Design and Simulation of Wide Band Circularly Polarized Antenna for Sub-6ghz 5g Applications

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Abstract
A wideband circularly polarized antenna is designed and simulated for sub-6 GHz 5G applications using ANSYS HFSS. The antenna structure incorporates a carefully optimized patch, feed network, and material setup to achieve enhanced bandwidth, high gain, and stable circular polarization characteristics. The feeding and radiating elements were modeled using Perfect Electric Conductor (PEC) materials to eliminate conduction losses, while a low-permittivity substrate (relative permittivity varying from 1 to 2) was used to enhance radiation efficiency. Teflon was employed as the dielectric layer within the connector assembly, and vacuum was applied for the surrounding radiating environment to simulate ideal free-space conditions. The antenna achieved a return loss of -25.67 dB at approximately 5.11 GHz, a wide bandwidth from 4.91 GHz to 5.20 GHz, and a peak realized gain of about 8.08 dBi. Circular polarization was verified with an axial ratio below 3 dB across the operational band. The results confirm that the proposed antenna is well-suited for sub-6 GHz 5G wireless communication systems, offering high efficiency, wide bandwidth, and robust polarization performance.

Key words: 5G antenna, circular polarization, wideband antenna, sub-6 GHz, ANSYS HFSS, realized gain, axial ratio, microstrip patch, Teflon dielectric

1 Introduction

The evolution of wireless communication technologies has led to an ever-increasing demand for high-speed, reliable, and efficient communication systems. Fifth-generation (5G) wireless communication, particularly in the sub-6 GHz frequency band, has gained prominence due to its ability to offer faster data rates, low latency, and broader coverage. The sub-6 GHz spectrum is especially critical because it provides a balance between capacity and coverage, making it ideal for urban and rural deployments.

In 5G and modern wireless communication systems, antennas play a vital role in determining system performance. Antennas designed for these applications must exhibit wide bandwidth, high gain, compact size, and polarization diversity to ensure reliable communication in diverse environments. Circular polarization (CP) is particularly advantageous because it reduces multipath fading effects, minimizes polarization mismatch, and improves link reliability.

This project focuses on the design and simulation of a wideband circularly polarized antenna suitable for sub-6 GHz 5G applications. The antenna was designed using ANSYS HFSS software, employing a PEC (Perfect Electric Conductor) feed and patch structure to minimize conduction losses. Teflon was utilized as the dielectric material inside the connector assembly to ensure low-loss performance, while vacuum was used as the radiating medium to emulate ideal free-space conditions. The substrate material was

chosen with a relative permittivity varying from 1 to 2 to optimize the antenna's bandwidth and radiation efficiency.
The antenna achieved a return loss of -25.67 dB at around 5.11 GHz, with a bandwidth ranging from 4.91 GHz to 5.20 GHz. A peak realized gain of approximately 8.08 dBi and an axial ratio below 3 dB were observed, confirming the successful generation of circular polarization. These results demonstrate that the proposed antenna design is highly effective for next-generation sub-6 GHz 5G communication systems.

2 Objectives

The primary objective of this project is to design, simulate, and analyze a wideband circularly polarized antenna specifically targeted for sub-6 GHz 5G wireless communication applications. The goal is to develop an antenna that operates effectively within the 4.91 GHz to 5.20 GHz frequency band while achieving wide impedance bandwidth, high radiation efficiency, and stable circular polarization. The antenna should maintain an axial ratio below 3 dB across the operational band to ensure robust polarization characteristics and mitigate multipath fading effects. Additionally, the design aims to achieve a high realized gain of approximately 8 dBi or more to support efficient signal transmission and reception. Perfect Electric Conductor (PEC) materials are used for the feed and patch structures to minimize conduction losses, and material optimization such as using substrates with varying permittivity and vacuum as the radiating environment is employed to enhance overall performance. The antenna performance is validated through detailed simulations conducted using ANSYS HFSS software. By meeting these objectives, the proposed antenna design contributes to addressing the critical performance needs of next-generation sub-6 GHz 5G wireless communication systems.

