A Novel Dual Slot Circular Patch Antenna Design for Multi-band Applications

Amiya B. Sahoo, Guru P. Mishra, Biswa B. Mangaraj

Abstract – **A novel, dual slot, coaxial fed patch antenna which resonates in multiple frequency bands is proposed in this paper. The antenna which is circular in shape is originally designed to resonate at 2.4 GHz WLAN band. Different slots are made over the patch, and the slot dimensions, antenna dimensions, feed point location are optimized to design a multi-band antenna. The antenna design and optimization are carried out using ANSYS HFSS software. The proposed antenna resonates in seven frequency bands. The antenna is physically fabricated, and the simulated results are validated with measured results. With characteristics such as return loss, gain, radiation pattern, impedance matching make it suitable for WiMAX, Aeronautical Mobile, Radiolocation, Maritime radio navigation, Fixed-satellite, Earth Exploration Satellite, Radio Astronomy, Direct Broadcast Satellite (DBS), etc. applications.**

Keywords – **Circular Patch, Coaxial Feed, HFSS, Multi-band, Slot.**

I. Introduction

A significant development in wireless communication system necessitates low cost, small size, lightweight, multi-band antenna structures. Microstrip patch antennas with suitable slots are the appropriate candidates for satisfying these requirements. For GPS, WLAN, WiMAX, LTE, Ultra-Wide-Band (UWB) applications several slot antenna designs are available in the literature [1-19]. In [1], a tunable triple band antenna having 2 U-slots on the radiating patch is designed and physically realized. Three varactor diodes are inserted in the structure to tune the antenna in a particular frequency. It can operate over 2.07 to 2.6 GHz, 2.86 to 3.57 GHz, and 4.59 to 5.39 GHz bands. Small size, multi-band operation, and independent tuning make it suitable for practical applications. A conformal multi-band antenna for ingestible and implantable devices is proposed in [2]. The antenna resonates in the MICS (402–405 MHz), midfield band (1.45–1.6 GHz), and ISM (2.4–2.45 GHz) bands. To tune the antenna a T-shaped slot is made in the conducting ground plane and the antenna can be wrapped inside a 3-D capsule to exhibit its performance in various biomedical devices. In [3], a compact multi-band dual-antenna system is designed. The antenna can be printed on a circuit board of a smartphone system with an area of 60×15 mm^2. The antenna covers the GSM 850/900, DCS, GPS, UMTS, PCS, 2.4-GHz WLAN, and LTE 2300/2500 bands and makes it suitable for smartphone applications. A directive multi-band antenna with high gain is presented in [4]. The antenna design includes a rectangular slot on the ground plane structure and a complementary stub of the same size on the dielectric medium. The proposed antenna resonates in WLAN and WiMAX bands with an average gain of 9.1 dBi, radiation efficiency of 95% and front-to-back ratio better than 14 dB. In [5], a high gain wideband circular patch antenna is proposed which has low cross-polarization and monopole-like radiation pattern. It consists of a simple circular patch carved with an annular slot and the ground plane is also circular in shape. It provides 9.1 dBi of a peak gain and 36.5% of impedance bandwidth centred at 5.2 GHz. A compact rectangular patch antenna with defected ground structure and two F-shaped slots on the radiating patch is designed [6]. It resonates in 2.4 / 5.2 / 5.8 GHz WLAN and 2.5 / 3.5 / 5.5 GHz WiMAX band. The small size (19×25 mm^2) antenna is fabricated and there is a good degree of agreement between the simulated and fabricated antenna. An inverted-F shaped antenna for cell phone application is proposed in [7]. The proposed antenna is suitable for cell phones having a metal-rimmed boundary. The proposed antenna resonates in GSM 850/900/PCS/DCS/LTE 2300/2500/UMTS 2100 operating bands. The antenna is fabricated and its measured results show it is suitable for WWAN/LTE cell phone applications. In [8] a low cost, multi-band, inkjet-printed, monopole antenna is suggested and fabricated. The proposed antenna consists of 4 branch lines on the top radiating patch and 3 L-shaped slots on the bottom ground plane. The antenna can cover wireless/ mobile application bands such as GSM 1900, WLAN, PCS, and UMTS. A multimode multi-band SIW (Substrate-Integrated Waveguide) cavity-backed antenna with annular ring slot is proposed in [9]. The main advantage is that each of its working frequencies is independently tuned. This antenna is physically fabricated and measurements are done. The validity between simulated and measured results shows that the antenna can be used for practical applications. In [10], a microstrip coupling fed multi-band antenna for handheld devices is presented. The antenna consists of a U-shaped slot and a T-shaped slot within a small antenna area. The antenna can cover the GSM, PCS, DCS, LTE, UMTS and TDD-LTE frequency bands. Its radiation efficiency is acceptable for realistic applications. A dual-antenna for multi-band applications is presented in [11]. The antenna system consists of a folded fork-shaped ground branch and two symmetric antenna elements. It is operating at GSM 850/900, LTE 700/2300/2500/3400, PCS, DCS 2.4-GHz WLAN, UMTS, 5-GHz WLAN, and 3.5-GHz WiMAX application bands. In [12], a printed antenna with three rectangular slots on the ground plane for multi-band applications is proposed. Differential Evolution optimization algorithm is used to optimize the dimensions and positions of the rectangular slots.

