Circularly Polarized Dodecagonal Patch Antenna with Polygonal Slot for RFID Applications

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Abstract—This paper presents a compact 2.45 GHz single feed directional circularly polarized (CP) microstrip antenna for radio frequency identification (RFID) applications. The proposed antenna comprises a dodecagonal microstrip patch embedded with an irregular polygonal slot, fabricated on an FR4 substrate. Two antennas, one with right-handed circular polarization (RHCP) and the other with left-handed circular polarization (LHCP), both resonating at a frequency of 2.45 GHz are presented. The measurement results show a 3 dB axial ratio bandwidth of 5.5%, a 10 dB impedance bandwidth of 5.7% for both the antennas, a peak gain of 4.82 dBi for RHCP antenna and 4.67 dBi for LHCP antenna. In addition, the antennas provide symmetrical patterns with 88° half-power beam width. The overall size of the antenna is 50 mm × 50 mm × 1.6 mm and offers an area reduction of 21.17%.

1. INTRODUCTION

Usage of circularly polarized (CP) antenna in wireless systems is an effective way to mitigate multi-path effects. Hence CP antenna is widely accepted as a key subsystem for various wireless systems including RFID [1]. It is possible to avoid the false identification of targeted objects by RFID readers if the antennas used are circularly polarized. A single co-axial fed circularly polarized antenna is simpler in its structure than dual-fed ones, as it can excite CP radiation without using an external polarizer. In a singly fed CP antenna, the generated mode is usually excited in an electrically thin cavity region of the microstrip antenna. The generated mode is separated into two orthogonal modes by the effect of a perturbation segment such as a slot, truncated segment or other asymmetries. A wide variety of perturbation methods have been adopted in literature for designing a single feed circularly polarized microstrip antenna. One 'V' shaped slot embedded into a cross shaped rectangular patch antenna [2], square patch embedded with a cross slot and an L-shaped open-end microstrip line linked to a tag chip, terminated by a shorting pin on the other end and capacitively coupled to the patch [3], an arrowhead-shaped slot is embedded in the first quadrant along the diagonal axes of a square patch [4], a circular patch antenna with central elliptical slot [5], two stacked patches fed with an S-shaped impedance-matching network [6] are some of the distinct techniques employed to excite circularly polarized radiation.

In this work, a novel microstrip patch antenna — 12 sided polygon (dodecagon) shaped patch — with the perturbation technique of embedding a central irregular hexagon shaped slot, for exciting CP radiation designed for the 2.45 GHz band is proposed. Good CP bandwidth and compactness is achieved on account of the central slot. The structure exhibits good impedance matching, gain and circularly polarized radiation characteristics over the entire operating band.

2. ANTENNA GEOMETRY

The proposed antenna is designed on an FR4 substrate of size $50\,\text{mm} \times 50\,\text{mm} \times 1.6\,\text{mm}$, with dielectric constant 4.4, thickness 1.6 mm and $\tan\delta = 0.02$.

