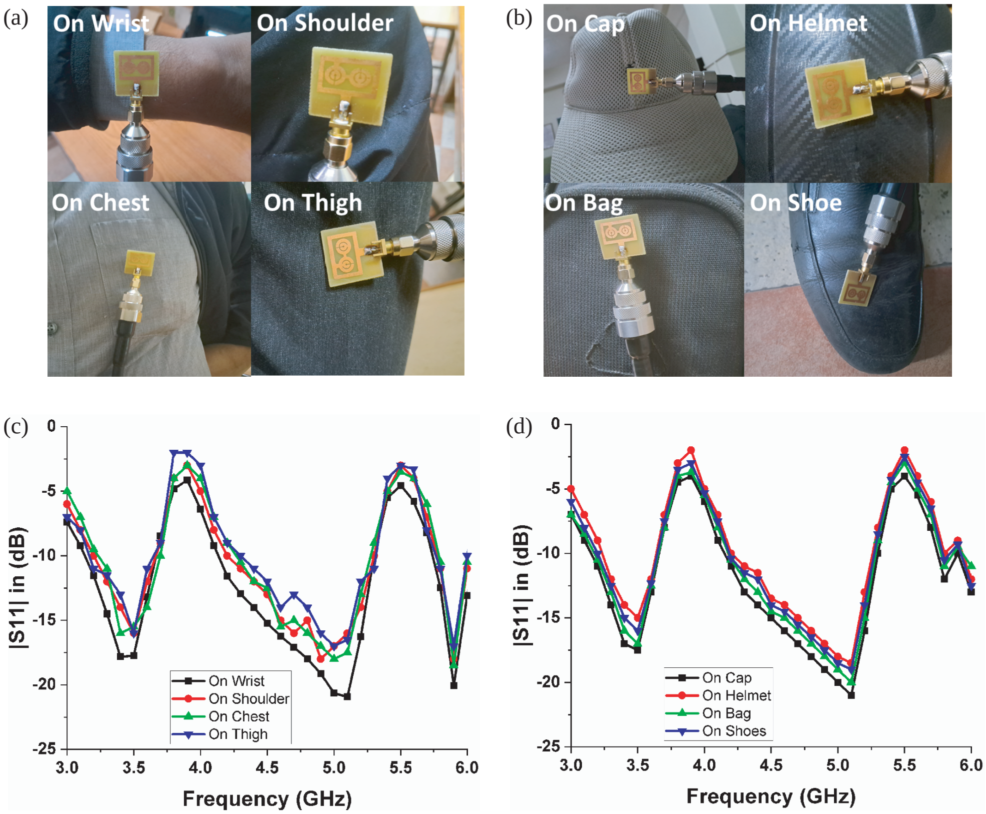

FIGURE 3. Analysis of antenna on wearable environment, (a) Measurement on different body parts, (b) Measurement on wearables, (c) $|S_{11}|$ for different body parts, (d) $|S_{11}|$ for wearables.

from 3.14 GHz to 3.68 GHz, 4.19 GHz to 5.30 GHz, and 5.75 GHz to 6.05 GHz as shown in Fig. 1(d).

The height of ground is 6.3 mm for all the steps to maintain the mutual coupling.

3. DETERMINATION OF SAR ON HOMOGENEOUS PHANTOM MODEL

To measure the effect of electromagnetic wave on human tissues, specific absorption rate (SAR) is measured on 1 Kg unit mass, averaged on 1 g/l0 g of tissue sample by Equation (1).

$$\mathrm{SAR}_{\mathrm{average}}(r,\omega) = \frac{1}{V}\int \frac{\sigma(r,\omega)\,|E(r,\omega)|_2}{2\rho(r)}\,dr \qquad (1)$$

where,

(r,ω) = Conductivity in Siemens/Meter
r = Position of Vector
V = Volume in meter cube
σ = Sample electrical conductivity
ρ = Sample Density
$|E(r,\omega)|_2$ = Electrical field in Volts/meter

To analyze the performance of antenna for the use in biomedical applications such as wearable device, the antenna structure is positioned over a four-layered phantom model. In the four-layer model, the thickness of skin is 2 mm; fat is 3.5 mm; muscles and bones are of 10 mm thickness each [8] as depicted in Fig. 2(a). The antenna is analyzed for 3 resonating frequencies of 3.46 GHz, 5.09 GHz, and 5.92 GHz. The characteristic values of bone, muscular tissue, fatty tissue, and skin is depicted in Table 2 that is effective for the resonant frequency.

