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A Dual-Band Rectangular Spiral Antenna for S-Band Applications

Chilakala L. Reddy[1], Kallakunta R. Kumar[2], Nalluri Venkateswarlu[3], Kota M. Babu[4], Tottempudi V. Rama Krishna[5], Ambati Navya[2,*], and Kantamaneni Srilatha[6]

[1]*Department of ECE, G Pullaiah College of Engineering and Technology, Kurnool, Andhra Pradesh, India*
[2]*Department of ECE, KLEF, Vaddeswaram, Guntur, Andhra Pradesh, India*
[3]*Department of ECE, Anurag Engineering College, Ananthagiri, Kodad, Telangana, India*
[4]*Department of ECE, Sri Venkateswara College of Engineering, Tirupati, Andhra Pradesh, India*
[5]*Department of ECE, Sanketika Vidya Parishad Engineering College, Visakapatnam, Andhra Pradesh, India*
[6]*Department of ECE, Kallam Haranathareddy Institute of Technology, Chowdavaram, Guntur, AP, India*

ABSTRACT: A compact size, dual-band rectangular spiral antenna with an inset feed is simulated and tested for S-band applications. Feeding of an antenna is given through a 50 Ω microstrip transmission line. The proposed design consists of a rectangular spiral radiating patch in the top plane and a Z-shaped structure in the bottom plane. Ansoft HFSSv13 has been utilised to design the rectangular spiral antenna, and parametric analysis has been done to verify the characteristics of an antenna. The rectangular spiral antenna is fabricated by utilising chemical etching, and it is tested by utilising MS2037C Anritsu combinational analyzer. Reflection coefficients of -16.5 dB and -16.2 dB, and fractional bandwidths of 8% (2.35–2.55 GHz) and 6.7% (3.22–3.44 GHz) are obtained at 2.4 GHz and 3.3 GHz, respectively. Maximum gains of 3.1 dBi and 3.34 dBi are obtained at the two resonating frequencies. Omnidirectional and dipole type radiation patterns are obtained for different values of θ and Φ. The rectangular spiral antenna occupies an area of $16 \times 16 \times 1.6\,\mathrm{mm}^3$, and it is fabricated by using FR4 material. Simulated results are in good agreement with the measured ones. These results make the antenna suitable for many Zigbee/IEEE 802.15.4-based wireless data networks that operate in the 2.4–2.4835 GHz band, and it is also suitable for a wide range of applications including FWA systems.

1. INTRODUCTION

5G wireless communication systems have been recently extensively used and employed in various applications as a result of rapidly expanding wireless communication technology. With greater data speeds and reduced latency than 4G systems, 5G promises to offer seamless connection [1]. The two resonant frequency bands utilized in this application are the fifth-generation frequencies. The authors have proposed a 2.4 GHz antenna that is electrically compact and has a partial ground plane designed for biomedical applications [2]. Ref. [3] presents an antenna based on superconductive arrays for 200 MHz band. Ref. [4] shows a compact slotted electrically small antenna (ESA) for multiple-input multiple-output (MIMO) applications, which combines a meander line with a semi-ground plane antenna. For a 2.4 GHz frequency band application, a trident form with a meandering line antenna is proposed [5]. Nonetheless, the patch antenna can be easily tuned to operate at different resonance frequencies, which qualifies it for a range of wireless applications using a single antenna.

In recent years, researchers have developed unique designs that enable patch antennas to resonate at several bands, offer larger bandwidth, higher gain, and are compact in size [6–12]. A sub-6 GHz 5G microstrip patch antenna (MPA), approximately 50 mm × 80 mm in size, is designed to operate in many bands using Teflon material [6]. The antenna achieves gains of 2.01 dBi, 3.51 dBi, and 2.25 dBi at 2.50 GHz, 3.51 GHz, and 4.67 GHz, respectively. An antenna in 5G-sub-6 GHz range was cross-shaped and had a Rogers RT5880 substrate resonating at 3.120 GHz [7]. By using the defected ground structure (DGS) technique, the desired frequency range was obtained. The antenna offers a broad bandwidth of 2.56 GHz despite having a gain of only 2.44 dBi. Similar to this, [8] employed the DGS approach to resonate at two different frequencies, 4.51 GHz and 4.89 GHz using the RO5880 substrate, which has a ε_r of 2.2. The antenna has an area of $77 \times 70.11\,\mathrm{mm}^2$ and achieves 3.02 dBi at 3.77 GHz and 3.01 dBi at 4.55 GHz. However, [8] gives no information regarding the bandwidth of the antenna.

Recent advances in patch antenna design have led to a significant improvement in the efficiency of sub-6 GHz communication networks. A single-band antenna used an Arlon AD300C substrate and a bandwidth of 1300 MHz with a gain of 2.5 dBi [9] and operated at 5.65 GHz. The air-gap approach [10] is a means of increasing the gain of MPAs operating at 2.4 GHz. It involves providing an air gap between the substrate and ground plane. By introducing a 3 mm air space, the gain increased from 2.5 dBi to 2.81 dBi, while the bandwidth decreased from 11.7 GHz to 7.2 GHz. The study did conclude that there is a trade-off between antenna gain and bandwidth when adopting this technique. Another way to increase an-

* Corresponding author: Ambati Navya (ambatinavya88@gmail.com).

