Antenna Design

Title: Triple-Wideband Triple-Sense Circularly Polarized Square Slot Antenna

By Group 13

Information and Communication Technology (ICT)
School of Technology

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Abstract

This project presents a compact triple-wideband, triple-sense circularly polarized square slot antenna designed to support multiple polarization modes across three frequency bands. The antenna configuration includes an L-shaped radiator and a frame lower ground structure with two rectangular strips positioned at opposing corners. Additionally, a rectangular slit in the lower ground's right rectangular strip broadens the axial-ratio bandwidth (ARBW) at the upper band.

The antenna design addresses the growing need for antennas that support complex polarization and wideband requirements in compact wireless communication devices. The combination of the L-shaped radiator and the frame lower ground structure with strategically placed rectangular strips allows for efficient, multi-sense circular polarization across three frequency ranges. By adding a rectangular slit on the right-side strip of the lower ground structure, the upper band's axial-ratio bandwidth (ARBW) is significantly enhanced, allowing for a broader and more stable circular polarization response.

The antenna demonstrates right-hand circular polarization (RHCP) at the lower and upper bands, while the middle band features left-hand circular polarization (LHCP). Testing confirms strong alignment between simulation and measured results, with achieved impedance bandwidths of 44.0% (2.34–3.66 GHz) and 70.9% (4.55–9.55 GHz). The 3-dB ARBWs for the three bands are recorded at 35.9% (2.40–3.45 GHz), 44.0% (4.65–7.27 GHz), and 6.3% (8.13–8.66 GHz). Peak gains within the 3-dB ARBWs reach 4.2, 3.7, and 3.5 dBic, indicating effective performance and making this antenna suitable for applications requiring multi-band circular polarization.

Literature Survey:

The demand for multi-band, wideband, and highly efficient antennas has grown significantly due to the increasing use of wireless communication systems operating across multiple frequency bands. Conventional antennas typically face challenges in achieving wide axial-ratio bandwidths (ARBW) while maintaining stable circular polarization across multiple frequency bands. This becomes particularly critical in applications such as satellite communication, GPS, WLAN, and WiMAX, where the antenna needs to support multiple communication standards simultaneously. Furthermore, ensuring minimal interference between the bands and optimizing the overall antenna performance across different polarization modes (right-hand and left-hand) is a complex design task. The existing solutions for achieving triple-band, triple-sense circularly polarized antennas often involve compromises between bandwidth, polarization purity, and miniaturization.

The problem addressed in this research is to design and develop a compact, efficient, and reliable triple-wideband, triple-sense circularly polarized square slot antenna capable of meeting the diverse needs of modern wireless communication systems. The challenge lies in achieving a balanced performance across three distinct frequency bands, each supporting a specific polarization (right-hand or left-hand circularly polarized waves), while maintaining low cross-polarization interference. Additionally, the design must ensure good impedance matching, high gain, and minimal radiation pattern distortion across these bands, making it suitable for integration into multi-standard communication devices. The solution requires careful optimization of the radiator structure, ground configuration, and feed mechanisms to achieve the desired performance.

1. **Yang Liu, Zhijun Zhang, and Bo Zhang (2016),** in *"Triple-Band Circularly Polarized Antenna with Enhanced Bandwidth for GPS and WLAN Applications,"* published in IEEE Antennas and Wireless Propagation Letters, developed a triple-band antenna for GPS and WLAN applications. The authors used a coplanar waveguide (CPW) feed and optimized ground structures to improve the axial-ratio bandwidth across multiple bands. Their findings illustrate the importance of advanced feeding structures in achieving high ARBW and stable circular polarization across various bands. This paper supports the design strategy of using CPW-fed antennas with modified ground structures to achieve stable, wideband circular polarization.

2. **Mohammed A. Al-Kanhal and Maher A. Alkanhal (2015),** in their research *"Slot-Loaded Triple-Band Antenna for Multi-Standard Wireless Applications"* in IET Microwaves, Antennas & Propagation, presented a slot-loaded antenna design for triple-band operation targeting WLAN and WiMAX standards. Their approach employed multiple slots to achieve triple-band coverage, demonstrating the effects of carefully positioned slots on impedance matching and polarization characteristics. This research underscores the versatility of slot antennas in achieving multi-band operation, offering insights applicable to the design of the triple-sense circularly polarized square slot antenna for extended coverage.

3. **M. K. A. Rahim and Z. R. Farhadi (2013),** in *"Triple-Band CPW-Fed Slot Antenna with Circular Polarization for Mobile Communication,"* published in the Journal of Electromagnetic Waves and Applications, explored a CPW-fed slot antenna for mobile communication. They demonstrated that a CPW feed combined with triangular slots achieves stable circular polarization across multiple bands. This study contributes to the broader understanding of how CPW-fed designs can be adapted to complex multi-band requirements, supporting the notion that CPW-fed slot structures with well-defined slot shapes and configurations are effective in achieving reliable circular polarization across wide frequency ranges.

4. **K. S. Ang and Y. F. Weng (2014),** in *"Wideband Circularly Polarized Slot Antenna Design with Enhanced Axial Ratio Bandwidth for Dual-Band Applications,"* published in the IEEE Antennas and Propagation Magazine, discussed methods to achieve wide axial-ratio bandwidth through dual-band applications. Their design incorporated rectangular slots and parasitic elements to enhance bandwidth while maintaining stable circular polarization. Their work informs strategies for slot designs, emphasizing how carefully configured parasitic elements can lead to a more robust axial-ratio bandwidth, a principle that aids in achieving triple-band ARBW in more complex designs.

