

Antenna and RF Systems Lab 3: Microstrip Antenna Design Student's name:

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Course: MSc Communication Engineering

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Introduction

This report details the design and simulation of a rectangular microstrip patch antenna operating at a frequency of 24 GHz. The primary aim is to explore the impact of varying dimensions on the antenna's performance, focusing on key parameters such as resonance frequency, S11, bandwidth, gain, and directivity. Through CST Microwave Studio simulations, this study seeks to establish a deeper understanding of how these parameters interact to influence antenna efficiency and radiation characteristics. By analyzing and comparing multiple configurations, the results aim to contribute valuable insights for optimizing microstrip patch antenna designs for practical applications. The primary aim is to analyze the performance of the antenna, including key parameters such as resonance frequency, S11, bandwidth, gain, and directivity. These parameters are studied through CST Microwave Studio simulations, where resonance frequency helps determine the operating frequency, S11 assesses impedance matching, bandwidth evaluates the operational frequency range, and gain and directivity highlight the antenna's efficiency and radiation pattern. Their analysis is crucial for optimizing the antenna's performance in practical scenarios. The objectives include understanding the effect of varying dimensions on the antenna's performance and comparing results for different designs. The study employs CST Microwave Studio for simulation and data analysis, following standard design steps to ensure accurate parameter measurement and evaluation.

The rectangular microstrip antenna design involves three configurations with varied widths ($W = 4.08$ mm, $W = 4.00$ mm, and $W = 4.20$ mm) to observe how dimensional changes influence performance metrics. These configurations allow for a comparative analysis of the antenna's impedance matching, bandwidth, and radiation characteristics, culminating in a discussion of the results and their implications for practical applications.

Background Theory

Microstrip patch antennas are widely used in modern communication systems due to their compact size, low cost, and ease of fabrication. These antennas typically consist of a radiating patch on one side of a dielectric substrate with a conductive ground plane on the other side. Key parameters in patch antenna design include resonance frequency, S11, bandwidth, gain, and directivity.

The resonance frequency is determined by the physical dimensions of the patch and the substrate properties, influencing how the antenna operates at specific frequencies. S11, the reflection coefficient, quantifies the mismatch between the antenna and the transmission line, with lower S11 values indicating better impedance matching. Bandwidth defines the range of frequencies over which the antenna performs effectively and is often critical for applications requiring high data rates.

Gain and directivity are measures of the antenna's efficiency and radiation characteristics. Gain, particularly IEEE gain, accounts for system losses, while realized gain includes practical inefficiencies. Directivity focuses on the concentration of radiated power in a preferred direction, which directly impacts the antenna's ability to focus energy. These parameters are interdependent; for instance, improved impedance matching (lower S11) often enhances bandwidth and gain. Understanding these relationships is vital for optimizing antenna performance for specific applications, as demonstrated in the simulations discussed in this report. These

antennas typically consist of a radiating patch on one side of a dielectric substrate with a conductive ground plane on the other side. Key parameters in patch antenna design include resonance frequency, S11, bandwidth, gain, and directivity.

The resonance frequency is determined by the physical dimensions of the patch and the substrate properties, while S11 represents the reflection coefficient, indicating how much power is reflected back due to impedance mismatching. Bandwidth refers to the range of frequencies over which the antenna operates effectively, with higher bandwidths often preferred for modern communication applications.

Gain and directivity are critical in evaluating the efficiency and directional performance of the antenna. IEEE gain considers losses, while realized gain reflects the practical gain after accounting for system inefficiencies. Directivity measures the concentration of radiated power in a specific direction. These parameters are interrelated and must be optimized during the design process to meet specific application requirements. For instance, improving impedance matching (achieving a lower S11 value) directly impacts the bandwidth and gain, as it minimizes power losses and ensures a more efficient transfer of energy between the transmission line and the antenna. Additionally, increasing directivity can enhance gain by focusing the radiation pattern in a specific direction, which is particularly important in applications requiring targeted signal transmission. In this simulation, such interrelationships guide the evaluation of how dimensional changes influence antenna performance, providing insights for refining design parameters. This theoretical foundation provides a basis for understanding the simulation and analysis presented in this report.

Procedures

Rectangular Microstrip Patch Antenna

The rectangular microstrip patch antenna was designed and simulated using CST Microwave Studio. The design followed specific parameters, including material selection and geometric configurations, to evaluate performance metrics at an operating frequency of 24 GHz. The procedures for each step are detailed below:

1. **Initial Design Parameters:** The antenna dimensions were set based on standard microstrip antenna guidelines. The following configurations were considered:
 - Configuration 1: $W = 4.08$ mm
 - Configuration 2: $W = 4.00$ mm
 - Configuration 3: $W = 4.20$ mm

The substrate material used was Rogers RO4350B, with a dielectric constant (ϵ_r) of 3.66. The substrate thickness was 0.25 mm, and the conducting patch and ground plane were made of PEC (Perfect Electric Conductor) material.

2. **Modeling and Port Setup:** Using CST's modeling tools, the rectangular patch was designed with precise dimensions for each configuration. A waveguide port was added to the feed line with an impedance normalized to 50 Ohms. The dimensions and material specifications ensured consistency across simulations.
3. **Simulation Setup:** The simulations were conducted in the time domain, with the frequency range set

to capture the resonance frequency and bandwidth accurately. Specific parameters observed included S11, input impedance, gain, and directivity. **Impedance Matching:** The input impedance of the antenna was compared against the 50 Ohm impedance of the transmission line. This comparison helped evaluate how well the antenna was matched to the feed line, a critical factor for minimizing reflections.

4. **Repetition for Configurations:** Each design configuration ($W = 4.08$ mm, $W = 4.00$ mm, and $W = 4.20$ mm) was simulated separately. The results for each configuration were recorded, focusing on the resonance frequency, S11 values, bandwidth, and radiation characteristics.
5. **Observation of Fields:** The electric (E-field) and magnetic (H-field) distributions were observed at the resonance frequency. These fields provided insights into the radiation mechanism and the impact of dimensional changes on performance.
6. **Far-Field Analysis:** The far-field radiation patterns, including gain and directivity, were analyzed for each configuration. These results highlighted how dimensional variations influenced the directional performance of the antenna.

Circular Microstrip Patch Antenna

1. **Initial Design Parameters:** The circular patch antenna was designed following a similar methodology to the rectangular patch. The primary design parameters included:

- Configuration 1: Radius = 1.87 mm
- Configuration 2: Radius = 1.80 mm
- Configuration 3: Radius = 1.90 mm

Additional features of the design included a slot with dimensions:

- Slot Width = 0.4 mm
- Slot Length = 0.85 mm

The feed line dimensions were set as follows:

- Feed Line Width = 0.2 mm
- Feed Line Length = 2.08 mm

The substrate used was Rogers RO4350B, with the same thickness and dielectric constant as the rectangular design. PEC material was used for both the patch and the ground plane.

2. **Simulation Setup:** The simulation steps mirrored those of the rectangular patch antenna. Specific parameters observed included S11, input impedance, gain, and directivity.
3. **Impedance Matching:** Similar to the rectangular patch, the input impedance of the circular patch was compared against the 50 Ohm impedance of the transmission line to evaluate matching.

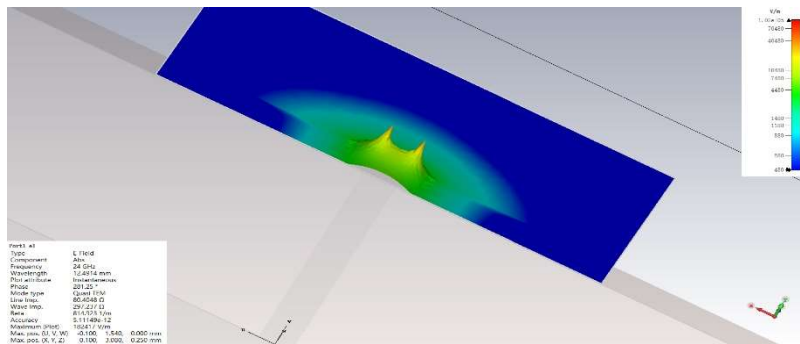
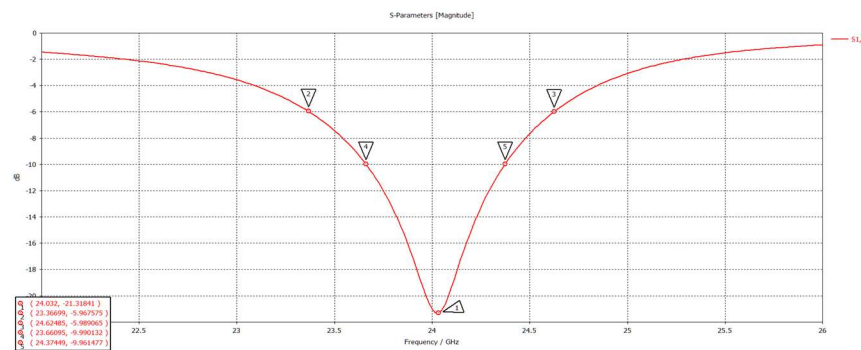
4. **Field Observations:** The electric (E-field) and magnetic (H-field) distributions were analyzed at the resonance frequency to understand the radiation mechanism and the effect of radius variations.
5. **Far-Field Analysis:** Far-field radiation patterns, including gain and directivity, were examined for each radius configuration. These results provided insights into how changes in the patch dimensions influenced directional performance.

