A Flexible and Compact Semicircular Antenna for Multiple Wireless Communication Applications

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Abstract. *This work presents a compact, quad-band planar antenna intended for assimilation into flexible and conformal devices. The CPW-fed semicircular shaped prototype with rake-shaped slots is designed, realized and characterized experimentally. The frequency bands covered by the proposed radiator are centered at 2.5, 3.7, 5.5 and 8 GHz with measured impedance bandwidths of 16%, 13.5%, 11.8% and 14.63%, respectively. The proposed antenna is thus enabled to support WLAN, ISM, Bluetooth, WiMAX, LTE and X-band applications. The antenna exhibits a significant gain. The radiation characteristics of the proposed radiator are measured in concave and convex bent shapes at various radii to analyze its flexibility. Performance of the antenna remains almost unaffected in the bent situation. Measurements demonstrate good coherence with simulations. The compactness and good performance of the design both in bent and unbent conditions proves it to be the better contender for future multiband conformal wireless applications.*

Keywords

Quad-band, CPW-feedline, flexible substrate, WLAN, WiMAX

1. Introduction

Microstrip patch antennas, because of their captivating aspects such as low profile, simple realization, and concurrence with planar monolithic microwave integrated circuit (MMIC) components, have been found the desirable type of antennas used for wireless communication systems. Modern typical portable devices are desired to operate at WLAN, Bluetooth, 2G, 3G, 4G and GPS standards. Consequently, it is required to integrate as many standards as possible on a single wireless device. In addition to this, the antennas that are integrated into handheld wireless devices need to be compact, lightweight, easy to fabricate and flexible.

Many different antennas have been reported in the literature with the ability to operate at multiple frequency bands [1–8]. However, these multi-frequency radiators do not meet the conformal requirements as they were realized on a rigid and thick substrate like FR-4. Antennas presented in [1–3] are triple band rigid antennas with large geometrical dimensions. Prototype presented in [4] is a large hexaband antenna. Quad-band antennas have also been reported [5–8] exhibiting larger dimensions thus deficient in the required compactness.

Recently, flexible substrates such as paper and polymers have witnessed great progress because of their appealing characteristics of being cheaper, lightweight and more environment friendly in fabrication processing and disposal in addition to their flexible feature. Due to these advantages, numerous antennas with flexible substrates have been reported. A flexible bow-tie antenna with dual band operation and overall geometrical size of 80 × 60 mm^2 is reported [9]. In [10], a single band flexible textile antenna with comparatively large geometry is realized on 2 mm thick substrate for 2.45 GHz body area networks. The analysis of the radiator in bent condition has also been carried out. A dual-band inkjet printed multiband antenna on paper substrate with compact dimensions of 10 × 37.3 × 0.44 mm^3 is reported [11]. However, the flexibility analysis has not been taken into account. In [12] a compact polyamide substrate based radiator is proposed with dimensions of 24 × 24 mm^2 for WLAN applications but the antenna does not exhibit multiband operation. Similarly an inkjet printed multiband antenna on thin flexible substrate Kapton with geometrical size of 70 × 70 mm^2 is reported [13]. Flexibility aspect of the iterative radiator is also analyzed. A CPW-fed quad-band radiator with overall geometry of 90 × 60 mm^2 is presented [14] to operate at four frequency bands. The radiator is realized on flexible Rogers RT/Duroid 5880 substrate with 0.127 mm thickness and the performance in bent situation has also been investigated. In [15] an elliptical dual band, monopole antenna with geometric size of 48 × 33 mm^2 and fabricated on flexible 0.13 mm thick Kapton substrate is reported. The performance analysis in deformed and bent configurations has been carried out. An inkjet printed triple band antenna realized on resin coated paper substrate with overall dimensions of 35 × 40 mm^2 is proposed in [16]. The work in [17] presents a proximity coupled-fed microstrip flexible antenna with overall geometry of 40 × 40 mm^2 and dual band operation. In [18] a flexible antenna for Rogers RT/Duroid 5880 with thickness of 0.127 mm have been reported but it is not multiband. It has been observed from previously reported work that a compromise between antenna size and number of frequency bands achieved exists at all times.

