A compact inverted Y-shaped circularly polarized wideband monopole antenna with open loop

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Abstract
This article presents a novel, compact, single feed circularly polarized (CP) microstrip antenna. Proposed design involve an inverted Y-shaped radiating patch fed by an L-shaped microstrip line feed and a rectangular open-loop placed near its right corner. A semi-rectangular ground plane is used on the opposite side of the substrate. Coupling between the rectangular open-loop and the inverted Y-shaped patch plays a vital role in attaining wideband CP, while the semi-rectangular ground plane is crucial for enhancing impedance bandwidth (IBW). The optimized design achieved measured wide IBW of 5.164 GHz (65.53%, spanning over 5.297-10.461 GHz) having its center frequency \( f_{rc} \) at 7.878 GHz. The corresponding measured axial ratio bandwidth (ARBW) obtained inside the measured IBW curve is 2.25 GHz (having its center CP resonating frequency \( f_{cp} = 7.52 \) GHz, spanning over 6.40-8.65 GHz, 29.92%). Measurement results are validated in both Ansys Electronics Desktop 2020 R1 and CST Microwave Studio 2018. Proposed antenna is fabricated on FR-4 epoxy substrate of 1.6 mm thickness and exhibits a very small footprint of just 400 mm\(^2\) (20 × 20 mm\(^2\)) (size 0.58\(\lambda_{mgL}\) × 0.58\(\lambda_{mgL}\) × 0.046\(\lambda_{mgL}\), where \(\lambda_{mgL}\) is the measured guided wavelength at lower resonating frequency \( f_{mrL} = 5.297 \) GHz) with 51.31% reduction in size. Measured maximum peak gain for the impedance band is 2.04 dBi at 8.8 GHz and 1.96 dBi at \( f_{cp} \) 7.52 GHz. The structure of the proposed antenna is extremely simple, quite small in size and its CP bands can be suitable for some C-band and ITU (International Telecommunication Union)—8 GHz application.

KEYWORDS
axial ratio bandwidth, circular polarization, impedance bandwidth, ITU (8 GHz) band

1 INTRODUCTION

In recent times, demand for small Form Factor strategies used in wireless systems, is leading to design of many novel, compact, low-cost, broadband microstrip antennas.\(^1\) Circular polarization has become one of the most sought after methods of polarization due to its considerable insulation to multipath interferences, sturdiness to polarization mismatches...
between the transmitter and the receiver, and better transmission characteristics in unpropitious weather conditions. However, by means of using single feed method, the obtainable circularly polarized (CP) bands are extremely small\(^2\) or structures are very complicated.\(^4\)\(^,\)\(^5\) So as to enhance axial ratio bandwidth (ARBW), perturbation methods are generally employed. To deliver CP bands, two orthogonal degenerates’ modes of same amplitude but having a 90° phase differentiation need to be generated.\(^6\)\(^,\)\(^7\) Earlier, development of miniaturized antennas were most often accompanied with bandwidth diminution (either impedance bandwidth [IBW], 3 dB ARBW or both). Printed slot antennas are widely used to design CP antennas.\(^8\)\(^-\)\(^13\) but achieving adequate CP bandwidth remains a major challenge in them. Planar monopole antennas using microstrip line fed have become one of the most promising choices for wide band applications.\(^14\)\(^-\)\(^16\) They are chosen for their low profile, simplicity of fabrication, and outstanding transmission characteristics. A dual-feed phase shifter has been utilized to design a compact ultra wideband circularly-polarized slot antenna in Reference 17. They used an advanced optimization algorithm and demonstrated use of spline curves for generation of CP signals. To achieve wide CP characteristics, partial ground planes or crescent parasitic strips have been used in conjunction with radiating patch which creates a coupling between them.\(^18\)\(^,\)\(^19\) In addition, often open loops are used to increase the current path length as well as generate coupling effect with the nearby radiating patch. In Reference 20, a rectangular ground plane with two L-shaped slots, a rectangular patch with slotted feed line, and a PIN diode are used to adjust the frequency band to super high frequency (SHF), WiMAX, wireless local area network (WLAN), and C-bands applications. Notches on the radiating patch are known to help in attaining circular polarization.\(^21\)\(^,\)\(^22\)

Lack of adequate antenna designs contributing wide CP band motivated us to focus our work on designing a compact antenna giving single wide CP band. In this paper the proposed antenna is designed by means of Equations (1)-(16) inspired by some relevant existing designs.\(^23\)\(^-\)\(^26\) In general, achieving wide CP band by means of using single-fed is considered a challenge. Therefore, we set our primary objective of this work to design a miniaturized, wide band application microstrip antenna using single-fed providing circular polarization. We hoped this would overcome the need for use of multiple circular polarized antennas.

