



# Design and Analysis of CPW-Fed Antenna for Quad-Band Wireless Applications

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## Abstract

In this article, the author proposes and designs a multi-band coplanar waveguide (CPW)-fed Om-shaped ( $\mathfrak{Z}^{\circ}$ ) antenna on an FR4 substrate with dimensions of  $80 \times 80 \times 1 \text{ mm}^3$ . The proposed antenna has a quad-band, and operates with four resonance frequencies ( $f_r$ ) at  $f_{r1} = 2.96 \text{ GHz}$ ,  $f_{r2} = 3.85 \text{ GHz}$ ,  $f_{r3} = 4.40 \text{ GHz}$ , and  $f_{r4} = 5.50 \text{ GHz}$ , for S-band, IMT band, C-band, and Wi-Max-band applications respectively. The impedance bandwidth (IBW) of the proposed antenna confirmed reflection coefficients of less than  $-10 \text{ dB}$ , ( $S_{11} \leq -10 \text{ dB}$ ) was 60 MHz (2.93–2.99 GHz), 90 MHz (3.80–3.89 GHz), 130 MHz (4.35–4.48 GHz), and 110 MHz (5.44–5.55 GHz), respectively, for quad-band applications. The proposed antenna has a gain of 2.2 dBi, 11.8 dBi, 11 dBi, and 9.4 dBi, respectively, at the resonant frequencies of 2.96 GHz, 3.85 GHz, 4.40 GHz, and 5.50 GHz. The antenna has been designed and simulated by using computer simulation tool (CST) software, which established a good agreement between the measured and simulated results. The results are compared with reported work, and the proposed geometry provides a multiband with good IBW for wireless applications.

**Keywords** CPW · Om-shaped · quad-band · IWB

## Introduction

Microwave and wireless engineers' interest in research on compact microstrip antenna design has recently grown due to the requirement for small antennae for wireless communication. Microstrip antennas are commonly employed in the microwave frequency range due to their simplicity and compatibility with printed-circuit technology. A microstrip antenna is merely a piece of metal of any shape that is placed

on top of a grounded dielectric substrate. For a variety of factors, microstrip patch antennae are appealing in antenna applications. They are lightweight, inexpensive, and have planar geometry. Multiband antennae with excellent radiation characteristics and large impedance bandwidths with desired radian patterns are required for advanced communication systems. The best antenna that meets these requirements is one fed by a coplanar waveguide, since it provides low leakage of radiation and less dependence of characteristics impedance on the substrate material and height, because its patch, feed, and ground are lying in the same plane, which confirms its easy integration with all other microwave devices.<sup>1,2</sup>

A planar geometry triple-band CPW-fed antenna has been developed for wireless applications. The wide IBW performance of the antenna is ensured by using different shapes of tuning stubs and modified ground plane structures, as reported in.<sup>3,4</sup> A rectangular multiband planar antenna with a defected ground structure has been demonstrated. T-shaped slits are introduced on either side of the radiating patch which offers a dual-band with better IBW. Further, a zig-zag-shaped slit has been inserted, due to which the antenna resonates at an additional third band, as described

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in.<sup>5</sup> CPW-fed patch antenna designs have been proposed for triple- and quad-band applications with various shapes of structures. Slot-loading methods have been used with different substrate materials to reduce the size of a patch antenna and to produce multiband operation in a stated frequency range, as reported in.<sup>6,7</sup> The other desirable features of CPW-fed antenna are its working capability against adverse weather and geographical conditions, and the non-requirement of alignment to achieve accurate polarization between trans-receive antennae.<sup>8,9</sup>

Circularly polarized (CP) antenna excites two orthogonal modes of radiation pattern acting in phase quadrature.<sup>10,11</sup> Antenna designers, in general, choose different shapes of the slots, such as square, rectangular, and ring, with appropriate tuning stubs and substrate materials for wider axial ratio bandwidths.<sup>12,13</sup> Large dimensions and limited IBW characteristics are the main limitations of CP antennae. However, the configuration and geometrical designs of CP antennae also have very complex provisions and fabrication processes.<sup>14,15</sup> The CP antenna might have different types of symmetric or asymmetric structures with various shapes of radiating patches. The wideband performance of the antenna is ensured by using different shapes of tuning stubs and modified ground plane structures, as reported in.<sup>16</sup> In this article, the author has designed antennae on Roger (RO-5880) substrate with dimensions of  $104 \times 107 \times 0.51 \text{ mm}^3$ . The antenna operates in the dual-band having bandwidths of 2.40–2.80 GHz and 5.1–5.6 GHz with a gain of 5 dBi.<sup>17</sup>

The author has designed a miniaturized dual-band CPW-fed annular slot antenna with an arc-shaped tuning stub having dimensions of  $70 \times 70 \times 0.8 \text{ mm}^3$ . It operates at 1.74 GHz and 3.76 GHz, respectively, with maximum peak gains of 3.8 dBi and 5.1 dBi.<sup>18</sup> A planar geometry triple-band CPW-fed antenna has been developed for wireless applications. The wide IBW performance of the antenna is ensured by using different shapes of tuning stubs and modified ground plane structures, as reported in.<sup>19</sup> A rectangular triple-band planar antenna has been demonstrated for WLAN and WiMAX applications and obtained a maximum gain of 3.05 dBi. The dimensions of the antenna were  $120 \times 40 \times 0.8 \text{ mm}^3$  and the substrate material used was FR4.<sup>20</sup> The performance of the antenna mainly depends on the properties of the dielectric materials used in the antenna design and fabrication. The study of the microwave materials and their dielectric properties at microwave frequencies is a precondition for selecting appropriate materials for numerous microwave applications.<sup>21</sup> A circularly polarized square slot antenna for the UHF RFID (0.84–0.98 GHz) frequency band was reported to have dimensions of  $116 \times 116 \times 1.6 \text{ mm}^3$ .<sup>22</sup>

This research work has been greatly inspired by the above research papers, and a unique wideband CPW-fed microstrip antenna with various shapes is thus projected and designed for

wireless applications. The proposed antenna (step-3) uses a unique technique to achieve multi-band operation. The proposed antenna has been constructed with an Om-shaped ( $\infty$ ) radiating patch, and produces four resonance frequencies ( $f_r$ ) at  $f_{r1} = 2.9 \text{ GHz}$ ,  $f_{r2} = 3.8 \text{ GHz}$ ,  $f_{r3} = 4.4 \text{ GHz}$ , and  $f_{r4} = 5.5 \text{ GHz}$ , respectively, for S-band, IMT band, C-band, and Wi-Max-band applications.

The proposed structure of the antenna has been simulated by the finite integration technique in a CST V.17 electromagnetic simulator in the antenna template transient mode. The results of the proposed CPW antenna, such as return loss, voltage standing wave ratio (VSWR), IBW, and gain have been achieved and have shown good agreement between the measured and simulated results in CST. The design and evaluation steps of the antenna are described in the following sections. The proposed antenna configurations with utilized design methodologies are explained in Sect. "Antenna Geometry and Design Steps"; Sect. "Parametric Study" covers the optimization with a parametric study of the proposed antenna. Sect. "Result Analysis" analyzes its performances, and gives comprehensive comparison with other reported works, and, finally, Sect. "Conclusions" concludes with the future scope of this research.

