

Research Article

Wide CPW-Fed Multiband Wearable Monopole Antenna with Extended Grounds for GSM/WLAN/WiMAX Applications

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A novel wide coplanar waveguide- (CPW-) fed multiband wearable monopole antenna is presented. The multiband operation is achieved by generating slanted monopoles of different lengths from an isosceles triangular patch. The different operating frequencies of the proposed antenna are associated with the lengths of the slanted monopoles, which are determined under quarter wavelength resonance condition. The CPW line is used as a multiband impedance-matching structure. The two grounds are slightly extended for better impedance matching. The proposed antenna is designed to cover the 1800 MHz GSM, 2.4 GHz/5.2 GHz WLAN, and 3.5 GHz WiMAX bands. The measured peak gains and impedance bandwidths are about 4.18/3.83/2.6/2.94 dBi and 410/260/170/520 MHz for the 1550-1960 MHz/2.3-2.56 GHz/3.4-3.57 GHz/5.0-5.52 GHz bands, respectively. The calculated averaged specific absorption rate (SAR) values at all the resonant frequencies are well below the standard limit of 2 W/kg, which ensures its feasibility for wearable applications. The antenna performance under different bending configurations is investigated and the results are presented. The reflection coefficient characteristics of the proposed antenna is also measured for different on-arm conditions and the results are compared. A good agreement between experimental and simulation results validates the proposed design approach.

1. Introduction

In today's world, for applications which involve wearable antennas, like health monitoring of patients and firefighting and military personal or body-centric communications, it becomes absolutely necessary that a single antenna operates on multiple bands, with SAR values well below the standard limits and its performance should not degrade under bent conditions. In order to satisfy these specific wireless communication requirements, multiband wearable antennas which can operate at 880–960 MHz/1710–1880 MHz for Global System for Mobile (GSM) communications, 2.4–2.484 GHz/5.15–5.825 GHz for wireless local area network (WLAN), and 3.4–3.69 GHz/5.25–5.85 GHz for Worldwide Interoperability for Microwave Access (WiMAX), are desired.

In the past few years, many single-, dual-, and multiband wearable antennas have been proposed [1–13]. In previous works, different methods have been used for designing

single-band wearable antennas, such as antennas with an electromagnetic band gap (EBG) structure [1], antennas based on metamaterial structures [2, 3], monopole antennas fed by CPW [4], and electrotexile patch antennas [5]. Similarly, dual-band wearable antennas fed by CPW on a polypropylene substrate, polygon-shaped slotted wearable antennas on a jean substrate, wearable antennas using a metasurface, polyimide-based wearable antennas, and dual-mode textile antennas on a polydimethylsiloxane (PDMS) substrate have been reported in [6–10]. In [11–13], a multiband body-borne antenna for GSM/PCS/WLAN communications, a multiband wearable antenna using a metal rim, and a quad-band wearable slot antenna with low SAR values have been presented.

CPW-fed monopole antennas have been used frequently for the achievement of multiband operations [14–19]. CPW-fed dual-frequency monopole antennas have been presented in [14–16]. In [17], a three-band operation is achieved

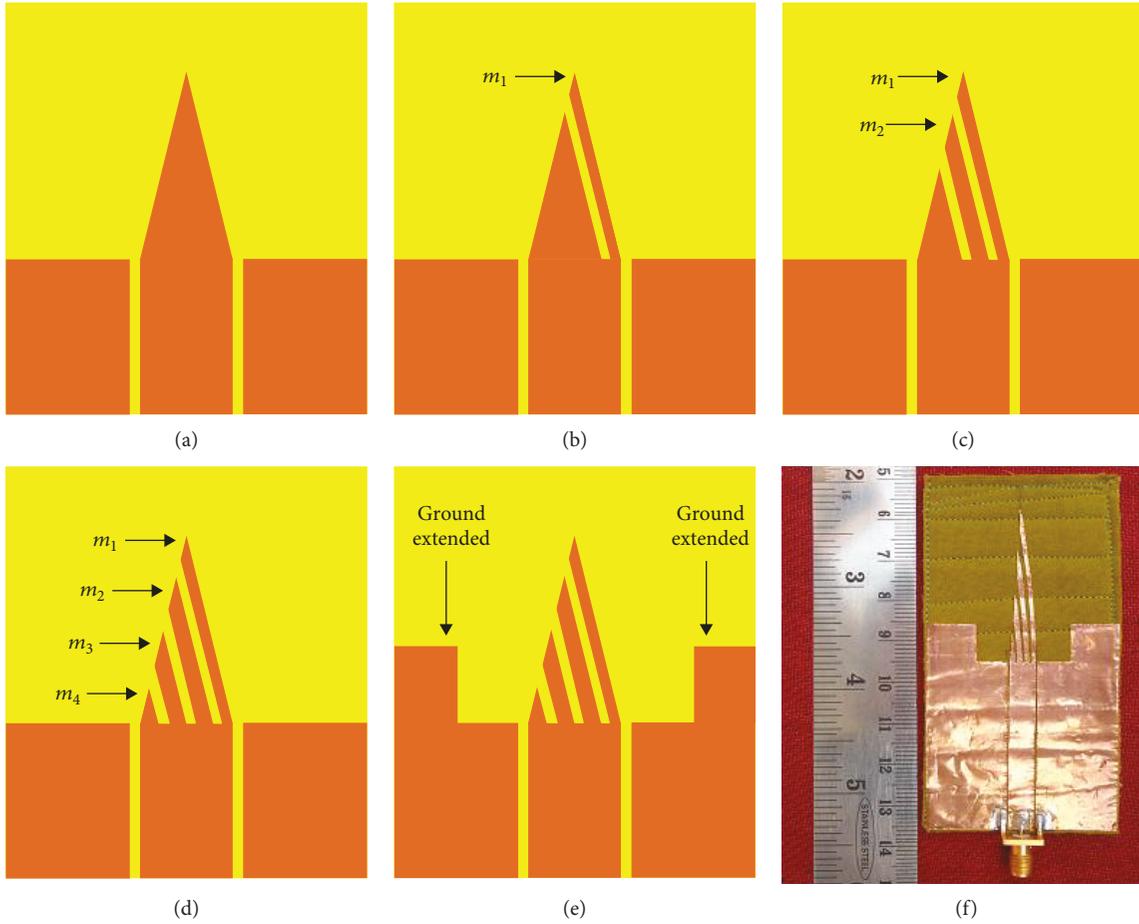


FIGURE 2: Geometries of (a) Antenna I, (b) Antenna II, (c) Antenna III, (d) Antenna IV, and (e) Antenna V and (f) photograph of the proposed handmade Antenna V.

The size of the proposed antenna considering the substrate size is $45.5 \times 85 \times 1 \text{ mm}^3$. The design procedure of the antenna, which consists of five steps, is elaborated and shown in Figure 2.

Step 1. Initially, a CPW-fed triangular patch with parameters $L = 85.0 \text{ mm}$, $W = 45.5 \text{ mm}$, $L_g = 40.0 \text{ mm}$, $W_g = 19.4 \text{ mm}$, $L_T = 38.5 \text{ mm}$, $W_T = 3.15 \text{ mm}$, $W_1 = 6.3 \text{ mm}$, $g = 0.2 \text{ mm}$, and $\theta = 85.5^\circ$ is designed. This wide CPW-fed triangular patch wearable antenna is designated Antenna I as shown in Figure 2(a). The effective dielectric constant for this design is $\epsilon_{\text{eff}} = 1.13$.

