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Research Article

Ram Horn-Shaped Inspired Folded Compact Antenna for 4G LTE-A and WLAN Portable Mobile Applications

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A compact dual-band ram horn-like folded antenna is presented in this work. The antenna is based on a ram horn-like folded strip, asymmetric microstrip feeding (AMF) technique, partial ground, and protruding stub at the ground plane. The dimension of the proposed antenna is 0.11 $\lambda_g \times 0.17\ \lambda_g$ at 2.3 GHz ($10 \times 15\ \mathrm{mm}^2$). The proposed shape is achieved through the combination of two circular arcs with different radii. The antenna operates at 2.3 GHz and 5.8 GHz with a measured bandwidth of 100 MHz and 820 MHz, a gain of 0.62 dBi and 2.2 dBi, and radiation efficiency of 93.67% and 99.87%, respectively. The prototype of the proposed antenna is fabricated and measured. The measured result shows a good agreement with the simulated result. The parametric study of the proposed antenna is performed and results are presented. Besides, a comparative study between the antennas proposed in this work and the state of the art is performed and presented. The proposed antenna is comparatively small in size than all the recently reported works in the literature while ensuring good radiation characteristics. Therefore, the antenna proposed in this work is a better candidate for future portable sub-6GHz fifth-generation (5G), Advance Long-term Evolution (LTE-A), Worldwide Interoperability for Microwave Access (WiMAX), and Wireless Local Area Network (WLAN) applications.

1. Introduction

The compact multiband antenna has become the darling of the wireless communication community because of the need for miniaturized devices on the part of both the manufacturers and users [1–4]. Many microwave system researchers have invested effort in realizing compact antennas such as [5–10]. Techniques such as meandering, slotting, slitting, shorting pin/plate, lumped elements, and metamaterial/metasurface [11–15] have been exploited. The main goal of slotting, slitting, shorting pin/plate, and lumped element techniques is to make the antenna effective length longer than its physical length [16–18]. However, the meandering technique ensures maxima use of the antenna space [19]. For example, authors in [9] used a meandering strip and shorting pin to achieve a compact antenna ($36 \times 15\ \mathrm{mm}^2$) operating at 2.4 GHz. The same meandering technique has been recently exploited by authors in [5–8]. Furthermore, the slotting technique has been used by authors in [2, 20–25]. For example, authors in [20] used the Audi logo-shaped as a slot on a rectangular patch on a $20 \times 12\ \mathrm{mm}^2$ FR-4 substrate to achieve a triband antenna operating at 3.9 GHz, 5.0 GHz, and 7.1 GHz, respectively. Also, authors in [22] use circular nested square slots comparative to an ancient coins symbol in China. The radiating patch was etched on an $88.5 \times 60\ \mathrm{mm}^2$ FR-4 substrate and the operating frequencies of the antenna are 1.6 GHz, 2.6 GHz, 3.7 GHz, and 5.3 GHz. In addition, authors in [14] reported the use of metamaterial for the antenna miniaturization. The authors used a double negative metamaterial based on the rectangular split ring resonator as the slot on the ground plane of the proposed antenna to achieve a 50% miniaturization. In the same light, authors in [15] have also used metasurface to achieve 67% miniaturization. In recent times, folded monopole antenna has attracted antenna design engineers due to its ability to reduce overall antenna size [25–34]. Folded monopole antenna uses the principle of space filling to miniaturize the antenna radiating patch. For example, authors in [34] proposed three folded-rectangular strip branches radiating patch etched on a $20 \times 18\,\text{mm}^2$ FR-4 substrate.

2.3 GHz band is one of the most useful communication bands. It was designated International Mobile Telecommunication (IMT) by the ITU. Even though it was originally used for WiMAX applications, it has been generally adopted for the deployment of 4G LTE applications. This band has also been proposed for sub-6GHz 5G communication deployment due to its large TDD band spectrum, good propagation behavior, and provision of better capacity. For example, Singtel Optus, STC, and Telkom in Australia, Saudi Arabia, and South Africa, respectively, are performing 5G trials in this band. In the same light, the 5 GHz band is also one of the commonly used bands in wireless communication such as the 5 GHz band WLAN and ISM. Therefore, the miniaturization of the antenna operating in these bands is of importance for future communication.

