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Multiband Antenna for GPS, IRNSS, Sub-6 GHz 5G and WLAN Applications

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Abstract—An elliptical shape multi-band microstrip patch antenna with narrow semicircle cuts and bulges on two horizontal ends is proposed for Global Positioning System (GPS), Indian Regional Navigation Satellite System (IRNSS), Sub-6 GHz 5G and Wireless Local-Area Network (WLAN) wireless communication applications. The proposed antenna operates at 1.56 GHz, 2.49 GHz, 3.5 GHz, and 5.24 GHz for desired applications, respectively. The proposed antenna, fed by coaxial feeding mounted on Rogers AD255C substrate, has optimized physical dimensions of $80 \times 80 \times 3.175\,\text{mm}^3$. The semicircle cuts and bulges on horizontal ends on the elliptical element contribute to exciting higher-order modes and affect the current distribution at the resonant frequencies resulting in producing multi-band operations. The proposed antenna is fabricated and tested. The measured return loss characteristic (S_{11}) below -10 dB is -15.2 dB, -19 dB, -22.3 dB, & -27.9 dB, with the radiation efficiency of 58.7%, 94.8%, 93.2%, & 84.9% and peak gain of 3.49 dBi, 6.49 dBi, 4.93 dBi, & 4.46 dBi for desired application band, respectively. The proposed antenna also offers impedance bandwidths of 40 MHz (1.55–1.59 GHz), 90 MHz (2.43–2.52 GHz), 100 MHz (3.44–3.54 GHz), & 90 MHz (5.23–5.32 GHz) at resonant frequencies and relatively stable radiation patterns. Simulated and measured results for the proposed antenna exhibit good agreement. The proposed multi-band antenna offers a simple design and improved performance.

1. INTRODUCTION

A necessity for multi-band antennas covering many applications frequency bands such as cellular communications network/generation, Second Generation (2G), Third Generation (3G), Fourth Generation (4G), Fifth Generation (5G), IRNSS, GPS, Wireless Fidelity (Wi-Fi), and Worldwide Interoperability for Microwave Access (WiMAX), at once is currently in the demand for wireless communication systems because they can reduce the number of antennas required. It is difficult to design an effective multi-band antenna that can function effectively in multiple assigned frequency bands offering a simple design, compact size, easy manufacturing, simplicity of integration with other circuit elements and feed networks, etc. [1–3]. Recently, there has been a lot of research on traditional microstrip antenna designs/geometries including slots, fractals, split ring resonators (SRRs), reconfigurable frequency, parasitic elements, etc. operating at multi-resonant frequencies sought in many real-world applications including navigation, mobile, radar, and other wireless communication systems [1–3]. Researchers and designers are nowadays working on novel multi-band antennas that offer a simple design, low complexity, small size, suitable impedance bandwidth, radiation patterns, gain, radiation efficiency, directivity, etc. [1–3]. However, designing a structure for multi-band operations

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that offers a low-profile design and like performance in each band is still challenging for researchers. Several methods have currently been reported for the design of multi-band antennas [3–6].

One of the most effective wireless systems is a satellite-based navigation system. The U.S. government maintains the control of GPS, a well-known satellite-based navigation system. Several other nations, including India, Russia, EU, China, and Japan, have also launched their navigation satellite systems, IRNSS, GLONASS, Galileo, BeDou, and QZSS, respectively. The Indian Space Research Organization (ISRO)-India has also developed a new space-based positioning and navigational system known as IRNSS which operates at 1176.45 MHz & 2492.028 MHz in the L5 & S-band, respectively [7]. For satellite, cellular networks, defence, military, and civilian purposes, numerous researchers, engineers, and organizations are developing multi-band antennas that accommodate GPS, IRNSS, and other wireless communication applications. Mandal and Pattnaik [8] reported a coplanar waveguide (CPW)-fed multi-band wearable monopole antenna to cover the 1.8 GHz, 2.4 GHz/5.2 GHz, & 3.5 GHz for Global System for Mobile Communications (GSM), WLAN, & WiMAX bands, respectively by creating slanted monopoles of various lengths from an isosceles triangular patch. Kwon et al. [9] reported a three-dimensional compact shark-fin antenna covering 0.850 GHz, 1.575 GHz, 2.4 GHz, and 5.9 GHz for MIMO-LTE, GPS, WLAN, and Wireless Access in the Vehicular Environment (WAVE) bands, respectively. Naik et al. [10] demonstrated a spiral-based antenna for GPS and IRNSS. Modi et al. [11] reported a compact multi-band wide-band antenna for IRNSS, 4G, 5G, and satellite applications. The literature review shows that many intriguing and cutting-edge ideas have been recently explored to create multi-band microstrip antenna structures with linear polarization, bandwidth, and pattern changeable characteristics. It is also realized that multi-band microstrip patch antennas are usually designed using common patch shapes, rectangle, triangle, square, annular-ring, etc. However, it is possible to attain an electrically small-size multi-band microstrip patch antenna without compromising radiation performance if the shape is made circular or elliptical compared to other patch shapes [1, 2, 12]. Trzaska [22, 23] reported methods for measuring Electromagnetic Field (EMF) in the near-field and far-field. In line with this, it was tried to accommodate satellite-based navigation systems GPS and IRNSS along with WLAN and Sub-6 GHz 5G wireless applications in view of an Indian navigation system.

