Design and Optimization of a 2.5 GHz Inset-Fed Microstrip Patch Antenna

Engineering Project Report

This report reconstructs the original antenna assignment into a professional engineering project format. It presents the design requirements, analytical sizing, CST simulation workflow, feed-line tuning, parametric optimization, and final electromagnetic performance of an inset-fed rectangular microstrip patch antenna.

Project parameter	Final / reported value
Target resonant frequency	2.5 GHz
Substrate material	FR-4, relative permittivity epsilon_r = 4.4
Substrate thickness	0.575 mm
Copper thickness	0.035 mm
Interface	50 ohm microstrip line with SMA connector
Optimized feed width Wf	1.08 mm
Optimized patch width Wpatch	36.51 mm
Optimized patch length Lpatch	23.3 mm
Optimized inset depth Fi	6 mm
Optimized S11 at 2.5 GHz	-28.15 dB
Peak realized gain at 2.5 GHz	4.84 dBi
Side-lobe level	approximately -14.6 dBi

Professional project description: A compact 2.5 GHz inset-fed rectangular microstrip patch antenna was designed and optimized on an FR-4 substrate using CST Studio Suite. The work included analytical patch sizing, 50 ohm microstrip feed optimization, SMA connector integration, parametric tuning of patch length and inset depth, and full-wave electromagnetic evaluation using S-parameters, electric-field visualization, and far-field gain plots.

1. Project Scope and Engineering Objective

The project focused on the design of an inset-fed rectangular microstrip patch antenna intended to resonate at 2.5 GHz. The antenna was implemented on an FR-4 dielectric substrate and interfaced through a 50 ohm microstrip feed line connected to an SMA connector. The engineering goal was to obtain acceptable impedance matching at the target frequency while maintaining a simple PCB-based antenna geometry.

The main performance target was to achieve a return loss below -10 dB at the resonant frequency. The final optimized simulation reported S11 = -28.15 dB at approximately 2.5 GHz, meeting the matching requirement with a strong margin.

The original source provides simulation results only. No physical fabrication, VNA measurement, tolerance study, radiation chamber measurement, bandwidth table, or efficiency value was provided. Therefore, this reconstructed report presents the work as a simulated engineering design rather than a measured hardware validation.

2. Design Requirements

Requirement	Specified value / purpose
Operating frequency	2.5 GHz
Antenna topology	Inset-fed rectangular microstrip patch antenna
Substrate	FR-4 dielectric
Relative permittivity	epsilon_r = 4.4
Substrate thickness	H = 0.575 mm
Track/copper thickness	T = 0.035 mm
Feed interface	50 ohm microstrip and SMA connector
Matching criterion	S11 below -10 dB at resonance

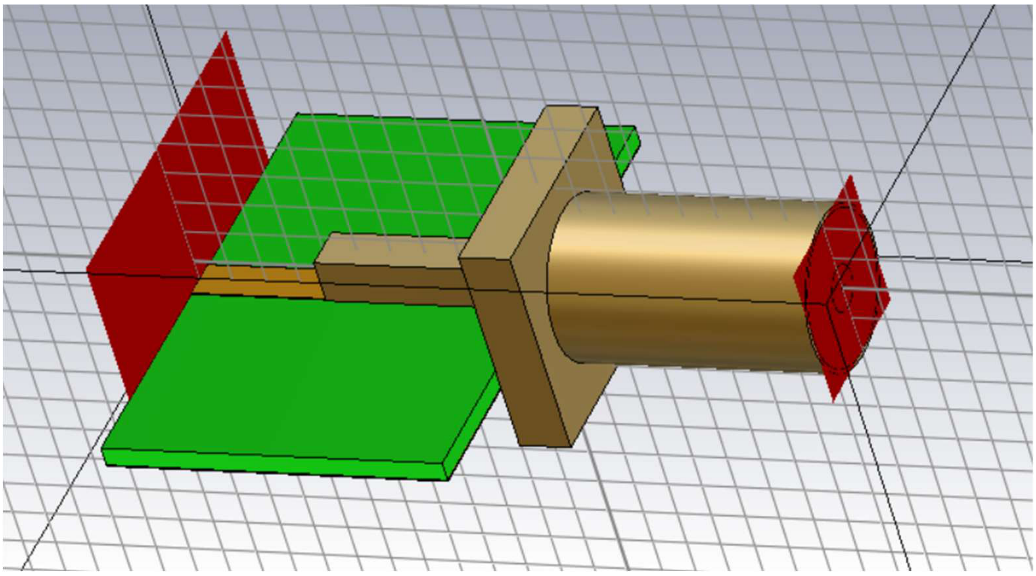

Figure 1. CST model used for microstrip feed-line impedance optimization with SMA connector.