In this article, a compact flexible quad-band antenna with CPW feed line is presented. The overall geometrical size of the prototype is 24 × 24 mm^2 and is realized on flexible Rogers RT/Duroid 5880 substrate with 0.127 mm thickness. Circular patch is considered as one of the most popular patch antennas. It took a lot of attention by the researchers as a single element and array, too. Unlike the rectangular patch, a circular patch has only one dimension to control. The proposed radiator can achieve the advantage of purposed size reduction and ease of fabrication due to the planar configuration. Likewise, CPW feed allows the antenna to integrate with other microwave circuits and RF devices. The presented antenna covers frequency bands of 2.2–2.6, 3.4–3.9, 5.15–5.8, and 7.3–8.5 GHz, respectively thus supporting WLAN, ISM, Bluetooth, WiMAX, LTE and X-band applications.

2. Antenna Design and Working Mechanism

The important parameters are taken into consideration while designing the patch antennas such as resonant frequency, dielectric constant, thickness of the substrate and the shape of the radiator/patch. Figure 1 illustrates the layout of the presented antenna. Aiming at the objectives of impedance matching and achieving maximum gain for the desired bands, the antenna incorporates a semicircular slotted patch with semicircular ground and a 50 Ω coplanar waveguide (CPW) feedline. The radius of the patch based on the resonant frequency is calculated using the following equations [19].

$$a = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_\mathrm{r}F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}}, \tag{1}$$

$$F = \frac{8.791\times10^9}{f_\mathrm{r}\sqrt{\varepsilon_\mathrm{r}}}, \tag{2}$$

$$a_\mathrm{e} = a\left\{1+\frac{2h}{\pi a\varepsilon_\mathrm{r}}\left[\ln\left(\frac{\pi a}{2h}\right)+1.7726\right]\right\}^{1/2}, \tag{3}$$

$$(f_\mathrm{rc})_{110} = \frac{1.8412\upsilon_\mathrm{o}}{2\pi a_\mathrm{e}\sqrt{\varepsilon_\mathrm{r}}} \tag{4}$$

where a is the radius of the circular patch, h is the substrate height, ε_r is relative permittivity of the substrate and f_r is the resonant frequency. The antenna with overall dimensions of 24 × 24 mm^2 is realized on flexible Rogers RT/Duriod 5880 substrate with thickness, h = 0.127 mm, ε_r = 2.2 and δ = 0.0009. The elementary geometry of the proposed circular patch antenna is designed for 2.5 GHz resonant frequency using CST®MWS®. By using all these parameters the radius R1 of the circular patch is calculated and found to be 11 mm. Table 1 further elaborates the dimensions of the proposed design.

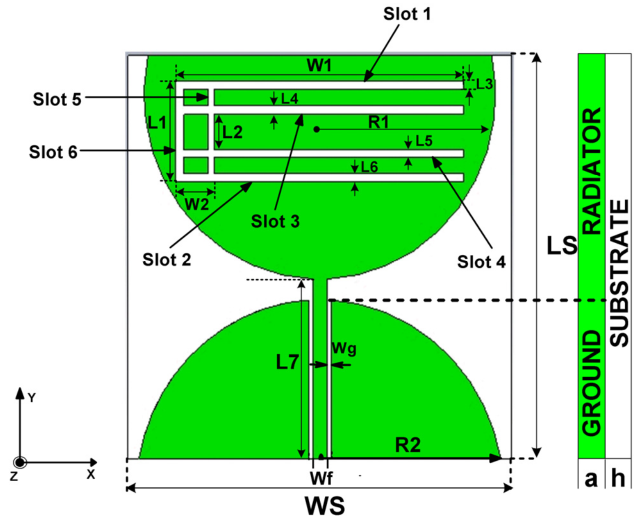


Fig. 1. Geometric dimensions of the proposed prototype.

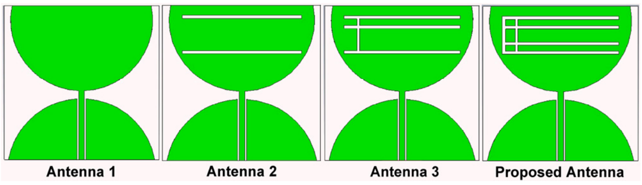
Parameter	Size(mm)	Parameter	Size(mm)
L_S	24	W_S	24
L_1	6	W_1	18
L_2	2.1	W_2	2.4
L_3,L_4,L_6	0.5	W_f	1
L_5	0.4	R_2	11.5
L_7	10.7	a	0.035
R_1	11	h	0.127

Tab. 1. Optimized dimensions of the proposed antenna.