By introducing some asymmetry in the structure, the resonant frequencies of two degenerate modes can be made slightly different from each other with equal amplitude and a phase difference of 90° between them, for producing CP. The simplest way to split the fundamental mode is, to cut a slit through the center [5]. The novelty in this work is the selection of shape for the patch and the method of introducing asymmetry by means of the irregular hexagonal slot as depicted in Figure 1(d). The slot is positioned in the center of the patch and oriented along the X axis. The dimensions of the slot are chosen such that $b < c < d$. The parameter 'k' is defined as the ratio, 'd' to 'c' with 'b' constant. The choice of dimensions of the slot and the feed position ensure the splitting of the fundamental mode into degenerate modes and phase quadrature between them. The radiation of circularly polarized wave is highly sensitive with respect to the position of the feed point and the dimensions of the central slot [5]. The antenna is excited through the co-axial probe at the location 'X' to produce Right Handed Circular Polarization (RHCP) and at the feed location 'Y' to radiate electromagnetic waves with Left Handed Circular Polarization (LHCP). The feed point for RHCP antenna is the mirror image as that of the LHCP antenna with respect to the center of the patch, chosen along the locus of $50\,\Omega$ characteristic impedance and is adjusted for the best matching.
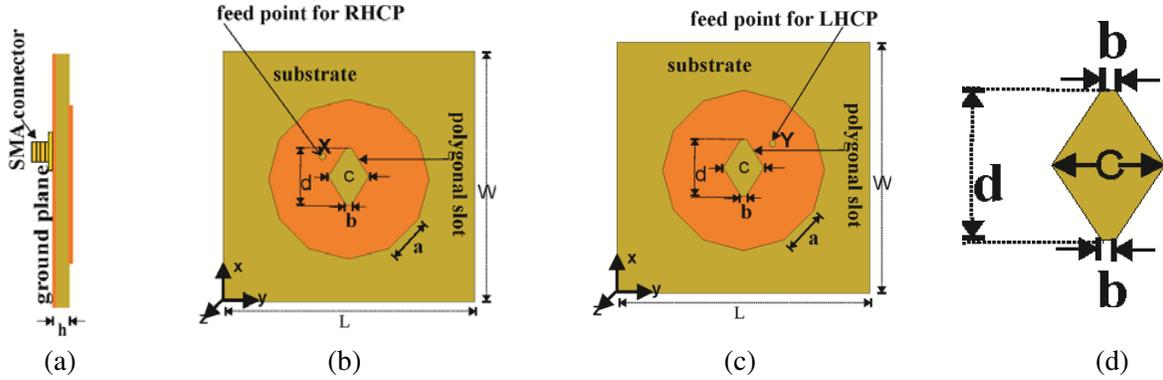
Figure 1. Geometry of the proposed antenna. (a) Side view, (b) top view of the RHCP antenna, (c) top view of the LHCP antenna and (d) the central slot geometry. Guided wavelength $\lambda g = 0.0604\,\text{m}$, $a = 8.28\,\text{mm}$ $(0.137\lambda g)$, $b = 1\,\text{mm}$ $(0.0166\lambda g)$, $c = 8\,\text{mm}$ $(0.1325\lambda g)$, $d = 11.4\,\text{mm}$ $(0.189\lambda g)$, $k = 1.425$, $L = W = 50\,\text{mm}$ $(0.8278\lambda g)$, X $(29\,\text{mm}, 19.8\,\text{mm})$ and Y $(29\,\text{mm}, 30.2\,\text{mm})$.

3. DESIGN

In order to design the dodecagonal patch antenna, the design of the circular patch antenna is considered first, as it is closely related to the proposed structure [7]. The side length 'a' of the regular dodecagon for a resonant frequency of $f_r = 2.77\,\text{GHz}$ is computed as follows. The dominant mode resonance frequency of a circular patch is given by [7] as,

$$f_r = \frac{X_{mn}c}{2\pi r_e \sqrt{\epsilon_r}} \tag{1}$$

where 'f_r' is the resonant frequency of the patch, $X_{mn} = 1.8412$ for the dominant mode TM_{11}, 'r_e' the effective radius of the equivalent circular patch,

$$r_e = r\left\{1 - \frac{2h}{\pi r \varepsilon_r}\left(\ln\frac{\pi r}{2h} + 1.7726\right)\right\}^{0.5} \tag{2}$$

where 'r' is the radius of the circular patch and 'h' the height of the substrate. The edge of the regular dodecagon 'a' may be found out [7] as,

$$a = r_e \sqrt{\frac{\pi}{11.196}} \tag{3}$$

When a patch antenna is considered, its mode impedance $Z_{mn}(\omega)$ may be expressed [5] as,

$$Z_{mn}(\omega) = R_{mn}\zeta_{mn}(\omega) \tag{4}$$

where 'mn' represents the mode, $m, n = 0$ to ∞; R_{mn} represents the sum of the radiation, dielectric and metal losses; $\zeta_{mn}(\omega)$ is the normalized frequency response written in terms of the quality factor Q_{mn} and modal resonance frequency ω_{mn}. The quality factor Q depends to a large extent on the antenna geometry. By the proper selection of the feed point, the dominant mode is detuned into two equal amplitude orthogonal degenerate modes, orthogonal even mode TM_e and orthogonal odd mode TM_o, without considering the higher order modes. Even mode is the mode that is symmetric with respect to the Y axis and odd mode is symmetric with respect to the X axis. Correspondingly total input impedance may be written [5] as,

$$Z_{in} = Z_e + Z_o \tag{5}$$

where Z_e and Z_o are the even mode and odd mode impedances respectively. ω_e is the even mode angular frequency and ω_o the odd mode angular frequency, with $\omega_e < \omega_o$. By introducing the asymmetry, the resonant frequencies of two degenerate modes are made slightly different from each other. The normalized impedance ratio is defined [5] as,