Simulation Results, Discussion, and Analysis

Rectangular Microstrip Antenna

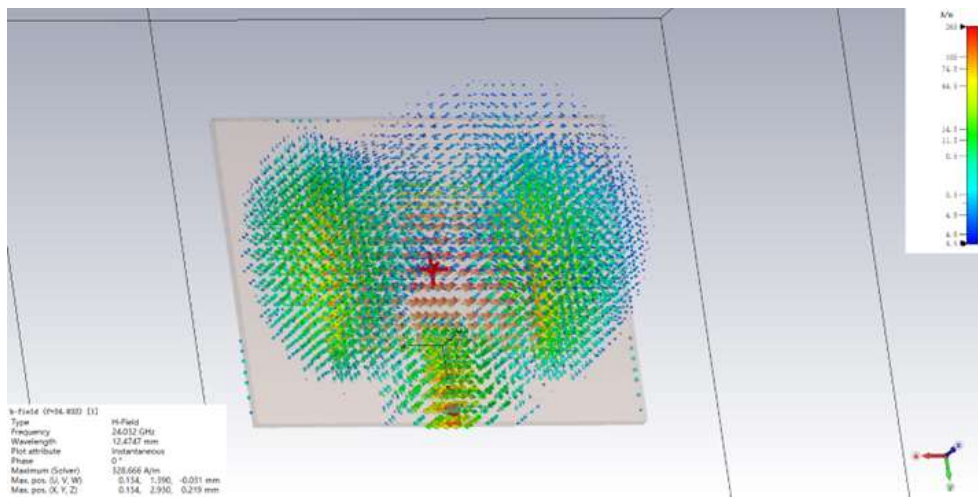
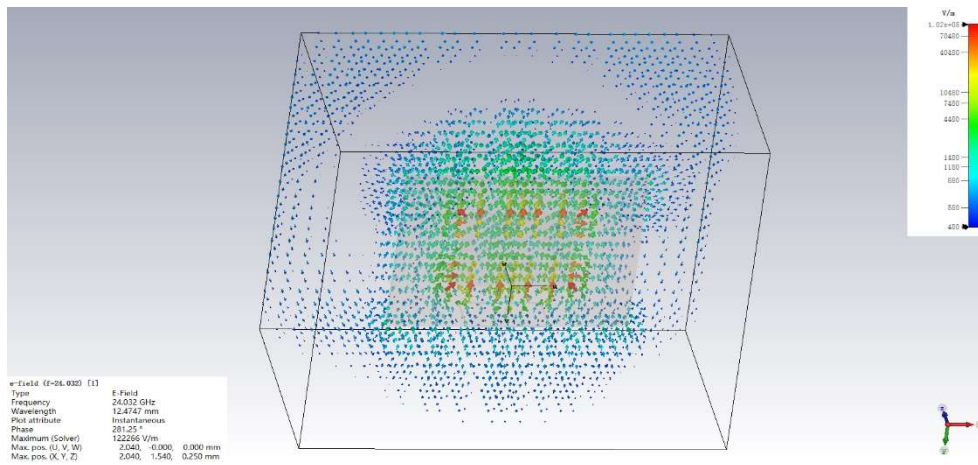
Configuration for $W=4.08$ mm

1. **S11 Parameters:** The S11 parameter graph (Figure 1) shows the reflection coefficient as a function of frequency. The minimum S11 value of -21.32 dB is observed at the resonance frequency of 24.032 GHz, indicating effective impedance matching. The -6 dB and -10 dB bandwidths were measured to evaluate the operational range of the antenna.

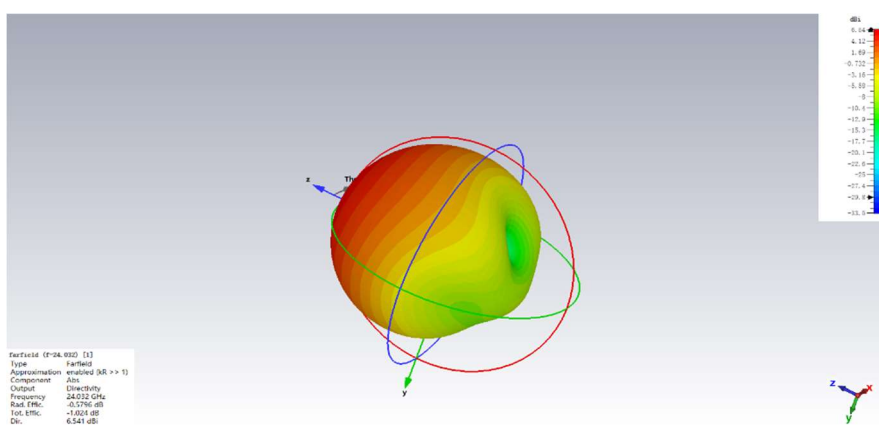


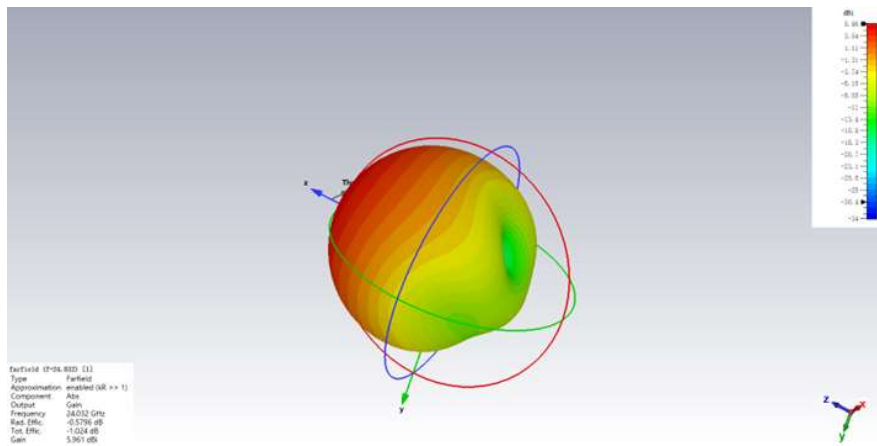
2. **Electric and Magnetic Fields:** The E-field and H-field distributions at the resonance frequency of 24.032 GHz are visualized in Figures 2 and 3. These distributions highlight strong localization and

effective radiation patterns.

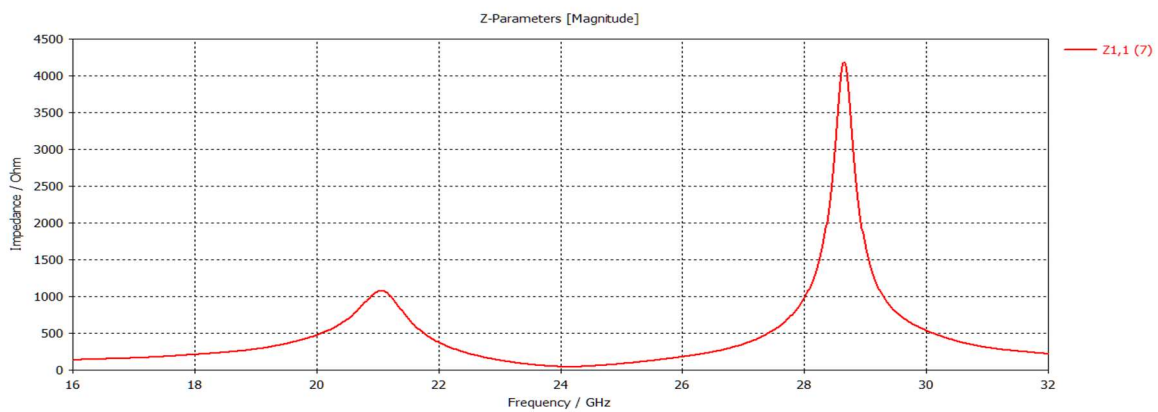


- Far-Field Analysis:** The far-field radiation pattern (Figures 4 and 5) shows a gain of 5.96 dBi and a directivity of 6.54 dBi. These results confirm efficient radiation concentrated in the desired direction.





