

Design of Fork-Shaped Antenna for IoT Applications

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ABSTRACT: This research develops an innovative, compact, and efficient antenna for IoT devices that guarantees reliable wireless communication across various frequency bands. We propose a new three-element, fork-shaped multiband antenna design for multiband operation and higher isolation between the radiating elements. Split-Ring Resonators (SRRs) are implemented to enhance the antenna's electromagnetic performance and isolation between the radiating elements. The antenna design is realized using an FR-4 substrate with dimensions of $40 \times 35 \times 1.6 \text{ mm}^3$. Simulation results show the presence of five resonance frequencies: 3.17 (3.13–3.20), 3.74 (3.62–4.2), 4.90 (4.4–5.91), 5.39, and 6.84 (6.11–7.23), 7.91 (7.76–8.06) GHz with reflection coefficients -10.78 , -20.21 , -18.04 , -16.49 , and -26.27 dB, respectively. Using resonating elements enhances electromagnetic field confinement and provides isolation between the radiating elements. The fabricated prototype shows good agreement between simulated and measured results. The maximum gain of the proposed antenna is 3.79 dB, and the radiation efficiency ranges from 66% to 94%. These findings confirm that the proposed antenna, owing to its compact dimensions, multiband characteristics, and favorable electromagnetic performance, is a promising candidate for IoT-based wireless communication applications.

1. INTRODUCTION

The rapid expansion of the Internet of Things (IoT) has created growing demand for compact, lightweight, low-cost, and efficient antennas capable of supporting reliable wireless communication. IoT devices are increasingly deployed in applications such as smart homes, industrial automation, environmental monitoring, healthcare, agriculture, and intelligent transportation. Since these devices often operate under strict limitations on size, power consumption, and available installation space, antenna design plays an important role in determining the overall communication performance of an IoT system. Microstrip patch antennas are widely considered suitable for IoT applications because of their low profile, simple fabrication, ease of integration with electronic circuits, and relatively low manufacturing cost. However, conventional patch antennas generally suffer from limitations such as narrow impedance bandwidth, restricted operating frequency, and comparatively large physical dimensions at lower frequencies. Therefore, modifying the radiating geometry provides an effective approach for improving antenna characteristics while maintaining a compact structure. Recent studies have demonstrated the effectiveness of structural modifications for achieving multiband and enhanced antenna characteristics. Ref. [1] proposes a compact triple-band antenna employing multiple split-ring resonators, demonstrating how resonant structures can be incorporated into a planar antenna to obtain multiple operating bands for wireless applications. A similar investigation evaluated a star-fractal antenna integrated with a defected ground structure (DGS) and a metasurface, demonstrating how combining geometrical modifications with electromagnetic structures can en-

hance compact antenna performance [2]. A multiband antenna design for terrestrial applications further demonstrates the importance of carefully engineered antenna geometries for achieving multiple resonances and desirable radiation characteristics, as studied in [3].

Although these approaches provide significant improvement, integrating complex resonant structures, DGS configurations, or metasurfaces can increase design complexity and fabrication requirements. Hence, there remains a need for antenna configurations that can provide improved electromagnetic characteristics using a comparatively simple, compact geometry. In this context, the fork-shaped configuration offers an interesting approach because its branches can generate additional current paths and modify the radiator's effective electrical length. Appropriately optimizing fork dimensions can influence the resonant frequency, impedance bandwidth, gain, and radiation efficiency [4].

The paper proposes a compact fork-shaped antenna for IoT applications, featuring a novel electro-mechanical design with a miniature $40 \times 35 \text{ mm}^2$ footprint and six narrow resonant bands across 0–8 GHz. Its symmetric comb structure provides optimized stress distribution for high micro-electromechanical system (MEMS) sensitivity and stable current distribution for radiation, achieved through a four-step iterative design using split-ring resonators and parasitic elements. Despite using a lossy FR-4 substrate, the antenna achieves up to 94% efficiency and 3.79 dBi gain, demonstrating strong potential for compact, multiband IoT wireless communication applications.

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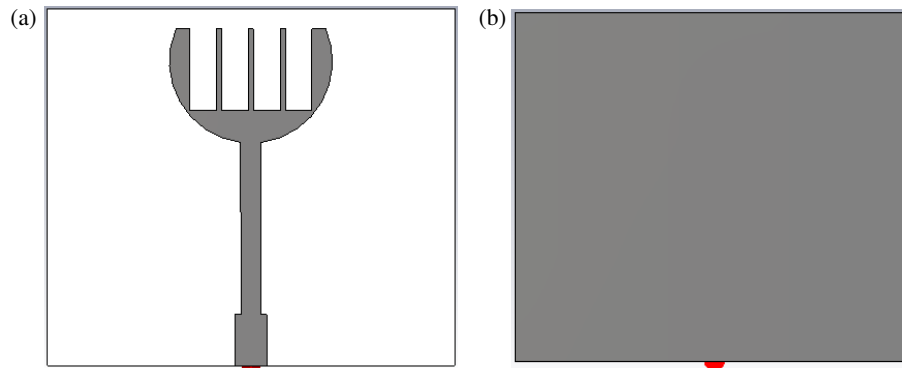


FIGURE 1. Geometry of fork-shaped single element. (a) Front view and (b) back view.

2. LITERATURE SURVEY

Many studies have conducted literature surveys of fractional antenna designs. This study proposes a compact fractal antenna for multi-band communication and healthcare applications. By employing fractal geometry, the antenna achieves multi-band operation while maintaining compact dimensions, good impedance matching, and satisfactory radiation performance. The proposed design demonstrates the effectiveness of fractal structures in developing compact, efficient, and cost-effective antennas for modern wireless communication and biomedical systems [5]. This study presents a fractal antenna for multi-band wireless applications using a self-similar fractal geometry. The proposed antenna achieved multi-band operation with compact dimensions, good impedance matching, and stable radiation characteristics. The study demonstrates that fractal antenna designs are effective in supporting multiple wireless communication bands while reducing antenna size and improving overall performance. Ref. [6] developed a compact CSRR-based microwave sensor for non-invasive blood glucose monitoring. The sensor showed high sensitivity and reliable performance, and miniaturized fractal radiating element has been designed for biomedical sensing applications [7, 8]. The fractal structure improved the sensor compactness and sensitivity, making it suitable for bio-sensing applications. A compact fractal multiband antenna was developed for mid-band 5G wireless communication. The proposed design achieved multi-band operation with good impedance matching and stable radiation performance [9]. In this study, a compact quad-port Grass-Hook multiple-input multiple-output (MIMO) antenna for tri-band applications has been developed. This antenna shows excellent isolation performance for wireless communication systems. Circularly polarized multi-band fractal microstrip antennas were designed using square and Giuseppe Peano geometries [10, 11]. The designed antenna operates in a multi-band mode with reduced size and better radiation properties. This study investigates a miniaturized dual-band Wi-Fi antenna designed for portable applications. The antenna performance was stable and effective, making it ideal for small wireless devices [12]. For ultra-wideband (UWB) applications, a small MIMO antenna with two perpendicular L-shaped slot elements is suggested. It achieves an impedance bandwidth of 3.1–

10.6 GHz with notch bands at 3.9–5.6 GHz and 7.5–8.9 GHz. A complementary split-ring resonator (CSRR) creates notch bands; a triangular corner cut permits circular polarization; and a T-shaped decoupling stub improves isolation. The antenna is small, measuring $32 \times 32 \times 0.8 \text{ mm}^3$ [25].

