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A Low Profile High Gain Ultra Lightweight Circularly Polarized Annular Ring Slot Antenna for Airborne and Airship Applications

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ABSTRACT In this paper a low profile circularly polarized annular ring slot antenna (CPARSA) with high gain is presented. An inverted U-shaped meandered slot is cut at the inner patch of annular ring to obtain the circularly polarized (CP) radiation. This annular slot loaded ground plane on a substrate thickness of 0.5 mm results in a very low profile ($0.009\lambda_0$) antenna in term of free space wavelength at its center operating frequency. The largest side lengths of octagonal shaped antenna are $0.89\lambda_0 \times 0.89\lambda_0$ according to its center frequency. Measured impedance bandwidth of 23.54% from 5.4 GHz – 7.0 GHz (for $|S_{11}| \leq -10$ dB) and AR bandwidth (AR<3dB) of 5.15% from 5.67 GHz – 5.97 GHz are achieved by the antenna. Meanwhile, stable radiation pattern is observed throughout the entire bandwidth with peak gain of 7.6dBi at the center frequency of 5.8 GHz. A defected ground plane is employed in the design which results in reduction of surface waves leading towards higher gain of antenna. The proposed antenna operating at 5.8 GHz band is fabricated on low cost substrate with standard printed circuit board (PCB) process. The proposed design provides favorable characteristics for various lightweight applications including miniaturized drones and airborne applications. To validate the prototype, measured results are compared with simulation outcomes and good agreement is obtained.

INDEX TERMS CPARSA, circular polarization, microstrip-fed slot, wideband, slot antenna, airborne.

I. INTRODUCTION

Circularly polarized (CP) and high gain antennas with their favorable characteristics such as low profile, less massy and planner structure that offer ease in integration with monolithic IC's are demanded recently. CP antennas are also favorable in situations where polarization mismatch may degrade the performance of communication system [1], [2]. Advantages of circular polarization over linear polarization are generally because of high efficiency in mobility, alleviate in multi-path distortion and polarization mismatch losses [3]–[5]. Moreover, CP antennas have influence to overcome multipath fading and mitigate Farady rotation effects [6] that can help to reduce the loss. These characteristics make them favorable candidate for wireless power transfer applications.

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Circular polarization requires generation of two equal but orthogonal radiating modes. This can be achieved either by employing multiple feeds or a single feed. Several CPARSA designs producing circular polarization have been reported in literature [5]–[13]. A circularly polarized antenna based on fractal geometry architect was reported for UHF RFID applications. The measured gain of the antenna is 1.35 dBi [5]. Another design based on metallic ground reflector was presented in [6] for dedicated short range communication (DSRC) applications. Although the antenna retains peak gain at 4.95 dBic but its 6.926 mm dense profile limits the use of antenna for various lightweight applications. Another design reported in [7] embeds an elliptical slot at the patch center with a coaxial probe feed mechanism and provides 7.75% impedance bandwidth and AR below 1dB at 5.8 GHz. It provides highest gain of 4.8 dBic and is meant for DSRC but a relatively thicker substrate of 1.55mm was employed in this design. A 2×2 CP substrate integrated waveguide (SIW) slot array antenna with a single probe feed was presented in [8]. The reported antenna provides 3.1% impedance bandwidth and 3.6% ARBW with measured peak gain of 7.1 dBi at highest frequency. The design reported in [9] utilizes a co-centered elliptical slot in circular disc with coplanar annular sectors patches to enhance the aperture efficiency. Although antenna achieved a high gain of 7.16 dB but with thick substrate of 1.6 mm that is even thicker than the peer structure reported in [7]. In another ARSA design [10], CP radiation was achieved by loading a lightening-shaped slot in the annular-ring and fed by microstrip-line (MSL) resulting in 16.9% CP bandwidth with 3.1dBic gain. A wideband CP antenna with moderate gain of 3.94 dBi for UAV applications was proposed in [11]. Though the antenna finds number of applications in wireless communication however the larger ground size and relatively thicker substrate put constraints on its use in UAVs applications. Another antenna for UAV applications was presented in [12] but associated drawbacks of larger in size and profile. In [13] a circular disc shaped multilayer and non-planner antenna for avionics applications was presented. In the proposed structure, the inductive loading of radial stub and shortening pins widened the impedance bandwidth to 17% with the realized gain less than 4 dBi but at the cost of significant increase in antenna volume. Another CP microstrip patch antenna for smaller satellite application was presented in [14]. This antenna provides higher gain of 7.29 dBi with larger ground plane but a very thick substrate of 20 mm is used which results in a heavier structure of 25 grams. Another circularly polarized antenna with vertical shorted plates is proposed for GNSSs applications [15]. It should be kept in mind that the antenna is achieving wide bandwidth and circular polarization due to vertical plates at the cost of multilayer structure. A circularly polarized antenna for satellite ground station is proposed in [16]. Although antenna is achieving low profile and compact size but applicable to limited use due to very narrow impedance and axial ratio bandwidths. Two antennas with dielectric resonating structure are reported in [17], [18]. It is notable that these antennas are compact in size according to their center frequency but at the same time lacking in bandwidth and gain value as compared to proposed design. Furthermore, these antennas are bulky in structure due to dielectric resonating material. Recently, several antennas for 5.8 GHz ISM band and WBAN (wireless body area network) applications have been reported in open literature [19]–[24]. Some of these antennas are noteworthy to satisfy the impedance bandwidth requirements but their use is limited in lightweight airborne applications due to increased thickness and weight of the employed substrate. Moreover the thicker substrate antennas may not be considered as a significant preference for wearable and WBAN applications.