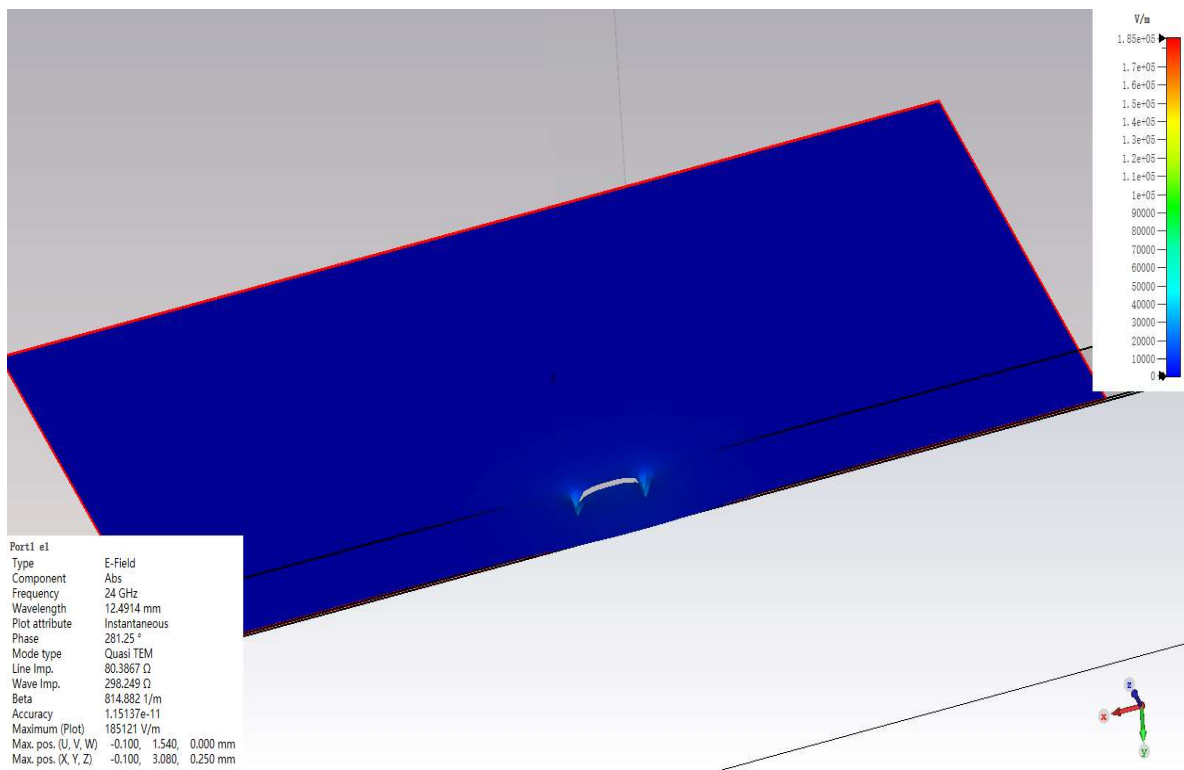
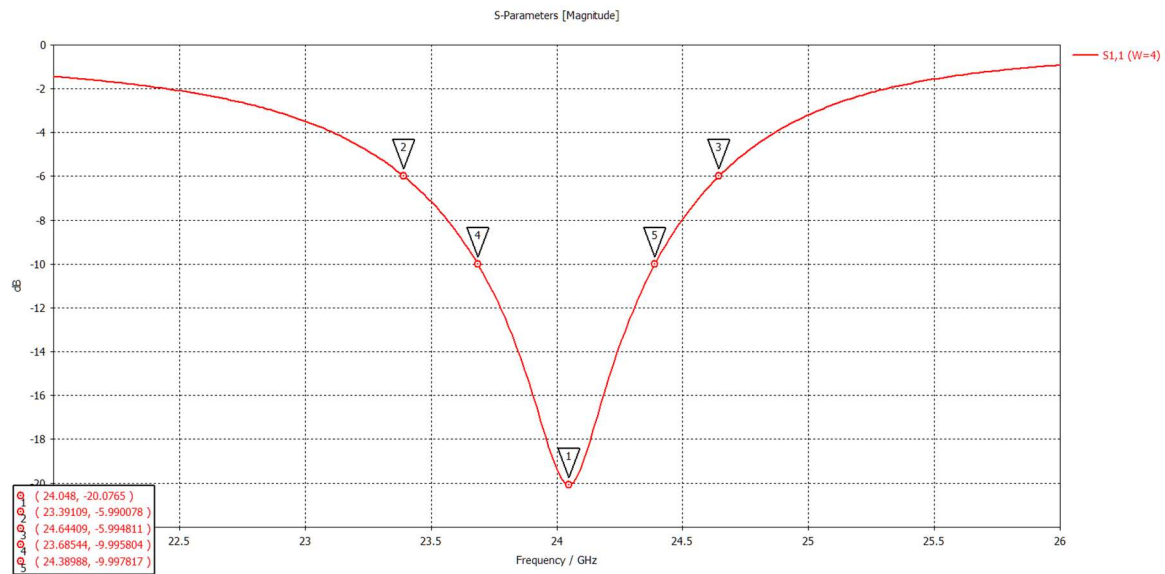
4. **Input Impedance:** The input impedance, illustrated in Figure 6, demonstrates proper matching with the 50 Ohm transmission line, ensuring minimal reflection losses.



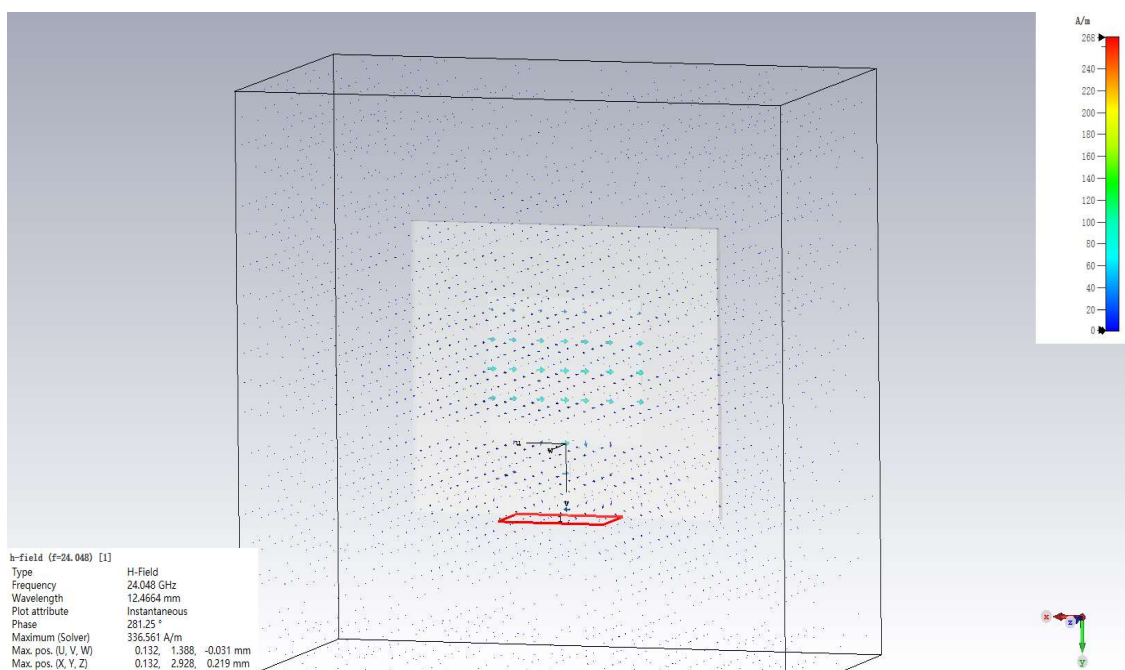
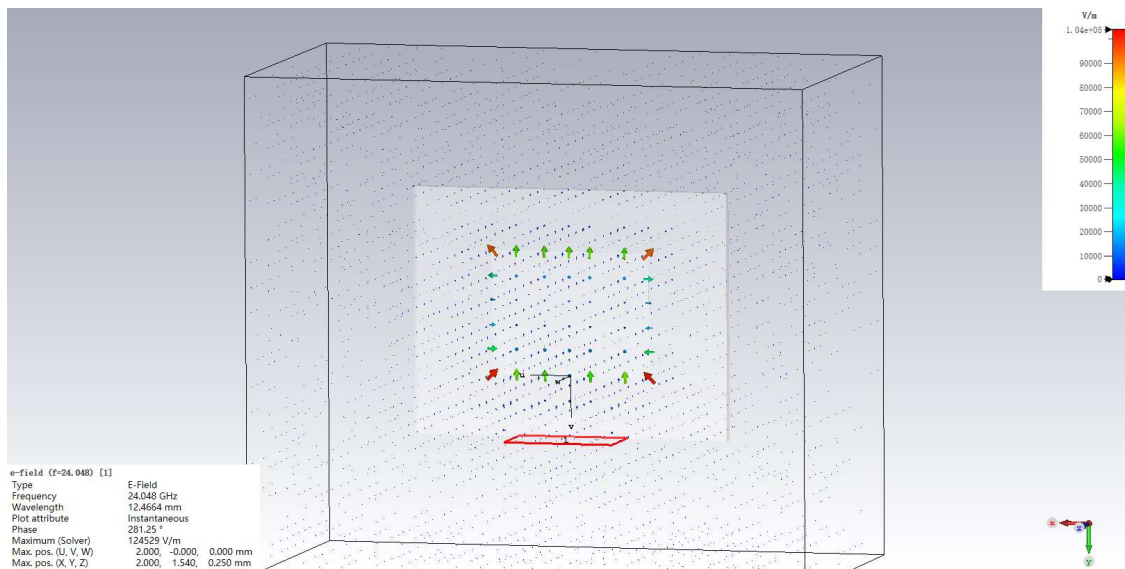
5. **Efficiency Metrics:** The radiation efficiency is calculated as -0.7596 dB, while the total efficiency is -1.024 dB, confirming minimal losses and effective energy transfer.