TABLE 1. Mid-band frequency spectrum at sub-6 GHz.

Countries	1–3 GHz Band	3–4 GHz Band	4–5 GHz Band
India		3.30–3.60 GHz	
USA	2.50 GHz–2.60 GHz	3.45–3.70 GHz, 3.70–3.98 GHz	4.49–4.99 GHz
Korea	2.30–2.39 GHz	3.40–3.70 GHz, 3.70–4.00 GHz	
China	2.50 GHz–2.60 GHz	3.30–3.60 GHz	4.50–5.00 GHz
Japan		3.60–4.10 GHz	4.50–4.90 GHz
Canada		3.47–3.65 GHz, 3.65–4.00 GHz	
Germany		3.40–3.880 GHz	

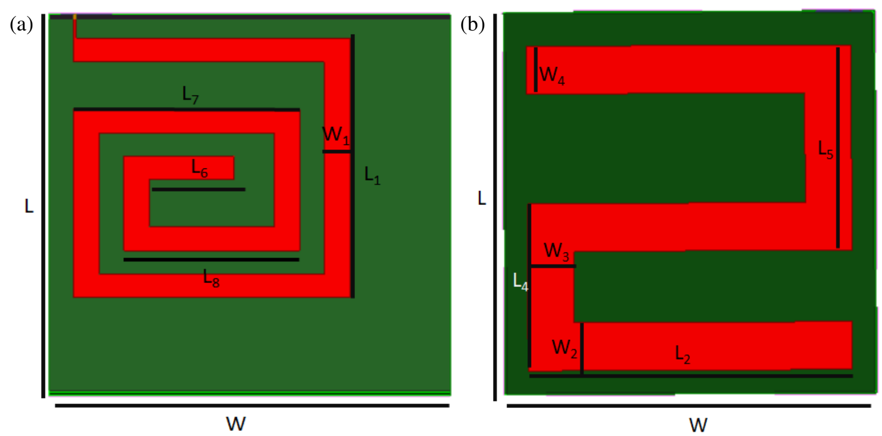

FIGURE 1. Rectangular spiral antenna. (a) Top view. (b) Bottom view.

tenna gain is to use a reflective layer, as in [11] which adds four spacers across the four corners of the patch antenna. The antenna, which is 60 mm × 55 mm × 8 mm, operates at 2.5 GHz with a gain of 5 dBi and has a narrow bandwidth of 0.47 MHz. Moreover, an FR-4 substrate was used in [12] to design a 28 mm × 20 mm wideband antenna that might function in the n77 and n78 bands of 5G New Radio. The antenna had a gain of 2.2 dB and a bandwidth of 700 MHz. A triple-band MIMO antenna has been designed and analyzed for sub-6 GHz applications including fixed wireless access and internet of things (IoT) applications [13]. A hexagon-shaped co-planar waveguide feed-based frequency reconfigurable antenna is designed and analyzed for sub-6 GHz applications [14]. A dipole antenna is designed with metallic sheets for ultra-high frequency (UHF) and very high frequency (VHF) applications [15]. A reflector array antenna is designed and analyzed at millimetric band for on the move applications [16]. A frequency selective surface antenna is designed and analyzed for IoT applications [17]. A dual-band patch antenna has been designed and analyzed for sub-6 GHz wireless communication applications [18]. An electrically small antenna with a circular slot has been designed and analyzed for GPS applications [19]. A multi-band hybrid dielectric resonator antenna has been designed and analyzed for wireless applications [20]. Electrically small antennas are designed and analyzed for radio frequency identification (RFID) applications [21, 22]. A brief concept of rectangular spiral antennas is reported [23, 24].

Sub-6 GHz frequency ranges for 5G wireless communication applications are shown in Table 1.

This article presents the design of a rectangular spiral antenna using a Z-shaped structure that addresses the aforementioned issues. The design combines a rectangular spiral antenna with a 50 Ω transmission line, and a Z-shaped structure is used to achieve high gain and wide bandwidth. The work that is being presented demonstrates an effective combination of small size, easy design, wide operational region, and high gain. This is how the rest of the article is arranged. Section 2 provides the mathematical analysis and design procedure for the rectangular spiral antenna. Section 3 presents various performance parameters of the rectangular spiral antenna, while Section 4 concludes the article.

