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Circularly Polarized Hexagonal Microstrip Antenna Loaded with Slot and Complementary Split Ring Resonator

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Abstract

The development of a compact and straightforward circularly polarized hexagon-microstrip patch antenna with two layers and a single feed is presented. Circular polarization is achieved using two strategies. The first technique incorporates a narrow slot along one vertex of a hexagonal patch's diagonal, opposite the feed line. The second one is based on embedding a complementary split ring resonator on the hexagonal patch. The proposed antenna is excited by an aperture coupling feed, and it is implemented on two substrate materials; the patch substrate is Roger droid/RT-5880, and the second feed substrate is RO 4350. This work compares the performance of the suggested antennas, including their radiation characteristics, axial ratio, and return loss, in two different scenarios. The proposed antenna has overall dimensions of (0.8λ0 - 0.8λ0 - 0.037λ0) at 3.4 GHz. The slot patch antenna has 2.65% bandwidth for its 3-dB axial ratio and 5.71% impedance bandwidth from 3.4 to 3.6 GHz at 3.5 GHz of the center frequency. The proposed patch antenna also demonstrates a maximum gain of 1.2 dBi. High-frequency structure simulation software was used to design and simulate the proposed hexagon configurations.

Keywords: Circular Polarization; Slot Antenna; Microstrip Antenna; WiMAX.

1. Introduction

Circularly Polarized (CP) microstrip antennas have attracted significant attention in modernistic applications such as satellite, WiFi, WiMAX, and mobile communications. CP microstrip antenna has many features; it allows the signal more polarization flexibility between the transmitter and receiver antennas [1]-[6]. Additionally, they provide better mobility and weather penetration, mitigation in multi-path effects, reduced fading effect, and overcoming the Faraday rotation in the ionosphere layer, and the orientation of the transmitter to the receiver. Therefore, they have received much attention for satellite communications, radio frequency identification (RFID) reader antenna, GPS, modern wireless systems, antennas for energy harvesting, and wireless communication systems [7]-[12].

Circularly polarized microstrip patch antennas (CP-MPAs) could have many various configurations. The essential operation of CP is to emit two linear polarization modes with the same strength and 90° phase difference. Several researches on CPMAs have been reported in [7]-[13]. CP microstrip patch antennas can use different types of feed technologies. The scheme of the antenna feed could be mainly classified into three groups: single-feed [14],[15], dual-feed [16], and sequential array [17]. A circular polarization antenna with a single feed is more straightforward than a dual feed and sequential variety in terms of the complexity of the antenna structure.

To excite an orthogonal pair of modes with a 90° phase-shift for achieving CP, the single feed approach provides a slight perturbation to the patch structure at the appropriate location for the feed. For single-feed configurations, standard perturbation methods include introducing cross or multiple slots, truncating corners, and loading slits, spur lines, and boundary stubs. To create two orthogonal modes with identical amplitude but perpendicular to each other, a radiating patch is often equipped with one or multiple slots or slits in a particular orientation [13]. Complementary split ring resonator (CSRR) structures were recently etched in the ground or patch to achieve circular polarization, as reported in [18]. Nevertheless, single-feed patch antennas often have a very narrow impedance bandwidth. Axial-ratio bandwidth is useless for many wireless communication applications [2]. The typical permitted axial ratio bandwidth for single-feed instances does not exceed 10% [2]. Dual-feed and sequential array structures could produce a wider AR bandwidth, but these structures may require more space and have more complex design requirements [5].

This work aims to achieve a circularly polarized hexagon microstrip patch antenna (HMPA). This work is divided into two major parts: the first technique is related to using the slot along the diagonal. The CP characteristics can be easily achieved by appropriately changing the narrow slot's dimensions. The second method uses a Complementary Split Ring Resonator (CSRR) on HMPA. Additionally, an aperture coupling single-feed is used as a feeding technique. The suggested HMPA was designed and optimized using full-wave simulation software; HFSS v.11 is utilized to produce simulation results.

This paper's investigation is completed in four sections. The next section introduces antenna design equations. Section 3 represents the antenna configuration of the proposed HMPA. Section 4 discusses the simulation and analysis of the results. Finally, section 5 summarizes brief conclusions about the suggested antenna.