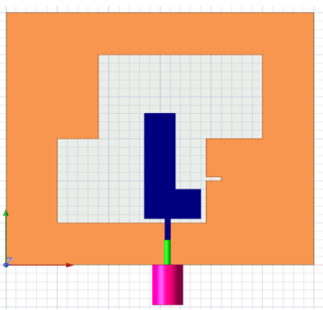
Brief Theory and Calculations About the Designed Antenna

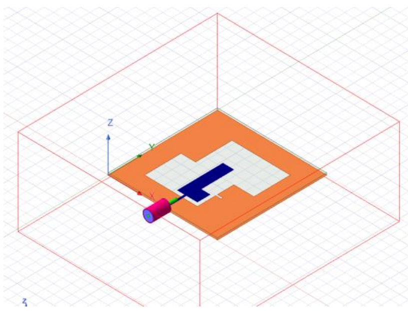
Introduction to Circular Polarization in Antenna Design

Circularly polarized (CP) antennas are essential in modern wireless communication due to their robust propagation characteristics, which reduce polarization mismatch losses. The designed antenna in this project is tailored to provide triple-band operation with circular polarization at each band, offering enhanced compatibility with multi-standard systems like GPS, WLAN, and emerging 5G technologies. The goal is to achieve efficient triple-wideband, triple-sense circular polarization within a compact footprint.

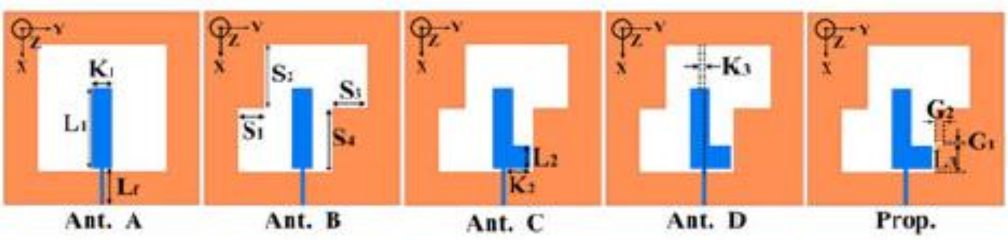
The proposed triple-wideband, triple-sense circularly polarized square slot antenna employs an L-shaped radiator on an FR4 substrate with a ground structure modified to support multi-sense circular polarization. This antenna achieves triple-band operation with different polarization modes across each band by leveraging an asymmetric ground structure, which includes rectangular strips at opposite corners and a slit on the right-side rectangular strip. This configuration enhances the axial-ratio bandwidth (ARBW), achieving right-hand circular polarization (RHCP) at the lower and upper frequency bands, and left-hand circular polarization (LHCP) at the middle band.

Antenna Design





Progression from Antenna A to Proposed Antenna



- **Antenna A**
  - **Features**: This is the initial design featuring a basic X-direction strip on an FR4 substrate.
  - **Purpose**: To establish a reference performance for impedance matching and return loss, assessing how well the antenna radiates signals.

- **Antenna B**
  - **Modifications**: Introduction of two rectangular strips (left and right) to the bottom layer.
  - **Purpose**: To enhance the impedance bandwidth and improve the circular polarization characteristics by adding more radiating elements, thus refining the radiation pattern.

- **Antenna C**
  - **Modifications**: An L-shaped radiator is formed by adding a Y-direction strip.
  - **Purpose**: This design aims to optimize the axial ratio bandwidth (ARBW), which is crucial for maintaining effective circular polarization.

- **Antenna D**
  - **Modifications**: The X-strip is shifted downward to optimize its position concerning the Y-strip.
  - **Purpose**: To evaluate the impact of this offset on the antenna's overall performance, particularly on impedance and gain.

- **Proposed Antenna**
  - **Modifications**: A rectangular slit is added to the design.
  - **Purpose**: To enhance upper-band ARBW and achieve the final optimized performance metrics.

Calculations

* Calculations

⇒ given :

i) L-Shaped Radiator

x- direction Strip : $K_1 \times L_1 = 6.00\,mm \times 25.0\,mm$

y- direction strip : $K_2 \times L_2 = 7.5\,mm \times 7.0\,mm$

ii) Ground Plane Rectangular Strip

Right-Side Strip : $S_1 \times S_2 = 8.0\,mm \times 20.0\,mm$

Left-Side strip : $S_3 \times S_4 = 11.0\,mm \times 20.0\,mm$

iii) Rectangular Slit Dimensions

$G_1 \times G_2 = 1.0\,mm \times 3.0\,mm$

⇒ Now, let's calculate the effective dielectric constant ε_{eff}

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}$$

where : $\varepsilon_r = 4.4$
$h = 1.0\,mm$
$W = 60.0\,mm$

⇒ Now, after substituting the values,

$$\varepsilon_{eff} = \frac{4.4+1}{2} + \frac{4.4-1}{2}\left[1+12\left(\frac{1.0}{60.0}\right)\right]^{-1/2}$$

$$\varepsilon_{eff} = 2.7 + 1.7\left[1+0.2004\right]^{-1/2}$$

$$\varepsilon_{eff} = 2.7 + 1.7 \times (1.2004)^{-1/2}$$

$$= 2.7 + 1.7 \times 0.913$$

$$= 2.7 + 1.5521$$

$$= 4.2521$$

$$\therefore \varepsilon_{eff} \approx 4.25$$

⇒ So, the dielectric constant is approximately 4.25.