Therefore, in this work, an ultracompact ram horn-like folded dual-band antenna is proposed. The proposed antenna is fed with a 50 Ω asymmetric microstrip feedline. The contribution of this work is the proposal of an ultracompact dual-band antenna suitable for LTE and WLAN applications compared to the recently published works in the open literature.

The remaining section of this paper is divided as follows. The detailed design and analysis of the proposed antenna are presented in Section 2. The results and discussion, which includes S_{11}, a parametric study of some design parameters, radiation pattern, gain, and efficiency, are presented in Section 3. The proposed antenna is compared with the recently published works in the literature and presented in Section 4, and the conclusion is presented in Section 5.

2. Antenna Design and Analysis

The radiating patch of the proposed antenna is a strip folded in a ram horn-like shape, fed with a 50 Ω asymmetric microstrip feedline, and a partial ground with a protruding stub made up the ground plane, as shown in Figure 1. The ram horn-like shape is realized through the concatenation of two slit rings, as shown in Figure 1(c). The antenna is built on a $10 \times 15\,\text{mm}^2$ duroid5880 substrate of 1.57 mm thickness. The detailed configuration is given in Figure 1, and the optimized parameters are given in Table 1. The distance between the edge of the radiating patch and the substrate is 1 mm at the two sides and 0.75 mm at the top. The frequency of a quarter-wavelength strip can be determined by using equation (1) [2, 35]. Therefore, the expected fundamental mode resonance of the strip can be predicted. The equivalent (total) length of the strip that made up the ram horn is determined from equation (2). The first term at the RHS of equation (3) denotes the circumference of a circle, while the second term denotes the length of the slit of ith ring:

$$f_r \approx \frac{C_o}{4L_t\sqrt{(\varepsilon_r+1)/2}}, \tag{1}$$

where

$$L_t = L_{R_1} + L_{R_2}, \tag{2}$$

and

$$L_{R_i} = 2\pi r_i - S_i, \quad \text{for } i = 1 \text{ and } 2, \tag{3}$$

where

$$S_i = \frac{(\theta-\varphi_i)x2\pi r_i}{\theta}, \qquad r_i = R_i + w_r. \tag{4}$$

The AMF width (w_f) is calculated using the standard microstrip line equations (5)–(9) [35, 36]:

$$Z_0 = \begin{cases} \dfrac{120\pi}{\sqrt{\varepsilon_{eff}}\left\{w_f/h + 1.393 + 0.677\,\ln\left(w_f/h + 1.444\right)\right\}}, & \text{for } \dfrac{w_f}{h} \le 1, \\[2ex] \dfrac{60}{\sqrt{\varepsilon_{eff}}}\ln\left(\dfrac{8h}{w_f} + \dfrac{w_f}{4h}\right), & \text{for } \dfrac{w_f}{h} \ge 1, \end{cases} \tag{5}$$

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+12\left(h/w_f\right)}}\right). \tag{6}$$

Since the value of the characteristic impedance is known in this case to be 50 Ω, the width of the microstrip line can be calculated using