Step 2. The first slanted monopole m_1 at a resonant frequency of 1800 MHz is generated by slotting the triangular patch. The theoretical length of the slanted monopole m_1 under quarter-wavelength resonance condition is 39.19 mm. The length L_T and width W_T of the triangular patch is taken to match the length L_{m1} of the first slanted monopole m_1 , which is given by

$$L_{m1} = (L_T^2 + W_T^2)^{0.5}. \quad (4)$$

For the selected length L_T and width W_T of the isosceles triangular patch, the value of θ comes out to be approximately 85.5° , which is estimated as

$$\theta = \sin^{-1} \frac{L_T}{L_{m1}}. \quad (5)$$

Due to the mutual coupling between the slanted monopole m_1 and the rest of the triangular patch which affects the resonant frequency, the final length L_{m1} of the slanted monopole m_1 is modified to be 38.62 mm. The width W_{m1} of the first slanted monopole m_1 is 1.0 mm. This slanted monopole with the remaining triangular patch is denoted Antenna II. It is shown in Figure 2(b). The width W_{s1} of the first slot is 0.4 mm. It is considered in such a way to match the length of the second monopole m_2 .

Step 3. The second slanted monopole m_2 at a resonant frequency of 2.4 GHz is generated by making another slot in the remaining triangular patch. Theoretically, the quarter wavelength at 2.4 GHz is 29.39 mm, whereas practically, the length L_{m2} of the slanted monopole m_2 is kept at 30.45 mm with a width W_{m2} of 1.2 mm. Two slanted monopoles m_1 and m_2 along with the remaining triangular patch as shown

in Figure 2(c) is designated Antenna III. The width W_{s2} of the second slot is 0.35 mm. It is considered to match the length of the third monopole m_3 .

Step 4. The third slot with a width of $W_{s3} = 0.45$ mm is cut in a triangular patch to generate the third slanted monopole m_3 at a resonant frequency of 3.5 GHz. The quarter wavelength at 3.5 GHz is 20.15 mm. The final length L_{m3} of the third slanted monopole m_3 is kept at 20.53 mm with a width W_{m3} of 1.5 mm. This antenna with three monopoles and the remaining triangular patch is designated Antenna IV as shown in Figure 2(d). The remaining triangular patch is the fourth monopole which resonates at 5.38 GHz. The length L_{m4} and width W_{m4} of this fourth monopole is 8.578 mm and 1.4 mm, respectively.

Step 5. In the case of Antenna IV, the reflection coefficient and bandwidth of the four bands at 1800 MHz, 2.4 GHz, 3.5 GHz, and 5.38 GHz are not adequate and need to be improved. To improve the reflection coefficient and bandwidth of the four bands, both ground patches are extended with length L_{ag} and width W_{ag} . The required four-band operation is obtained when $L_{ag} = 9$ mm and $W_{ag} = 12$ mm. These extended grounds provided voltage standing wave ratio (VSWR) values close to 1 at four resonating frequencies, which proves improved impedance matching. Improved impedance matching further decreases the reflection coefficient and increases the bandwidth of the four respective bands. The antenna with four monopoles along with extended grounds is the final required design denoted Antenna V. Antenna V is shown in Figure 2(e). The photograph of the handmade Antenna V is shown in Figure 2(f).

3. Simulation and Measurement Methodology

The antenna design is simulated using a high-frequency structure simulator (HFSS). The simulation is performed for the reflection coefficients (S_{11}) of the proposed antenna with varying L_{ag} and W_{ag} , for 3-dimensional and 2-dimensional radiation patterns, gain, radiation efficiency, surface current density distribution, and SAR values at all resonant frequencies. The reflection coefficient (S_{11}) of the handmade Antenna V is measured using the ANRITSU MS46322A vector network analyzer. The expression used to measure the gain of the Antenna V is given as [13] follows:

$$\text{Gain of the test antenna} = G + (P_T - P_R), \quad (6)$$

where G is the gain of the reference pyramidal horn antenna known over the anisotropic antenna, P_T and P_R are the power received by the test antenna and the power received by the reference antenna, respectively.

A three-layer human tissue model is used for the estimation of SAR values at the measured resonant frequencies of the proposed antenna. The permittivity (ϵ_r) and conductivity σ (S/m) of the skin (dry and wet), fat, and muscle layers at 1780 MHz, 2.40 GHz, 3.46 GHz, and 5.26 GHz are listed in Tables 1 and 2 [7, 13, 23, 26]. The thickness, mass density,

TABLE 1: Permittivity (ϵ_r) of skin, fat, and muscle.

Layer	Permittivity (ϵ_r)			
	1780 MHz	2.40 GHz	3.46 GHz	5.26 GHz
Skin (dry)	38.90	38.06	37.04	35.56
Skin (wet)	43.88	42.92	41.53	39.30
Fat	5.35	5.28	5.17	5.00
Muscle	54.47	53.63	52.25	49.77

TABLE 2: Conductivity σ (S/m) of skin, fat, and muscle.

Layer	Conductivity σ (S/m)			
	1780 MHz	2.40 GHz	3.46 GHz	5.26 GHz
Skin (dry)	1.17	1.44	1.99	3.25
Skin (wet)	1.22	1.56	2.27	3.80
Fat	0.07	0.10	0.15	0.25
Muscle	1.37	1.77	2.62	4.53

TABLE 3: Thickness, density, and loss tangent of skin, fat, and muscle layers.

Layer	Thickness (mm)	Density (kg/m ³)	Loss tangent
Skin	3	1090	0.418
Fat	10	1100	0.186
Muscle	30	1050	0.342

and loss tangent [7] of the skin, fat, and muscle layers are summarized in Table 3. The surface size of the human tissue model used for SAR calculations is 200×200 mm². The IEEE C95.3 standard, in which SAR is averaged over 10 g of biological tissue, is used to calculate averaged SAR [2, 13].

In order to investigate the effects of slight and severe bending on antenna performance, two diameters have been taken for bending analysis. The 160 mm diameter offers slight bending, while the 110 mm diameter offers severe bending. The reflection coefficients (S_{11}) of the proposed antenna have been measured for light and severe bending configurations along x and y planes, and are compared with simulation results. Two on-arm conditions, with and without cloth, have been used to measure the performance of the proposed antenna on human body.

4. Results and Discussion

The simulated reflection coefficients (S_{11}) of Antenna I to Antenna V are summarized in Figure 3. The effect of L_{ag} and W_{ag} on the overall reflection coefficient (S_{11}) is illustrated in Figures 4 and 5. Antenna I covers two bands from 1840 MHz to 2400 MHz (560 MHz, 26.42%) and 5.4 GHz to 6.3 GHz (900 MHz, 15.38%).

Antenna II has three bands that cover from 1660 MHz to 1920 MHz (260 MHz, 14.53%), 2.52 GHz to 2.7 GHz (180 MHz, 8.34%), and 5.2 GHz to 5.8 GHz (600 MHz, 10.9%). Antenna III covers three bands from 1660 MHz to 1960 MHz (300 MHz, 16.57%), 2.36 to 2.46 GHz (100 MHz, 4.15%), and 5.3 GHz to 5.84 GHz (540 MHz, 9.69%).

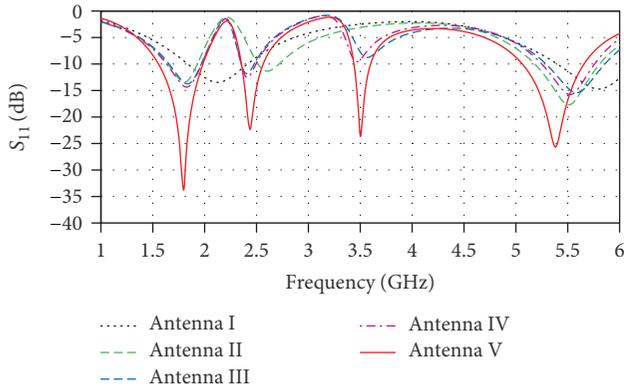


FIGURE 3: Simulated reflection coefficient (S_{11}) of Antenna I to Antenna V.