2. Antenna Design Equations

The design equations for the hexagonal microstrip patch antenna are derived using a method similar to that of a circular patch. The HMPA's resonance frequency is determined by [19]:

$$f_r = \frac{X_{mn} c}{2\pi a_e \sqrt{\varepsilon_r}} \quad (1)$$

Where: f_r is the resonance frequency (in this work f_r =3.5 GHz), X_{mn} =1.8411 for TM_{11} mode as in circular patch antenna, c is the speed of light in free space, ε_r is the relative permittivity of substrate material.

$$a_e = a\left[1 - \frac{2h}{\pi r \varepsilon_r}\left(ln\left(\frac{\pi r}{2h}\right) + 1.7726\right)\right]^{0.5} \quad (2)$$

Where: a is the radius of the circular patch and h is the substrate height.

The hexagon side Length 'L' for a resonant frequency of f_r = 3.5 GHz is given as follows [20]:

$$L = 1.099\ a_e \quad (3)$$

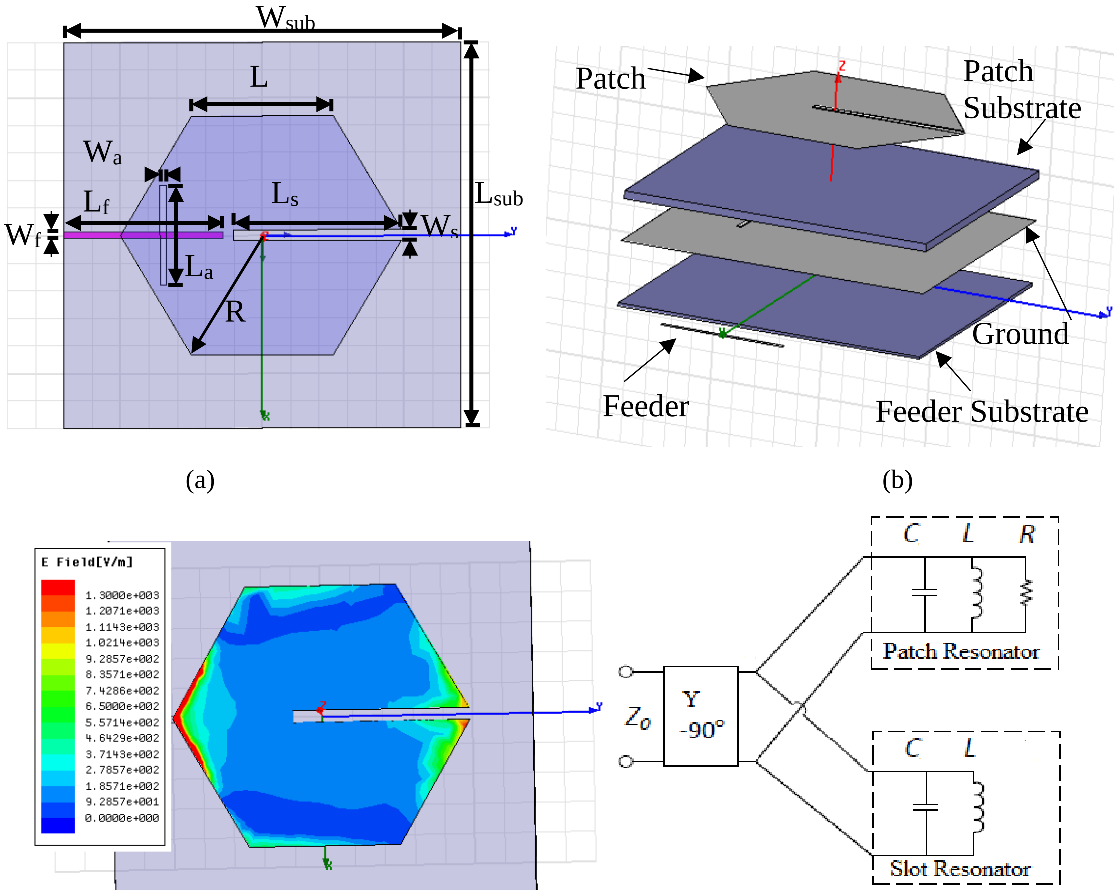
3. Antenna Configuration and Design

Circular polarization can be produced if two orthogonal patch modes are simultaneously excited with equal amplitude and 90° out of phase. Generally, a microstrip patch with a single feed produces a linear polarization. To achieve CP for a single feed microstrip patch, perturbing the patch is accomplished at the appropriate location with respect to feeding, such as truncating a pair of patches at opposite coroner or slots. In this work, choosing a narrow straight slot (L_s×W_s) incorporated into HMPA along the diagonal axis provides the necessary perturbation. The fundamental resonance mode of HMPA can be split into two orthogonal modes with identical magnitude and 90 relative phase shifts. Thus, the hexagonal microstrip patch antenna can produce circular polarization without requiring a hybrid coupler.