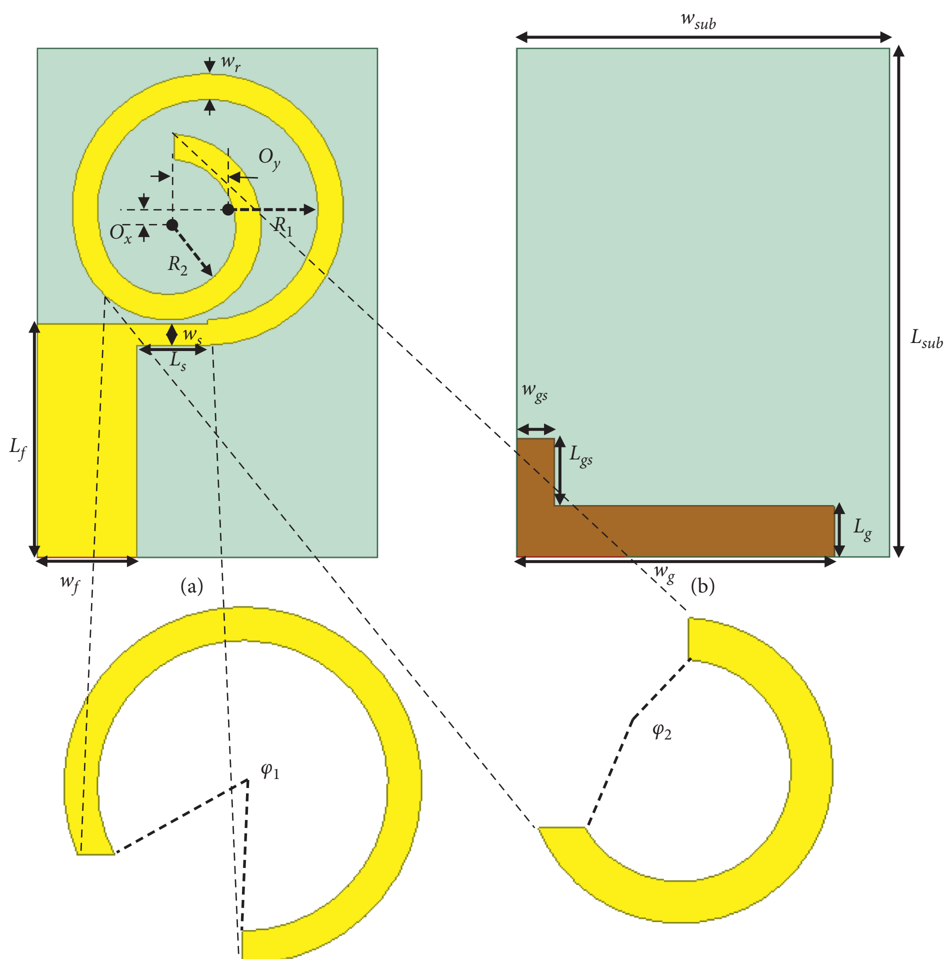

FIGURE 1: Configuration of the proposed ram horn-like folded antenna: (a) top view, (b) bottom-view, and (c) concatenated slit rings.

TABLE 1: Optimized design parameter of the proposed ram horn-like folded antenna, $\varphi_1 = 241.9^o$ and $\varphi_2 = 170.1^o$.

Parameter	$\mathbf{w_{sub}}$	$\mathbf{w_g}$	$\mathbf{w_{gs}}$	$\mathbf{w_f}$	$\mathbf{w_s}$	$\mathbf{L_{sub}}$	$\mathbf{L_{gs}}$	$\mathbf{L_g}$
Value (mm)	10	8.5	1	2.9	0.6	15	2	1.5
Parameter	$\mathbf{L_f}$	$\mathbf{L_s}$	$\mathbf{R_2}$	$\mathbf{R_1}$	$\mathbf{O_x}$	$\mathbf{O_y}$	$\mathbf{w_r}$	
Value (mm)	6.9	2.1	2	3.25	0.6	2.9	0.75	

$$w_f = \begin{cases} \dfrac{2h}{\pi}\left[B - 1 - \ln(2B-1) + \dfrac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B-1) + 0.39 - \dfrac{0.61}{\varepsilon_r}\right\}\right] & \text{for } \dfrac{w_f}{h} > 2 \\[2ex] \dfrac{8he^A}{e^{2A} - 2} \quad \text{for } \dfrac{w_f}{h} < 2 \end{cases}, \tag{7}$$

where

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right), \tag{8}$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}}, \tag{9}$$

where L_t is the equivalent length of the unfolded strip, L_{R_i} is the length of the ith arc-strip, S_i is the arc gap of the ith ring, R_i is the inner radius of the ith ring, φ_i is the angle subtended by ith arc, w_f is the width of the microstrip feedline, h is the thickness of the dielectric, Z_0 is the line characteristic impedance ($50\,\Omega$), ε_r is the permittivity of the substrate, and ε_{eff} is the effective permittivity.