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The antenna is physically designed and it can operate in GPS, Wi-Fi, and WiMAX bands. A multi-band slot antenna for GPS, WiMAX, WLAN applications is presented in [13]. The antenna contains a rectangular slot, a T-shaped feed, an inverted T-shaped stub, and two E-shaped stubs to generate the desired frequency. The measured result from the fabricated antenna reveals that the proposed antenna can be used for the above applications. In [14], a metamaterial-loaded multi-band antenna is presented. The proposed antenna initially designed for 5.2 GHz frequency band, with an inverted-L shaped slot and metamaterial loading the antenna covers 2.4/5.2/5.8 GHz WLAN and 2.5/3.5/5.5 GHz WiMAX band. The antenna is very compact (6.5×12.9×1 mm^3) with acceptable efficiency and gain. A microstrip line fed compact (27×30.5×1.6 mm^3) UWB antenna is proposed in [15]. The antenna covers the band (3.1-10.6 GHz) with rejection band notches for WiMAX, WLAN, and ITU. Instead of Defected Ground Structure (DGS), slots are made on the microstrip line for the desired frequency band and better gain. In [16], a small triple band monopole antenna for WLAN and WiMAX application is presented. The proposed antenna consists of two L-shaped slots and two U-shaped slots on the radiating patch. The antenna resonates in desired frequency bands with acceptable gain and omnidirectional radiation pattern. A folded slot and co-located multi-band antenna is presented in [17]. The antenna contains three slots arranged in a columnar structure. By properly adjusting the position and dimension of slots, the antenna resonates in PCS, DCS, UMTS, WiMAX bands with omnidirectional radiation pattern. In [18], an antenna with a U-shaped slot for 4G application is proposed. The antenna is excited with coupling feed. By adjusting the design parameters it resonates in LTE, DCS, PCS, UMTS bands with substantial gain and radiation efficiency. A simple coplanar waveguide (CPW) fed bow-tie monopole antenna is proposed for LTE, WLAN and WiMAX applications in [19]. The antenna is fabricated on a 0.8 mm-thick FR4 substrate and with size only 19×9 mm^2 and operates in 2.5/3.5/5.5 GHz frequency band.

From the above literature survey, it is observed that an antenna operating in multiple frequency bands with considerable gain and proper impedance matching is highly essential. Hence, a circular patch antenna with two slots for multi-band applications is proposed in this article. It is initially designed for 2.4 GHz WLAN application. Making two simple slots on the radiating patch, the proposed antenna resonates in multiple frequency bands with excellent return loss, gain, impedance matching characteristics. The initial design of a circular patch antenna [20] is obtained using equations from (1) to (4). Then the antenna is simulated, and its dimensions are being optimized using HFSS software. The optimized antenna resonates in WiMAX, Aeronautical Mobile, Radiolocation, Maritime Radio Navigation, Fixed-satellite, Earth Exploration Satellite, Radio Astronomy, Direct Broadcast Satellite (DBS), etc. application bands making it suitable for various wireless applications.

In this article, after the introduction in Section I, design procedure of newly proposed patch antenna is presented in Section II. In Section III radiation characteristics and multi-band performance of this antenna for different applications are discussed. Section IV provides a brief conclusion of this article.

II. Design Procedure for Proposed Antenna

A circular patch antenna is the most popular configuration next to the rectangular patch antenna. Therefore, many times researchers not only prefer the single element circular patch but also its array. In this article, an optimum design of the circular patch antenna with two slots is accomplished for multi-band applications.

A circular patch antenna consists of a thin metallic circular strip on the top of a substrate of height (h), which is fabricated above a ground plane. TM_{110} is the dominant mode supported by the circular microstrip antenna. For this mode, taking fringing effect into account the radius of the circular patch antenna is given by [20]:

$$R = \frac{F}{\{1+\frac{2h}{\pi\varepsilon_r F}[\ln(\frac{\pi F}{2h})+1.7726]\}^{1/2}} \quad (1)$$

where:

$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}}, \quad (2)$$

R = Radius of the circular patch in cm,

h = Height of the substrate in cm,

ε_r = Dielectric constant of the substrate,

f_r = Resonant frequency of the patch in Hz.

Initially, the substrate material is chosen which is commercially available, i.e., the FR4 epoxy substrate having height 1.6 mm, dielectric constant 4.4, and loss tangent 0.02. Subsequently, the radius for which the patch resonates at 2.4 GHz WLAN frequency band is found out using Eqs. (1) and (2). The substrate and ground plane dimensions (length (L), width (W)) are found out using equations:

$$L = 2\times R + 12\times h \quad (3)$$

$$W = 2\times R + 12\times h \quad (4)$$

The initial design of simple circular patch is as shown below.

