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Two-Pair Slots Inserted CP Patch Antenna for Wide Axial Ratio Beamwidth

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ABSTRACT In this article, a low profile circularly polarized (CP) antenna with wide 3-dB axial ratio beamwidth (ARBW) is presented. Two-pair of parallel slots are etched on a circular patch and manifested as magnetic dipoles (MDs). These narrow slots are arranged symmetrically about the axes, and one pair is orthogonal to another pair of slots. The philosophy of CP radiation across a wide angular range strongly depends on the spacing between the paired-dipoles, for example spacing of $0.22\lambda_0$, two-orthogonal far-field radiated components become equal across a wide-angle. Moreover, this particular spacing between the paired-dipoles provides a symmetrical electric field distribution along the periphery of the patch, which ensures the broadside LHCP radiation with wide 3-dB ARBW of 228° and 214° at the plane of $\varphi = 0°$ and $\varphi = 90°$, respectively. The measured results from the fabricated prototype exhibit good agreement with the simulated results. The antenna has impedance bandwidth (IBW) and CP bandwidth (CPBW) of 2.6% (64 MHz), and 0.9% (22 MHz), respectively. The broadside radiation holds antenna gain higher than 5 dBic across the entire CPBW.

INDEX TERMS Axial ratio beamwidth, circular polarization, electric field, magnetic dipole, slotted-patch.

I. INTRODUCTION

Discriminated polarization in wireless communication due to multipath radio waves and misalignment between the end points is circumvented using circularly polarized (CP) antennas instead of other antennas. A CP antenna with a broader 3-dB axial ratio beamwidth (ARBW) can afford wide area coverage on ground stations and is successfully trialed in many satellite communication applications. Therefore, several techniques have been explored in the existing literature. For example, the CP beamwidth associated with 3D configurations were studied with cavity integrated curvature dipole [1], folded quadrifilar helical [2], three-dimensional grounds [3], and sequentially rotated radiating patches [4]. Such antennas perform under the principle of field diffraction from their embedded structural elements. The method of wave construction for beamwidth enrichment of CP antenna is established by squared [5], cylindrical [6] and inverted pyramidal [7] cavity–backed reflector. In [8], the principle of field refraction is verified by constructing a cone-shaped air cavity into a 3D dielectric cylinder for extending 3-dB ARBW of conventional CP antenna. The defected ground structure (DGS) often enhances the cross-polarization (XP) magnitude in the radiation of a linearly polarized antenna. Therefore, a fractal DGS was embedded for increasing XP to the required level, which contributes to a beamwidth improvement of the CP antenna [9].

A rigorous study on beamwidth characteristics with dipole antennas has been introduced in [10], [11] and taken much care about indistinguishable E- and H-plane radiation by concurrent field excitation. In [12], the production of sufficient surface current on both arms of the dipole is chosen for creating a wide-beam CP radiation. Simultaneous excitation of electric and magnetic current with magnetoelectric (ME)

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dipole is employed as a prospective candidate for designing of CP antenna [13]. The coupled field between parasitic elements and ME dipole antenna is controlled by adjusting the capacitance of installed varactor diode for reconfiguration of 3-dB ARBW [14].

In recent years, more attention is going on the planar form of CP antennas due to their low profile with a stub, slot, or shorted load. In [15], the stubs dimension and their placement were selected as crucial parameters for designing of wide beamwidth CP antenna. Strips based scheme on slotted patch is examined to study a CP antenna for beamwidth enhancement [16]. A critical study on the slotted fractional part concerning the patch is investigated for beamwidth clarification of CP antenna [17]. In [18], the beamwidth of CP antenna is presented as function of mutual coupled field between slotted structures. The techniques like shorted post [19], shorted plate [20], and SIW based approach [21] have been preferred to enrich the beamwidth performance of the CP antenna. Antennas on a suspended substrate [22] and an extended length of the dielectric substrate [23] have been used to implement wide beamwidth CP antenna. In summary, it appears challenging to design a wide 3-dB ARBW planar CP antenna without using a complex feeding network and multi-layered structure.

In this work, the incorporation of four identical narrow slots (12.8 mm×0.6 mm) on a circular patch is conceived to design a planar CP antenna with extremely wide 3-dB ARBW. The slot on a patch is served as a MD, and hence, considering the property of MD, a pair was formed between two parallel dipoles to realize the CP radiation. Further, the orthogonal placement of two-pair of MDs with a particular spacing between the paired-dipole enhances the CP beamwidth to a large extent. Proposed low profile structure is able to exhibit more than 214° symmetrical 3-dB ARBW patterns in both the principal planes with effective cross-polarization discrimination (XPD). In the subsequent sections, antenna design methodology and its achievement are discussed in detail. All the simulations are carried out using the FEM-based Ansys® HFSS™ EM simulator.