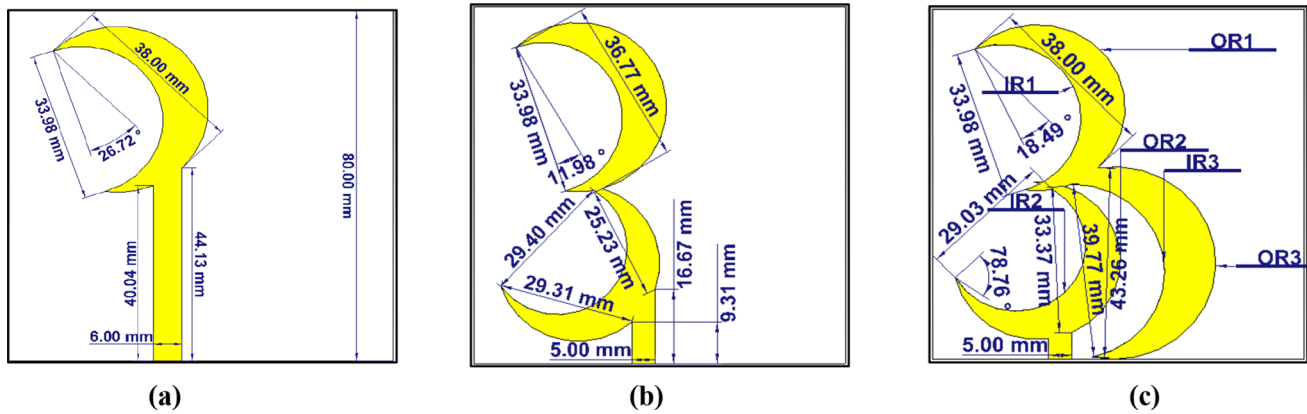
## Antenna Geometry and Design Steps

The evolution of some asymmetric structures of antennas which have been developed and investigated, as shown in Fig. 1. Three different antenna configurations are reported and compared in this paper. The first one, antenna-1, contains a simple single arc-shaped slotted CPW-fed antenna as shown in Fig. 1a. The second one, antenna-2, uses a double arc-shaped slotted CPW-fed antenna, as shown in Fig. 1b. The third one, antenna-3 (proposed design), has an Om-shaped slotted CPW-fed antenna, as illustrated in Fig. 1c, which shows the geometry of the proposed antenna, with its conductor printed on a square-shaped FR4 substrate of a thickness ( $h$ ) of 1.0 mm, a relative permittivity ( $\epsilon_r$ ) of 4.4, and a dielectric loss tangent ( $\tan \delta$ ) of 0.02. The area of the substrate plane ( $L \times W$ ) has been chosen to be  $80 \times 80 \text{ mm}^2$ .

The resonance frequency ( $f_r$ ) of a CPW-fed antenna depends on different design parameters like the shape and size of the radiating patch stub, substrate material, and thickness. The total area of the radiating stub ( $A_r$ ) resonator was used to determine the number of resonance frequencies ( $f_{rN}$ ) by using:

$$f_{rN} = \frac{c}{2A_r \sqrt{\epsilon_{\text{reff}}}} \quad (1)$$

where  $N$  is the number of resonating frequencies,  $A_r$  is the area of the arc,  $\epsilon_{\text{eff}}$  is the effective dielectric constant, and  $c$  is the speed of light.



**Fig. 1** Design steps of Om-shaped slotted CPW-fed antenna: (a) design step-1: antenna-1, single arc-shaped slotted CPW-fed antenna; (b) design step-2: antenna-2, double arc-shaped slotted CPW-fed antenna; (c) design step-3: antenna-3 (proposed design), Om-shaped slotted CPW-fed antenna.

**Table I** Optimized geometrical units of the base and proposed antennae

Design steps	Geometrical design parameters of antennas (mm)								
	Arc-1		Arc-2		Arc-3		Feed-line		Substrate (FR4) ( $L \times W \times h$ ) mm <sup>3</sup>
	OR1	IR1	OR2	IR2	OR3	IR3	Length	Width	
Antenna-1	38.00	33.98	–	–	–	–	44.13	6	80 × 80 × 1
Antenna-2	38.00	33.98	36.77	29.40	–	–	16.67	5	80 × 80 × 1
Antenna-3	38.00	33.98	38.00	29.03	43.26	39.77	6.00	5	80 × 80 × 1

### Design Step-1 with Single Arc

Antenna-1 has a single arc-shaped design; in this design, the diameters of the inner and outer arcs are 33.98 mm and 38 mm, respectively. The angle between these cutting slots is  $26.72^\circ$ . The CPW-fed line length is 44.13 mm, having a width of 6 mm, as shown in Fig. 1a and listed in Table I.

### Design Step-2 with Dual Arc

Antenna-2 is a combination of two arc-shaped geometry; in this design, the upper arc shape is identical, and the same parameters are taken from antenna-1 geometry. Here, the only difference in the angle between the cutting slots, in design step-2, the angle between the cutting slot is  $11.98^\circ$ . In the lower arc shape design, the diameters of the inner and outer circles are 29.40 mm and 36.77 mm, respectively. In this structure, the CPW-fed line length is 16.67 mm and has feed-line width of 5 mm, as shown in Fig. 1b and listed in Table I.

### Design Step-3 with Om-Shaped

The proposed antenna-3 is a combination of three arc-shaped geometries, and is called an Om-shaped antenna.

The diameter of the outer radius arc (OR1) is 38 mm, and the diameter of the inner radius arc (IR1) is 33.98 mm, as shown in Fig. 1c. Similarly, the outer and inner diameters of arcs OR2, OR3, IR2, and IR3 are 38 mm, 43.26 mm, 29.03 mm, and 39.77 mm, respectively. In this structure, the CPW-fed line length is 6 mm and has a feed-line width of 5 mm. Figure 1c depicts the Om-shape of the proposed CPW-fed square patch antenna, and the geometrical design parameters listed in Table I.

Figure 2 illustrates the  $|S_{11}|$  parameter (return loss) of the three different geometrical configurations of the antenna composed of step-1, step-2, and step-3, which are shown in Fig. 1a, b, and c, respectively. The electrical performances of the antennae are compared and listed in Table II with different arc-loaded radiating resonator stubs. Antenna-1 was investigated for single-band applications with a single arc stub. The obtained resonance frequency resonating at 3.85 GHz with  $-30$  dB return loss is displayed in red color in Fig. 2. The obtained result of antenna-2 with two arc-stub showed that two resonance frequencies were resonating at 3.83 GHz and 4.48 GHz, respectively, with  $-30$  dB and  $-24$  dB return losses for dual-band applications, shown in green color in Fig. 2. The proposed Om-shaped antenna-3 can be used for quad-band applications ranging ( $S_{11} \leq -10$  dB) from 2.90–3.01 GHz, 3.77–3.85 GHz,