The paper is organized as follows. Section 2 provides details of the design approach and configuration of the proposed antenna. Simulated and measured results are discussed in Section 3. Lastly, the proposed antenna is summarized in a conclusion section.

2. ANTENNA DESIGN APPROACH AND CONFIGURATION

2.1. Antenna Design Approach

A circular patch/disc antenna that serves as the foundation of the proposed antenna design can be properly analyzed using a cavity model. Radiating modes supported by the circular patch antenna can be determined by modeling the patch, a ground plane, and a separator medium as a substrate that form a circular cavity. The modes TM^z can be supported by a circular microstrip patch antenna with a relatively low substrate height, h, (i.e., $h < 0.05\lambda_0$, where λ_0 is a free-space wavelength) with almost constant fields along z (i.e., z is taken perpendicular to the patch). A radius, a, of the circular patch can be used to control or vary the modes, changing the absolute resonance frequency of each mode without changing the order of the modes [1]. A vector potential method to locate the fields inside the cavity by determining the magnetic vector potential A_z as Equation (2) for the electric and magnetic field of TM^z mode must fulfill the homogeneous wave equation as Equation (1) [1]:

$$\nabla^2 A_z(\rho,\phi,z) + k^2 A_z(\rho,\phi,z) = 0 \tag{1}$$

$$A_z = B_{mnp} J_m(k_\rho \rho')\left[A_2\cos(m\phi') + B_2\sin(m\phi')\right]\cos(k_z z') \tag{2}$$

where, $k_\rho = \chi'_{mn}/a$, $k_z = p\pi/h$, $m = 0, 1, 2, \ldots$, $n = 1, 2, 3, \ldots$, $p = 0, 1, 2, \ldots$.

The fields inside the cavity are represented by the primed cylindrical coordinates ρ', ϕ', and z'. Therefore, in the cavity model, Equations (3)–(6) are used to determine the resonant frequencies for the TM^z_{mn0} modes by considering $p = 0$ & $k_z = 0$ in constraint Equation (3) [1]. As a correction factor, while the fringing effect is taken into account, the actual radius (a) is swapped out for an effective radius

(a_{eff}) as given in Equation (6) [1].

$$(k_\rho)^2 + (k_z)^2 = (k_r)^2 = \omega_r^2 \mu\varepsilon \tag{3}$$

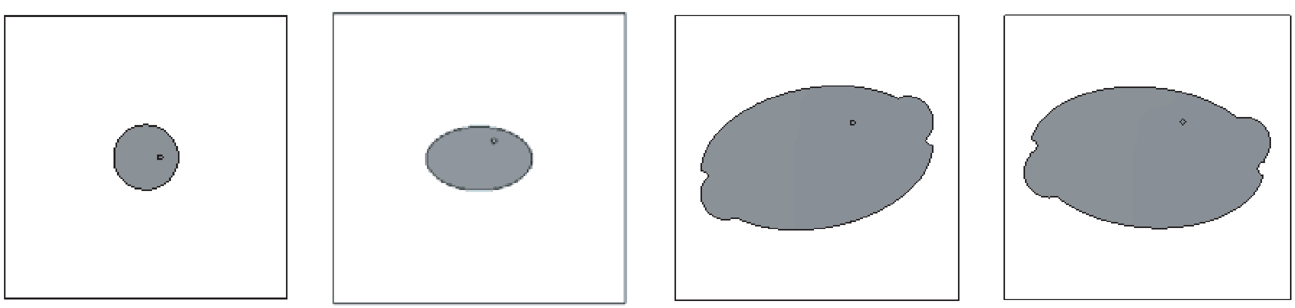
$$(f_r)_{mn0} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\left(\frac{\chi'_{mn}}{a}\right) = \frac{\chi'_{mn}\vartheta_0}{2\pi a\sqrt{\varepsilon_r}} \quad \Rightarrow \; (f_{rc})_{mn0} = \frac{\chi'_{mn}\vartheta_0}{2\pi a_{\mathit{eff}}\sqrt{\varepsilon_r}} \tag{4}$$

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}}, \quad F = \frac{8.791\times 10^9}{f_r\sqrt{\varepsilon_r}}, \quad \text{h in cm} \tag{5}$$

$$a_{\mathit{eff}} = a\left\{1 + \frac{2h}{\pi a\varepsilon_r}\left[\ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2} \tag{6}$$

where f_r: resonant frequency, a: actual radius of a circular patch, ε_r: substrate dielectric constant, h: substrate height, a_{eff}: effective radius after considering a fringing effect, v_0: speed of light, χ'_{mn}: zeroes of the Bessel function's ($J_m(x)$) derivative *with* $\chi'_{11} = 1.8412$, $\chi'_{21} = 3.0542$, and $\chi'_{31} = 4.2012$ values to establish the order of the resonant frequencies.