$$\beta_\zeta(\omega) = \frac{\zeta_o(\omega)}{\zeta_e(\omega)} = \frac{1 + jQ\left(\dfrac{\omega}{\omega_e} - \dfrac{\omega_e}{\omega}\right)}{1 + jQ\left(\dfrac{\omega}{\omega_o} - \dfrac{\omega_o}{\omega}\right)} \tag{6}$$

where 'Q' is the quality factor and assumed to be the same for the detuned modes. The angle of $\beta_\zeta(\omega)$ is the phase difference of the CP field components, while the magnitude is proportional to the axial ratio. Here the angle of $\beta_\zeta(\omega)$ is designed to be $90°$ and the magnitude to be less than $3\,dB$. The fundamental mode splits into degenerate orthogonal modes, where for the odd mode, which is oriented towards the slot (X axis), the perturbation is minimum, being the top and bottom width of the slot is narrow enough. If the slot had been a rectangular geometry with width 'b' and height 'd', with no change in orientation, the odd mode surface current would not have been affected by this perturbation and the resonant angular frequency would have been approximately same as that of the fundamental resonant frequency [8]. In the even mode (oriented about the Y axis), the surface current is forced to traverse more length around the slot and hence the resonant frequency ω_e is reduced. If a second orthogonal cut is made at the center [3], it will enhance the electrical path of the odd mode and the corresponding resonant frequency will be reduced. In the proposed structure, instead of making an orthogonal cut, the central width of the hexagonal slot is made larger than the top and bottom width. The effect of the

(a)   (b)
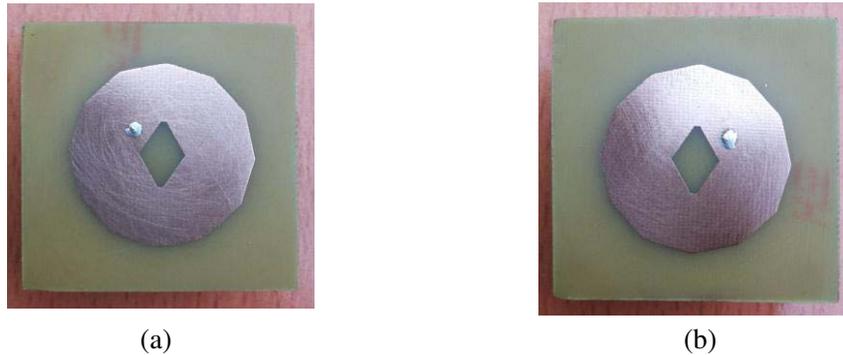
Figure 2. Photographs of the antenna prototypes. (a) RHCP antenna, (b) LHCP antenna.

second orthogonal cut is achieved due to this enhancement of central width. As in the case of even mode, current in the odd mode also has to traverse more length and therefore resonant frequency is reduced. By selecting appropriate dimensions for the slot, the two degenerate mode frequencies are made nearly equal. The central slot, thus introduces annular effect and thereby enhanced bandwidth [8]. Though the edge of the dodecagonal patch is designed for a resonant frequency of 2.77 GHz, due to the presence of the central slot the resonant frequency is reduced to 2.45 GHz and hence an area reduction of 21.17% is achieved.

4. RESULTS AND DISCUSSION

Using the computed parameters, the structure is simulated using Ansys HFSS13.0. The simulation graphs of return loss, axial ratio and surface current pattern are plotted and depicted in Figures 3 to 5. Antenna prototypes are fabricated on an FR4 substrate with optimized parameters and the antenna measurements are done using the ZVB20 Network Analyzer. The measured and simulated reflection characteristics of the RHCP antenna are compared in Figure 3. It is noted that the fundamental resonant frequency of the antenna without slot is 2.77 GHz, whereas with slot the simulated resonant frequency is 2.46 GHz and the experimental result is 2.45 GHz. A variation of the axial ratio with 'k' is studied by simulation as in Figure 4. It is observed that when the value of $k \geq 1.25$, axial ratio becomes less than 3 dB and thus one criterion for CP radiation is satisfied. $k = 1.425$ gives good results.
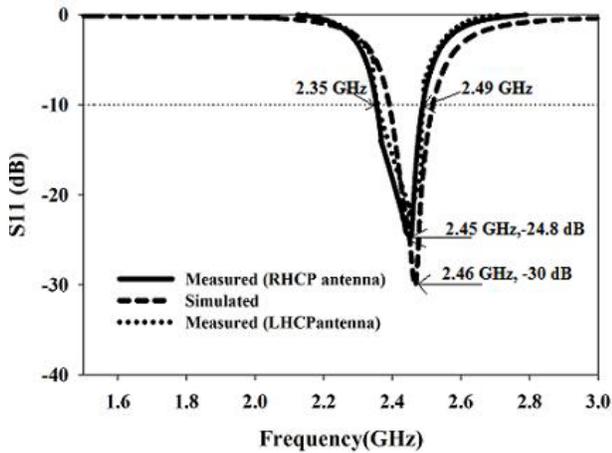

