Progress In Electromagnetics Research C, Vol. 116, 249–264, 2021

Reconfigurable Antenna Design for Internet of Medical Things

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Abstract—This proposal presents a novel design of a reconfigurable antenna with frequency, polarization, and pattern diversities for wireless body area networks. The design makes use of a 3.2 mm thick FR4 substrate of $39 \times 36\,\mathrm{mm}^2$ dimensions with a square patch and partial ground structure. The antenna operates in sixteen different modes and resonates at various frequencies ranging from 2.456 to 14.384 GHz. The proposed model has the capability to exhibit elliptical as well as linear polarization with different radiation patterns. For suitability of the proposed design in healthcare applications its SAR analysis has been performed along with other antenna characteristics like reflection coefficient, gain, radiation pattern, and axial ratio. Four PIN diodes have been used to switch the antenna operational modes.

1. INTRODUCTION

Modern telecommunication systems have emerged with the requirement of multiple antenna standards. Various applications require an altogether different set of operating frequencies, polarization, and pattern. Employing different antennas for different requirements is not that feasible, which demanded for a single antenna capable of catering to all requirements. This has laid the foundation of cognitive and reconfigurable antennas which are reconfigured or rebuilt to cater the desired operating characteristics and specifications [1]. The reconfiguration is accomplished by a thoughtful alteration of antenna's effective aperture [2]. For the purpose, switches (electrical, optical or thermal), actuators (motors or linear actuators), or material change (plasmonics or liquid crystals) can be used. The reconfigurability can be classified as frequency, polarization, radiation pattern, and hybrid [3]. Modern antennas face the limitation of low fractional bandwidth (typically 7%). Such antennas are not compatible with nowadays wireless communication systems [4]. In addition, recent developments in wireless communications urge the necessity of multiband antennas [5]. Mostly antennas exhibit elliptical polarization; a few antennas show linear polarization; and some offer circular polarization characteristics. Linear polarization is desired in C-band and Ku-band applications whereas circular polarization is highly required in satellite communications [6]. In [7], authors have proposed a frequency reconfigurable antenna with slots that resonated at frequencies 2.3304 GHz, 2.2425 GHz, and 2.054 GHz as per the slots orientation in counterclockwise direction at 0°, -45°, and -90°, respectively. In [8], a band reconfigurable antenna has been investigated that offered a wideband and four narrow band modes of operation. A pentagon slot resonator frequency reconfigurable antenna has been reported with wideband operational characteristics in [9]. Wireless applications require a multiband antenna as it offers the features of multiple antennas of different resonant frequencies [10]. A multiband frequency reconfigurable antenna has been investigated in [11] which switched between quad band and dual band modes with the PIN diode's OFF and ON states, respectively. Authors of [12] have proposed a frequency and polarization reconfigurable antenna

Received 13 September 2021, Accepted 27 November 2021, Scheduled 7 December 2021
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that operated at two WLAN frequencies with linear (vertical and horizontal) as well as circular (RHCP and LHCP) polarization. A dual band polarization reconfigurable antenna has been proposed in [13] that resonated at 2.53 GHz and 2.81 GHz with two orthogonal linear polarizations. In [14], authors presented a frequency and pattern reconfigurable antenna for LTE and GSM bands. The reconfiguration was achieved with the help of three PIN diodes. Paper [15] suggests a circular polarization reconfigurable antenna at 3.4 GHz that offers both LHCP and RHCP with the help of two PIN diodes. A polarization reconfigurable antenna has been investigated in [16], with LHCP and RHCP at 3.6 GHz. In [16], authors have investigated a circular polarization reconfigurable antenna with a C-slot that operates in two bands 3.35–3.77 GHz and 3.4–3.72 GHz. Defected ground structures played an important role in antenna design. Paper [17] proposes a reconfigurable antenna with DGS operating at 2.4 & 2.7 GHz. A dual feed dual band pattern reconfigurable antenna has been proposed in [18] which operated in three different modes at 0.816 and 1.072 GHz. A CPW-fed polarization reconfigurable antenna has been proposed in [19] at 5.8 GHz. The antenna offered LHCP and RHCP configurations with the bias status of two PIN diodes. Paper [20] proposes a frequency reconfigurable antenna for Wi-Fi and 5G applications. A frequency reconfigurable antenna array has been proposed in [21] for millimeter wave and 5G applications. The antenna switched between 28 and 38 GHz as per the switching diode's switching state. A high gain multiband antenna for wireless applications has been investigated in [22] which made use of metamaterial cell to improve the bandwidth and gain of the antenna. A frequency reconfigurable antenna for WBAN applications has been reported in [23] with 1.575, 2.45, and 5.2 GHz operating frequencies for industrial, scientific, medical, and Wi-Fi applications. A frequency and pattern reconfigurable antenna has been investigated in [24] using a single PIN diode. The antenna resonates at 2.47 and 5.36 GHz with switch ON and at 3.8 GHz with switch OFF. Authors of [25] have proposed a frequency reconfigurable antenna that switched between single and dual modes of operation with the PIN diode's ON and OFF states, respectively. Authors of [26] have introduced a four directional beam frequency reconfigurable antenna with four PIN diodes and variable height transformer oil.

In addition to the applications discussed in the papers cited so far, antennas are getting more widely used in healthcare applications wherein wearable devices are used to monitor various medical parameters of patients [27]. Thus, the antenna plays a major role in wireless body area networks (WBANs). For the purpose the antenna should have acceptable efficiency, significant gain, and above all a low specific absorption rate (SAR) [28]. In [29], a textile antenna for WBAN applications has been suggested that has steering capabilities. Authors of [30] have presented the study of SAR in human body. Paper [31] suggests a pattern reconfigurable antenna for WBAN networks operates at 5.8 GHz.

In this paper, a novel square-shaped reconfigurable antenna for internet of medical things has been designed with another circular radiating patch and partial ground structure with two symmetrical stubs on a 3.2 mm thick FR4 substrate. The antenna has $39 \times 36\,\text{mm}^2$ dimensions. The circular radiating patch gets connected with the outer square patch with the help of two PIN diodes. The square patch is fed by two microstrip feeds 90° apart through a pair of PIN diodes. The feedline switch 2 enables linear polarization. Partial ground structure improves gain, and the two stubs provide wider bandwidths. The novelty of the design lies in its ability to act as a non-contacting feed, single feed, and dual feed microstrip patch antennas per the PIN diodes' DF1 and DF2 switching states. In addition, the antenna is able to exhibit diversities in frequency, polarization, as well as pattern along with multiband and wideband operations at the same time. The SAR values of the antenna have been simulated on human arm 6 layer tissues model viz., skin, fat, muscle, nerve, blood, and bone. The antenna design has been simulated on commercially available Ansys High frequency structure simulator (HFSS) v 13.0. A prototype had been fabricated and experimentally studied.

2. ANTENNA DESIGN AND OPERATION

The antenna geometry is shown in Fig. 1. The square patch with inner circular radiating patch is etched on the upper surface of a 39×36 mm 3.2 mm thick FR4 substrate. The lower surface has a partial ground structure with two stubs. The patch is fed with two orthogonal microstrip feeding lines. Both the feeding lines have PIN diodes (DF1 & DF2) to connect and disconnect the line with the patch. The inner circular radiating patch can be connected or disconnected with the square patch with the help of another pair of PIN diodes (DR1 & DR2).