3. Feed-Line Impedance Optimization

The antenna feed was optimized first because the microstrip line must provide an approximately 50 ohm interface to the SMA connector and external RF equipment. The feed width Wf was treated as the main variable during this step.

An initial feed width of Wf = 1.2 mm produced a simulated line impedance of approximately 46.86 ohm at 2.5 GHz. This was below the accepted 50 +/- 1 ohm design target. The feed width was then adjusted to Wf = 1.08 mm, which produced approximately 49.91 ohm and was accepted as the final feed-line width.

Feed width Wf	Simulated line impedance	Decision
1.20 mm	46.86 ohm	Rejected - below 50 +/- 1 ohm target
1.08 mm	49.91 ohm	Accepted - within target range

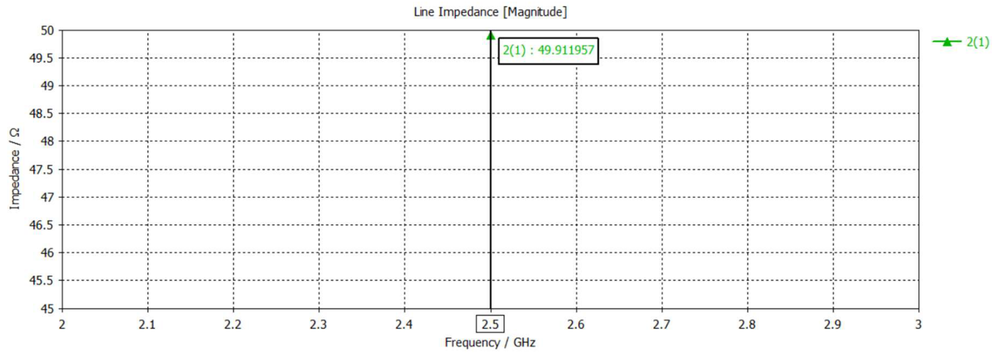

Figure 2. Simulated line impedance for Wf = 1.2 mm.

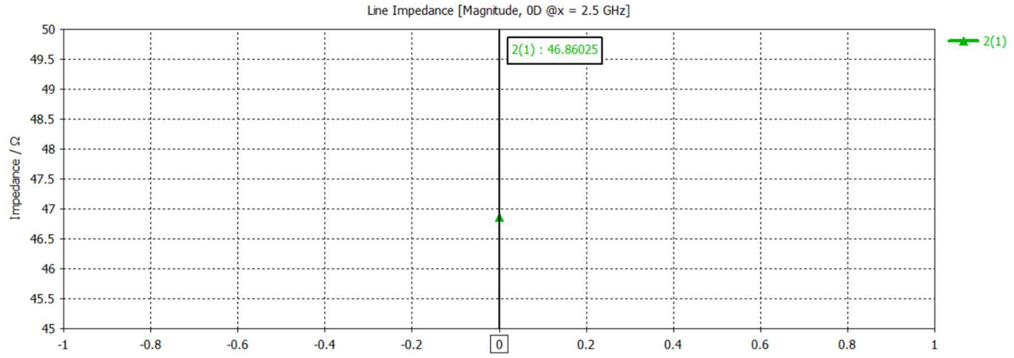

Figure 3. Simulated line impedance for Wf = 1.08 mm.

4. Preliminary Patch Dimensioning

The initial patch dimensions were calculated using standard rectangular microstrip patch antenna design equations with c0 = 3 x 10^8 m/s, resonant frequency fr = 2.5 GHz, substrate relative permittivity epsilon_r = 4.4, and substrate height h = 0.575 mm.

Calculated / selected parameter	Value
Initial patch width W	36.51 mm
Effective relative permittivity epsilon_eff	4.259
Length extension Delta L	0.2667 mm
Initial calculated patch length L	28.53 mm
Feed gap Gf	2 mm

The calculated geometry was used as an analytical starting point. Since microstrip antenna resonance and impedance matching depend strongly on coupled electromagnetic effects, the initial dimensions were then refined through full-wave simulation.