In this article, a single-fed circularly polarized annular ring slot antenna with low profile and extremely lightweight structure suitable for airborne and airship applications is proposed. The proposed antenna is very thin, yet it exhibits high gain and circular polarization in a reasonable range of frequencies making it suitable for several 5.8 GHz ISM band applications. The design is very simple and is based on a ring slot structure where an inverted U-shaped meandered section, which serves as an asymmetry, is introduced in the ring slot to generate circularly polarized radiation. An impedance bandwidth of 23.54% and ARBW of 5.15% has been achieved with a smooth gain of 7.6 dBi within the entire bandwidth. The thickness of the antenna is $0.009\lambda_0$, where λ_0 is the free space wavelength at the lowest frequency, while the antenna weighs only 2.08 grams. With its thin structure and lightweight characteristics the proposed antenna is a potential candidate for modern applications including lightweight drones and UAV's wings compatible structures. Moreover, the antenna supports WLAN (5.725-5.825 GHz), WBAN (5.8 GHz), ISM band (5.8 GHz) and 5.65 – 6.0GHz (specified by IEEE 802. 11a) bands wireless communication systems.

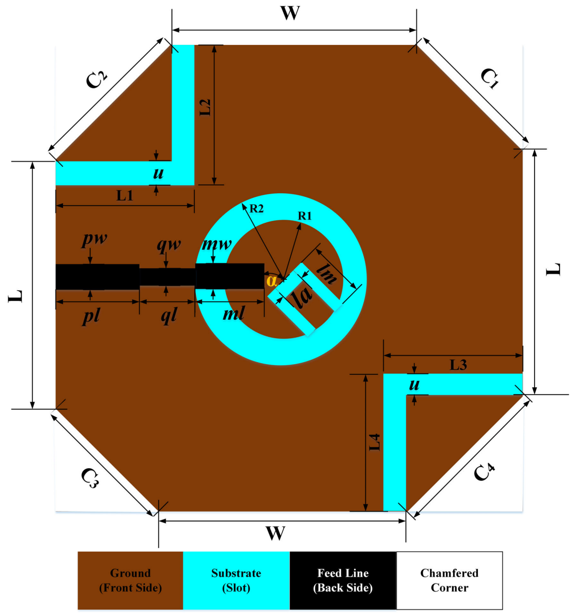


FIGURE 1. Proposed design.

Section II is mainly on the antenna geometry and operating principle of the antenna. Antenna synthesis steps are described in section III. The influence of antenna parameters on antenna performance is described in section IV, while section V consists of antenna measurement results. Finally, section VI concludes the paper.

II. ANTENNA DESIGN AND OPERATING PRINCIPLE

Fig. 1 (a) depicts the configuration of proposed annular ring slot antenna. A ground plane was placed on a 0.5mm thin Teflon substrate that has a relative permittivity of 2.65 whereas the loss tangent is 0.001. The radiation element consists of an annular ring slot with inner and outer radii $R_1 = 6.6$ mm and $R_2 = 7.7$ mm respectively. The slot is etched in the ground plane which is placed on the top of the substrate. The antenna is fed by a transmission line of dimension $ml \times mw$ and a quarter wave transformer with dimensions $ql \times qw$ to maintain proper impedance matching between antenna and feed point. The impedance transformer is used to match the low impedance feed line and high impedance ring slot at the feed point. The microstrip line was extended beyond the inner slot in order to realize an open circuit. An inverted U-shaped slot section was etched on inner slot (radius R_1) with an anticlockwise orientation at an angle $\alpha = 45^o$ from x-axis. In this way the 50 ohm microstrip feed line was 135^o away from the rectangular slot section. The dimensions of rectangular slot are lm=6 mm and wm=3mm. Due to employment of light weight substrate, low profile and small area of the antenna, the overall weight of the antenna as verified from the fabricated prototype turns out to be much suitable for UAV applications.

Basic equations for the design of annular ring slot antenna are available in the open literature [25]. For appropriate selection of annular slot radii, equation (1) has been used to authenticate that the fundamental resonant mode occurs at a frequency whose wavelength in a ring slot approximately corresponds to the mean circumference of ring slot. That is,

$$f_0 = \frac{c}{\pi\,(R_1 + R_2)} \times \sqrt{\frac{\varepsilon_r + 1}{2\varepsilon_r}} \tag{1}$$

where f_0 is the fundamental frequency of conventional ring slot antenna, c represents the speed of light, ε_r signifies effective dielectric constant, $\pi(R_1+R_2)$ is the mean circumference of annular ring slot. The slot radii were initially calculated from the above equation and were optimized by simulating the antenna in commercially available software HFSS v. 15.0. The antenna dimension details are provided in Table 1.

TABLE 1. Detailed dimensions of the proposed antenna.