In this paper, three antenna configurations are discussed and compared. The first part is related to the design of HMPA with the straight slot. The second is an HMPA loaded with one CSRR, and the third configuration is loaded with two hexagonal CSRRs of identical size. The basic 2D geometry of the proposed aperture-coupled CP-HMPA with its parameters is depicted in Fig. 1(a). The hexagon patch antenna has a side length (L) and radius (R). The feeding network comprises an aperture coupling feed (L_a, W_a). The aperture coupling technique couples the radiator to the microstrip feed line (L_f, W_f) through an aperture. The impedance matching of the antenna could be tuned by changing the dimensions of the aperture coupling feeding. This single-feed aperture coupling greatly simplifies the feed network compared to conventional dual-feed network circular polarized antennas. Fig.1 (b) represents the 3D structure of the proposed hexagon patch antenna, and its optimized dimensions are listed in Table 1.

The primary proposed HMPA structure consists of two substrate layers. The hexagonal patch radiator is mounted on the first substrate material. HMPA is designed on Roger duroid/RT-5880 dielectric substrate of ε_r = 2.2 dielectric constant and height of substrate of h = 1.58 mm. In this work, an aperture coupling feed network working at 3.5 GHz (WiMAX band) was printed on the bottom of the second dielectric substrate RO4350 with 0.51 mm thick dielectric with a permittivity of 3.44. The microstrip feed line is placed at the center of the aperture. A slot is etched on the patch antenna in the first antenna design. The proposed HMPA has an overall size of 70×70×2 mm^3.

The HMPA radiator can be represented by a shunt RLC resonator, and the slot can be modeled as an LC resonator. The mutual coupling between the two resonators can be represented by the admittance with a phase delay of -90 degrees. Fig 1 (c) depicts the equivalent circuit of the proposed first configuration.



(a) (b)

(c) (d)

Figure 1. The proposed antenna configuration is loaded with a slot (a) 2D structure, (b) 3D structure, (c) Field distribution, and (d) Equivalent circuit of the proposed HMPA.

Table 1. Antenna-optimized dimensions in (mm)

Parameters	Values	Parameters	Values
W_{sub}	70	Ls	30
L_{sub}	70	R	25
W_f	1.1	L	25
L_f	28	W_c	1.1
Ws	2	L_c	18

The second configuration is incorporated in the next step by etching a hexagon CSRR onto the patch antenna. CSRR has been used to allow the excitation of the pair orthogonal modes along the diagonals of the hexagon patch. Thus, the circular polarization radiation is obtained. Properly adjusting the slot, the width distance between the two rings, the position of CSRR, and the distance between the two CSRRs can achieve optimal performance for circular polarization. The optimal dimensions of CSRR that enable the best return loss and AR are displayed in Table (2).

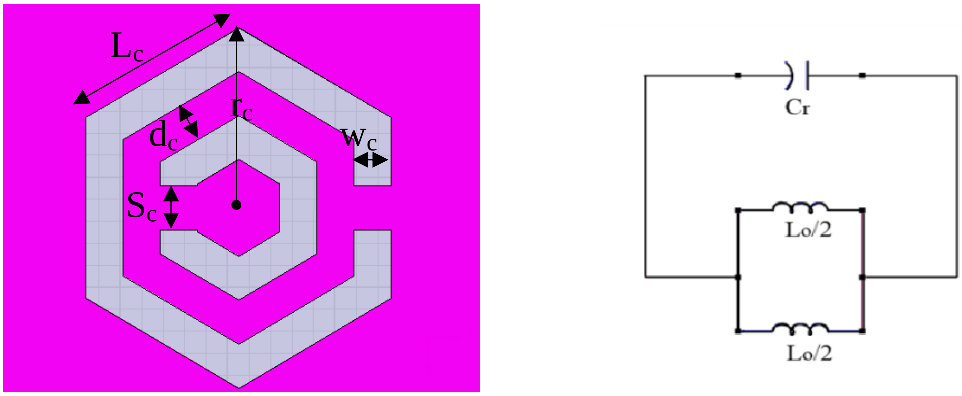
Parallel L-C resonant circuits are represented for both SRR and CSRR with identical resonance frequencies given by [18]:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