2. GEOMETRY AND DESIGN METHODOLOGY

Rectangular spiral antenna is a slight variation of a Archimedes spiral structure. Furthermore, it is a simpler structure and occupies small space. The proposed design and geometry of the rectangular spiral antenna are shown in Figure 1. The design parameters of the rectangular spiral antenna are shown in Table 2. The rectangular spiral antenna is designed on an FR4 substrate

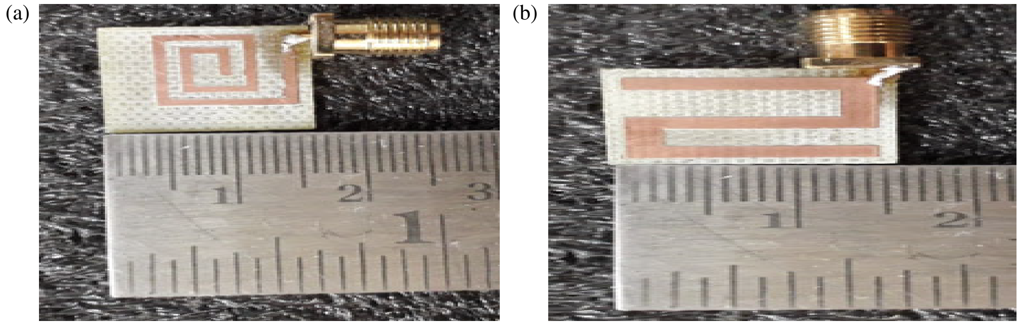

FIGURE 2. Prototype images of rectangular spiral antenna. (a) Top view. (b) Bottom view.

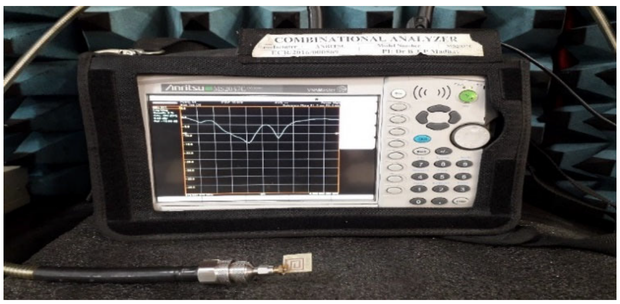

FIGURE 3. Measurement of rectangular spiral antenna with an MS2037C Anritsu combinational analyzer.

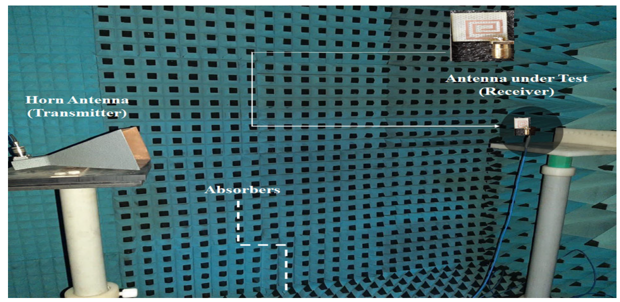

FIGURE 4. Measurement of rectangular spiral antenna in an anechoic chamber.

which has a ε_r of 4.4, tan δ of 0.02, and thickness of 1.6 mm. By varying the dimensions of the transmission lines, it can improve the efficiency of the antenna compared to traditional microwave patch antennas. The rectangular spiral antenna occupies an area of $16 \times 16 \times 1.6\,\text{mm}^3$, and it is united by a $50\,\Omega$ microstrip transmission line. A Z-shaped structure is used as the ground plane. The rectangular spiral antenna is simulated by using the finite element method (HFSS). Prototype of the rectangular spiral antenna and its measurement using the MS2037C Anritsu Combinational Analyzer are shown in Figure 2. The dimensions that were utilised while designing the rectangular spiral antenna are obtained from the mathematical formulae (1)–(5). Length of the microstrip transmission line is obtained by using (1). The selection of the antenna feeding method plays an important role because it affects the gain, reflection coefficient, bandwidth, and other important parameters of an antenna. Based on these specifications and factors, HFSS is used to simulate and optimize the antenna dimensions. The major challenge of the spiral antennas is impedance matching because of the small antenna size. This leads to large reactance and small radiation flow. In our scenario, inductive reactance of the patch is matched with the capacitive load. The Z-shaped structure acts as a capacitive load. The gap between the lines provides internal capacitance and inductance in the bottom plane. The resonant frequencies of the antenna are varied by changing the length and width of the rectangular spiral-shaped structure and Z-shaped structure, according to which a rectangular spiral antenna is designed at the top plane and a Z-shaped structure in the ground plane for S-band applications. Figure 1 represents the top view and bottom view of the rectangular spiral antenna, and their dimensions are represented in Table 2. Figure 2 represents the prototype of the rectangular spiral antenna, which is obtained by using chemical etching, and the measurement of that antenna with MS2037C Anritsu combinational analyzer is shown in Figure 3. As per the Archimedean Spiral principle, length and width of the spiral antenna are calculated by using Equations (1, 2) [23, 24].

TABLE 2. Dimensions of the rectangular spiral antenna.