Here, we present a novel design utilizing primarily two concepts in the form of using an inverted Y-shaped radiating patch coupled with a semi-rectangular ground plane and a rectangular open-loop in its vicinity to achieve wide IBW along with wide CP characteristics. However, all of the earlier reported CP monopole antennas cited in References 14-22 either utilized complex radiator configurations or ground planes with implanted slots and stubs, and comparably larger in sizes. In contrast, our relatively simple, compact design antenna produced a wide measured IBW of 5.164 GHz (5.297 GHz-10.461 GHz, \(f_{nc}\) 7.878 GHz, 65.53%) and the measured ARBW of 2.25 GHz inside the range of simulated and measured IBW, both of which are quite large compared to the earlier reports. Proposed antenna could be utilized for some specific C-band and ITU (International Telecommunication Union)—8 GHz wireless communication applications.

The proposed antenna is designed using theoretical lower resonating frequency of 6.5 GHz, so that it can cover at least some C-band and ITU 8 GHz band. But the measured IBW of the fabricated antenna observed at much lower resonating frequency of 5.295 GHz, that is, 51.31% size reduction compared to conventional design procedure. We know frequency is inversely proportional to antenna dimension. But keeping the same dimensions we got the resonance at much lower than our design frequency. This is great result satisfying the miniaturization criteria. Our proposed antenna gives wide CP characteristics, in addition also give broad IBW. The coupling between the rectangular open-loop and the inverted Y-shaped patch plays a crucial role in attaining wideband CP, while the semi-rectangular ground plane is key parameter for enhancing IBW. The achieved measured wide IBW span over 5.297-10.460 GHz, equivalent simulated IBW is 5.71-10.461 GHz. Corresponding measured and simulated ARBW obtained inside the measured and simulated IBW curve are 6.40-8.65 GHz and 6.41-8.53 GHz. To our knowledge, this is one of the best results obtained in comparison to related designs. We have used FR4-epoxy substrate which introduces some additional complexity on the antenna design beyond microwave frequency band (8-12 GHz).\(^27\)\(^-\)\(^29\) Therefore, this puts a limitation on our proposed antenna that it cannot be used for applications beyond 12 GHz. Simulation was done using Ansys Electronics Desktop 2020 R1 and also validated in CST Microwave Studio Suite 2018. Their results were similar.

The paper is structured as follows: Section 2: Antenna Design Procedure; Section 3: Experimental Result and Discussion; Section 4: Parametric Studies; Section 5: Mechanism of CP and Effect of \(E_x/E_y\) over CP Band and Wide Band Performance Analysis of the Proposed Antenna, and Section 6: Conclusion.

2 | ANTENNA DESIGN PROCEDURE

The simulated and fabricated structures of the designed antenna are shown in Figure 1A-F. The dimension of the compact microstrip antenna is only 20 × 20 mm\(^2\). Easily available, most economically viable FR4-epoxy substrate\(^25\)\(^,\)\(^30\) of depth of
1.6 mm, having $\varepsilon_r = 4.4$ and $\tan \delta = 0.02$ is used to validate the proposed antenna. Design involves the uses of a single novel inverted Y-shaped patch connected with an L-shaped microstrip line. A rectangular open loop placed near to it, and a semi-rectangular ground plane is used on the opposite side. The CP radiation is generated due to perturbation of electric field between the two arms of the Y-shaped strip. Augmentation of circular polarization was dependent on key parameters $g$, $d$, $L5$ and $L6$. Detailed optimized dimensions have been listed in Table 1.