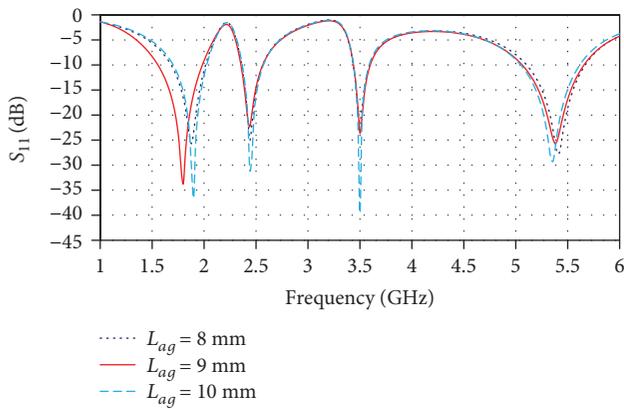


FIGURE 4: Reflection coefficient (S_{11}) of Antenna V at $W_{ag} = 12$ mm and $L_{ag} = 8, 9,$ and 10 mm.

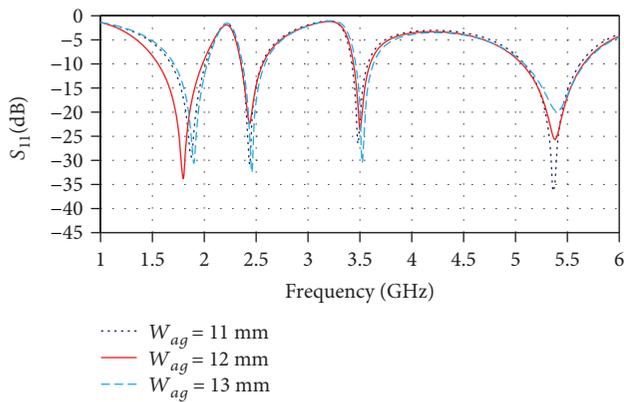


FIGURE 5: Reflection coefficient (S_{11}) of Antenna V at $L_{ag} = 9$ mm and $W_{ag} = 11, 12,$ and 13 mm.

Antenna IV has three bands that cover from 1640 MHz to 1960 MHz (320 MHz, 17.78%), 2.36 GHz to 2.48 GHz (120 MHz, 4.96%), and 5.26 GHz to 5.74 GHz (480 MHz, 8.73%). Antenna V covers four required bands from 1550 MHz to 1980 MHz (430 MHz, 24.36%), 2.36 GHz to 2.56 GHz (200 MHz, 8.13%), 3.43 GHz to 3.59 GHz (160 MHz, 4.56%), and 5.08 GHz to 5.65 GHz (570 MHz,

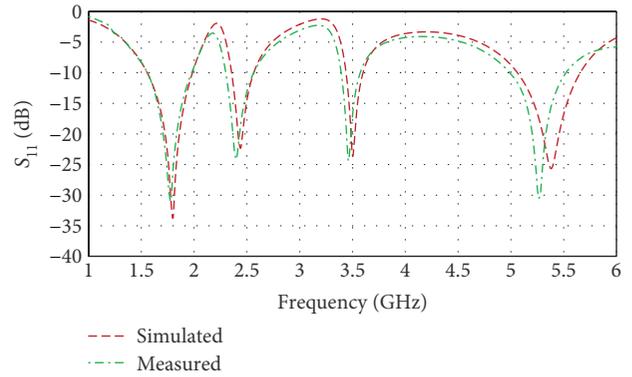


FIGURE 6: Measured and simulated reflection coefficient of Antenna V.

10.62%). The resonant frequencies of the simulated Antenna V are 1800 MHz, 2.44 GHz, 3.5 GHz, and 5.38 GHz, with reflection coefficient values of -33.7 dB, -22.3 dB, -23.6 dB, and -25.6 dB, respectively.

The first band of Antenna V covers the 1710–1880 MHz GSM band. The second band of Antenna V satisfies the requirement of 2.4–2.484 GHz WLAN applications. The third band of Antenna V operates within the 3.4–3.7 GHz WiMAX range. The fourth band of Antenna V covers the 5.15–5.35 GHz WLAN operational band. Figure 6 shows the measured and simulated reflection coefficients of Antenna V.

The measured operating bands of Antenna V are 1550 MHz to 1960 MHz (410 MHz, 23.36%), 2.3 GHz to 2.56 GHz (260 MHz, 10.69%), 3.4 GHz to 3.57 GHz (170 MHz, 4.87%), and 5.0 GHz to 5.52 GHz (520 MHz, 9.89%). The measured resonant frequencies of Antenna V are 1780 MHz, 2.40 GHz, 3.46 GHz, and 5.26 GHz, with reflection coefficient values of -30.8 dB, -24.15 dB, -24.3 dB, and -30.4 dB, respectively.

From the simulated and measured results, a slight shift in the resonant frequencies accompanied by a change in reflection coefficient values has been found. This can be attributed to the inconsistency in the fabrication process and soldering tolerance.

Refereeing to these results, the proposed antenna can satisfy the 1800 MHz GSM, 2.4/5.2 GHz WLAN, and 3.5 GHz WiMAX bands, resulting in a four-band operation.

Figure 7 shows the surface current distributions of Antenna V at 1800 MHz, 2.44 GHz, 3.5 GHz, and 5.38 GHz. The surface current densities are at the maximum in the corresponding monopoles at the respective simulated resonant frequencies of 1800 MHz, 2.44 GHz, 3.5 GHz and 5.38 GHz. In monopole elements that are sufficiently thin electrically and not too long, the element current distribution is approximately sinusoidal [27]. The first quarter-wavelength monopole m_1 corresponding to 1800 MHz is the thinnest among all four monopoles, and its current distribution is nearly sinusoidal.

Since the measured resonant frequencies of Antenna V are 1780 MHz, 2.40 GHz, 3.46 GHz, and 5.26 GHz, Figure 8 shows the 3-dimensional simulated radiation patterns of Antenna V at measured resonant frequencies. Figures 9–12