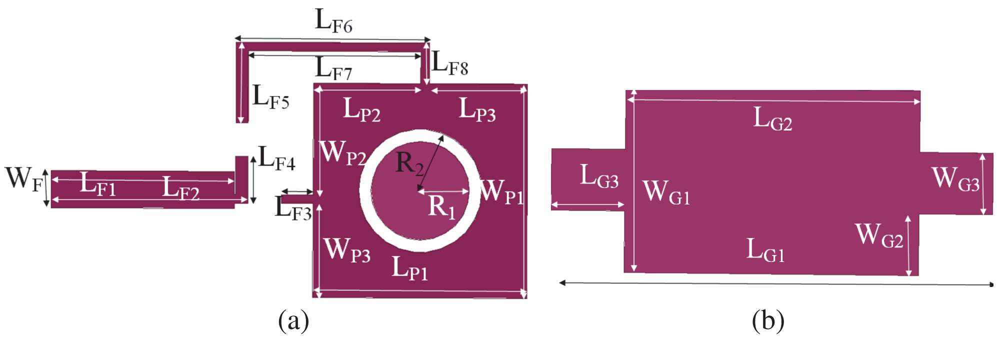


Figure 1. (a) Antenna patch. (b) Antenna ground.

The radius of the inner circular radiating patch has been decided (= 4 mm) with the help of a parametric analysis. The partial ground resulted in an improved gain whereas the stubs helped in widening of bandwidth.

The dimensions of the patch and ground are tabulated in Table 1. A prototype of the design is fabricated, and the performance of the prototype is studied and compared with the simulated values. For simulation the PIN diodes are replaced with their equivalent circuits as shown in Fig. 2.

Table 1. Geometrical parameters of proposed design.

Patch				**Ground**	
Parameter	**Value (mm)**	**Parameter**	**Value (mm)**	**Parameter**	**Value (mm)**
LF1	14.9	LP1	17.4	LG1	36
LF2	15.9	LP2	8.34	LG2	24
LF3	4.47	LP3	8.34	LG3	6
LF4	3.81	WF1	3	WG1	15
LF5	6.46	WP1	17.4	WG2	5
LF6	15	WP2	8.34	WG3	5
LF7	13.56	WP3	8.34		
LF8	3.3	$R1$	4		
		$R2$	5		

The equivalent circuit of PIN diode (BAR64-03WE6327) is shown in Fig. 2. PIN diode switching circuit is shown in Fig. 3. For simulation the PIN diode in ON condition is represented with a resistance of 3 ohms whereas in OFF condition it is a parallel combination of 5 kohms resistor and a 0.15 pF capacitor [32].

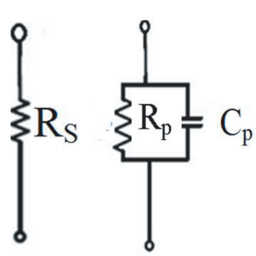


Figure 2. Equivalent Circuit of PIN diode.

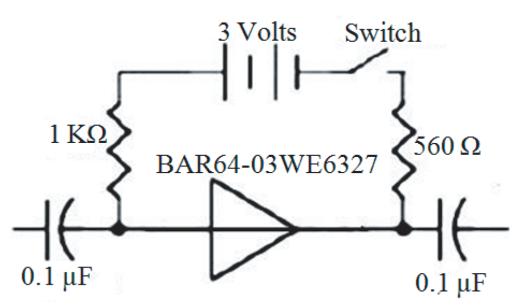


Figure 3. PIN diode switch.

Figure 4 shows the complete antenna design with PIN diodes. The antenna operates in 16 different modes as per the switching status of four PIN diodes. The switching state and antenna modes are tabulated in Table 2. In order to design the inner radiating patch of antenna, a parametric analysis was done. The results of the analysis are illustrated in Fig. 5. The study was performed by varying the radius R1 while keeping all other dimensions constant.

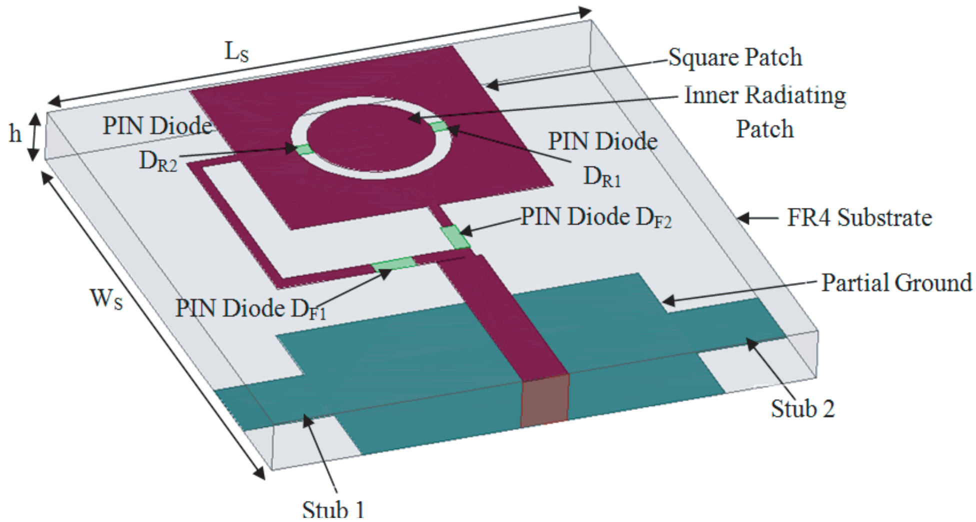


Figure 4. Antenna design with PIN diodes.