3. ANTENNA DESIGN EVOLUTION AND OPTIMIZATION

Designing the proposed antenna was carried out iteratively with an objective to minimize size and maximize impedance bandwidth and radiation efficiency. The development process started from a standard monopole and gradually progressed with introducing fractals into the structure, along with optimizing the feed line and ground plane sizes. The effect of each new design modification on antenna performance was studied numerically through analysis of the reflection coefficient, impedance bandwidth, gain, and radiation properties [13, 14]. Further, a comprehensive parameter study was conducted for tuning antenna dimensions and obtaining the required resonant frequencies.

3.1. Single Element Antenna

Fig. 1 shows the schematic diagram of the proposed fork-shaped structure. It is made of a comb-like structure attached with a small beam mounted on the lower side of the substrate.

The symmetric comb-finger layout improves sensitivity, while rounded edges ensure uniform stress distribution and enhanced stability. The thin beam enables controlled displacement of the sensing element, and the substrate-attached bottom section provides overall mechanical support. Due to their compact size and high sensitivity, such structures are widely used in MEMS resonators, capacitors, and actuators [15–17].

3.2. Two-Element Antenna

Figure 2 shows the dual-comb antenna configuration. It involves two semi-circular electrodes with comb shapes, placed orthogonally and electronically connected to each other through a central supporting beam.

Each comb structure is composed of uniformly spaced bars, which enable efficient capacitive interaction and increase de-

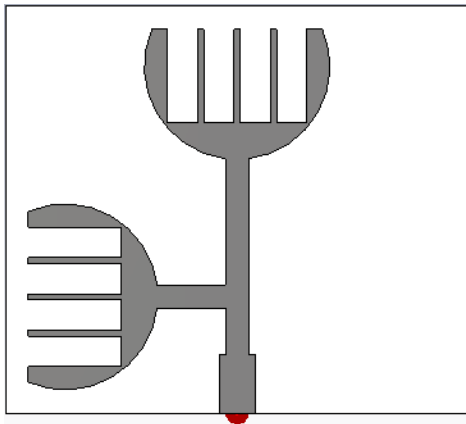


FIGURE 2. Two-element fork-shaped antenna.

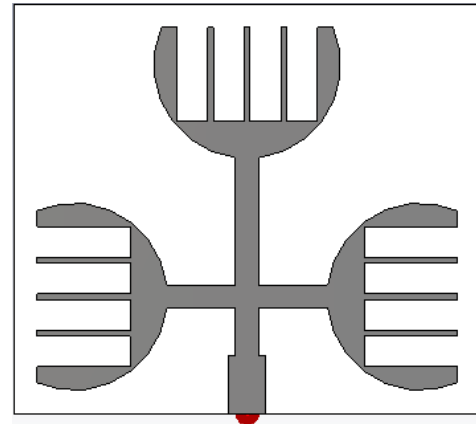


FIGURE 3. Three-element fork-shaped antenna array.

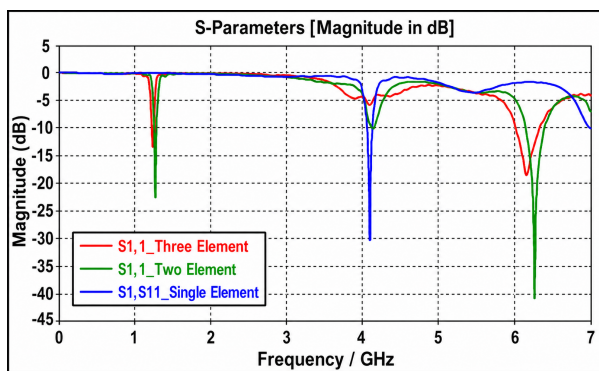


FIGURE 4. Parametric results of fork-shaped antenna element.

vice sensitivity. The geometry presented here provides a more stable structure, increased sensitivity, and efficient device integration. It can therefore be used in MEMS capacitive sensors, resonators, and actuators [26]. The orthogonal configuration of the comb structures also helps in multidirectional sensing.

3.3. Three Element Antenna

Figure 3 depicts the schematic of the designed comb-drive MEMS structure, which is composed of three comb-drive structures linked through a middle beam. These comb drives contain evenly spaced fingers. The comb structures are connected through horizontal and vertical elements, which have a cross shape. This structure allows the uniform displacement of structure elements.

The main strip line acts as the feeding element between anchors. The symmetric, multidirectional comb-finger design ensures uniform current distribution, improves sensitivity, and enables detection of different modes. Its compact size and high mechanical stability make it suitable for MEMS capacitive sensors and resonators.

Figure 4 presents a parametric study of the proposed antenna configurations with single, two, and three elements in the range 0–7 GHz. The reflection coefficient characteristics of the different configurations have been analyzed and compared to evaluate the resonant behavior and impedance-matching capabilities of different configurations.

Resonant characteristics of the single-element configuration are clearly visible around 4 GHz with a minimum return-loss value of about -30 dB. Resonance bands for the two-element configuration are seen at approximately 1.2, 4.0, and 6.2 GHz. A minimum return loss of the higher-frequency resonance is obtained around -40 dB, which reflects multiband operation due to electromagnetic coupling between resonating elements.

The three-element configuration shows multiple resonant characteristics and a wide bandwidth. The reflection coefficient values less than -10 dB represent satisfactory impedance matching in the corresponding operating frequency band. The comparative study shows that increasing the number of antenna elements significantly affects resonant frequencies and multiband operation capability for the proposed configuration [18, 19].

It has been concluded from the results that the multi-element configuration provides better frequency selectivity and electromagnetic properties and, therefore, can be used for wireless communication applications in multiple frequency bands.

4. DESIGN OF PROPOSED ANTENNA AND PARAMETRIC ANALYSIS

To achieve the required compactness, impedance bandwidth, and radiation characteristics for Internet of Things (IoT) applications, the proposed antenna incorporates a fork-shaped resonator, two hexagonal elements positioned symmetrically on either side of the main radiator and integrated with split-ring resonators (SRRs), and two rectangular elements incorporated into the ground plane. The initial design was inspired by a single-element fork-shaped antenna, which can support multiple resonant modes in a compact physical area, as illustrated in Fig. 5. Two hexagonal elements are incorporated on both sides of the antenna, which transforms the structure into a three-element fork-shaped antenna with improved multiband characteristics. Additionally, an SRR is introduced to achieve the necessary bandwidth for IoT applications.

Several geometric modifications, including inserting a slot and optimizing the patch, ground plane, and radiating-element dimensions, were introduced to control surface currents and improve impedance matching. The antenna was developed pro-

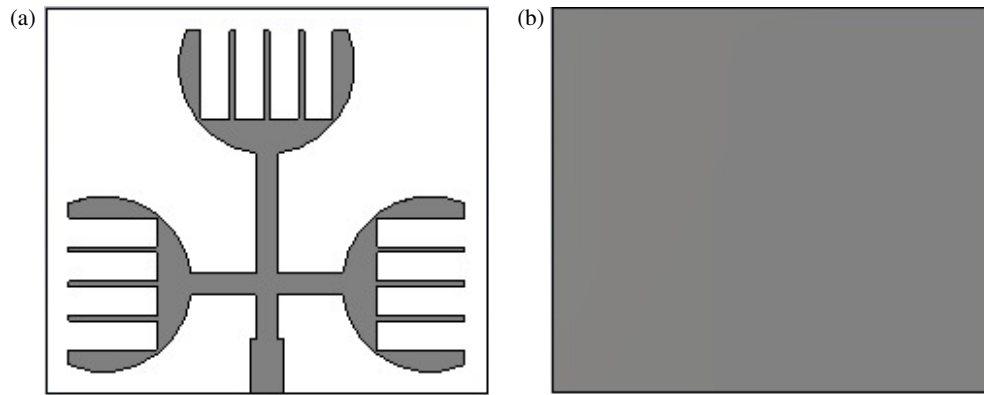


FIGURE 5. Three-element fork antenna with complete ground (Iteration-1). (a) Front view and (b) back view.