**Figure 3.** S_{11} plots of the proposed antennas.
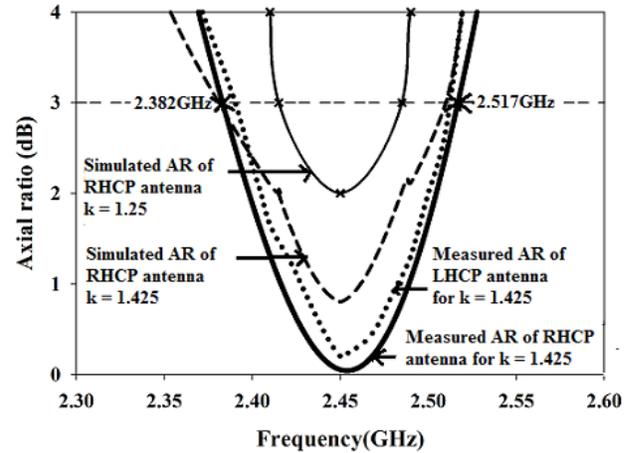
Figure 4. Axial ratio plot.

$\varphi = 0^{\circ}$ $\varphi = 90^{\circ}$ $\varphi = 180^{\circ}$ $\varphi = 270^{\circ}$

(a)   (b)   (c)   (d)
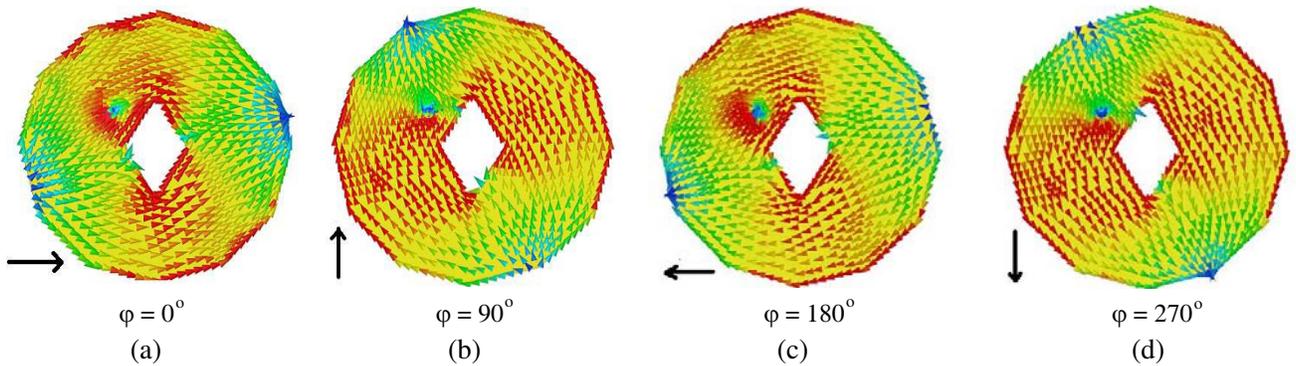
Figure 5. Simulated surface current distribution of the RHCP antenna at four different values of the excitation phase angle φ.