Symbol	Value	Symbol	Value
L	18.1	R_1	6.6
W	19.1	R_2	7.7
ml	7.7	h	0.5
mw	1.9	*a*	45^0
ql	7.5	*pl*	7.9
qw	1	*pw*	2.2
lm	6	*la*	1.5
L1,L3	16	L2,L4	16.1
C1,C3	13.1	C2,C4	14.1

Note: All dimensions are in millimeter (mm)

III. ANTENNA EVOLUTION

The proposed design has been evolved through several steps to attain optimal performance is shown in Fig. 2. In the first step in ANT-1, a simple microstrip feedline with two quarter-wave transformers was chosen to ensure the 50 ohm impedance matching at feed point. An annular ring slot was etched on a ground plane and the width of the slot was calculated by equation (1). An inverted U-shaped meandered section was employed to obtain the circular polarization. In the second step (ANT-2), two corners of the rectangular ground plane were chamfered. The substrate under chamfered ground was cut to reduce the antenna weight and size. In ANT-3, two L-shaped slots with width u=1 mm were cut in the ground plane at the corners which were not chamfered. Finally, two other corners were cut which resulted in an octagonal shaped antenna that is an ANT-4. It is worth mentioning that in the last step the substrate was also removed beneath the chamfered parts of ground plane which results in reduced antenna weight of 2.08 grams.

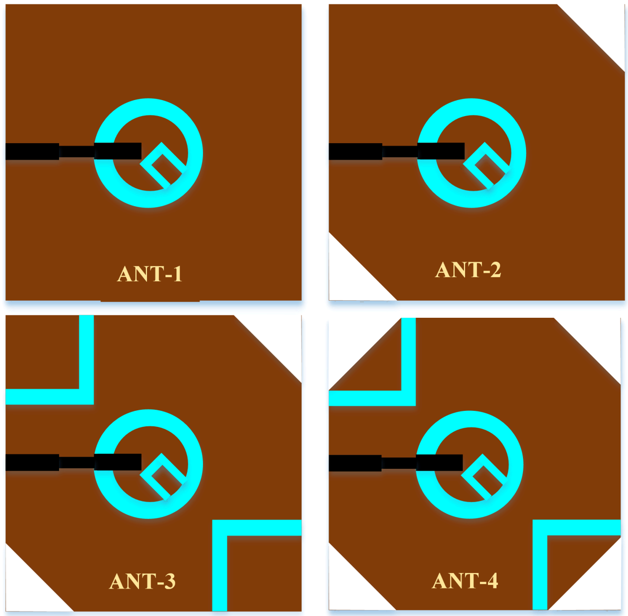


FIGURE 2. Antenna evolution steps ANT-1 to ANT-4.

In order to verify the generation of circular polarization, the simulated current distribution at 5.8 GHz has been obtained from HFSS software. It can be seen in the Fig. 3 that at Phi=0^o the intense portion of the current goes in –y direction. At Phi=90^o the maximum current goes in +x direction. It can be clearly observed that at Phi=180^o the acute portion of the current takes +y direction. Finally, at Phi=270^o the major portion of the current goes in −x direction. This shows the current tracks the anticlockwise rotation and therefore the polarization is RHCP. Typically, annular ring slot antenna produces bidirectional radiation so both RHCP and LHCP can be observed.

The effect on return loss and axial ratio due to antenna evolution from ANT-1 to ANT-4 has been presented in Fig. 4. The effect of antenna evolution (ANT-1 through ANT-4) is seen to be negligibly small as apparent from Fig. 4(a). The antenna evolution on the other hand has a high impact on the ARBW as noticed from Fig. 4(b). The trend in the curves of Fig. 4(b) illustrate that the axial ratio value for ANT-1 doesn't fulfill

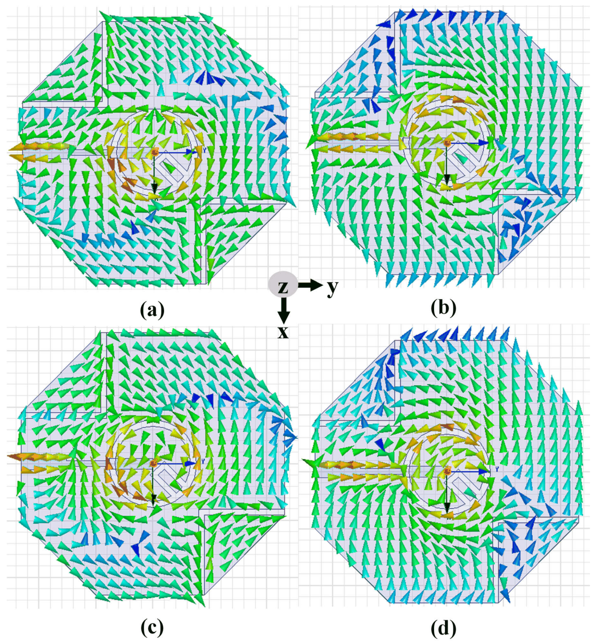


FIGURE 3. Current Distribution at 5.8 GHz (a) Phi=0° (b) Phi=90° (c) Phi=180° (d) Phi=270°.

the criteria (AR≤3 dB) for circular polarization. The required value (AR≤3) dB for circular polarization is achieved in ANT-2 however within a very small bandwidth. The improvement in AR bandwidth can significantly be noticed from the AR curve of ANT-3 in Fig. 4(b). It is obvious from the respective curve in Fig. 4(b) that the AR bandwidth is further widened by a small amount after employing the structure of ANT-4. It is worth mentioning here that axial ratio was calculated in the broad side direction (theta=0°, phi=0°).