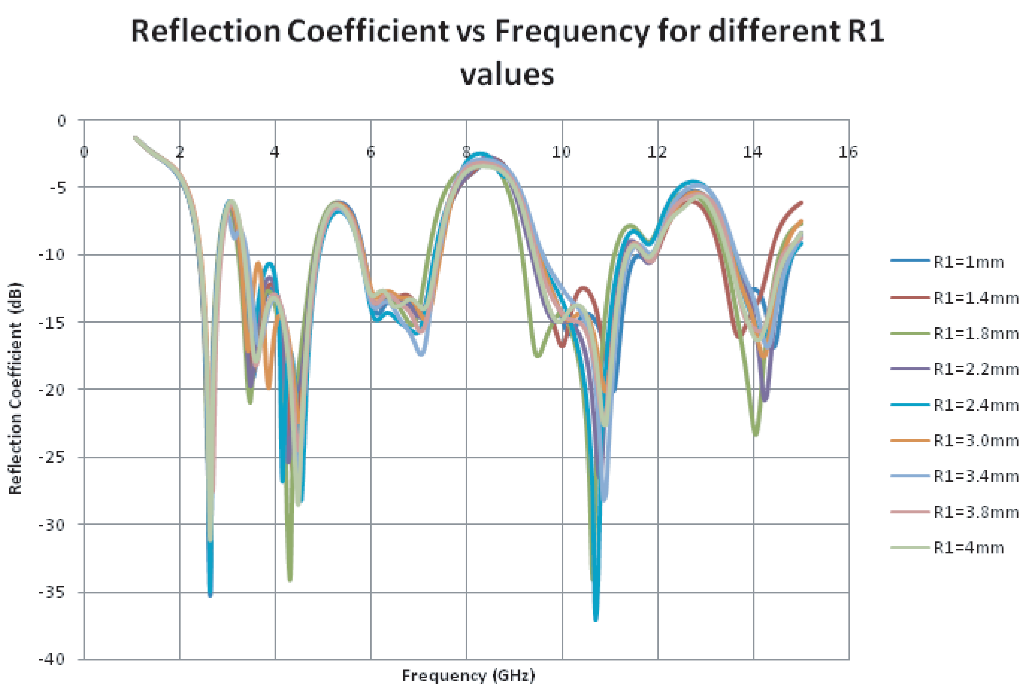


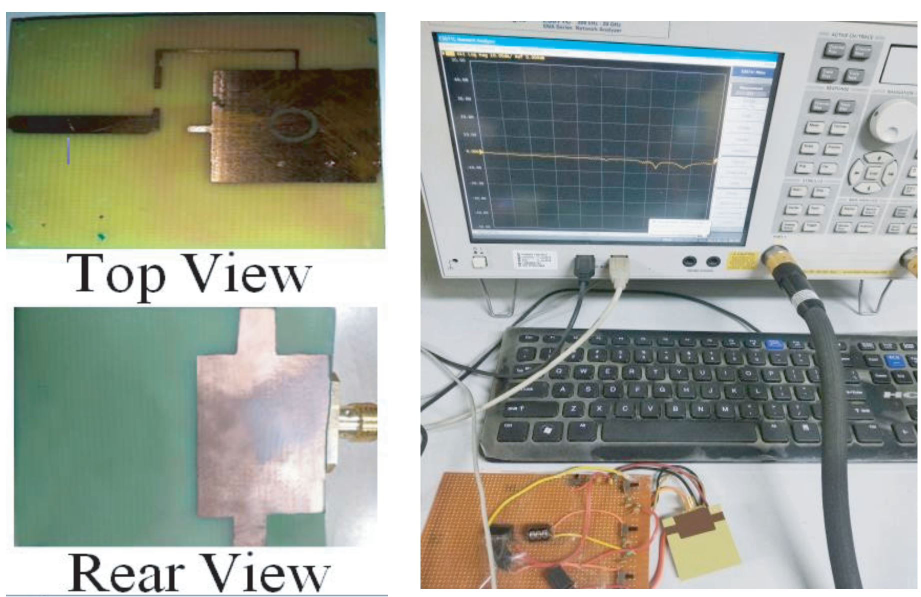
Figure 5. Inner radiating patch radius parametric analysis.

Table 2. Operating modes of antenna with PIN diodes' switching status.

Antenna Mode	**PIN diode DF1**	**PIN diode DF2**	**PIN diode DR1**	**PIN diode DR2**	**Antenna Mode**	**PIN diode DF1**	**PIN diode DF2**	**PIN diode DR1**	**PIN diode DR2**
0	OFF	OFF	OFF	OFF	8	ON	OFF	OFF	ON
1	OFF	OFF	OFF	ON	9	ON	OFF	OFF	OFF
2	OFF	OFF	ON	OFF	10	ON	OFF	ON	OFF
3	OFF	OFF	ON	ON	11	ON	OFF	ON	ON
4	OFF	ON	OFF	OFF	12	ON	ON	OFF	OFF
5	OFF	ON	OFF	OFF	13	ON	ON	OFF	ON
6	OFF	ON	ON	ON	14	ON	ON	ON	OFF
7	OFF	ON	ON	OFF	15	ON	ON	ON	ON

3. RESULTS AND DISCUSSION

The antenna has been studied on HFSS version 13. The reflection coefficients, VSWR, gain, peak gain, axial ratio, radiation efficiency, directivity, radiation pattern, and 3D plots have been studied. A prototype of the design has been fabricated and studied experimentally. Fig. 6 shows the fabricated antenna.



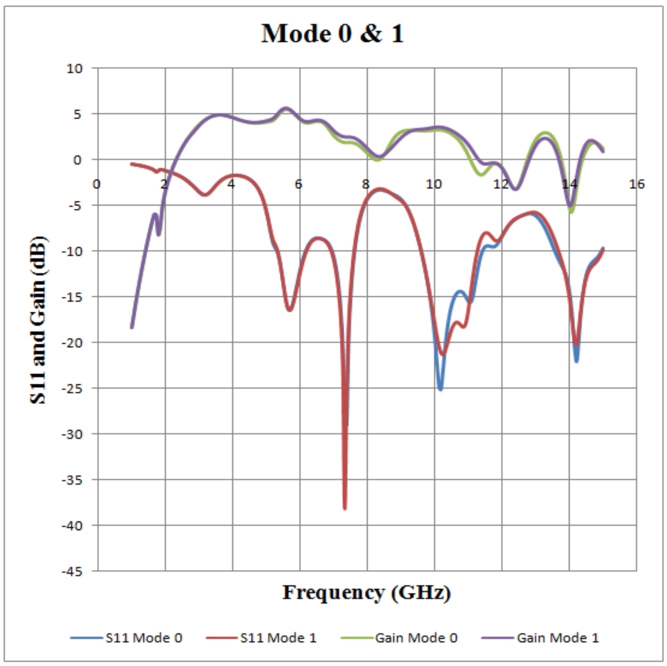
(a) (b)

Figure 6. (a) Fabricated antenna. (b) Measurement set up with VNA.

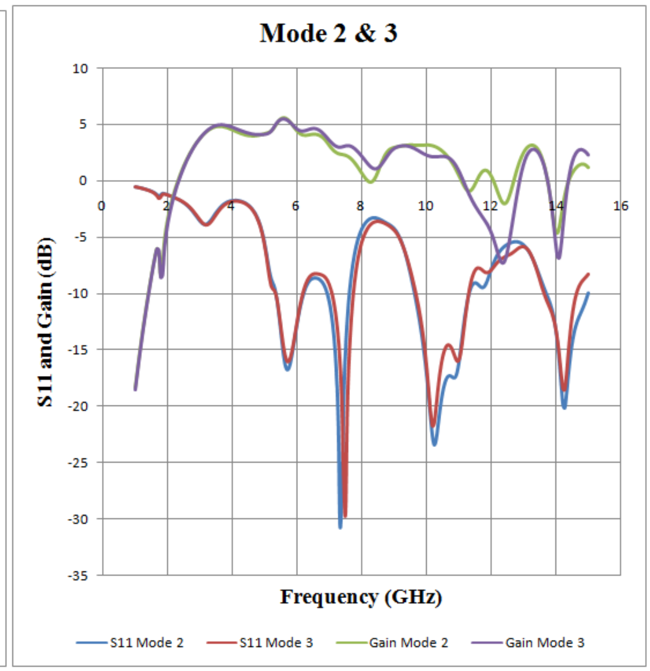
Figure 7 shows the reflection coefficients and total gain of antenna in all sixteen modes. The antenna has been experimentally studied with the help of Agilent Technologies — E5071C (ENA series) 300 kHz–20 GHz network analyzer. The measured and simulated results of reflection coefficient vs frequency for modes 1, 4, 6, and 11 are plotted in Figs. 8(a)–(d).