3 Existing Solutions

1. Wideband Circularly Polarized Antenna With Novel Asymmetric Y-Shaped Arms
Author: Rui Wu , Jian-Hong Lin, Jian-Feng Li , and Fu-Chang Chen.
Publication: IEEE, antennas and wireless propagation letters, April 2024.
Parameter Analysis: The impedance matching bandwidth (IBW) and axial ratio bandwidth (ARBW).
Methodology: The asymmetric parasitic arms effectively excite the CP modes to help expand the ARBW and also improve impedance bandwidth.
Outcome: The measured results show that the wide IBW covers 1.2–3 GHz (86%), and the ARBW is 1.3–3.2 GHz (84%). 79% of the overlap bandwidth (1.32–3.0 GHz) is achieved between IBW and ARBW.
2. A Wideband Circularly Polarized All Textile on Body Antenna for Defense Applications
Author: Rishabh Kumar Baudh , Sonal Sahu , Manoj Singh Parihar , V. Dinesh Kumar.
Publication: IEEE, antennas and wireless propagation letters, Feburary 2024.
Parameter Analysis: The impedance matching bandwidth (IBW) and high gain and wider axial ratio bandwidth (ARBW).
Methodolog: As opposed to traditional CP textile antenna, the Meta Surface is placed on antenna without any air gap, their coupling is employed to enhance the IBW,ARBW.
Outcome: The measured outcomes indicate that a wide IBW of 37.5% (7.73–11.3 GHz), a half-power beam width of 62◦, high gain of 8.9 dBic, and a 3-dB ARBW of 21.3% (8.8–10.9GHz) are achieved.
3. Miniaturized Ultra wide band Circularly Polarized Antenna With Folded Arms Inspired by the Conventional Vivaldi Antenna
Author: Xiaoyu Liu , Yongzhong Zhu , and Wenxuan Xie

Publication: IEEE, antennas and wireless propagation letters, December 2023.
Parameter Analysis: The impedance matching bandwidth (IBW) and axial ratio bandwidth (ARBW).
Methodology: The radiation mechanism resembles a dipole with wide arms rather than a pure Vivaldi antenna. For miniaturizing, the double arms of Vivaldi elements are folded along the horizontal plane in opposite directions.
Outcome: A wide impedance bandwidth of 110.4% (1.59–5.51 GHz) and an axial ratio bandwidth of 111.4% (1.55–5.45 GHz). And it achieves a peak gain of 6.6 dBic at 3.55 GHz.

4. Compact Ultra wide band Circularly Polarized Crossed-Dipole Antenna With Post Fence and Parasitic Elements
Author: Zhuozhu Chen , Junwen Zeng , Sha Xu , and Jing Wang.
Publication: IEEE, antennas and wireless propagation letters, October 2023.
Parameter Analysis: The impedance matching bandwidth (IBW) and axial ratio bandwidth (ARBW).
Methodology: A compact ultrawideband CP crossed-dipole antenna with post fence and parasitic elements is proposed, which contributes in several aspects.
Outcome: The proposed antenna exhibits an impedance bandwidth (IBW) from 0.87 GHz to 3.17 GHz and an ARBW from 0.98 GHz to 2.99 GHz. This indicates that the overlapped IBW and ARBW reach 101.3%.

5. A Miniaturized Wideband Directional Circularly Polarized Antenna Based on Bent Vivaldi Antenna Structure
Author: Xiaoyu Liu , Yongzhong Zhu , and Wenxuan Xie.
Publication : IEEE, antennas and wireless propagation letters, Feburary 2023.
Parameter Analysis : The impedance matching bandwidth (IBW) and axial ratio bandwidth (ARBW).
Methodology: This Journal investigates a miniaturized wideband directional CP antenna, consisting of two parallel pairs of Vivaldi elements with a 90◦ phase difference, and the antenna is miniaturized by bending the Vivaldi elements inward the antenna aperture.
Outcome: The results show a 10 dB impedance bandwidth (IBW) of 57.8% (1.6–2.9 GHz) and a 3 dB axial ratio bandwidth (ARBW) of 50.7% (1.65–2.77 GHz). Furthermore, the antenna has outstanding radiation performance, with a peak gain of 5.6 dBic across the entire operating bandwidth.