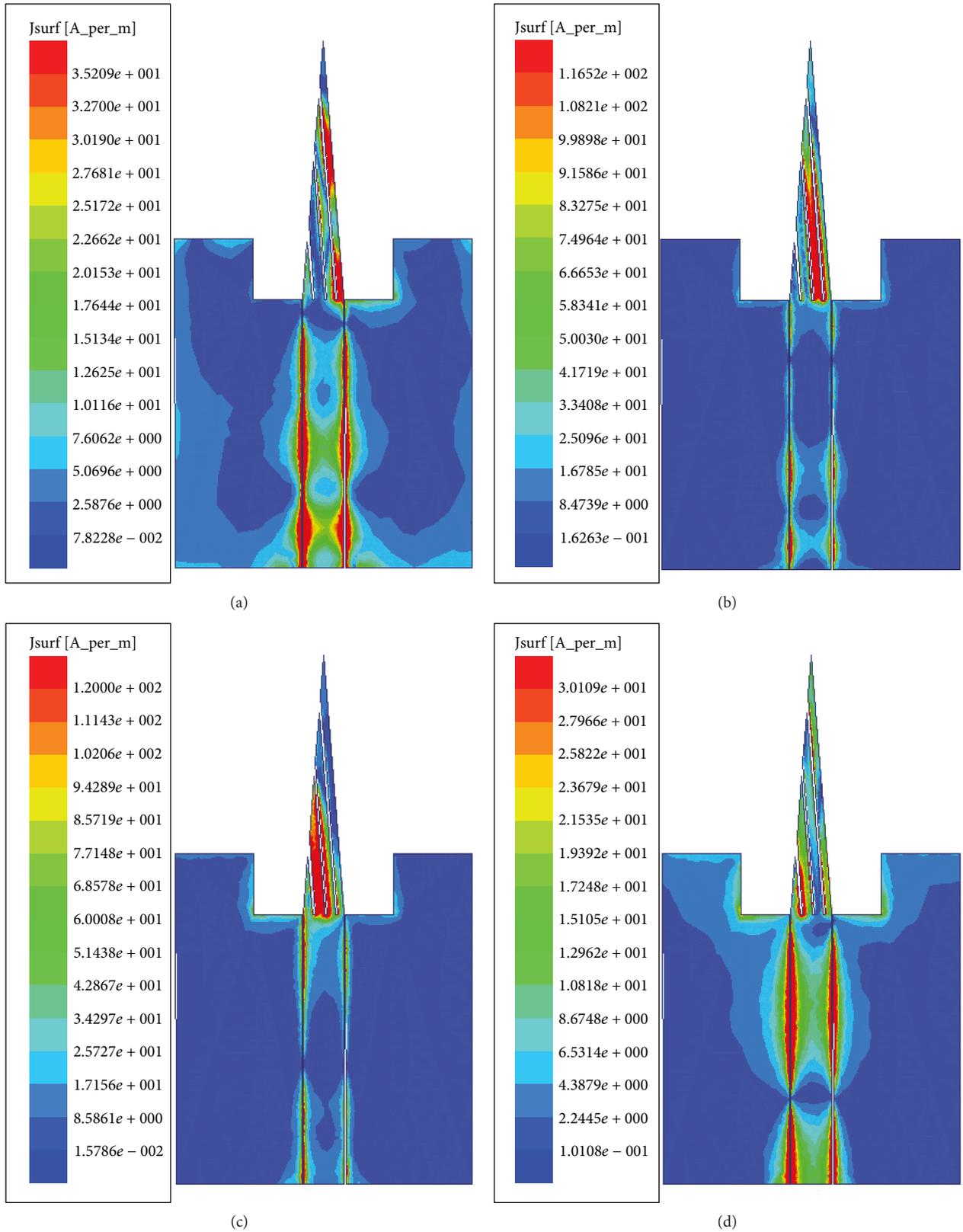


FIGURE 7: Surface current density distributions of Antenna V at (a) 1800 MHz, (b) 2.44 GHz, (c) 3.5 GHz, and (d) 5.38 GHz.

illustrate the 2-dimensional simulated and measured radiation patterns in $x-z$, $y-z$, and $x-y$ planes of Antenna V at measured resonant frequencies.

CPW-fed antennas normally suffer backward radiation. The radiation patterns at 1780 MHz and 2.4 GHz are quite similar and also suffered backward radiation, which is the

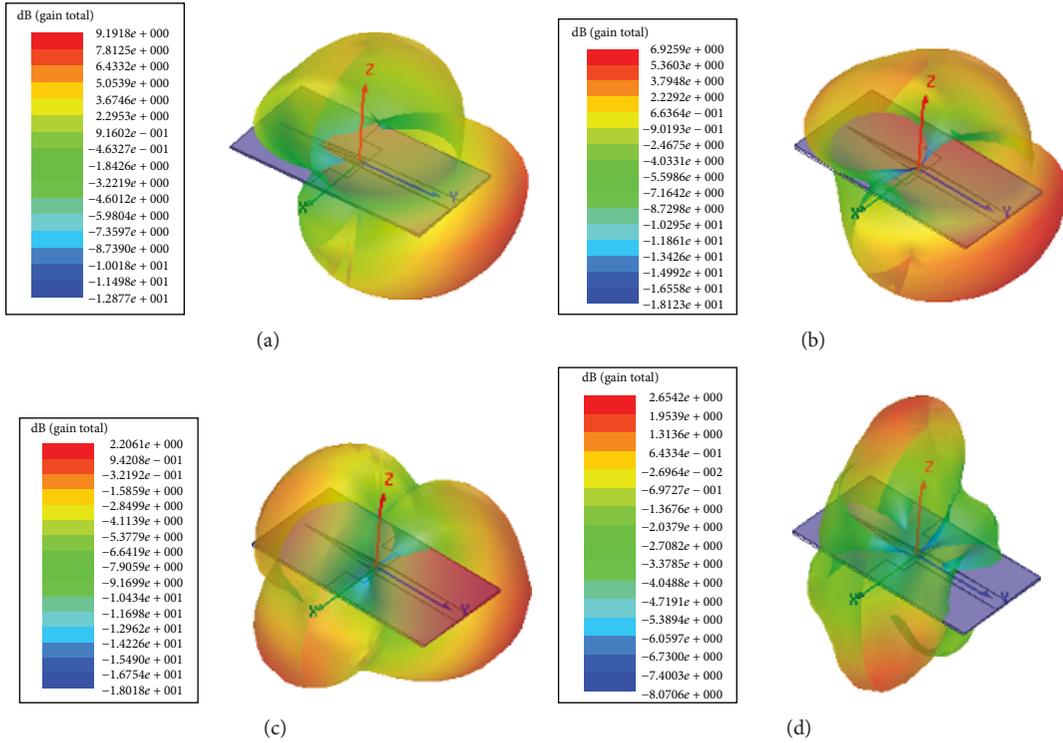


FIGURE 8: 3-Dimensional simulated radiation patterns of Antenna V at (a) 1780 MHz, (b) 2.40 GHz, (c) 3.46 GHz, and (d) 5.26 GHz.

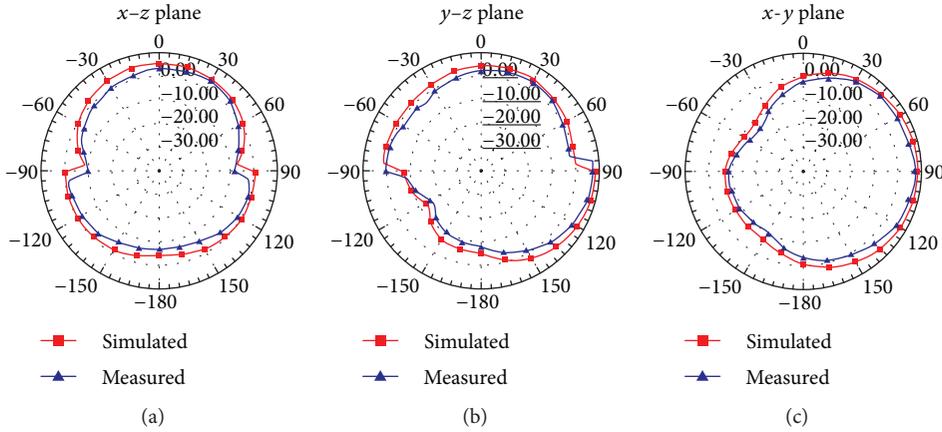


FIGURE 9: 2-Dimensional simulated and measured radiation patterns of Antenna V at 1780 MHz.

reason for the shapes of their radiation patterns. However, at 3.46 GHz and 5.26 GHz, the radiation patterns are distinct.