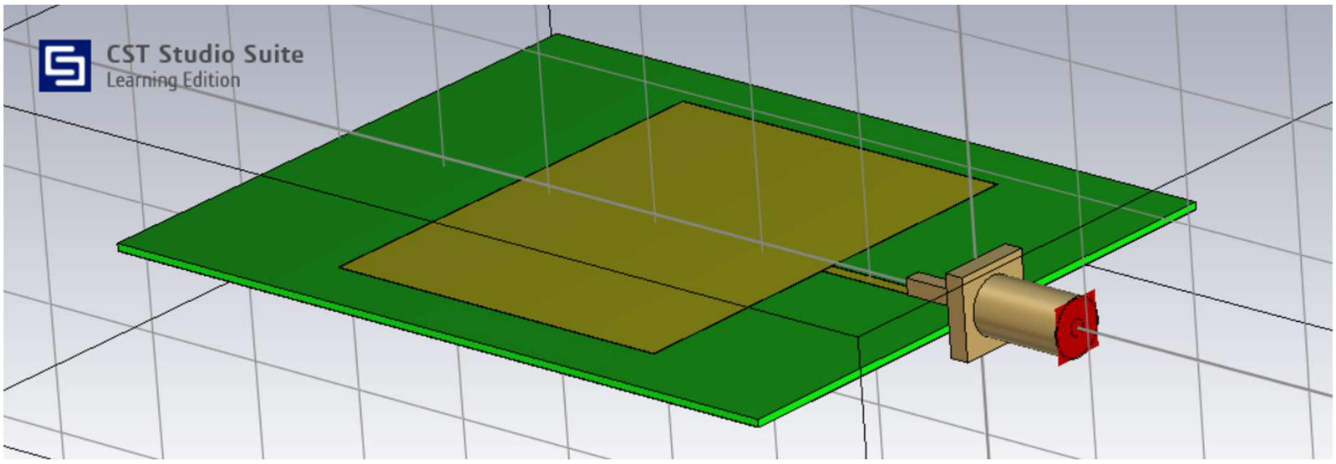

Figure 4. Initial patch geometry constructed in CST before inset optimization.

5. CST Model Development

The CST model was built using the optimized feed width, SMA connection, FR-4 dielectric board, copper patch, ground plane, inset feed geometry, and feed gaps around the microstrip line. The source document notes that the feed-gap regions are part of the same dielectric board material even though they appear in a different color in the CST visualization.

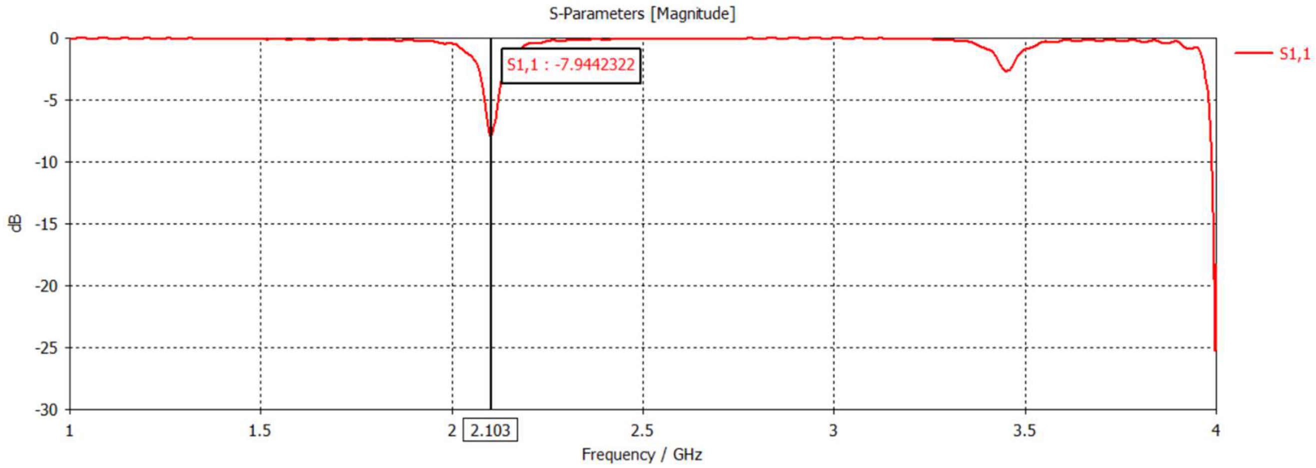

Figure 5. CST antenna model after introducing the inset feed and feed gaps.