IV. PARAMETRIC STUDY

To authenticate the effect of design parameters on performance of the antenna, a parametric study was conducted. Initially, the radii of inner and outer slots were calculated by formula given previously in equation (1) to set the resonance point. The dimensions were further adjusted such that the antenna was resonant at 5.8GHz. Further, the rectangular slot was cut and its dimensions and tilt angle were adjusted for optimum performance. The effect of radii of slots in annular ring, the dimensions of rectangular slot, and the tilt angle of the rectangular slot are the important parameters affecting the performance of antenna.

A. EFFECT OF INNER RADIUS OF ANNULAR RING SLOT

By varying the inner circular radiusR1 from 6.4mm to 6.8mm the corresponding curves of return loss and axial ratio have been shown in Fig. 5 (a) and (b), respectively. It can be noticed from curves that as we change the radius R_1 from 6.4mm to 6.8mm the centre frequency moves towards lower frequency and decrease in return loss bandwidth can also be noticed clearly. It should be kept in mind that while changing R1 the

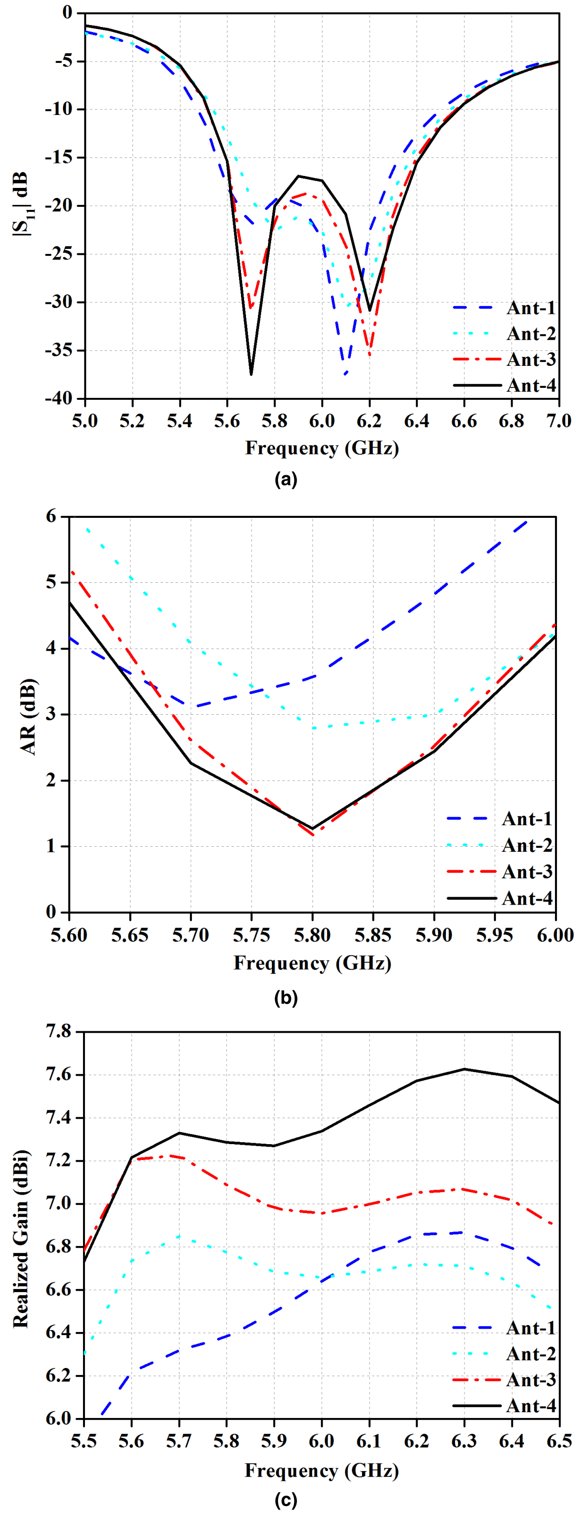


FIGURE 4. Simulation results of antenna evolution for ANT-1 to ANT-4 (a) Return Loss (b) Axial ratio (c) Gain.

radius R2 was kept constant at value of 7.7mm.Both the curves for return loss and axial ratio are following the similar trend in this parametric change. This decrease is because of increase in mean circumference of the annular-ring slot

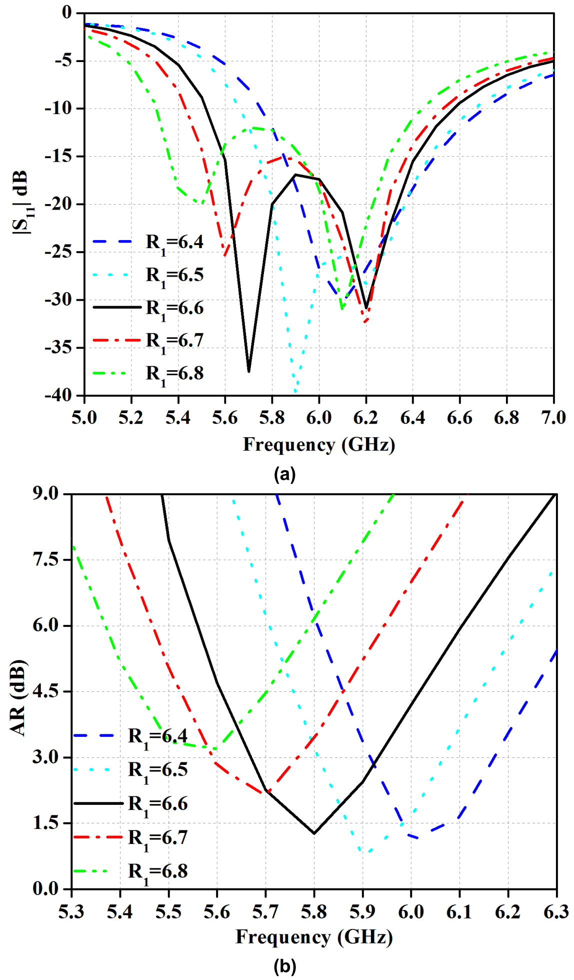


FIGURE 5. Effect of R_1 on (a) S_{11} (b) AR.