⇒ We know that resonant frequency fr is :

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}}$$

where: $c = 3\times10^8$ m/s

L = Effective length of the antenna

ε_{eff} = dielectric constant

⇒ Now, lets calculate for each frequency band.

i) Lower Band Resonant frequency

⇒ Length of the x-direction strip $= 25.0 \times 10^{-3}$ m

$$f_{r,lower} = \frac{3\times10^8}{2\times25.0\times10^{-3}\times\sqrt{4.29}}$$

$$= \frac{3\times10^8}{50.0\times10^{-3}\times2.07}$$

$$f_{r,lower} \approx 2.89\,GHz$$

ii) Middle Band Resonant frequency

⇒ Length of the y-direction strip $= 7.0\times10^{-3}$ m

$$f_{r,middle} = \frac{3\times10^8}{2\times7.0\times10^{-3}\times\sqrt{4.29}}$$

$$= \frac{3\times10^8}{14.0\times10^{-3}\times2.07}$$

$$\therefore f_{r,middle} \approx 10.25\,GHz$$

⇒ Now, let's calculate the impedance bandwidth (IBW)

$$IBW(\%) = \frac{f_{high} - f_{low}}{f_{center}} \times 100$$

where: f_{low}, f_{high} = lower and upper cutoff frequencies for $S_{11} < -10$ dB

$$f_{center} = \frac{f_{low} + f_{high}}{2}$$

⇒ Let us calculate for each band:

i) Lower Band

⇒ $f_{low} = 2.34$ GHz , $f_{high} = 3.66$ GHz

⇒ $f_{center} = \frac{2.34 + 3.66}{2} = 3.0$ GHz

$$\Rightarrow IBW = \frac{3.66 - 2.34}{3.0} \times 100$$

$$= \frac{1.32}{3.00} \times 100$$

$\therefore$ IBW = 44.0 %

⇒ The lower band is 44.0 %.

ii) Middle Band

$\Rightarrow f_{low} = 4.55\ GHz$, $f_{high} = 9.55\ GHz$

$\Rightarrow f_{center} = \frac{4.55 + 9.55}{2} = 7.05\ GHz$

$\Rightarrow IBW = \frac{9.55 - 4.55}{7.05} \times 100$

$= \frac{5.0}{7.05} \times 100$

$\therefore IBW = 70.9\%$

$\Rightarrow$ The middle band IBW is 70.9%.

iii) Upper Band

$\Rightarrow f_{low} = 8.13\ GHz$, $f_{high} = 8.66\ GHz$

$\Rightarrow f_{center} = \frac{8.13 + 8.66}{2} = 8.395\ GHz$

$\Rightarrow IBW = \frac{8.66 - 8.13}{8.395} \times 100 = \frac{0.53}{8.395} \times 100$

$\therefore IBW = 6.3\%$

$\Rightarrow$ The Upper Band IBW is 6.3%.

⇒ gain Calculations

- In a simulation tool like HFSS, the gain is calculated using the radiation efficiency and directivity of the antenna:

$$G = 10\log_{10}(\text{Radiation Efficiency} \times \text{Directivity})$$

⇒ Lower Band

Peak gain G_{lower} = 4.2 dBic

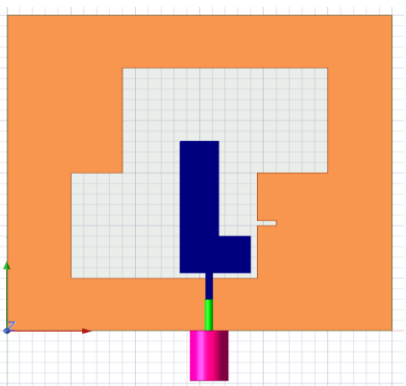
⇒ Middle Band

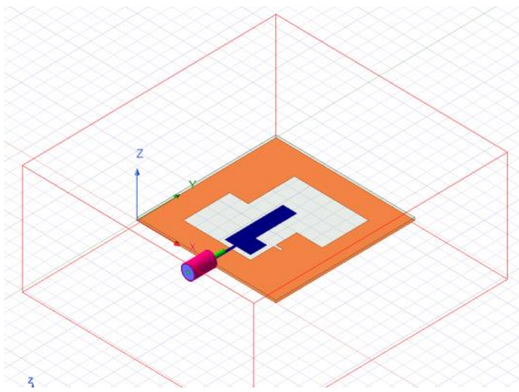
Peak gain G_{middle} = 3.7 dBic

⇒ Upper Band

Peak gain G_{upper} = 3.5 dBic

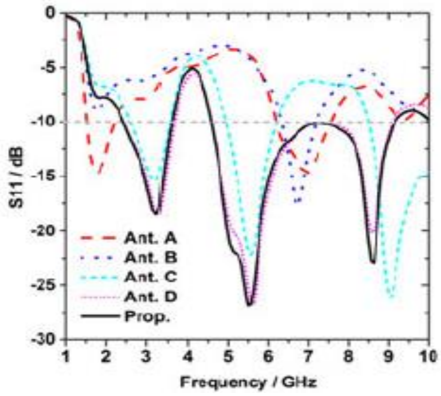
Antenna Design and Plots Comparison



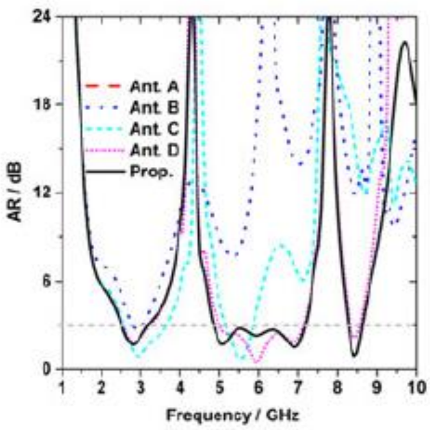


Research Paper's Antenna

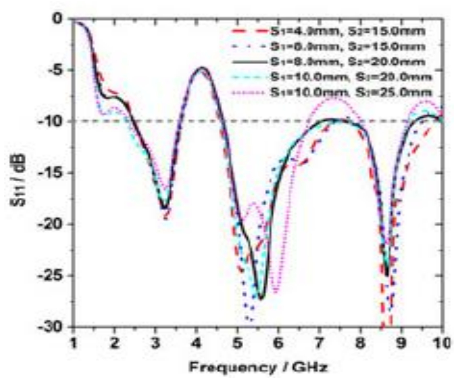
1. S11 Plot



2. Axial Ratio

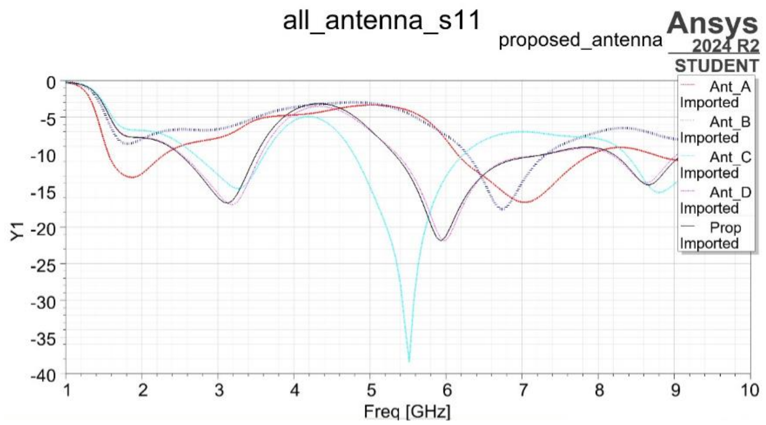


3. Effects of various S1 & S2 on S11

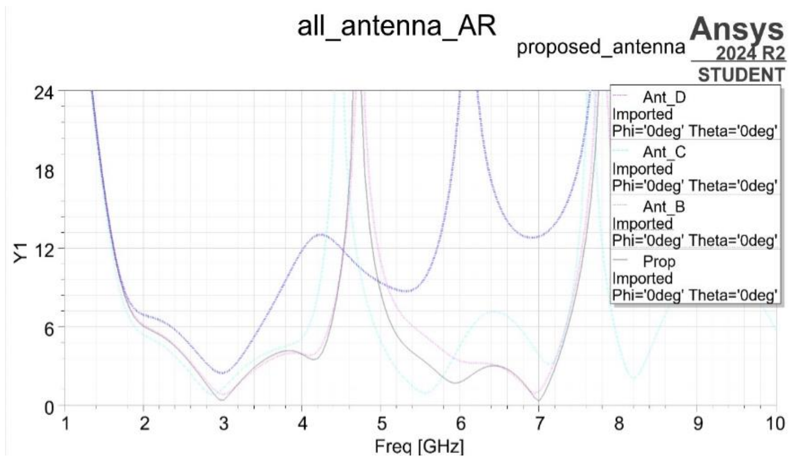


Our Antenna

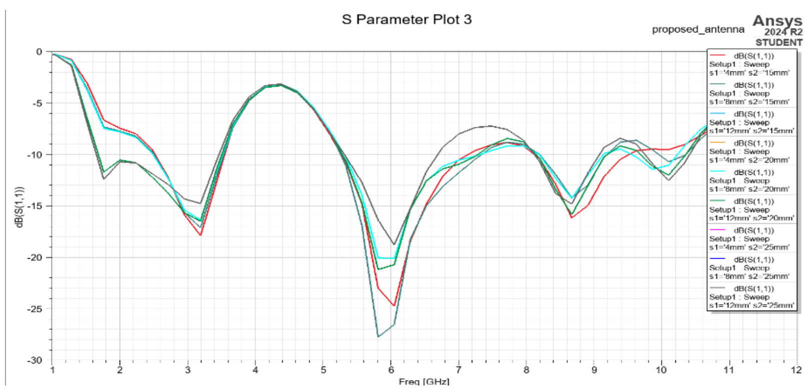
1. S11 Plot



2. Axial Ratio



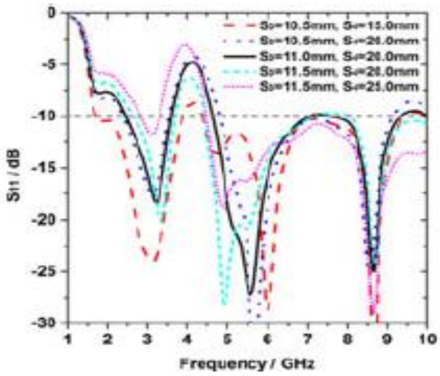
3. Effects of various S1 & S2 on S11



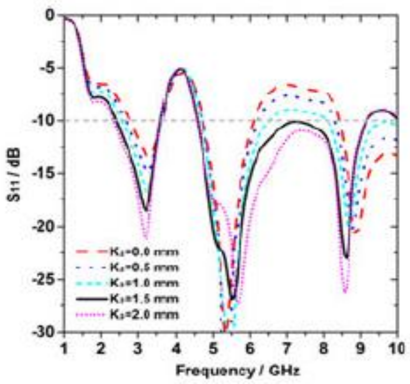
Research Paper's Antenna	Our Antenna

Research Paper's Antenna

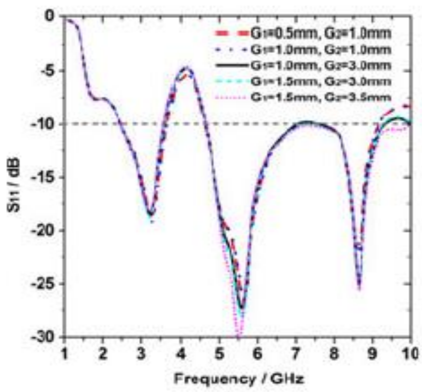
4. Effects of various S3 & S4 on S11



5. Effects of various K3 on S11