Table 2. Optimized dimensions of CSRR

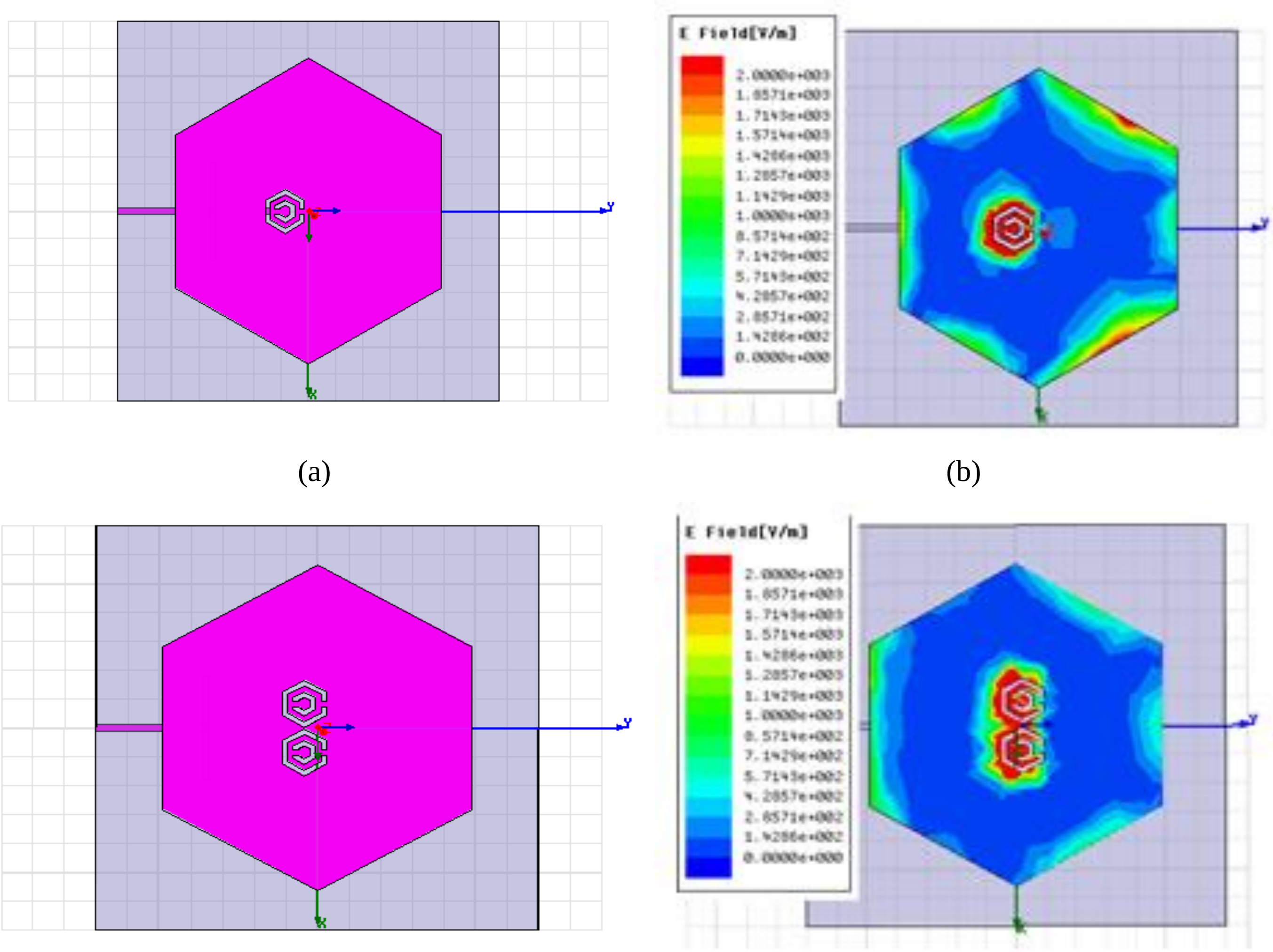
Parameters	Values(mm)
w_c	4.1
L_c	8.6
S_c	1
d_c	1
r_c	4.1

Fig. 2(a and b) display the CSRR unit element and its equivalent circuit. Metamaterial unit cells are used in antenna design because of their distinctive properties. By loading CSRRs on the patch, a similar resonance can also be created near the patch's intrinsic resonance. Fig 3(a and c) depicts HMPA etched with one and two hexagon CSRRs on the patch. The other specifications are the same as in the first design. The field distribution of the patch antenna is provided in Fig. 3(b and d). It is noticed that the field distribution in CSRR is stronger.



(a) (b)

Figure 2. CSRR structure (a) 2D geometry (b) Equivalent circuit for CSRR.



(a) (b)

(c) (d)

Figure 3. The proposed antenna with CSRR: (a) with one CSRR; (b) Field distribution for one CSRR (c) with two CSRR (d) Field distribution for two CSRR.