The antenna is analyzed at different positions near human phantom to verify its performance such as return loss (S_{11}) as shown in Fig. 2(c), radiation efficiency as depicted in Fig. 2(d), and peak realized gain as in Fig. 2(e).

To develop a more satisfactory performance and impact of the human body on antenna performance, the antenna is practically positioned on various body parts such as wrist, shoulder, chest, and thigh as depicted in Fig. 3(a). It is observed that there are very marginal changes that are observed as shown in Fig. 3(b). Similarly, by positioning the antenna on different wearable objects such as cap, bag, helmet, and shoes, there is no considerable deviation in the return loss as shown in Fig. 3(c) as well as 3(d). These results satisfy that the antenna is working well in practical situations.

4. RESULTS AND DISCUSSIONS

The designed antenna is compact and works desirably for three bands, where the 10 dB impedance bandwidth exists from 3.14 GHz to 3.68 GHz, 4.19 GHz to 5.30 GHz, and 5.75 GHz to

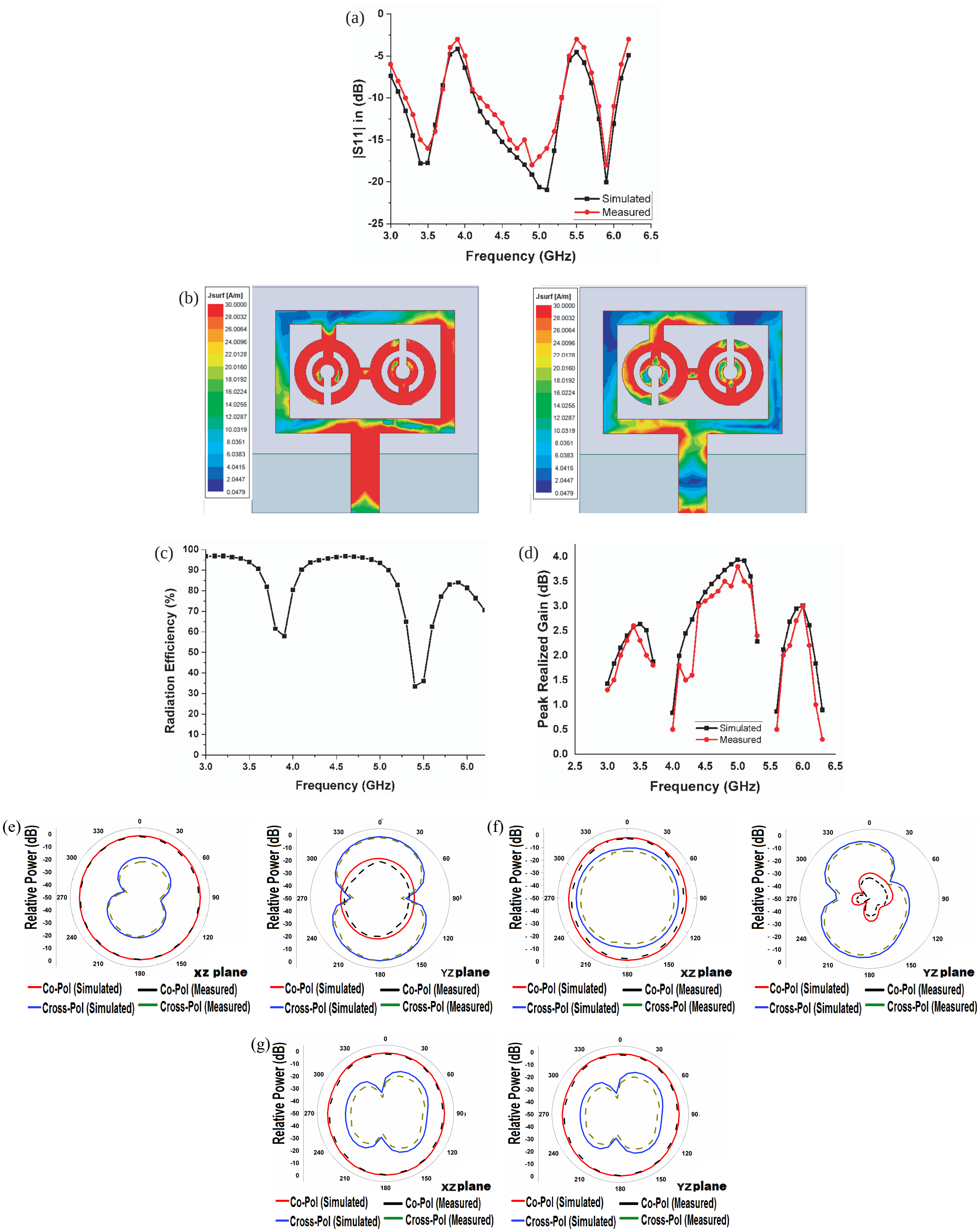

FIGURE 4. (a) $|S_{11}|$ of the proposed antenna (simulated and measured), (b) Surface current at 3.9 GHz ,5.5 GHz, (c) Radiation efficiency of antenna, (d) Peak realized gain of antenna (simulated and measured), (e)–(g) Radiation pattern (simulated and measured) at 3.4 GHz, 5.0 GHz, 5.9 GHz.

TABLE 2. Human body tissues (characteristic values) [13].

Tissue Name	Frequency (GHz)	Loss Tangent (σ)	Relative Permittivity (ε_r)	Conductivity (S/m)
Skin	3.46	0.28322	36.836	2.1474
Muscle		0.25961	51.196	2.7358
Fat		0.15672	5.1542	0.16627
Bone		0.2997	10.687	0.65927
Skin	5.09	0.30975	35.7	3.1313
Muscle		0.29612	49.422	4.1441
Fat		0.17431	5.0207	0.24781
Bone		0.34752	9.9973	0.98378
Skin	5.92	0.33137	35.013	3.8211
Muscle		0.32078	48.324	5.1052
Fat		0.30097	4.9439	0.18485
Bone		0.37342	9.6217	1.1833