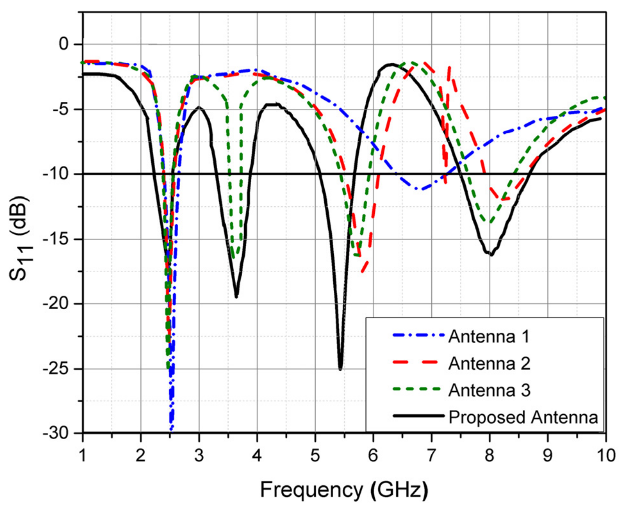
Figure 2(a) clearly illustrates the evolution of the design proposed in this work. For better understanding of the mechanism adopted to develop the model, the return loss (S_{11}) for the four design stages is plotted in Fig. 2 (b).

Initially, Antenna1 is designed as a basic semicircular patch of radius R1 with CPW feedline of width W_f. The ground is also semicircular with radius R2. This primary structure is designed to resonate at 2.5 GHz frequency with $S_{11} < -10$ dB, as shown in Fig. 2(b). Antenna2 is modeled by subtracting two horizontal slots 1 & 2 from the semicircular patch of Antenna1. This generates two additional resonances at 5.8 GHz and 8.3 GHz. In the third step, a vertical slot 5 of width 0.4 mm and a horizontal slot 3 are withdrawn. Due to the mutual coupling between the slots, the previously obtained resonances at 5.8 and 8.3 GHz improve and shift to 5.7 and 8 GHz respectively for Antenna3. The frequency shift at 2.5 GHz band is negligible while another narrow band at 3.6 GHz is also achieved. Finally proposed antenna is achieved by subtracting horizontal slot 4 and vertical slot 6. By incorporating these two slots, resonant frequencies attained at 3.6 and 5.7 GHz are shifted to 3.7 and 5.5 GHz, whereas a slight improvement in bandwidth has been found for the 2.5 GHz and 8 GHz frequency bands. The impedance bandwidth at 3.7 GHz is also improved from 200 MHz (3.5–3.7 GHz) to 500 MHz (3.3–3.8 GHz). Thus, the final radiating structure with optimum results has been obtained. This final proposed design delivers four resonances at 2.5, 3.7, 5.5 and 8 GHz supporting 2.4/5.2/5.5 GHz WLAN, 2.5/3.5 GHz WiMAX [20], LTE 2300/2500, ISM, Bluetooth and X-band applications.

The working mechanism of the proposed multiband antenna can be better demonstrated by analyzing surface current distribution at four resonant frequencies, i.e. 2.5, 3.7, 5.5 and 8 GHz as depicted in Fig. 3(a)–3(d). Figure 3(a) shows current is mainly concentrated at the feedline and the outer edges of the circular patch for 2.5 GHz. While for 3.7 GHz, the current density is widely observed at vertical slot 5, as illustrated in Fig. 3(b). Similarly, it is evident from Fig. 3(c) that major current distribution is seen on vertical slots and horizontal slot 1 & 2 for 5.5 GHz resonance. For 8 GHz resonant frequency, the major density of current is observed on vertical slot 6 and horizontal slots, as clearly shown in Fig. 3(d).



(a)



(b)

Fig. 2. (a) Evolution stages of the antenna. (b) Resultant S_{11}.

3. Results and Discussion

According to the optimal values of the prototype as provided in Tab. 1, the quad-band antenna is fabricated and measured to endorse the performance. Measured results are obtained by the R&S®ZVL13 Vector Network Analyzer. The fabricated prototype in different configurations is shown in Fig. 4.