Figure 13 shows the measured and simulated peak gains versus the frequency of Antenna V. The measured and simulated peak gains in the 1550–1960 MHz band vary from 3.3 to 4.18 dBi and 8.51 to 9.33 dB, respectively. The measured and simulated results in the 2.3–2.56 GHz band described that the gain variations are from 3.24 to 3.83 dBi and 5.63 to 7.15 dB. For the third and fourth operating bands of 3.4–3.57 GHz and 5.0–5.52 GHz, the measured peak gains are about 1.86–2.6 dBi and 2.01–2.94 dBi. The simulated peak gains for the 3.4–3.57 GHz and 5.0–5.52 GHz bands lie within 1.74 to 2.41 dB and 1.59 dB to 2.75 dB, respectively. The simulated radiation efficiency of the proposed Antenna V is shown in Figure 14. For the 1550 MHz–1960 MHz band, the radiation

efficiency is about 91.92 to 94.94%. In the second band of 2.3–2.56 GHz, the radiation efficiency varies from 82.16 to 95.69%.

The results in the 3.4–3.57 GHz and 5.0–5.52 GHz bands described that the radiation efficiency variations are from 80.89 to 94.10% and 80.20 to 87.82%, respectively.

4.1. Specific Absorption Rate (SAR) Estimation. Figure 15 shows the three-layer human tissue model [13] used for SAR calculations at the measured resonant frequencies of Antenna V. The estimated SAR values for dry and wet skin are investigated and the results are compared in Table 4.

Referring to these results, SAR values tend to increase with an increase in the simulating frequency of the human tissue model except at 5.26 GHz. It is due to the pointed

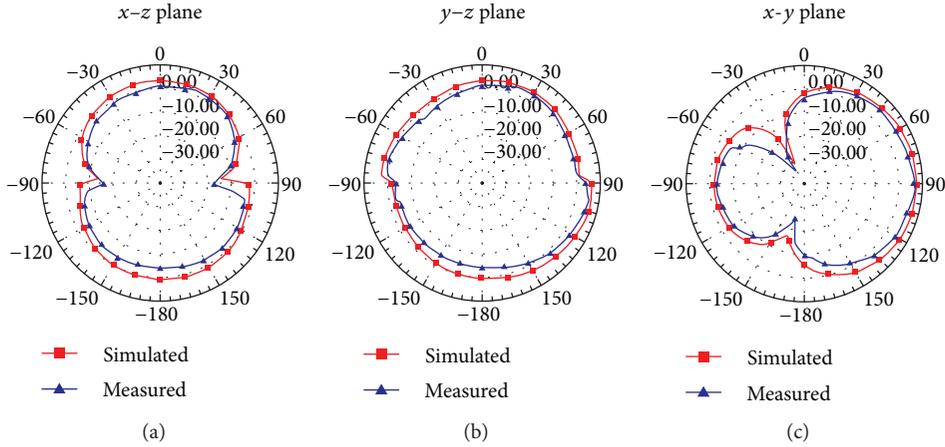


FIGURE 10: 2-Dimensional simulated and measured radiation patterns of Antenna V at 2.40 GHz.

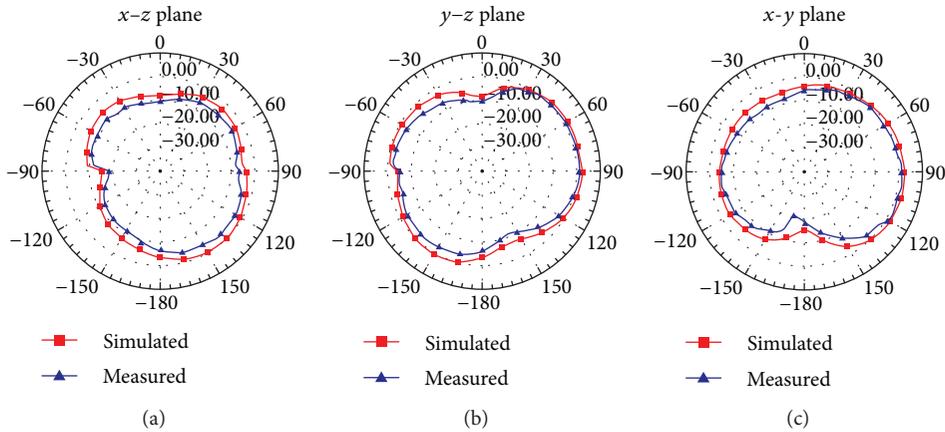


FIGURE 11: 2-Dimensional simulated and measured radiation patterns of Antenna V at 3.46 GHz.

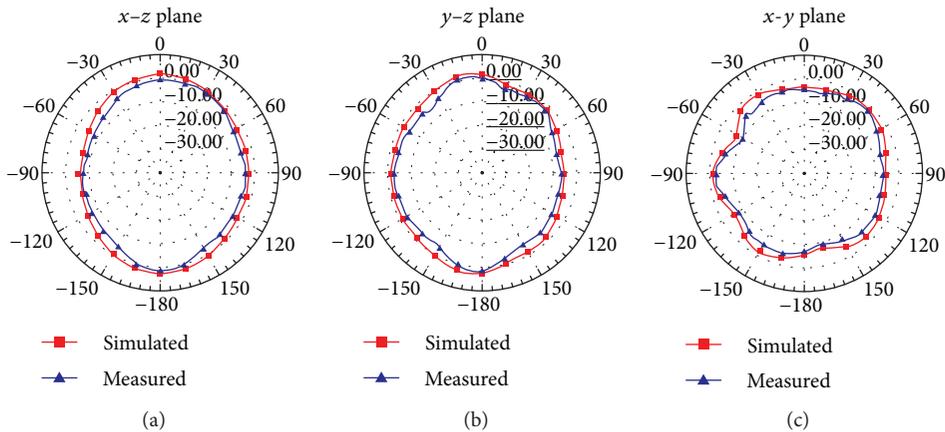


FIGURE 12: 2-Dimensional simulated and measured radiation patterns of Antenna V at 5.26 GHz.

radiation pattern in the z direction at 5.26 GHz, which shows that a small amount of radiation is illuminating the human tissue model, and therefore, the reason for the low SAR value at 5.26 GHz.

The estimated SAR value for the human tissue model with wet skin is higher than that of the model with dry skin for 1780 MHz, whereas for 2.4 GHz, 3.46 GHz, and 5.26 GHz,

the SAR values for the model with dry skin are higher than that of the model with wet skin.

4.2. *Antenna Performance under Bending Configurations.* Bending is investigated in the x and y planes by keeping the handmade Antenna V around the PVC (polyvinyl chloride) pipes [3, 13] with diameters of 160 mm and 110 mm as

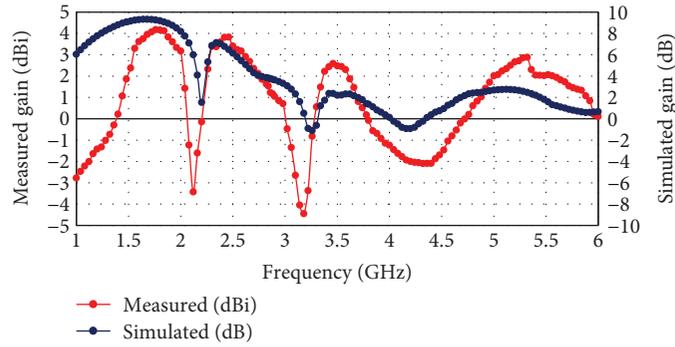


FIGURE 13: Measured and simulated peak gain of the proposed Antenna V.