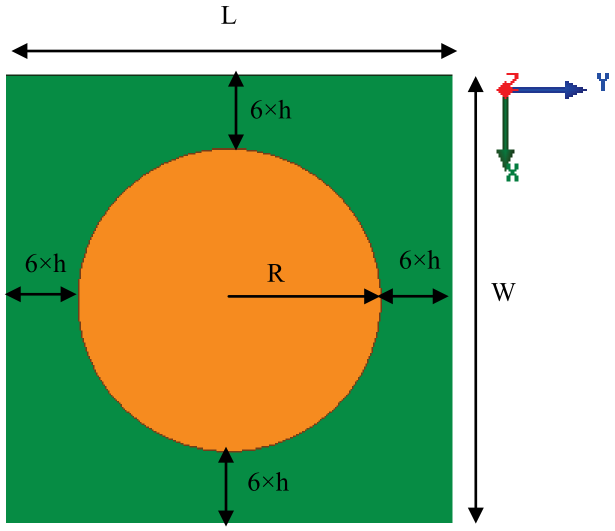


Fig. 1. Top view: Circular patch along with the substrate

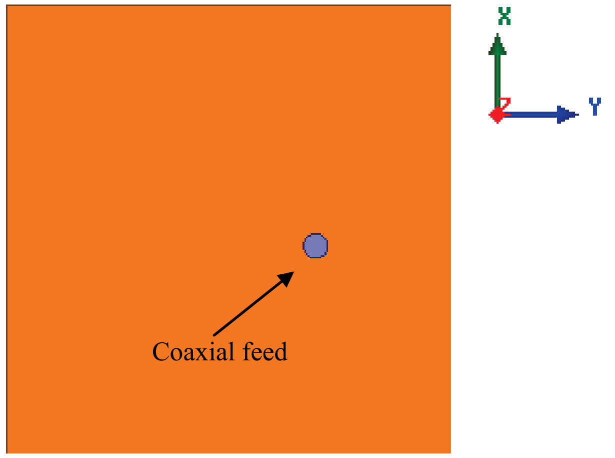


Fig. 2. Bottom view: Ground plane with the coaxial feed

Several feeding techniques are available such as coaxial feed, microstrip inset feed, proximity coupled feed [21], etc. to excite the microstrip patch. Here, the feed is applied through a coaxial line having the outer radius 1.6 mm and inner radius 0.7 mm that is the dimension of an SMA connector practically available. The feed point location (ρ_0) on the patch can be found out using Eq. 5 to match a 50 Ohm SMA connector

$$R_{in} = \frac{1}{G_t} \frac{J_1^2(k\rho_0)}{J_1^2(kR_e)}, \tag{5}$$

where: R_{in} = Input impedance (50 Ohm), G_t = Total conductance of the patch due to radiation, $J_1(x)$ = Bessel function of the first kind of order 1, k = Phase constant, ρ_0 = Radial distance of feed point from the center of the patch, and R_e = Effective radius of the circular patch in cm.

The circular patch antenna is completely designed using HFSS software. Here, FR4 epoxy is the substrate as discussed earlier. Subsequently, the dimensions of the patch are found out using equations from (1) to (4). The co-axial feed location from the center of patch along y-direction for 50 Ohm impedance matching, is found out using equation (5). The feed point distance (ρ_0) from the centre is found to be 11.45 mm. The detailed dimension of the patch antenna is shown in Table 1, and the performance of simple circular patch antenna resonating at 2.4 GHz is as shown in Table 2. The return loss characteristic of the patch is as shown in Fig. 3.

TABLE 1
OPTIMAL DIMENSION OF SIMPLE CIRCULAR PATCH ANTENNA

Dimension	**Value (mm)**
Length of Substrate / Ground Plane (L)	59.22
Width of Substrate / Ground Plane (W)	59.22
Radius of the patch (R)	20.01
Height of substrate (h)	1.6
Outer Radius of Coaxial feed (r_1)	1.6
Inner Radius of Coaxial feed (r_2)	0.7
Feed point distance from center (ρ_0)	11.45

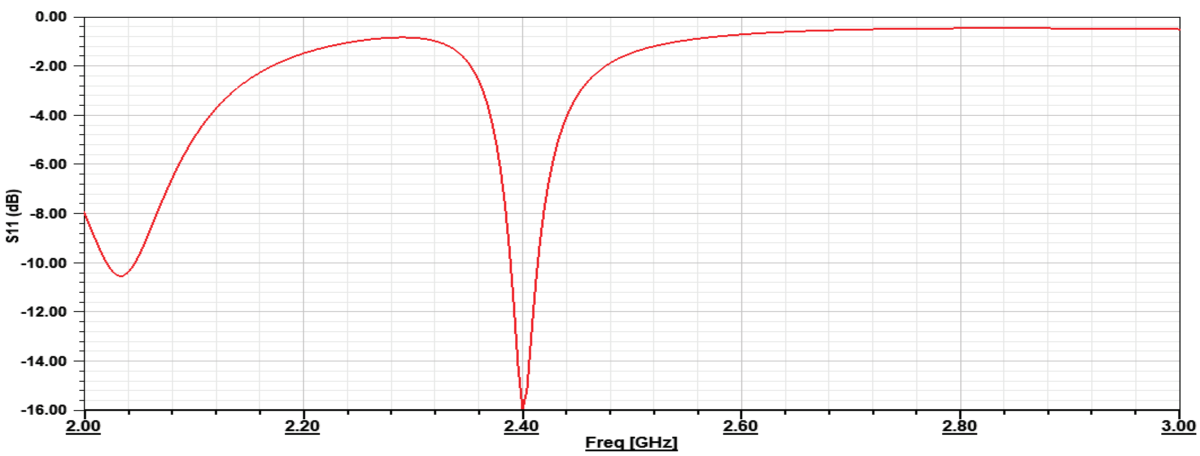


Fig. 3. Return loss characteristics of the simple circular patch

TABLE 2
PERFORMANCE OF SIMPLE CIRCULAR PATCH ANTENNA

Sl. No	Resonant Frequency (GHz)	Return Loss (dB)	Gain (dB)	
			E-Plane	H-Plane
1	2.40	-16	4.51	4.51