3. Results and Discussion

3.1. Reflection Coefficient (S11). The fabrication of the prototype of the proposed ram horn-like folded antenna is shown in Figure 2, which demonstrates the practicability of the proposed antenna radiating patch shape. Figure 3 shows the measured and simulated S_{11} results of the antenna proposed in this work. It can be observed that, for both simulated and measured results, two modes are excited which implies that the proposed antenna is a dual-band antenna. It can be observed that, for simulation, the two resonances are 2.3 GHz and 5.7 GHz with a -10 dB bandwidth of 70 MHz and 481 MHz and a return loss of 15.42 dB and 17.6 dB, respectively. It can be observed that there is a shift toward the lower frequency, while the resonance at the upper frequency of the measured $S11$ is maintained. That is, the measured resonances are 2.3 GHz (2.298 GHz) and 5.8 GHz, respectively. It can also be observed that the measured −10 dB bandwidth is 100 MHz and 820 MHz at lower and upper bands, respectively. In terms of return loss, the measured reflection coefficient at the lower and the upper bands is 13.3 dB and 23.36 dB, respectively. The variation in the results could be traced to the effect of cable and connector losses as well as the fabrication errors. It can be deduced that this antenna can be used in WiMAX and 5 GHz band WLAN applications. In other to study the effect of the ground plane and its protruding stub, the parametric study is done and presented in the next section.

3.2. Parametric Study. The parametric study of the proposed ram horn-inspired shape antenna is carried out to understand the impact of some design parameters and justify the optimized values of the parameter presented in Table 1. The parametric study specifically focused on the ground plane effect on the resonance behavior of the antenna proposed.

3.2.1. Effect of w_g. Figure 4 shows the effect of w_g on the resonance behavior of the proposed antenna. It can be observed that an increase in the value of w_g leads to a tunning effect towards lower frequency at the upper band. It can also be noticed that, as w_g increases from 6 mm, aside from shifting the resonant frequency downward, the impedance matching is also enhanced until 7 mm after which the reflection coefficient starts increasing. 5.8 GHz is the desired frequency at the upper band; therefore, 8.5 mm is taken as the optimized value of g_w in the proposed configuration. It can also be observed that variation in w_g has no significant frequency tunning effect at the lower band, but it has a pronounced effect on its impedance matching, as shown in Figure 4. The tunning and impedance matching effect of w_g is more pronounced at the upper band of the proposed ram horn-like folded antenna than at the lower band. Conclusively, g_w can be used to both tune the upper band resonant frequency as well as the impedance matching of both lower and upper bands.

3.2.2. Effect of L_g. As can be seen in Figure 5, L_g significantly affects the impedance matching of the proposed ram horn-like folded antenna at both bands. It can be observed that as L_g increases, the reflection coefficient increases which implies that 1 mm has the best impedance matching at both frequency bands as shown in Figure 5. Nonetheless, to ensure good ground plane support for the proposed antenna, 1.5 mm has been taken as the optimized value in the proposed configuration. As can be noticed from Figure 5, the highest suitable length of the ground plane to achieve a 10 dB return loss in both frequency bands is 2 mm. Therefore, ground length has a tremendous effect on the impedance matching of the proposed structure at both frequencies.

3.2.3. Effect of $\mathbf{L_{gs}}$. Figure 6 shows how S_{11} changes with L_{gs}. It can be observed that an increase in L_{gs} not only reduces the impedance matching at both bands but also results in frequency tunning at the upper band. As shown in Figure 6, to ensure a 10 dB return loss at the lower band, the maximum value of L_{gs} should be 4 mm. Although 1 mm has the best impedance matching at the upper band, it does not have the best S_{11} at the lower band. Therefore, for a reasonable reflection coefficient at both resonant frequencies, 2 mm is choosen as the optimal value in this paper.