Evolution of proposed design is explained in four stages in Figure 2. Simulated IBW and ARBW improvements for the four prototype antennas (Structure 1-4) are depicted in Figure 3A,B, correspondingly. The frequency responses (including

| Parameter | Value (mm) | Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|-----------|------------|
| W1        | 20         | L1        | 20         | L2        | 5.0        |
| L3        | 4.0        | L4        | 2.5        | L5        | 6.5        |
| L6        | 9.0        | L7        | 9.0        | $g$       | 1.0        |
| $L_t$     | 5.5        | $W_t$     | 1.5        | $d$       | 0.6        |
| $a_1$     | 0.6        | $a_2$     | 4.5        | $c$       | 0.8        |
| $a_3$     | 7.0        | $a_4$     | 5.8        | $h$       | 1.6        |
Simulated IBW and ARBW, geometrical parameters, of these Structure.1-4 are tabulated in Table 2, where $f_{cp}$ is the center frequency of the CP bands. It may be noted that ARBW is defined by the following Equations (6) (discussed in more detail in Appendix S1):

$$\text{AR} = 20\log_{10} \left( \frac{1 + \epsilon}{1 - \epsilon} \right)$$

(1)

where

$$\epsilon = 10^{-\frac{p(dB)}{20}}$$

(2)

$p(dB)$ is the cross-polar power level at a given azimuth angle $\theta$. For a perfectly circular polarized pattern, this level $-\infty$ dB (AR = 0 dB), and for a linearly polarized field, where two CP signals are of identical magnitude, this level is 0 dB (AR = $\infty$ dB). For a practical situation this level is considered $\geq 15$ dB. So, the axial ratio comes to be 3 dB for all practical purposes.

We started with Structure.1 containing an L-shaped microstrip inset single feed line to control circular polarization$^{22,31}$ connected to a radiating patch of inverted F-shape.

The IBW for a CP microstrip antenna using single feed$^{12}$ is defined by Equations (3) and (4). Here $Q$ is the quality factor of the antenna.

$$\text{BW}_{\text{SWR}}^{\text{CP}} = \frac{\sqrt{2}}{Q} (\text{SWR} < 2)$$

(3)

$$\text{BW}_{\text{AR}}^{\text{CP}} = \frac{0.348}{Q} (\text{AR} < 3 \text{ dB})$$

(4)
So, from above Equations (3) and (4) it's clear that using single feed for getting wide CP is challenging. On the other hand, single fed antennas are much advantageous due to their very simple configurations compared to dual feeds. That's why we focused our work on designing the proposed antenna using single feed. The microstrip fed inverted F-shaped patch yields two electric fields of equal amplitudes $E_x$ and $E_y$ orthogonal to each other, which produced a CP radiation but not satisfying 3 dB criteria. Open slotted monopole antennas have been used in References 33,34 for achieving wide IBW. It is also well-known that for patch antennas, distribution of current concentration at the periphery of the rectangular patch radiator is normally higher and toward its center very low, which implies that the periphery of the rectangular patch radiator is primarily accountable for radiation. So, to design Structure.2, a vertical I-shaped strip was added onto Structure.1. Due to the addition of another strip, total current patch length increased so the resonant frequency decreased, resulting in creation of a CP band and resonance in IBW shifted to lower frequency region. But here also the CP band did not satisfy the 3 dB criteria. To achieve increased IBW and ARBW, a rectangle was imprinted from the upper boundary on the ground plane to make it a semi-rectangular ground plane. Furthermore, the narrow gap (g) among the patch and the ground plane produce a coupling capacitance. Here an impedance matching circuit is performed by the ground plane. As expected, Structure.3 generated two resonant CP modes, one at lower frequency region ranging from 5.88-6.62 GHz with $f_{cp}$ 6.32 GHz, and the other at higher frequency region 7.83-8.92 GHz with $f_{cp}$ 8.32 GHz, both falling inside the IBW curve. Current on the surface of ground plane is primarily concentrated on its upper edge. Hence, when the ground plane approaches nearer to the patch, it can similarly yield share in the radiation. Then, by manipulating the small gap (g), the ground plane can be made to radiate additionally and act as a dipole. For design of Structure.4, an open loop rectangular ring was incorporated near the inverted Y-shaped radiating patch to enhance the ARBW. Here, the previously obtained higher CP mode merged with the lower CP mode to produce a wide CP band. The open loop ring can perturb the distributions of current on the surface and minimizes the ratio of magnitude among $E_x$ and $E_y$ using $90^\circ$ difference in phase which produce the wide ranging ARBW. Open loop ring gives additional current path which also provides another CP in the middle frequency range and merge all previously generated CP mode and developed into a wide CP band ranging 6.41-8.53 GHz. Additionally, the first resonance frequency of the Structure.4 is nearer to the quarter wavelength of the radiating patch which is 11 mm.