Parameters	Values (mm)
Length of the Substrate (L)	16
Length of the resonating element (L_1)	11
Length of the resonating element (L_2)	14
Length of the resonating element (L_3)	12
Length of the resonating element (L_4)	7
Length of the resonating element (L_5)	8.6
Length of the resonating element (L_6)	4.4
Length of the resonating element (L_7)	9
Length of the resonating element (L_8)	7
Width of the Substrate (W)	16
Width of the resonating element (W_1)	1
Width of the resonating element (W_2)	2
Width of the resonating element (W_3)	2
Width of the resonating element (W_4)	2

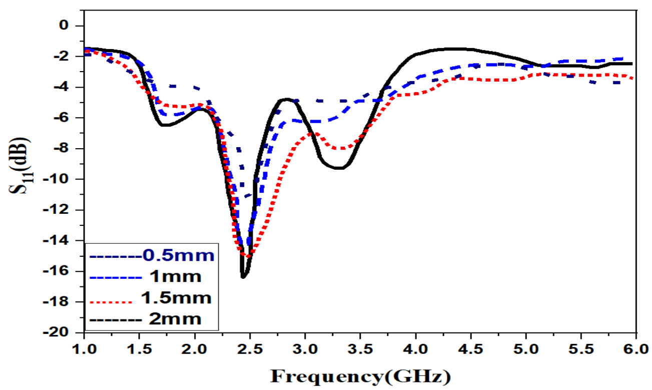

FIGURE 5. Parametric analysis of the rectangular spiral antenna by varying W_4.

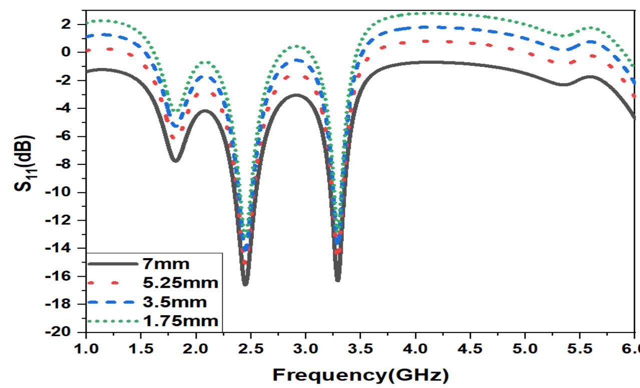

FIGURE 6. Parametric analysis of the rectangular spiral antenna by varying L_4.

$$L = \frac{\lambda}{4}\left(1 - \frac{97.82}{Z_C}\right) \quad (1)$$

where λ is the wavelength at resonant frequency and is given as

$$\lambda = \frac{C}{F_r} \quad (2)$$

$$\frac{W}{h} = \frac{8 \times e^A}{e^{2A} - 1} \quad (3)$$

$$Z_C = 120\ln\left(\text{ctg}\left(\frac{\theta_0}{4}\right)\right) \quad (4)$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_{r+1}}{2}} + \frac{\varepsilon_r + 1}{\varepsilon_r - 1} * \left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (5)$$

where Z_c is the characteristic impedance and obtained by using Equation (3), and h is the thickness of the substrate. ε_r is the substrate's dielectric constant.

Figures 5 and 6 present the parametric analysis of the rectangular spiral antenna by varying L_4 and W_4. The reflection coefficient of the first band increases by increasing W_4, and high amount of reflection coefficient is obtained when width of the rectangle is 2 mm. Figure 6 is obtained by varying L_4. In addition to the first resonant frequency band, an additional band is obtained at 3.3 GHz. Resonant frequency of the rectangular spiral antenna is increased by increasing the length L_4. The best reflection coefficient is obtained when the length and width of W_4 and L_4 are 2 mm and 7 mm. Reflection coefficients of -16.5 dB at 2.4 GHz and -16.2 dB at 3.3 GHz are obtained.

3. RESULTS AND DISCUSSIONS

Reflection coefficient is the front-end parameter that has to be measured for any RF device. Figure 7 represents the reflection coefficient of the rectangular spiral antenna. Black solid line represents the simulated reflection coefficient of the rectangular spiral antenna. Simulated antenna resonates at 2.4 GHz and 3.3 GHz with reflection coefficients of -16.5 dB and -16.2 dB with an impedance bandwidth of 0.2 GHz and 0.22 GHz, respectively, is applicable to Zigbee/IEEE 802.15.4-based wireless data networks operating in the 2.4–2.4835 GHz band, and is also suitable for a wide range of applications including FWA systems. Red dashed line represents the reflection coefficient of the prototype antenna and is measured by using MS2037C Anritsu Combinational Analyser. Close agreement between the simulated and measured results has been observed with minor variation because of the substrate limitations, fabrication tolerance, and measurement conditions.

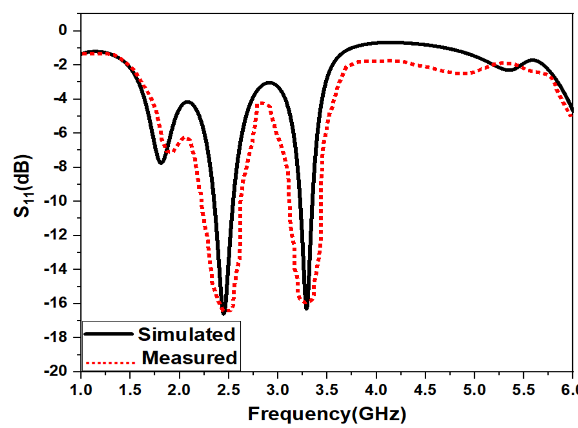

FIGURE 7. Reflection coefficient of the rectangular spiral antenna.