3.1. Frequency Reconfiguration

The proposed antenna exhibits frequency diversity as it resonates at 41 different frequencies from 2.456 to 14.44 GHz in different modes. The operating frequencies along with their corresponding reflection coefficients in all modes are tabulated in Tables 3–6. The target frequency is 2.456 GHz which can be used in healthcare application for wearable devices for babies, patient, astronauts, and elderly people health parameters' monitoring.



(a)



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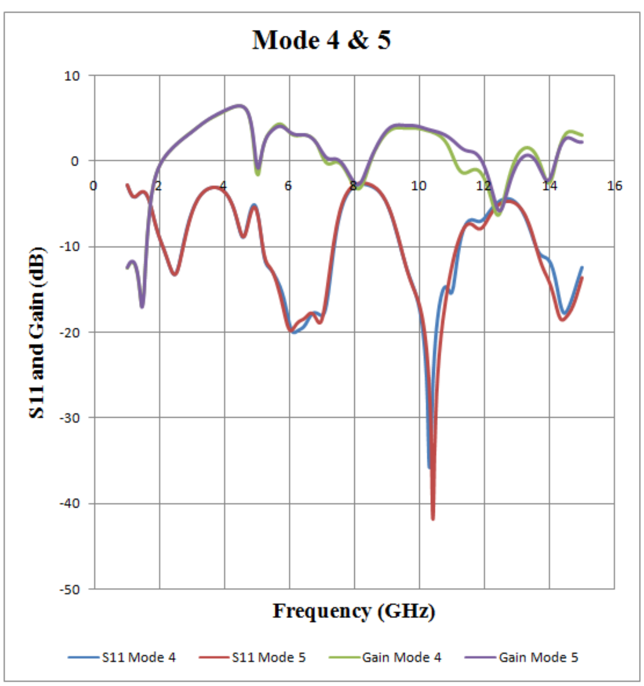

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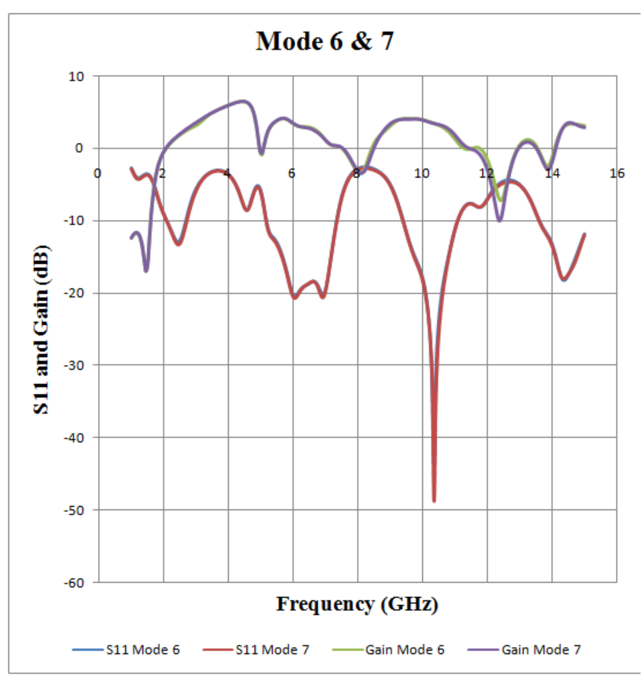
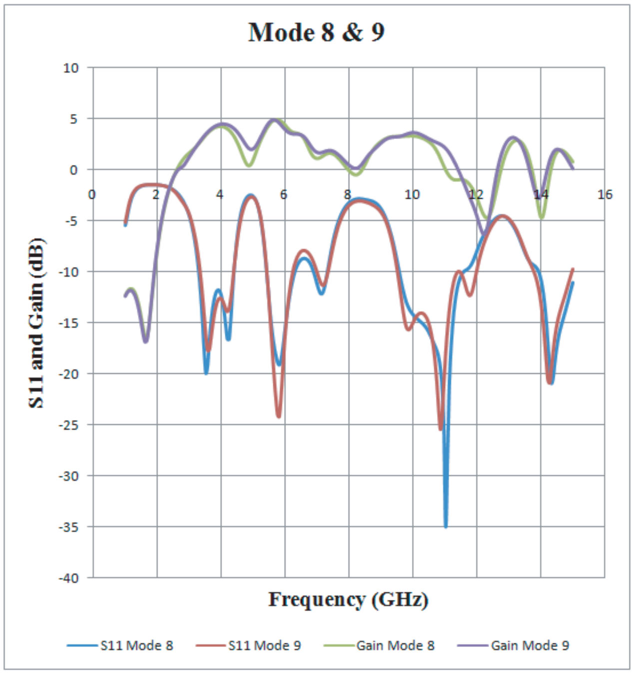
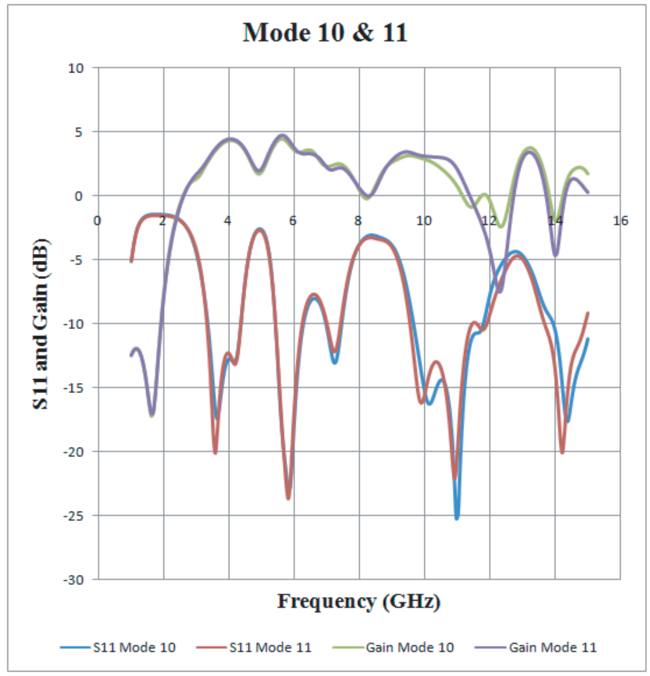


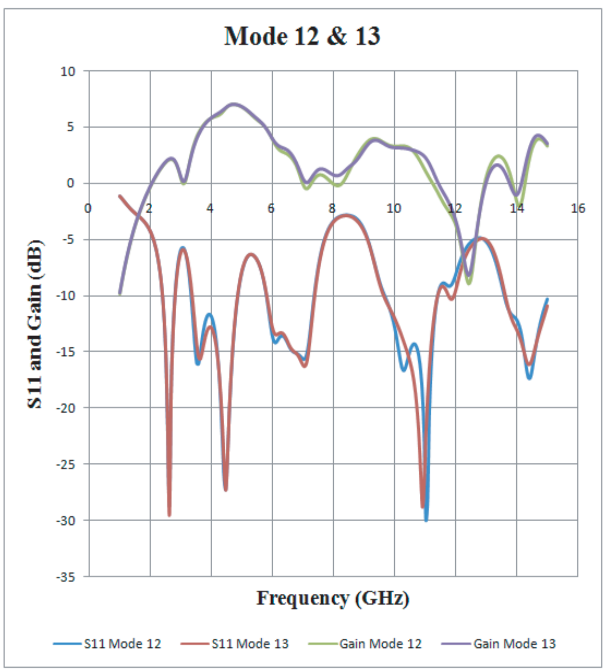
(d)