A design process that results in functional designs of the proposed microstrip patch antenna starts with the excitation of dominating TM^z_{110} mode based on the cavity model formulation as described in Equations (1)–(6) [1]. The conventional circular patch antenna is used to produce the fundamental frequency of 5.208 GHz by exciting dominant mode TM_{11}. The second resonating frequency of 3.516 GHz is achieved by reshaping the antenna in an elliptical shape and by segregating the dominant mode TM_{11} into its orthogonal modes' components (TM_{11h} & TM_{11v}) (i.e., by exciting orthogonal resonance modes). The third resonating frequency of 2.45 GHz is achieved by exciting one higher order mode TM_{21} along with orthogonal modes, by reshaping the antenna with an elliptical shape patch, and by introducing semicircle cuts & bulges on the patch. The fourth resonating frequency of 1.56 GHz is achieved by exciting two higher-order modes TM_{21} and TM_{31} with orthogonal modes simultaneously and by reshaping the antenna and changing the position of the feed, semicircle cuts & bulges, and patch. Other higher-order modes are adjusted in such a way that they will not resonate. Figure 1 shows a stepwise design of the proposed antenna geometry using the cavity model-circular patch theory. Step-1 shows single-band; Step-2 shows dual-band; Step-3 shows triple-band; and Step-4 shows quad/multi-band design evolution.



(a) (b) (c) (d)

Figure 1. Stepwise design of the proposed antenna using cavity model-circular patch theory. (a) Step-1: Single-band (Radius: 9.2 mm, Frequency: 5.208 GHz). (b) Step-2: Dual-band (Radius: 14.5 mm & 8.8 mm, Frequency: 3.516 GHz & 5.202 GHz). (c) Step-3: Triple-band (Radius: 33 mm & 19.81 mm, Frequency: 2.45 GHz, 3.44 GHz & 5.23 GHz). (d) Step-4: Quad/Multi-band (Radius: 33 mm & 19.3 mm, Frequency: 1.56 GHz, 2.49 GHz, 3.5 GHz & 5.24 GHz).

3. ANTENNA CONFIGURATION

The proposed multi-band antenna consists of an elliptical shape patch with narrow semicircle cuts and bulges on two horizontal ends for GPS, IRNSS, Sub-6 GHz 5G, and WLAN wireless communications

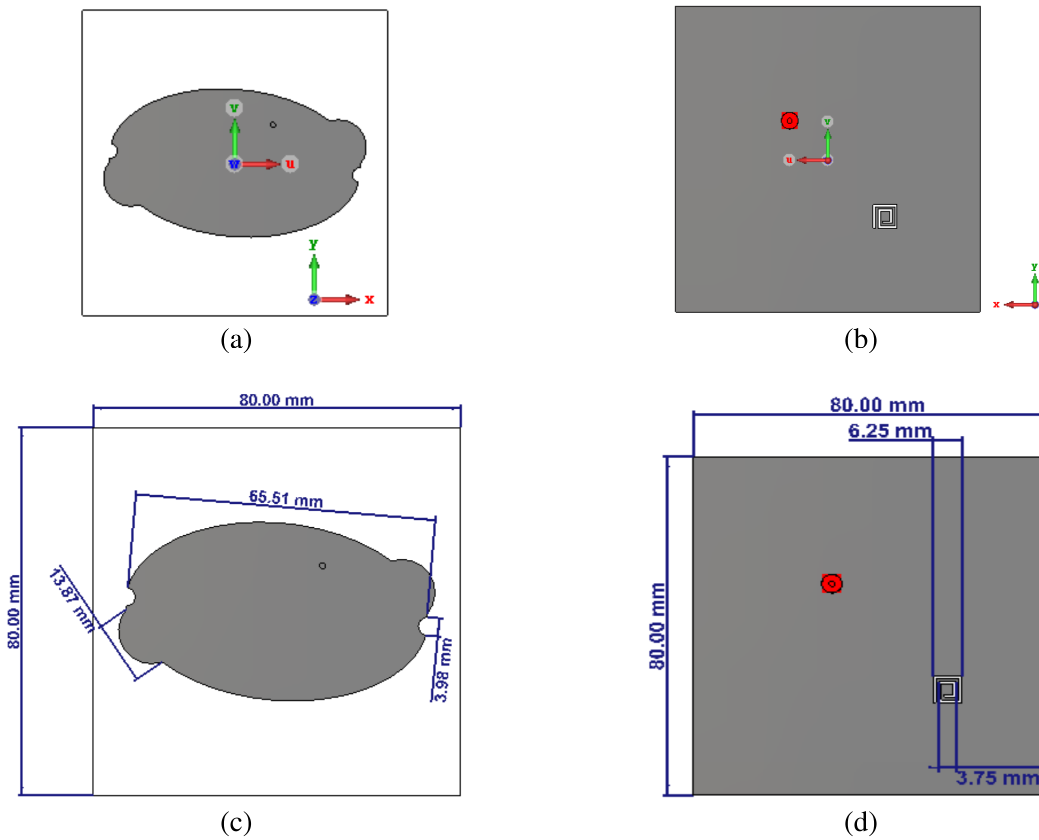


Figure 2. Proposed antenna design: (a)–(b) Top view & bottom view. (c)–(d) Top view & bottom view with dimensions.