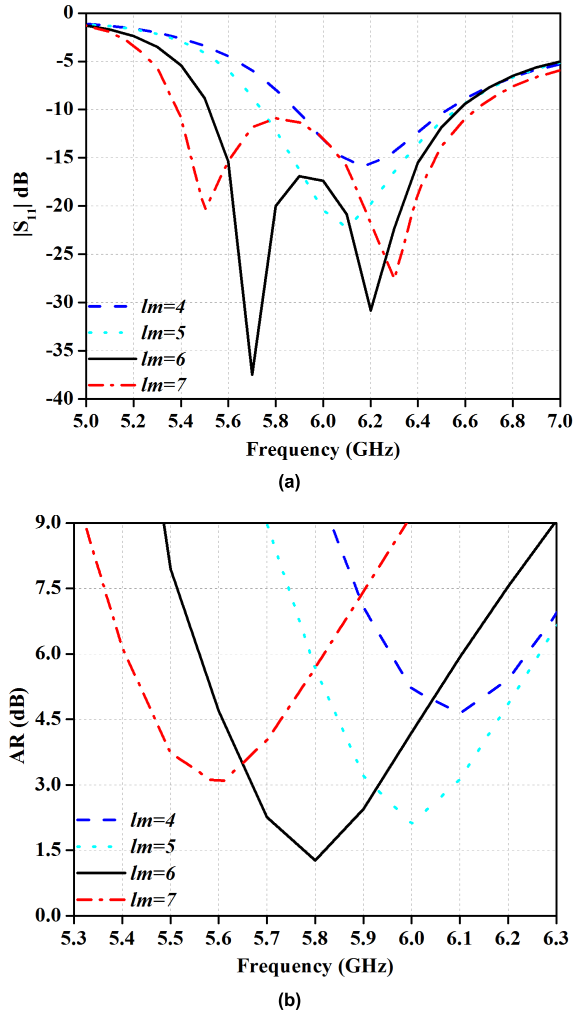


FIGURE 6. Meandered section effect on (a) S_{11} (b) AR.

(π (R_1+R_2)) as cited in equation (1). So, the optimum value for R_1 was selected as6.6mm where circular polarization (AR<3dB) can be sustained with significant overlapped bandwidth of return loss under −10dB.

B. EFFECT OF RECTANGULAR SLOT SECTION

Fig. 6 shows the effect of varying length (*lm*) of inverted U-shaped slot on center frequency and axial ratio value. It can be clearly seen that center frequency decreases with the increase in length. It was found that in case of length *lm*=4mm and *lm*=7mm the antenna was not providing circular polarization. Although, at *lm*=5mm axial ratio value was under 3dB but a very narrow bandwidth was achieved. An optimum length of *lm*=6mm results in acceptable value of axial ratio at center frequency of 5.8GHz and an AR bandwidth of 300MHz was achieved. As expected, the simulated return loss for different lengths of *lm*=4mm to *lm*=7mm follows the same trend as was noticed in the AR value. That is, with the increase in length of rectangular slot, the resonance point shifted towards lower frequencies. It needs to be mentioned here that at *lm*=7mm impedance bandwidth is wider as compared to other meandered section length but at this value antenna is not radiating circularly polarized wave properly. Therefore the optimum value of lm which results in largest overlapped impedance and AR bandwidth comes out to be *lm*=6mm. There was no significant effect of variation in the length *la* of the rectangular slot.

C. EFFECT OF TILT ANGLE OF RECTANGULAR SLOT

The variation effect of tilt angle α from 35° to 55° (with the increment of 5°) of inverted U-shaped slot on antenna performance was studied. At angles of 35° and 40°, the results show that antenna provides axial ratio less than 3 dB however it does not provide the required bandwidth with 5.8GHz as center frequency. At a tilt angle of 45° the axial ratio bandwidth of 300 MHz was achieved with 5.8GHz as center frequency. The same effect was observed on the return loss by varying the tilt angle as shown in Fig. 7 (a) and (b).It needs to be mentioned that while varying the tilt angle all other parameters were kept constant and the rectangular slot length (*lm*) was selected as 6mm. A slight variation was noticed in antenna gain with the change of tilt angle but overall antenna possesses the gain in between 7.3-7.6dBi.