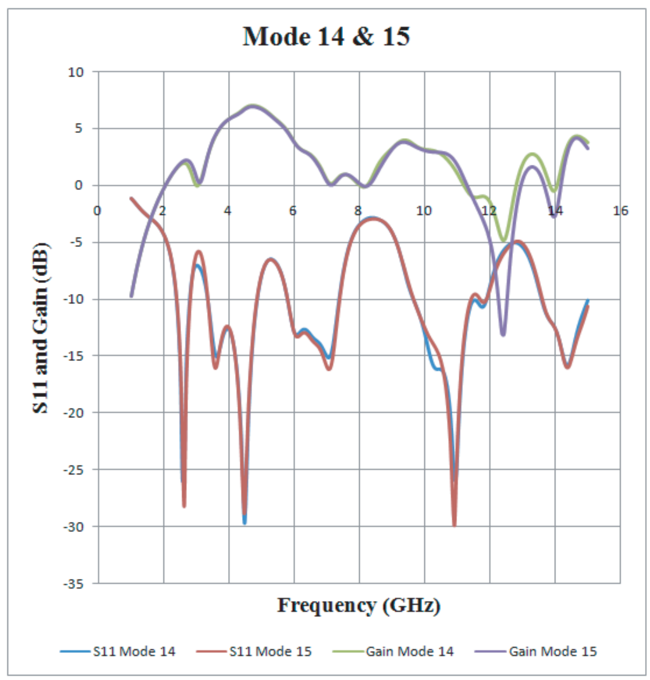
(e)



(f)



(g)



(h)

Figure 7. Reflection Coefficients and total gain of antenna in (a) modes 0 & 1, (b) modes 2 & 3, (c) modes 4 & 5 and (d) modes 6 & 7. Reflection Coefficients and total gain of antenna in (e) modes 8 & 9, (f) modes 10 & 11, (g) modes 12 & 13 and (h) modes 14 & 15.

3.2. Polarization Reconfiguration

The antenna exhibits polarization diversity. Polarization of an antenna refers to the path which is traced by the tip of the electric field vector as a function of time. In antenna there may be linear, circular,

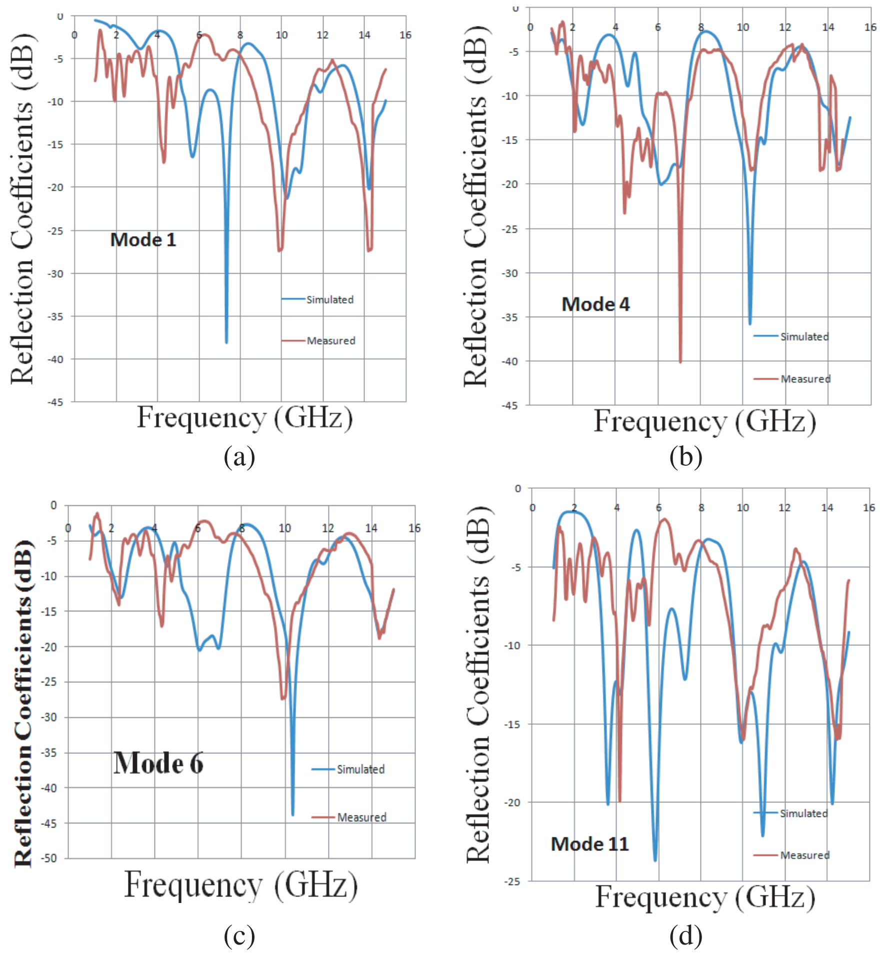


Figure 8. Measured and simulated reflection coefficients of antenna in (a) mode 1, (b) mode 4, (c) mode 6 and (d) mode 11.

Table 3. Resonant frequencies of antenna with corresponding S_{11} for modes (0–3).

Mode	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**	**Mode**	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**
0	5.704,	−16.467	**1**	5.704	−16.4443
	7.384	−29.016		7.328	−38.0958
	10.184	−25.1415		10.24	−21.2886
	14.216	−22.0759		14.216	−20.1857
Mode	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**	**Mode**	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**
2	5.704	−16.7347	**3**	5.704	−16.0287
	7.328	−30.5784		7.496	−29.5661
	10.24	−23.3983		10.184	−21.7472

Table 4. Resonant frequencies of antenna with corresponding S_{11} for modes (4–7).

Mode	Resonant Frequency (GHz)	Reflection Coefficient (dB)	Mode	Resonant Frequency (GHz)	Reflection Coefficient (dB)
4	6.152	−19.9688	5	2.456	−13.2521
	10.296	−35.5819		6.04	−19.7904
	14.44	−17.7002		10.408	−41.7738
				14.384	−18.544
Mode	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**	**Mode**	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**
6	2.456	−12.9836	7	2.456	−13.2596
	6.04	−20.4686		6.04	−20.638
	6.936	−20.2072		6.936	−20.4924
	10.352	−43.7632		10.352	−48.6511
	14.384	−18.2421		14.328	−17.9464

Table 5. Resonant frequencies of antenna with corresponding S_{11} for modes (8–11).