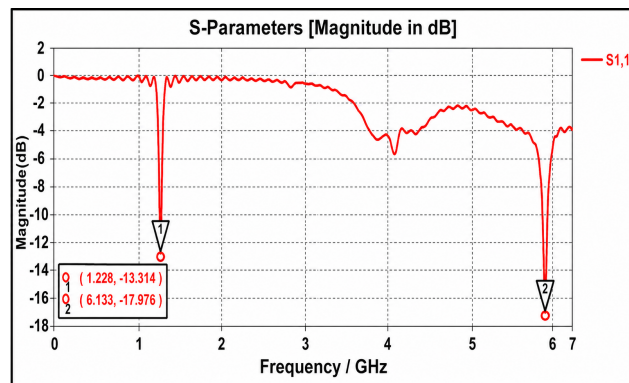


FIGURE 6. S_{11} for 1st iteration and geometry of antenna.

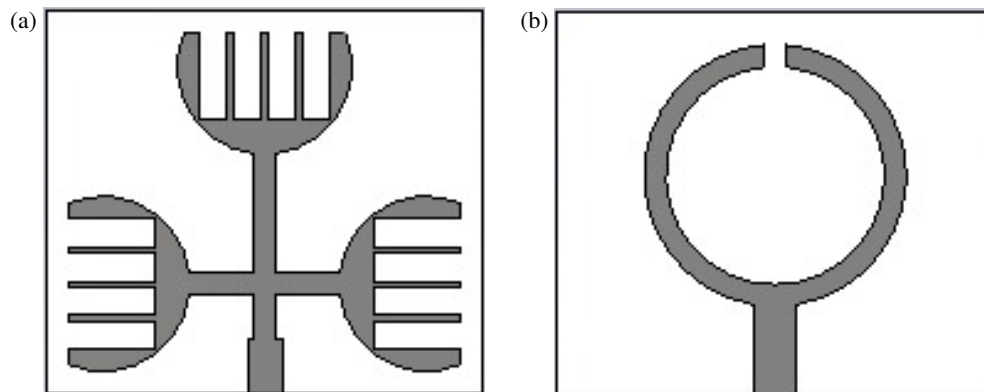


FIGURE 7. Three-element fork with ring-shaped ground (Iteration-2). (a) Front view and (b) back view

gressively, beginning with a preliminary design near the target frequency, followed by iterative optimization to achieve the required resonant frequencies, reflection coefficient, impedance matching, and radiation characteristics while maintaining a compact multiband structure [20, 21].

From the S_{11} response, as shown in Fig. 6, the initial design shows that there is two-band functionality, with resonant frequencies good enough to facilitate low-frequency IoT connections. From the S_{11} response, more changes will be required to make the design functional in other bands. To address this limitation, a split-ring resonator (SRR) was incorporated into the antenna configuration during the second design iteration. As

illustrated in Fig. 7, integrating the SRR introduces additional resonant modes, thereby enhancing the multiband characteristics of the proposed antenna.

In the second iteration, the antenna could achieve only one operating band, as shown in Fig. 8. The relatively high reflection loss and reduced overall efficiency are the motivation for further optimization. To address these limitations, an additional SRR was introduced in the antenna, which played an important role in providing better impedance matching, current distribution, and tuning of the antenna's resonance performance. Fig. 9 shows the resulting configuration and its performance.

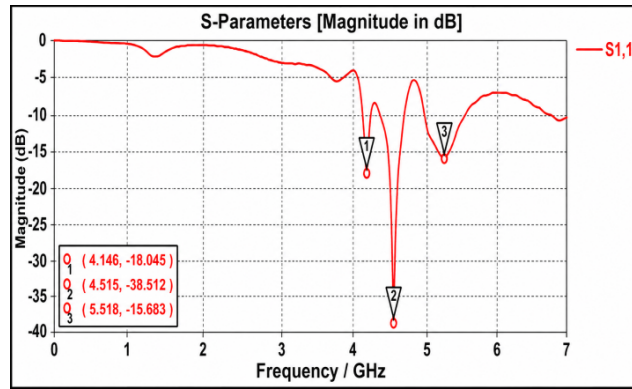


FIGURE 8. S_{11} of Iteration 2.

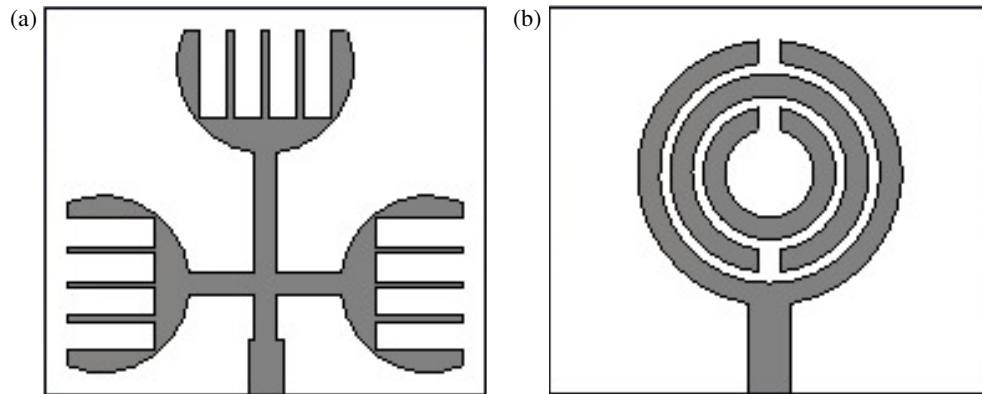


FIGURE 9. Three-element fork with ring resonator (Iteration-3). (a) Front view and (b) back view.

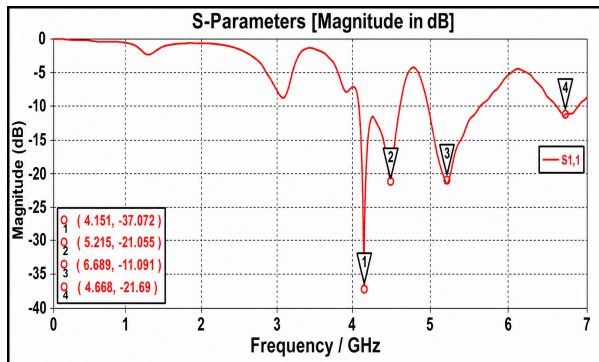


FIGURE 10. S_{11} for the 3rd iteration.

In the third design iteration, presented in Fig. 10, the antenna showed only a single operating band. Although incorporating ring resonators resulted in three distinct resonant bands, only one resonance was located within the desired frequency range. To overcome this limitation and achieve the targeted operating frequencies, two rectangular parasitic elements were introduced symmetrically on either side of the split-ring resonator, as illustrated in Fig. 11. This alteration refined the resonant response for better multiband performance.