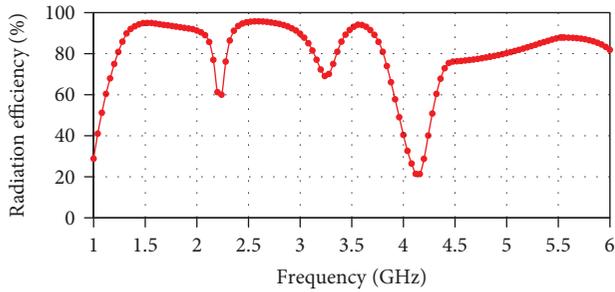


FIGURE 14: Radiation efficiency of the proposed Antenna V.

TABLE 4: Estimated SAR (W/kg) values for the three-layer human tissue model with dry and wet skin.

Frequency	Average SAR (W/kg)	
	Dry skin	Wet skin
1780 MHz	0.2293	0.2549
2.40 GHz	0.3892	0.3861
3.46 GHz	0.4640	0.4447
5.26 GHz	0.2535	0.2512

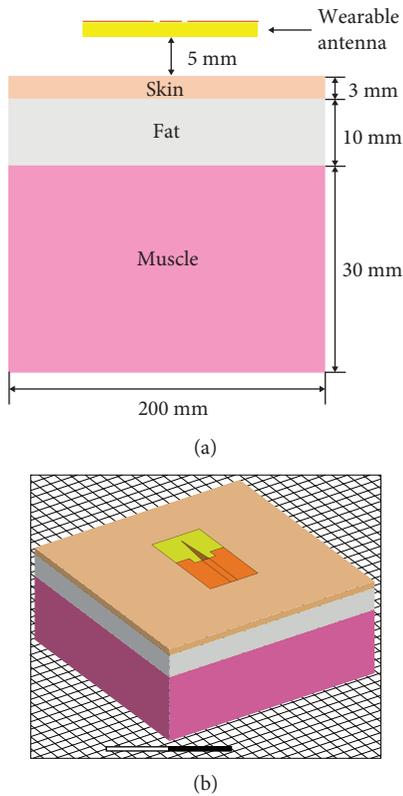


FIGURE 15: Modelling of (a) Antenna V on a three-layer human tissue model for SAR calculation and (b) Antenna V over a three-layer human tissue model in HFSS [13] (reproduced courtesy of the Electromagnetics Academy).

shown in Figure 16. Figure 17 shows the four cases of bending during HFSS simulation.

Figures 18–21 compare the measured reflection coefficient of the flat Antenna V in free space with the simulated and measured reflection coefficients of Antenna V, bent along the x and y planes on PVC pipes with radii of 55 mm and 80 mm. Frequency detuning, which is observed when simulated and measured results are compared for all four cases of the bending of Antenna V, is presented in Table 5.

For both simulated and measured results, the 1780 MHz band shifts to the right side of the spectrum for all four bending cases of Antenna V. Similarly, in the case of the simulated results, the 2.4 GHz band shifts to the right side of the spectrum for all four cases of bending of Antenna V along the x and y planes. The measured results described that the 2.4 GHz band shifts to the right side of the spectrum for Cases 2 and 3, but it does not shift for Cases 1 and 4.

The simulated results of the four bending cases illustrated that the 3.46 GHz band shifts to the left side for Cases 1, 3, and 4, whereas it shifts to the right side of the spectrum for Case 2. However, the measured results show that the 3.46 GHz band shifts to the left side for Cases 1 and 3, does not shift for Case 2, and shifts to the right side of the spectrum for Case 4.

The simulated as well as measured results show that the last 5.26 GHz band shifts to the left side of the spectrum for all four bending cases of Antenna V. In our proposed antenna, it could be easily seen that the antenna has strong currents on its ground planes, especially around the CPW feed line. The ground planes are actually a part of the proposed CPW-fed antenna. Taking this into account, it could be deduced that the distribution of the currents in the ground plane will change with the size and or/shape of the ground plane. As a result, the impedance and radiation performance

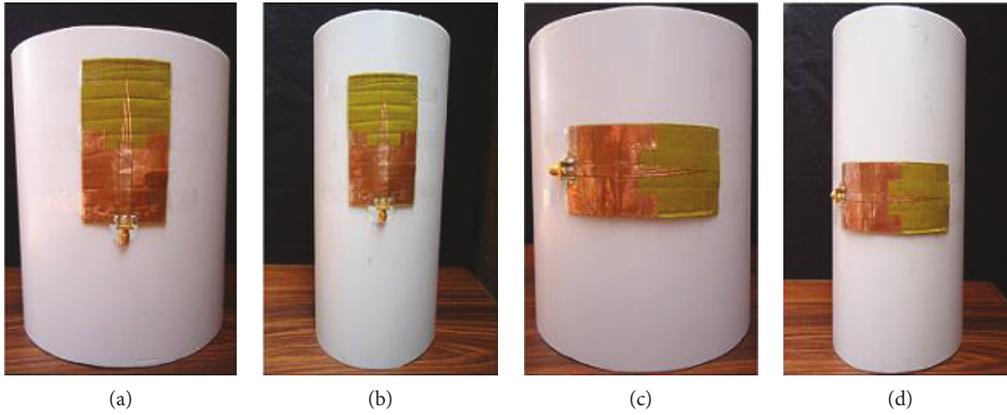


FIGURE 16: Photographs of Antenna V under four bending conditions on a PVC pipe (a) bent along the x plane on an 80 mm radius, (b) bent along the x plane on a 55 mm radius, (c) bent along the y plane on an 80 mm radius, and (d) bent along the y plane on a 55 mm radius.