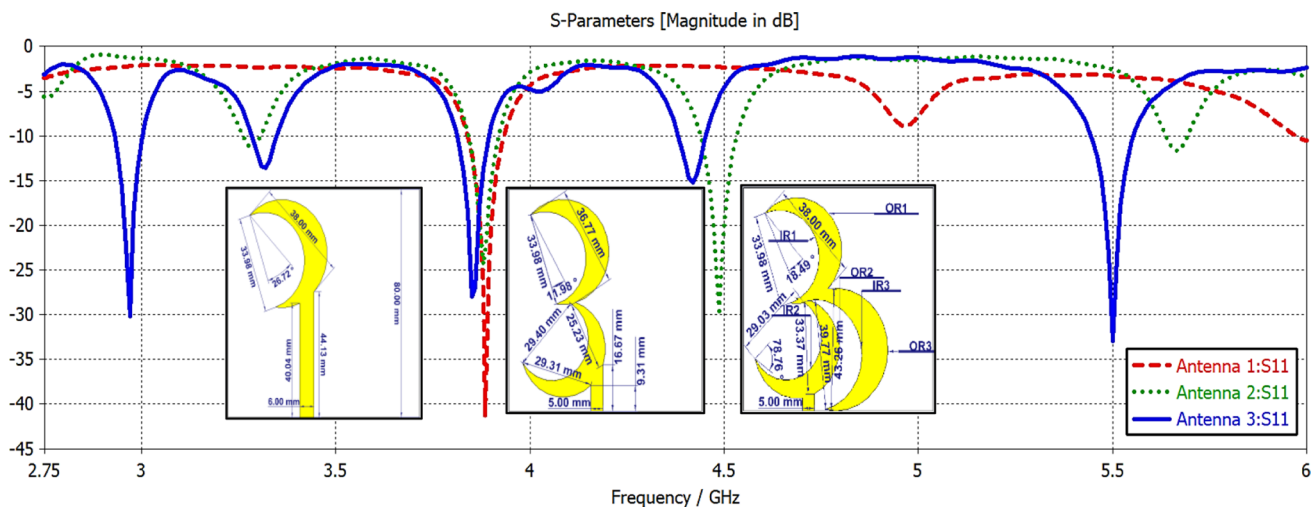


Fig. 2  $|S_{11}|$  parameters of antenna-1, antenna-2 and proposed antenna-3 (Color figure online).

Table II Comparison of the electrical performance of the antennae

Design steps	VSWR	$f_r$ (GHz)	IBW, (GHz) ( $S_{11} = -10$ dB)	$ S_{11} $ (- dB)	Band
Antenna-1	1.03	3.85	3.80–3.98, (0.18)	30	Single
Antenna-2	1.02	3.83	3.80–3.91, (0.11)	30	Dual
	1.06	4.48	4.40–4.52, (0.12)	24	
Antenna-3 (proposed)	1.01	2.96	2.90–3.01, (0.11)	30	Quad
	1.08	3.80	3.77–3.85, (0.08)	28	
	1.46	4.40	4.35–4.45, (0.10)	15	
	1.04	5.50	5.45–5.55, (0.10)	33	

4.35–4.45 GHz, and 5.45–5.55 GHz, respectively, at resonating frequencies of 2.96 GHz, 3.80 GHz, 4.40 GHz, and 5.50 GHz, shown with blue color in Fig. 2 and listed in Table II.

The optimized VSWRs are presented in Table II for all three different types of antennae to compare their VSWR parameters, and shown in Fig. 3. The antenna-1's VSWR is 1.03 at 3.85 GHz, with a bandwidth of 4.91–5.03 GHz, and antenna-2's is 1.06 at 4.94 GHz, with a bandwidth of 3.80–3.98 GHz. The proposed antenna-3 has the values of VSWR 1.01, 1.08, 1.46, and 1.04, respectively, at resonance frequencies 2.96 GHz, 3.80 GHz, 4.40 GHz, and 5.50 GHz along with wide IBW for quad-band wireless applications.

### Parametric Study

The parametric study is important to achieve appropriate impedance matching of the antenna and the design parameters. The width of the feed line stub is widely considered during the design of the antenna to achieve the number of resonance frequencies and bands of the CPW-fed antenna. Resonance frequencies and bands can be controlled by

changing the length and width of the feed line stubs as per the requirement of users.<sup>7</sup> The width of the feed line stub ( $W_d$ ) is used to determine the number of resonance frequencies ( $f_{rN}$ ) by using:

$$f_{rN} = \frac{c}{2W_d\sqrt{\epsilon_{\text{reff}}}} \tag{2}$$

where  $W_d$  is the width of the feed line,  $\epsilon_{\text{eff}}$  is the effective dielectric constant, and  $c$  is the speed of light.

The feed line width of the CPW-fed antenna is subjected to certain modifications, and it has been found that these variations have an impact on the  $|S_{11}|$  and other antenna characteristics.

### $W_d$ Variation of Antenna-1

The effects of the feed-line width ( $W_d$ ) on the return loss  $|S_{11}|$  and IBW of antenna-1 is presented in Fig. 4 and tabulated in Table III. The  $W_d$  was varied from 5.0 mm to 6.5 mm, while the remaining geometrical parameters were fixed, the resonance frequency ( $f_r$ ) was 4.94 GHz approximately in the entire range from  $5.0 \text{ mm} \leq W_d \leq 6.5 \text{ mm}$ ,

except 6.0 mm for the single-band operation. When the width was 6.0 mm, the resonance frequency was 3.85 GHz in the lower frequency band as shown in Fig. 4. Table III

shows that the feed line affects the  $S_{11}$  and IBW parameters of antenna-1. It has the same resonance frequency of 4.94 GHz, when  $W_d$  is 5.0 mm, 5.5 mm, and 6.5 mm.

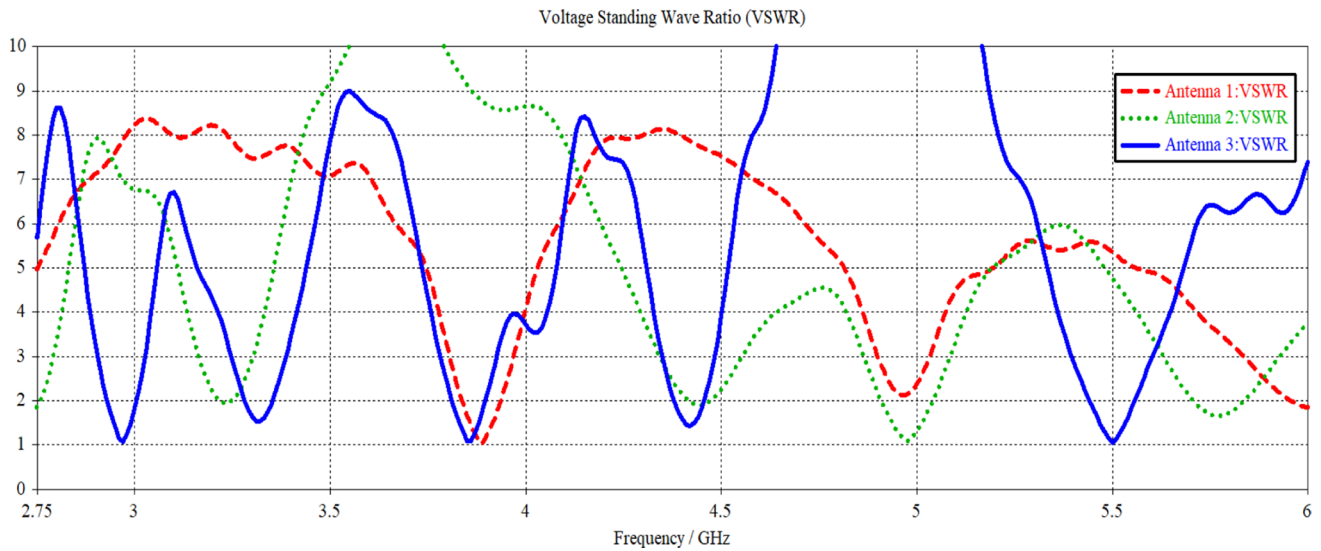


Fig. 3 VSWR of antenna-1, antenna-2, and proposed antenna-3 (Color figure online).

