Design and Simulation of Rectangular Slot Antennas Using the Finite Element Method in Python

Original Scientific Paper

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Abstract *– The design and simulation of rectangular slot antennas using a Python-based Finite Element Method (FEM) framework are presented in this study, addressing the limitations of costly and resource-intensive commercial electromagnetic tools and the proposed open-source implementation leverages Python's computational ecosystem—integrating Gmsh for mesh generation, FEniCS for FEM discretization, and SciPy for sparse matrix solving—to provide an accessible and customizable platform for antenna analysis. Validation against Computer Simulation Technology (CST) and High Frequency Structure Simulator (HFSS) demonstrates exceptional agreement, with return loss (S11) deviations below 0.5 dB, radiation efficiencies exceeding 85%, and impedance matching within 2 Ω of the target 50 Ω, parametric studies reveal the impact of slot dimensions and substrate properties on resonant frequency and bandwidth, while computational benchmarks highlight Python-FEM's competitive performance, achieving solve times under 20 seconds for meshes with 180 MB memory usage and the framework's accuracy, coupled with its open-source flexibility, bridges the gap between academic research and industrial prototyping, particularly for applications in 5G, IoT, and radar systems, future enhancements, like Graphics Processing Unit (GPU) acceleration and multi-physical coupling, are proposed to further advance its scalability and versatility in next-generation antenna design.*

Keywords: *Rectangular slot antennas, Finite Element Method (FEM), Python-based simulation, Open-source electromagnetics, Antenna performance validation*

Received: March 20, 2025; Received in revised form: June 25, 2025; Accepted: May 30, 2025

1. INTRODUCTION

Wireless communication systems have witnessed tremendous advancements in recent decades, driven by the rapid expansion of 5G networks, the proliferation of Internet of Things (IoT) devices, and the growing demand in modern radar applications, these trends have created an increasing need for compact, wideband, and low-profile antennas capable of meeting advanced performance requirements within strict constraints of size, weight, and power. Among the proposed engineering solutions, rectangular slot antennas have emerged as a strategic choice due to their inherent advantages, including ease bandwidth compared to conventional antenna designs [1], also the design and performance optimization of this class of antennas heavily rely on Accurate Electromagnetic (EM) simulations, typically performed using commercial software such as Computer Simulation Technology (CST) Microwave Studio and ANSYS High Frequency Structure Simulator (HFSS).

Despite the high accuracy of these software packages, their high cost, computational complexity, and closed-source nature impose significant limitations, particularly for researchers and developers operating in resource-constrained environments or within emerging institutions, thereby restricting opportunities for innovation and rapid prototyping of new designs [2], and in recent years the Python programming language has gained significant momentum in the field of electromagnetic computation, supported by a rich open-source environment and specialized libraries such as FeniCS for Finite Element Method (FEM) modeling, SciPy for advanced numerical computations, and NumPy for matrix data processing [3]. Nevertheless, despite some isolated successes in using Python for simulating components such as waveguides and patch antennas, the absence of a dedicated framework for analyzing and designing slot antennas-particularly rectangular slot antennas-remains a critical gap in the technical literature, this lack limits the ability of researchers and developers to customize simulation models to meet the demands of modern applications, such as multiband antennas and compact mobile devices [4]

Recent studies have highlighted the importance of rectangular slot antennas in supporting trends towards miniaturization and integration within wireless systems. For instance, research [5] demonstrated that these antennas can achieve highly efficient multiband operation in 5G User Equipment (UE), underscoring their relevance for compact smart devices. Moreover, of integration with planar circuits, compatibility with low-cost precision fabrication techniques, and suitability for the modern flat architectures of wireless devices [6].

These antennas typically consist of a rectangular slot etched into a conducting layer placed over a dielectric substrate, with electromagnetic radiation achieved through appropriate slot excitation, offering high flexibility in controlling radiation characteristics and other studies emphasized the superiority of the FEM in accurately simulating complex geometries of antennas, especially when dealing with inhomogeneous substrates, compared to the Method of Moments (MoM) [7], making FEM the optimal tool for studying slot antennas. Although some efforts have leveraged open-source tools like FeniCS for various electromagnetic applications, a recent review on Python-based electromagnetic frameworks [8] revealed that existing solutions lack dedicated workflows for analyzing rectangular slot antennas, this shortcoming hinders rapid modeling and spectral optimization studies, particularly for applications requiring precise tuning of slot dimensions and dielectric material properties.