Fig. 12 shows the fourth iteration with S_{11} results in the range of 0–7 GHz. The antenna resonates at frequencies 3.164 GHz, 3.796 GHz, 5.322 GHz, and 6.524 GHz with

S_{11} of -10.57 dB, -16.57 dB, -28.06 dB, and -28 . These results demonstrate the multiband characteristics of the proposed antenna, with particularly good impedance matching at 5.322 GHz and 6.524 GHz. However, we still need more appropriate frequency bands for our antenna. Therefore, additional changes were introduced in the next iteration. Fig. 13 presents front and back views of the final antenna geometry along with its dimensions. The hexagonal rings incorporated into the antenna structure act as parasitic resonant elements that modify the antenna's electromagnetic behavior. Due to the ring's closed-loop shape, the antenna has a long surface current path, which leads to increased electrical length and contributes to the miniaturization process. Electromagnetic coupling between the rings and the main radiating element occurs due to a spatial region around the antenna, where the effect on each other is possible. Electromagnetic coupling results in additional inductance and capacitance effects, which may create or shift resonant modes. As a result of such an interaction, the surface currents and input impedance are changed, improving impedance matching and, in some cases, broadening the impedance bandwidth. The ring parameters (perimeter, conductor width, coupling distance) determine the resonant frequency and the level of electromagnetic coupling. Therefore, hexagonal rings can be used for the antenna's frequency tuning, impedance matching, bandwidth enhancement, and electrical miniaturization.

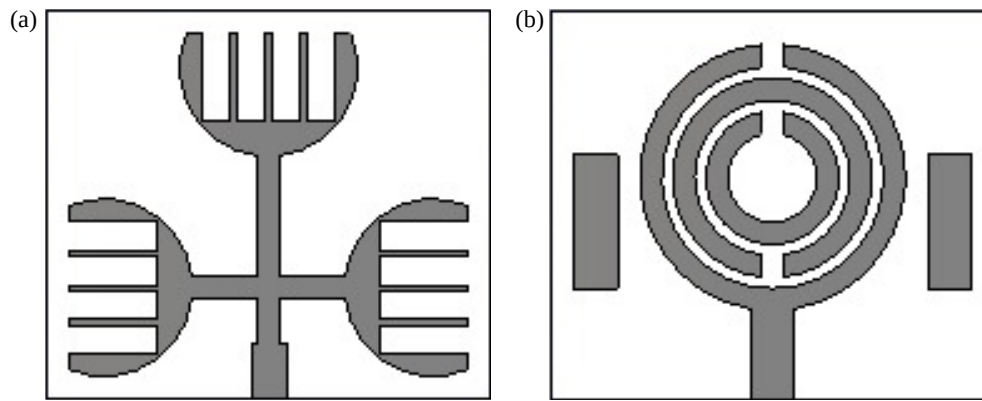


FIGURE 11. Three-element fork antenna with a ring resonator and parasitic element (Iteration-4). (a) Front view and (b) back view.

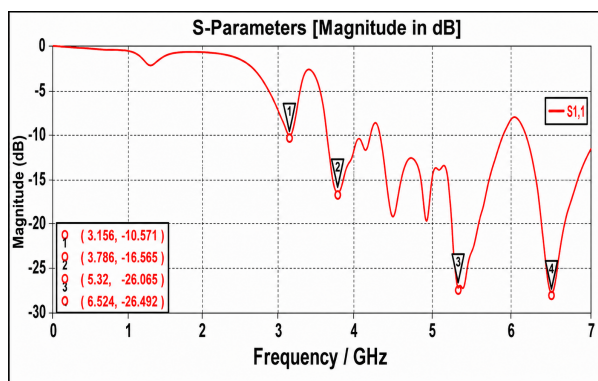


FIGURE 12. S_{11} for the 4th iteration.

Table 1 gives the geometrical dimensions of the proposed three-element antenna. All dimensions are obtained by optimization of the antenna's parametric design for the desired resonant frequency, impedance matching, and mutual coupling. The substrate's overall size is $40 \times 35 \text{ mm}^2$, whereas all other dimensions are for radiating elements, feeding lines, slots, and modified ground plane. All these dimensions are optimized to obtain an enhanced bandwidth, gain, and radiation characteristics. These optimized dimensions were then used for the simulation and fabrication of the prototype antenna.

TABLE 1. List of parameters.

Parameter	Dimension (mm)	Parameter	Dimension (mm)
$L1$	40	$a2$	2.6
$W1$	35	$f2$	0.5
$A1$	16.9	$c1$	2
$S1$	5	$s2$	2
$B2$	13.8	$h2$	4
$a3$	3.15	$h1$	8.15
$c4$	2	$d1$	24
$z2$	0.85	$D2$	4
$W4$	3	$D3$	12
$E3$	4	$R1$	9.3

In Fig. 14, the comparison is made among S_{11} characteristics in different iterations of the antenna design (Iterations 1–5). The impedance response changes significantly as the antenna geometry is refined. The first iteration exhibits resonances near 1.24 and 6.15 GHz, indicating initial multiband operation. With further geometric modifications, the resonant frequencies shift upward, and additional resonances emerge, resulting in improved multiband characteristics. The second iteration gives resonances at 4.14, 4.52, and 5.12 GHz, and the one near 4.52 GHz has a very low S_{11} value of -39.5 dB . The third iteration gives resonances at 4.15, 4.46, 5.22, and 6.69 GHz, while there are resonances at 3.16, 3.76, 5.32, and 6.53 GHz in Iteration 4. In the last iteration (Iteration 5), there are several resonances around 3.17, 3.74, 4.50, 4.95, 6.50, and 6.83 GHz. Almost all of these resonances are below the -10 dB limit, which is a good indicator of proper impedance matching.

5. RESULT AND DISCUSSION

5.1. Reflection Coefficient

The proposed antenna operates through controlled surface-current distribution, increased effective electrical length, and improved impedance matching. Parasitic elements introduce additional current paths, producing stronger resonances and supporting multiband operation. Ring resonators enhance electromagnetic-field concentration around the radiating structure, improving impedance bandwidth and radiation efficiency while enabling higher-order resonances.

The S_{11} parameter (Fig. 15) of the proposed antenna shows multiband behavior with several resonance points in the range of 1–8 GHz. The resonance points of interest in the antenna are observed at 3.17, 3.74, 4.5, 4.95, 5.45, and 6.83 GHz, and their reflection coefficients are found to be approximately equal to -10.78 , -20.21 , -15.04 , -17.36 , -25.45 , and -26.33 dB , respectively. As all these resonant points fall below the -10 dB value, good impedance matching is achieved at corresponding frequencies. Resonance points observed around 5.452 and 6.832 GHz show particularly good power transfer between the feed and radiating structure. Multiple resonances can be attributed to different current paths due to parasitic/ring elements.

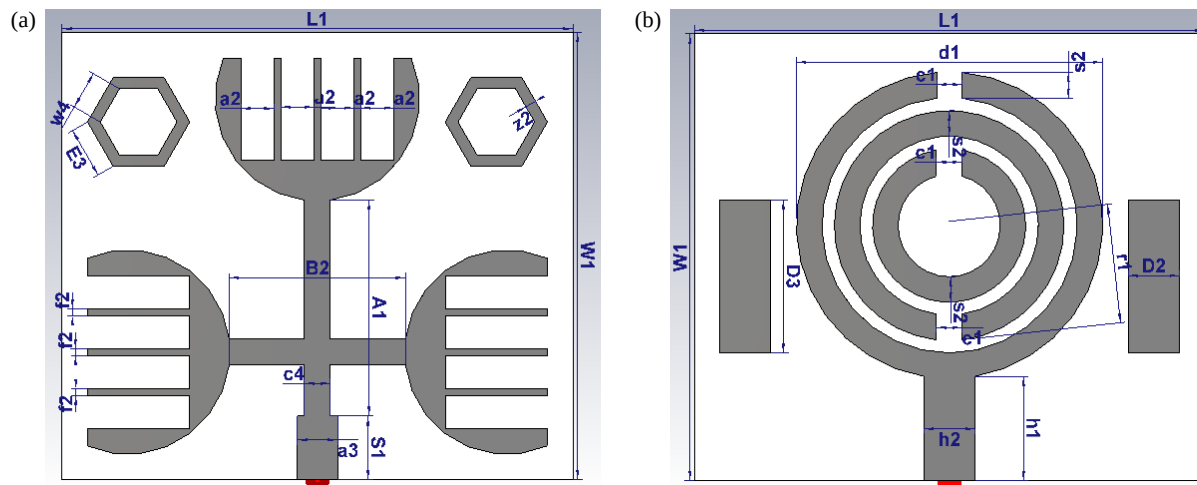


FIGURE 13. Final antenna geometry. (a) Front view and (b) back view.