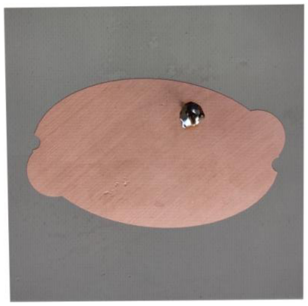
applications as shown in Figure 2. The proposed antenna having dimensions of $80 \times 80 \times 3.175\,\text{mm}^3$ is mounted on a Rogers AD255C substrate with a loss tangent $(\tan\delta) < 0.002$ and relative permittivity (ε_r) of 2.6. The antenna is fed by a coaxial probe feeding at (10 mm, 10 mm) point. The antenna is optimized to get more appropriate resonance at 1.56 GHz, 2.49 GHz, 3.5 GHz, & 5.24 GHz for the desired application. A square spiral shape slot in the ground plane is introduced to remove undesired bands. The characteristics of the proposed antenna are simulated in CST Studio Suite 2020, and the measurement of the fabricated antenna is carried out in an anechoic chamber as shown in Figure 3.

In this study, measurements of the reflection coefficient, voltage standing wave ratio (VSWR), radiation patterns, gain, and efficiency of the proposed antenna are performed and compared with the simulated results.

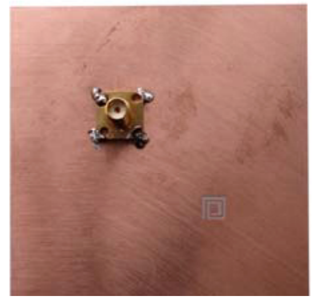
4. RESULTS AND DISCUSSION

CST Studio Suite 2020 has been used for the simulations of various parameters of the proposed antenna, and measurements of the fabricated antenna are made in an anechoic chamber using a vector network analyzer (VNA). The simulated reference impedance (z_{ref}) of the reported antenna is $48.55\,\Omega$.

The measured reflection coefficient (S_{11}) and VSWR of the proposed antenna are shown in Figure 4(a) and Figure 4(b), respectively with the concerned simulated results. Figure 4 shows the measured results, and the simulated results accord well. From Figure 4, it is observed that the measured return loss at resonance is −15.2 dB, −19 dB, −22.3 dB, & −27.9 dB, and the measured VSWR value is 1.42, 1.25, 1.08 & 1.17 at 1.56 GHz, 2.49 GHz, 3.5 GHz, and 5.24 GHz, respectively. With reference to each resonance frequency, the proposed antenna provides impedance bandwidths of 40 MHz, 90 MHz, 100 MHz, and 90 MHz.



(a)



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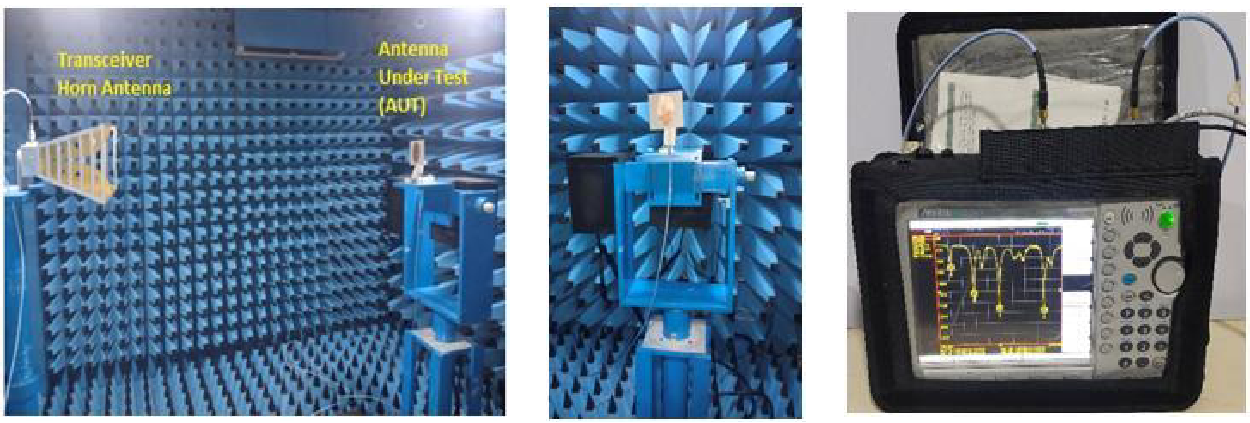
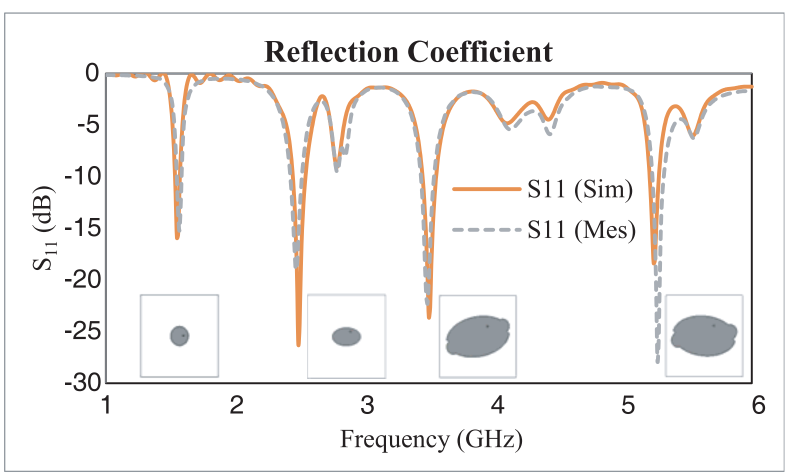