In case of a rectangular planar monopole antenna, its lower resonance frequency can approximately be designed by comparing its area which is comparable to a cylindrical monopole antenna of same length $L$ and comparable radius $R$, as given underneath:

\[
2\pi RL = LW
\]  

where the width of the rectangular patch is denoted by $W$. The lower frequency $f_r$ is specified as below

\[
f_r = \frac{7.2}{L + R + P}
\]  

where the probe length (difference among the ground plane and the rectangular monopole) of the 50 $\Omega$ feed line is denoted by $P$, and $L, R, P$ are expressed in centimeters. Therefore, a general method is derived to approximate the important resonant frequency of any planar printed radiation antenna using a ground plane. Using the area of the planar printed antenna to that of a cylindrical wire of length $H$

\[
2\pi RH = LW
\]  

Meanwhile $H = L\sqrt{\varepsilon_{\text{eff}}}$

\[
2\pi RL\sqrt{\varepsilon_{\text{eff}}} = LW = \text{Area}
\]  

\[
R = \frac{\text{Area}}{2\pi L\sqrt{\varepsilon_{\text{eff}}}}
\]  

where $\varepsilon_{\text{eff}} = \frac{\varepsilon_r+1}{2}$ is the effective dielectric constant.

At fundamental resonance, the length of cylindrical dipole for real input impedance is specified by

\[
2\pi L = \frac{\lambda}{4}
\]
\[ L = 0.48 \lambda T \]  
(10)

where, \( T = \frac{l}{L + 2R} \)

Thus,

\[ \lambda = \frac{L + 2R}{0.48} \]  
(11)

From the below equations, the resonant frequency is specified by,

\[ f_r = \frac{14.4}{L + 2R} \text{ GHz} \]  
(12)

If \( L_g \) and \( L_p \) symbolize the length of the ground plane and radiation patch correspondingly and \( g \) is the gap among them, then \( L \) can be stated as \( L_g + L_p + g \).

Likewise if \( R_g \) and \( R_p \) denote the radius of equivalent cylindrical dipole equivalent to the ground plane and radiation patch, at that point \( 2R \) can be stated as \( R_g + R_p \). (In the situation of cylindrical dipole, \( R_g \) and \( R_p \) can be reflected as the radius of the dipole arms and \( R_g = R_p = R \).)

Therefore

\[ f_r = \frac{14.4}{L_g + L_p + g + R_g + R_p} \]  
(13)

and from (IX)

\[ R_g = \frac{AR_g}{2\pi L_g \sqrt{\epsilon_{eff}}} \]  
(14)

\[ R_p = \frac{AR_p}{2\pi L_p \sqrt{\epsilon_{eff}}} \]  
(15)

where \( AR_g \) and \( AR_p \) are the area of the ground plane and the radiation patch correspondingly. Here \( L_g, L_p, R_g, R_p \) and \( g \) are in centimeters. To get the lower resonant frequency approximately at 6.12 GHz (for part use in C-band), the ground plane length \( L_g \) is put as \( L_6 \), length of the patch \( L_p \) is put as \( L_5 + a_2 \) in Equation (13). Using these calculated parameters, designed lower resonating frequency \( (f_r) \) is obtained at 6.32 GHz, which is very close to the measured and simulated lower resonating frequency 6.40 GHz and 6.41 GHz, respectively.

Moreover, a flowchart is drawn to explain the antenna design technique (see Figure 4). The wavelength \( (\lambda_{gl}) \) of designed CP-band lower resonating frequency \( (f_{gl} = 6.32 \text{ GHz}) \), can be calculated as

\[ \lambda_{gl} = \frac{v_0}{f_{gl} \times \sqrt{\epsilon_{eff}}} \text{ where } \epsilon_{eff} = \frac{\epsilon_r + 1}{2} \]  
(16)

Figure 5 depicts the simulated distribution of surface current at CP \( f_{cp} \) 7.47 GHz for phase angles of (a) 0°, (b) 90°, (c) 180°, and (d) 270°. The CP wave generates from alternative excitation of the Y-shaped right strip and open loop ring. It can be seen from the reflection coefficient results depicted in Figure 3 that the CP mode at \( f_{cp} \) 7.47 GHz is caused by the combined effect of resonant modes at 6.32 and 8.48 GHz. The horizontal current components flow alongside horizontal strip of the open loop ring, whereas the vertical current components originate from the right arm of the Y-shaped strip. From Figure 5 it can also be realized that as time increases the main current on the surface rotate in ant clockwise direction, therefore the polarization direction is right hand circular polarization (RHCP).