3.2.4. Effect of $\mathbf{w_{gs}}$. w_{gs} does not have a significant effect on the resonant frequency of the proposed antenna, but a small variation can be seen in the reflection coefficient of the antenna as it increases. Although 0.5 mm has the best S_{11} at both frequencies, this is more pronounced at the lower band as can be seen in Figure 7. It can be observed that 1 mm has a comparative S_{11} with 0.5 mm at both resonant frequencies. Besides, to avoid significant fabrication error and to further enhance the ground plane support of the proposed antenna, 1 mm was chosen as the optimized value in the proposed configuration.

3.3. Radiation Pattern, Gain, and Radiation Efficiency. As shown in Figure 8(a), the radiation pattern at E-plane and H-plane is bidirectional and omnidirectional, respectively, at 2.3 GHz with a peak of −1.5 dB at 10^o and a 3 dB beamwidth of 70^o. The E-plane and H-plane radiation pattern at 5.8 GHz is a dumbbell and omnidirectional pattern, respectively, with a peak of 2.36 dB at 180^o and a 3 dB beamwidth of 130^o, as shown in Figure 8(b). As shown in Figure 9, a peak gain of 0.62 dBi and 2.2 dBi is achieved at the lower and upper bands, respectively. The peak efficiency at the lower and the upper band is 93.67% and 99.87%, respectively, as shown in Figure 9. With this analysis, the ram horn-like folded antenna proposed shows an acceptable performance despite its compactness.

3.4. Current Distribution. To understand the mode of operation of the proposed antenna, the vector current distributions at the two resonant frequencies are plotted and analyzed. As can be seen in Figure 10(a), a high current concentration is noticed on the folded strip and the feeding branch except at the strip-tip where there is mode cancelation at 2.3 GHz. It can also be observed that the ground

(a) (b)

Figure 2: Prototype of the proposed ram horn-like folded antenna. (a) Top view. (b) Ground plane.

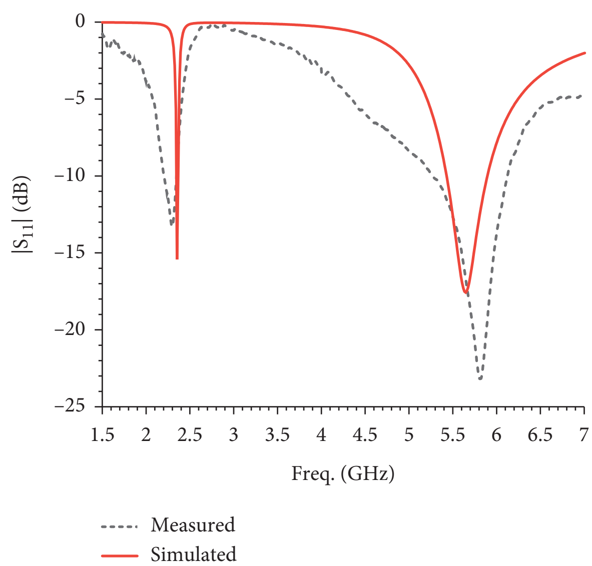

Figure 3: Simulated and measured S11 of the proposed ram horn-like folded antenna.

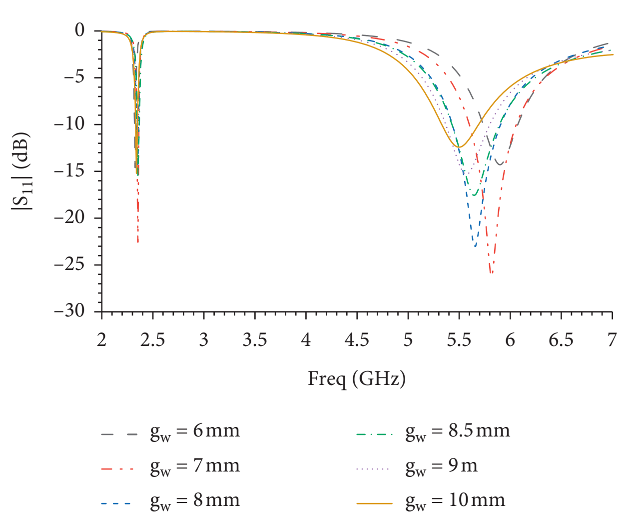

Figure 4: S_{11} variation due to g_w.