To make a multi-band antenna the current distribution in the patch need to be altered. So two slots i.e. an arc slot and a pentagonal slot are carved out of the patch. The design parameters such as the radius of the patch, starting point of the arc, pentagonal slot, slot angles, feed point location, and width of the slots are being optimized using parametric optimization in HFSS software. The radius of the optimized patch is found to be 22.3 mm. The starting point, arc angle, and width are found to be (-4.5, 20), 295 degrees and 0.5 mm for the arc slot and (-3.5, 18), 290 degrees and 0.5 mm for the pentagonal slot respectively. The optimum coordinate of the feed point is found to be (-2, 11.45). The top and bottom view of the circular patch with both the slots are shown in Figs. 4 and 5, respectively. The return loss characteristics and the performance parameters of this antenna are as shown in Fig. 6 and Table 3, respectively.

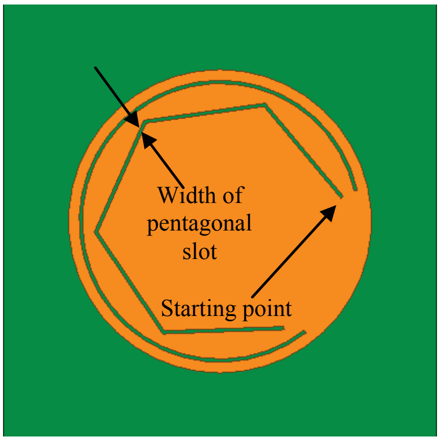


Fig. 4. Top view: Circular patch along with both arc and pentagonal slot

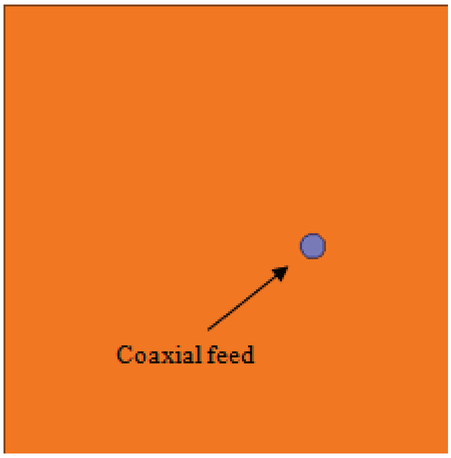


Fig. 5. Bottom view: Circular patch along with both arc and pentagonal slot

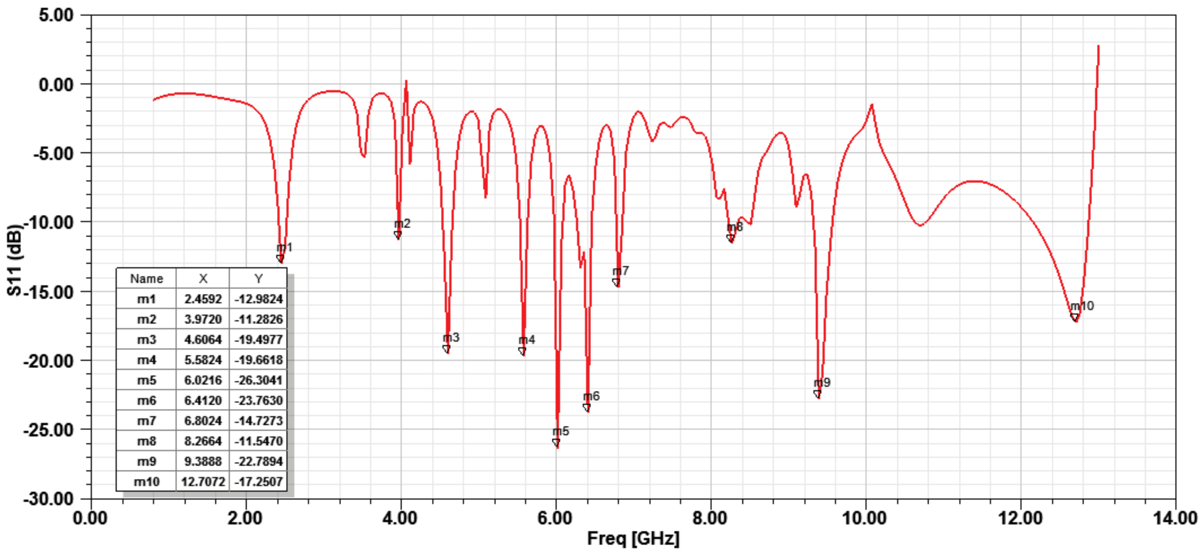


Fig. 6. Return loss versus frequency plot for the circular patch with both arc and pentagonal slot