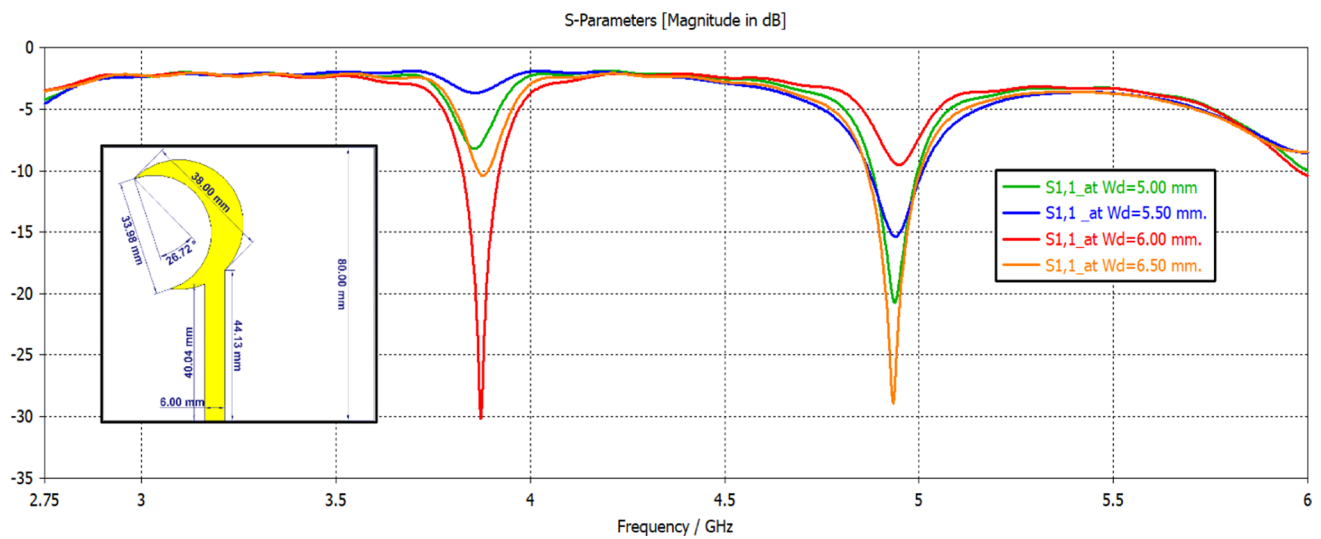


Fig. 4  $|S_{11}|$ -parameters of antenna-1 with variation from  $5.0 \text{ mm} \leq W_d \leq 6.5 \text{ mm}$  (Color figure online).

**Table III** Effects of  $W_d$  on  $|S_{11}|$  and IBW parameters of antenna-1

Parametric analysis	$W_d$ (mm)	$f_r$ (GHz)	IBW, (GHz) ( $S_{11} = -10 \text{ dB}$ )	$ S_{11} $ (- dB)	Band
Antenna-1	5.0	4.94	4.88–5.00	20.74	Single
	5.5	4.94	4.86–5.01	15.30	Single
	6.0	3.85	3.80–3.98	30.16	Single
	6.5	4.94	4.80–5.00	28.84	Single

### $W_d$ Variation of Antenna-2

Figure 6 displays the variations in  $W_d$  for the design evolution of antenna-2 with a range of  $5.0 \text{ mm} \leq W_d \leq 6.5 \text{ mm}$ . For this range, the antenna resonates at two different resonance frequencies, 4.44 GHz and 4.94 GHz, except at 5.0 mm width. When  $W_d$  was 5.0 mm, the two resonance frequencies were found for dual-band application  $f_{r1} = 4.94 \text{ GHz}$  and  $f_{r2} = 5.75 \text{ GHz}$  for the first and second bands. The first band has the same resonance frequency ( $f_{r1} = 4.94 \text{ GHz}$ ) as found in the previous bands, and the second band resonates ( $f_{r2} = 5.75 \text{ GHz}$ ) at a higher frequency, as shown in Fig. 5 and listed in Table IV.

Table IV shows the effects of  $W_d$  variations on  $|S_{11}|$  and IBW parameters of antenna-2. It exhibits identical resonance frequencies of 4.44 GHz and 4.94 GHz when the  $W_d$  is 5.5 mm, 6.0 mm, and 6.5 mm, respectively.

### $W_d$ Variation of Antenna-3

Figure 6 depicts the proposed antenna-3 for quad-band applications with a  $W_d$  range of  $5.0 \text{ mm} \leq W_d \leq 6.5 \text{ mm}$  along with the constant of other geometrical design parameters. The predicted proposed antenna has four resonance frequencies, 2.96 GHz, 3.85 GHz, 4.40 GHz, and 5.50 GHz, and the same for different values of  $W_d$  because of perfect impedance matching, as listed in Table V.

Table V shows the effects of  $W_d$  variations on the  $|S_{11}|$  and IBW parameters of the proposed antenna-3. It has four identical resonance frequencies of 2.96 GHz, 3.85 GHz, 4.40 GHz, and 5.50 GHz, respectively, for quad-band wireless applications.