The first time-domain simulation of the patch model did not satisfy the return-loss requirement. The simulated S11 minimum was approximately -7.94 dB, which is not below the -10 dB matching threshold. This result confirmed that analytical patch sizing alone was insufficient and that geometry optimization was required.

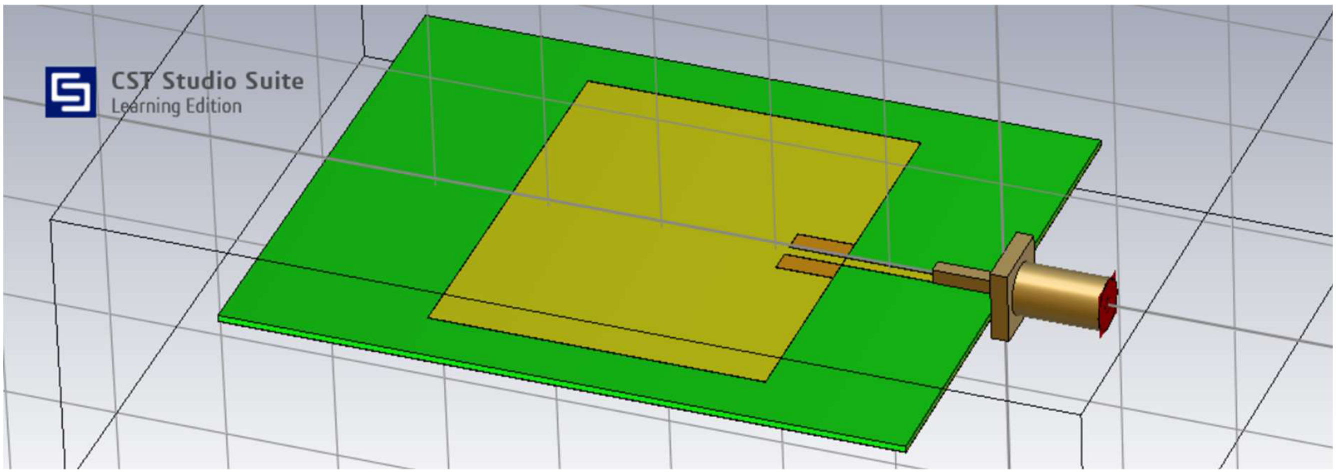

Figure 6. Initial S11 response before parametric optimization.

6. Parametric Optimization Strategy

Patch length Lpatch and inset feed depth Fi were used as the main optimization variables. The design approach treated Lpatch as the primary resonance-control parameter and Fi as the primary impedance-matching parameter. This is a practical antenna optimization workflow because changes in inset depth can also slightly disturb the resonance frequency, requiring iteration.

A CST parametric sweep was performed over Fi and Lpatch. The source results identified the best candidates around Fi = 6 mm with Lpatch values of 22 mm, 23 mm, and 24 mm. The final selected value was Lpatch = 23.3 mm with Fi = 6 mm because it produced the best match close to the 2.5 GHz target.

Optimization variable	Role in tuning	Final selected value
Lpatch	Primary control of resonant frequency	23.3 mm
Fi	Primary control of inset-feed matching	6 mm
Wf	50 ohm microstrip feed impedance	1.08 mm
Gf	Feed-gap geometry	2 mm
Lf	Feed-line length	19 mm

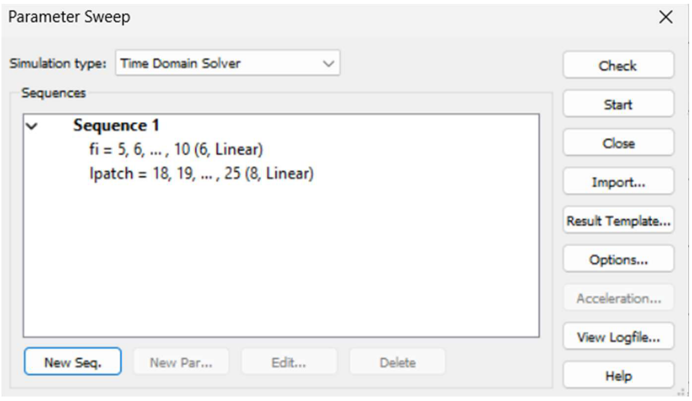

Figure 7. CST parameter sweep setup for Fi and Lpatch.