(c)

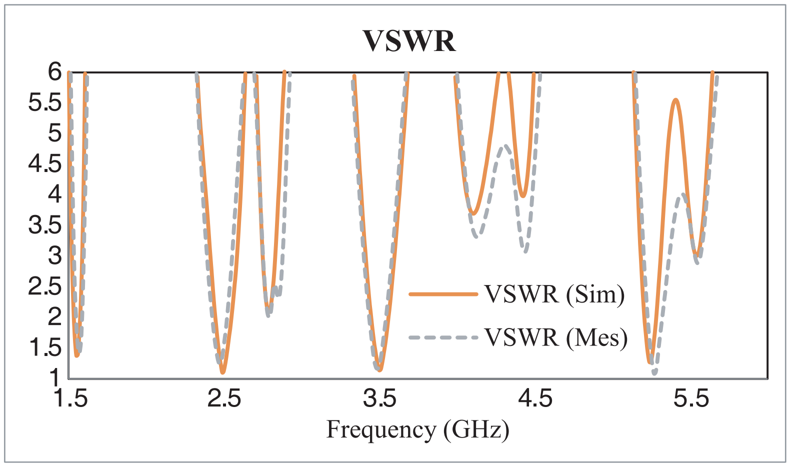
Figure 3. (a)–(b) Top view & bottom view of proposed fabricated antenna. (c) Photographs of measurement setup in the anechoic chamber.

The antenna is fed by coaxial probe feeding at (10 mm, 10 mm) point, and it is also tried to match the antenna's reference impedance 50 Ω with the line impedance of the transmitter or reception circuitry to achieve optimal power transfer as depicted in Figures 2 & 3. The feeding location is optimized using a simulation study. The simulated and measured impedances are shown in Figure 5(a) and Figure 5(b), respectively.

Figure 6 shows the current distributions at the 1.56 GHz, 2.49 GHz, 3.5 GHz, and 5.24 GHz resonance frequencies. The current concentrates at the edges of the patch by forming a loop from

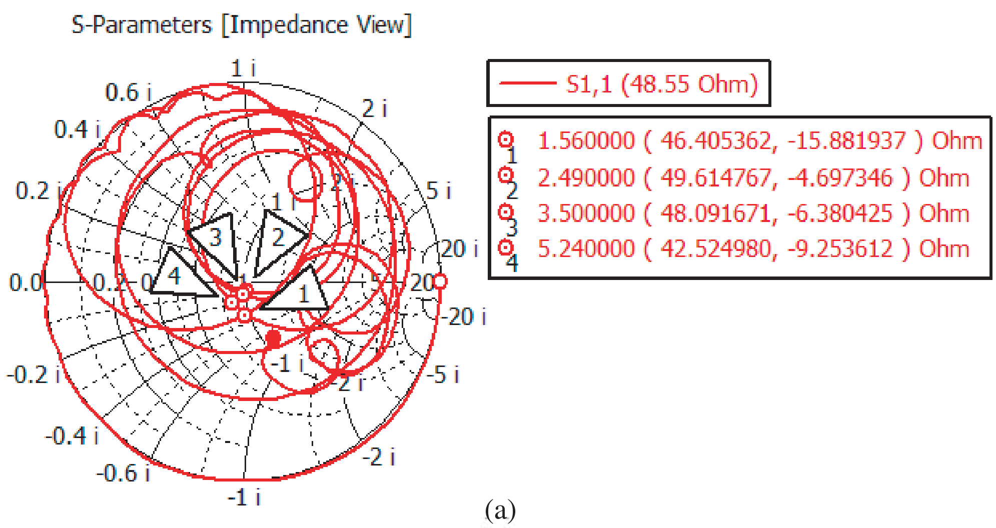


(a)

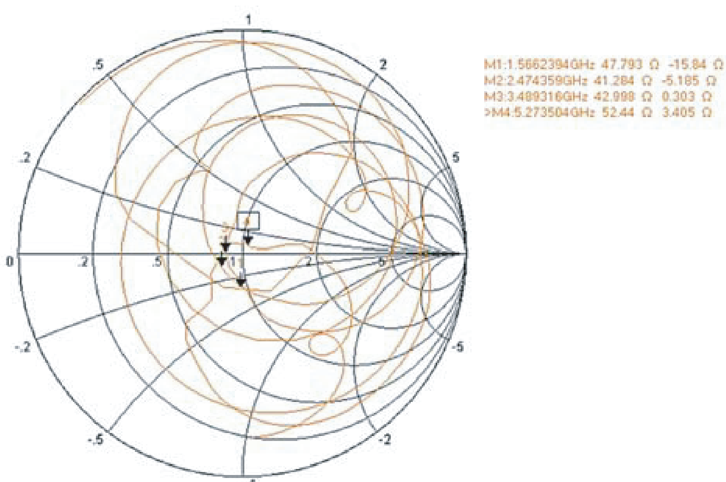


(b)

Figure 4. Measured and simulated (a) reflection coefficient and (b) VSWR of the proposed antenna.