II. ANTENNA CONFIGURATION AND DESIGN ANALYSIS

Initially, a circular patch of radius, 21.5 mm is designed to operate in the ISM band (2.42 GHz - 2.462 GHz). The generation of CP radiation depends on the insertion of appropriate fractional slotted area in the antenna. It is observed that an antenna with a $<1\%$ ($\approx 0.7\%$) fractional slotted area [17] radiates linearly polarized waves. However, the 3-dB ARBW of CP radiation is tuned with the placement of slotted structure in the antenna. Now, to realize CP radiation, two narrow slots (1 and 1′) of 1% fractional area are etched perpendicularly on the diagonal line of the patch, as shown in Fig. 1(a). To manifest the effect of parallel dipoles [10], these slots are placed symmetrically about the center of the patch, and in parallel with each other. Hence, these slots are considered as one pair of slots as well as a pair of MDs with a spacing of 30.4 mm. This design provides

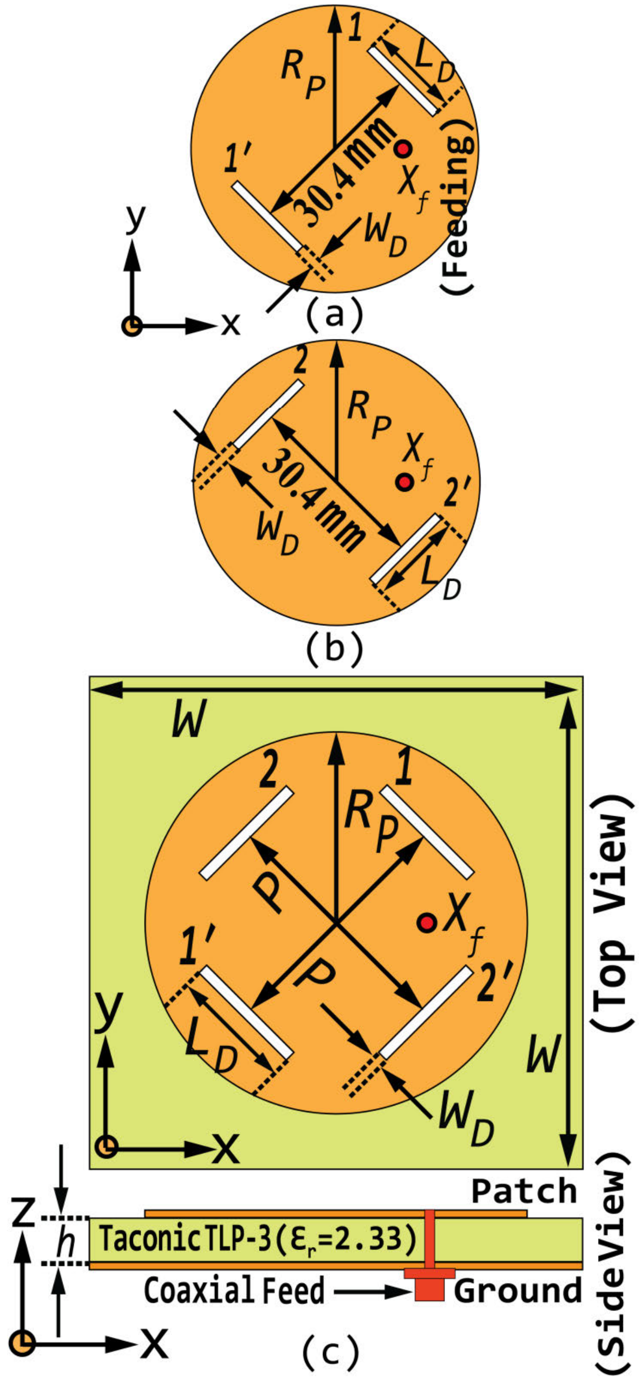

FIGURE 1. Antenna configurations; (a) CP antenna with one pair of MDs (1 and 1′), (b) CP antenna with one pair of MDs (2 and 2′), and (c) Proposed CP antenna with two pair of MDs. [Structural dimension: $W = 61.2$ mm ($0.49\lambda_0$), $h = 1.575$ mm ($0.013\lambda_0$), $R_P = 21.5$ mm ($0.17\lambda_0$), $L_D = 12.8$ mm ($0.1\lambda_0$), $W_D = 0.6$ mm ($0.005\lambda_0$), $P = 27.8$ mm ($0.22\lambda_0$), $X_f = 6.8$ mm] [λ_0 = free space wavelength corresponding to CP frequency 2.421 GHz].

IBW of 2.9% (2.412 GHz - 2.484 GHz), CPBW of 0.7% (2.425 GHz -2.443 GHz), and 3-dB ARBW of 162° across the angular range from −80° to +82° at 2.436 GHz, as shown in Fig. 2. Now, to investigate the reason behind this lower 3-dB ARBW, the electric field on the patch surface is studied, as shown in Fig. 3 (a). The asymmetric and non-uniform