Mode	Resonant Frequency (GHz)	Reflection Coefficient (dB)	Mode	Resonant Frequency (GHz)	Reflection Coefficient (dB)
8	3.52	−19.9487	9	3.576	−17.7481
	4.248	−16.6269		5.816	−24.2152
	5.816	−19.1469		7.16	−11.3395
	7.16	−12.1675		9.848	−15.7132
	11.08	−28.3191		10.856	−25.4663
	14.328	−20.9398		14.272	−20.9199
Mode	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**	**Mode**	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**
10	3.632	−17.452	11	4.192	−13.1272
	5.816	−22.9741		5.816	−23.6572
	7.216	−13.0743		7.216	−12.1584
	10.128	−16.2898		9.904	−16.1767
	10.968	−25.2342		10.912	−22.0904
	14.384	−17.6564		14.216	−20.0605

or elliptical polarization. When there is a single component of electric field or two components with a phase difference of 0° or 180°, it is the linear polarization. When the two electric components are equal in magnitude and have a 90° phase difference, it is the circular polarization case. All other cases come under elliptical polarization. Actually, linear and circular polarizations can be understood as special cases of elliptical polarization. Practically, the polarization of an antenna is determined by its axial

Table 6. Resonant frequencies of antenna with corresponding S_{11} for modes (12–15).

Mode	Resonant Frequency (GHz)	Reflection Coefficient (dB)	Mode	Resonant Frequency (GHz)	Reflection Coefficient (dB)
12	2.624	−28.6556	13	2.624	−29.5429
	3.576	−16.0584		3.632	−15.6497
	4.472	−27.2299		4.472	−27.3108
	6.096	−14.1739		7.048	−16.3032
	7.048	−15.6403		10.912	−28.8288
	10.296	−16.654		11.864	−10.3224
	11.024	−29.9067		14.384	−16.1217
	14.384	−17.3115			
Mode	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**	**Mode**	**Resonant Frequency (GHz)**	**Reflection Coefficient (dB)**
14	2.568	−25.9463	15	2.624	−28.1232
	3.632	−15.0666		3.576	−16.0394
	4.472	−29.6805		4.472	−28.7606
	7.048	−15.1384		6.096	−13.2927
	10.912	−25.8913		7.048	−16.1468
	14.384	−15.8227		10.912	−29.819
				11.808	−10.2718
				14.384	−15.9999

ratio which is the ratio of minor to major axis of the polarization ellipse. For equal major and minor axes the polarization ellipse transforms into a circle. Thus for circular polarization, the axial ratio is 1 or 0 dB (ideally), and practically axial ratio less than or equal to 3 dB (sometimes 6 dB) is assumed as the case of circular polarization. For linear polarization, this axial ratio is infinite ideally (practically a value greater than 30 dB is considered).

In this design, the antenna exhibits linear polarization in mode 4 at 14.44 GHz, in modes 6 and 7 at 2.456 GHz, and in mode 14 at 14.384 GHz. The axial ratios in these cases are 36.88 dB, 30.17 dB, and 37.67 dB, respectively, as shown in Fig. 9. Linear polarization occurs when:

1. There is no phase difference between E_x and E_y or
2. Either $E_x = 0$ or $E_y = 0$.

It has been observed that whenever diode DF2 is ON the resulting electric current flows from the source to patch in such a way that the resulting fringing fields have either E_X tending to zero or the angle between E_x and E_y tending to zero as shown in Table 7.

Vertically polarized antenna is very convenient for automobile applications, hence such an antenna can be used for babies and patient's monitoring while they are moving in vehicles. Polarization diversity is helpful in catering the problems arising from polarization mismatch, multipath fading, and distortion in wireless body area networks as discussed in [33].

In all other modes and all other frequencies, the antenna exhibits elliptical polarization.

3.3. Pattern Reconfiguration

The proposed antenna is pattern reconfigurable as it shows different radiation patterns in different modes at different frequencies as shown in Fig. 10. The main lobe switches from −30° (in mode 9 at

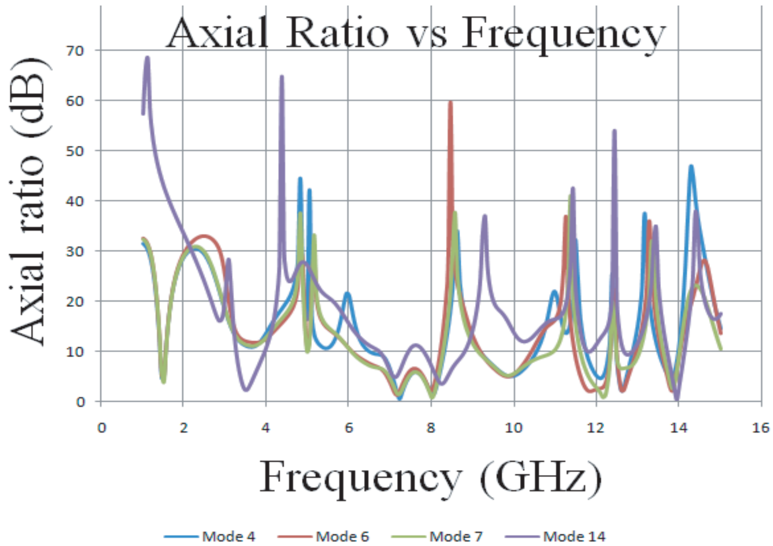


Figure 9. Axial ratio in modes 4, 6, 7 and 14.

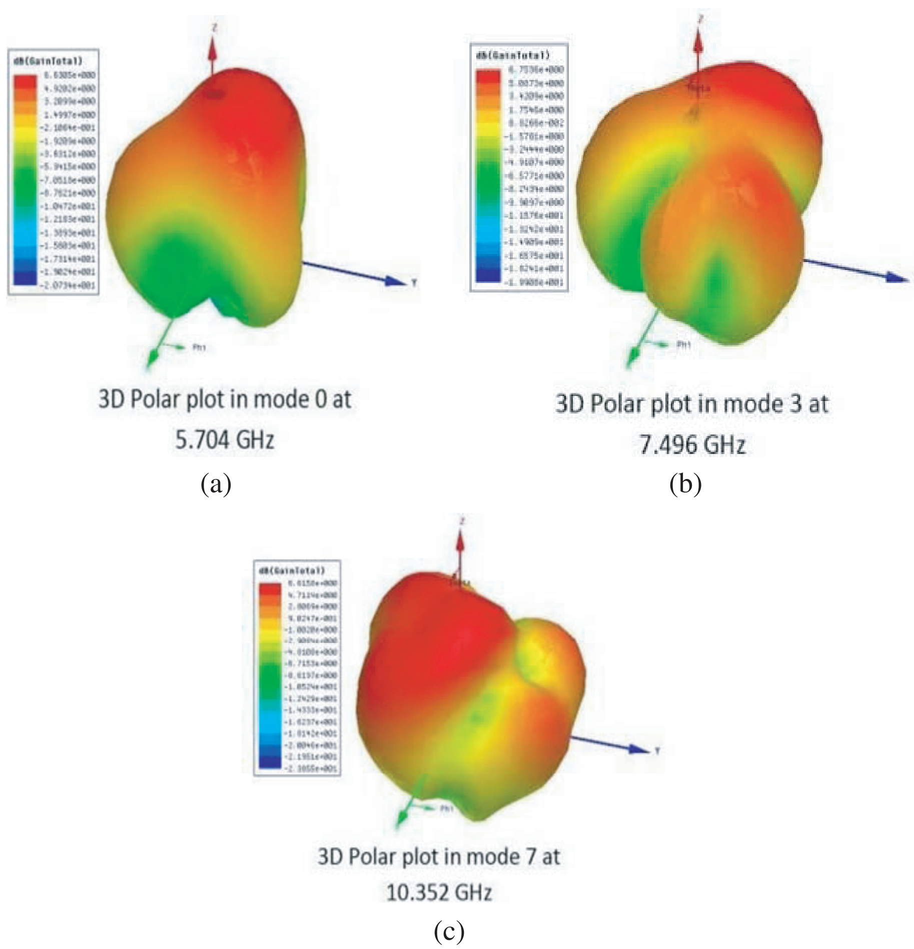


Figure 10. 3D Polar plots of antenna in (a) mode 0 at 5.704 GHz, (b) in mode 3 at 7.496 GHz and (c) mode 7 at 10.352 GHz.