TABLE 3. Evaluation of published articles compared to the proposed work.

Ref.	**Antenna Size (mm)**	**Operating Frequencies (GHz)**	**Max Gain (dB)**
[1]	40 × 40	2.10, 2.9, 3.5, 4.5, 5.7 and 6.5	6.55
[2]	30 × 17	2.45	1.86
[3]	30 × 31	2.40–2.60 and 3.40–3.79	2.25
[4]	32 × 38	2.4, 5.8 and 3.35, 7.25–7.75, 8–8.5	4.8
[5]	32 × 36	1.67–7.34	8.63
[6]	29.5 × 22	3.61, 8.44–10.86 and 14.92–15.7	4.11
[7]	30 × 20	2.34, 3.32, 6.5	4.14
[8]	30 × 20	2.45, 3.3, and 5.8	3.4
[9]	30 × 20	5.55–5.94 and 6.78–8.78	4.97
Proposed	**24 × 24**	**3.46, 5.09, 5.92**	**5.52**

6.05 GHz as depicted in Fig. 4(a). The antenna exhibits band notch at 3.9 GHz as well as 5.5 GHz due to two circular CSRR structures. The surface current at 3.9 GHz as well as 5.5 GHz is revealed in Fig. 4(b). Fig. 4(c) depicts the radiation efficiency. It is observed that the radiation efficiency is more than 95% in the operating bands, and the radiation efficiency decreases to 55% and 33% at 3.9 Ghz and 5.5 GHz respectively because of the existence of band notch at these points. Similarly, the gain is 2.7 dBi, 4.0 dBi, and 2.9 dBi at the first, second, and third bands, whereas the gain is negative at the notch bands as shown in Fig. 4(d). The radiation patterns (simulated and measured) are stable as shown in Figs. 4(e), 4(f), and 4(g). The antenna is designed to work on the WiMax, WLAN, Aeronautical Radio navigation and Radio-Location and ISM band applications and reject unwanted bands to save the operating bands from interference. The notch bands are relevant by the considerable dip in the efficiency and gain at these bands. The antenna is matched by recently published contributions in Table 3, where the antenna has proved to be more compact, maintaining other antenna parameters.

The design and simulation was accomplished using HFSS-19 simulation software, and the graphs are plotted in Origin, graph plotting software.