Figure 5 illustrates simulated and measured return loss showing good coherence. The obtained commercial bands and respective bandwidth of each band are summarized in Tab. 2. The first considerable frequency band with $S_{11} < -10$ dB is 2.25–2.55 GHz with 16% impedance bandwidth covering the WLAN, WiMAX, LTE 2300/2500, Bluetooth and ISM bands. The second and third bands with 13.5% and 11.8% of bandwidth respectively, are suitable for the Fixed & Mobile WiMAX as well as WLAN applications. The fourth band supports X-band applications with 14.63% impedance bandwidth. Good coherence is observed between measured and simulated results; however, insignificant differences are due to the unavoidable use of coaxial cable and SMA connector for measurement [21], [22].

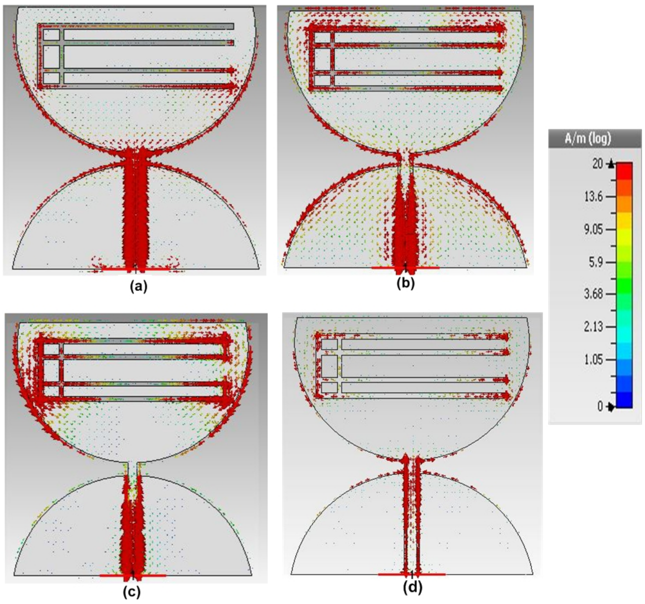


Fig. 3. Surface current density at: (a) 2.5 GHz, (b) 3.7 GHz, (c) 5.5 GHz, (d) 8 GHz.

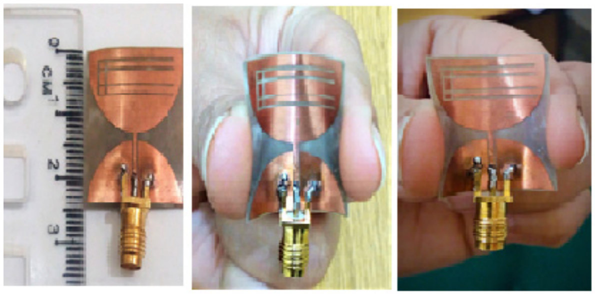


Fig. 4. Fabricated antenna in planar, convex and concave configuration.

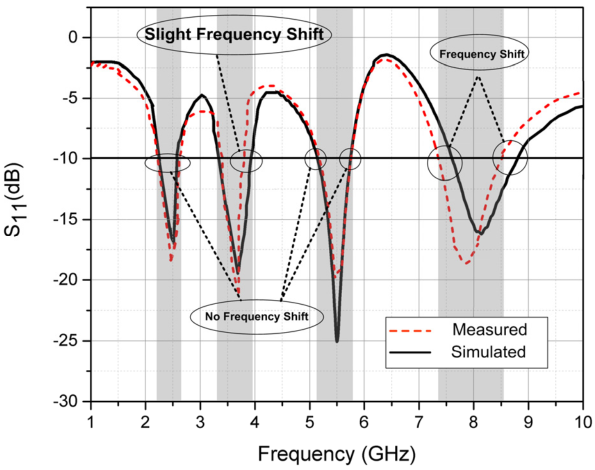


Fig. 5. Simulated and measured return loss (S_{11}).

The simulated and measured gain for each acquired band of the presented radiator is depicted in Fig. 6. The gain values are 1.7, 0.7, 3.8 and 2.1 dB for 2.5, 3.7, 5.5 and 8 GHz resonant frequencies, respectively. The gain for some resonant frequencies is low due to CPW feedline. As there is no ground on the other side, the patch antenna starts to radiate at other directions. Consequently the radiated power is distributed over a large area reducing gain. In the proposed work maximum achieved radiation efficiency is 76%. Table 3 summarizes the radiation efficiency and gain comparisons of the proposed antenna for each band.