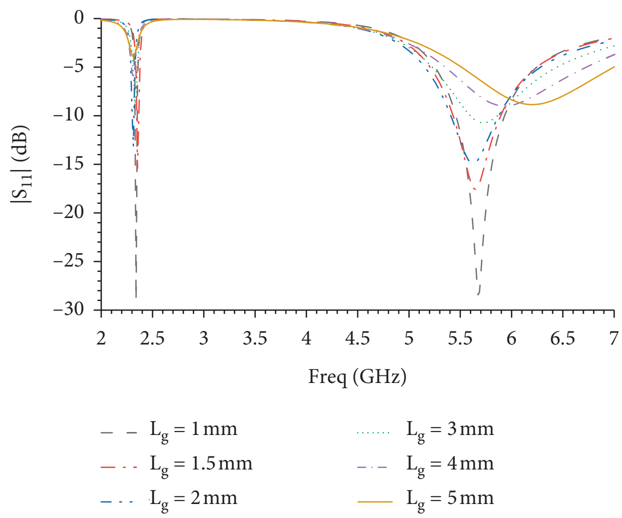

Figure 5: S11 variation due to L_g.

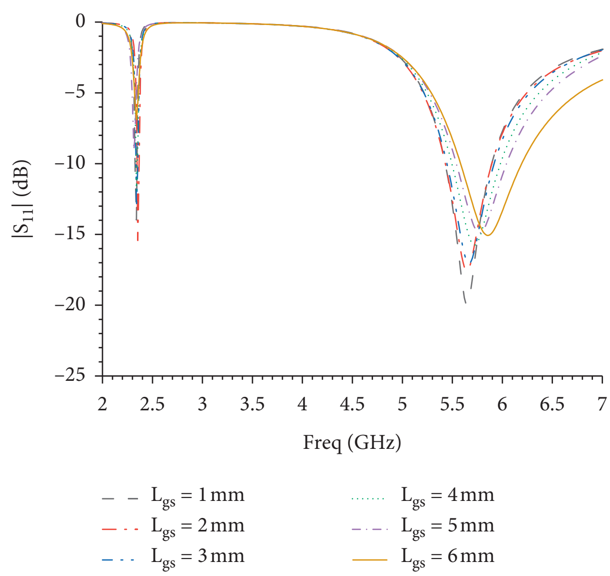

Figure 6: S11 variation due to L_{gs}.

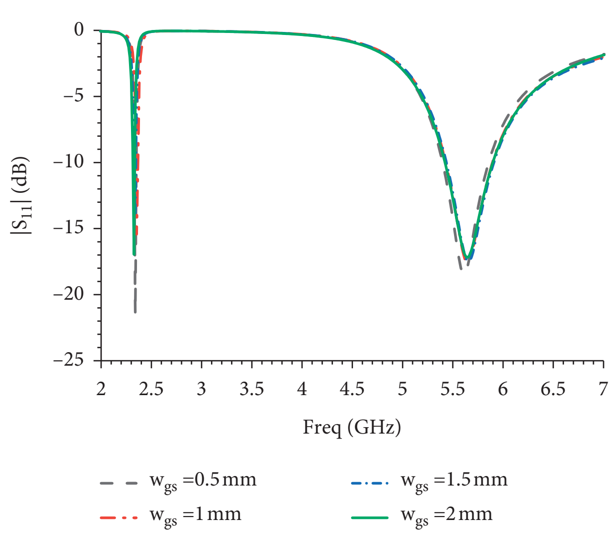

Figure 7: S11 variation due to w_{gs}.