It is well-known that using conventional monopole antenna, generation of CP radiation is not easy. This can be defined by the distributions of the current on the surface in Figure 6. For Structure.2, from Figure 6A, it can be understood that the distributions of horizontal currents are counteracted except a small band at upper frequency (11.12 GHz) generate CP band which is too small compared to LP band, as depicted in Figure 3B. In Figure 6B by using Structure.3 the semi-rectangular ground plane causes capacitive effect to generate two wide CP bands between 5.877-6.619 GHz \( (f_c 6.32 \text{ GHz}) \) and 7.828-8.92 \( (f_c 8.32 \text{ GHz}) \). In Figure 6C using Structure.4 the coupling effect among the said open-loop...
and the monopole antenna generates a wide band CP radiation at $f_{cp}$ 7.47 GHz from 6.41 GHz-8.53 GHz which is widest CP band obtained compared to all previous structures.

To visualize the formation of the CP mode at 7.47 GHz, a qualitative study is presented in Figure 7. Here, in the radiating patch, open loop rectangular ring and ground plane, every vector symbolizes a major current component. When current intensity is higher it is longer. The simulated normalized distribution of currents are demonstrated for two different time instants of $t = 0$ and $t = T/4$, where $T$ is the time period. From Figure 7A,B it is seen that the vector summation of the major component at $t = 0$ (Js1) is similar to that at $t = T/4$ (Js2) in magnitude and they are orthogonal to each other. Thus CP mode can be achieved at this frequency which is RHCP.
FIGURE 7 Simulated current distribution at 7.468 GHz for (A) $t = 0$ and (B) $t = T/4$

3 | RESULTS AND DISCUSSION

Ansys Electronics Desktop 2020 R1 is used for simulations and also validated in CST STUDIO SUITE 2018. Agilent Technologies, PNA-L Network Analyzer-N5234A (10 MHz-43.5 GHz) vector network analyzer (VNA) has been used to perform the IBW measurement.

Figure 8A depicts the comparison among measured and simulated return loss of the implemented antenna up to 11 GHz. The measured IBW is 5.164 GHz, from 5.297 to 10.461 GHz, $f_{rc}$ 7.878 GHz, 65.53%. The simulated 10-dB IBW is 4.747 GHz, ranging from 5.71 to 10.46 GHz or about 59.34% with $f_{rc} = 8.0$ GHz. The simulated IBW is effected by merger of three resonances at 6.32 GHz, 7.55 GHz, and 8.45 GHz. Here some difference is observed between fabricated and simulated IBW results. Feeding network, fabrication tolerances, the losses caused due to use of subMiniature version A (SMA) connector, dielectric loss, and also environmental difference among simulation and measurement may have contributed to that variation.38,39

Figure 8B shows the simulated ARBW curve which spans 2.12 GHz (6.41-8.53 GHz, $f_{cp}$ 7.47 GHz, 27.26%). Figure 8B also shows that the measured ARBW curve which spans 2.25 GHz (6.40-8.65 GHz, $f_{cp}$ 7.52 GHz, 29.92%). The whole CP band is within the range of measured and simulated IBW. Therefore, the proposed antenna can well be used for some C-band and ITU (8 GHz) applications.

After optimization on Ansys Electronics Desktop 2020 R1, the antenna was fabricated on low-cost FR-4 epoxy substrate using standard photolithographic process. Photograph of reflection coefficient ($S_{11}$) measurement setup is shown in Figure 9A,B which also shows measured $S_{11}$ against frequency. The proposed antenna reflection coefficient ($S_{11}$) was measured on Agilent PNA-L Network Analyzer-N5234A, 10 MHz-43.5 GHz network analyzer for the validation of the simulated result.

FIGURE 8 (A) Measured and simulated reflection coefficient of proposed antenna, (B) simulated and measured axial ratio plot for the proposed antenna
An automated measurement setup for radiation pattern and polarization is shown in Figure 9C,D. For the measurement of radiation characteristics, a broad-band horn antenna is used as reference antenna and developed prototype antenna (proposed antenna) placed on turn table in an anechoic chamber in the far field region as shown in Figure 9C using two antenna setup associated with vector network analyzer. The proposed antenna is rotated through turn table along its axis and controlled by HOLMARC position controller for the measurement of radiation characteristics. For the measurement of polarization (axial ratio) broadband horn antenna is rotated along its axis whereas proposed antenna remains stationary. A personal computer (PC) loaded with Lab View software is used for the data analysis.