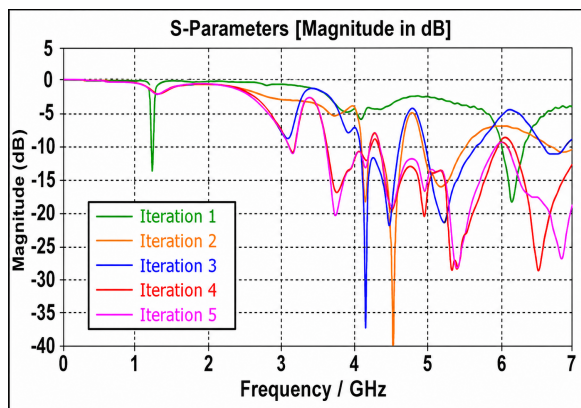


FIGURE 14. Parametric results of all iterations (1 to 5).

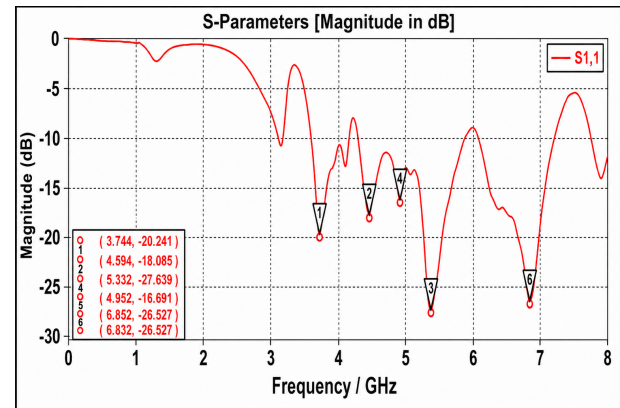


FIGURE 15. Reflection coefficient of the final design.

The resonance at 3.17 GHz is within the sub-6 GHz spectrum and makes the proposed antenna suitable for 5G NR, WiMAX, private 5G, IoT, and broadband wireless communication applications, depending on the specific regional frequency allocation. The 3.74 GHz resonance will find its place in WiMAX and sub-6-GHz 5G communication applications, especially around the 3.3–3.8 GHz band. The 4.5 GHz resonance can cater to C-band wireless, satellite, and radar applications as per the availability of the frequency band. The 4.95 GHz resonance can be employed in C-band wireless applications, along with some other communication applications, and the 5.45 GHz resonance is applicable to high-speed wireless communication. The 6.83 GHz resonance places the antenna response into the upper part of the C-band and hence, can be useful for C-band satellite, radar, and broadband wireless applications.

5.2. Radiation Characteristics

The 3D and 2D radiation plots of the designed antenna verify that the antenna has stable radiation properties in the selected frequency band. Radiation at low frequencies has broad and uniform properties, whereas at high frequencies, radiation

has some strong lobes and high directivity. Despite these frequency-dependent properties, the antenna can generate radiation in a broad angle range. In conclusion, the antenna maintained a balanced radiation pattern while effectively transmitting energy.

The three-dimensional (3D) and two-dimensional (2D) far-field radiation patterns (Fig. 16) of the designed antenna at 3.11, 3.74, 4.50, 4.95, 5.39, and 6.8 GHz illustrate the frequency-dependent radiation behavior of the proposed antenna. For instance, at 3.11 GHz, the proposed antenna has a relatively broad, uniform 3D radiation pattern, which implies a relatively good angular coverage and moderate directivity level.

The antenna shows broad, nearly uniform **2D and 3D radiation patterns** at 3.74 GHz, indicating stable energy distribution. At higher frequencies (4.50–5.39 GHz), both **2D and 3D patterns** become more concentrated, directional, and multi-lobed, with several nulls. This frequency-dependent behavior is mainly due to the increased electrical size and electromagnetic coupling between the antenna elements, resulting in constructive and destructive interference. Overall, the antenna maintains good radiation characteristics, with greater directivity at higher frequencies.