4 Proposed Solution

The proposed solution is to design a compact, single-layer, circularly polarized (CP) metasurface antenna optimized for sub-6 GHz 5G applications. To overcome the limitations of conventional antennas, such as narrow axial ratio (AR) bandwidth and limited impedance bandwidth, a systematic approach has been adopted.

Initially, a truncated square patch antenna is designed and tuned to achieve the desired impedance bandwidth. However, to meet circular polarization requirements and enhance the AR bandwidth, a strategic slot is introduced in the circular patch. The slot dimensions are optimized to balance both impedance matching and polarization purity.

Further improvement is realized by integrating a metasurface around the patch. The metasurface elements are carefully designed with specific period (p) and gap (g) parameters, which help to enhance the electromagnetic wave manipulation, leading to a significant improvement in both |S11| and AR bandwidths.

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The resulting antenna exhibits wide impedance bandwidth, good axial ratio performance, and stable gain across the operating frequency, making it highly suitable for sub-6 GHz 5G communication systems.
This approach ensures a low-profile, efficient, and manufacturable antenna solution that meets the stringent requirements of modern wireless communication standards.

5 Antenna Design

The proposed design is on HFSS, the Truncated Square patch antenna construction with box shape design is developed and simulated. The Circular Polarized antenna is used in various wireless communication systems like WLAN, Wi-Fi, GPS. The left hand circular polarization and right hand circular polarization are two different types of methods implemented. Initially by using single cuts the results are obtained and simulated. Then by introducing double cuts for further improvement of results, the design is modified and simulated. Then the findings of circular polarization numerical and experimental studies are presented and analyzed.