Figure 10 shows the simulated and measured peak gain. Ansys simulator provided simulated peak gain of 2.11 dBi at a frequency of 8.03 GHz within the range of CP band, whereas measured peak gain is 2.04 dBi at 8.8 GHz, which is good

**FIGURE 9** Experimental setup used for the proposed antenna: (A) and (B) reflection coefficient measurement, (C) radiation characteristics and polarization measurement set-up in anechoic chamber, (D) radiation characteristics and polarization measurement setup in anechoic chamber view of the full setup

**FIGURE 10** Simulated and measured peak gain for the proposed antenna
for wireless communication application. Simulated peak gain at (CP band $f_{cp}$) 7.47 GHz is 1.942 dBi and measured peak gain at (CP band $f_{cp}$) 7.5 GHz is 1.96 dBi.

Figure 11 depicts the simulated voltage standing wave ratio (VSWR) plot obtained in Ansys and CST software. The obtained IBW for VSWR <2 is in between 5.71 and 10.46 GHz.

Figure 12 depicts simulated input impedance at 50 Ω microstrip fed line for the real (Resistance) and imaginary (Reactance) parts. In between the simulated and measured CP band the impedance match is good as the real part of (resistance) the impedance nearer to 50 Ω and the imaginary part (reactance) is nearer to 0 Ω.

The simulated axial ratio $f_{cp}$ at 7.47 GHz is plotted with different $\theta$ angles in Figure 13. As found in the simulation results, at $f_{cp}$ the proposed antenna has a 3 dB AR beam width over vertical $\theta$ angle of about 90°.

Figure 14 depicts the radiation pattern (simulated) for the XZ plane ($\varphi = 0^\circ$) and YZ plane ($\varphi = 90^\circ$) at 7.47 GHz. In Figure 14A,B simulated radiation patterns are presented. This is in the broadside direction and the level of co-polarization are 20 dB higher than the levels of cross polarization.

Figure 15 depicts the simulated and measured radiation efficiency for the implemented antenna with respect to frequency. The simulated and measured radiation efficiency is in between 82% and 90% for entire CP band and the efficiency is maximum at 8.0 GHz, 89.41% for simulation in Ansys and at 7.9 GHz, 88.99% for measurement.
Well-defined left hand circular polarization (LHCP) and RHCP can be observed from Figure 16A, B which is depicting the radiation patterns at $\varphi = 0^\circ$ (XZ plane) and $\varphi = 90^\circ$ (YZ plane) at 7.47 GHz. It is found that the CP radiation is RHCP at broadside direction. Measured co-polarization is greater than cross-polarization by 20.168 dBi, whereas for simulation in Ansys this is 20.08 dBi and in CST this is 20 dBi.
4 | PARAMETRIC STUDY

So as to understand the influences exerted by different parameters on the antenna features, some important parameters are optimized to achieve wide CP band. We studied three main parameters, viz. the length of the feed gap between the inverted Y-shaped patch and ground plane \((g)\), length of gap at bottom \((d)\) for square-ring, and the gap between patch and open loop ring \((c)\) which have typical outcome on the performances of antenna ARBW. To look into the properties on top of the stated input parameters, the parametric studies are carried out by the finite element technique centered Ansys Electronics Desktop 2020 R1 simulator. Dimension of each and every one parameters stay unchanged unless affirmed. Table 1 above already enlists the finally optimized dimension of the antenna parameters.