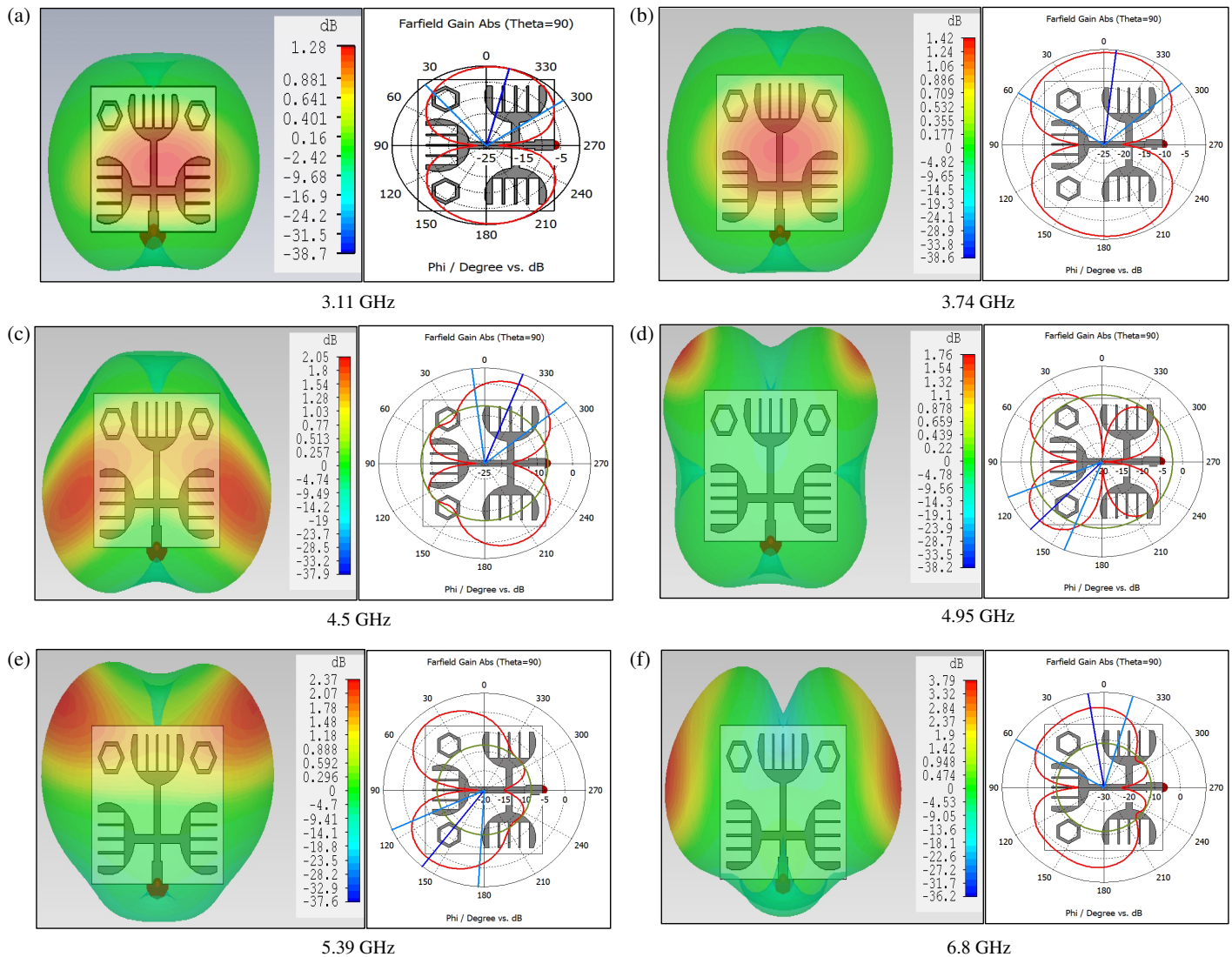


FIGURE 16. 3D and 2D radiation pattern.

5.3. Surface Current Distribution

Hexagonal parasitic elements also show distinct current activity, enabling multi-band operation and enhancing impedance matching. The direction of current vectors indicates a well-distributed flow, resulting in efficient radiation and a seamless impedance transition. The maximum current density confirms strong excitation and effective energy transfer into the radiating structure.

The ring resonator and slot-loaded area also show discernible currents, demonstrating their function in adjusting frequency and forming resonance, as shown in Fig. 17. The antenna is a dependable option for wireless communication, as all these findings show that it stimulates the desired resonant mode at 3.745 GHz. The surface current distribution at 5.39 GHz provides a clear picture of the antenna's behavior at the highest frequency.

At 5.39 GHz, the antenna shows strong, well-distributed surface currents across the radiating structure, resulting in effective energy transfer and enhanced radiation. The coupled cur-

rent paths contribute to stable radiation characteristics, confirming reliable antenna operation at this frequency and its suitability for IoT applications.

5.4. Radiation Efficiency

Figure 18 shows the radiation efficiency of the proposed antenna. The antenna efficiency at 3.1 GHz is estimated to be 83%, and the efficiency gradually increases with increasing frequency to reach a maximum of about 94% at 4.5 GHz. In this region, the antenna's radiation efficiency is very high. However, after 4.5 GHz, the efficiency drops significantly and attains a minimum value of 66% near 5.1 GHz. This decline may be attributed to various factors, including impedance mismatch, surface waves, and loss due to dielectric and conductors. However, beyond 5.1 GHz, the efficiency improves significantly to reach an efficiency of about 87% at 5.4 GHz, maintaining a constant efficiency until 6 GHz.

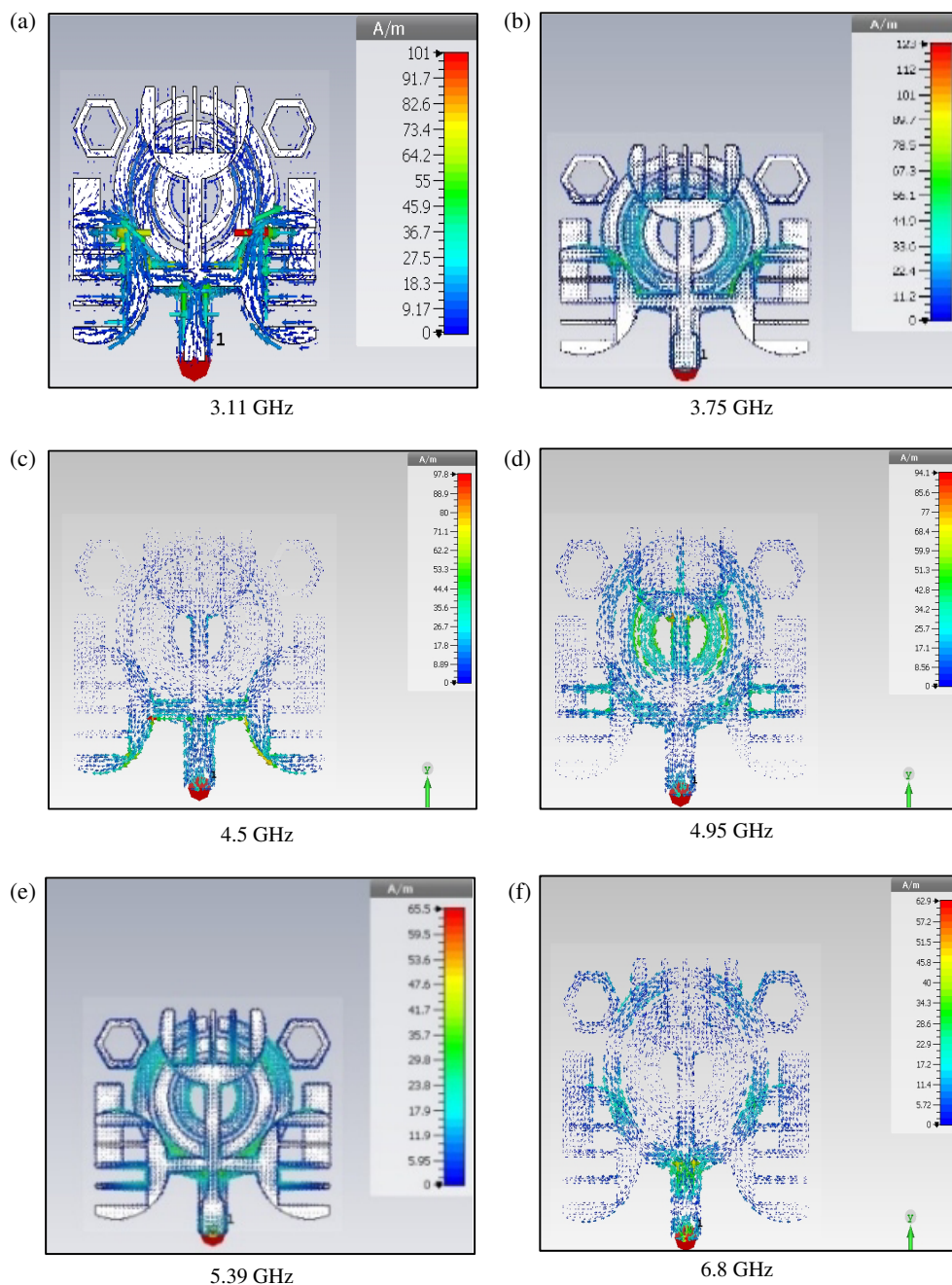


FIGURE 17. Surface current distribution.

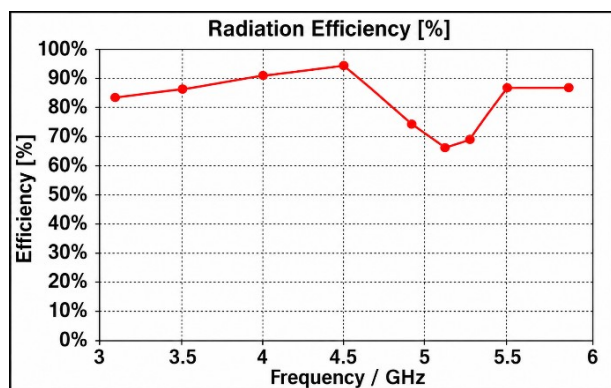


FIGURE 18. Radiation efficiency of the antenna.