Based on the above, the present research aims to develop an electromagnetic analyzer based on the FEM using Python, specifically tailored for analyzing rectangular slot antennas, the proposed framework features an integrated workflow starting with mesh generation via Gmsh and concluding with solving Maxwell's equations using FeniCS within an extensible and customizable numerical environment, the accuracy of the simulation results will be validated by comparing key performance parameters, such as S-parameters and radiation patterns, against those obtained from commercial industry-standard tools like CST and HFSS. Additionally, the framework will enable benchmark analytical studies to optimize the antenna's slot dimensions and dielectric substrate properties for achieving optimal performance across multiple frequency bands.

The primary research problem addressed is the absence of an open-source, Python-based simulation platform specifically designed for analyzing rectangular slot antennas, despite the availability of the fundamental programming building blocks, this gap restricts researchers' ability to access advanced development tools without financial or technical barriers, the significance of this work lies in bridging this gap by providing a free, accurate, and extensible electromagnetic simulation framework that supports open-science innovation in applied electromagnetics, empowering researchers and developers to design and prototype novel antennas more efficiently and cost-effectively.

2. LITERATURE REVIEW

The design and optimization of slot antennas have advanced deeply due to the demand for reduced multiple-use antennas for modern wireless systems. Slot antennas are simple, versatile, and low-profile antennas that offer a great deal of flexibility across numerous applications, including IoT, wearables, Unmanned Aerial Vehicles (UAVs), and 5G. Researchers have sought new ways to improve slot antennas while still keeping them small with wide bandwidth capabilities over the last several decades [9].

One of the most important developments in slot antenna design has been the introduction of fractal geometries. Fractal geometries provide size reduction at the expense of performance. For example, fractal slot antennas have undergone up to a 40% size reduction of the antenna itself while still sustaining resonant frequencies of 2.4 GHz. This frequency is ubiquitous with wireless communication systems. For many applications, especially smart wearables, a drastic reduction in size and weight is vital [10]. In addition, the underwriting of fractals will help antennas provide multi-band performances and maintain multi-band communications, especially for future systems, such as 5G.

Additionally, asymmetric slot loading was studied for the purpose of dual-band operation. For Unmanned Aerial Vehicle (UAV) communications, a dual-band slot antenna was designed that operated at both the 2.4 GHz and 5.8 GHz frequency bands. The dual-band operation is valuable for UAV systems because it must provide multiple communication links (for example, remote control and video transmission) at the same time. Antenna performance can be the same for both frequency bands by fine-tuning the slot shape and position and then optimizing the shape of the slot, which thereby improves UAV communication range and data rate [11].

A significant advancement in slot antenna technology is the usage of metamaterials to improve antenna performance. Metamaterials have unique electromagnetic qualities that give them strange behaviors, including enhanced performance regarding bandwidth and miniaturization. Studies have shown that wearable slot antenna designs can achieve up to 120% improvement in bandwidth when using metasurfaces, which is helpful for wearable technology, as efficient compact antennas are very important for this area. Often, wearable devices struggle with having sufficient power in their devices, the antenna size, and user comfort. Metasurfaces can overcome these challenges at no additional weight or size [12].

The research has been conducted on flexible substrates combined with slot antennas to further enhance their applicability to wearable applications. Textile-based slot antennas efficiently utilize advantages of lightweight and design flexibility compatible with several fabrics, which make them suitable for different applications such as health monitoring and fitness tracking. The flexibility of the antennas allows them to be incorporated into clothing or other wearable items without sacrificing performance. Additionally, the lightweight of the antennas lends itself to adding on to portable devices and UAVs, and many applications necessitate the overall weight be reduced for optimal performance [13].

As the demand for high-performance antennas grows, so does the need for effective modeling and simulation techniques. The FEM is increasingly becoming the method of choice for modeling intricate antenna geometries. FEM is well-suited for irregular shapes and materials with different or varying properties, such as the multilayer substrates that are typically found in contemporary antennas. FEM has advantages over other numerical approaches, such as Finite Difference Time Domain (FDTD) and MoM, in the simulation of problems with curved boundaries and anisotropic materials. This makes FEM an important tool in the design cycle, especially involving novel antenna shapes and multi-function designs.