(a)



(b)

Figure 5. Simulated and measured impedances of the proposed antenna.

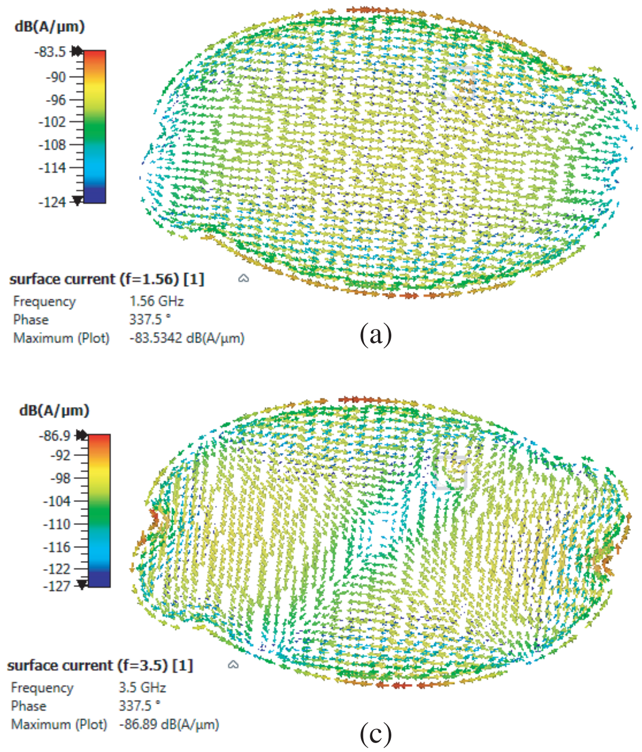
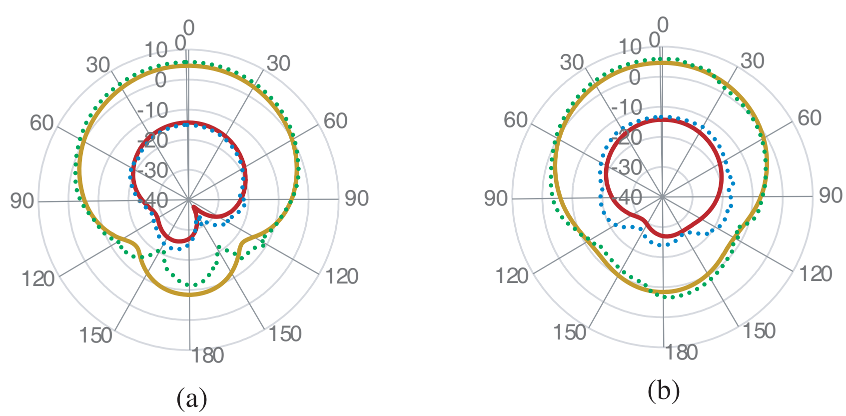


Figure 6. Surface current distributions at (a) 1.56 GHz, (b) 2.49 GHz, (c) 3.5 GHz and (d) 5.24 GHz of the proposed antenna.

semicircle cuts on both sides of the patch. It is also demonstrated that the current density is maximum at the center part of the patch and moves towards horizontal corners at higher frequencies. The surface current distribution at each frequency along with reshaping the antenna and changing the patch components' position also contributes to the excitation of higher-order modes and produces effective radiation at a specific band.

The simulated and measured normalized far-field radiation patterns at 1.56 GHz, 2.49 GHz, 3.5 GHz, and 5.24 GHz in E-plane (yz-plane, phi = 90) and H-plane (xz-plane, phi = 0) are shown in Figure 7. It is realized that the proposed antenna has a broadside radiation pattern at each resonant frequency, and the specific excited TM_{mn0}^{z} radiating modes produce a linearly polarized electric far-field in the yz-plane. Measured and simulated radiation patterns are matched well.

Figure 8 shows the measured radiation efficiencies of 58.7%, 94.8%, 93.2%, & 84.9% as well as measured gains of 3.49 dBi, 6.49 dBi, 4.93 dBi, & 4.46 dBi of the proposed antenna at the desired resonant frequencies. It is observed that the measured radiation efficiency and gain are matched well with the