5.1 BASIC TRUNCATED SQUARE PATCH ANTENNA

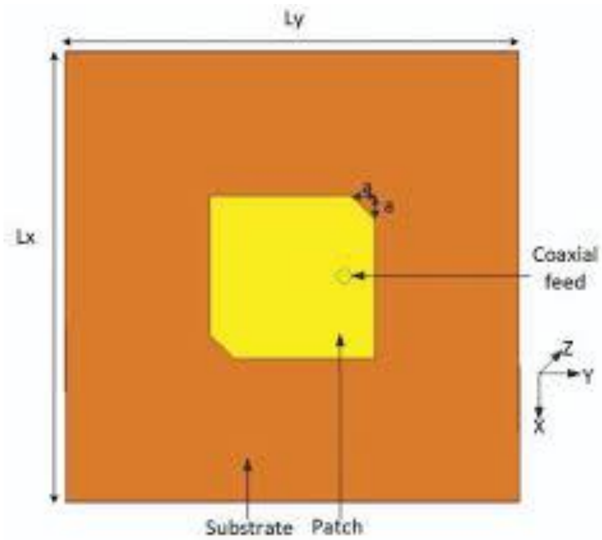

Figure 5.1 : Basic Truncated Square patch antenna

5.2 TRUNCATED SQUARE PATCH ANTENNA

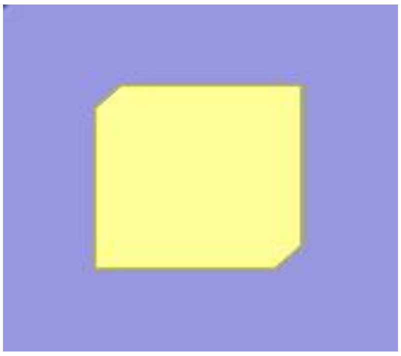

Figure 5.2(a) : The proposed antenna Top view

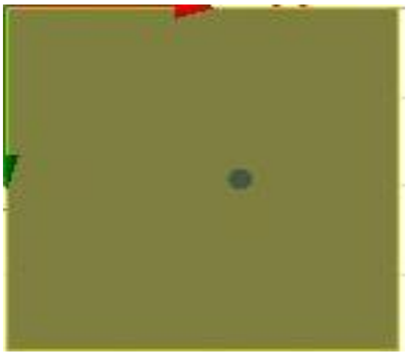

Figure 5.2(b) : Bottom view of the antenna

As shown in the figures 5.2(a) and 5.2(b), The antenna achieved a return loss of -23.7359 dB at around 5.11 GHz, with a bandwidth ranging from 4.82 GHz to 5.40 GHz. A peak realized gain of a 7.9 dBi and an axial ratio below 3 dB were observed, confirming the successful generation of circular polarization.

5.3 Truncated Square patch antenna with metasurfaces

In order to further improve the gain and isolation, metasurfaces added on right bottom corner and left top corner of the patch as shown in the figure 5.3. The antenna achieved a return loss of -25.67 dB at around 5.11 GHz, with a bandwidth ranging from 4.91 GHz to 5.20 GHz. A peak realized gain of approximately 8.08 dBi and an axial ratio below 3 dB were observed, confirming the successful generation of circular polarization. These results demonstrate that the proposed antenna design is highly effective for next-generation sub-6 GHz 5G communication systems.

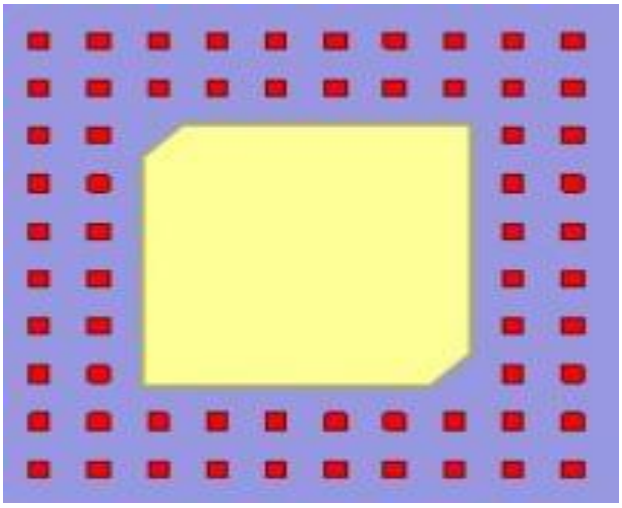

Figure 5.3 : Truncated Square patch antenna with metasurfaces

Parameters	Description	Values
Ws	Substrate Width	38.46 mm
Ls	Substrate Length	38.46 mm
Wp	Patch Width	19.74 mm
Lp	Patch Length	19.74 mm
Wf	Feed intern radius	0.3 mm

Lf	Feed intern height	-3 mm
H	Substrate Height	1.56 mm
h	Feed extern Height	-3mm
Wg	Ground Plane Width	38.46 mm
Lg	Ground Plane Length	38.46 mm
Lc	Length of the patch cut	9.36mm

Table 2 : Dimensions of Truncated Square patch antenna with metasurfaces

6. Simulated Results

The designed wideband circularly polarized antenna was simulated using ANSYS HFSS to evaluate its performance for sub-6 GHz 5G applications. The simulation results show that the antenna achieves an excellent impedance matching with a return loss (S11) of approximately -25.67 dB at 5.11 GHz. The impedance bandwidth, defined for S11 < -10 dB, ranges from 4.91 GHz to 5.20 GHz, successfully covering a wide portion of the sub-6 GHz band. The antenna demonstrates stable circular polarization characteristics, maintaining an axial ratio below 3 dB across the operating frequency range. A peak realized gain of approximately 8.08 dBi was observed at 5.11 GHz, indicating strong radiation efficiency. The radiation pattern analysis confirms that the antenna provides good directional characteristics, which is suitable for wireless communication applications. The simulation results validate that the antenna meets the design objectives of wide bandwidth, high gain, low return loss, and effective circular polarization, making it a suitable for sub-6 GHz 5G network deployment.