Configuration for W=4.00 mm

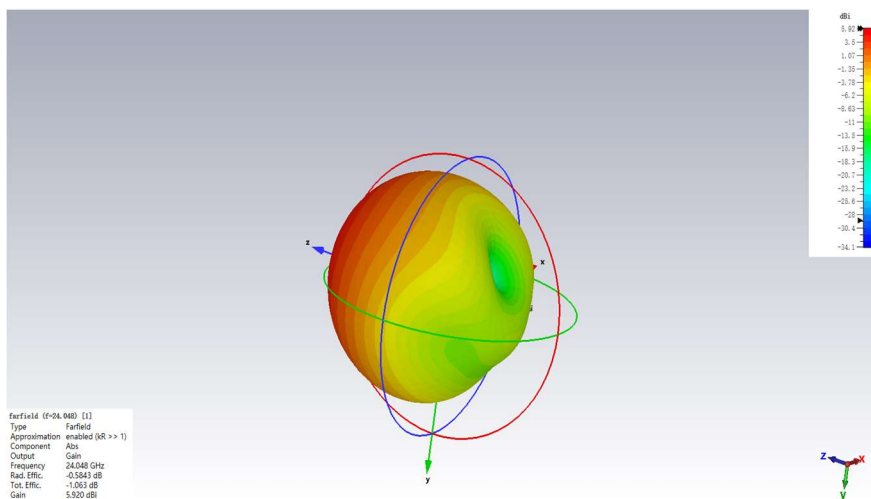
1. **S11 Parameters:** The S11 parameter graph (Figure 7) shows a minimum S11 value of -20.08 dB at a resonance frequency of 24.048 GHz. This configuration demonstrates effective impedance matching and stable performance.

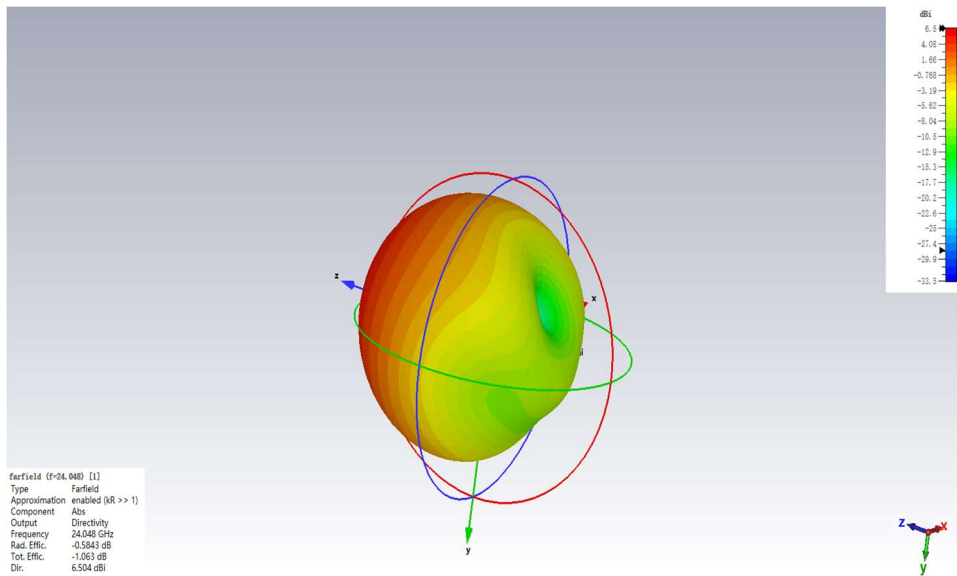


2. **Electric and Magnetic Fields:** The E-field and H-field distributions at 24.048 GHz (Figures 8 and 9) reveal uniform radiation patterns and enhanced field localization compared to $W=4.08$ mm.

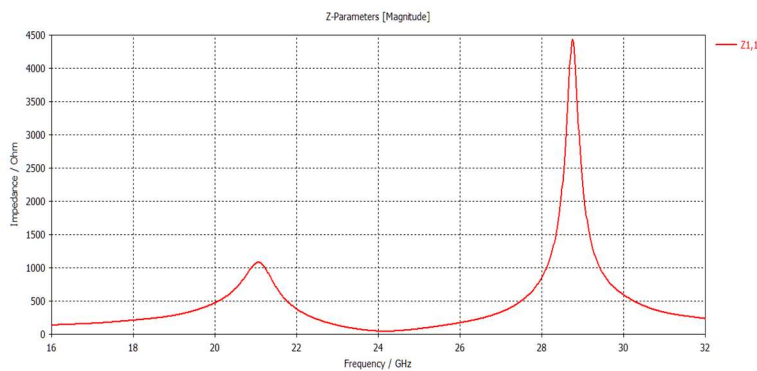


3. **Far-Field Analysis:** The far-field radiation (Figures 10 and 11) records a gain of 5.92 dBi and a directivity of 6.50 dBi. This reflects consistent performance with improved impedance matching.





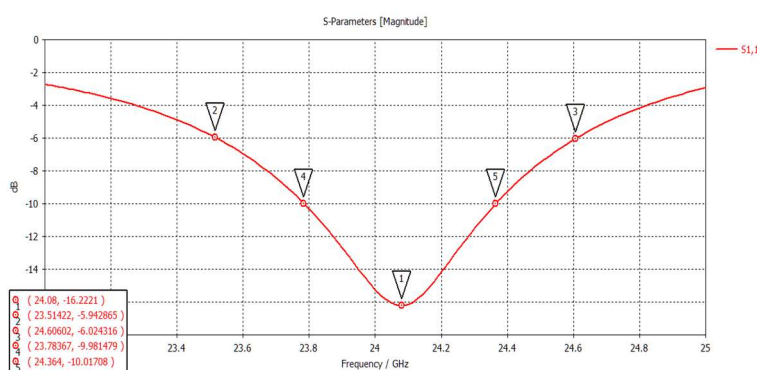
- Input Impedance:** Figure 12 illustrates the input impedance, confirming proper matching and low reflection losses.

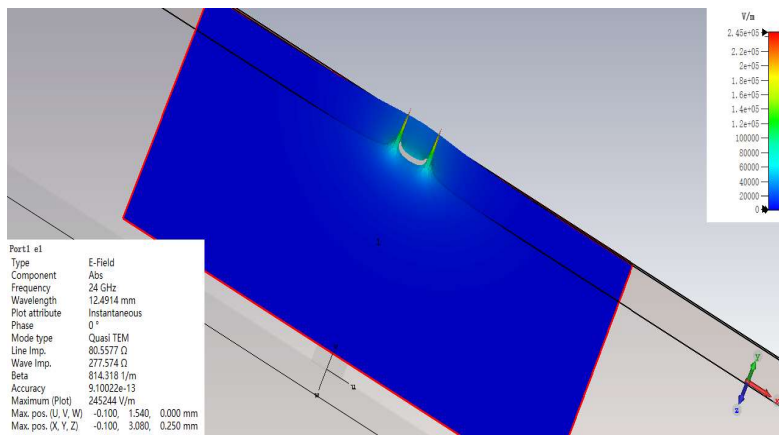


- Efficiency Metrics:** The radiation efficiency is -0.5843 dB, while the total efficiency is -1.063 dB, showcasing low losses and consistent energy transfer.