Table 7. Details of E-field of Antenna in modes where diode DF2 is in ON condition.

Mode	Frequency (GHz)	E_x (Volts/mtr.)	E_y (Volts/mtr.)	Angle between E_x and E_y (Degrees)
4	2.456	0.324945398	9.276800326	45.3357045
	14.44	1.5781902	10.60678883	3.8023551
5	2.456	0.379358272	9.245515103	76.80144794
6	2.456	0.324239882	9.145766242	39.2370244
7	2.456	0.303915225	9.247573545	70.77338669
14	14.384	3.961423611	10.70036033	2.3024007
15	2.456	0.406891051	9.232139274	302.5206849
	14.384	2.629664153	10.50234659	18.3114454

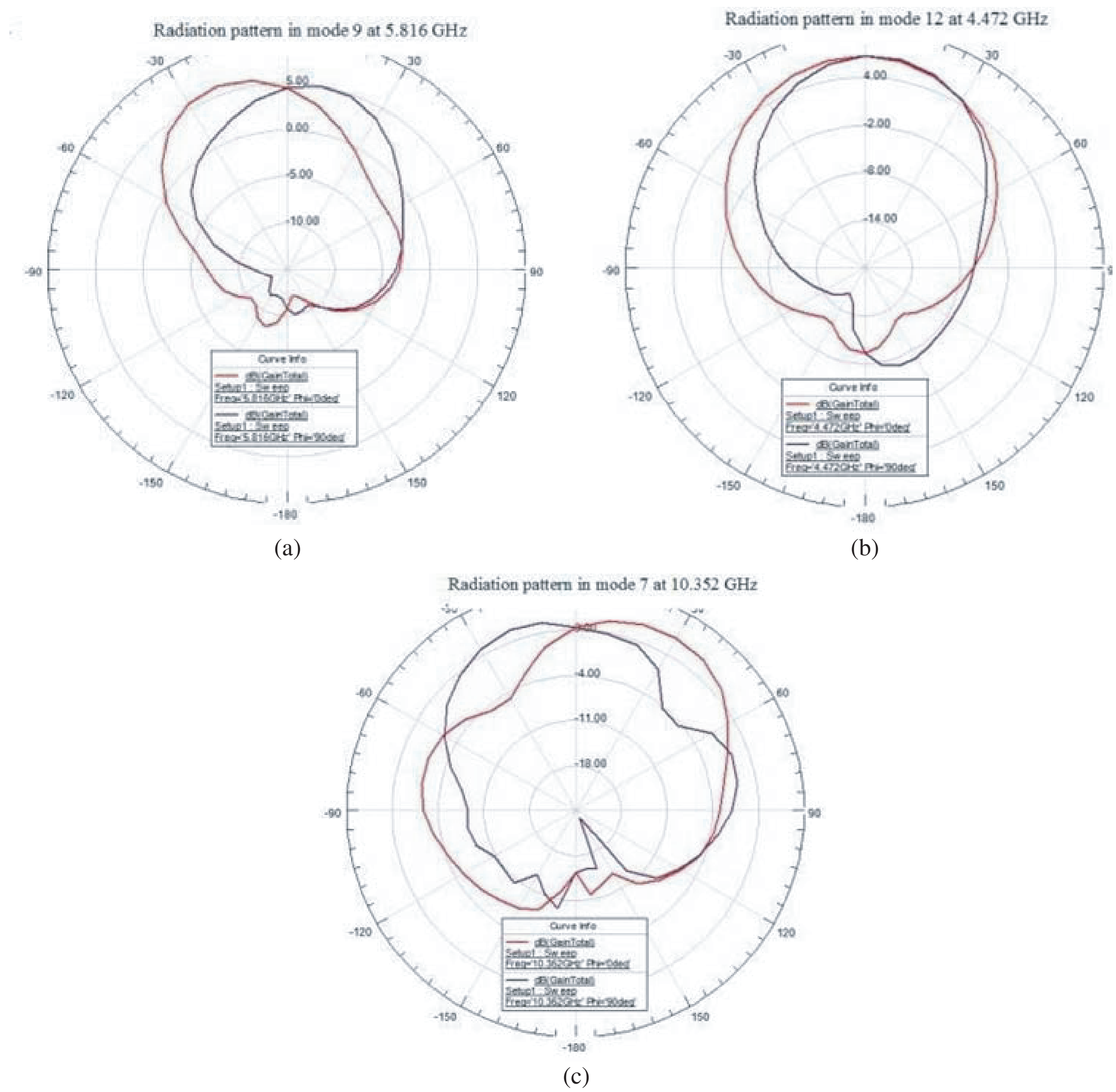


Figure 11. Radiation patterns of antenna in (a) mode 9 at 5.816 GHz, (b) in mode 12 at 4.472 GHz and (c) mode 7 at 10.352 GHz.

5.816 GHz) to +30° (in mode 7 at 10.352 GHz) as shown in Fig. 11. Many a times a antenna with beam steering is required which is capable to steer the beam in desired directions in order to enhance the efficiency of communication [34].

3.4. SAR Values of Antenna for Human Arm Tissues

To measure an antenna's performance in WBAN specific absorption rate is a basic tool or rate which is defined as the rate at which RF electromagnetic energy is imparted to unit mass of biological body. SAR is a measure of the rate at which energy is absorbed by the human body when it is exposed to a radio frequency (RF) electromagnetic field. Thus, SAR measures exposure to fields between 100 kHz and 10 GHz. For simulation the dielectric properties of various human tissues have been taken from [35]. Human arm has been modeled as a six layer cylinder as shown in Fig. 12.

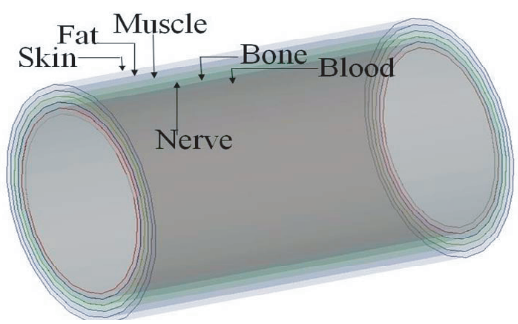


Figure 12. Six layer human arm model in HFSS.

The Federal Communications Commission (FCC) of the U.S. Government established the SAR limit to 1.6 W/kg averaged over 1 gram of actual tissue, whereas the Council of the European Union established the limit to 2.0 W/kg averaged over 10 g of actual tissue.