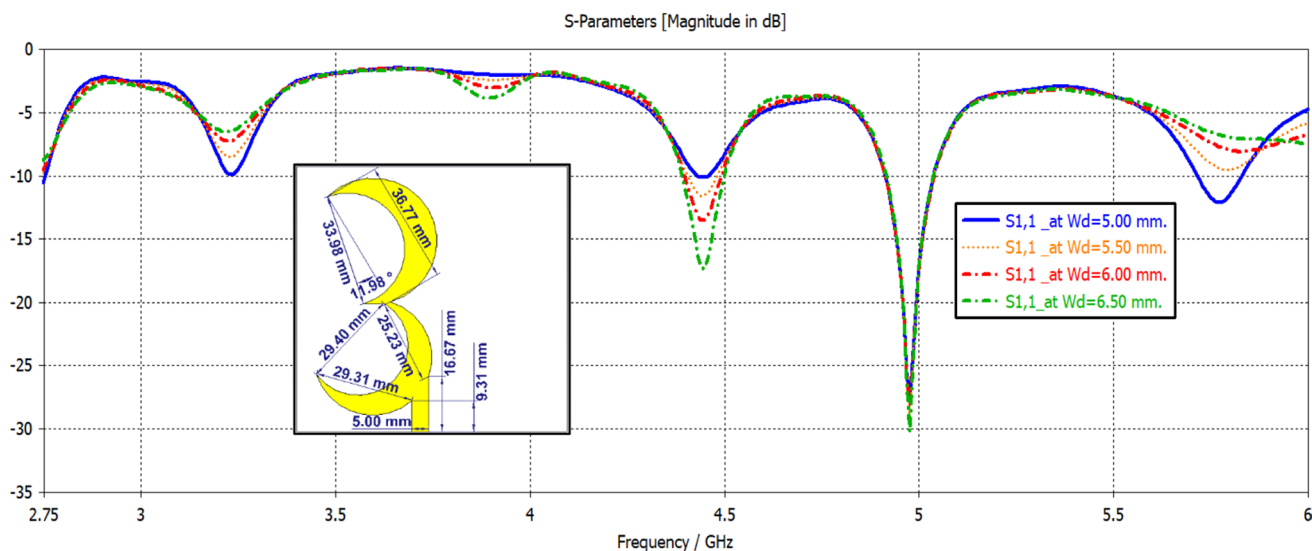


Fig. 5  $|S_{11}|$ -parameters of antenna-2 with the variation from  $5.0 \text{ mm} \leq W_d \leq 6.5 \text{ mm}$  (Color figure online).

**Table IV** Effects of  $W_d$  on  $|S_{11}|$  and IBW parameters of Antenna-2

Parametric analysis	$W_d$ (mm)	$f_r$ (GHz)	IBW, (GHz) ( $S_{11} = -10 \text{ dB}$ )	$ S_{11} $ (- dB)	Band
Antenna-2	5.0	4.94	4.91–5.03	27	Dual
		5.75	5.70–5.80	12	
	5.5	4.44	4.39–4.48	12	Dual
		4.94	4.91–5.03	29	
	6.0	4.44	4.40–4.50	13	Dual
		4.94	4.91–5.03	27	
6.5	4.44	4.40–4.50	17	Dual	
	4.94	4.91–5.03	30		

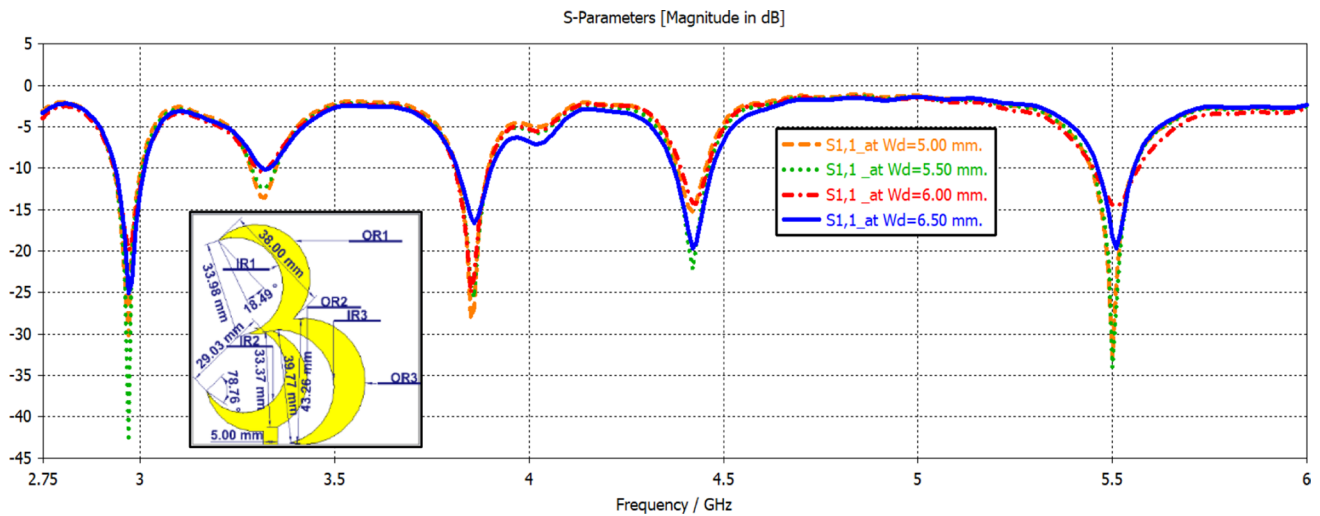


Fig. 6  $|S_{11}|$ -parameters of proposed antenna-3 with the variation from  $5.0 \text{ mm} \leq W_d \leq 6.5 \text{ mm}$  (Color figure online).

**Table V** Effects of  $W_d$  on  $|S_{11}|$  and IBW parameters of proposed antenna-3

Parametric analysis	$W_d$ (mm)	$f_r$ (GHz)	IBW, (GHz) ( $S_{11} = -10 \text{ dB}$ )	$ S_{11} $ (- dB)	Band
Antenna-3	5.0	2.96	2.93–3.00	29	Quad
		3.85	3.81–3.89	27	
		4.40	4.38–4.45	15	
		5.50	5.44–5.55	32	
	5.5	2.96	2.93–2.99	41	Quad
		3.85	3.80–3.89	25	
		4.40	4.35–4.47	22	
		5.50	5.44–5.55	33	
	6.0	2.96	2.93–3.01	20	Quad
		3.85	3.80–3.89	24	
		4.40	4.37–4.46	14	
		5.50	5.44–5.56	14	
6.5	2.96	2.93–3.01	25	Quad	
	3.85	3.81–3.89	16		
	4.40	4.35–4.47	19		
	5.50	5.45–5.55	19		

### Results Analysis

The simulation and measurement results of a CPW-fed proposed antenna-3 with several resonance frequencies and impedance bands are described in this section. The proposed antenna's return loss ( $|S_{11}|$ ) was measured on a Keysight Technologies (N5224B) network analyzer for the validation of the simulated results.

### Measured Return Loss ( $|S_{11}|$ )

The desired simulated results have been obtained, as shown in Fig. 6, and compared with the measured results shown in Fig. 7. According to the observed results, antenna-3 has four resonance frequencies, 2.94 GHz, 3.80 GHz, 4.35 GHz, and 5.50 GHz, with corresponding return losses of 30 dB, 28 dB, 15 dB, and 33 dB, as tabulated in Table VI.