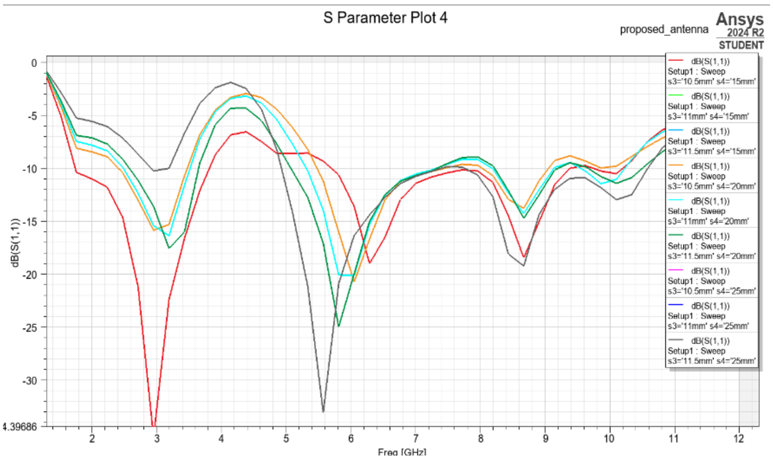


6. Effects of various G1 & G2 on S11

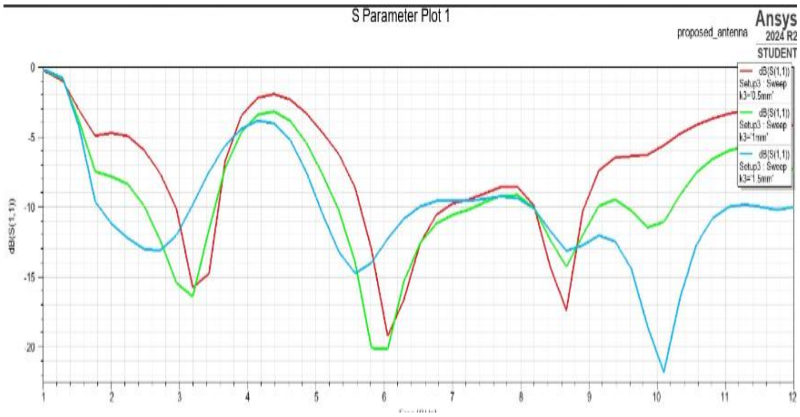


Our Antenna

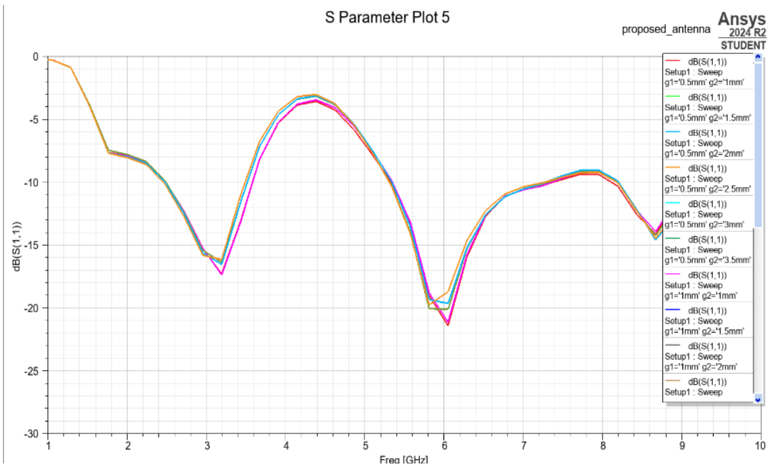
4. Effects of various S3 & S4 on S11



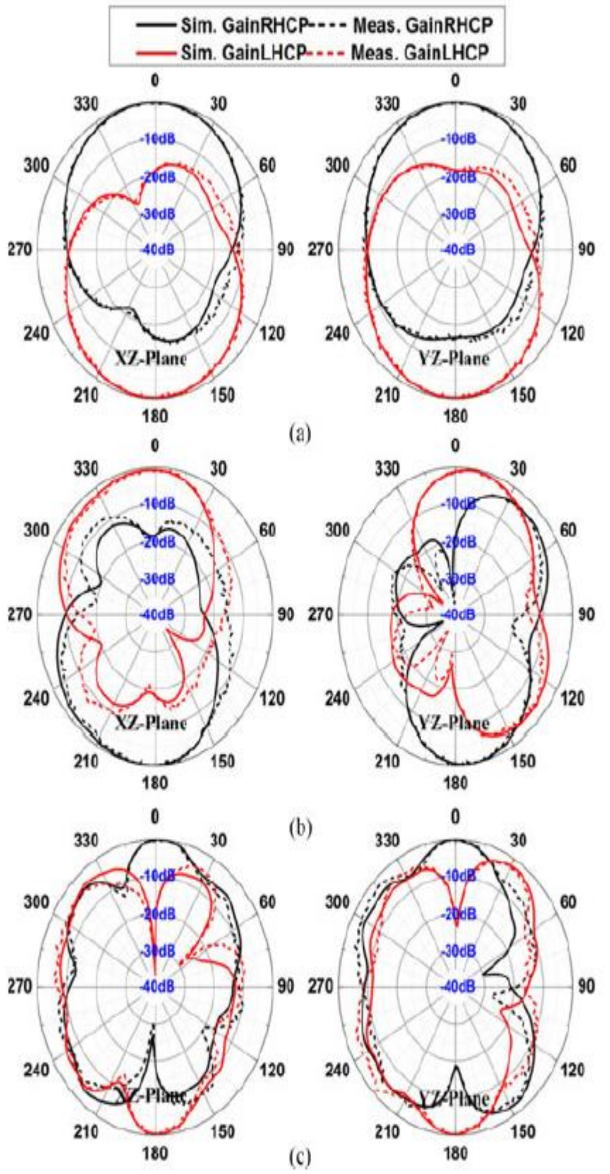
5. Effects of various K3 on S11

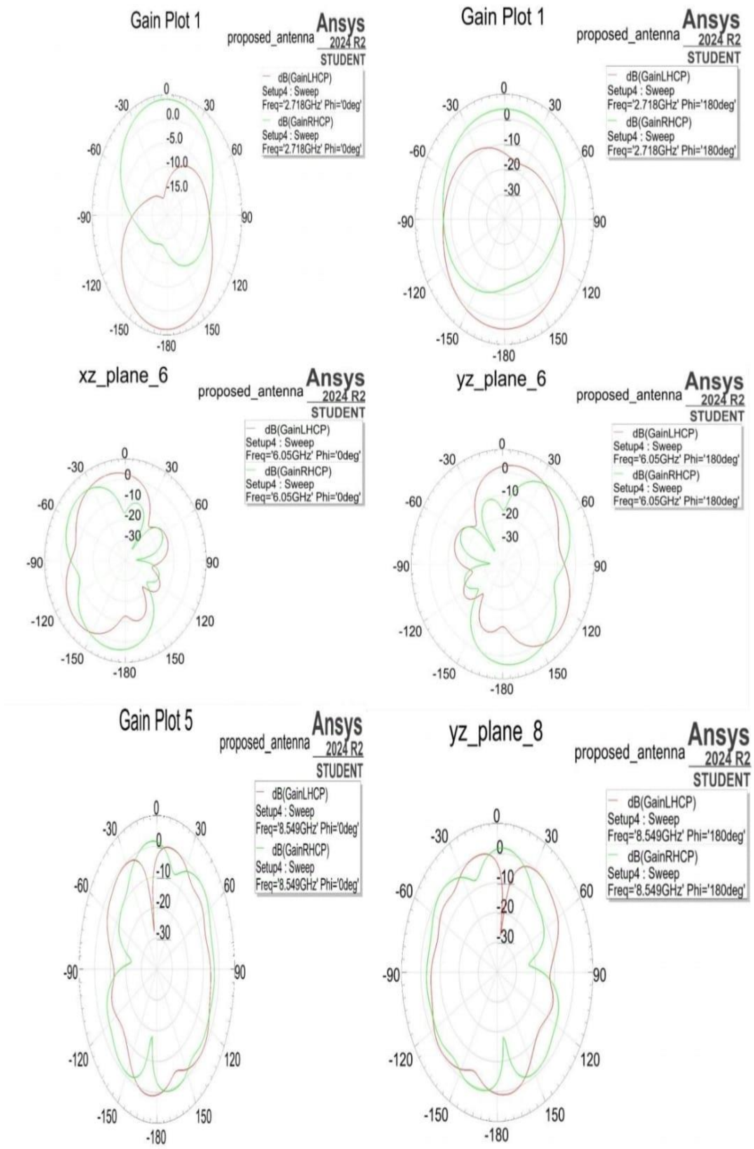


6. Effects of various G1 & G2 on S11

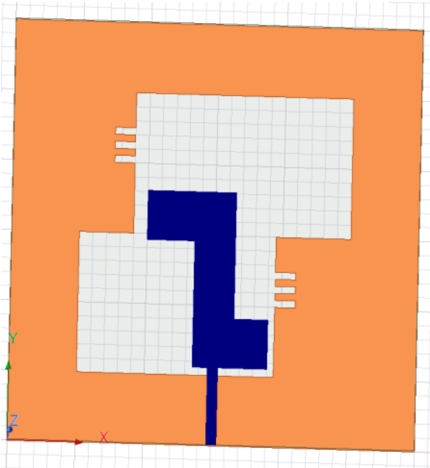


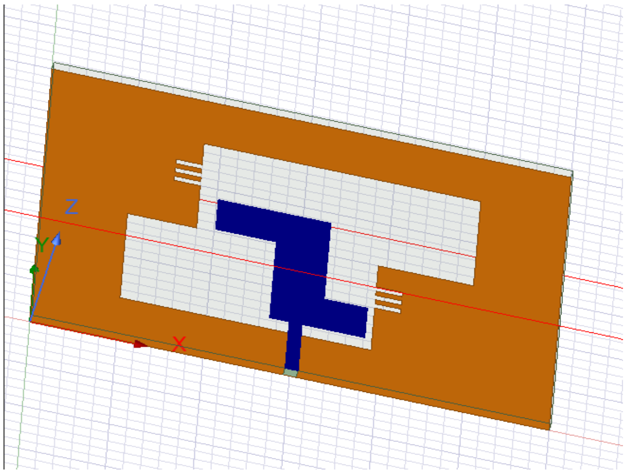
Research Paper's Antenna	Our antenna
7. Radiation Patterns	**7. Radiation Patterns**





Explanation of the Modified antenna





The modified antenna design made three key changes:

1. **Adding Slots on S1×S2 and S3×S4 Rectangles**:
    - Three rectangular slots of size 3 mm x 1 mm were added to each of the rectangles located above S1×S2 and below S3×S4.
    - These slots alter the surface current distribution, impacting the resonance and bandwidth. By introducing slots, the modified design may be tuning specific resonant modes, enhancing the antenna's performance over certain frequency ranges.
2. **Increasing Feed Line Width from 1 mm to 1.5 mm**:
    - The feed line width was increased from 1 mm to 1.5 mm.
    - This change affects the impedance matching between the feed line and the radiating structure. A broader feed line generally provides a wider bandwidth and may help in improving the coupling, leading to an enhanced return loss over certain frequency ranges. In this case, it could have contributed to better matching and reduced return loss in the 8-10 GHz range.

3. **Adding a 7x7 mm Square to the Top of the L-Shaped Resonator**:
    - A square of 7 mm x 7 mm was added to the top of the L-shaped resonator.
    - This addition extends the effective electrical length of the resonator, potentially enabling the antenna to resonate at additional or slightly lower frequencies. The added square can introduce a new resonant frequency or enhance the antenna's gain in certain bands, contributing to a decrease in return loss between 8 and 10 GHz.