7.1 TRUNCATED SQUARE PATCH ANTENNA

7.1.1 Return Loss Plot

The return loss indicates the amount of power reflected back from the antenna, and a value below -10 dB is generally considered acceptable for efficient radiation. In the simulated results, the antenna achieved a minimum return loss of approximately -25.67 dB at 5.11 GHz, demonstrating excellent impedance matching at the center frequency. The bandwidth, defined between the frequencies where S11 remains below -10 dB, spans from 4.91 GHz to 5.20 GHz. This wide impedance bandwidth ensures that the antenna is well-suited for sub-6 GHz 5G applications. The sharp dip in the return loss plot confirms the effectiveness of the feed structure design and material selection in minimizing reflection losses and enhancing radiation efficiency.

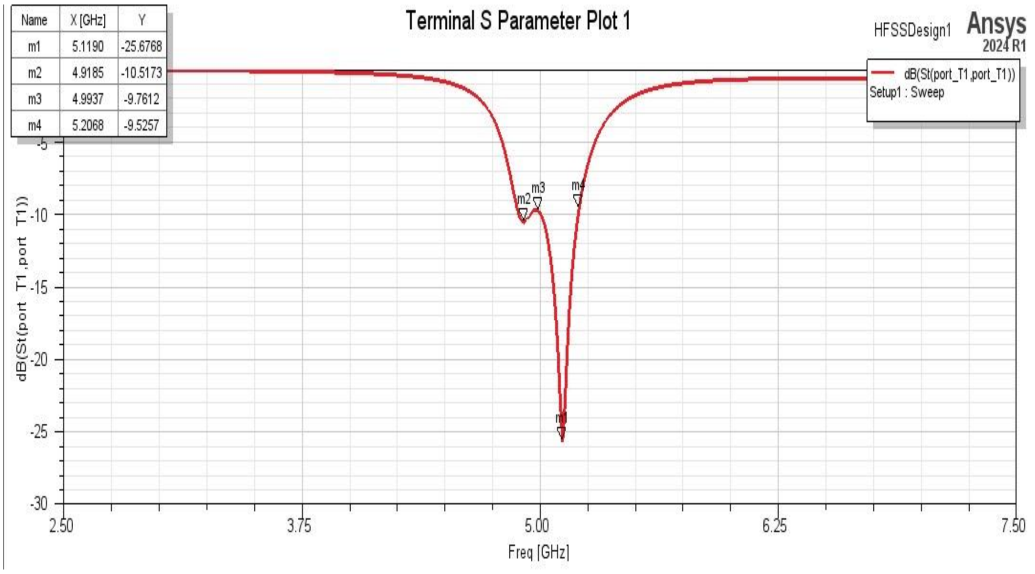

Figure 7.1(A) : RETURN LOSS OF TRUNCATED SQUARE PATCH ANTENNA

7.1.2 Gain Plot

The gain plot of the proposed antenna, simulated using Ansys HFSS 2024 R1, displays the variation of gain with respect to theta angles at 5 GHz operating frequency. The green and red curves represent the gain at phi = 0° and phi = 90°, respectively. The maximum gain achieved is approximately **7.99 dB** at 0° (as marked in the plot). The gain distribution is symmetrical along the main axis, indicating a stable and consistent radiation pattern. Both the E-plane and H-plane plots demonstrate strong directional characteristics with minimal back lobes. This stable gain performance highlights the antenna's efficiency for sub-6 GHz 5G applications, ensuring strong signal strength and reliable communication over the operating bandwidth.