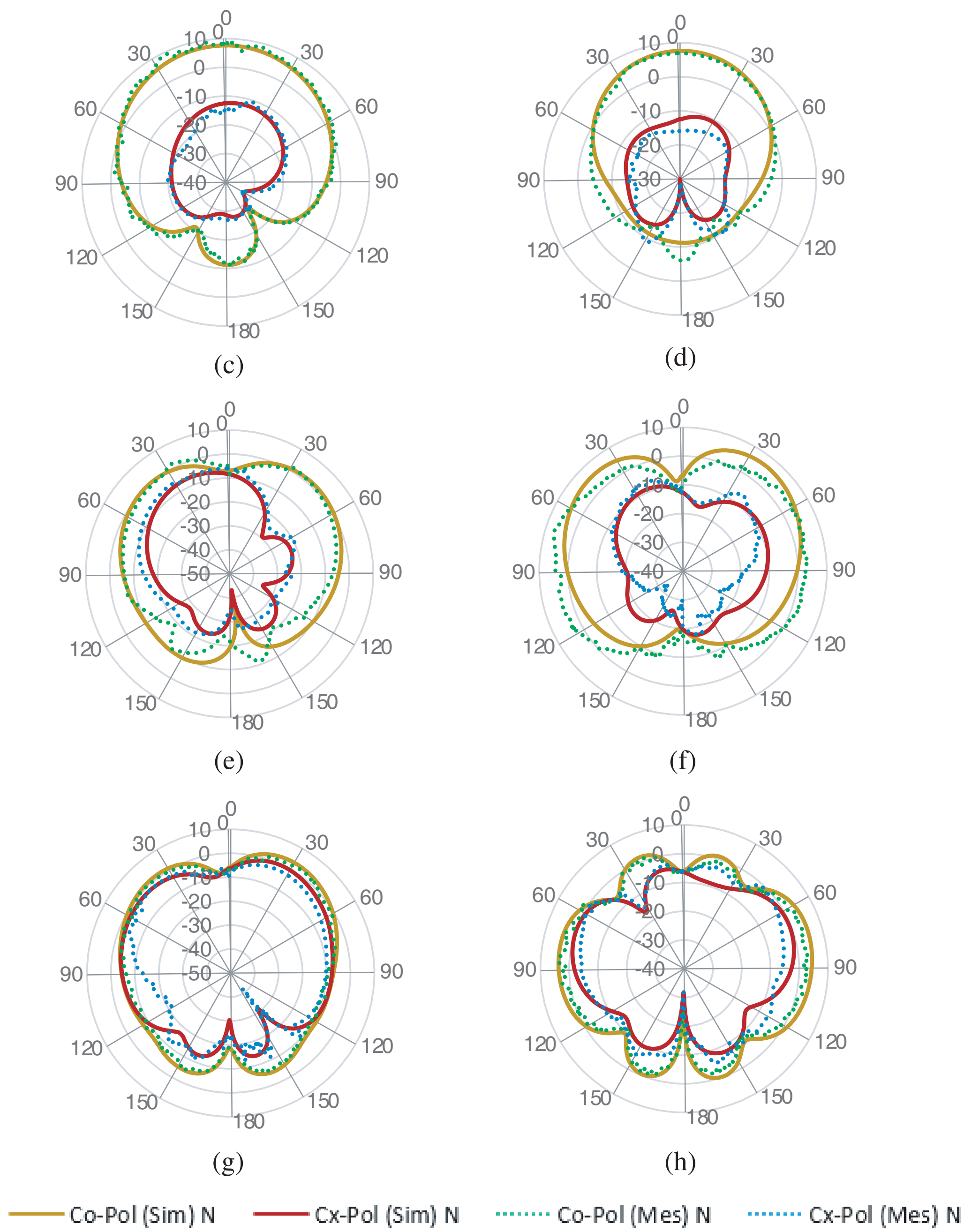


Figure 7. Measured and simulated normalized far-field radiation patterns of the proposed antenna: (a) E Field — 1.56 GHz, (b) H Field — 1.56 GHz, (c) E Field — 2.49 GHz, (d) H Field — 2.49 GHz, (e) E Field — 3.5 GHz, (f) H Field — 3.5 GHz, (g) E Field — 5.24 GHz, (h) H Field — 5.24 GHz.

simulated results.

Minor variations are observed between the measured and simulated results due to fabrication errors, measuring environment, and substrate characteristics. Table 1 demonstrates the performance comparison of the proposed antenna with various reported designs in terms of dimensions, geometry complexity, frequency bands, applications, methods used, substrate, gain, radiation efficiency, and feeding techniques. It is noticed that the proposed antenna offers simple, low-profile design, appropriate gain and efficiency with a similar radiation pattern to the other reported designs for the desired applications. It is observed from Table 1 that the proposed antenna is a strong contender for satellite navigation systems along with emerging wireless communication applications used in internet of things (IoT) and 5G-enabled devices. The proposed antenna demonstrates a single layer, simple fabrication, ease of RF circuit integration, and stable radiation patterns for desired bands.

Table 1. Proposed antenna performance comparison with reported multi-band antennas.