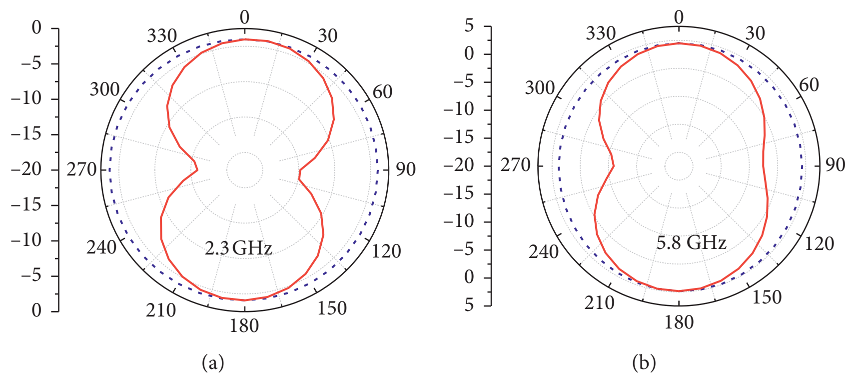

Figure 8: 2D radiation pattern of the ram horn-like folded antenna.

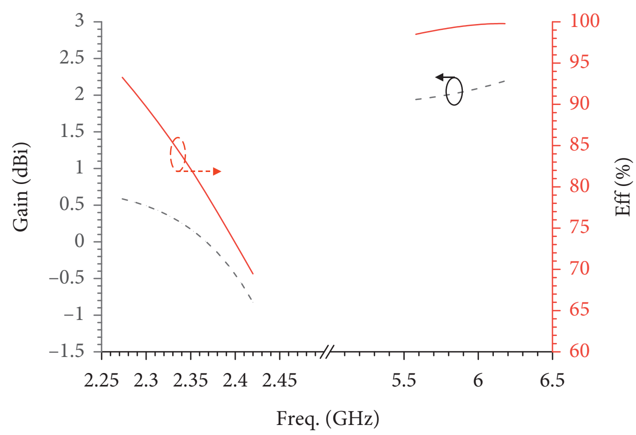

Figure 9: Gain and efficiency of the ram horn-like folded antenna proposed.

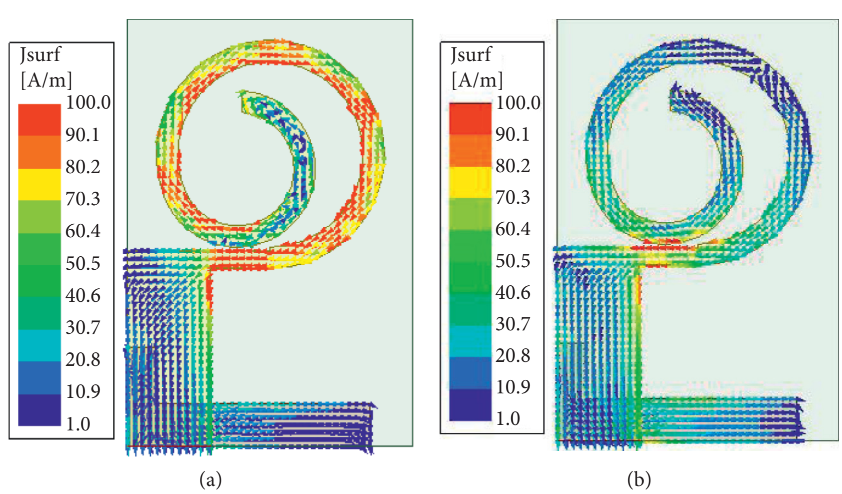

Figure 10: Vector current distribution of the proposed ram horn-like folded antenna: (a) 2.3 GHz and (b) 5.8 GHz.

plane does not contribute much to the resonant frequency at 2.3 GHz. These validate the fundamental mode frequency predicted by equation (1) and the results of the parametric study. At 5.8 GHz, a high current concentration is observed around the feedline-branch strip and some part of the folded strip. It can also be observed in Figure 10(b) that there is a

Table 2: Comparison of the ram horn-like folded antenna with recent works.