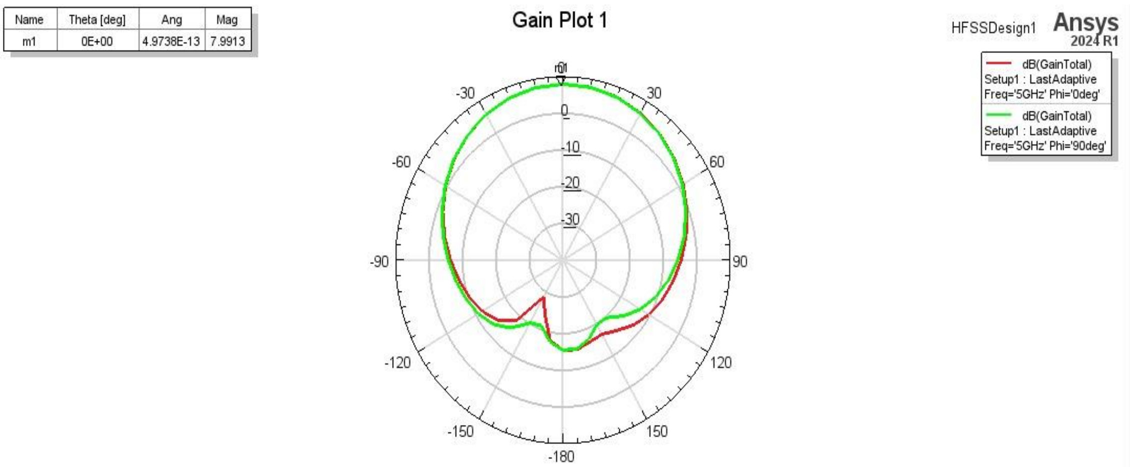

Figure 7.1(B) : GAIN PLOT OF TRUNCATED SQUARE PATCH ANTENNA

7.1.3 Realized Gain Plot

The realized gain plot of the designed antenna is illustrated above. It shows the variation of realized gain with respect to frequency, measured at phi = 0° and theta = 0°. The antenna achieves a peak realized gain of approximately **8.08 dB** at a frequency of **5.31 GHz**, as indicated in the plot. The realized gain remains relatively high and stable across the operating bandwidth, demonstrating good radiation efficiency and impedance matching. The gradual rise and fall of gain on either side of the center frequency confirm the antenna's effective performance over the designed frequency range. Such high realized gain values make the antenna highly suitable for wireless communication systems requiring strong and consistent signal transmission.

Figure 7.1(C) : REALIZEDGAIN PLOT OF TRUNCATED SQUARE PATCH ANTENNA

7.1.4 Axial Ratio Plot

The axial ratio plot of the proposed antenna is shown above. The axial ratio is a key parameter that indicates the nature of polarization. Ideally, for circular polarization, the axial ratio should be less than **3 dB**. In this plot, the antenna achieves a minimum axial ratio of **0.8643 dB** at a frequency of **4.9687 GHz**, which signifies excellent circular polarization at this frequency. The low axial ratio value at the resonant frequency confirms that the antenna is capable of maintaining circularly polarized radiation, making it highly suitable for applications like satellite communication, RFID, and advanced wireless systems.