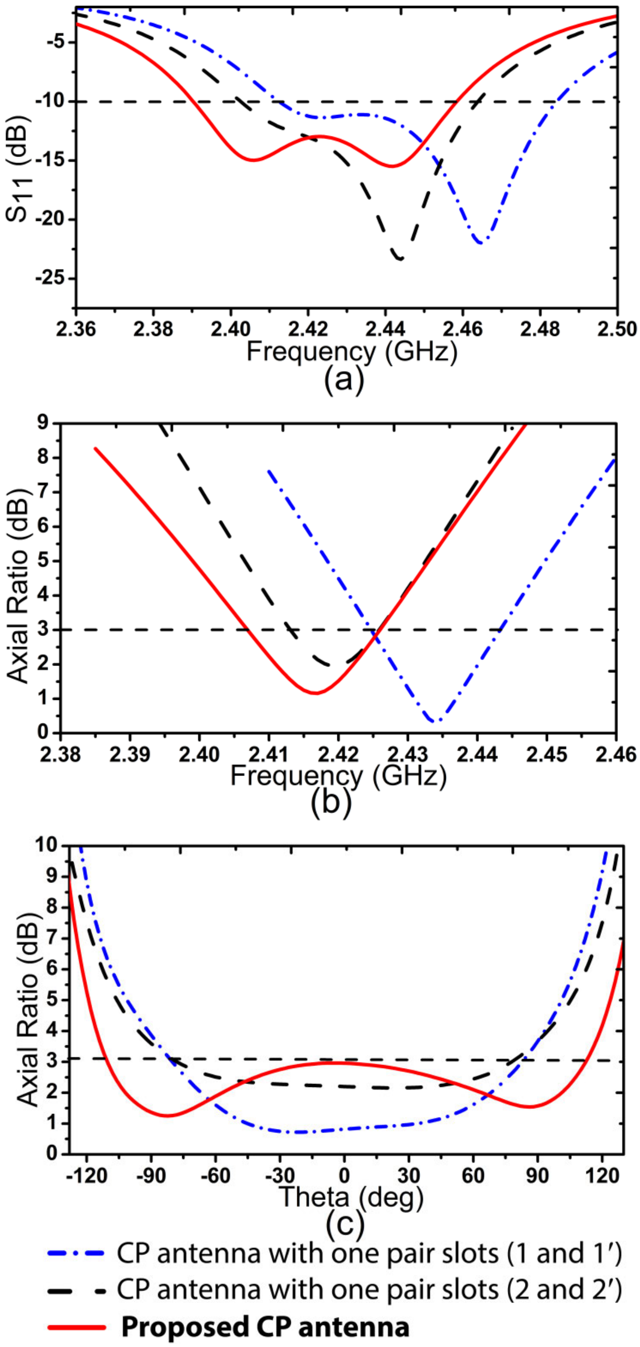

FIGURE 2. Analysis of different antenna structures (a) Reflection coefficient (S_{11}) vs frequency, (b) AR vs frequency, and (c) 3-dB ARBW vs theta at $\varphi = 0°$.

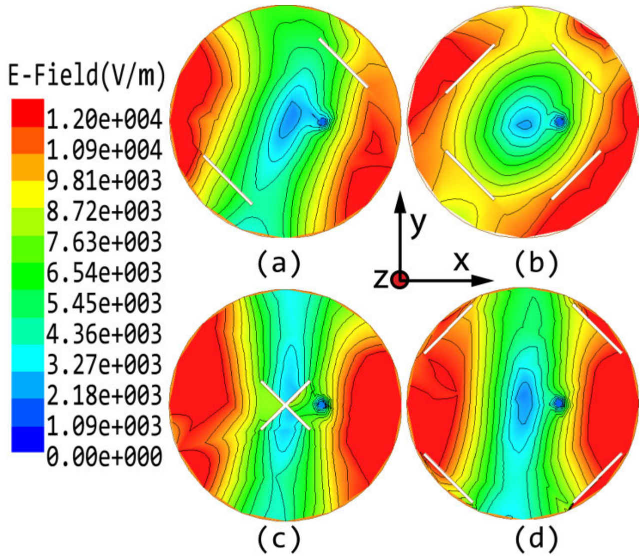

FIGURE 3. Electric field distribution on (a) CP antenna with one pair of MDs @ 2.436 GHz; and on CP antenna with two pair of MDs for different values of *P* (b) $P = 0.22\lambda_0$ @ 2.415 GHz (proposed), (c) $P = 0$ @ 2.402 GHz, and (d) $P = 0.32\lambda_0$ @ 2.457 GHz. [All distributions are captured in same scale].

TABLE 1. The Simulated 3-*dB* ARBW of the Proposed CP Antenna for Different Values of *P*.