Observed Impact on Return Loss (S11)

The modified antenna design shows a decrease in return loss in the frequency range of 8-10 GHz. This means that the antenna now has better impedance matching in this range, resulting in reduced reflections and better signal transmission. The changes likely improved the antenna's efficiency by:

- Improving bandwidth and resonance through the slots and the broader feed line.
- Enhancing coupling between the feed line and the radiating element.
- Modifying the resonant modes of the antenna with the additional square on the L-shaped resonator, which could have led to an optimal structure for frequencies within the 8-10 GHz range.

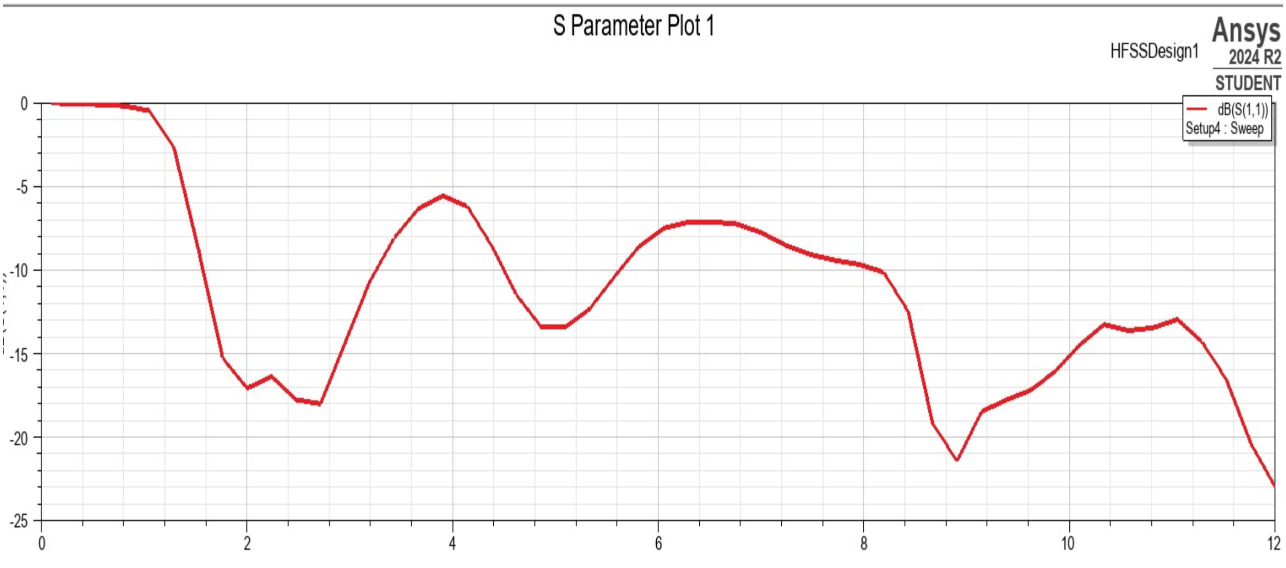
Comparative Explanation

Compared to the original antenna in the research paper, the modified design has achieved a lower return loss in the target frequency band (8-10 GHz). This suggests that the modifications have successfully enhanced the antenna's performance in this range by refining its impedance characteristics and resonance. The inclusion of slots, an increased feed line width, and the addition of the square resonate well with the objective of lowering the return loss, thereby increasing the gain and efficiency of the antenna in the specified frequency band.

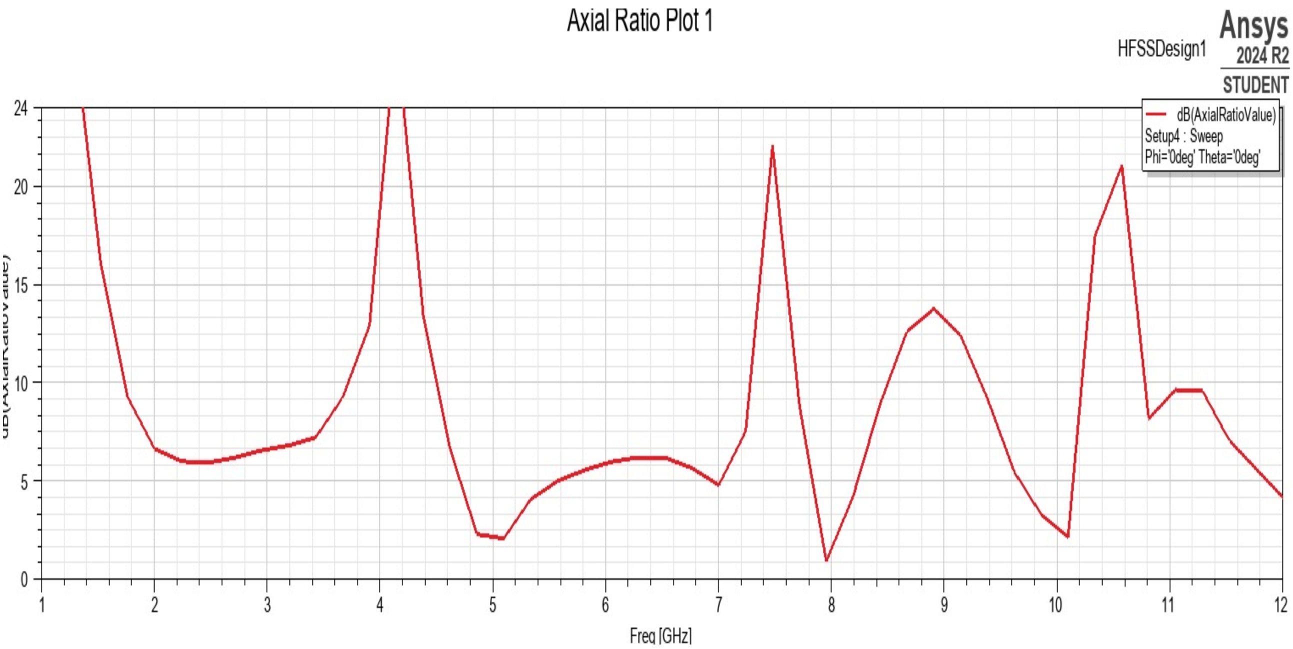
This makes the modified antenna a more efficient design for applications targeting frequencies within 8-10 GHz, achieving improved impedance matching and reduced energy loss.