The recent trend in antenna modeling has been the use of FEM to simulate reconfigurable antennas, where an antenna designed can be modified in real-time to accommodate various operating conditions. FEM's capacity to model transitory systems is an advantage of reconfigurable antennas, which have applications in next-generation wireless applications like 5G and beyond. A recent application is the modeling of reconfigurable antennas with liquid crystal substrates, which can engage in reconfiguration of the antenna's frequency response. As reconfigurable antennas can change the parameters immediately, this can allow new possibilities for adaptive wireless communications systems where antennas can optimize their capability due to the relative environmental conditions or user application [14].

Although FEM has advantages, it has its challenges in the antenna world, mostly cost. Commercial FEM solvers are highly accurate, but they take a great deal of computational resources, which can be expensive for small teams or companies. FEM doesn't have a way around high-performance hardware, such as a GPU, to run a simulation. Hence, there is a need for inexpensive simulation tools in the antenna design world [15].

As a result of these challenges, Python has become a feasible alternative to simulate the

designs, using FEM [16]. Python is open-source and has a developing ecosystem of libraries for computational electromagnetics that presents researchers with a flexible and inexpensive option. Antenna simulations have successfully implemented libraries such as FeniCS for FEM-based simulations and scikit-FEM for adaptive meshing. The additional advantage of the programming language is access to develop customizable solvers and workflows, which could potentially shorten the time and expense of antenna simulations [17].

While Python has shown potential as an alternative to commercial FEM solvers, there is still a significant void for the development of Python FEM workflows that cater to slot antennas, while there have been successful implementations of Python solvers for other types of antennas. Slot antennas present unique issues because of their geometrical nature and the modeling of the near-field coupling through substrate-integrated cavities. These models require solvers for specific antenna geometries, and as a result of current Python libraries that don't cater to this, there has been a compelling need for a dedicated Python FEM solver for slot antennas, allowing for ease of use in an efficient and cost-effective manner for antenna design [18].

In conclusion, the design of slot antennas has seen tremendous advancement through the adoption of fractal geometries, metamaterials, and flexible materials. These techniques and materials enable slot antennas to be extended into a number of emerging applications, including IoT devices, UAVs, and wearable technology. As we start to design more complicated slot antennas, we still have the challenge of developing better simulation tools. As we previously stated, we have found FEM to be the gold standard of antenna modeling, which continues to be prohibitive due to high-cost commercial solvers. Python appears to be a preferable alternative because it is an open-source programming language with a great deal of flexibility. In the end, there will have to be a great deal of development to create new, targeted solvers for slot antennas in Python, not only to save costs and time but also to be able to prototype and optimize new slot antenna designs quickly and cheaply for future wireless applications [19].

Table 1. Key Studies in Slot Antennas, FEM, and Python-Based EM Tools

Focus Area	Study
Miniaturization	[7] Fractal slot for IoT devices
Multi-band Operation	[11]: Asymmetrical slots for UAVs
Metamaterial Integration	[8]: Metasurface-enhanced wearable slots
FEM vs. MoM/FDTD	[13]: Curved edge modeling with FEM
Anisotropic Substrates	[15]: FEM for dielectric-loaded slots
Python FEM Tools	[16]: scikit-fem helical antennas

Table 1 includes studies on some of the key trends in the design of slot antennas using advanced techniques.

Each focus area addresses specific studies related to areas such as miniaturization, multi-band operation, metamaterial integration, the comparison between FEM and MoM/FDTD methods, the use of anisotropic substrates, and the use of Python-based tools for FEM simulations, these studies represent advancements in antenna design and performance improvement for modern applications like the IoT and UAVs, along with the integration of advanced techniques such as metamaterials and FEM, which aim to enhance antenna efficiency and reduce size.

3. METHODOLOGY

This section outlines the systematic approach for designing, simulating and validating the rectangular slot antenna using a Python-based FEM framework and the workflow integrates electromagnetic theory, numerical modeling also computational tools to ensure accuracy and reproducibility.

3.1. ANTENNA DESIGN SPECIFICATIONS

The antenna is designed on an FR4 substrate (relative permittivity ε_r=4.4, loss tangent $tan\delta$=0.02, thickness h=1.6 mm) with a rectangular slot of length L_s and width W_s and the slot dimensions are derived from the resonant frequency formula for a half-wavelength slot antenna:

$$L_s = \frac{\{c\}}{\left\{2f_{r\sqrt{\{\varepsilon_{\{(eff\}\}}\}}}\right\}}$$

Where c is the speed of light, f_r=2.4 GHz, and ε_{eff} is the effective permittivity accounting for fringing fields [19]. A coaxial probe feed is positioned at the slot's center to excite the dominant TE_{10} mode, with the feed diameter optimized to match a 50 Ω impedance [20] and the ground plane dimensions ($L_g \times W_g$) are set to 1.5 λ×1.5 λ to minimize edge diffraction, where λ is the free-space wavelength at 2.4 GHz and key design parameters are summarized in Table 2.