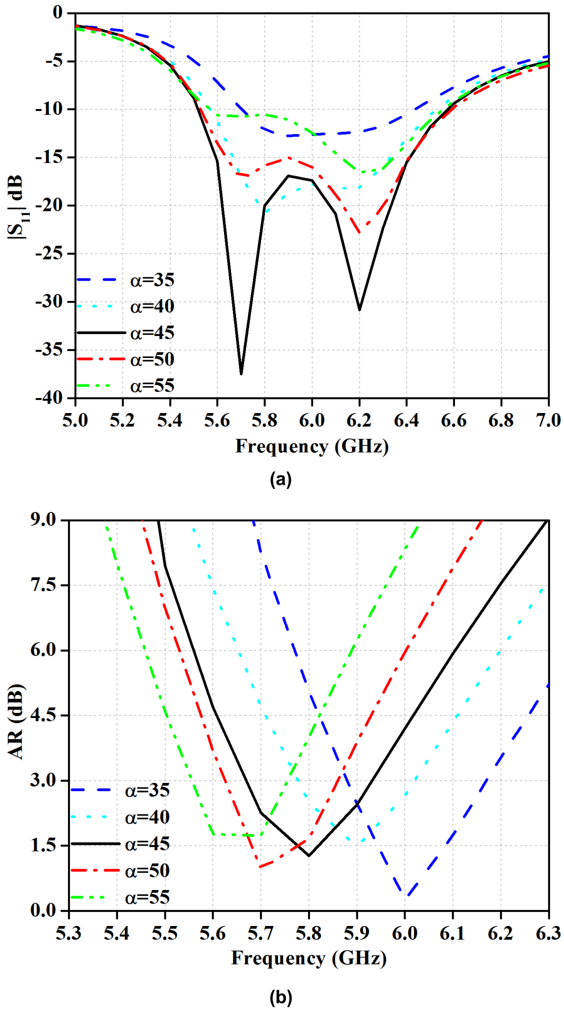


FIGURE 7. Tilt angle effect on (a) S_{11} (b) AR.

V. MEASURED AND SIMULATED RESULTS

To validate the proposed design and simulated results, the antenna was fabricated and the return loss was measured through a vector network analyzer. Fig. 8(a) depicts that simulated and measured results show good agreement between return loss $|S_{11}| < -10$dB curves and corresponding value of $|S_{11}| = -28.7$dB at resonance frequency of 5.8 GHz was obtained. Simulated and measured results shows that impedance bandwidths are 20.33% (5.3 GHz – 6.5 GHz) and 23.54% (5.2 GHz – 6.55 GHz), respectively.

The simulated and measured axial ratio bandwidth versus frequency, where broadside direction (theta=0°, phi=0°) was considered for AR calculations, was found to be 4% (5.67 GHz – 5.93 GHz) and 5.15% (5.67 GHz – 5.97 GHz) respectively around the center frequency of 5.8 GHz which can be clearly observed in Fig. 8 (b). Moreover, antenna exhibits AR<3dB within the entire axial ratio bandwidth and minimum value for AR achieved through measurement is 0.8 dB at 5.8 GHz.

The standard horn antenna (HD-58SGAH20+N) was used as a reference to measure the antenna gain. The gain of the

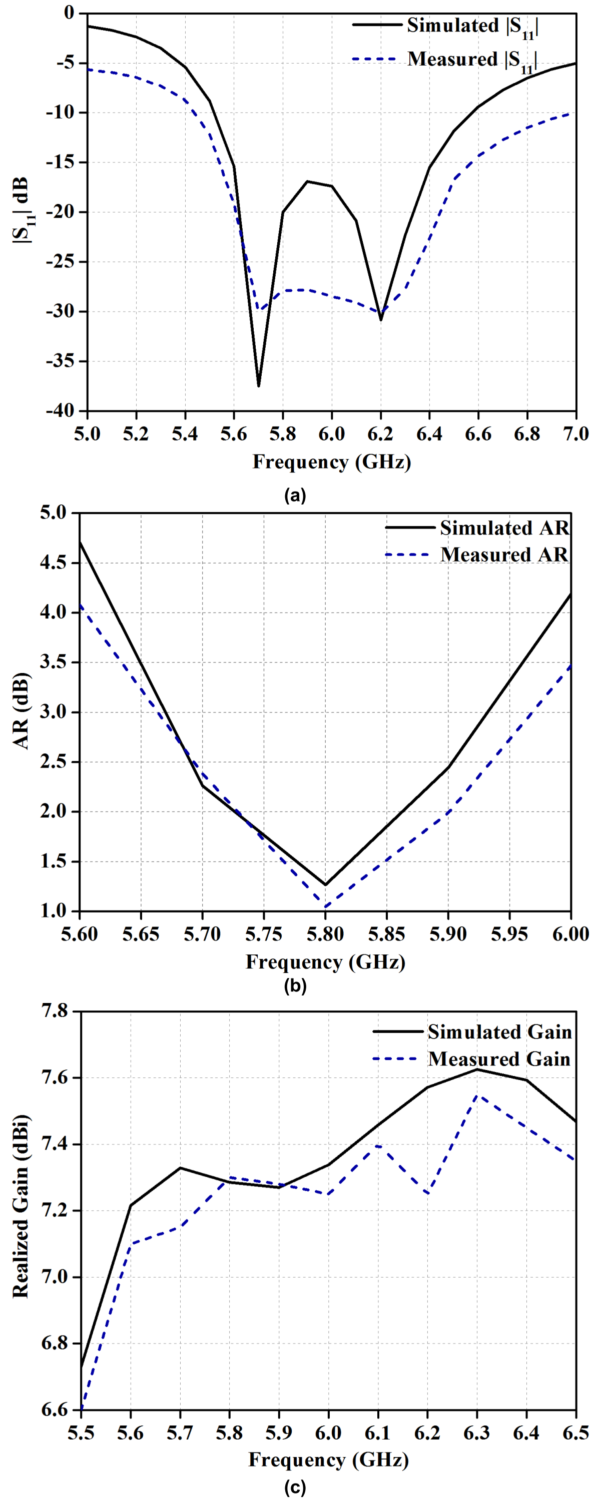


FIGURE 8. Simulated and Measured Results (a) S_{11} (b) AR and (c) Gain.