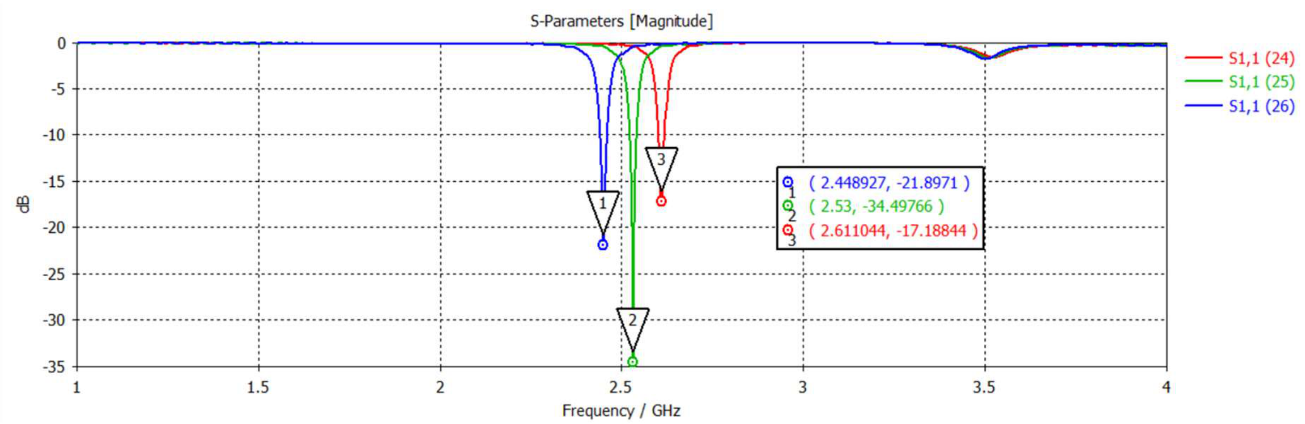

Figure 8. Parametric sweep results showing candidate resonance/matching conditions.

7. Optimized Antenna Performance

The optimized antenna satisfied the specified return-loss criterion. The final CST S-parameter result reported S11 = -28.15 dB at approximately 2.5 GHz. This indicates strong impedance matching between the 50 ohm feed interface and the patch antenna at the target frequency.

Performance metric	Reported result
Resonant frequency	approximately 2.5 GHz
S11 at resonance	-28.15 dB
Return-loss requirement	below -10 dB
Requirement status	Satisfied
Peak realized gain	4.84 dBi
Side-lobe level	approximately -14.6 dBi

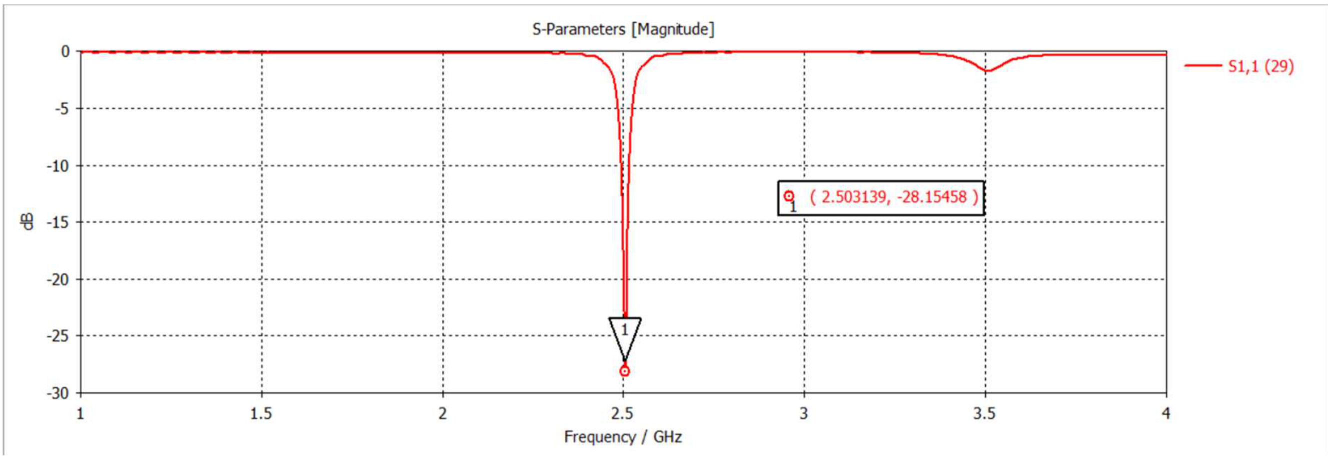

Figure 9. Optimized S11 response showing -28.15 dB near 2.5 GHz.