In HFSS the average SAR averaged over 10 gm of six human arm tissues has been simulated in vicinity of the proposed antenna in modes 0 and 15 at 2.456 GHz and 2.624 GHz, respectively. The results are shown in Fig. 13 and Fig. 14.

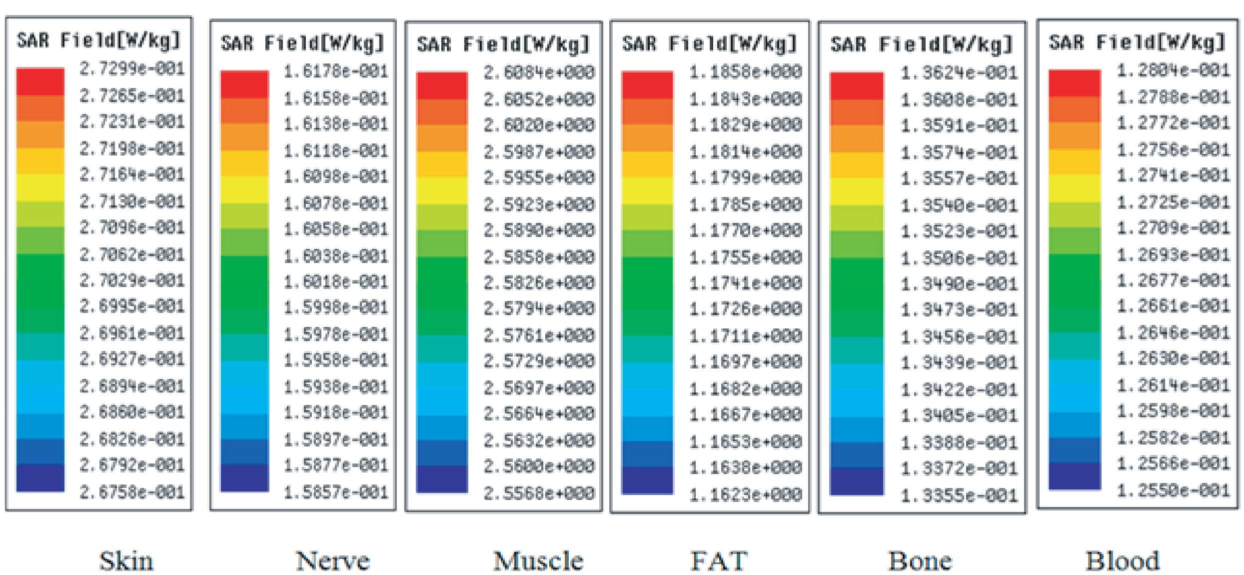


Figure 13. SAR values on six tissues of human arm with antenna in mode '0' at 2.456 GHz.

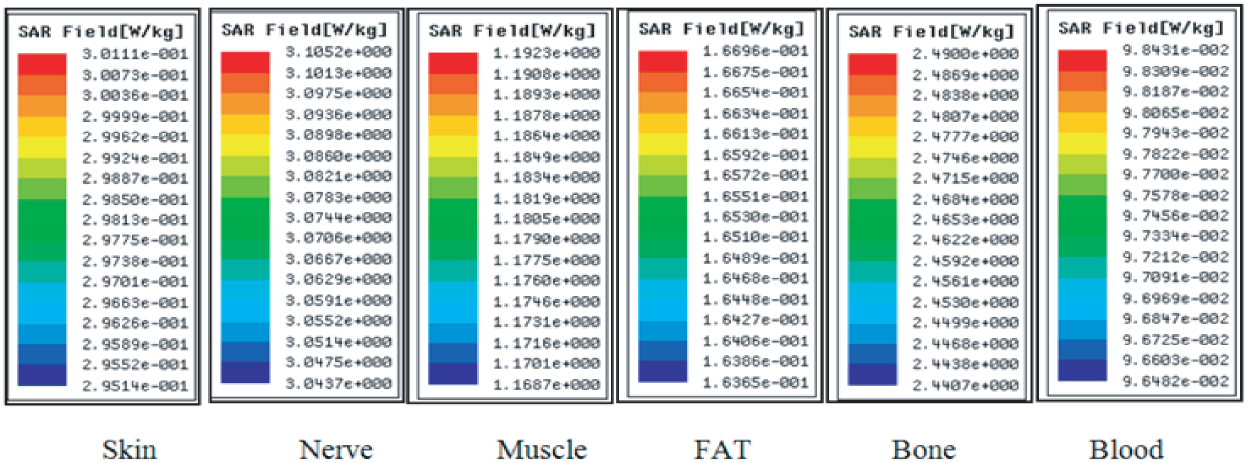


Figure 14. SAR values on six tissues of human arm with antenna in mode '15' at 2.624 GHz.

4. CONCLUSION AND FUTURE SCOPE

A novel antenna with frequency, polarization, and pattern reconfigurable characteristics has been studied. The antenna makes use of two pairs of PIN diodes. One pair (DF1 & DF2) is used to connect or disconnect the square patch from the feed line whereas the other pair (DR1 & DR2) connects or disconnects the inner circular radiating patch with the outer square patch. The antenna operates in 16 modes to maximize the antenna performance in changing operating conditions or requirements. Hence, higher number of modes means more usability and applicability of reconfigurable antenna [36, 37]. The antenna is a suitable candidate for healthcare domain which has been checked with the SAR analysis in HFSS. The design can be used in wearable devices as well because of its varied resonant frequencies. In addition, it can be used in various wireless applications like Wi-Fi, Bluetooth, Wi-Max, WLAN, and other S, C, X, and Ku band applications. The proposed antenna is compared with the reference antennas in Table 8.

Table 8. Comparison of proposed design with reference antenna.

Paper Ref. No.	Antenna Size (mm^2)	Operating Frequency (GHz)	Max. fractional Bandwidth (%)	Maximum gain (dB)	Maximum number of bands	Reconfigurable characteristics	Switching element
8	15 × 48	0.83–2.5	*	7.6	*	Frequency	6 PIN diodes
9	*	1.24–2.78	24.24	*	2	Frequency	2 PIN diodes
11	28 × 30	1.6–9.5	*	3.1	4	Frequency	1 PIN diode
12	50 × 14.7	5.2 & 5.8	0.96	6.3	1	Polarization	6 PIN diodes
13	50 × 50	2.53 & 2.81	*	4.12	2	Polarization	2 PIN diodes
19	30 × 26.5	2.4 & 28	*	9.18	1	Frequency	1 PIN diode
22	26 × 25	1.575–5.2	*	3.85	2	Frequency	5 PIN diodes
25	100.8 × 100.8	5.21–6.56	*	9.12	1	Frequency with beam switching	4 PIN diodes
Proposed	39 × 36	2.456–14.384	36.81	6.73	4	Frequency, polarization and pattern	4 PIN diodes

*: Not available

A prototype of the antenna has been fabricated and studied experimentally, and the measured results agree well with their simulated counterparts. The deviations of measurement results from simulated ones are mainly due to the fabrication defects and non-ideal characteristics of electronic components used. The study can be further extended to achieve circular polarization, further improvements in gain and reduction in SAR values.

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