P	$0\lambda_0$, (0 mm)	$0.11\lambda_0$, (14 mm)	$0.16\lambda_0$, (19.8 mm)	**$0.22\lambda_0$, (27.8 mm)**	$0.26\lambda_0$, (32.8 mm)	$0.32\lambda_0$, (39 mm)
3-dB ARBW	124°	164°	180°	**222°**	100°	70°

confinement of the electric field at the orthogonal sides of the paired-MDs makes the radiation only from two regions which lead to restricting the 3-dB ARBW. A similar characteristic is identified in CP antenna with one pair of slots (2 and 2′) of 1% fractional area in Fig. 1(b) and its performance is shown in Fig. 2 with IBW of 2.5% (2.402 GHz - 2.464 GHz), CPBW of 0.45% (2.414 GHz - 2.425 GHz) and 3-dB ARBW of 154° across the angular range from −78° to +76° at 2.422 GHz. To enhance the 3-dB ARBW further, considering the orthogonal placement of paired dipoles [10], another pair of identical slots (2 and 2′) are etched symmetrically about the center of the patch and orthogonal to the earlier pair of slots (1 and 1′), as shown in Fig. 1(c). The length and width of each dipole, are set as L_D and W_D, respectively. The parameter, P is assigned as the spacing between the paired-dipoles. The proposed CP design with 2.11% fractional slotted area provides IBW of 2.8% (2.39 GHz - 2.458 GHz), CPBW of 0.74% (2.407 GHz - 2.425 GHz), and 3-dB ARBW of 222° across the angular range −110° to +112° at 2.415 GHz, as shown in Fig. 2. The electric field distribution for the proposed design ($P = 0.22\lambda_0$) is symmetrical about the center of the patch and uniform along the periphery of the patch, as shown in Fig. 3(b). This symmetrical and uniform electric field is the resultant E-field caused by superimposing of two-asymmetric and non-uniform field distributions from the antenna in Fig. 1(a) and 1(b).This kind of field distribution indicates uniform radiation from the entire periphery of the circular patch, which helps to overcome the restricted 3-dB ARBW problem of initial designs (Fig. 1(a) and 1(b)). When $P = 0$, the proposed antenna turns into a slotted cross-dipole [24], and the field is radiating only from the two sides of the patch, as shown in Fig. 3(c). For the selection of P beyond $0.22\lambda_0$, the 3-dB ARBW is reduced as the field symmetries and uniformity is distressed, as shown in Fig. 3(d).

From the electric field distribution analysis it is found that the spacing (P) between the paired-dipoles is a crucial

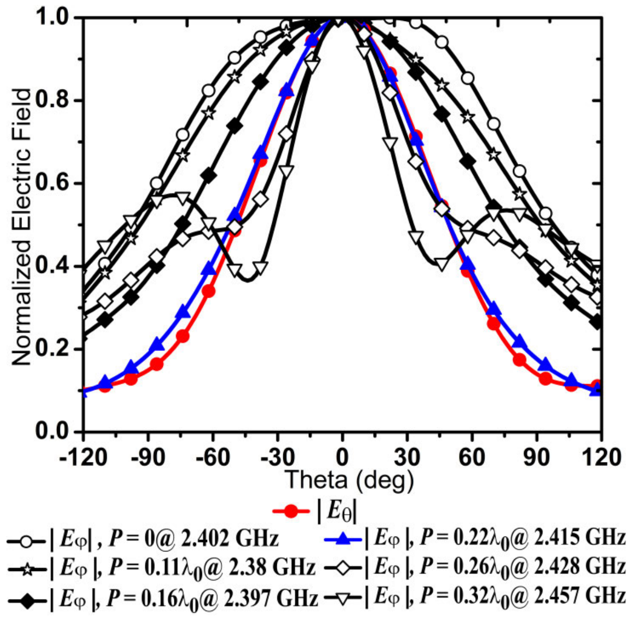

FIGURE 4. Simulated normalized field magnitude of E_θ and E_φ for several values of *P* in the *XZ* plane.

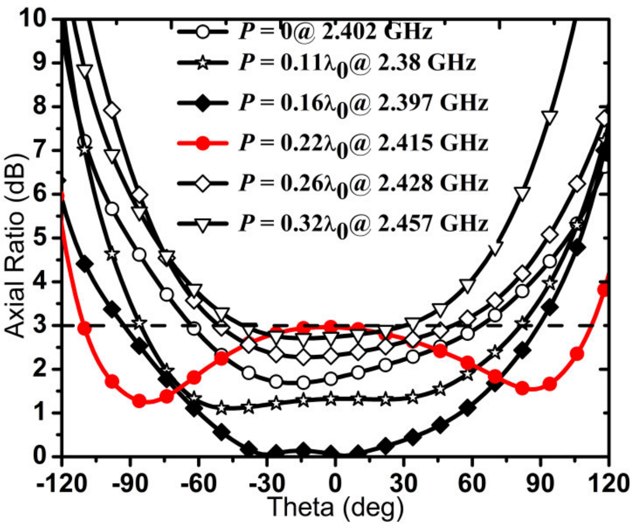

FIGURE 5. Simulated AR for several values of *P* in the *XZ* plane.