Ref	Size (λ_g^2)	Freq. (GHz)	Gain	Eff. (%)	Approach	Complexity
[6]	0.70 × 0.70	2.5/4.2/5.5/6.8	0.5–4.5 dBi$^+$	84/90/89/96	Meandering and DGS	High
[12]	0.50 × 0.52	2.4/3.5	2.25/0.88 (dBi)	76/85	Metamaterial	High
[13]	0.44 × 0.49	1.22/1.57/2.45/3.42	1.75/3/6/3(dBi)	73/63/86/57	Multiple slots	High
[15]	0.55 × 0.35	4.0	5.1 dBi	71.6	Metasurface	High
[23]	0.38 × 0.38	2.23/3.49/5.48/7.48	7.85 dBi*	NR	Balloon and rectangular	High
[10]	0.41 × 0.19	2.5/5.4	2.23/3.48 dB	97.2/99.9	Semileaf shaped with slit	High
[26]	0.73 × 0.25	0.9/1.95/5.8	3.2/3.8/9.2dBi	67–95	Folded branch with slit	High
[32]	0.42 × 0.77	0.85/1.8/2.6	10 dB$^\#$	60–90$^+$	Folded monopole with SRR	Medium
[33]	0.22 × 0.20	1.575/2.9/3.5/4.8/5.5	2.2/2.8/3.2/4.5/4.4 dBi	50/78/84/92/94	Loaded IFA with Via	High
[36]	0.38 × 0.42	2.48/3.49	2.4/3.5 (dB)	NR	Meandering, SSR, and CPW	High
[37]	0.95 × 0.95	3.39	4.15 dBic	87.32	R-DRA, aperture coupled	High
[38]	0.26 × 0.17	1.22/6.06	0.99/3.72 dBi	57/91.8	CRLH-TL and CPW	High
[39]	0.31 × 0.14	2.5/3.35/5.7	1.7/1.5/2.05	81.1/79.6/81.5	Multiple resonator	High
[40]	0.35 × 0.35	3.3/5.01/7.46/9.48	0.4/0.28/4.19/2.05	46.6/50.8/72.2/50.9	Metamaterial	High
[41]	0.42 × 0.49	3.59/5.53$^+$	3/3.6 dBi	93/87	C-SRR, H-CRR, and ACGP	Medium
[42]	0.96 × 0.56	1.45/2.45/3.85/5.13/5.8	2.7/4.8/4.1/2.5/4.2	NR	Window grille shape	High
This work	0.11 × 0.17	2.3/5.8	0.62/2.2dBi*	93.67/99.87*	Ram horn shaped, AMF, ground protruding stub	Medium

*peak value; $^+$range; $^\#$diversity gain; $^+$extracted from the comparative table; NR, not reported; C-SRR, circular split ring resonator; H-CRR, hexagonal closed ring resonator; ACGP, asymmetric coplanar ground plane; CRLH-TL, composite right-/left-handed transmission line; R-DRA, rectangular-dielectric resonator antenna; SSR, square split ring; MTM, metamaterial; DGS, defected ground structure; CPW, coplanar waveguide.

significant current around the edge of the ground plane which shows that the ground plane plays an important role in the resonance at the upper band. This is in agreement with the parametric study presented before.

4. Comparative Study

To validate the compactness of the ram horn-like folded antenna proposed in this work, a comparative analysis along with the recently published works is carried out and presented in Table 2. Guided wavelength size at the lowest resonant frequency has been used for normalization purposes. It can be observed that the proposed antenna is comparatively compact than the recently reported works in literature. It can also be observed that the proposed antenna shows competitive performance in terms of size, gain, and efficiency when compared with the recent works, as shown in Table 2.

5. Conclusion

A compact ram horn-like folded dual-band antenna for LTE-A and WLAN applications is proposed in this work. The proposed antenna design is based on a folded monopole, partial ground, AMF, and protruding stub. The overall antenna footprint is $15 \times 10\,\mathrm{mm}^2$, and it operates at 2.3 GHz and 5.8 GHz with a gain of 0.62 dBi and 2.2 dBi, and radiation efficiency of 93.67% and 99.87%, respectively. The comparative analysis of the antenna proposed in this work with the state of the art shows that the proposed antenna is the smallest yet maintaining good radiation characteristics. Therefore, the antenna proposed in this work is a competitive candidate for future portable wireless communication.

Data Availability

The data supporting the findings of this study are all presented within the article.

Conflicts of Interest

There are no conflicts of interest among the authors.

Acknowledgments

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