As seen in Figure 4, the radiation pattern was evaluated inside an anechoic chamber in order to assess the effectiveness of the rectangular spiral antenna. The normal horn antenna (INFOMW LB-20200-SF) at one end serves as the transmitting antenna, while the rectangular spiral antenna serves as the receiving antenna. Size of the horn antenna is $120 \times 90 \times 60\,\text{mm}^3$, and its weight is 900 g. As seen in Figure 4, the measurement was performed by rotating (360°) azimuthally across the horizontal direction (x-direction). Rectangular spiral antenna is much smaller than that of the microstrip patch antenna. Figure 8 represents the simulated and measured radiation patterns in E-plane and H-plane at 2.40 GHz and 3.3 GHz. In E-plane and H-plane when θ and Φ have 0°, the antenna exhibits an om-

TABLE 3. Comparison of rectangular spiral antenna with the existing literature.

Reference	Antenna Type	Antenna size (λ_0^2)	Gain (dBi)	VSWR	S_{11} (dB)
[2]	Dual band	0.24×0.24	2.4	1.1	-14
[4]	Dual band	0.34×0.16	2.85	1.8	-15
[7]	Dual band	0.34×0.34	—	1.7	-14.78
[8]	Dual band	0.16×0.16	—	1.3	-15
Proposed model	Dual band	0.128×0.128	3.1	1.5	-16.5
			3.34	1.6	-16.2

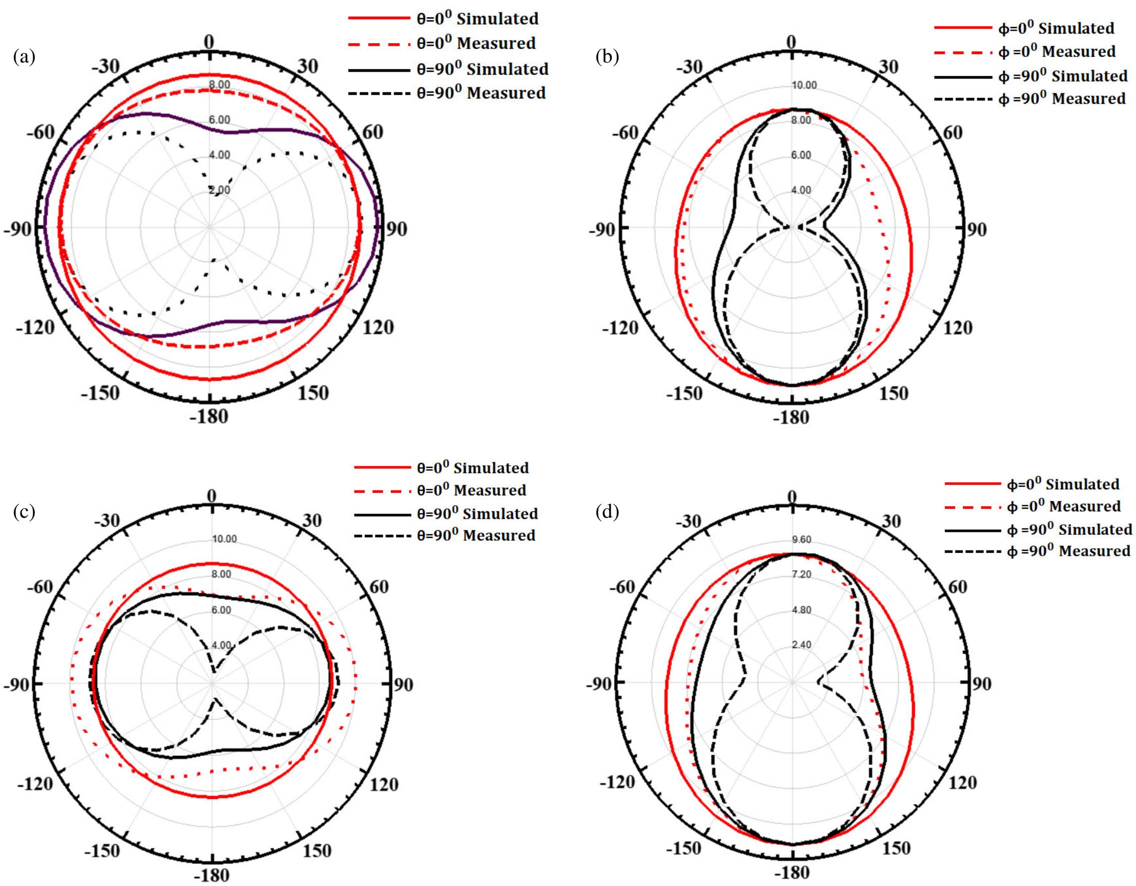

FIGURE 8. Radiation pattern of the rectangular spiral antenna. (a) E-plane at 2.4 GHz, (b) H-plane at 2.4 GHz, (c) E-plane at 3.3 GHz, (d) H-plane at 3.3 GHz.