4. Simulation Results

The simulation results of three suggested antennas are introduced using high-frequency structure simulation (HFSS) software. HFSS has been used to measure axial ratio, reflection coefficient, and radiation pattern in E and H planes. The prototype hexagon patch antenna (without slot) performance was initially investigated as in Table (3). The configuration is modified by creating a slot, as displayed in Fig. 1(b). Circular polarization would be achieved by adequately choosing different dimensions of this slot. The comparative performances of the CP antenna, such as axial ratio and return loss with varying values of this slot, are discussed and tabulated in Table 3. Table 3 shows that the traditional HMPA cannot achieve circular polarization (AR=24.6>3). On the other hand, the other three configurations with different slot lengths generate circular polarization (AR<3).

Table 3. Performance of different configurations of hexagons with and without slot

	Slot Length (mm)	**S_{11} (dB)**	**S_{11} (dB)**	**S_{11} (dB)**	**AR (< 3)**
Ex1	0	-25.7 at 3.5GHz	14.5at 4GHz	-22 at 4.6GHz	24.6 at 3.5GHz
Ex2	30	-18.8at 3.5GHz	-15.6at 4.2GHz	-32.7at 4.8GHz	1.09 at 3.5GHz
Ex3	18.5	-18.5at 3.5GHz	-15.6at 4.2GHz	-30at 4.8GHz	1.31at 3.5GHz
Ex4	12	-18.2at 3.5GHz	-16.2at 4.1GHz	-26.1at 4.8GHz	1.7 at 3.5GHz

Fig. 4(a) depicts the simulated results for the S-parameters, AR, and radiation pattern in principle planes of the proposed CP-HMPA. From Fig. 4(a), it can be seen that the antenna system can be operated at three bands, 3.5, 4.2, and 4.82 GHz, which corresponds to return loss of -18.8, -15.6, and -32.7 dB, respectively. Fig. 3(b) demonstrates a simulated axial ratio of 1.09 dB at 3.5 GHz (AR<3), which satisfies the circular polarization at this frequency. It is noticed that the axial ratio bandwidth of circular polarization was 40 MHz. It was also noticed that a 200 MHz impedance bandwidth (10 dB return loss) was achieved for HMPA. The radiation patterns in the principal planes are exhibited in Fig. 4(c).

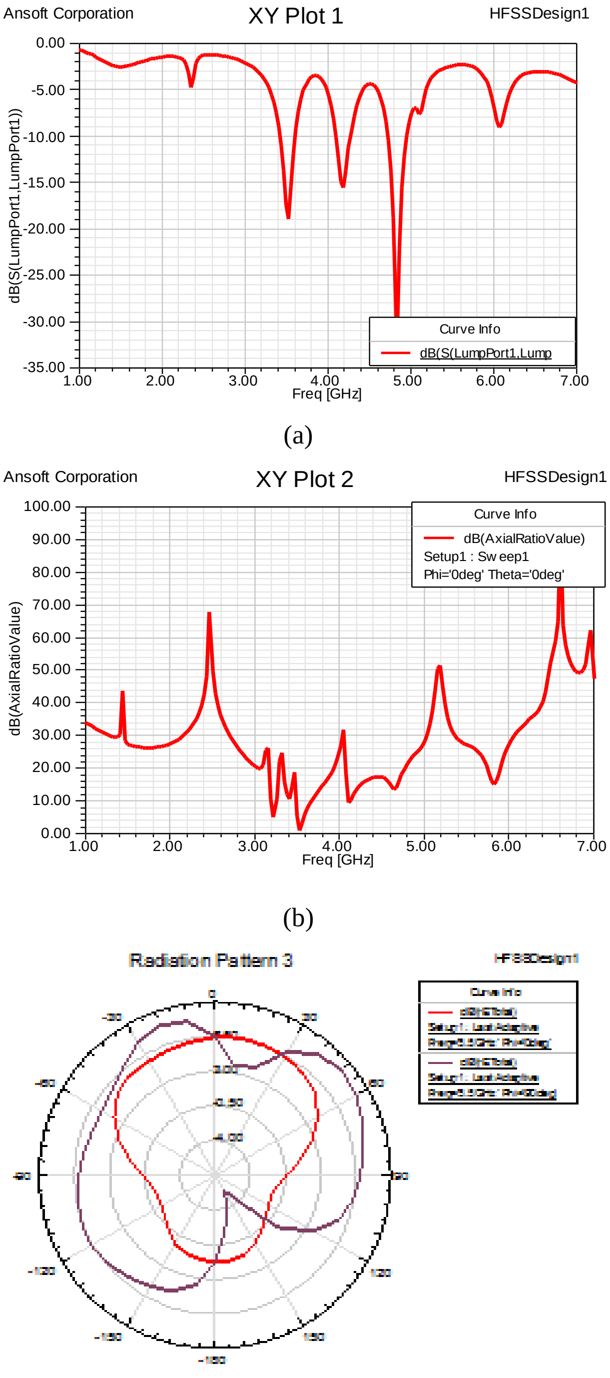
In the second design (as depicted in Fig.3(a)), the other specifications are the same as in the first antenna prototype. As shown in Fig. 5(a), the return losses are -18 dB, -17dB, -13 dB, and -24 dB at 3.4, 3.8, 4.25, and 5.2 GHz, respectively. The circular polarization (AR<3) is achieved at a frequency of 3.4 GHz, as shown in Fig. 5(b). Fig. 5(c) depicts the radiation pattern in the E and H planes. The return loss -10 dB bandwidth is 91.4 MHz at the center frequency of 3.4 GHz. The 3-dB axial ratio CP bandwidth is 93 MHz at the center frequency of 3.4 GHz.