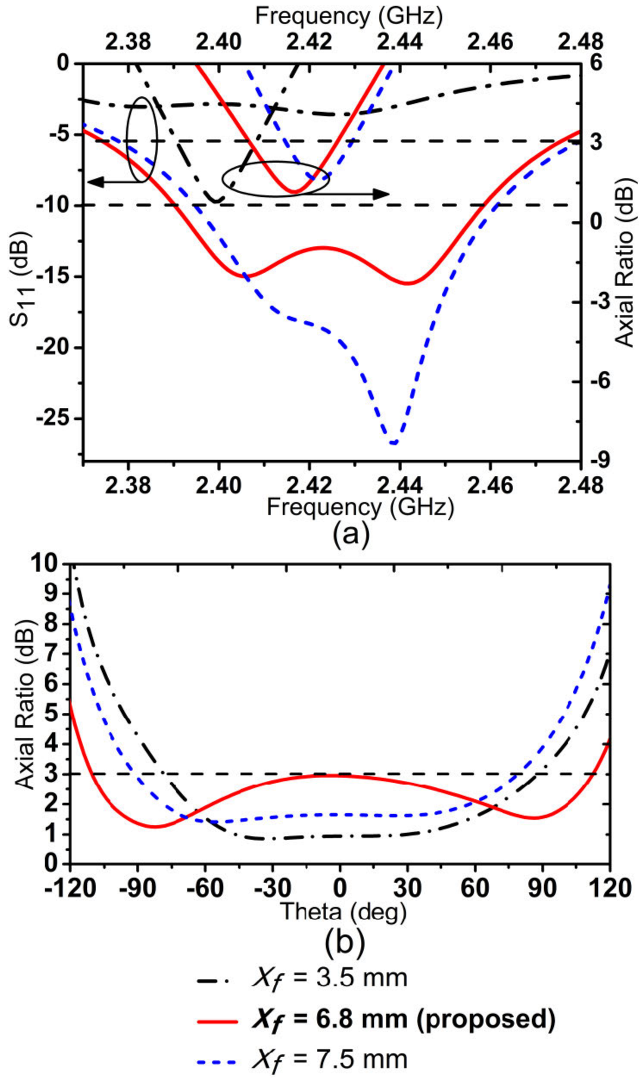

FIGURE 6. Effects of feed point location (X_f) variation on (a) AR and S_{11}, and (b) 3-dB ARBW.

parameter to tune the 3-dB ARBW and also to maximize the 3-dB ARBW. To comprehend the principle of wide 3-dB ARBW clearly, it can be assumed that the electric field in each MD varies as a function of sinusoidal wave. Now, to perceive the influence of the parameter, *P*, the simulated normalized electric field components ($\boldsymbol{E_\theta}$ and $\boldsymbol{E_\varphi}$) and the corresponding AR are plotted in Fig. 4 and Fig. 5, respectively as a function of the polar angle theta (θ) in the *XZ* plane. It is noticed that the $\boldsymbol{E_\theta}$ component is nearly unaffected and it is an independent function of *P* variation. However, the level of $\boldsymbol{E_\varphi}$ component progressively drops as *P* is increased from 0 to $0.11\boldsymbol{\lambda_0}$, $0.16\boldsymbol{\lambda_0}$, $0.22\boldsymbol{\lambda_0}$, $0.26\boldsymbol{\lambda_0}$, and $0.32\boldsymbol{\lambda_0}$. When $P =$ 0 or enormously small, $\boldsymbol{E_\varphi}$ component is nearly flattened across a wide range of θ and it is far away from E_θ. The two orthogonal far-field components, E_θ and E_φ are diverged for $P = 27.8$ mm ($0.22\lambda_0$), and the proposed CP antenna exhibits a wide 3-dB ARBW of 222° at the plane of $\varphi = 0°$. For other values of *P* ($P \neq 0.22\lambda_0$), the level of E_φ is far away from E_θ, which leads to narrower 3-dB ARBW. Moreover, due to the proper matching between E_θ and E_φ components (Fig. 4) across a wide angular range for $P = 0.22\lambda_0$, the electric field on the patch surface of the proposed CP antenna is uniformly distributed along the periphery of the patch (Fig. 3(b)), which leads to extremely wide 3-dB ARBW (Fig. 5). The 3-dB ARBW performance of the proposed CP antenna for different values of the crucial parameter *P* is summarized in Table 1. This analysis helps to finalize the value of *P* as $0.22\lambda_0$, to realize the maximum 3-dB ARBW.

It is well known that proper impedance matching depends on the location of the feed point; the input impedance increases as the feed point distance (X_f) is increased. Moreover, it is observed that X_f affects the 3-dB ARBW and IBW rather than its CPBW as shown in Figure. 6(a)-(b).