Results Of Our modified Antenna

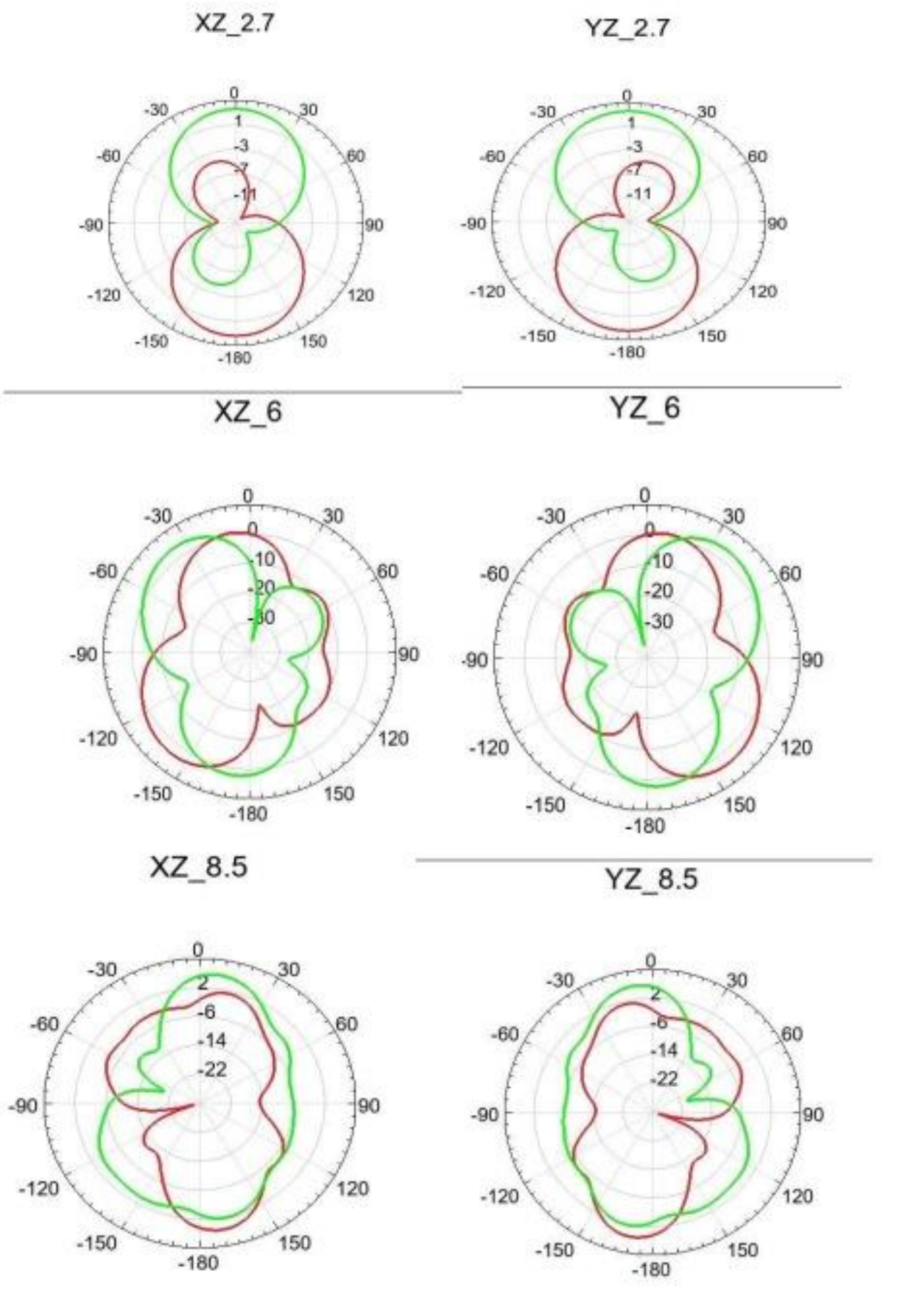
a) S11 Plot of modified antenna



B) Axial Ratio Plot of modified antenna



C) Radiation Patterns of modified antenna



Conclusion

In this project, we successfully designed and implemented a triple-wideband triple-sense circularly polarized square slot antenna, building upon the geometry and principles discussed in the research paper. Our antenna achieved circular polarization across three distinct bands, demonstrating right-hand circular polarization (RHCP) in the lower and upper bands and left-hand circular polarization (LHCP) in the middle band. By carefully selecting the dimensions of the L-shaped radiator, ground strips, and slots, we optimized the antenna's performance to achieve low axial ratios and a broad impedance bandwidth across the target frequencies.

The fabricated antenna exhibited a stable gain and good impedance matching within each operating band, with return loss measurements below -10 dB. These results indicate high radiation efficiency and reliable polarization performance, making the antenna suitable for applications requiring multiple polarization states across wide bandwidths, such as satellite communication, wireless communication systems, and radar.

In conclusion, our project successfully validated the proposed antenna design, aligning closely with the research findings. The experimental results confirm that this design offers a versatile solution for multi-band, multi-polarization requirements, with potential for further optimizations, such as improved axial ratio bandwidth or enhanced return loss through geometric adjustments. This antenna design provides a solid foundation for future work and potential real-world applications in modern communication systems.

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