TABLE 3

PERFORMANCE OF CIRCULAR PATCH ANTENNA WITH BOTH ARC AND PENTAGONAL SLOT

Sl. No	Resonant Frequency (GHz)	S_{11} (dB)	Gain (dB)		Impedance	
			E-Plane	H-Plane	Real	Imaginary
1	2.4592	-12.9824	4.92	4.69	35.17593	12.37053
2	3.972	-11.2826	5.58	7.31	46.20557	26.99471
3	4.6064	-19.4977	6.26	0.23	51.26765	-10.7148
4	5.5824	-19.6618	1.64	1.37	48.72671	10.24094
5	6.0216	-26.3041	-6.36	-5.22	53.18729	-3.84876
6	6.412	-23.763	-1.46	0.00	44.11031	1.599841
7	6.8024	-14.7273	10.65	10.72	56.00674	18.82106
8	8.2664	-11.547	5.65	3.72	35.97863	-18.582
9	9.3888	-22.7894	1.86	5.04	56.17889	-4.60908
10	12.7072	-17.2507	15.42	19.05	52.21615	13.98386

From Table 3, it is observed that the antenna resonates in ten different bands, but when its gain is concerned, the antenna has negative gain in two of the resonant frequencies. Again in two of the cases, the real part is not close to 50 Ohm (< 40 Ohm), and in another two cases, the imaginary part of the impedance is not close to zero Ohm (> 14 Ohm). All these cases are highlighted in red colour. So there are four cases where the antenna is operable highlighted in yellow colour.

Thus, to match the impedance, the feed point location is varied along x-direction and y-direction with the help of parametric optimization in HFSS software. With the constraint that the feed point should not touch the slots, the feed point is varied, and results are exported to (.txt) format. Later, a MATLAB program is written to read these files and find out in which cases the average of real parts of the impedance for all multi-band frequencies is close to 50 Ohm and the average of the magnitude of imaginary parts is close to 0 (Zero) Ohm.

There are 18 cases, where the average of the real part lies between 47-51 Ohm and average of the imaginary part less than 12 Ohm. From these 18 cases, 6 cases are eliminated where the real and imaginary parts differ much from 50 Ohm and 0 Ohm respectively. Then for remaining 12 cases, the gain of the antenna is found out at different resonant frequencies, and effective operable frequencies are found out. The best one obtained has an optimum feed point at (-9, 11.45). Its performance parameters are as shown in Table 4. Out of 10 resonant frequencies, one having negative gain and two frequencies have impedance mismatching. Therefore, seven remaining operable resonant frequencies have positive gain, the average real impedance 49.31 Ohm and the average imaginary impedance 8.30 Ohm. Hence, this antenna is selected for physical fabrication.

TABLE 4

PERFORMANCE OF CIRCULAR PATCH ANTENNA WITH BOTH ARC AND PENTAGONAL SLOT

Sl. No	Frequency Band (GHz)	Resonant Frequency (GHz)	S_{11} (dB)	-10 dB Bandwidth (MHz)	% of BW	Gain (dB)		Impedance	
						E-Plane	H-Plane	Real	Imaginary
1	2.42-2.54	2.4592	-13.3283	120	4.87	3.13	3.11	76.56	-6.5
2	5.57-5.70	5.6312	-21.1497	130	2.3	1.7	1.59	50.07	-8.8
3	6.48-6.62	6.5584	-21.6231	140	2.13	1.97	1.81	52.13	8.22
4	7.10-7.24	7.1928	-15.8285	140	1.94	3.17	5.32	38	9.37
5	7.63-7.80	7.7296	-16.3628	170	2.19	-2.2	-2.48	41	-10.78
6	8.11-8.23	8.1688	-21.408	120	1.46	4.72	3.44	54	-7.57
7	8.66-8.94	8.8032	-19.4497	280	3.18	1.63	4.9	45	-9.08
8	9.03-9.15	9.096	-11.6287	120	1.31	5.07	10.97	40.66	22.65
9	9.24-9.80	9.3888	-24.6464	560	5.96	4.86	7.01	54	4.12
10	10.57-11.40	10.8528	-19.2177	830	7.64	3.24	4.23	52	10.98

III. RESULTS AND DISCUSSION

A. Simulation Result

Initially, a simple circular patch antenna is designed at 2.4 GHz frequency. The novelty of the patch is achieved when two different slots are etched on the same circular patch. With the introduction of two different slots on the patch and optimizing the antenna design parameters such as the radius of the patch, starting point of the arc, pentagonal slot, slot angles, feed point location and width of the slots, modified patch antenna resonates at 7 different bands effectively. There are several other parameters associated with a patch, which define various performance measures of the same, e.g., some of these parameters are return loss, gain, impedance, VSWR, etc. Considering the return loss as the first parameter, the performance of the modified patch is evaluated at all 7 frequency bands. This return loss gives an idea about the impedance matching between the microstrip patch and the feed line. It not only depends on the dimensions of the metallic patch, substrate, ground plane, but also on the position of the feed and feed dimensions. The simulated frequency versus the return loss graph of the optimized antenna is as shown in Fig. 7. It is observed from the above graph that the optimized antenna has return loss below -10 dB at 10 different frequency bands, but as discussed earlier we will consider only 7 effective resonant frequencies.