As shown in Fig.3(c), the third modified configuration of the proposed HMPA is related to using a pair of identical CSRR on HMPA.

Fig. 6(a) displays return loss, axial ratio, and radiation pattern for the third configuration of the proposed antenna. It is noticed that the return losses are -18 dB, -17 dB, -15 dB, and -29 dB at 3.4, 3.8, 4.2, and 5.9 GHz, respectively. From Fig. 6(b), AR is 1.7 (AR<3) at 3.8 GHz and circular polarization is achieved at this frequency. Finally, the radiation patterns of the principal planes of this proposed configuration are shown in Fig. 6(c). Table (4) displays comparative circular polarization performance for different references.

Fig. 7 (a) and (b) depict the optimized parameters based on return loss and AR for four configurations, respectively. A traditional HMPA (without a slot) displays a bad axial ratio, whereas the proposed hexagonal antenna configuration with a slot and CSRR shows an axial ratio of less than 3.

To compare four configurations (conventional HMPA, HMPA with slot, one CSRR HMPA, and two CSRR HMPA) concerning S-parameters and axial ratio. It is noticed that conventional HMPA and slot HMPA resonate at three bands. Meanwhile, HMPA with one and two CSRR resonate in four bands, as shown in Fig. 7(a). On the other hand, the conventional configuration cannot achieve the circular polarization. While the other proposed configurations achieve circular polarization at a single band, as exhibited in Fig. 7(b).