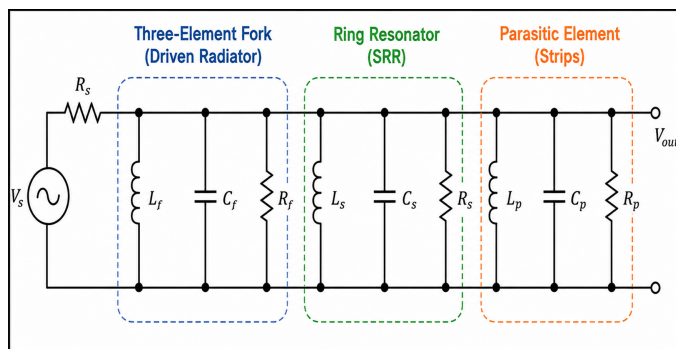


FIGURE 19. Equivalent electrical circuit of antenna.

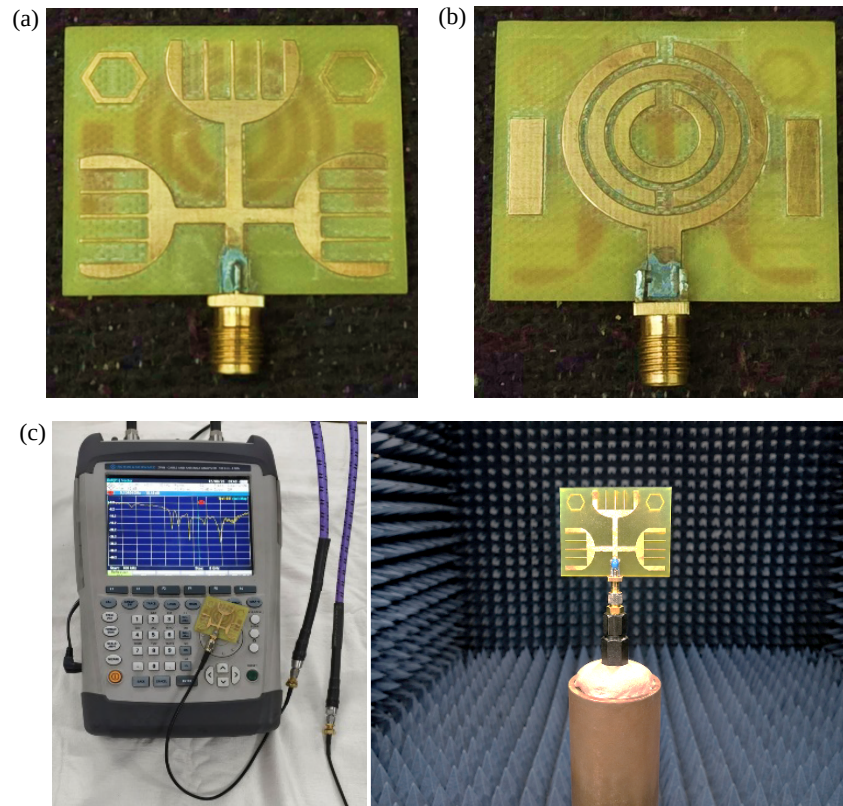


FIGURE 20. Fabricated prototype of a three-element antenna array. (a) Front view, (b) back view, (c) measurement setup.

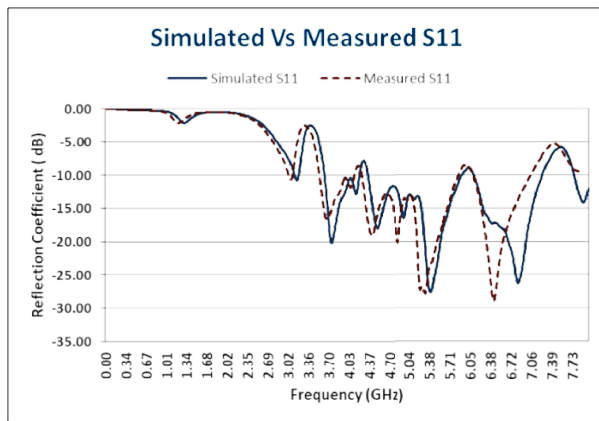


FIGURE 21. Comparison of the reflection coefficient.

5.5. Equivalent Electrical Circuit

The electrical circuit model of the proposed antenna design (Fig. 19) shows that the three-element fork antenna, ring resonator, and parasitic strips can be expressed in three coupled parallel RLC resonant circuits. The three-element fork antenna forms the main driven element; the fork's current path; C_r stands for the capacitance between the tightly spaced arms; and R_r corresponds to the radiation losses and conductor/dielectric losses. The ring resonator (SRR) can be expressed by L_s , C_s , and R_s , wherein the circular structure provides inductance, and the ring gap gives capacitance. It is excited by electromagnetic coupling to the driven fork and results in a further resonant mode. Parasitic strips are expressed by L_p , C_p , and R_p . The strips are

not connected to the feed but are excited by electromagnetic coupling.

The resonance frequencies of each section can be approximately written as

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Therefore, changing the dimensions or spacing of antenna elements changes their effective L and C , thereby controlling resonant frequencies. The interaction of the three resonators produces multiple closely spaced resonances, which can overlap to provide enhanced impedance bandwidth, improved matching, and better radiation performance.