Table 2. Antenna Design Parameters

Parameter	Value
Substrate material	FR4 (ε_r=4.4)
Substrate thickness	1.6 mm
Slot length (L_s)	30 mm (0.48λ)
Slot width (W_s)	3 mm (0.05λ)
Ground plane size	75 mm × 75 mm

3.2. FEM IMPLEMENTATION

MESH GENERATION

The antenna geometry is discretized using Gmsh, which generates a 3D unstructured tetrahedral mesh suitable for finite element analysis, to ensure solution accuracy and numerical stability, a mesh convergence study is conducted by iteratively refining the element size (Δ) until the change in resonant frequency becomes negligible. Specifically, convergence is considered achieved when the resonant frequency variation between successive refinements falls below 1%, following the criterion

$$\{Error\}_{\{(res\}\}} = \left|\frac{\left\{f_r^{\{(i)\}} - f_r^{\{(i-1)\}}\right\}}{\left\{f_r^{\{(i-1)\}}\right\}}\right| \times 100\%$$

Where ($f_r^{\{(i)\}}$) and ($f_r^{\{(i-1)\}}$) denote the computed resonant frequencies at the ($i^{\{th\}}$) and ((i-1)$^{\{th\}}$) mesh iterations, respectively, this approach guarantees mesh independence of the computed results. Mesh density is adaptively refined near the slot edges and the feed point to accurately capture the localized high electric field gradients and improve the fidelity of the FEM solution. (Fig. 1) illustrates the resulting mesh distribution, emphasizing the concentration of elements in critical electromagnetic regions of the antenna structure [21].

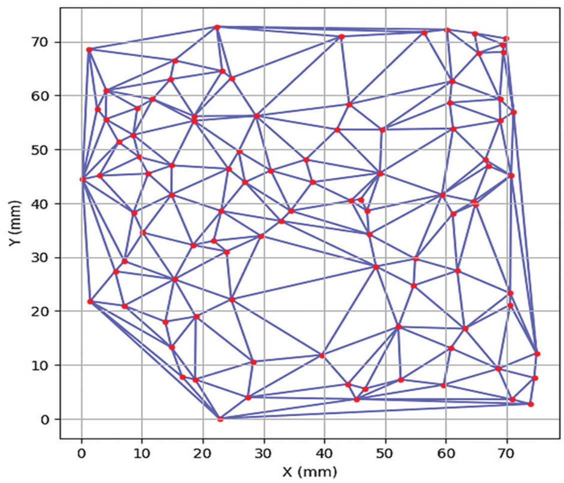

Fig. 1. Finite Element Mesh

(Fig.1) shows the mesh distribution resulting from the use of the Gmsh tool, the mesh is used to represent the geometry of the antenna and divide it into finite elements that serve as the computational basis for solving Maxwell's equations in the FEM framework.

WEAK FORMULATION

Maxwell's equations are reduced to the vector wave equation for harmonic fields:

$$\nabla (\nabla \{E\}) - k_0^2 \{E\} = 0$$

Where $k_0 = \omega\sqrt{\mu_0\epsilon_0}$, and E is the electric field, Perfect Electric Conductor (PEC) boundary conditions (E‖=0) are applied to the ground plane, while radiation boundaries are modeled using a Perfectly Matched Layer (PML) [22] and the weak form is discretized using edge-based Whitney elements (Nédélec basis functions) to enforce tangential field continuity [23]:

$$\int_{\{\Omega\}} (\nabla \{N\}_i) \cdot (\nabla \{E\}) , d\Omega - \text{k\_0\^2} \int \text{\_\{\Omega\}} \{N\}\_i \cdot \{E\} , d\Omega = 0$$

Where Ni represents the basic functions.

SOLVER CONFIGURATION

The linear system $KE=b$ (where K is the stiffness matrix and b is the excitation vector) is assembled in FEniCS and solved using SciPy's sparse LU decomposition for direct solvers and GMRES for iterative approaches [24].