Band No.	Bandwidth	Obtained commercial bands
1	2.25–2.55 GHz (300 MHz)	WLAN (2400–2480 MHz), LTE 2300 (2305–2400 MHz), LTE 2500 (2500–2690 MHz) ISM & Bluetooth (2400–2480 MHz), WiMAX (2500–2690 MHz)
2	3.4–3.8 GHz (400 MHz)	Fixed & Mobile WiMAX (3600–3800 MHz)
3	5.2–5.75 GHz (550 MHz)	WLAN (5150–5350 MHz, 5470–5725 MHz)
4	7.4–8.5 GHz (1100 MHz)	X-band applications

Tab. 2. Achieved frequency bands with respective bandwidth.

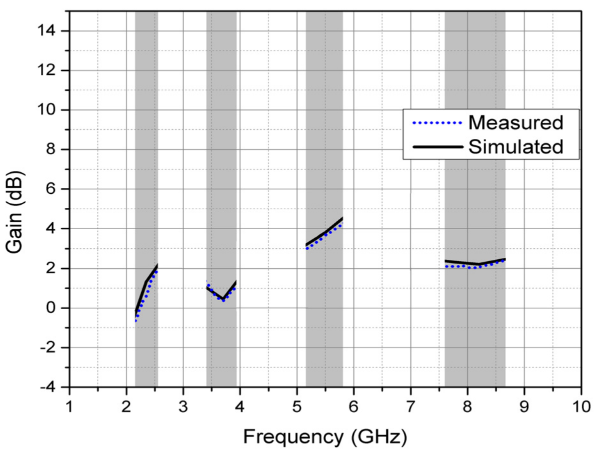


Fig. 6. Simulated and measured gain.

Frequency	2.5 GHz	3.7 GHz	5.5 GHz	8 GHz
Simulated Gain (dB)	1.8	0.8	3.99	2.2
Measured Gain(dB)	1.7	0.7	3.8	2.1
Radiation Efficiency	63%	62%	76%	65%

Tab. 3. Comparison between simulated and measured gain.

Figure 7(a)–7(d) exhibits simulated and measured radiation patterns for both E-plane(y-z) and H-plane(x-z) at 2.5, 3.7, 5.5 and 8 GHz for unbent configuration. In E-plane the bi-directional radiation patterns have been obtained while for the H-plane, an omni-directional behavior has been detected. Thus, the monopole-like response has been acquired. Hence, it is evident from the radiation characteristics that the antenna shows a steady response for the attained operating bandwidth.

4. Flexibility Analysis

Flexible antennas are substantial components for current and future wireless applications, comprising sensor systems and wearable on-body applications. There is always a compromise between attaining conformability and low cost. For flexible antennas, compact size and good radiation parameters with performance maintained throughout bending are the key design objectives. However, the performance of the antenna could be affected when converting from planar to bent configuration depending on the geometry, substrate material, and other factors. In this work, the bending affect of the antenna is investigated at three different angles 50º, 28.6º, and 21º with 27, 48, and 65 mm radii respectively. As the cylinder is used as the reference structure of the antenna for bending purpose, the outer radius of the cylinder is calculated using

$$S = r\theta \tag{5}$$

where S is the arc length, r is the radius of the circle and θ is the measure of the central angle in radians. Analysis of reflection coefficient and radiation characteristics of the antenna in convex and concave positions with three different radii has been done using CST®MWS® simulator. Keeping in view the requirements and bending abilities for upcoming flexible wireless devices, a radius of 65 mm is selected to investigate flexibility for both convex and concave formations and reflection coefficient is then measured. The antenna in bent form is illustrated in Fig. 8.

Figure 9(a), (b). illustrates the simulated and measured reflection coefficient (S_{11}) of the radiator at three diverse radii in convex and concave bent positions as well as in the unbent configuration. In case of convex bending no noteworthy deprivation is witnessed, except a minor shifting of the first band band (2.25–2.55 GHz) to 2.35–2.55 GHz. While for the concave configuration an insignificant shifting of the resonant frequency of the second band from 3.7 GHz to 3.8 GHz is observed. The primary reason behind this is the bending of the outer edges