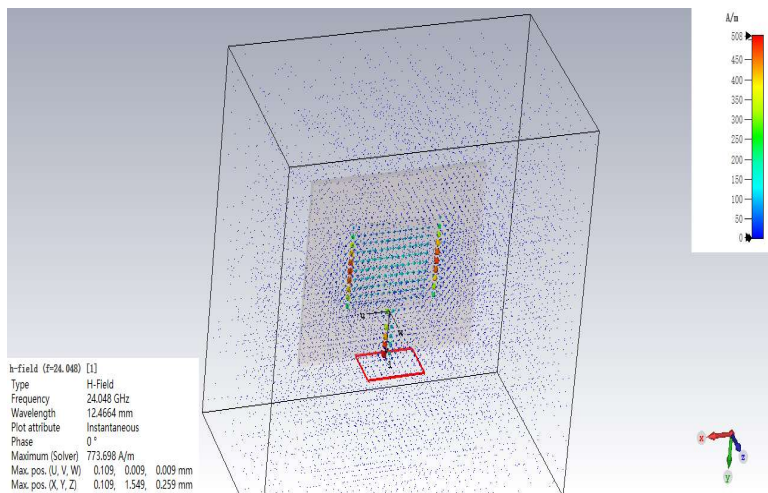
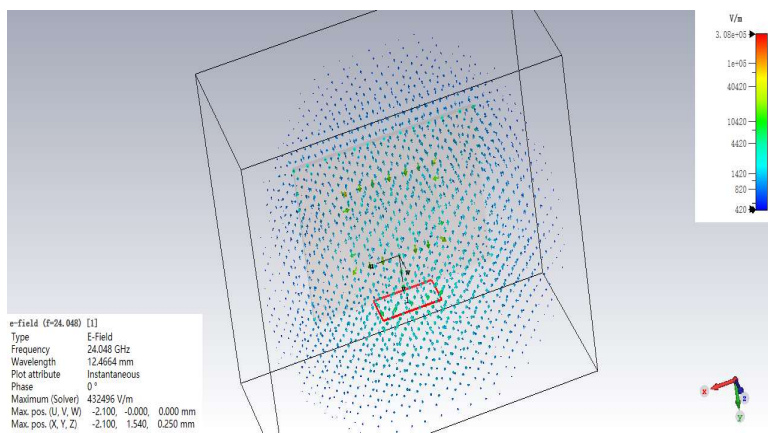
Configuration for $W=4.20$ mm

- S11 Parameters:** The S11 parameter graph (Figure 13) displays a minimum S11 value of -16.22 dB at a resonance frequency of 24.08 GHz. This configuration achieves sufficient impedance matching but lower performance compared to $W=4.00$ mm.

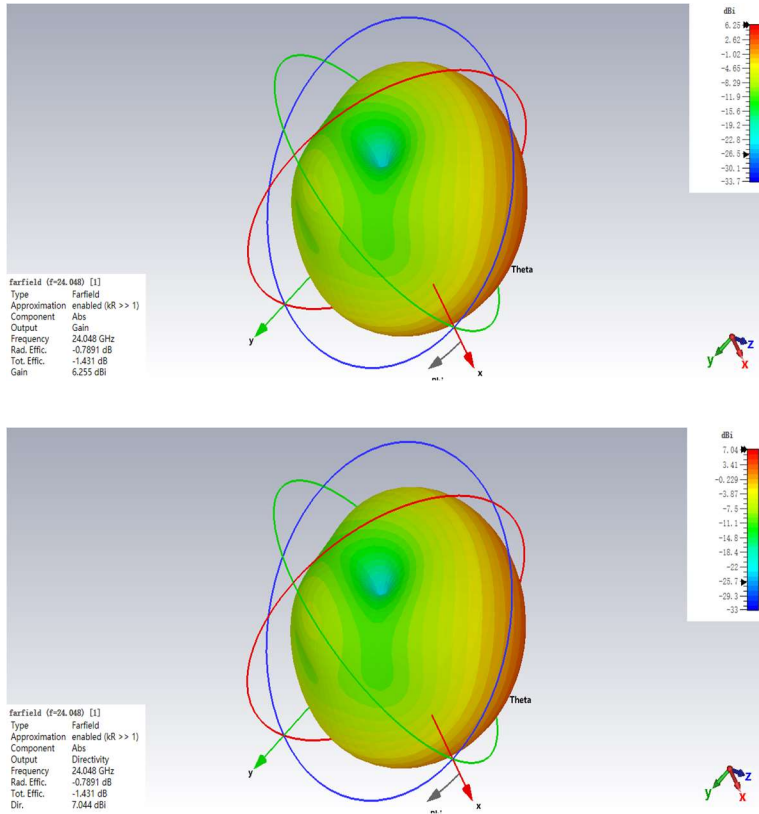




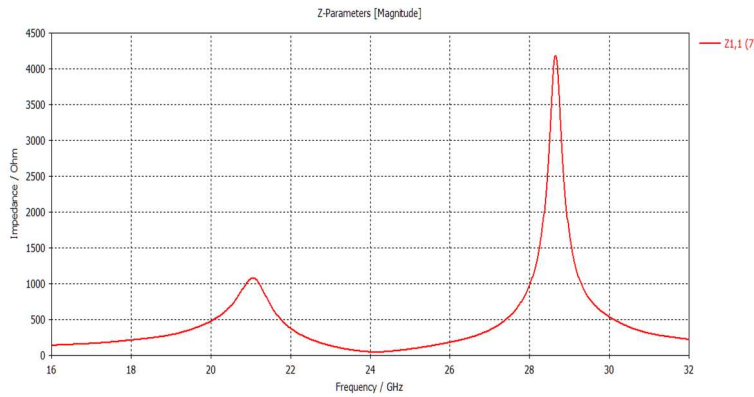
2. **Electric and Magnetic Fields:** Figures 14 and 15 show the E-field and H-field distributions at 24.08 GHz. These indicate consistent radiation patterns but slightly reduced localization.



3. **Far-Field Analysis:** The far-field radiation (Figures 16 and 17) highlights a gain of 6.25 dBi and a directivity of 7.04 dBi. This configuration supports focused radiation with reduced efficiency.



- Input Impedance:** The input impedance in Figure 18 confirms matching with the transmission line and minimized reflection losses.



- Efficiency Metrics:** The radiation efficiency is -0.7891 dB, and the total efficiency is -1.431 dB, indicating slightly higher losses than the other configurations.

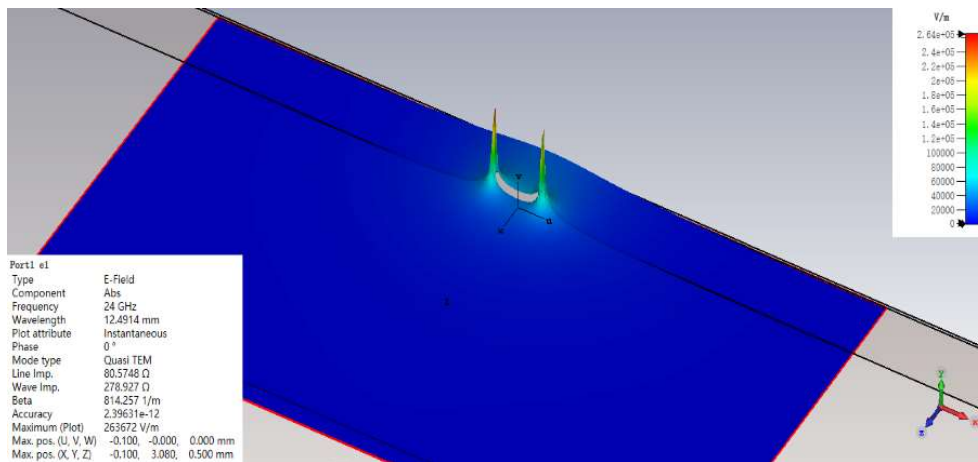
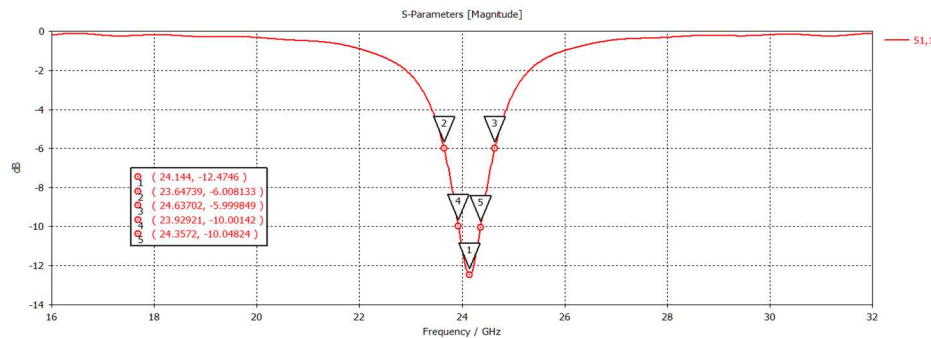
Discussion and Analysis

Comparing the three configurations, W=4.00 mm provides the most balanced performance with the lowest S11 value, high efficiency, and consistent field patterns. W=4.08 mm demonstrates strong impedance matching and radiation efficiency, while W=4.20 mm shows slightly reduced performance due to increased patch dimensions. The results highlight the importance of optimizing dimensions for achieving desired operational characteristics.