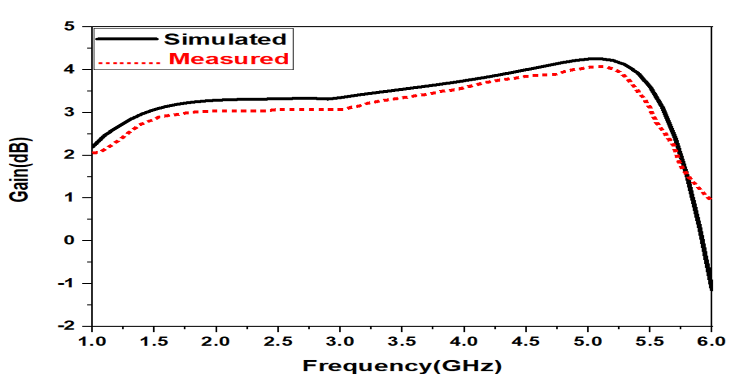

FIGURE 9. Gain of the rectangular spiral antenna.

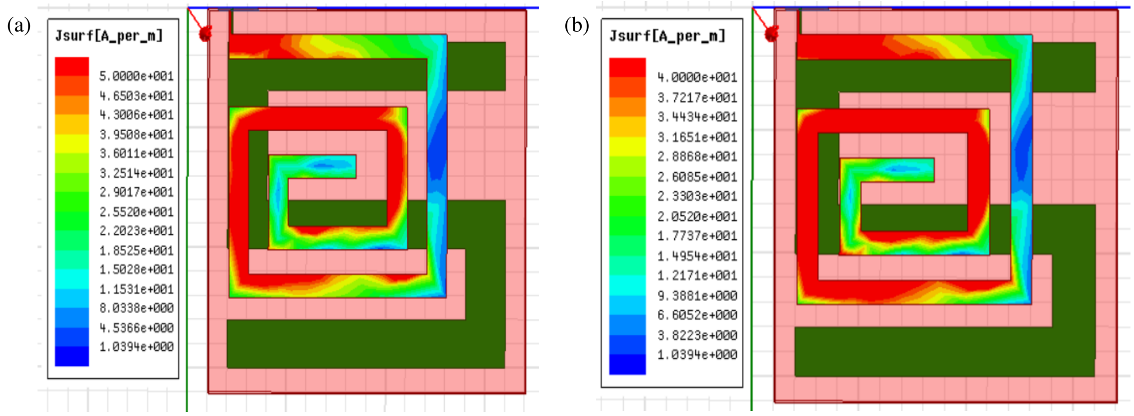

FIGURE 10. Surface current distributions of the rectangular spiral antenna. (a) 2.4 GHz, (b) 3.3 GHz.

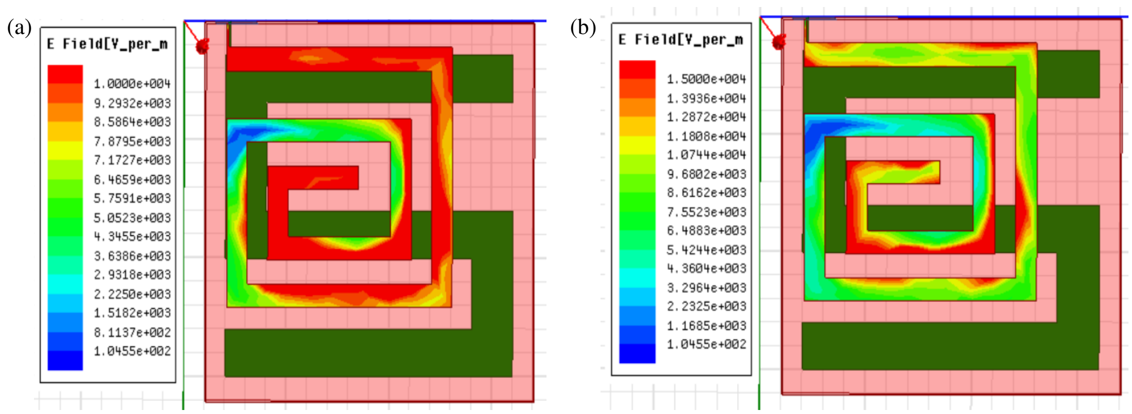

FIGURE 11. E-field distributions of the rectangular spiral antenna. (a) 2.4 GHz, (b) 3.3 GHz.

nidirectional radiation pattern, and when θ and Φ have $90°$, the antenna exhibits bidirectional pattern with good co-polarization and cross-polarization radiation in the broadside direction, or more than 20 dB at each of the two resonant frequency bands ($E\&H$). The simulated and measured radiation patterns are in close agreement with each other.