5. CONCLUSION

A compact, wearable tri-band antenna is designed for ISM, WiMax, WLAN, Wi-Fi 6E(6 GHz), Aeronautical Radio Navigation and Radio-Location applications. The three bands exist from 3.14 GHz to 3.68 GHz, 4.19 GHz to 5.30 GHz, and 5.75 GHz to 6.05 GHz. The antenna works effectively as a wearable antenna and does not lose its transmission characteristics even in the proximity of phantom model. The band notch is designed at 3.67 GHz to 4.13 GHz and 5.30 GHz to 5.75 GHz eliminating the interference from these unwanted bands. The antenna is compact, has high gain and efficiency. The antenna is also tested for practical environments such as different body parts and wearable objects. The antenna is proved to be a good candidate for wearable applications.

REFERENCES

[1] Selvi, N. T., P. T. Selvan, S. P. K. Babu, and R. Pandeeswari, "Multiband metamaterial-inspired antenna using split ring resonator," *Computers & Electrical Engineering*, Vol. 84, 106613, 2020.

[2] Chaturvedi, D. and S. Raghavan, "A compact metamaterial-inspired antenna for WBAN application," *Wireless Personal Communications*, Vol. 105, No. 4, 1449–1460, 2019.

[3] Hasan, M. M., M. Rahman, M. R. I. Faruque, M. T. Islam, and M. U. Khandaker, "Electrically compact SRR-loaded metamaterial inspired quad band antenna for Bluetooth/WiFi/WLAN/WiMAX system," *Electronics*, Vol. 8, No. 7, 790, 2019.

[4] Rao, M. V., B. T. P. Madhav, T. Anilkumar, and B. P. Nadh, "Metamaterial inspired quad band circularly polarized antenna for WLAN/ISM/Bluetooth/WiMAX and satellite communication applications," *AEU — International Journal of Electronics and Communications*, Vol. 97, 229–241, 2018.

[5] Sharma, N. and S. S. Bhatia, "Edge-coupled parasitic split ring resonator based metamaterial inspired low-cost diamond shaped fractal antenna for multiband wireless applications," *International Journal of Electronics*, Vol. 109, No. 2, 317–336, 2022.

[6] Saraswat, R. K., "A hybrid fractal metamaterial inspired multiband antenna for wireless applications," *Wireless Personal Communications: An Internaional Journal*, Vol. 124, No. 3, 2593–2612, 2022.

[7] Jha, P., A. Kumar, A. De, and R. K. Jain, "CPW-fed metamaterial inspired compact multiband antenna for LTE/5G/WLAN communication," *Frequenz*, Vol. 76, No. 7-8, 401–407, 2022.

[8] Sharma, N., A. Kumar, A. De, and R. K. Jain, "Design of compact hexagonal shaped multiband antenna for wearable and tumor detection applications," *Progress In Electromagnetics Research M*, Vol. 105, 205–217, 2021.

[9] Sharma, N., A. Kumar, A. De, and R. K. Jain, "Circularly polarized antenna for ISM (5.8 GHz), satellite communications and UWB applications," in *2021 8th International Conference on Signal Processing and Integrated Networks (SPIN)*, 303–307, Noida, India, 2021.

[10] Kumar, A., S. Das, and R. L. Yadava, "DGS and SRR based FSS microstrip antenna for 5G communication," in *2018 4th International Conference on Computational Intelligence & Communication Technology (CICT)*, 1–5, Ghaziabad, India, 2018.

[11] Verma, R. K., A. Kumar, and R. L. Yadava, "Compact multiband CPW fed sub 6 GHz frequency reconfigurable antenna for 5G and specific UWB applications," *Journal of Communications*, Vol. 15, No. 4, 345–349, 2020.

[12] Kumar, A., "Compact 4×4 CPW-fed MIMO antenna with Wi-Fi and WLAN notch for UWB applications," *Radioelectronics and Communications Systems*, Vol. 64, No. 2, 92–98, 2021.

[13] Italian National Research Council, Institute for Applied Physics, Florence, Italy, "An internet resource for the calculation of the dielectric properties of body tissues in the frequency range 10 Hz–100 GHz," Available: http://niremf.ifac.cnr.it/tissprop/.