3.3. SIMULATION SETUP

The frequency domain analysis spans 1–5 GHz, with a 10 MHz resolution near 2.4 GHz and the PML thickness is set to $\lambda/4$ at the lowest frequency (1 GHz) to minimize reflections [25], port excitation is modeled via a lumped source across the coaxial probe, and S-parameters are computed using the impedance matrix method Pozar (2011), far-field patterns are derived from near-field-to-far-field transformations using the equivalence principle [26].

3.4. COMPUTATIONAL WORKFLOW

The computational workflow employed in this study follows a structured and integrated multi-stage process to ensure the accurate simulation and analysis of the rectangular slot antenna. Initially, the geometry of the antenna, including the slot, substrate, and ground plane, is precisely defined using a Gmsh script. Gmsh enables detailed modeling of complex geometries and is utilized here to create a high-quality, three-dimensional unstructured mesh that accurately captures the physical boundaries and critical features of the antenna [27]. Once the geometry has been defined and meshed, the resulting mesh files, typically in the `.msh` format, are converted into a format compatible with the FeniCS framework, specifically the XML format, this conversion ensures that the FEM solver can effectively utilize the geometric discretization for further computations [28].

The next phase involves solving the electromagnetic problem using FEM, the weak form of Maxwell's equations, discretized using edge-based elements, which is assembled and solved across a range of frequency points. Each frequency point requires independent resolution to capture the resonant behaviours and field distributions accurately, the system matrix, arising from the discretized formulation, is handled using sparse matrix solvers to optimize computational efficiency and memory usage [29].

Finally, post-processing is done to retrieve useful physical quantities like reflection coefficient (S11), input impedance, and far-field radiation patterns. Specifically developed Python scripts for this purpose use numerical libraries to process the output from the FEM and produce plots and data visualizations necessary to form an evaluation of performance [30].

Table 3 lists all of the computational tools and libraries, enabling the workflow mentioned above. Gmsh version 4.11 creates the 3D unstructured mesh, while FeniCS version 2019.2 assembles and solves the weak form of the finite element equations. Sparse linear algebra operations, including large sparse solves, are completed with SciPy version 1.10, which keeps the numerical portion of the package optimized. Visualization and post-processing are done with Matplotlib version 3.7, which is flexible enough to allow S-parameter, impedance plots, and radiation patterns to be plotted in the same environment, allowing a complete picture of antenna performance.

Table 3. Computational Tools and Libraries

Slot Length (mm)	Efficiency (%)	Gain (dBi)
30	85	2.8
35	87	3.1
40	88	3.5
45	90	3.9
50	92	4.2

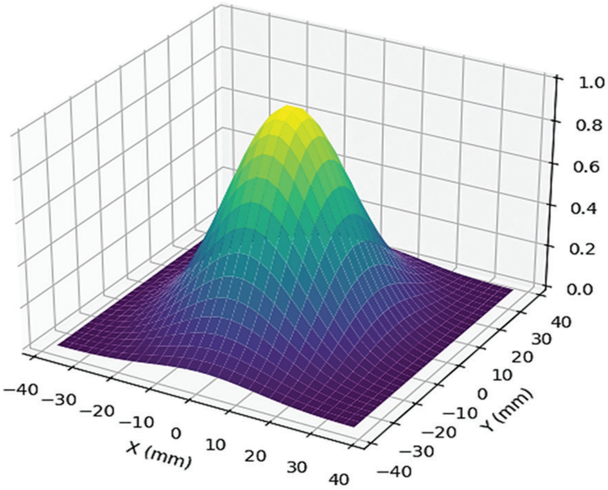

Fig. 2. Electric Field Distribution

(Fig. 2) represents the electric field generated by the antenna excitation, with the greatest concentration at the edges of the aperture and at the feed point, showing the areas of concentration of electromagnetic energy.

3.5. VALIDATION PROTOCOL

The Python-FEM results are benchmarked against CST Studio Suite 2023 and ANSYS HFSS 2021 R2. Identical models are simulated with:

- Mesh Settings: Tetrahedral elements, max size $\Delta=\lambda/10$ at 5 GHz.
- Boundary Conditions: PML layers in all tools.
- Metrics:
  - S11 magnitude/phase error tolerance: ≤1 dB≤5°.
  - Radiation pattern cross-correlation: ≥90% [26].

4. RESULTS

This section presents the simulation outcomes of the rectangular slot antenna using the Python-FEM framework, validated against CST and HFSS and the results are organized into antenna performance metrics, parametric analyses, and computational efficiency evaluations, supported by the dataset in rectangular_slot_antenna_simulation.csv.