The return loss for all these 7 resonant frequencies is less than -15 dB as shown in Table 5. The bandwidth for all these bands is more than 120 MHz. In the frequency band of 10.57 to 11.40 GHz, the antenna has a wide band of 830 MHz. It is observed that VSWR is less than 1.4 for all the 7 frequency bands. The maximum value of VSWR is 1.38 only in one case as shown in the third serial number of Table 5. These low VSWR values suggest that most of the input power is transferred to the antenna at the desired frequencies and less power is reflected back. The antenna has a substantial gain in all 7 frequency bands. The E-plane gain has a minimum gain of 1.63 and a maximum of 4.86 dB. Similarly, for H-plane the minimum and maximum gains are 1.59 and 7.01 dB, respectively. The average of magnitudes of the real and the imaginary impedances are found to be 49.31 Ohm and 8.30 Ohm, respectively. Since the real parts of impedance for resonant frequencies are close to 50 Ohm, and imaginary parts are small, the impedance matching is achieved to a greater extent. As per the International Telecommunication Union (ITU) specifications, the application band of the proposed antenna is mentioned in the last column of Table 5. Thus, the antenna is suitable for communication in the WiMAX, Aeronautical Mobile, Radiolocation, Maritime Radio Navigation, Fixed-satellite, Earth Exploration Satellite, Radio Astronomy, Direct Broadcast Satellite (DBS), etc. applications.

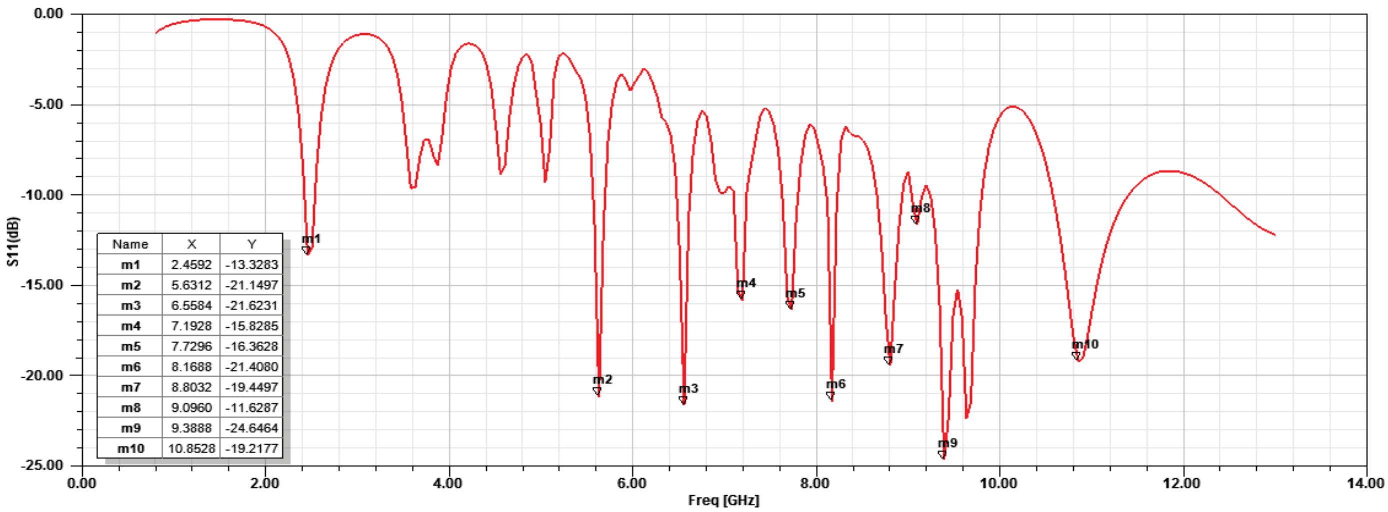
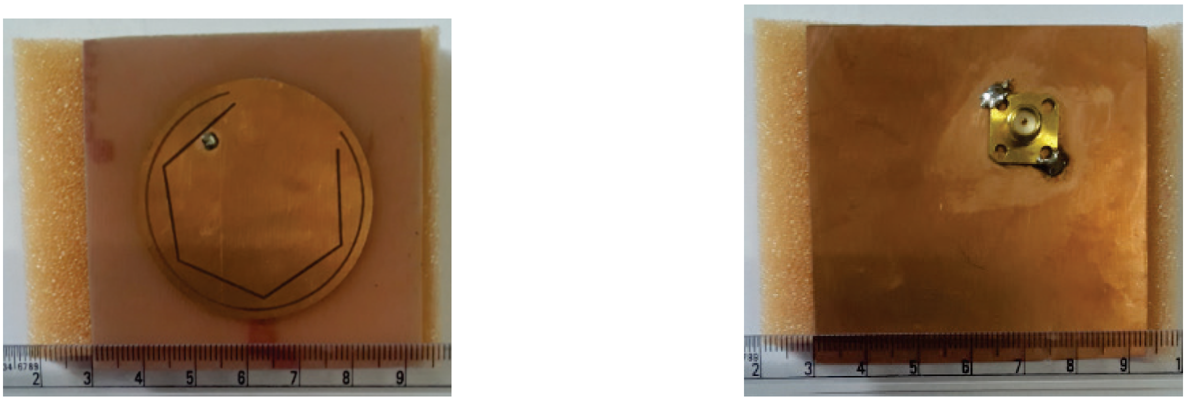