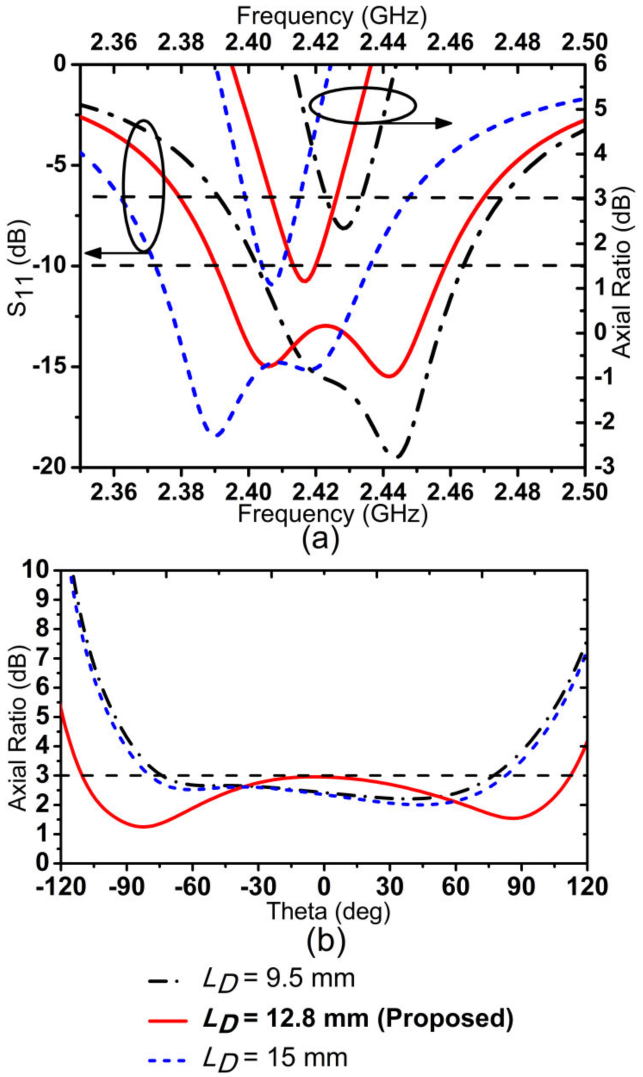

FIGURE 7. (a) AR and S_{11} (b) 3-dB ARBW with respect to varied L_D.

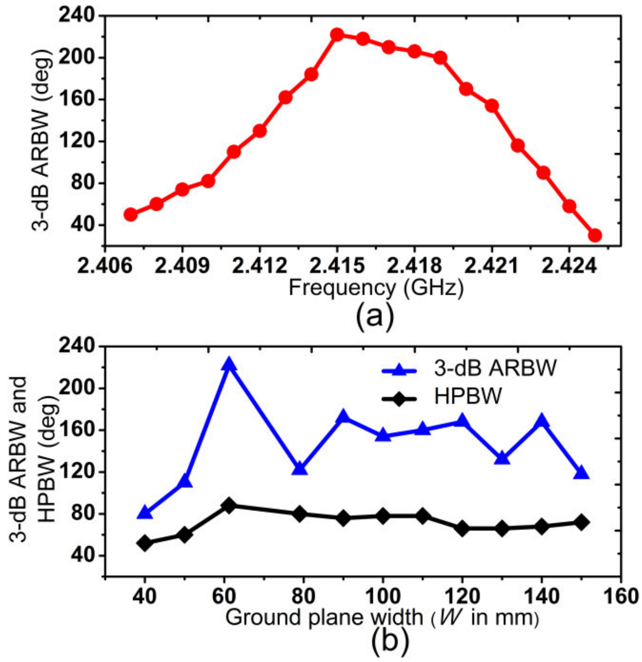

FIGURE 8. Plots of (a) 3-dB ARBW over entire CPBW and (b) 3-dB ARBW and HPBW for different dimension of ground plane [$\varphi = 0°$ plane].

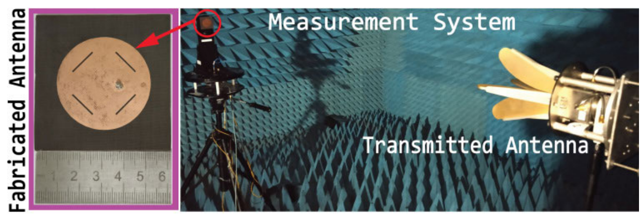

FIGURE 9. Photographs of the fabricated sample and its measurement setup.

Therefore, during the optimization of feeding location, the wide 3-dB ARBW with sufficient CPBW is considered as the higher priority. The feed point is chosen along the x-axis at a distance $X_f = 6.8$ mm from the center of the patch.

It was observed from the antenna working principle; the beamwidth of the CP antenna is greatly affected by the area of the slotted section. The influences of slot length variation on the CP characteristics of the proposed antenna are summed up in Figure. 7. For the slot length (L_D) other than the proposed one ($L_D = 12.8$ mm), there is a shift in the CP band, and it also exhibits a poor 3-dB ARBW. Further, it offers better impedance matching at the lower and higher frequency for the increment and decrement of the slot length, respectively.

A CP antenna with wide beamwidth for a single frequency (just a fraction of the entire CP band) does not validate the practicality of the CP antenna. Therefore, it is essential to check the beamwidth (3-dB ARBW) performance of the CP antenna across its entire CP band. From the literature survey, it is found that achieving a constant 3-dB ARBW across the entire CP band is not feasible in practice. Considering this issue, the CP antenna designers always try to minimize the fluctuation of 3-dB ARBW across the CP band. To observe the 3-dB ARBW performance of the proposed CP antenna across the entire CP band, the values of 3-dB ARBW are plotted in Fig. 8(a). In this investigation, it is found that about 66.7% of total CPBW is detected for more than 90° 3-dB ARBW, which strongly validates the suitability of the proposed approach for the practical implementations of the CP antenna. The ground plane inherently acts as a reflector for antenna. Therefore, it is important to check the impact of ground plane's size on 3-dB ARBW and half-power beamwidth (HPBW) of the proposed antenna, and it is summarized in Fig. 8(b). For the ground plane dimension of $W = 61.2$ mm, both the 3-dB ARBW (222°) and HPBW (88°) are maximum in the plane of $\varphi = 0°$. Hence it is chosen as the optimum dimension for the ground plane of the proposed CP antenna. In a long-distance communication system, the 3-dB ARBW of the CP antenna is given the most priority than its HPBW and a HPBW of 30° to 40° [5] is even acceptable for such applications. Low profile planar CP antenna is always suffered from poor HPBW. The HPBW of a CP antenna can be enhanced using some high-profile