Figure 9 represents the overall gain of the rectangular spiral antenna, and a maximum value of 3.1 dBi and 3.34 dBi has been observed at 2.4 GHz and 3.3 GHz, respectively. Current distributions of the rectangular spiral antenna at 2.4 GHz and 3.3 GHz are shown in Figure 10. Maximum field distribution is denoted by red color. Maximum values of 50 Am^{-1} and 40 Am^{-1} have been observed at 2.4 GHz and 3.3 GHz, respectively. Maximum amount of current is distributed at the edges and center of the antenna. E-field distribution of the rectangular spiral antenna is shown in Figure 11. The surface current distributions of the antenna are important to identify where the antenna is radiating, and red color indicates the maximum amount of radiation. From Figure 10 it is observed that maximum amount of radiation is observed at the center and edges of the antenna. Rectangular spiral antenna is inspired from the Archimedean rectangular spiral. Figure 12 represents the rectangular spiral antenna and is obtained from Ansoft HFSS as well as MATLAB. Radiation efficiency of 87% has been observed at both the resonating frequencies.

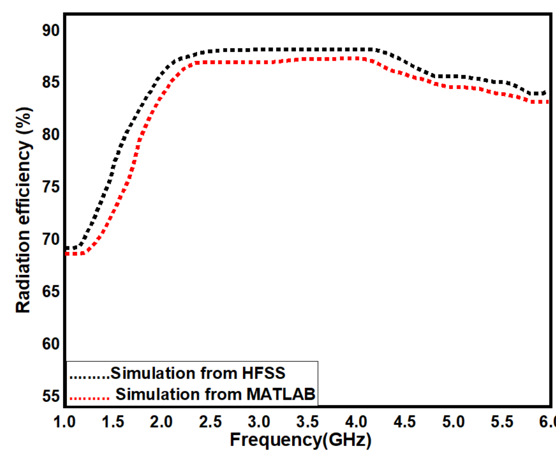

FIGURE 12. Radiation efficiency of the rectangular spiral antenna.

Table 3 represents the comparison table of the rectangular spiral antenna with the available existing literature. Even though the antenna in [2] resonates at various bands and offers less voltage standing wave ratio (VSWR), it occupies more space than that of our proposed antenna. The antenna in [4] offers a gain of 2.85 dBi and occupies less space, and it is a complex structure and is difficult to fabricate. The antennas in [7, 8] occupy less space and are easy to design but offer negative gain.

Our proposed rectangular spiral antenna is easy to design, occupies less space, and can be easily fabricated and makes the antenna suitable for Zigbee/IEEE 802.15.4-based wireless data networks and is also suitable for a wide range of applications including FWA systems.

4. CONCLUSION

In this work, we have designed, simulated, and tested a rectangular spiral antenna by using an inset fed technique at 2.4 GHz and 3.3 GHz by utilising FR4 for S-band applications. The rectangular spiral antenna has a compact size of $16 \times 16\,\text{mm}^2$, can be easily designed, and offers a bandwidth of 0.2 GHz and 0.22 GHz, with reflection co-efficient and gain of -16.5 dB, -16.2 dB and 3.1 dBi, 3.34 dBi at 2.4 GHz and 3.3 GHz, respectively. Prototype of the rectangular spiral antenna is measured and tested by utilising MS2037C Anritsu Combinational Analyser. It offers fractional bandwidths (FBWs) of 8% and 6.67%. Because of the strong relation between the simulated and measured results, the proposed antenna is suitable for Zigbee/IEEE 802.15.4-based wireless data networks and is also suitable for a wide range of applications including FWA systems.

REFERENCES

[1] Malaisamy, K., M. Santhi, and S. Robinson, "Design and analysis of 4×4 MIMO antenna with DGS for WLAN applications," *International Journal of Microwave and Wireless Technologies*, Vol. 13, No. 9, 979–985, 2021.

[2] Maema, H. and T. Fukusako, "Radiation efficiency improvement for electrically small and low-profile antenna by stacked elements," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 305–308, 2014.

[3] Tang, M.-C., B. Zhou, and R. W. Ziolkowski, "Low-profile, electrically small, huygens source antenna with pattern-reconfigurability that covers the entire azimuthal plane," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 3, 1063–1072, 2017.

[4] Chlavin, A., "A new antenna feed having equal E- and H-plane patterns," *Transactions of the IRE Professional Group on Antennas and Propagation*, Vol. 2, No. 3, 113–119, 1954.

[5] Siu, L., H. Wong, and K.-M. Luk, "A dual-polarized magneto-electric dipole with dielectric loading," *IEEE Transactions on Antennas and Propagation*, Vol. 57, No. 3, 616–623, 2009.

[6] Paul, L. C., S. C. Das, T. Rani, S. M. Muyeen, S. A. Shezan, and M. F. Ishraque, "A slotted plus-shaped antenna with a DGS for 5G sub-6 GHz/WiMAX applications," *Heliyon*, Vol. 8, No. 12, e12040, 2022.

[7] Sree, M. F. A., M. H. A. Elazeem, and W. Swelam, "Dual band patch antenna based on letter slotted DGS for 5G sub-6 GHz application," in *Journal of Physics: Conference Series*, Vol. 2128, No. 1, 012008, 2021.