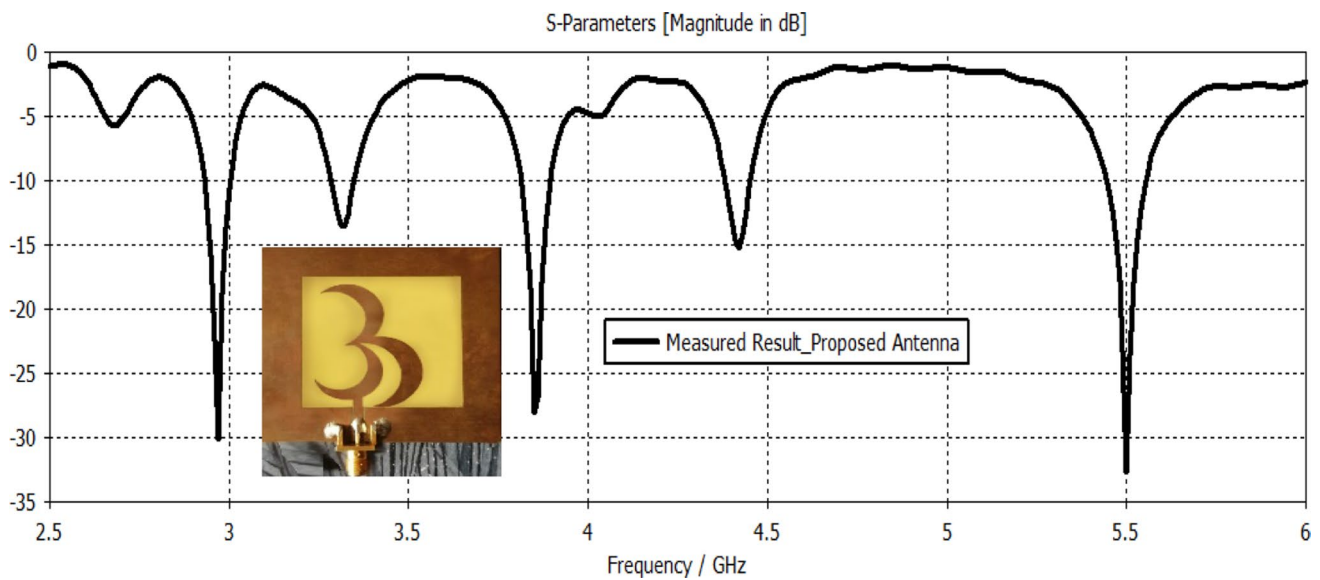


Fig. 7 Measured  $|S_{11}|$ -parameter of proposed antenna-3.

Table VI Measured and simulated results analysis of antenna-3

Performance of antenna-3	$W_d$ (mm)	$f_r$ (GHz)	IBW, (GHz) ( $S_{11} = -10$ dB)	$ S_{11} $ (- dB)	VSWR	Gain (dBi)
Simulated result	5.5	2.96	2.90–3.01	41	1.07	02.2
		3.85	3.80–3.90	25	1.08	11.8
		4.40	4.30–4.47	22	1.46	11.0
		5.50	5.45–5.56	34	1.04	09.5
Measured result	5.5	2.94	2.88–3.02	30	–	–
		3.80	3.78–3.89	28	–	–
		4.35	4.31–4.48	15	–	–
		5.50	5.43–5.57	33	–	–

**Gain**

Figure 9 depicts the gain of the proposed antenna-3 as a function of frequency. At the resonance frequencies of 2.96 GHz, 3.80 GHz, 4.40 GHz, and 5.50 GHz, the maximum gain of the antenna was 2.2 dB, 11.8 dB, 11 dB, and 9.5 dB, respectively as listed in Table VI.

The proposed antenna-3 operates at four resonating frequency bands for quad-band wireless operations, covering the S-band, IMT, C-band, and Wi-MAX-bands. We note a better agreement between the simulation and measured results. For the measured results, the first band at the resonance frequency of 2.96 GHz has a low return loss (-30 dB) compared to the simulated return loss (-41 dB). Similarly, the third band (4.4 GHz) also differs from the simulated result (-7 dB) at 4.35 GHz. This may be attributed to several causes, such as fabrication tolerance and the effect of SMA connector soldering (Fig. 8).

The various results of the simulations and measurements of the proposed antenna are listed in Table VI.

**Surface Current Density**

The current distributions of the proposed antenna-3 at resonant frequencies of 2.96 GHz, 3.85 GHz, 4.30 GHz, and 5.50 GHz are shown in Fig. 9. At a resonant frequency of 2.96 GHz, the proposed antenna has a maximum current density at the edges of the last double arc-shaped design, as shown in Fig. 9a. At a resonant frequency of 3.85 GHz, the proposed antenna has a maximum current distribution at the joint part of all the arc shapes, as shown in Fig. 9b. In Fig. 9c, at a frequency of 4.4 GHz, the proposed antenna-3 is excited at all the edges of the arc but has a maximum current density at the edges of the double arc shape. At a resonant frequency of 5.50 GHz, the proposed antenna-3 has a maximum current distribution at the end of the double arc shape, as shown in Fig. 9d.



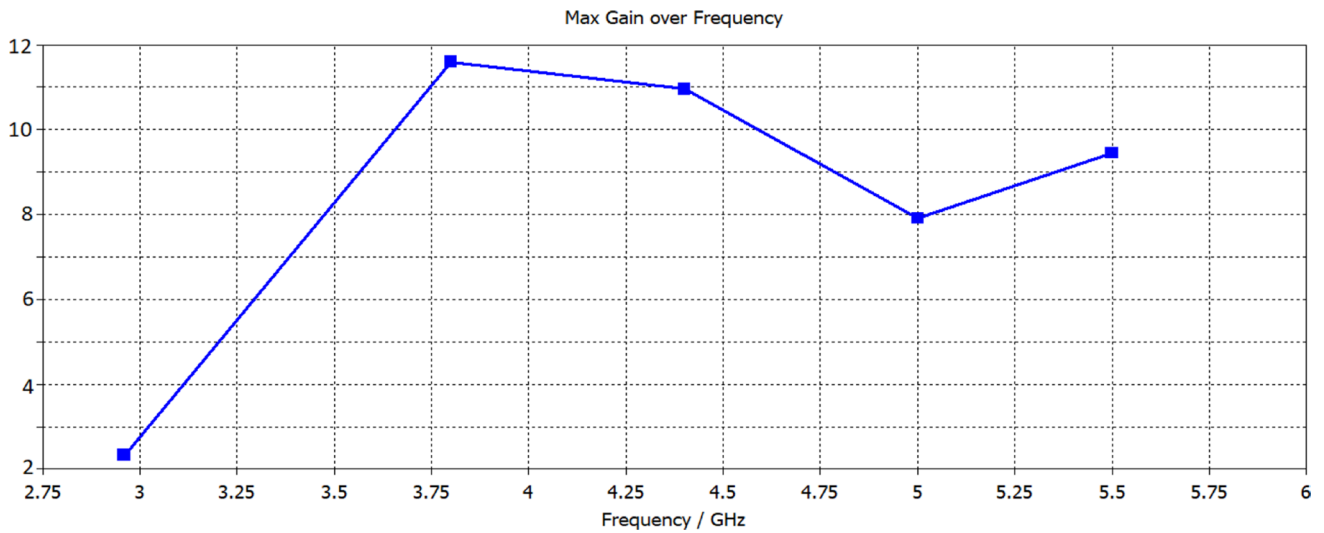


Fig. 8 Gain of proposed antenna-3.