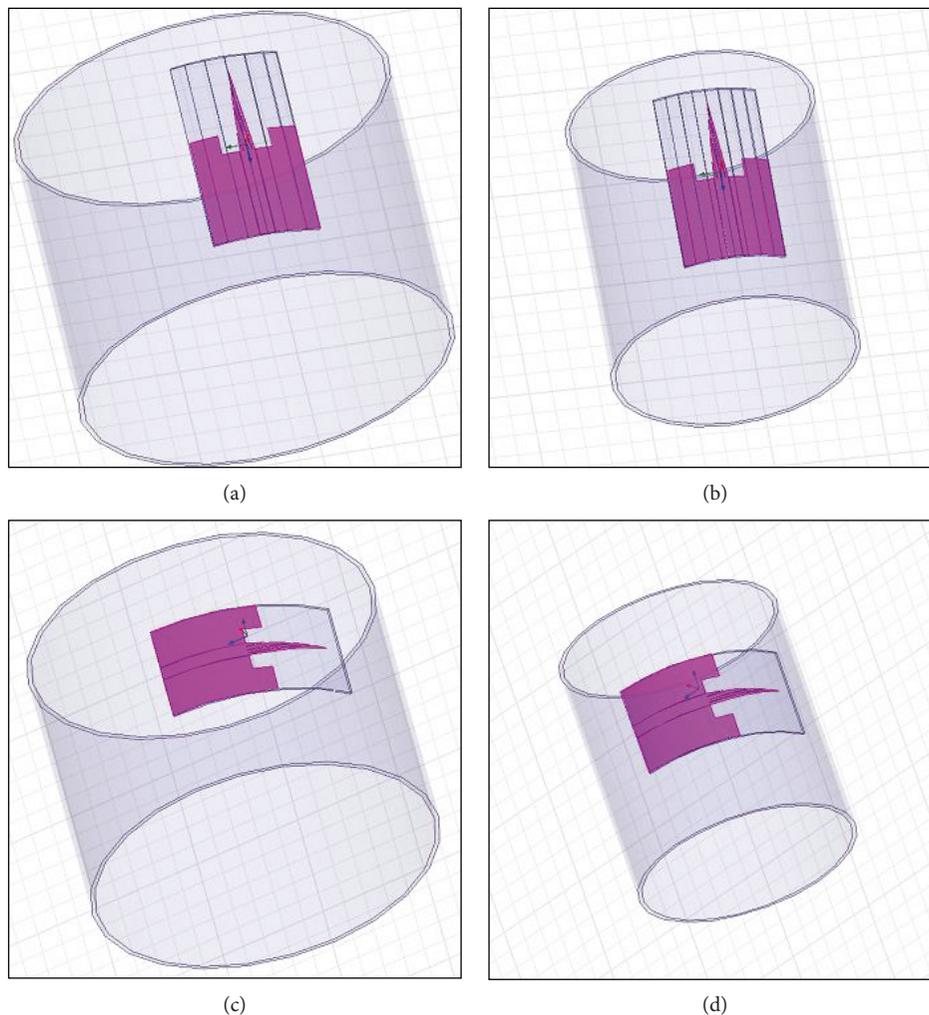


FIGURE 17: HFSS simulation photographs of Antenna V under four bending conditions on a PVC pipe (a) bent along the x plane on an 80 mm radius, (b) bent along the x plane on a 55 mm radius, (c) bent along the y plane on an 80 mm radius, and (d) bent along the y plane on a 55 mm radius.

of the antenna will change, similar to that in [6]. The bending of Antenna V along the x plane has more effects on ground planes, giving rise to an impedance mismatch, which is more

significant for the 3.46 GHz band. This band is also severely degraded during bending along the x plane, for both the 55 mm and 80 mm bending radius cases. Similarly, the

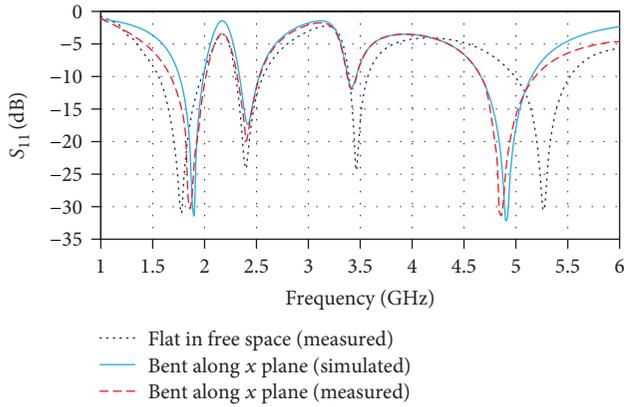


FIGURE 18: Simulated and measured reflection coefficients of Antenna V bent along the x plane on a PVC pipe with an 80 mm radius.

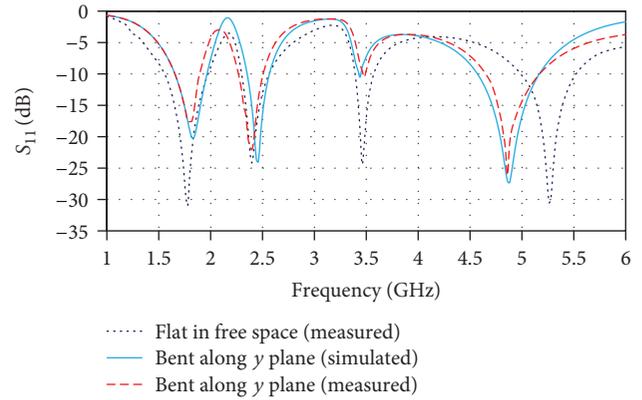


FIGURE 21: Simulated and measured reflection coefficients of Antenna V bent along the y plane on a PVC pipe with a 55 mm radius.

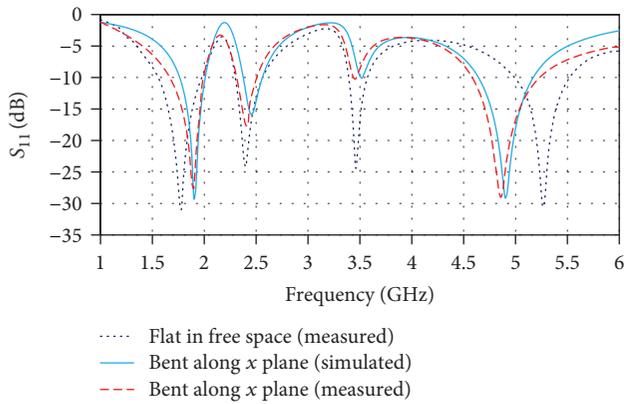


FIGURE 19: Simulated and measured reflection coefficients of Antenna V bent along the x plane on a PVC pipe with a 55 mm radius.

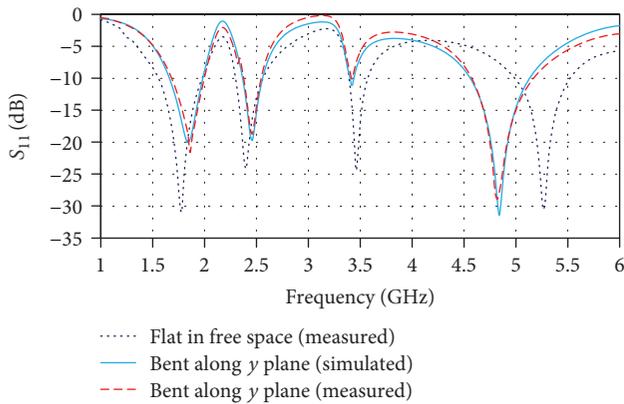


FIGURE 20: Simulated and measured reflection coefficients of Antenna V bent along the y plane on a PVC pipe with an 80 mm radius.

bending of Antenna V along the y plane changed the electrical length of the antenna and CPW line, which again increases the impedance mismatch of the proposed antenna,

especially for the 3.46 GHz band, degrading it for both the 55 mm and 80 mm bending radius cases.

For bending along the x plane, the measured and simulated frequency detuning values of Case 2 are either equal to or higher than that of Case 1, except for the 3.46 GHz band, for the measured value. On the contrary, for bending along the y plane, the measured and simulated frequency detuning values of Case 4 are either equal to or less than that of Case 3.

Maximum frequency detuning is observed for Case 3 at the 5.26 GHz band. In the measured results of the 2.4 GHz and 3.46 GHz bands, no frequency shift is observed for Cases 1, 4, and 2, respectively. Minimum frequency detuning has been found at the 3.46 GHz band for Case 4.

4.3. On-Arm Performance of the Proposed Antenna. Figure 22 illustrates the setup for two on-arm conditions of Antenna V during reflection coefficient measurement. The first condition is Antenna V on arm, without cloth, and the second condition is Antenna V on arm, with cloth [13, 24].

The measured reflection coefficients for the two on-arm conditions are compared with the measured reflection coefficient of the flat Antenna V in free space, and the results are presented in Figure 23. For both on-arm conditions, the 1780 MHz, 2.4 GHz, and 3.46 GHz bands shifted to the left side, whereas the 5.26 GHz band shifted to the right side of the spectrum. The reflection coefficient of all bands of Antenna V for the on-arm, without-cloth condition, decreases.

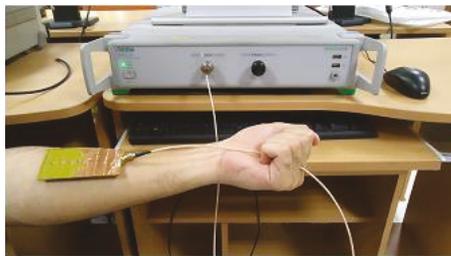
For the on-arm, with-cloth condition, the reflection coefficient of the 1780 MHz and 5.26 GHz bands decreases, while that of 2.4 GHz band increases and that of 3.46 GHz band remains unchanged.