[8] Tütüncü, B. and M. Kösem, "Substrate analysis on the design of wide-band antenna for sub-6 GHz 5G communication," *Wireless Personal Communications*, Vol. 125, No. 2, 1523–1535, 2022.

[9] Narayana, M. V., G. Immadi, A. Navya, M. V. Swathi, M. Nikhitha, B. Vineetha, and G. C. A. S. Swaroop, "Analysis of a quad port dual band MIMO antenna for sub-6 GHz applications," *Progress In Electromagnetics Research B*, Vol. 105, 137–151, 2024.

[10] Paul, L. C., S. C. Das, M. N. Hossain, and W.-S. Lee, "A wide-band rose-shaped patch antenna with a ground slot for sub-6 GHz applications," in *2021 IEEE Indian Conference on Antennas and Propagation (InCAP)*, 901–904, Jaipur, Rajasthan, India, 2021.

[11] Tang, X., Y. Jiao, H. Li, W. Zong, Z. Yao, F. Shan, Y. Li, W. Yue, and S. Gao, "Ultra-wideband patch antenna for sub-6 GHz 5G communications," in *2019 International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM)*, 1–3, Qingdao, China, 2019.

[12] Awan, W. A., N. Hussain, A. Ghaffar, A. Zaidi, and X. J. Li, "A compact flexible antennas for ISM and 5G sub-6-GHz band application," in *24th International ITG Workshop on Smart Antennas, WSA 2020*, 1–3, Hamburg, Germany, 2020.

[13] Immadi, G., M. V. Narayana, A. Navya, A. S. Madhuri, B. V. Krishna, and M. V. S. Gopi, "Analysis of a triple band MIMO antenna for sub-6 GHz applications," *Progress In Electromagnetics Research B*, Vol. 107, 47–62, 2024.

[14] Ullah, S., I. Ahmad, Y. Raheem, S. Ullah, T. Ahmad, and U. Habib, "Hexagonal shaped CPW feed based frequency reconfigurable antenna for WLAN and sub-6 GHz 5G applications," in *2020 International Conference on Emerging Trends in Smart Technologies (ICETST)*, 1–4, Karachi, Pakistan, 2020.

[15] Immadi, G., M. V. Narayana, A. Navya, A. Venkatesh, S. C. Spurjeon, S. S. Venkat, and S. Sanjay, "Design of high directional crossed dipole antenna with metallic sheets for UHF and VHF applications," *International Journal of Engineering and Technology*, Vol. 7, 42–50, 2018.

[16] Imamdi, G., M. V. Narayan, A. Navya, and A. Roja, "Reflector array antenna design at millimetric (mm) band for on the move applications," *ARPN Journal of Engineering and Applied Sciences*, Vol. 13, No. 1, 352–359, 2018.

[17] Immadi, G., M. V. Narayana, A. Navya, C. A. Varma, A. A. Reddy, A. M. Deepika, and K. Kavya, "Analysis of substrate integrated frequency selective surface antenna for IoT applications," *Indonesian Journal of Electrical Engineering and Computer Science*, Vol. 18, No. 2, 875–881, 2020.

[18] Kumar, M. N., M. V. Narayana, G. Immadi, P. Satyanarayana, and A. Navya, "Analysis of a low-profile, dual band patch antenna for wireless applications," *AIMS Electronics and Electrical Engineering*, Vol. 7, No. 2, 171–186, 2023.

[19] Reddy, K. H., M. V. Narayana, G. Immadi, P. Satyanarayana, K. Rajkamal, and A. Navya, "A low-profile electrically small antenna with a circular slot for global positioning system applications," *Progress In Electromagnetics Research C*, Vol. 133, 27–38, 2023.

[20] Rao, L. N., G. Immadi, M. V. Narayana, A. Navya, A. S. Madhuri, and K. Rajkamal, "A compact multiband hybrid rectangular DRA for wireless applications," *Progress In Electromagnetics Research Letters*, Vol. 117, 89–96, 2024.

[21] Majji, N. K., V. N. Madhavareddy, G. Immadi, N. Ambati, and S. M. Aovuthu, "Analysis of a compact electrically small antenna with SRR for RFID applications," *Engineering, Technology & Applied Science Research*, Vol. 14, No. 1, 12 457–12 463, 2024.

[22] Majji, N. K., V. N. Madhavareddy, G. Immadi, and N. Ambati, "A low-profile electrically small serrated rectangular patch antenna for RFID applications," *Engineering, Technology & Applied Science Research*, Vol. 14, No. 2, 13 611–13 616, 2024.

[23] Saynak, U., "Novel rectangular spiral antennas," Izmir Institute of Technology, Urla, İzmir, Turkey, 2008.

[24] Zhang, X., Y. Han, W. Li, and X. Duan, "A rectangular planar spiral antenna for GIS partial discharge detection," *International Journal of Antennas and Propagation*, Vol. 2014, No. 1, 985697, 2014.