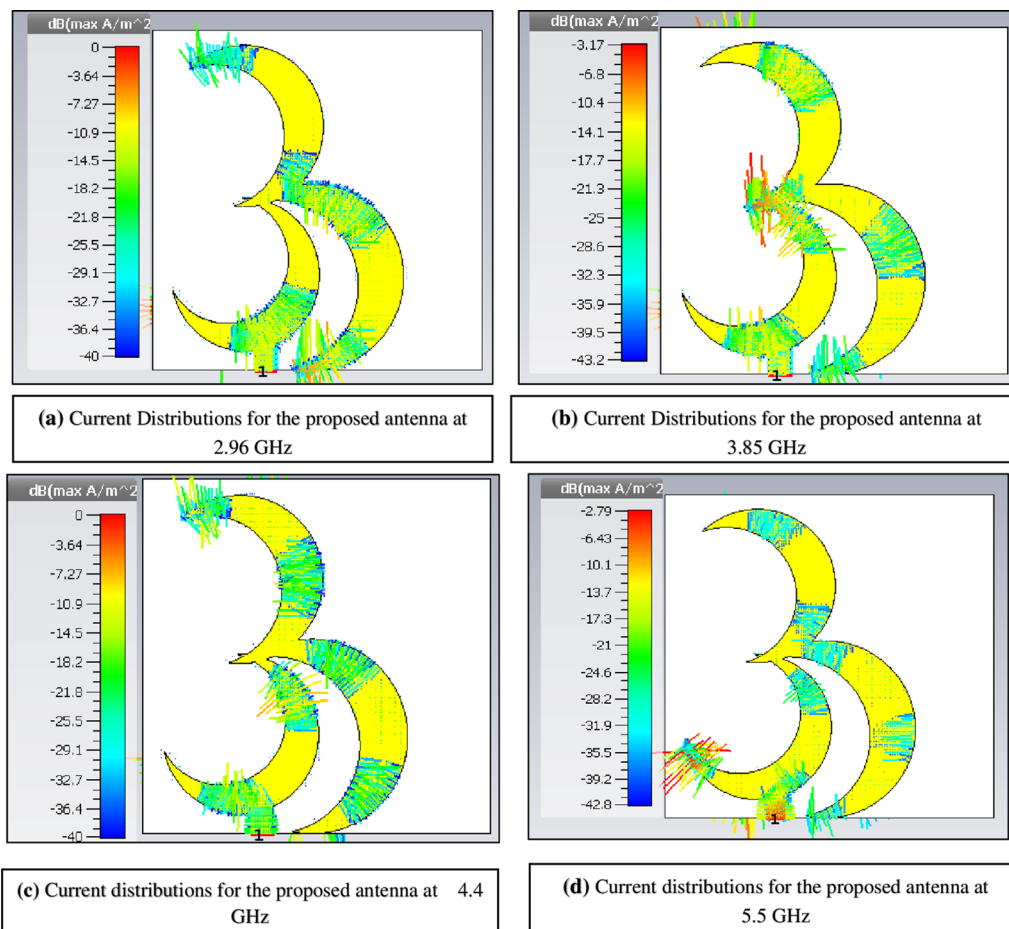


Fig. 9 Surface current density of the proposed antenna: (a) 2.96 GHz, (b) 3.80 GHz, (c) 4.4G Hz, and (d) 5.5 GHz (Color figure online).

## Radiation Pattern

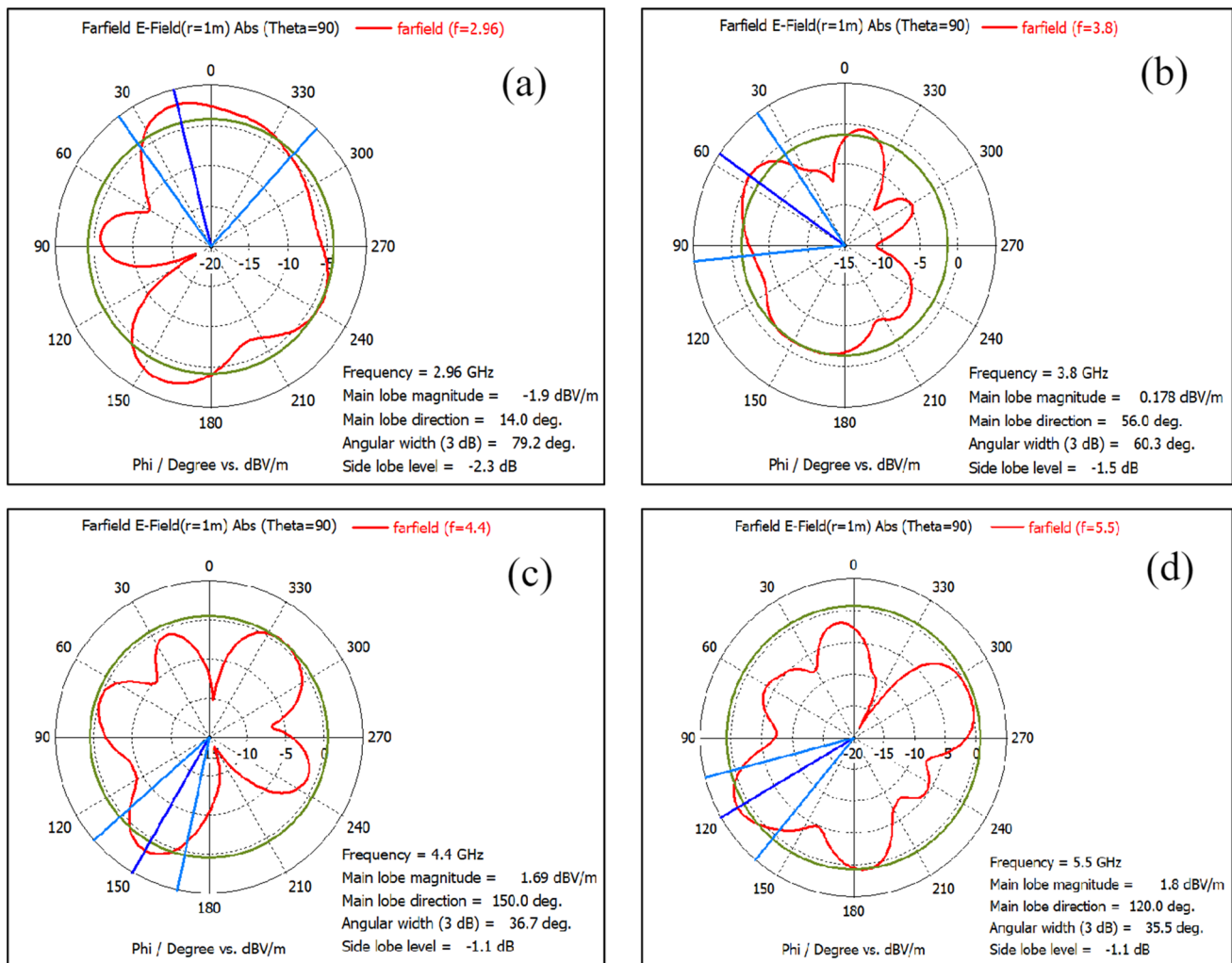
A graphic depiction of an antenna's radiation characteristics is the radiation pattern. The simulated E-plane ( $\phi = 0^\circ$ ) and H-plane ( $\phi = 90^\circ$ ) radiation patterns of the CPW-fed antenna-3, with four resonance frequencies of 2.96 GHz, 3.80 GHz, 4.4 GHz, and 5.5 GHz, are shown in Figs. 10a, b, c, and d, and 11a, b, c, and d, respectively. The proposed antenna-3 has an omnidirectional radiation pattern in the E-plane, while the radiation pattern in the H-plane has slightly departed from the omnidirectional radiation patterns due to the asymmetrical structure of the antenna for the S-band, IMT, C-band, and Wi-MAX bands.