proposed antenna has been obtained by

$$G = 10lg\left(10^{G_H/10} + 10^{G_V/10}\right) \tag{2}$$

where G_H and G_V are the horizontal and perpendicular planes, respectively. The measured and simulated gain of

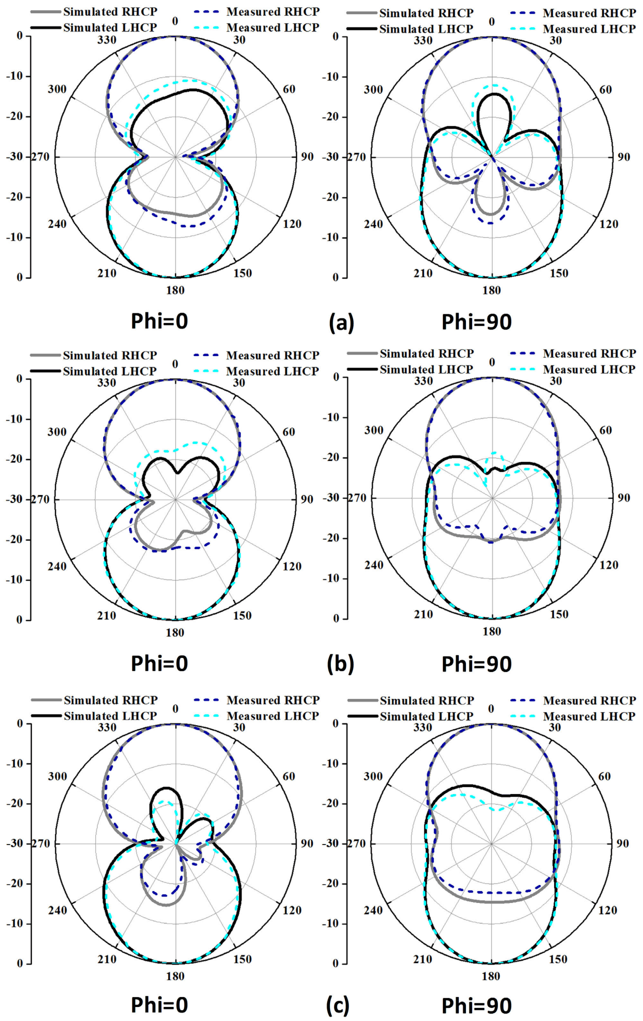
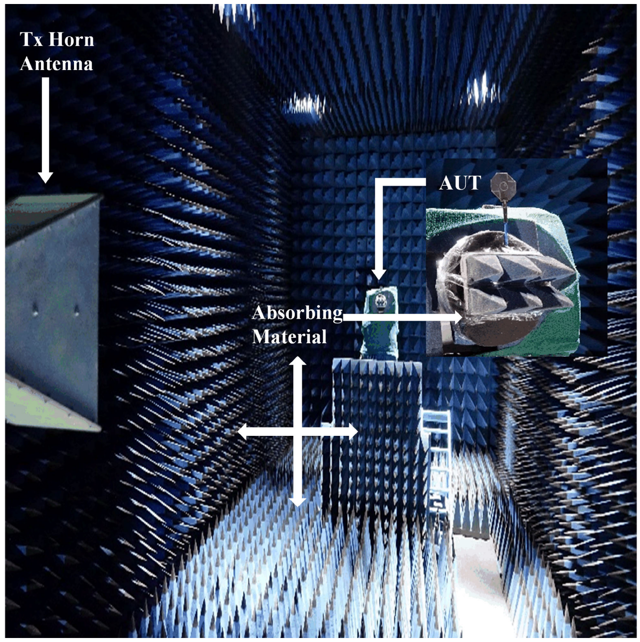
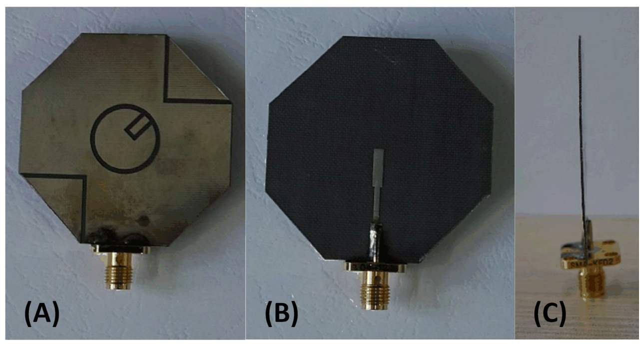


FIGURE 9. **Simulated and Measured Radiation Pattern (a) 5.7 GHz (b) 5.8 GHz(c) 5.9 GHz.**



(a)



(b)

FIGURE 10. **(a). Antenna measurement setup in an anechoic chamber, (b)Prototype of fabricated antenna (A) Front View, (B) Back View and (C) Side View.**

antenna has been shown in Fig. 8 (c). Simulated and measured results depict that antenna is capable of maintaining nearly uniform gain of 7.6dBi in the entire working band of antenna.