The surface current distributions simulated for RHCP antenna at the center frequency of 2.45 GHz are plotted in Figure 5. Surface current distribution at the excitation phase angle $\varphi = 0°$ is equal in magnitude and opposite in direction to that at $\varphi = 180°$. Same is the case of surface current distribution at $\varphi = 90°$ and $\varphi = 270°$. It is true for both the antennas and hence the criterion for CP is satisfied. As the direction of view chosen as $+Z$-axis, the direction of rotation of current is anticlockwise and the sense of polarization is confirmed as left handed circular polarization for the feed position Y. The direction of rotation of current is clockwise and the sense of polarization is confirmed as right handed circular polarization for the feed position X. The sense of polarization is also tested and verified using
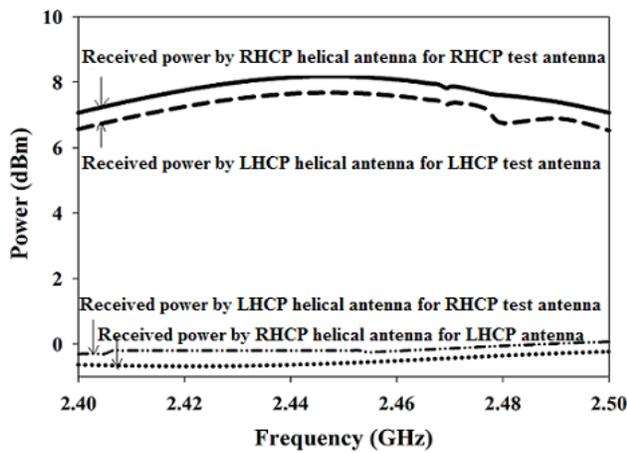
Figure 6. Plots of received power by RHCP and LHCP helical antennas.
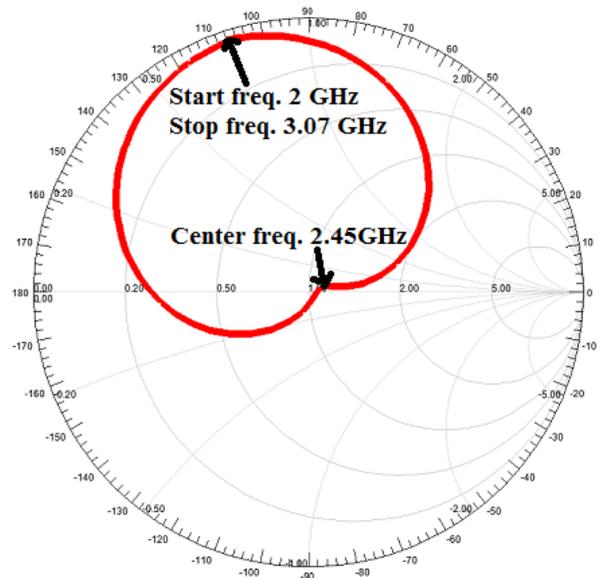

Figure 7. Simulated Smith chart of the RHCP and LHCP antennas.


(a)

(b)
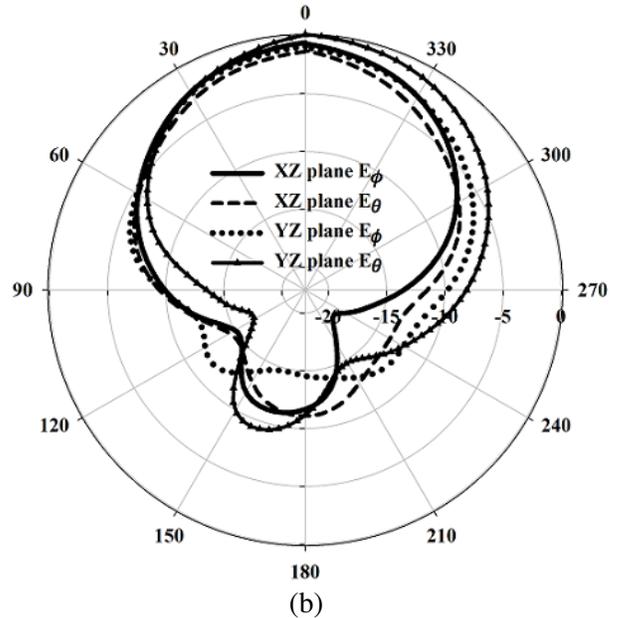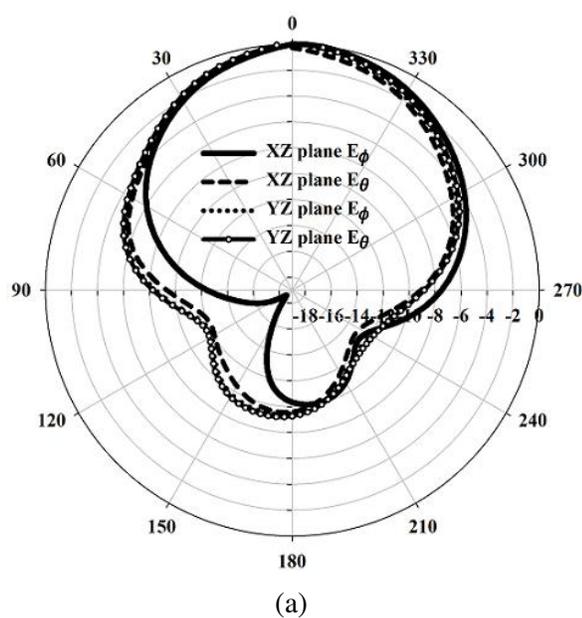
Figure 8. Measured radiation pattern plots of (a) RHCP antenna, (b) LHCP antenna.