Table VII shows the overall performance of the proposed antenna-3 in comparison with some other reported work in the literature.<sup>3,17-21</sup> Table VII shows a comparison of the proposed antenna with reported antennae in terms of various parameters, such as antenna dimensions, substrate material,

resonant frequency, and gain. The proposed antenna-3 has a better structure in comparison to these reported antennae<sup>17,20, 22</sup>. On the basis of the substrate material, the proposed antenna has better gain and other parameters, except for the triband resonant frequency.<sup>3</sup> The major aim of this research article was achieved by obtaining the quad-band operations with the maximum gain of 11.8 dBi.

## Conclusions

A CPW-fed Om-shaped antenna has been presented for the IBW of 2.93–2.99 GHz, 3.80–3.89 GHz, 4.35–4.48 GHz, and 5.44–5.55 GHz, respectively, for quad-band operations. The proposed antenna is expected to be a good candidate for S-band, IMT band, C-band, and Wi-Max-band applications at four resonant frequencies ( $f_r$ ) at  $f_{r1} = 2.96$  GHz,  $f_{r2} = 3.85$  GHz,  $f_{r3} = 4.40$  GHz and  $f_{r4} = 5.50$  GHz,



**Fig. 10** Radiation patterns for the E-field: (a) 2.96 GHz, (b) 3.80 GHz, (c) 4.4 GHz, and (d) 5.5 GHz (Color figure online).

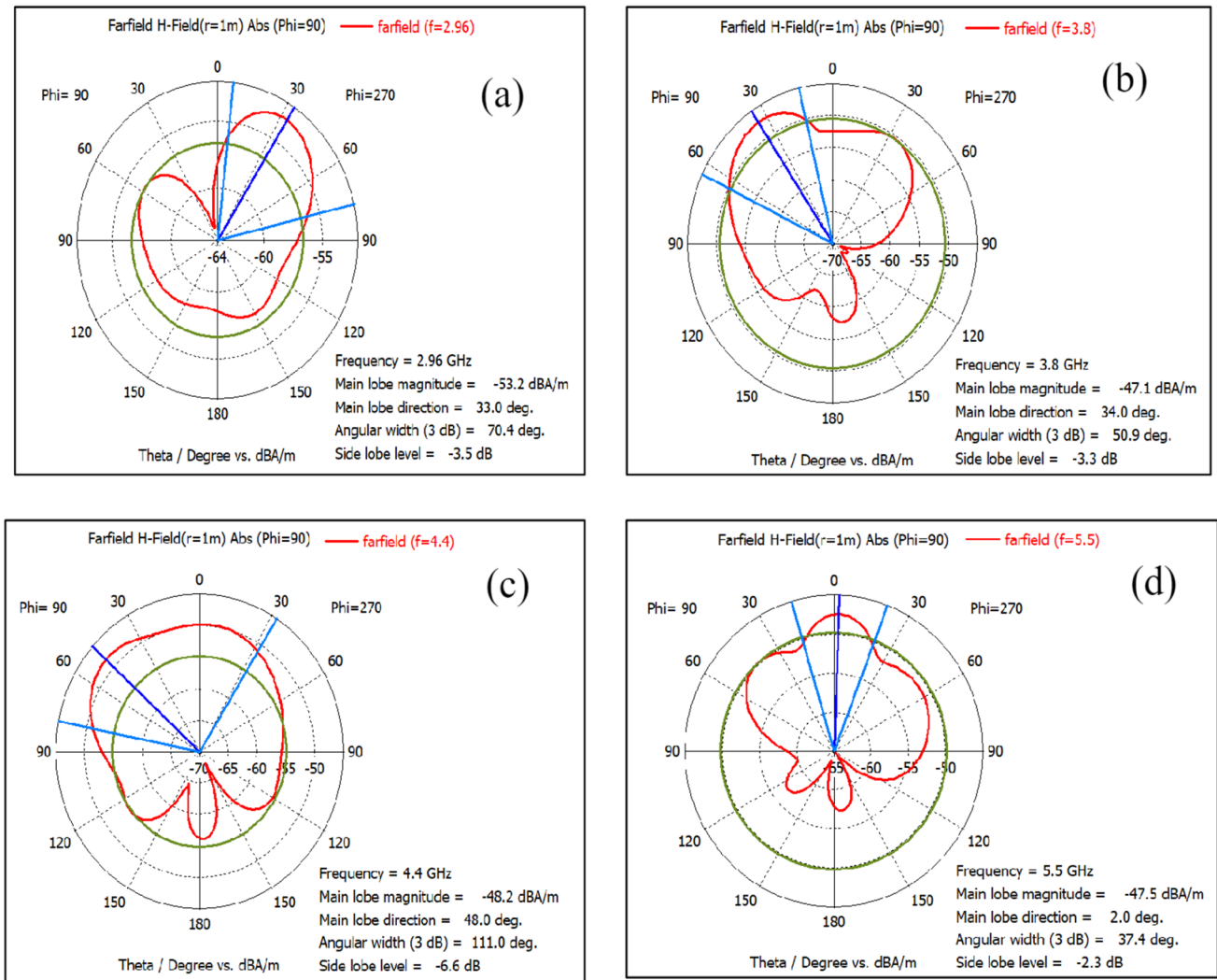


Fig. 11 Radiation patterns for the H-field: (a) 2.96 GHz, (b) 3.80 GHz, (c) 4.4 GHz, and (d) 5.5 GHz (Color figure online).

**Table VII** Performance comparison of the proposed antenna with other reported antennae

Ref.	Dimensions ( $L \times W \times h$ ) mm <sup>3</sup>	Substrate material	Number of bands	$f_{rN}$ in GHz ( $N = 1, 2, 3, 4$ )				Maximum gain (in dBi)
				$f_{r1}$	$f_{r2}$	$f_{r3}$	$f_{r4}$	
[3]	70 × 70 × 1.60	FR4	3	2.31	2.40	2.48	—	2.1
[17]	104 × 107 × 0.51	Rogers	2	2.45	5.42	—	—	5.0
[18]	70 × 70 × 0.80	FR4	2	1.74	3.76	—	—	5.1
[19]	64 × 62 × 2.0	Rogers	2	2.44	3.55	—	—	4.7
[20]	120 × 40 × 0.80	FR4	3	2.45	5.45	5.80	—	3.1
[22]	116 × 116 × 1.60	FR4	2	1.00	1.8	—	—	3.5
Proposed antenna	80 × 80 × 1.00	FR4	4	2.96	3.85	4.40	5.50	11.8

respectively. The effects of various design parameters have been thoroughly studied. The simulated results were found to be in good agreement with the experimental results. The antenna-3 has acceptable results for its radiation pattern,

current distribution characteristics, gain, VSWR, and  $|S_{11}|$  parameters, which are suitable and acceptable for wireless applications.

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**Conflict of interest** The authors declare that they have no conflict of interest regarding this study.

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