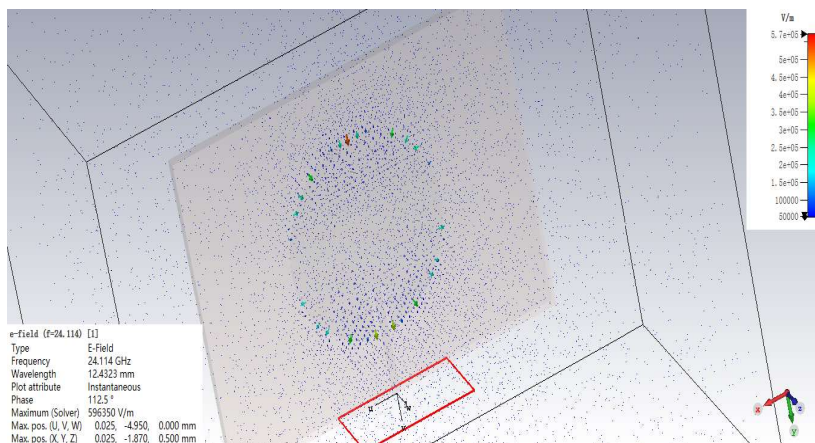
Circular Microstrip Patch Antenna

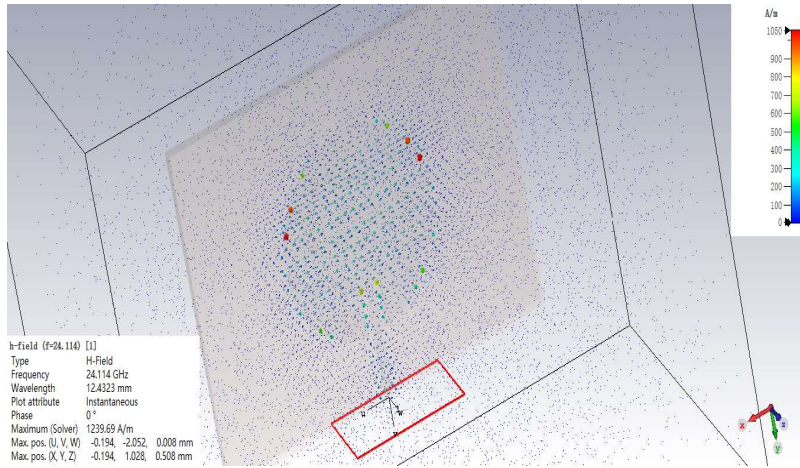
Configuration for $R=1.87$ mm

- S11 Parameters:** The S11 parameter graph (Figure 1) displays the reflection coefficient as a function of frequency. The minimum S11 value of -12.47 dB is observed at a resonance frequency of 24.144 GHz, indicating effective impedance matching. The -6 dB and -10 dB bandwidths were evaluated to determine the antenna's operational range.

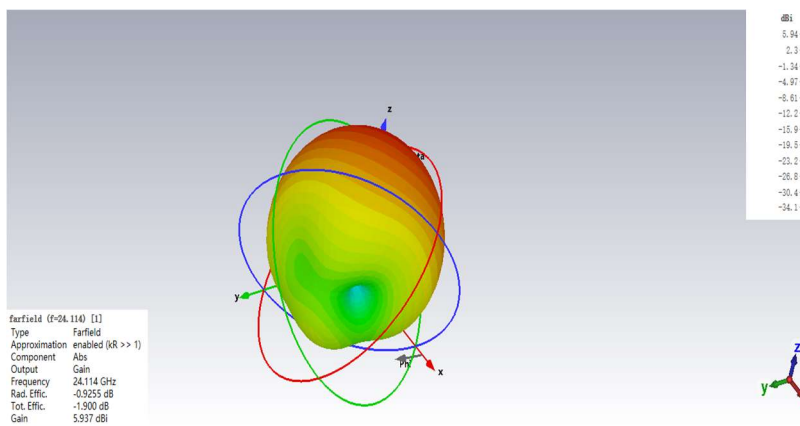
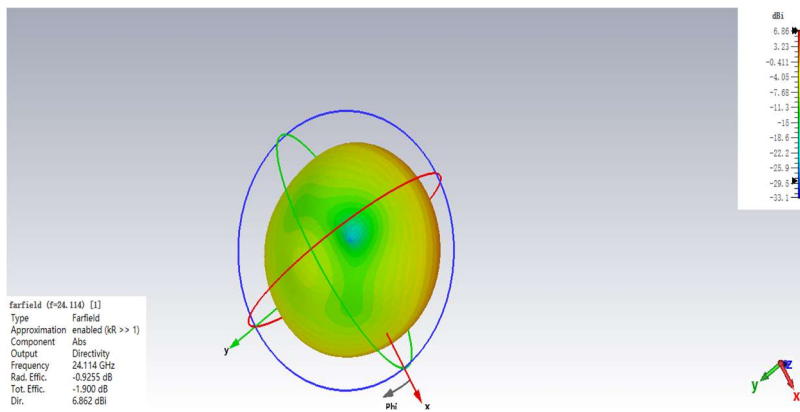


- Electric and Magnetic Fields:** The E-field and H-field distributions at the resonance frequency of 24.144 GHz are visualized in Figures 2 and 3, respectively. The patterns show strong localization and effective radiation characteristics, with the E-field peaking at 596,350 V/m and the H-field peaking at 1,239.69 A/m.

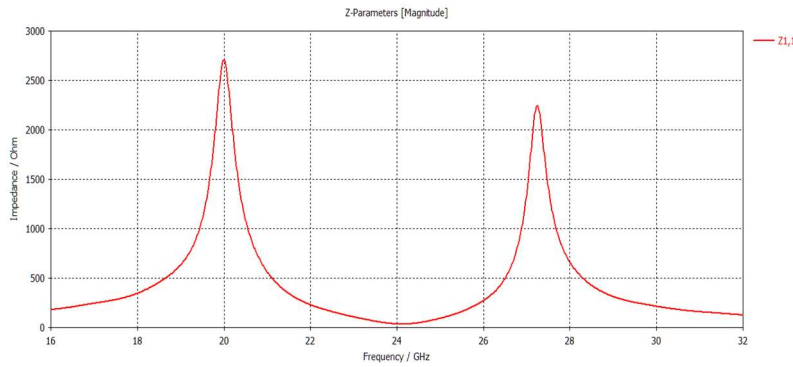




3. **Far-Field Analysis:** The far-field radiation patterns (Figures 4 and 5) highlight a gain of 5.937 dBi and a directivity of 6.862 dBi. These results demonstrate efficient radiation and a well-focused directional pattern.



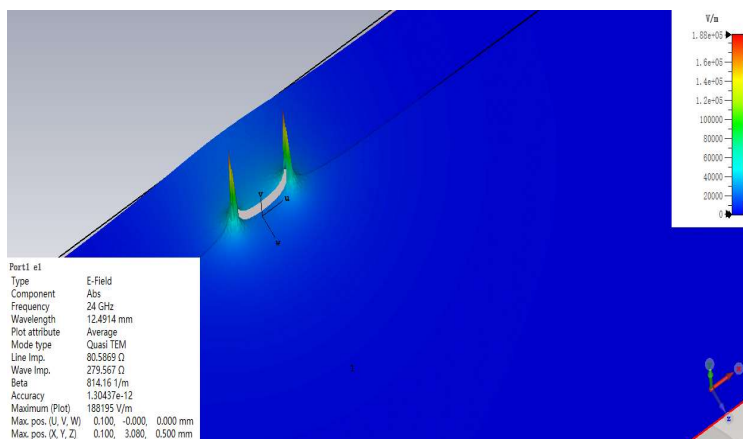
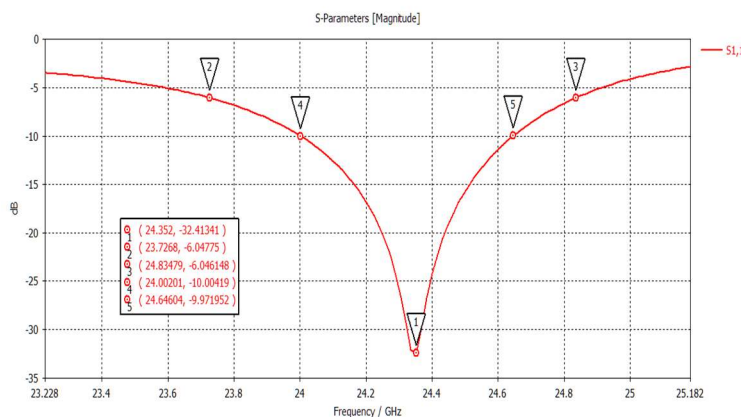
4. **Input Impedance:** The input impedance graph (Figure 6) illustrates proper matching between the antenna and the transmission line, ensuring minimal reflection losses. The impedance value aligns closely with the desired 50 Ohm standard.