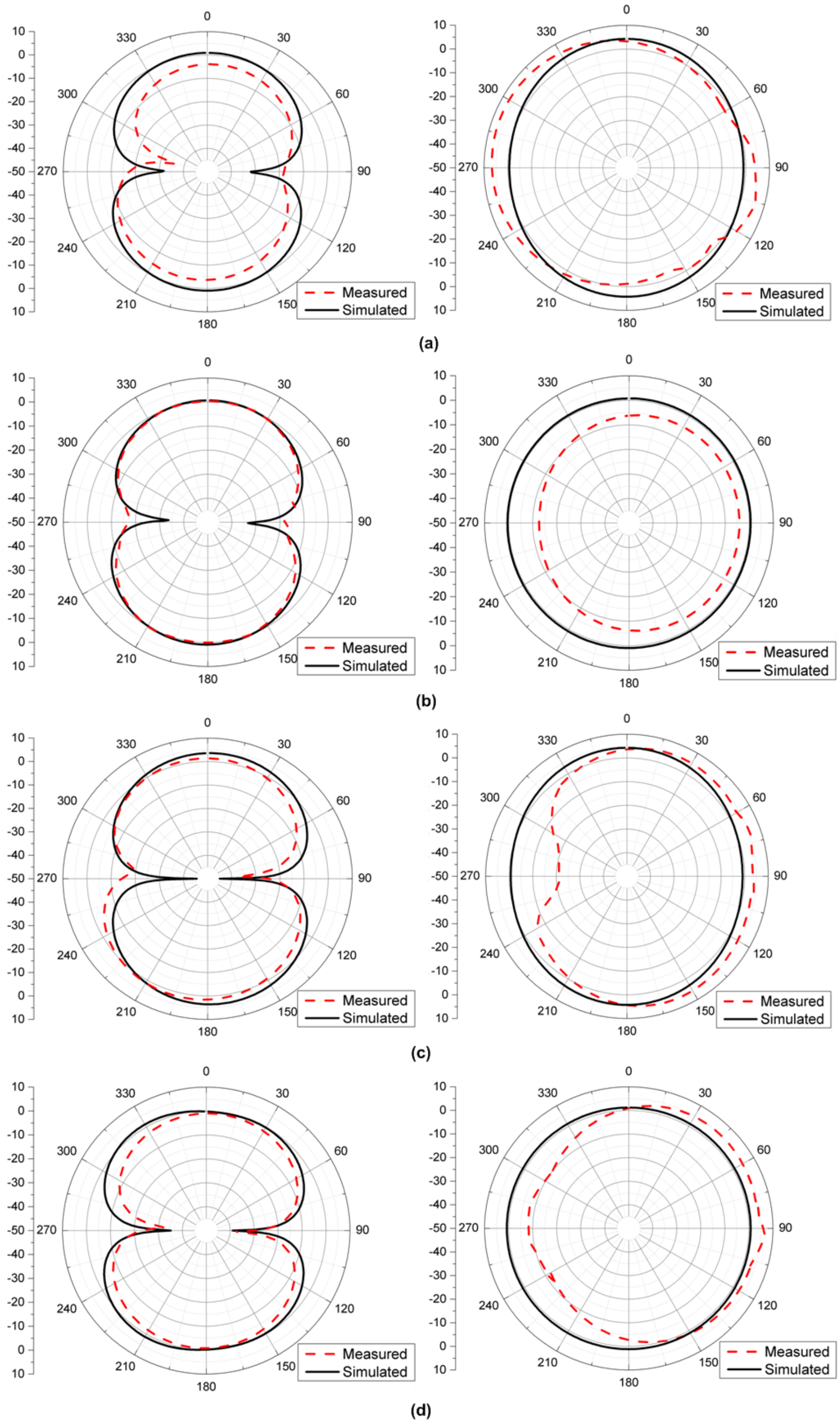
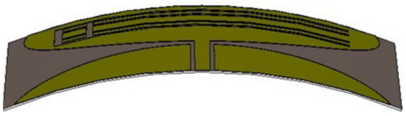


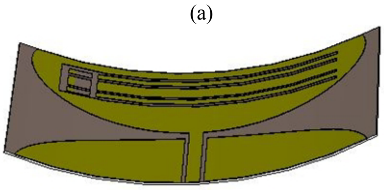
Fig. 7. Simulated and measured radiation patterns of the antenna at: (a) 2.5 GHz, (b) 3.7 GHz, (c) 5.5 GHz, (d) 8 GHz.

of the patch and vertical slots. Trivial narrowing of the band is found for the first band while impedance matching is enhanced for upper-frequency bands.