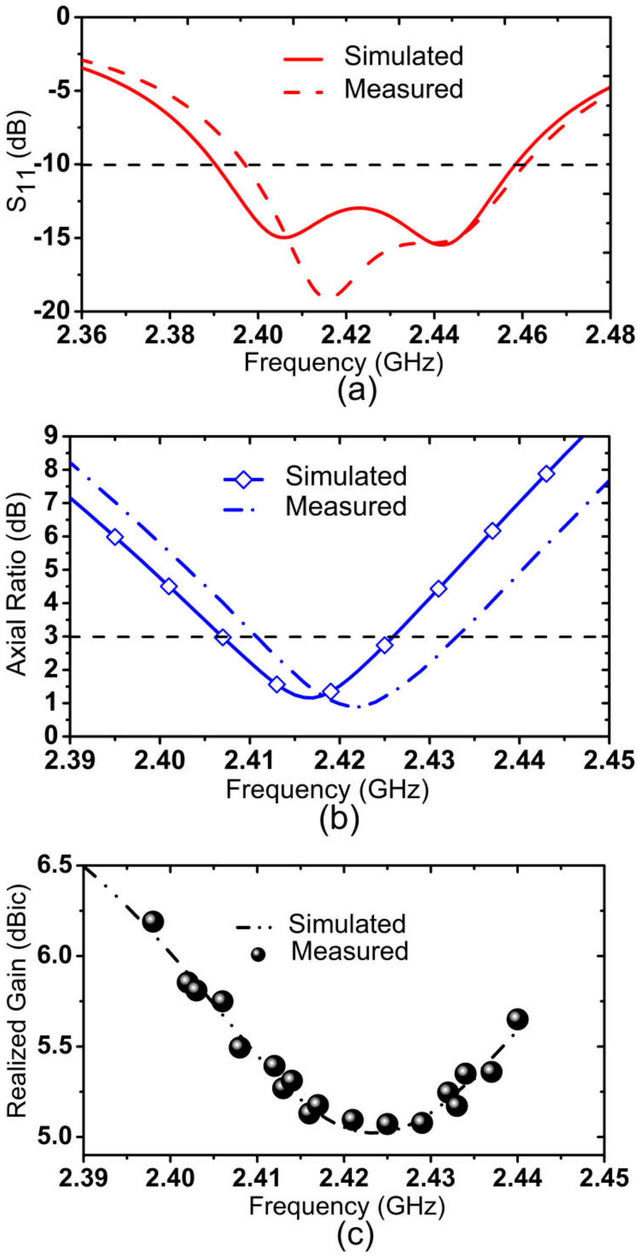

FIGURE 10. Simulated and measured (a) reflection co-efficient (S_{11}), (b) AR and (c) gain.

structures like 3-D structures and metal backed-cavity. It is also observed that for most of the planar CP antennas, HPBW is much lower than its 3-dB ARBW, and in some cases [11, 16], it is around 40° only.

III. RESULTS AND DISCUSSION

Based on the analysis of the previous section, the proposed design is finalized. To validate the simulated results, the proposed CP antenna was fabricated on a low loss Taconic TLP-3 substrate of dimension 61.2 mm×61.2 mm, dielectric constant (ε_r) = 2.33, loss tangent ($tan\delta$) = 0.0009, and thickness (h) = 1.575 mm. The photographs of the fabricated sample and its measurement setup are

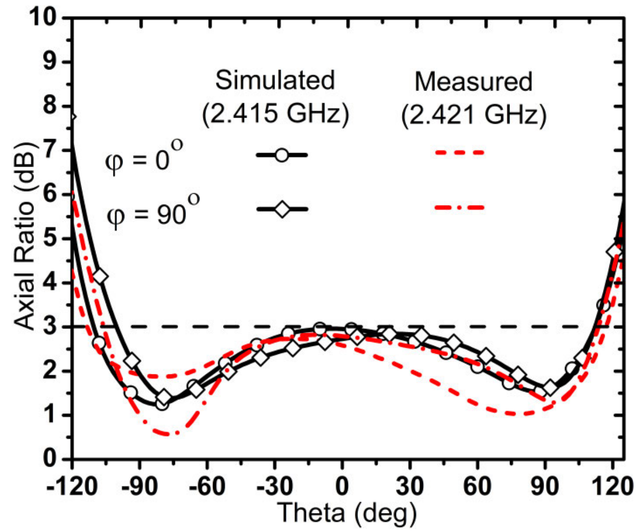

FIGURE 11. The 3-dB ARBW at the plane of (a) $\varphi = 0°$ and (b) $\varphi = 90°$.