Ref.	Dimension (mm^3)	Frequency /Band	Application	Method Used	Substrate	Gain	Efficiency (∼ %)	Feeding technique
[13]	135 × 60 × 0.5	670–1010/ 1530–2850/ 3360–3900/ 4870–8000 MHz	LTE/5G/ GPS/GSM/ UMTS/WLAN/ WiMAX	Folded driven monopole strip, Parasitic ground with slots	FR-4	0.60–4.30 dB	60.0–70.0%	Coaxial
[14]	56 × 44 × 0.8	1.575–1.665/ 2.4–2.545/ 3.27–3.97/ 5.17–5.93 GHz	GPS/WiMAX/ WLAN	Rectangular slot with a T-shaped feed patch, an inverted T-shaped stub, and E-shaped stubs	FR-4	3.55–5.02 dBi	76.8–96.6%	Microstrip
[15]	150 × 100 × 11.2	0.7–0.73/ 1.16–1.2/ 1.3–1.32/ 1.57–1.62/ 2.3–2.5/ 2.7–3.5 GHz	5G/GPS/ WLAN/ LTE/Radio Navigation	Slotted Microstrip patch	FR-4	4.30–9.00 dBi	-	Proximity & Microstrip
[16]	100 × 100 × 4.75	1.2276/1.1765/ 2.492/2.3 /2.5 GHz	IRNSS/ Satellite/ 4G/5G	Multilayer patch antenna	Rogers RT/ DUROID-5880 (tm) & FR-4	2.78 dB	-	Coaxial
[17]	120 × 120 × 29.6	1.1/1.5/ 2.3/2.6 GHz	GPS/CNSS/ WLAN/WiMAX	Dielectric Resonator	Ceramic & FR-4	5.00 dBi	-	Aperture
[18]	88.5 × 60 × 1.6	1.6/2.6/ 3.7/5.3 GHz	DCS/CDMA/ LTE/GPS/BDS/ GLONASS/ GALILEO/ WLAN/WiMAX	Monopole antenna with fractal	FR-4	1.16–3.75 dBi	40.0–72.0%	CPW
[19]	70 × 60 × 1.6	1.56/3.9/ 5.05 GHz	GPS/WLAN/ IMT	Fractal CPW Antenna	FR-4	2.25–3.06 dBi	-	CPW
[20]	73.3 × 73.3 × 4.8	1176.45/1575.42/ 2492.028 MHz	GPS/IRNSS	Stacked patch antenna	Arlon AD300N	4.69–5.39 dBi	-	Aperture
[21]	55.6 × 50.5 × 1.6	1.575/2.4/5.5/ 1.5–40 GHz	GPS/DCS/ PCS/UMTS/ ISM/IRNSS/ LTE/IoT/ Wi-MAX/ X/Ku/K/ Ka-band/ Sub-6 GHz 5G	Mushroom-shaped EBG, E-shaped decoupling structure & closed ring resonator	FR-4	7.50 dBi	-	Microstrip
This work	80 × 80 × 3.175	1.56/2.49/ 3.5/5.24 GHz	GPS/IRNSS/ Sub-6 GHz 5G/WLAN	Elliptical shape patch with narrow semicircle cut and bulges	Rogers AD 255C	3.49–6.49 dBi	58.7–94.8%	Coaxial

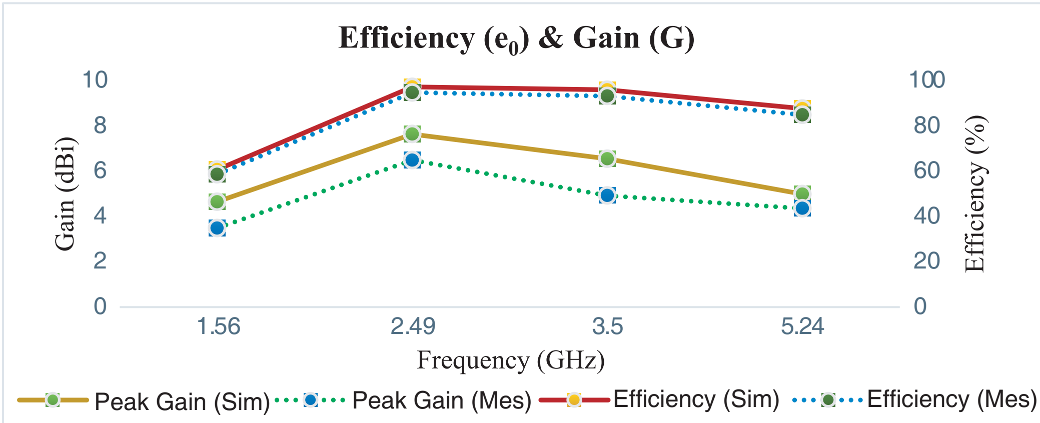


Figure 8. Gain and efficiency of the proposed antenna — Simulated and measured.

5. CONCLUSION

A multi-band antenna of an elliptical shape patch with narrow semicircle cuts and bulges on two horizontal ends resonates at 1.56 GHz, 2.49 GHz, 3.5 GHz, and 5.24 GHz is proposed for GPS, IRNSS, Sub-6 GHz 5G, and WLAN wireless applications. The proposed antenna achieves an impedance bandwidth of 40 MHz, 90 MHz, 100 MHz, and 90 MHz, peak gain of 3.49 dBi, 6.49 dBi, 4.93 dBi & 4.46 dBi, and radiation efficiency of 58.7%, 94.8%, 93.2%, & 84.9% for desired application frequencies, respectively. The antenna also offers a simple design, relatively stable and similar radiation patterns at each band. The simulated and measured results for the proposed antenna exhibit good agreement.

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