Figure 10 depicts the measured and simulated radiation patterns at 2.5 GHz and 5.5 GHz in both convex and concave configuration for different radii respectively. Measurements exhibit decent agreement with simulations. The gain correlation with and without bending is provided in Tab. 4. For convex bent form, an increment of 0.2 dB and 0.34 dB in gain is noticed for the resonant frequencies at 3.7 GHz and 5.5 GHz respectively for 65 mm. Likewise, in concave bent shape, an absolute rise of 0.33, 0.14 and 0.08 dB is observed in the 3.7, 5.5 and 8 GHz frequency bands, respectively. The principal reason for this realized alteration in gain is the trivial rise in the directivity of the antenna for bent configurations. The good robustness determines the capability of the proposed design for forthcoming flexible devices. Comparative analyses of the several previously reported works with the proposed quad-



(a)

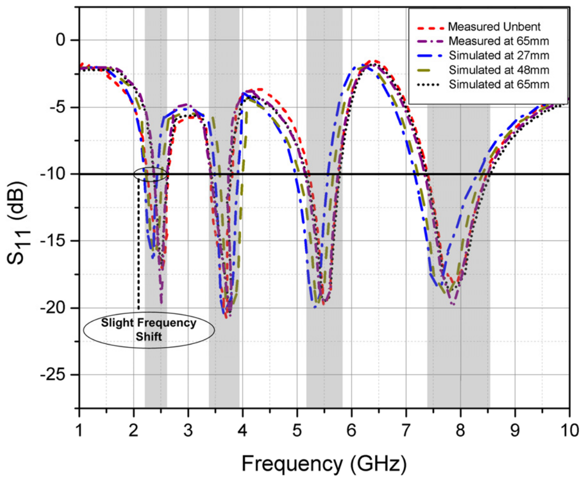


(b)

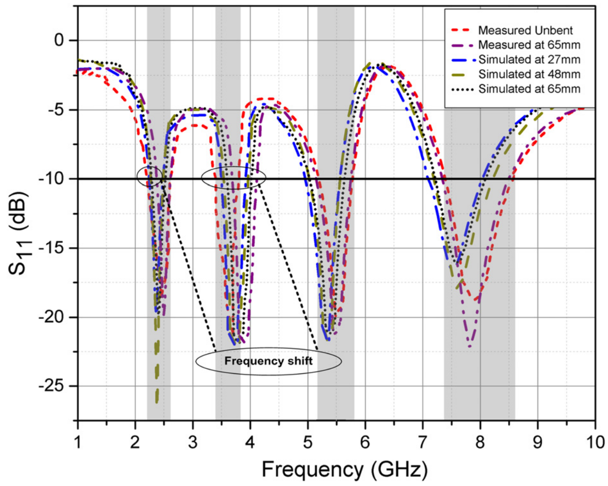
Fig. 8. (a) Convex bending. (b) Concave bending.

	Convex configuration		Concave configuration	
Band No.	**Without bending**	**With bending at R1 = 65 mm**	**Without bending**	**With bending at R1 = 65 mm**
1	1.7	1.44	1.7	1.46
2	0.7	0.909	0.7	1.03
3	3.8	4.14	3.8	3.94
4	2.1	1.67	2.1	2.18

Tab. 4. Gain comparison of the antenna for unbent and bent configuration.



(a)



(b)

Fig. 9. Measured and simulated reflection coefficient (S_{11}) of the antenna for (a) convex and (b) concave bending.

Ref.	Size	Maximum gain(dB)	Bands obtained
[9]	80 mm × 60 mm	6.20 dBi	3
[13]	70 mm × 70 mm	2.1 dBi	4
[134	90 mm × 60 mm	5.88 dBi	4
Proposed Work	**24 mm × 24 mm**	**3.8 dBi**	**4**

Tab. 5. Comparison between earlier reported flexible antennas.

band antenna has been presented in Tab. 5. It is evident that the obtained compact radiator exhibits good performance.

5. Conclusion

In this work, a compact and flexible semicircular antenna with the quad-band operation is exhibited with meticulous simulated and measured results. The rake- shaped slots generate resonances at 2.5, 3.7, 5.5, and 8 GHz and thus provide support for WLAN, WiMAX, LTE 2300/2500, ISM, Bluetooth and X-band applications. An insignificant shift in resonant frequency is revealed for convex bending, whereas no substantial variation is experienced for concave bending. An omnidirectional radiation pattern is obtained for the proposed prototype. The measured results reveal a maximum of 3.8 and 4.14 dB gain in unbent and bent configurations, respectively. Good radiation characteristics, as well as the robustness of the proposed design, demonstrate the appropriateness of the antenna for forthcoming flexible and conformal electronic devices.