The frequency detuning of Antenna V for the two on-arm conditions is given in Table 6. The frequency detuning values of Antenna V for the on-arm, without-cloth condition are higher than that for the on-arm, with-cloth condition.

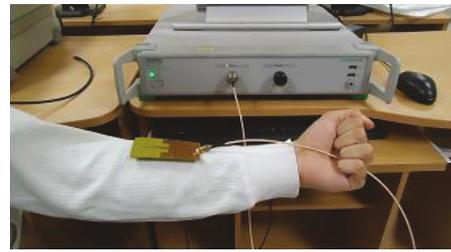
Maximum frequency detuning is calculated at the 1780 MHz band for the without-cloth condition during on-arm performance measurements. Minimum frequency

TABLE 5: Frequency detuning of Antenna V for bending in the x and y planes.

Resonant frequency	Simulated/measured	Frequency detuning (%)			
		x plane		y plane	
		Case 1 80 mm bending radius	Case 2 55 mm bending radius	Case 3 80 mm bending radius	Case 4 55 mm bending radius
1780 MHz	Simulated	6.74	6.74	3.37	2.24
	Measured	4.49	6.74	4.49	1.12
2.4 GHz	Simulated	0.83	2.50	2.50	2.50
	Measured	0.00	0.83	2.50	0.00
3.46 GHz	Simulated	1.15	1.73	1.15	0.57
	Measured	1.15	0.00	1.15	0.57
5.26 GHz	Simulated	6.84	6.84	7.98	7.22
	Measured	7.60	7.60	8.36	7.60



(a)



(b)

FIGURE 22: Setup for performance measurement of Antenna V for on-arm (a) without-cloth and (b) with-cloth conditions.

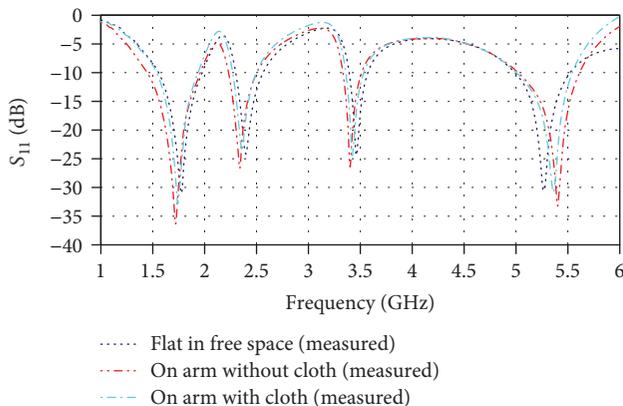


FIGURE 23: Measured reflection coefficients for on-arm conditions of Antenna V.

TABLE 6: Frequency detuning of Antenna V for on-arm conditions.

On-arm condition	Frequency detuning (%)			
	1780 MHz	2.4 GHz	3.46 GHz	5.26 GHz
Without cloth	3.37	2.50	1.73	2.66
With cloth	2.24	1.66	1.15	1.90

detuning is observed at the 3.46 GHz band for the with-cloth condition.

Finally, we compare the proposed antenna with other wearable antennas having single-band [1, 2, 4, 5], dual-band [6–10], tri-band [11, 12], and quad-band [13] operations, and the results are listed in Table 7. The

single-band wearable antennas in [1, 2] have comparatively lower SAR values at 2.4 GHz, but their sizes are larger than those of our proposed antenna. It can be seen that the sizes of the CPW-fed wearable antennas in [4–6, 8, 9] are smaller than those of our proposed four-band wearable antenna, but they are exhibiting only single-band and dual-band operations, respectively.

The gains of the dual-band wearable antennas in [7, 10] are better; however, their sizes are larger and their radiation efficiencies and bandwidths are lower than that of our proposed antenna. The gain, radiation efficiency, and SAR values of our proposed antenna are better than the tri-band wearable antennas proposed in [11, 12]. The quad-band wearable antenna in [13] has a larger size and lower bandwidths than that of the proposed antenna; however, its gain is higher for first, second, and fourth band, its radiation efficiencies are lower for the first three bands, and its SAR values are lower for the first two bands in comparison to the proposed antenna. The CPW line width of the proposed antenna is wider than the other works [4–6, 8, 9] illustrated in Table 7.

5. Conclusion

A novel wide CPW-fed multiband wearable monopole antenna and its design procedure have been proposed and successfully implemented. The antenna has a simple geometry and is easy to design on a polyester substrate. It has been shown that the proposed antenna with a wide CPW line is sufficient to cover the 1800 MHz GSM, 2.4/5.2 GHz WLAN, and 3.5 GHz WiMAX bands, resulting in a four-band operation. The antenna provides good radiation

TABLE 7: Comparison of the proposed antenna with existing literature.

Ref.	Size (mm ³)	Frequency (GHz)	BW (MHz/%)	Gain/directivity (dB or dBi)	Radiation efficiency (%)	SAR (W/kg)
[1]	46 × 46 × 2.4	2.4	660	7.8 dBi	—	0.0138
[2]	100 × 100 × 3	2.4	157	2.0 dB	45	0.0500
[4]	50 × 50 × 1	5.4	52.96%	9.67 dBi	—	—
[5]	40 × 40 × 0.6	5.7	—	6.49 dB	59	0.0043
[6]	34.29 × 48 × 0.45	2.45	458	3.9 dB	85	—
		5.8	590	4.6 dB	90	—
[7]	240 × 240 × 1	0.9	—	8.1 dBi	20.5	0.0011
		1.8	—	7.4 dBi	10.3	0.0034
[8]	24 × 32 × 0.305	5.2	4.07%	7.9 dB	90	0.0646
		5.8	4.16%	8.2 dB	90	0.0258
[9]	31 × 34 × 0.0508	2.46	648	1.68 dBi	91.6	—
		5.48	1378	1.64 dBi	91.6	—
[10]	$\pi \times (35)^2 \times 3$	2.45	84	4.16 dBi	63.5	0.248
		5.8	247	4.34 dBi	53	0.091
		0.9	—	—	41.6	—
[11]	105.5 × 80.8 × 0.015	1.9	—	2.0 dBi at all bands	75.8	—
		2.45	—		65.6	—
		1.55	—		—	—
[12]	40 × 40 × 0.8	1.95	—	>1.6 dB at all bands	>50 at all bands	0.62
		2.1	—			0.58
		1.8	320			4.91 dBi
[13]	70 × 70 × 2	2.4	60	7.84 dBi	75.22	0.358
		3.6	80	2.58 dBi	63.26	0.566
		5.5	180	4.12 dBi	88.95	0.798
		1.78	410	4.17 dBi	94.71	0.2293
Proposed antenna	45.5 × 85 × 1	2.40	260	3.81 dBi	93.42	0.3892
		3.46	170	2.60 dBi	90.52	0.4640
		5.26	520	2.74 dBi	83.97	0.2535

pattern characteristics and appreciable gain over each of the operating bands. The calculated SAR values at all the resonant frequencies of the wearable antenna are well below the acceptable limit of 2 W/kg, ensuring the safety of the user and viability of the proposed antenna for wearable applications. Further, the effect of bending in the x and y planes on antenna performance has been investigated and frequency detuning is discussed. Finally, the reflection coefficient characteristics has been measured for two on-arm conditions, with and without cloth, and the results are presented.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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