Fig. 7. Return loss characteristics of the optimized patch antenna with dual slot and impedance matching

TABLE 5
PERFORMANCE PARAMETERS OF OPTIMIZED DUAL SLOT CIRCULAR PATCH ANTENNA FOR MULTIBAND APPLICATIONS

Sl. No	Freq. Band (GHz)	Resonant Frequency (GHz)	S_{11} (dB)	-10 dB Band-width (MHz)	% of BW	VSWR	Gain (dB)		Impedance		Applications
							E-Plane	H-Plane	Real	Img	
1	5.57-5.70	5.63	-21.14	130	2.3	1.19	1.7	1.59	50.07	-8.8	WiMAX, Aaeronautical Mobile, Radiolocation, Maritime Radio Navigation
2	6.48-6.62	6.55	-21.62	140	2.13	1.18	1.97	1.81	52.13	8.22	Aeronautical Mobile, Fixed Satellite
3	7.10-7.24	7.19	-15.82	140	1.94	1.38	3.17	5.32	38	9.37	Amateur Radio, Broadcasting, Space Research
4	8.11-8.23	8.16	-21.40	120	1.46	1.18	4.72	3.44	54	-7.57	Maritime Mobile, Fixed Satellite, Earth Exploration Satellite
5	8.66-8.94	8.80	-19.44	280	3.18	1.23	1.63	4.9	45	-9.08	Maritime Mobile, Radiolocation, Aeronautical Radio Navigation, Maritime Radio Navigation
6	9.24-9.80	9.38	-24.64	560	5.96	1.12	4.86	7.01	54	4.12	Fixed Mobile, Broadcasting, Radiolocation, Maritime Radio Navigation, Earth Exploration Satellite
7	10.57-11.40	10.85	-19.21	830	7.64	1.24	3.24	4.23	52	10.98	Aeronautical Mobile, Radiolocation Radio Astronomy Fixed-Satellite, DBS Europe



(a) Top view (b) Bottom view

Fig. 8. Photograph of the proposed circular antenna

B. Antenna Fabrication and Verification

After the optimized dual slot circular patch antenna is obtained with good performance parameters, it is physically fabricated. The photograph of the fabricated antenna is shown in Fig. 8. The testing and measurement of this antenna are conducted in an anechoic chamber as shown in Fig. 9. The comparison of simulated return loss and return loss of fabricated antenna at different resonant frequencies is shown in Fig. 10.

It is observed that the simulated result and the measured results match with each other. The frequencies where the return loss is below -10 dB during measurement are found out. The E-plane and H-plane gains are measured at these frequencies. The measured and simulated patterns at some of these frequencies are shown in Fig. 11. It is observed that the measured and the simulated gains are quite close to each other.