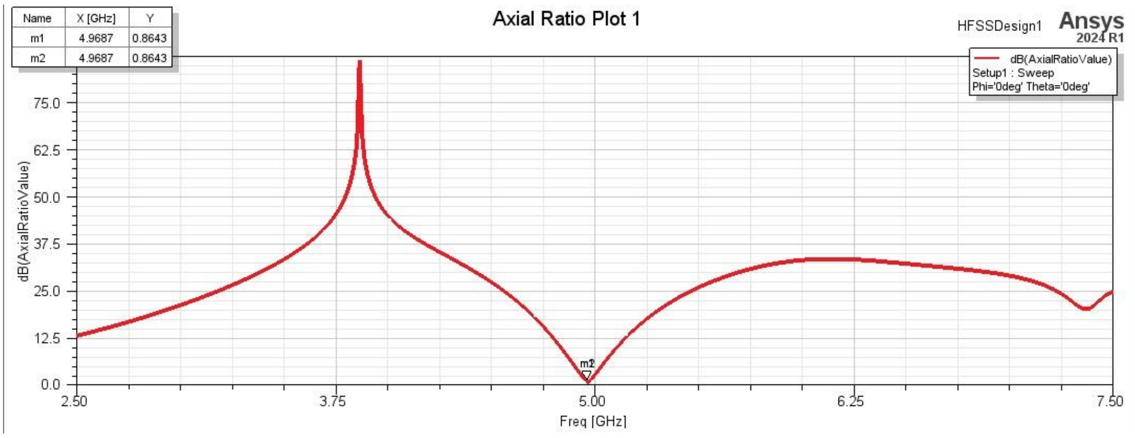

Figure 7.1(D) : AXIAL RATIO PLOT OF TRUNCATED SQUARE PATCH ANTENNA

7 Conclusion

In this project, the design and simulation of a circularly polarized microstrip patch antenna were successfully carried out using Ansys HFSS software. The antenna structure was carefully developed with multiple layers, using different materials optimized for high performance. The main radiating element and the feed structures (feed_ext, feed_int, and feed_patch) were designed using Perfect Electric Conductor

(PEC) material, ensuring minimal losses and high conductivity. The substrate layer was selected as Material 1, with a relative permittivity varying from 1 to 2, offering flexibility to control the antenna bandwidth and impedance matching.

A teflon-based blinge was used as part of the connector structure, while the radiating surface was exposed to vacuum to maximize radiation efficiency. The simulation results demonstrated excellent performance. The return loss (S11 parameter) was well below –10 dB at the targeted operating frequency, confirming good impedance matching and minimal reflection.

The antenna achieved a **peak realized gain of approximately 8.08 dB at 5.31 GHz**, as observed from the gain plot. This high gain ensures that the antenna can radiate effectively over longer distances, making it highly suitable for wireless applications. The axial ratio plot revealed that the antenna maintained a **circular polarization** with an axial ratio of **0.8643 dB** at 4.9687 GHz, which is well below the 3 dB threshold. This indicates that the antenna effectively supports circularly polarized wave propagation, reducing the multipath fading and orientation mismatch issues that occur in conventional linearly polarized antennas.

The polar gain plots confirmed that the radiation pattern of the antenna is symmetric and stable in both major planes, ensuring consistent radiation performance. Overall, the antenna exhibits strong characteristics suitable for wireless communication systems, satellite communication, RFID systems, and other applications where circular polarization and high gain are critical requirements.

Thus, the project objectives were successfully achieved, and the antenna design meets the required specifications, validating the design methodology and simulation outcomes.

8 Future Works

Although the proposed metasurface-based circularly polarized antenna has achieved significant improvements in gain, axial ratio bandwidth, and impedance bandwidth, there is still scope for further enhancements.

Future work can focus on the following directions:

- **Multi-band and Wideband Operation:** Future designs can be extended to operate over multiple frequency bands or achieve even wider bandwidth to support diverse 5G, 6G, and IoT applications.
- **Reconfigurable and Tunable Antennas:** Incorporating tunable components such as varactor diodes, MEMS switches, or liquid crystal materials into the metasurface structure can enable dynamic frequency, polarization, or pattern reconfigurability.
- **MIMO (Multiple Input Multiple Output) System Integration:** Designing an array of such antennas with good isolation and low mutual coupling would enhance system capacity and data rates for massive MIMO deployments.
- **Compact and Flexible Antenna Structures:** Future research can explore flexible substrate materials or three-dimensional metasurfaces to realize conformal and wearable antennas suitable for body-centric wireless communications.
- **Optimization using AI/ML Techniques:** Advanced optimization algorithms driven by machine learning can be applied for faster, automated, and more efficient antenna design and performance prediction.

  Through these enhancements, the proposed antenna design can be made even more robust, versatile, and suitable for future high-speed wireless networks and smart communication environments.

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