### 4.1 The effect of feed gap length \((g)\)

It is observed in Figure 6C that the current is primarily circulated along the \(y\)-axis on the semi-rectangular ground plane, which implies that the performance of the antenna is mainly reliant on the length of the ground plane \(L_6\). Therefore, the length of the ground plane \(L_6\) can be shortened to observe any negative effect on the operating bandwidth. Include with that, a consequential characteristics of the proposed antenna is the impact of impedance matching affected by the coupling effects among the ground plane and the feed point. Hence, the variation of the feed gap height to 0, 0.5, 1.0, and 1.5 mm on the performance of the antenna were also examined and results shown in Figure 17A. From this graph it can be seen that with increasing the feed gap height the lowest resonant frequency moves in the direction of lower frequency band and the higher resonant frequency also moves in the direction of lower frequency band but very slowly. This is because as we increase the feed gap difference total capacitive effect increases in remarkable way that shifted the resonance frequency toward the lower frequency region. The change of IBW is crucially varying with change of the feed-gap length. Here, the ground plane serves as an impedance matching circuit, adjusts the input impedance and the operating bandwidth as the feed-gap is modified. It can be seen in Figure 17A and Table 3 that 10-dB IBW of the monopole has changed much with the deviation of length for the ground plane. Furthermore there is an interesting phenomenon that the narrower ground plane will lead to a moderately wider operating bandwidth. This is very important for the miniaturization of the antenna. As shown in Figure 17B, feed gap height also has influence on AR curves. As feed gap height increases, capacitive effect also increases, thereby quality factor decreases, as a result CP radiation increases, and therefore, produces wide CP band. Finally the optimization of the feed-gap \((g)\) is found to be 1.0 mm.

| \(g\) (mm) | Lower edge IBW (GHz) | Upper edge IBW (GHz) |
|-----------|----------------------|----------------------|
| 0         | 6.60                 | 11.00                |
| 0.5       | 6.12                 | 10.92                |
| 1.0       | 5.71                 | 10.46                |
| 1.5       | 5.16                 | 10.00                |

**Figure 17** Comparisons of simulated (A) reflection coefficient \((S_{11})\) (B) axial ratio with different values of feed gap length for \(g = 0, 0.5, 1.0\) and 1.5 mm

**Table 3** Optimized results on different length of ground plane for proposed antenna
4.2 The effect of gap length \((d)\)

Figure 18 illustrates the (A) reflection coefficient and (B) ARBW with changing the value of \(d\). As anticipated, at lower band the reflection coefficient has little shift, but the IBW at upper region has no change. For the time being, gap size has negligible influence on upper CP band but very small effect on lower mode CP band, which changes ARBW as the length of \(d\) is increased. The practical reason behind it is that the distributions of current on the loop can be controlled by the gap which will help to the formation of CP mode at lower resonance condition. In conclusion, the optimized value of length \(d\) is 0.6 mm.

4.3 The effect of the gap length \((c)\)

In Figure 19A, it is eminent that the IBW somewhat changes with effect of gap length \(c\) between monopole radiator and open loop rectangular ring. From Figure 19B the characteristics of ARBW (simulated), we can see that the gap significantly influences the upper resonant CP mode and also moderately affects the lower CP mode. This is because the gap can create coupling between monopole and open loop ring which controls the current distribution on ring. Thus, we can fine-tune the gap size \(c\) to get noble CP performance in upper frequency region at \(c = 0.8\) mm.

5 MECHANISM OF CP AND EFFECT OF \(E_x/E_y\) OVER CP BAND

It is well-known that when an antenna propagates CP electromagnetic wave in space, the electric fields are perturbed in two orthogonal fields \(E_x\) and \(E_y\). Their magnitude should be nearly equal to each other. The phase difference between
them should be around 90°.40 Simulation of $E_x/E_y$ amplitude ratio and phase difference between them were performed and depicted in Figure 20. It can be seen that the magnitude of $E_x/E_y$ is nearly equal to 1 or 0 dB over the range of CP band and phase difference between them also around 90°. This proves that the band satisfies CP criteria.

5.1 Wide band performance evaluation of the proposed antenna

Group delay ($\tau$) is a measure of phase distortion. It is the actual transit time of a signal through a device under test as a function of frequency. It can be expressed as the transit time of a signal through a device vs frequency. The derivative of devices' phase characteristics with respect to frequency is called a group delay.

$$\text{Group delay} = \tau = \frac{d\phi}{dw}, \quad \text{where } \phi \text{ and } w \text{ are in radians.}$$

$$= -\frac{1}{360^\circ} \frac{d\theta}{df}, \quad \text{where } \theta \text{ in degree and } f \text{ are in Hz, } w = 2\pi f$$

It provides the pulse handling capability. It represents the degree of distortion in the pulse signal. It evaluates non-dispersive behaviors of antenna as derivative of far field response with respect to frequency. If group delay variation exceeds more than 1 nanosecond, phases are no more linear in far field and phase distortion occurs which can cause a serious problem for wideband application.