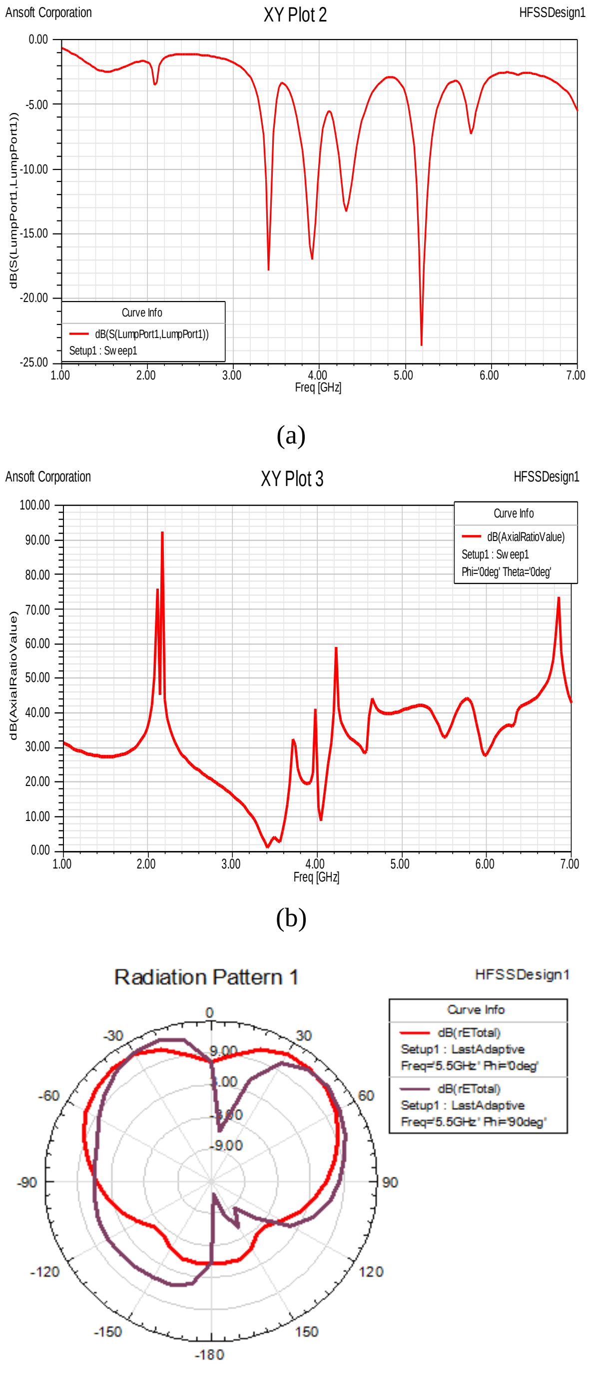


(a)

(b)

(c)

Figure 4. (a) Reflection coefficient for the proposed antenna (b) axial ratio against frequency (c) Radiation pattern



(a)

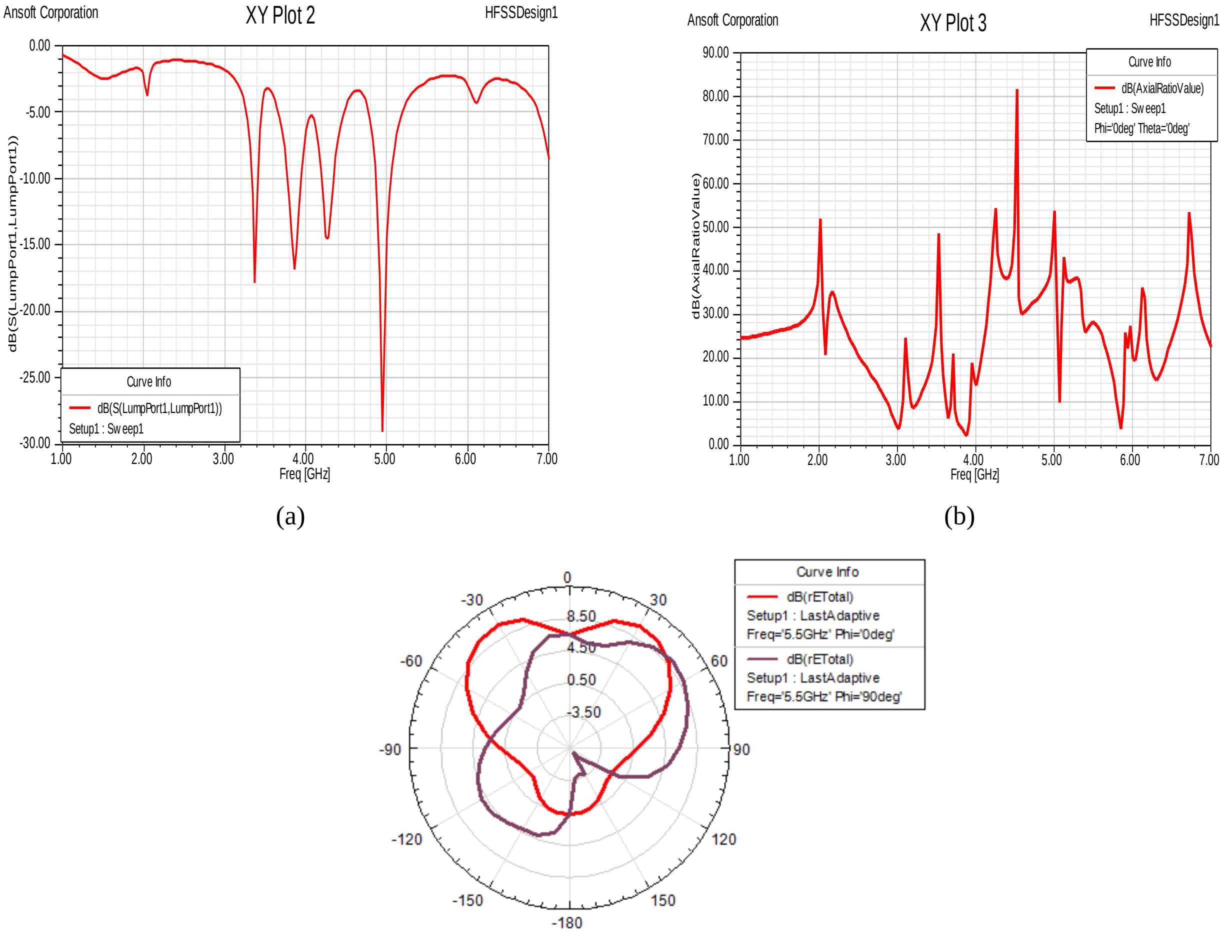
(b)