8. Electric-Field Distribution

The electric-field plots were used to visually inspect the field concentration and radiation behavior around the patch and feed region. The arrow plot shows the field direction, while the contour plot highlights the field magnitude distribution over the antenna structure.

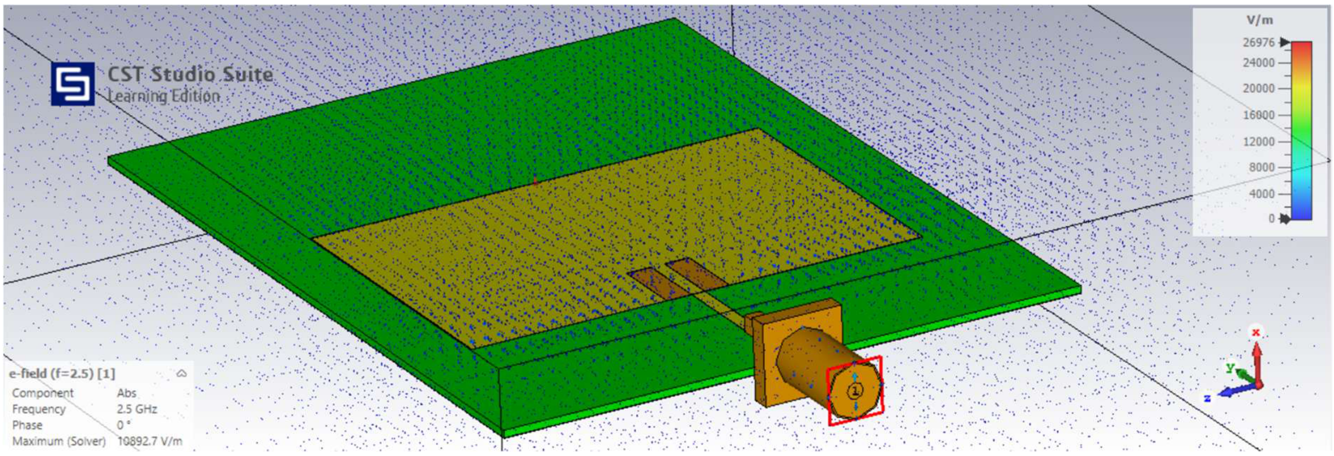

Figure 10. Electric-field distribution represented using arrows.

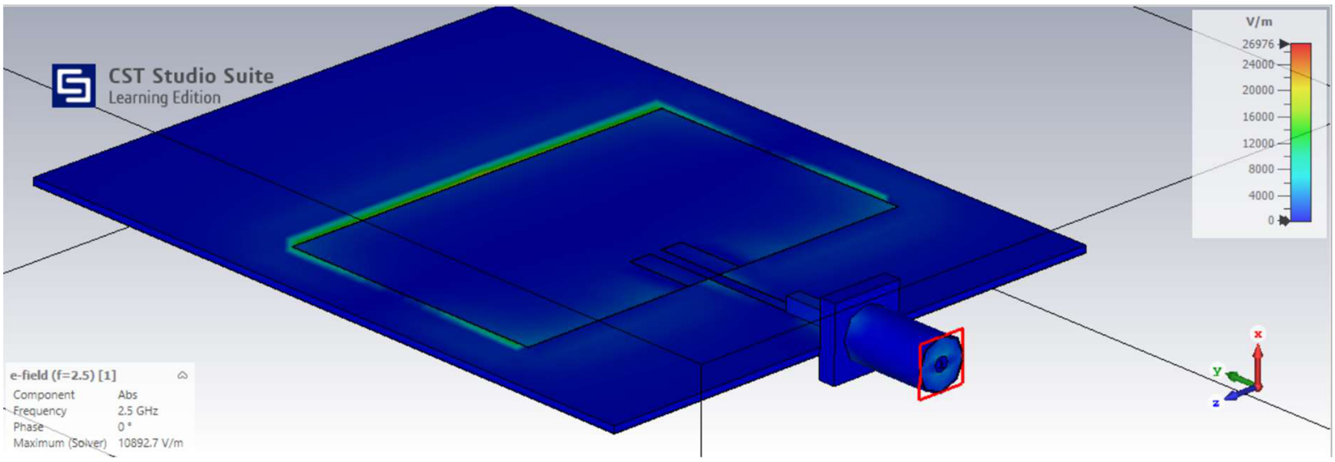

Figure 11. Electric-field distribution represented using contour magnitude.