(a) Front view (b) Back view

Fig. 9. Measurement of this antenna is conducted in an anechoic chamber

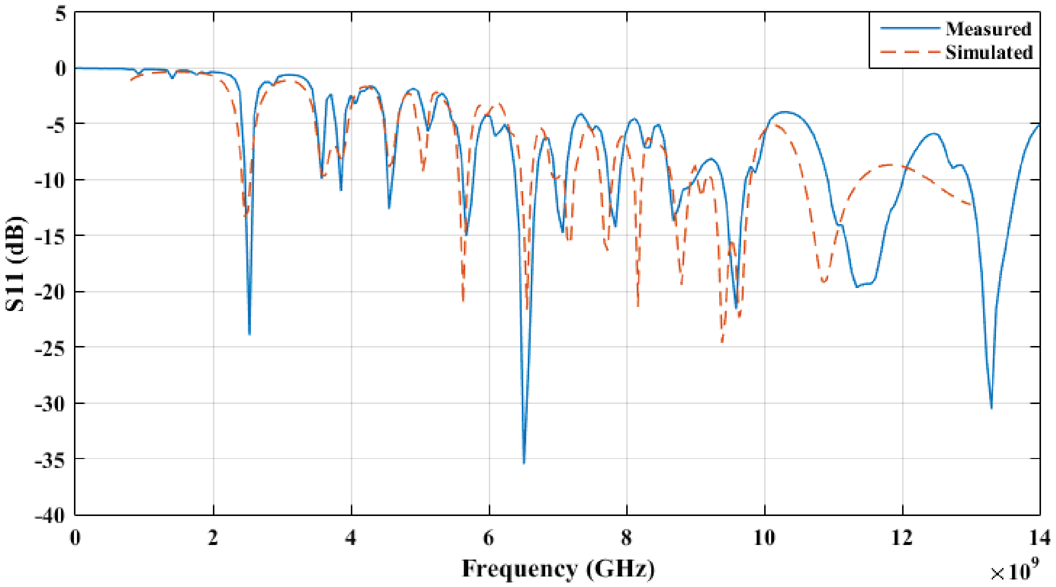


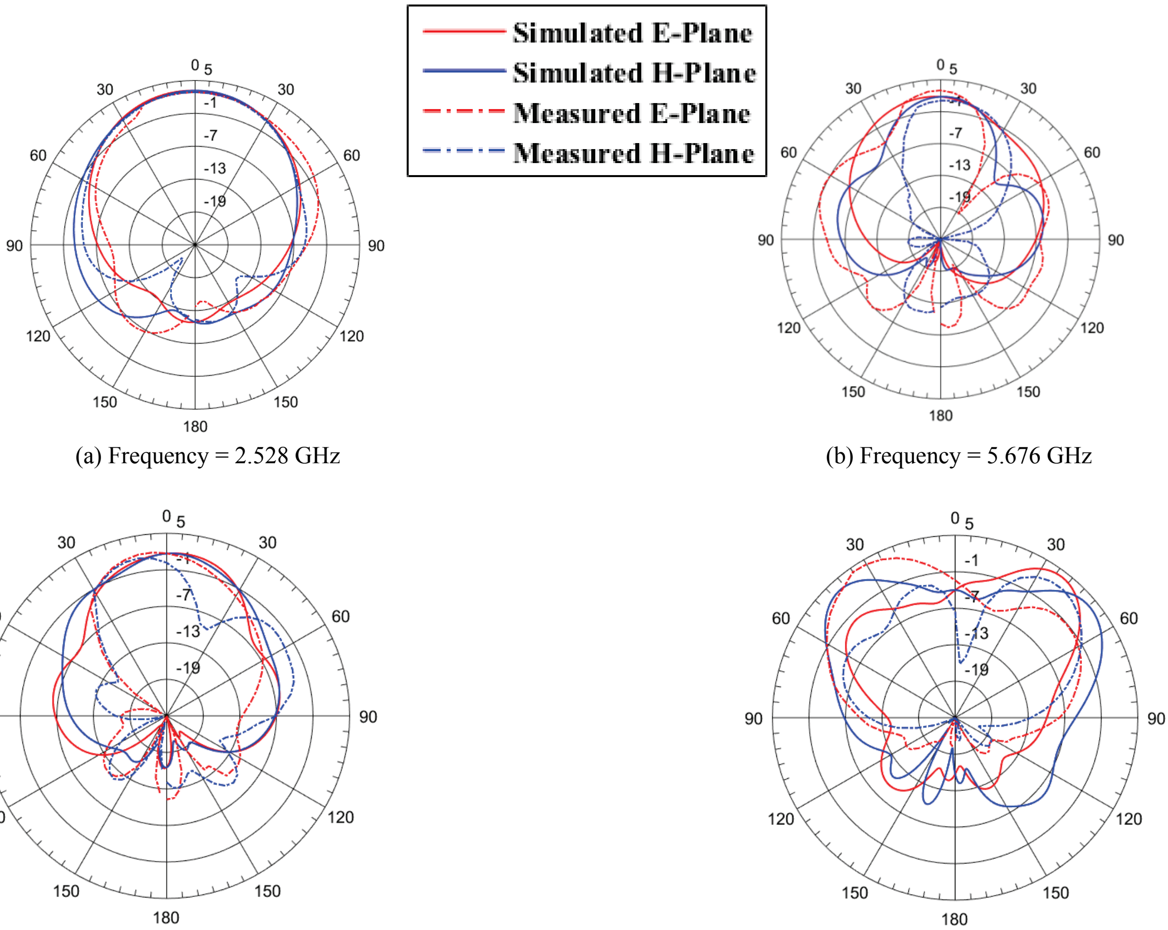
Fig. 10. Measured and simulated S_{11} parameter of the proposed antenna

According to the presented results and the discussion related to the return loss, bandwidth, impedance matching, gain, VSWR, and radiation characteristics of the antenna, it is observed that the proposed multi-band antenna can be a suitable candidate for various wireless applications.

IV. Conclusion

A novel coaxial line fed circular patch antenna with two different types of open slots is proposed for multi-band applications. Initially, a simple circular patch antenna is designed for 2.4 GHz WLAN band. Introducing a circular open ring slot and a pentagonal open ring slot and optimizing the antenna dimensions, the proposed antenna resonates at WiMAX, Aeronautical Mobile, Radiolocation, Maritime Radio Navigation, Fixed-satellite, Earth Exploration Satellite, Radio Astronomy, Direct Broadcast Satellite (DBS), etc. frequency bands.

It also shows good radiation characteristics and provides sufficient gain across these bands. The proposed antenna is physically realized, and its characteristics are validated with simulation result. The simple structure, compact size, multi-band frequency, good radiation characteristics, proper impedance matching, and excellent gain make this patch antenna suitable for the above practical wireless communication systems. Further, keeping antenna model constant but altering the antenna and slot dimensions, the antenna can be used for other wireless applications and implementation of Defected Ground Structure (DGS), can give a still better performance.



(a) Frequency = 2.528 GHz (b) Frequency = 5.676 GHz

(c) Frequency = 6.515 GHz (d) Frequency = 9.593 GHz

Fig. 11. Measured and simulated gain at different resonant frequencies obtained during measurement

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