Both the measured and simulated RHCP/LHCP radiation pattern at three different frequencies 5.7GHz, 5.8GHz and 5.9GHz are plotted in Fig. 9. It may need to be mentioned here that CP slot antenna without a reflector radiates a bidirectional wave. With the contrary circular polarization of antenna, the radiation patterns on either sides of the slot antenna are the same; that is, the front side radiates RHCP while the back side radiates LHCP wave.

The circularly polarized performance of the antenna was measured by using a rotating transmitting linearly polarized standard horn antenna by an NSI system in the anechoic chamber. By measuring three or more linear polarization components of circularly polarized antenna at different polarization angles by the standard linear polarized horn, the total radiation pattern and axial ratio information of the antenna can be obtained. To guarantee the measurement accuracy, the gain in the azimuth plane was calculated at each frequency point within the operating frequency range. This was done by first selecting one frequency say 5.6GHz and rotating the antenna in phi (0^o – 360^o with 10^o steps). The radiation pattern cut in this plane should be circular if one is expecting circular polarization. The procedure should be repeated at each frequency point i.e. 5.6GHz, 5.65GHz and so on up to 6GHz. However due to time limitation, the measurement was done only at selected frequencies and the data was interpolated to obtain the complete curve. The measurement setup and prototype of measured antenna is also shown in Fig. 10 (a) and (b) respectively.

Table 2 provides a comparison between the performance of proposed antenna and recently reported antennas of the similar type. The comparison includes return loss bandwidth, axial ratio bandwidth, gain, antenna size and profile. It is quite clear from the comparison table that proposed antenna

TABLE 2. Comparison of proposed antenna with reference antennas.

Ref.	Area (λ_0^2)	Thickness (λ_0)	S_{11} BW (MHz)	Polarization	Center Frequency (GHz)	Gain (dBi)	No. of Layers
[10][2018]	$1.16\lambda_0\times0.96\lambda_0$	$0.015\lambda_0$	1490	CP	5.79	6.1	1
[14][2015]	$0.61\lambda_0\times0.61\lambda_0$	$0.119\lambda_0$	62.5	CP	2.2826	7.29	1
[15][2019]	$0.45\lambda_0\times0.44\lambda_0$	$0.172\lambda_0$	2215	CP	2.215	4	3
[16][2017]	$1.36\lambda_0\times1.36\lambda_0$	$0.024\lambda_0$	120	CP	2.44	-	1
[17][2019]	$0.46\lambda_0\times0.46\lambda_0$	$0.018\lambda_0$	910	CP	3.395	6.86	DRA
[18][2017]	$0.57\lambda_0\times0.57\lambda_0$	$0.017\lambda_0$	101	CP	3.325	5.5	DRA
[19][2018]	$0.89\lambda_0\times0.78\lambda_0$	$0.029\lambda_0$	400	LP	5.72	5.8	1
[20][2016]	$1.45\lambda_0\times0.81\lambda_0$	$0.019\lambda_0$	400	LP	5.8	3.21	1
[21][2019]	$1.06\lambda_0\times0.60\lambda_0$	$0.028\lambda_0$	645	LP	5.5	6	1
[22][2019]	$\pi\times0.47\lambda_0^2$	$0.095\lambda_0$	400	CP	5.7	3.3	4
[23][2017]	$1\lambda_0\times0.6\lambda_0$	$0.015\lambda_0$	140	CP	5.8	6.57	1
[24][2018]	$1.88\lambda_0\times0.53\lambda_0$	$0.015\lambda_0$	1700	CP	5.65	7.1	1
Proposed	$\mathbf{0.89\lambda_0\times0.89\lambda_0}$	$\mathbf{0.009\lambda_0}$	**1350**	**CP**	**5.8**	**7.6**	**1**

Note: CP=Circularly Polarized, LP=Linearly Polarized, DRA= Dielectric Resonator Antenna

has high gain compared to recently reported designs of the same type. High gain value is a result of using low loss dielectric material, and suppression of surface waves due to the presence of L-shaped slots cut in the ground plane resulting in a defected ground plane structure. Although some of the reference designs report a higher gain or increased bandwidth as compared to the proposed design however, considering all the mentioned parameters simultaneously, the proposed antenna offers better performance as compared to other reported antennas.

VI. CONCLUSION

An annular ring slot antenna with circular polarization and high gain is presented in this paper. Circular polarization with this single fed slot antenna was achieved by creating an asymmetry in the ring slot resulting in perturbation of the current path. The proposed design has features of low profile ($0.009\lambda_0$), single feed, light weight, low cost, ease in fabrication and the advantage of practical mounting on large ground plane. In addition this antenna has high gain with bidirectional radiation pattern and easy to find applications at 5.8GHz. Measured and simulated results are in good agreement where impedance bandwidth of 23.54%, ARBW of 5.15% and 7.6dBi peak broadside gain was achieved.

The proposed antenna structure is extremely suitable for various airborne applications as well as UAVs, satellite communication, weather radar, small-form-factor (SFF) devices and dedicated short range communication (DSRC) systems. Moreover, the antenna is also a favorable choice for WLAN (5.725-5.825 GHz), WBAN and ISM bands (5.8 GHz) applications.

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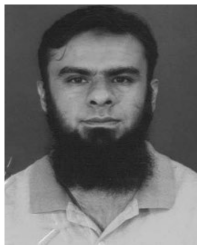

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