9. Far-Field Radiation Characteristics

The final design was evaluated using 2D and 3D far-field realized-gain plots. The reported peak realized gain at 2.5 GHz was 4.84 dBi, with the side-lobe level reported at approximately -14.6 dBi. These results indicate that the design produced a directional radiation pattern consistent with a rectangular patch antenna.

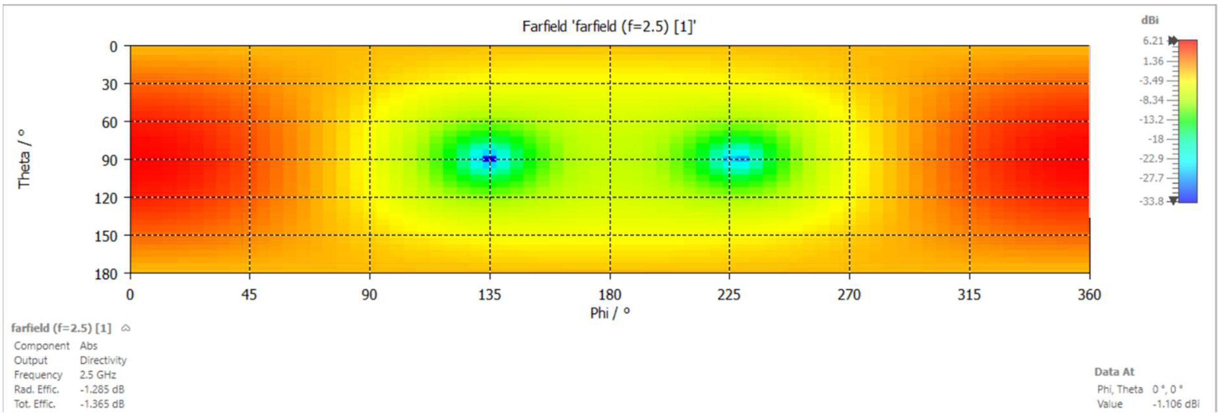

Figure 12. 2D equirectangular projection of realized-gain far-field radiation pattern.

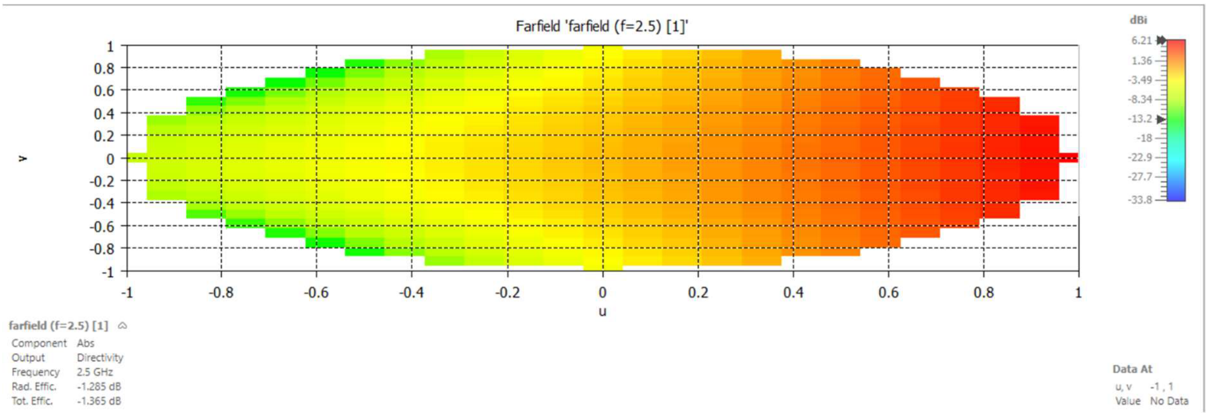

Figure 13. 2D orthographic projection of realized-gain far-field radiation pattern.