helical antennas designed at the measured resonant frequency 2.45 GHz as per the design methodology in [9, 10] and Figure 6 depicts corresponding received power plots. The simulated Smith chart depicted in Figure 7 indicates a dip marked at the center frequency 2.45 GHz corresponding to RHCP and LHCP antennas. Hence the excitation of two orthogonal degenerate modes in both the antennas is confirmed, justifying the circularly polarized radiation [11].

The measured radiation patterns of RHCP and LHCP antennas in the XZ and YZ planes for $\varphi = 0°$ and $90°$ are plotted in Figure 8. The patterns are almost identical. The gain is measured using gain-comparison method and depicted in Figure 9. It is observed that the gain is slightly more for the RHCP antenna than that of the LHCP antenna.

The measured values of the proposed RHCP and LHCP antennas are compared to the circular
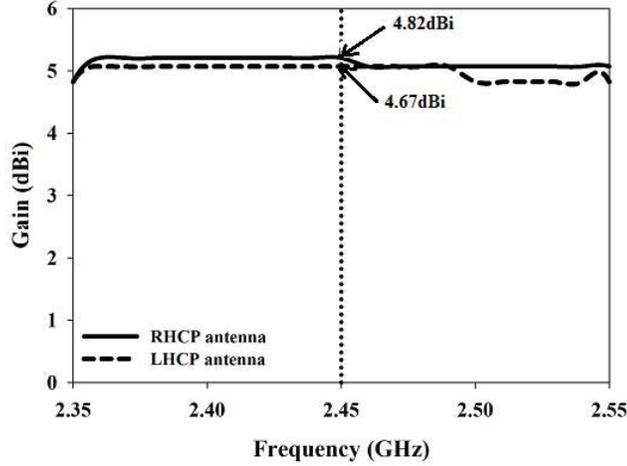

Figure 9. Measured gain plot of the proposed antennas.

Table 1. Comparison of measured values of the proposed antennas with the circular patch.

Parameter	Circular patch antenna with elliptical slot [5]	Proposed RHCP antenna	Proposed LHCP antenna
Center frequency	2.45 GHz	2.45 GHz	2.45 GHz
Return loss	19 dB	24.8 dB	22 dB
Gain	3.85 dBi	4.82 dBi	4.67 dBi
Minimum axial ratio	0 dB	0.06 dB	0.2 dB
Axial ratio bandwidth	30 MHz (1.22%)	135 MHz (5.5%)	135 MHz (5.5%)
10 dB impedance bandwidth	130 MHz (5.3%)	140 MHz (5.7%)	140 Hz (5.7%)
3 dB Beam width	-	88°	88°
Area reduction	9.5%	21.17%	21.17%

Table 2. Comparison of theoretical and optimized values of the proposed antennas.

Parameter	Theoretical value	Optimised value of the RHCP antenna	Optimised value of the LHCP antenna
Resonant frequency	2.42 GHz	2.45 GHz	2.45 GHz
Input impedance	57 Ω	56.1 Ω	58.6 Ω
Return loss	23.68 dB	24.8 dB	22 dB
Minimum axial ratio	0.2567 dB	0.06 dB	0.2 dB

patch antenna [5] and tabulated in Table 1. Theoretical values of the following antenna parameters for the proposed antennas are computed [10, 12], compared with the optimized values and tabulated in Table 2.

Here the theoretical value of the resonant frequency is computed based on 14.81% increase in electrical length due to the central slot on the patch antennas.

5. CONCLUSION

A single feed circularly polarized irregular hexagonal slotted regular dodecagonal patch antenna has been designed, simulated and experimentally investigated. The structure is novel due to the choice of dodecagon shape for the patch and the central hexagonal slot perturbation method. The antennas cover RFID band with a center frequency of 2.45 GHz, with broadside radiation characteristics. The measured 10 dB impedance and 3 dB axial ratio bandwidths confirm the usefulness of the structures to industrial, scientific and medical (ISM) bands in handheld RFID reader applications.

ACKNOWLEDGMENT

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