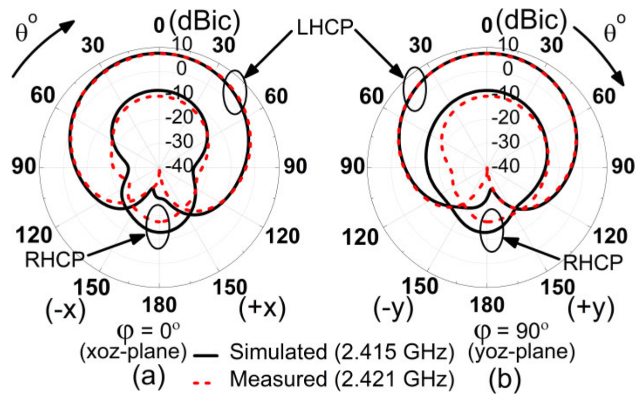

FIGURE 12. Simulated and measured LHCP and RHCP patterns at the plane of (a) $\varphi = 0°$ and (b) $\varphi = 90°$.

shown in Fig. 9. The antenna offers IBW of 2.6% [64 MHz (2.397 GHz - 2.461 GHz)], CPBW of 0.9% [22 MHz (2.411 GHz - 2.433 GHz)] and the realized gain higher than 5 dBic across entire CPBW, as shown in Fig. 10. The 3-dB ARBW of the proposed CP antenna reaches up to 228° at $\varphi = 0°$ and 214° at $\varphi = 90°$, as shown in Fig. 11.The measurement yields the HPBW of 92° and 90° at $\varphi = 0°$ and $\varphi = 90°$ planes, respectively, which are enough to implement a low profile planar CP antenna. The simulated and measured radiation patterns for the two principal planes $\varphi = 0°$ and $\varphi = 90°$ are in the broadside direction, as shown in Fig. 12. It is found that in both planes, the left-handed circular polarization (LHCP) is greater than the right-handed circular polarization (RHCP). Hence, the proposed CP antenna is LHCP in nature. This design also offers a sufficient amount (18 dB) of XPD between the LHCP and RHCP in both principal planes, which is widely accepted for practical applications of CP antenna. The inspection of all plots indicates a well matching behavior between the simulation and measurement results.

The inspected outcomes of recently published related works are compared with the measured characteristics of the

TABLE 2. Measured Characteristics of the Proposed CP Antenna Compared With the Other Related Works.

Antenna type	Total size (λ_0^3)	IBW (%)	CP BW (%)	XPD (dB)	Gain (dBic)	HPBW (deg) at $\varphi = 0°$	3-dB ARBW (deg)	
							$\varphi = 0°$	$\varphi = 90°$
Sequentially rotated patches [4]	0.1×0.1×0.13@ 2.4 GHz	13	NM	NM	<5	120	180	NM
Metal backed cavity [7]	0.33×0.33×0.21@ 1.575 GHz	3.4	0.8	15	<7.94	90	168	135
Dielectric cavity [8]	1.6×1.6×0.18@ 1.6 GHz	20	17	25	<5.5	133	162	164
Electric Dipole [11]	0.32×0.32×0.3@ 1.95 GHz	23.7	25	25	<4.3	40	195	NM
Slots + strips [16]	0.21×0.21×0.016@ 1.575 GHz	1.7	0.6	20	>5.4	40	188	188
Slotted [18]	0.29×0.29×0.013@ 2.487 GHz	3.4	0.9	18	>3.87	60	226	198
Shorted post [19]	π×0.5×0.5×0.013@ 1.575 GHz	2.4	0.6	25	<7.9	76	138	136
Magnetic dipole [this work]	π×0.35×0.35×0.013@ 2.421 GHz	2.6	0.9	18	>5	92	228	214

NM: *Not mentioned*

proposed CP antenna, as listed in Table 2 . It is noticed that the 3-dB ARBW of the proposed CP antenna in both the principal planes is higher than the included references of its class.

IV. CONCLUSION

A simple and compact CP slotted-circular patch antenna has been demonstrated for wide 3-dB ARBW applications. By utilization of symmetric and orthogonal placement of two-pair of slots and superimposing two orthogonal far-field components with maintaining equal magnitudes between them, a wide 3-dB ARBW can be achieved. The magnitude of E_φ component and the electric field distribution on patch surface are regulated by tuning the distance between the MDs. The analysis of electric field distributions and the magnitudes of far-field components as a function of the spacing between the slots (MDs), not only explicates a clear understanding of wide beamwidth CP radiation but also produces a simple relationship between the physical parameters of the antenna and its characteristics. The foundation of the proposed antenna is established by its extensive beamwidth in all the principal planes and across the entire CPBW. Therefore, it can be expected from the proposed design to catch up applications in many communication systems due to its low-profile and superior outcomes.

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