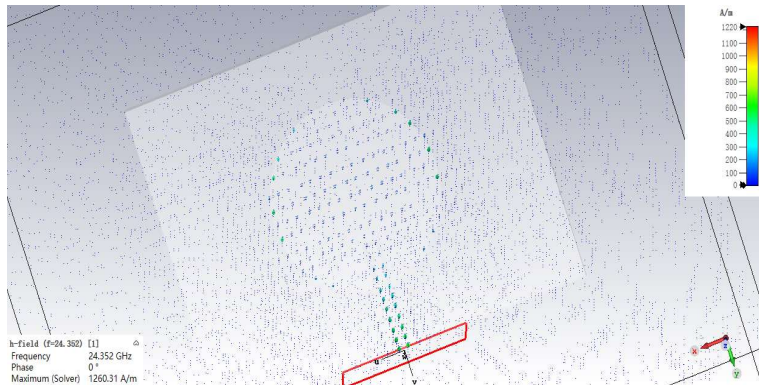
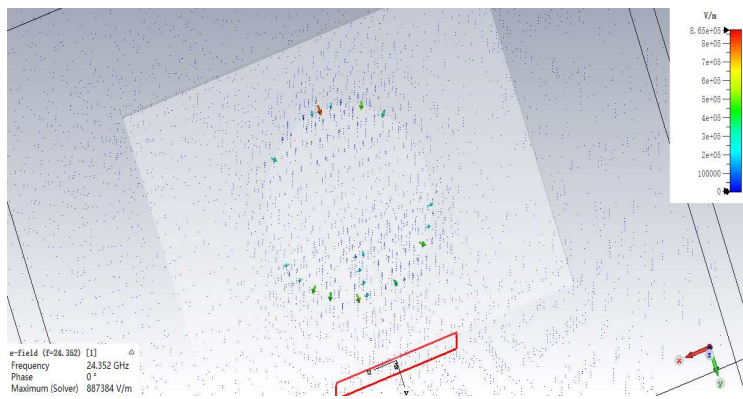
5. **Efficiency Metrics:** The radiation efficiency is calculated as -0.9255 dB, while the total efficiency is -1.902 dB. These metrics confirm reliable performance and minimal energy loss across the operational range.

Configuration for R=1.80 mm

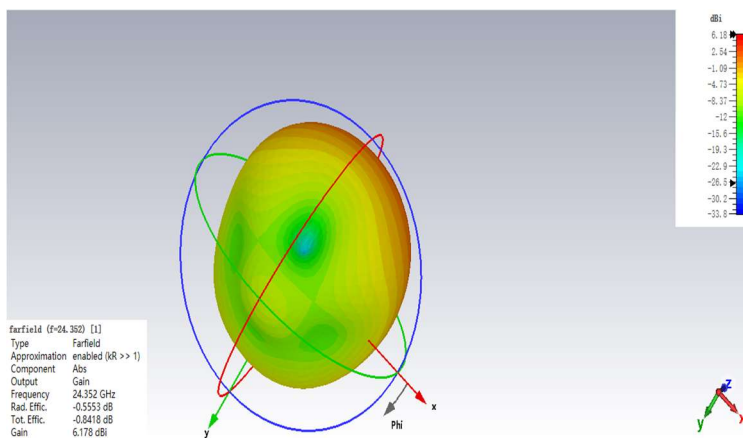
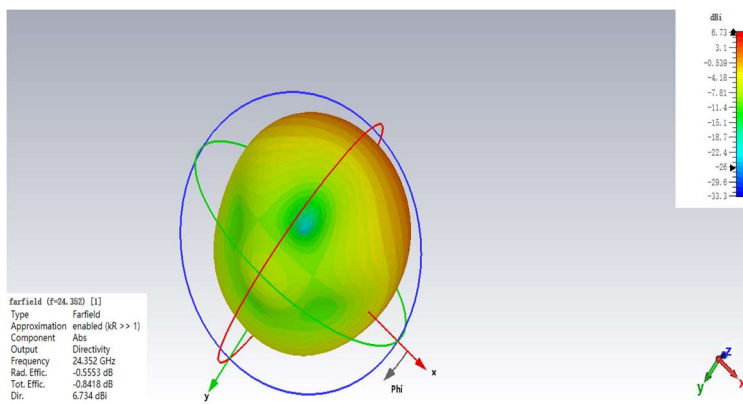
1. **S11 Parameters:** The S11 parameter graph (Figure 7) shows the reflection coefficient as a function of frequency. The minimum S11 value of -32.41 dB is observed at a resonance frequency of 24.352 GHz, demonstrating strong impedance matching. The -6 dB and -10 dB bandwidths were also measured.



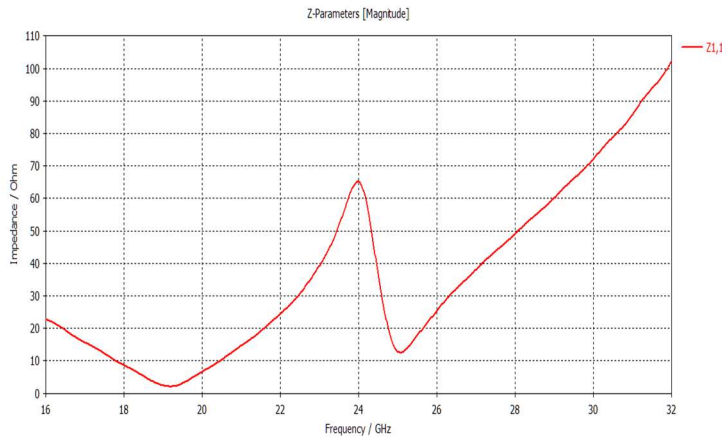
2. **Electric and Magnetic Fields:** The E-field and H-field distributions at the resonance frequency of 24.352 GHz are shown in Figures 8 and 9. The peak E-field is recorded at 887,384 V/m, and the H-field peaks at 1,260.31 A/m.



3. **Far-Field Analysis:** Figures 10 and 11 illustrate the far-field radiation patterns. The gain is 6.178 dBi, and the directivity is 6.734 dBi, indicating focused and efficient radiation.



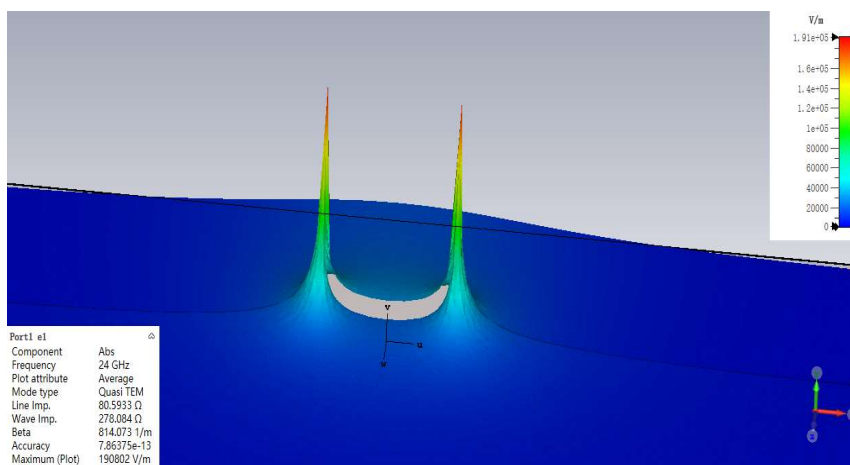
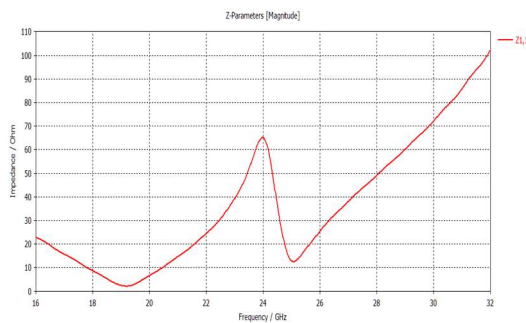
4. **Input Impedance:** The input impedance graph (Figure 12) confirms matching between the antenna and the transmission line, minimizing power loss.