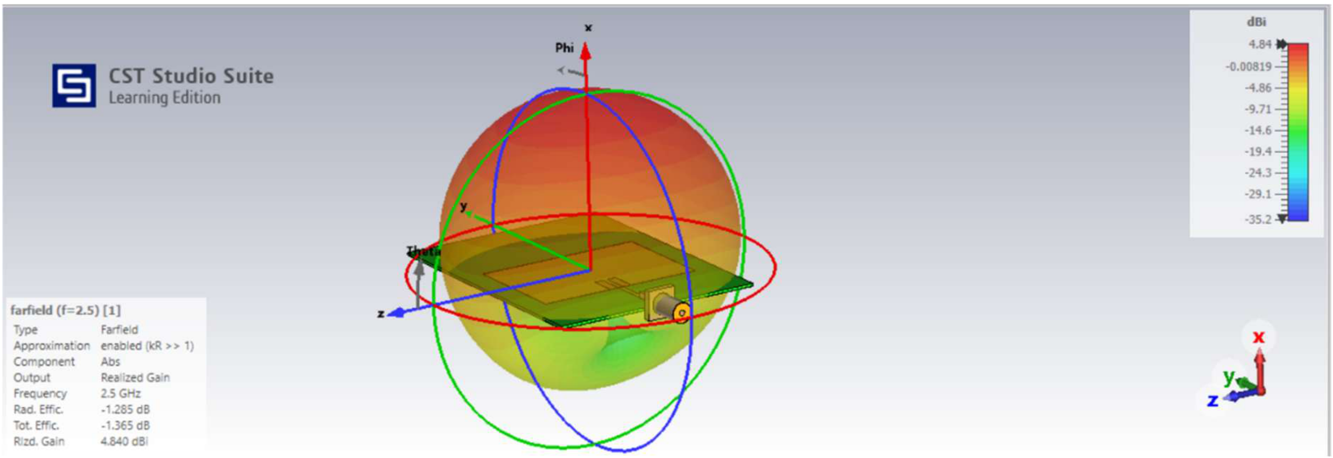

Figure 14. 3D realized-gain far-field radiation pattern at 2.5 GHz.

10. Final Design Summary

Final design parameter	Value
Substrate	FR-4
Relative permittivity	epsilon_r = 4.4
Substrate thickness	0.575 mm
Copper thickness	0.035 mm
Patch width Wpatch	36.51 mm
Patch length Lpatch	23.3 mm
Feed width Wf	1.08 mm
Feed length Lf	19 mm
Inset depth Fi	6 mm
Feed gap Gf	2 mm
Connector/interface	SMA connector with 50 ohm microstrip feed

11. Engineering Conclusion

A 2.5 GHz inset-fed rectangular microstrip patch antenna was designed, simulated, and optimized on an FR-4 substrate using CST Studio Suite. The project followed a practical engineering workflow: analytical dimension estimation, feed-line impedance matching, electromagnetic model construction, parametric sweep optimization, and final S-parameter and far-field performance evaluation.

The optimized geometry achieved S11 = -28.15 dB at approximately 2.5 GHz, exceeding the -10 dB matching requirement. The final far-field simulation reported a peak realized gain of 4.84 dBi and an approximate side-lobe level of -14.6 dBi. These outcomes support the design as a successful simulated antenna project suitable for further fabrication planning and experimental RF validation.

Recommended next steps would be PCB fabrication, SMA soldering, VNA-based S11 measurement, comparison of measured and simulated resonance, and radiation-pattern validation in a controlled antenna test environment. These steps were not included in the supplied source document and should be treated as future engineering validation work.

12. LinkedIn-Ready Project Title and Description

Title: Design and Optimization of a 2.5 GHz Inset-Fed Microstrip Patch Antenna Using CST Studio Suite

Description: Designed and optimized a 2.5 GHz inset-fed rectangular microstrip patch antenna on an FR-4 substrate using CST Studio Suite. The project involved analytical patch-dimension calculation, 50 ohm microstrip feed-line optimization, SMA connector integration, parametric tuning of patch length and inset depth, and full-wave electromagnetic simulation. The final optimized antenna achieved S11 = -28.15 dB at 2.5 GHz, with a peak realized gain of 4.84 dBi and a side-lobe level of approximately -14.6 dBi.

Skills: CST Studio Suite | Microstrip Patch Antenna Design | RF Simulation | S-Parameters | Impedance Matching | Far-Field Radiation Analysis | Parametric Optimization | PCB-Based RF Design