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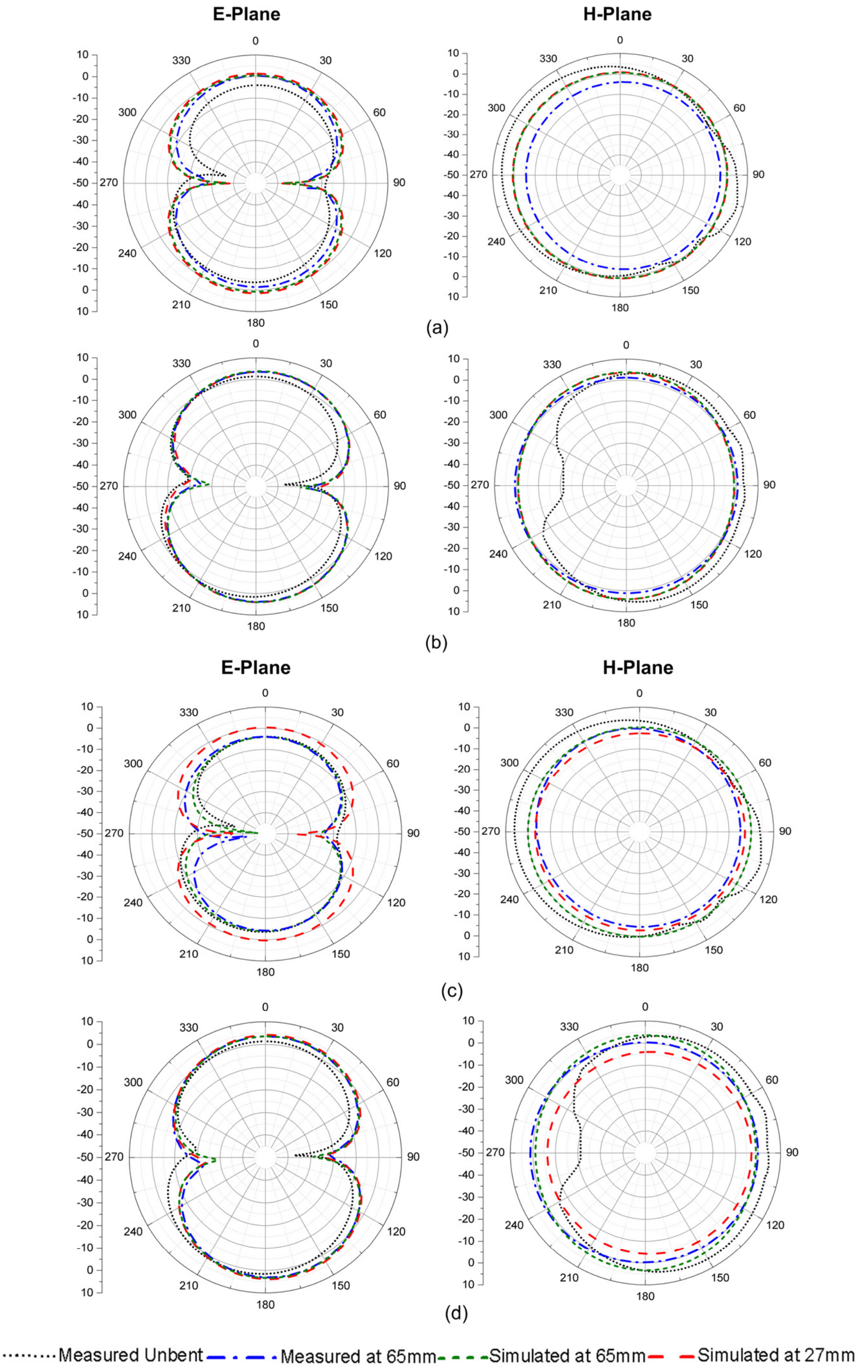

Fig. 10. Simulated and measured radiation patterns of convex bent at (a) 2.5 GHz, (b) 5.5 GHz and concave bent at (c) 2.5 GHz, (d) 5.5 GHz.

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