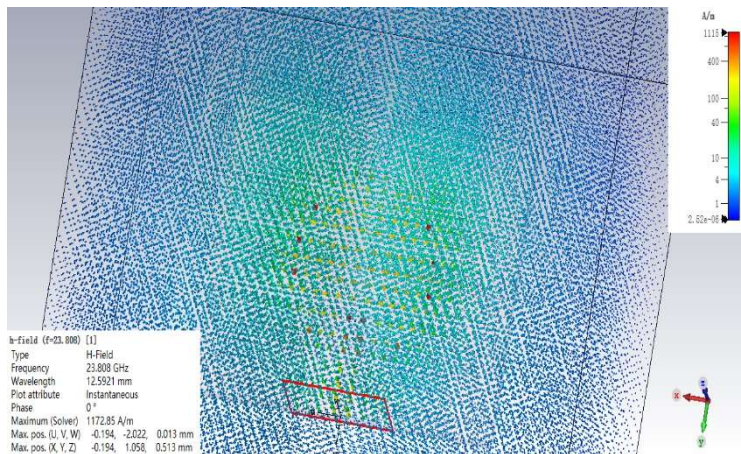
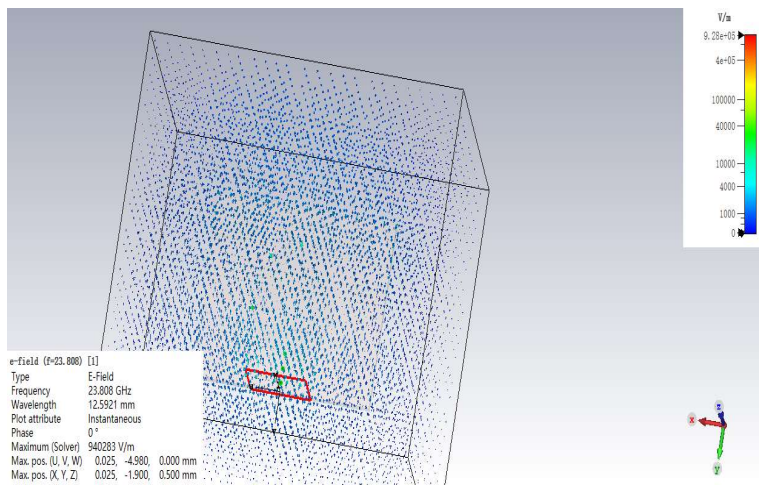
5. **Efficiency Metrics:** The radiation efficiency is calculated as -0.5553 dB, and the total efficiency is -0.8418 dB, highlighting minimal losses and strong performance.

Configuration for R=1.90 mm

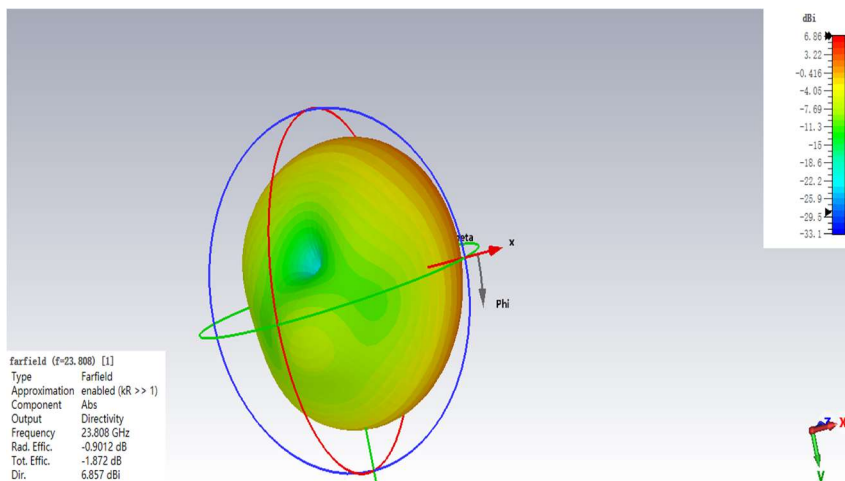
1. **S11 Parameters:** The S11 parameter graph (Figure 13) shows the reflection coefficient as a function of frequency. The minimum S11 value of -12.45 dB is observed at a resonance frequency of 23.808 GHz. The operational range is determined using the -6 dB and -10 dB bandwidths.

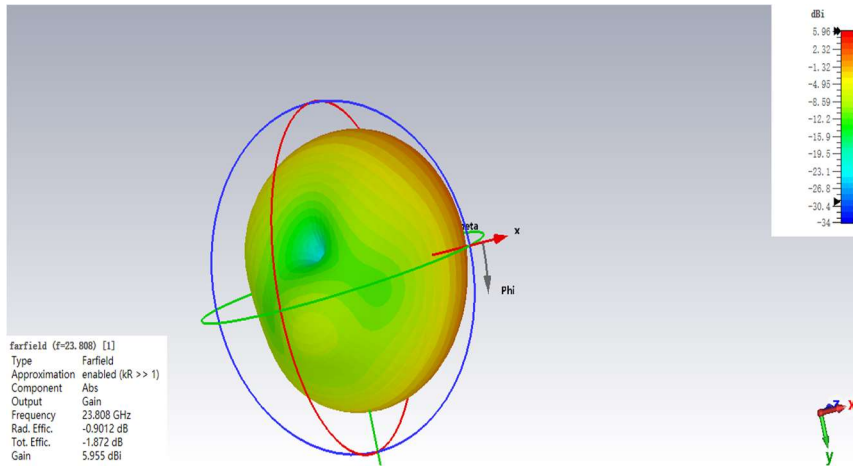


2. **Electric and Magnetic Fields:** Figures 14 and 15 display the E-field and H-field distributions at 23.808 GHz. The E-field peaks at 940,283 V/m, and the H-field peaks at 1,172.85 A/m.

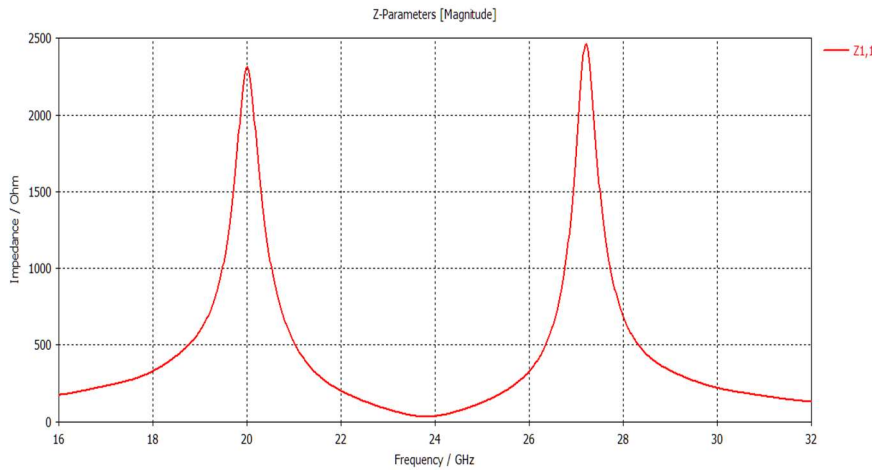


3. **Far-Field Analysis:** The far-field radiation patterns (Figures 16 and 17) indicate a gain of 5.955 dBi and a directivity of 6.857 dBi, showing efficient and focused radiation.





4. **Input Impedance:** The input impedance graph (Figure 18) confirms proper matching, ensuring efficient power transfer.



5. **Efficiency Metrics:** The radiation efficiency is -0.9012 dB, while the total efficiency is -1.872 dB, demonstrating reliable performance with slightly higher losses than the R=1.80 mm configuration.

Discussion and Analysis

Among the three configurations of the circular microstrip patch antenna, R=1.80 mm achieves the best overall performance. It shows the lowest S11 value, indicating the strongest impedance matching, alongside the highest efficiency and optimal gain and directivity. This configuration demonstrates superior energy transfer and minimal reflection, making it ideal for focused radiation applications.

R=1.87 mm provides balanced performance, maintaining effective impedance matching and good radiation characteristics, though slightly higher losses are observed compared to R=1.80 mm. It offers a compromise for scenarios where minor trade-offs in efficiency are acceptable.

R=1.90 mm, while still functional, shows increased reflection losses and reduced efficiency, attributed to the larger radius. These results suggest diminishing returns for performance as the radius increases beyond an optimal point.

This analysis underscores the critical role of radius selection in achieving high-performance circular microstrip patch antennas. R=1.80 mm emerges as the optimal configuration, providing a well-rounded balance of key parameters, highlighting the importance of precise tuning for specific application requirements.

Conclusion

This study evaluated the performance of rectangular and circular microstrip patch antennas through simulation and analysis. For rectangular antennas, $W=4.00$ mm emerged as the optimal configuration, balancing impedance matching, efficiency, and field performance. Circular antennas demonstrated that $R=1.80$ mm achieved the best results, excelling in S_{11} , gain, and efficiency. These findings highlight the importance of precise dimensional optimization in antenna design to achieve superior performance across various parameters and operational requirements. Both designs illustrate how specific configurations can be tailored to meet practical application needs, offering insights into efficient and targeted antenna development.

References

1. CST Studio Suite 2024. Dassault Systèmes. Simulation Software.
2. Balanis, C.A. (2016). "Antenna Theory: Analysis and Design." Wiley.
3. Rogers Corporation. RO4350B Material Properties. Technical Datasheet.
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5. Pozar, D.M. (2011). "Microwave Engineering." Wiley.