(c)

Figure 5. (a) Reflection coefficient for the proposed antenna (b) Simulated axial ratio against frequency (c) Radiation pattern in E and H-planes

Table 4. Comparison between the proposed work and several circular polarization antennas

Ref.	size	No. of bands	Impedance BW%	ARBW%	Gain
[2]	0.6λ×0.6λ	Two	3.7, 1.2	0.9, 0.6	1.7, 1.45
[17]	2.95λ×2.95λ	one	34.3	20.4	11.1
[18]	0.9λ×0.9λ	one	5.1	7.5	4.5
[21]	0.5λ×0.5λ	Three	3.6	2	----
Proposed work	0.8λ×0.8λ	One	2.65	5.71	1.2



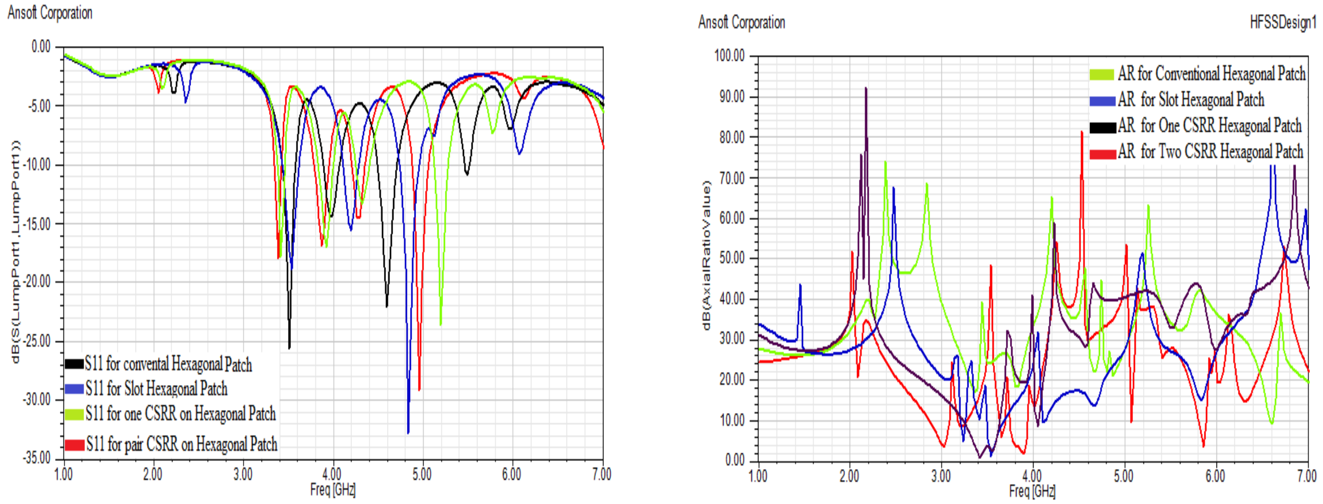
(a) (b)

(c)

Figure 6. Performance for the proposed antenna (a) Reflection coefficient (b) Simulated axial ratio against frequency (c) principal planes radiation pattern.

4. Conclusions

This work demonstrates a new and simple HMPA with two techniques to produce an excellent circular polarization radiation performance. The first technique is related to using a slot on a hexagonal patch. Triple bands (3.5, 4.2, and 4.8 GHz) and CP are achieved at 3.5 GHz. It uses single-feed with aperture coupling feed microstrip patch antennas with an embedded narrow slot that has been demonstrated. The circular polarization can be obtained by adequately adjusting the narrow slot's dimensions and using an aperture coupling feed. The second technique also produces CP radiation performance using HMPA loaded with CSRR at 3.4 GHz. The proposed antennas provide an ARBW of 1.14% and an impedance bandwidth of 5.71% for the first technique and an ARBW of 2.735% and an impedance bandwidth of 2.688 for the second technique. The proposed antennas are more suitable for wireless applications. The properties of the compact size and circular polarization CP make these designs ideal for RFID applications.



(a) (b)

Figure 7. Antenna performance for antenna (a) Reflection coefficient (b) Simulated axial ratio against frequency

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Sadiq A. proposed and developed the methodology.
Zaid A. H. verified the analytical methods and investigated them.
Zahraa H. M.: performed the software.
Mohammed Al-S.: investigated and validated the work.
Madhukar C. reviewed and edited the work.

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