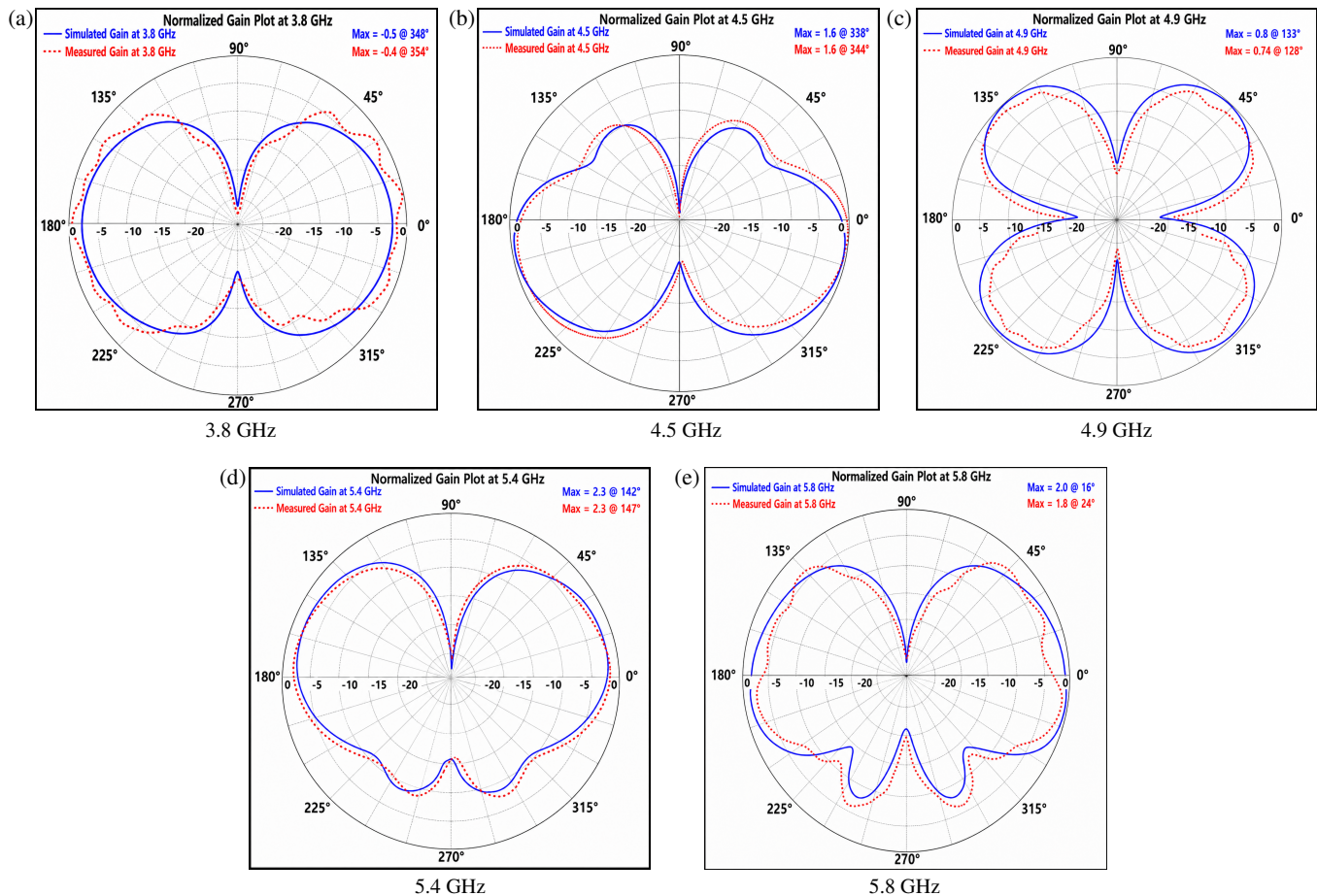
6. ANTENNA PROTOTYPE AND IMPLEMENTATION

Figures 20(a) and (b) present the fabricated prototype model of the suggested three-element antenna, which depicts the upper radiating element and the ground plane, respectively. The antenna was fabricated using the standard printed circuit board (PCB) photolithographic technique on an FR-4 epoxy substrate. An SMA connector was attached to the microstrip feed line to facilitate experimental measurements using an R&S Vector Network Analyzer (VNA), as illustrated in Fig. 20(c).

The top layer incorporates three compact radiating elements with curvilinear slots to extend the current path and generate multiple resonant frequencies. Two hexagonal parasitic elements further enhance impedance matching and radiation performance.

TABLE 2. Comparative analysis of the proposed antenna with other previously reported design.

Reference No.	Numbers of Band	Resonance Frequency Band GHz	Patch Size mm	Maximum Efficiency	Peak Gain dB
Proposed antennas	Multi-band (6)	3.17, 3.74, 4.50, 4.95, 5.45, 6.83	40×35	94%	3.79
[5]	3	2.45, 3.5, 5.8	40×40	82%	3.5
[6]	3	2.4, 3.5, 5.2	45×45	80%	3.19
[9]	3	2.4, 3.5, 5.8	38×38	85%	3.5
[10]	3	2.45, 3.5, 5.8	60×60	88%	3.4
[11]	3	1.57, 2.45, 5.2	48×48	86%	3.9
[13]	Wideband	3.1–10.6	70×70	90%	3.0
[25]	Single	2.4	50×50	78%	3.1

**FIGURE 22.** Measured vs. simulated radiation pattern of the antenna.

As shown in Fig. 20(b), the ground plane contains a defected structure (DGS) that uses concentric circular slots around a circular patch. The DGS affects the current distribution on the ground plane, inhibits surface-wave generation, and minimizes the coupling effect between the antenna elements. In addition, two rectangular parasitic strips are designed next to the DGS.

7. PERFORMANCE ANALYSIS OF MEASURED VS SIMULATED RESULTS

Figure 21 compares simulated and measured S_{11} responses of the proposed antenna. The results show good agreement across the tested frequency range, with similar resonance locations, curve profiles, and reflection minima. Minor differences in resonant frequency and magnitude can be attributed to fabrication

tolerances and measurement conditions. Overall, the close correlation validates the proposed design and confirms the reliability of the simulation results.

Figure 22 compares the results of simulated and measured two-dimensional normalized E -plane radiation patterns of the designed antenna at 3.8 GHz, 4.5 GHz, 4.9 GHz, 5.4 GHz, and 5.8 GHz. There is a very good match between theoretical model results and experimental measurement values across the entire tested frequency range. In the lower frequency bands of 3.8 GHz and 4.5 GHz, the radiation pattern shows a typical figure-of-eight with two strong lobes at 90° and 270° directions. With increasing the operating frequency up to 4.9 GHz, 5.4 GHz, and 5.8 GHz, the E -plane radiation pattern becomes more complicated and is multi-lobed and quasi-omnidirectional due to higher-order resonances within the radiating structure. Small differences in gain amplitude, asymmetric pattern shape, and angular null shift can be attributed to practical limitations such as manufacturing tolerances, parasitic loading of the SMA connector, small misalignments of the anechoic chamber equipment, and feeding cable scattering. This high degree of correlation between theoretical and experimental radiation patterns conclusively validates the robustness and reproducibility of the design methodology.

8. COMPARATIVE ANALYSIS OF PROPOSED ANTENNA

Table 2 summarizes the comparative analysis of the proposed antenna with previously reported designs. Although earlier patch antennas demonstrate multiband functionality, they are generally limited by larger physical size, fewer resonant bands, narrower bandwidths, and lower gain. In contrast, the proposed design achieves a compact form factor while supporting a greater number of resonant frequencies with enhanced bandwidth and higher gain, highlighting its superior performance and suitability for next-generation multiband wireless communication applications.

9. CONCLUSION

A miniaturized, multi-band fork-shaped antenna was systematically engineered and characterized for diversified Internet of Things (IoT) ecosystems. The proposed radiator integrates symmetric comb topologies interconnected via a cross-shaped feeding architecture to stimulate distinct multi-band modes, where the highly symmetrical arrangement ensures a uniform surface current distribution. This integrated electro-mechanical configuration shows excellent compatibility with MEMS capacitive sensors, resonators, and micro-actuators. Fabricated in a highly compact footprint of $40 \times 35 \text{ mm}^2$ on a cost-effective FR-4 substrate, the electromagnetic subsystem was developed using an iterative optimization strategy. By gradually integrating the circle-shaped ground plane, SRR, and symmetric rectangular parasitic elements, multiband selectivity and impedance matching have been improved across a wide range of the 0–8 GHz spectrum. The optimal prototype possesses six separate resonances at 3.17, 3.74, 4.50, 4.95, 5.45, and 6.83 GHz frequencies with an outstanding return loss of -10.78 , -20.21 ,

-15.04 , -17.36 , -25.45 , and -26.33 dB, respectively. In addition, the antennas' radiation performance parameters show superior figures, with maximum radiation efficiency and gain of 94% and 3.78 dBi, respectively. The agreement between the simulated predictions and experimental validations conclusively proves the structural viability of the design framework, highlighting this multi-element architecture as a highly robust, versatile solution for deployment across 5G NR, Wi-MAX, private 5G, standard IoT, C-band satellites, radar systems, and broadband wireless communication technologies.

10. FUTURE WORK

Future work will concentrate on the integration and one-chip fabrication of MEMS and antenna subsystems on one substrate for checking the performance of the chip co-design. Moreover, experimentation will be done to test the system's dynamic reliability with vibration and thermal stress continuously applied to it. The multi-band antenna will also be integrated with an RF energy-harvesting circuit to test the development of a self-powered wireless sensing node.

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