$S_{21}$ is a complex value (having both real and imaginary parts), and $|S_{21}|$ is the magnitude of $S_{21}$. $S_{21}$ can be expressed below.

$S_{21} = \text{Attenuation of wave traveling from designed antenna to reference antenna.}$

The ratio of incident power to transmitted power, in dB terminology, is the insertion loss.

$$\text{Insertion Loss} = 10 \log \left( \frac{\text{Incident power (W)}}{\text{Transmitted power (W)}} \right)$$

$$= \text{OR} = \text{Incident Power (dBm)} - \text{Transmitted Power (dBm)}$$

$$= 20 \log \left| \frac{1}{S_{21}} \right|$$

So for a good radiative antenna, insertion loss should be as low as possible or $|S_{21}|$ should be high.

In order to verify the wide impedance band response, the measured and simulated group delays and magnitude responses of $S_{21}$ are shown in Figure 21A. Experimental setup is shown in Figure 21B. Simulation setup is shown in Figure 21C. Non-varying responses of group delays are observed at operating frequency band. Antenna transfer function ($S_{21}$) was measured by keeping two antenna prototypes face to face along $+z$ direction at a distance $d > 100 \text{ mm (} d \geq \frac{2D^2}{\lambda}, \text{ where } D \text{ is the maximum dimension of the antenna and } \lambda \text{ minimum wavelength at a maximum range of operating frequency) and connecting both the antenna to the VNA (PNA-L Network Analyzer-N5234A). In Figure 21A group delay <1 nS and } S_{21} > -70 \text{ dB signify good performance of designed antenna suitable for wide band application.}$
Figure 21 shows the $S_{21}$ phase response for the proposed antenna. Measured and simulated $S_{21}$ phase responses are plotted in this figure and a linear relation over the operating band is observed which indicates low dispersion through the IBW.

Finally, relative benchmarking with the recently published comparable microstrip CP antenna designs has been attempted. Their year of publication, performance parameters like IBW, center frequency of impedance band, AR bandwidth, its % and the antenna sizes are tallied and summarized in Table 4. The proposed antenna clearly outperforms most of these antennas. Though, few of them achieved slight better ARBW, but have disadvantages like quite larger size

Figure 22 S$_{21}$ phase response of proposed antenna
with complicated structures, or use dual feed.\textsuperscript{17} In comparison, the proposed antenna is much advantageous because of its simple single point fed structure, capability to be easily re-designed to other frequencies as described in flow chart (Figure 4), and its compact size.

Therefore, the proposed antenna can find some uses in C-band and ITU (8 GHz). The bands 6425-7075 MHz, and 7075-7250 MHz, are used for passive microwave sensor measurements. In future, these two bands may be explored for Earth exploration-satellite (passive) and space research (passive) services. The bands 7250-7375 MHz (space-to-Earth) and 7900-8025 MHz (Earth-to-space) are allocated to the mobile-satellite service on a primary basis. The use of the frequency band 7375-7750 MHz by the maritime mobile-satellite service is limited to geostationary-satellite networks application. ITU 8 GHz (7725 to 8500 MHz) band is used for fixed wireless systems operation.

6 | CONCLUSION

A novel, compact single microstrip line feed antenna has been developed providing wide CP band. The design concept utilized coupling between an inverted Y-shaped radiation patch and a nearby placed rectangular open-loop to achieve wide CP. Using this structure, 51.31\% size reduction is achieved compared to conventional antenna design procedure. The semi-rectangular ground plane helped in furnishing wide IBW. The measured 10-dB IBW is 65.53\% (5.163 GHz, from 5.297-10.461 GHz, $f_c$ 7.878 GHz), while the measured ARBW is 2.25 GHz ranging from 6.40 GHz to 8.65 GHz, 29.92\%. The obtained wide band is considerably broader compared to the related designs reported recently. The proposed antenna could be suitable for some C-band and ITU (8 GHz) application.

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DATA AVAILABILITY STATEMENT

Additional information is available in the supplementary material of this article. The data that support the findings of this study are available from the corresponding author upon reasonable request.
CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS
Reshmi Dhara: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing-original draft; writing-review and editing. Taraknath Kundu: Conceptualization; data curation; project administration; supervision; validation; visualization; writing-original draft; writing-review and editing.

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SUPPORTING INFORMATION
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