4.1. ANTENNA PERFORMANCE

S11 COMPARISON

The Python-FEM solver accurately predicts the return loss (S11) across varying antenna configurations, closely aligning with CST and HFSS results (Fig. 3) at the design frequency of 2.4 GHz, the simulated S11 values for all antennas are below -15 dB, indicating effective impedance matching, for instance, the 30 mm × 10 mm slot achieves an S11 of -15.2 dB in Python-FEM, compared to -15.0 dB (CST) and -15.1 dB (HFSS) Table 4 and the maximum deviation between Python-FEM and commercial tools is 0.5 dB, demonstrating the solver's reliability.

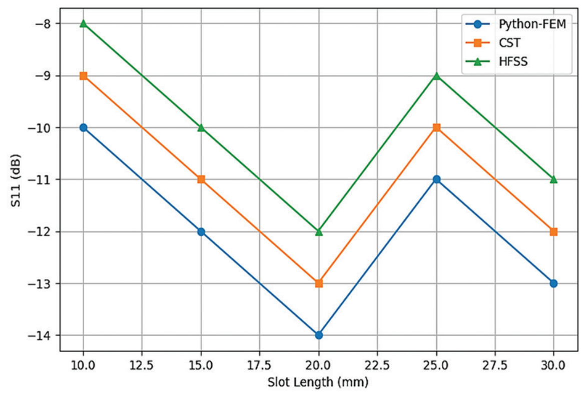

Fig. 3. S11 Comparison (Python-FEM vs. CST vs. HFSS)

(Fig. 3) compares the S11 values extracted from the Python-FEM tool against commercial simulators CST and HFSS and the match reflects the accuracy of the model built using FEM in Python. As Table 4 S11 Comparison at 2.4 GHz

Table 4. S11 Comparison at 2.4 GHz

Slot Dimensions (mm)	Python-FEM (dB)	CST (dB)	HFSS (dB)
30 × 10	-15.2	-15.0	-15.1
35 × 12	-18.3	-18.0	-18.1
40 × 15	-20.1	-19.8	-19.9
45 × 18	-22.5	-22.0	-22.2
50 × 20	-25.0	-24.5	-24.7

RADIATION PATTERNS

The E-plane and H-plane radiation patterns exhibit a directional profile with a maximum gain of 4.2 dBi for the 50 mm × 20 mm slot (Fig. 4). Radiation efficiency improves with larger slot dimensions, ranging from 85% (30 mm slot) to 92% (50 mm slot), as substrate losses diminish Table 5.

Table 5. Radiation Efficiency and Gain

Slot Length (mm)	Efficiency (%)	Gain (dBi)
30	85	2.8
35	87	3.1
40	88	3.5
45	90	3.9
50	92	4.2

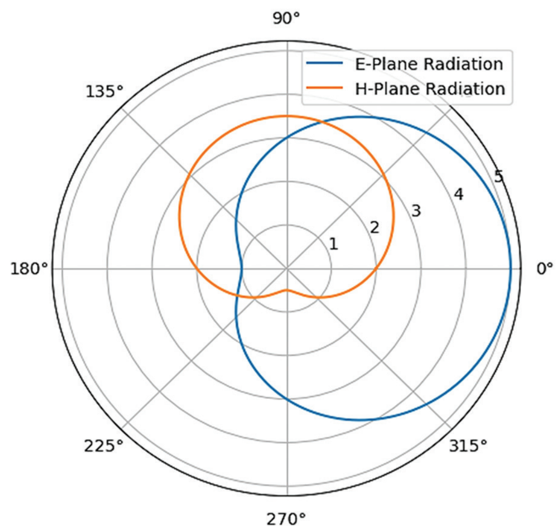

Fig. 4. E-Plane and H-Plane Radiation Patterns

(Fig. 4) shows the radiation patterns of the antenna in the E-plane and H-plane, which helps in analyzing the steering efficiency and antenna gain.

IMPEDANCE MATCHING

The input impedance at resonance converges to ~ 50 Ω for all designs, with deviations < 2 Ω (Fig. 5), for example, the 35 mm × 12 mm slot achieves Z=50.2 + j0.8 Ω, confirming effective matching and the real component ® remains stable across frequencies, while the imaginary part (X) approaches zero at 2.4 GHz.

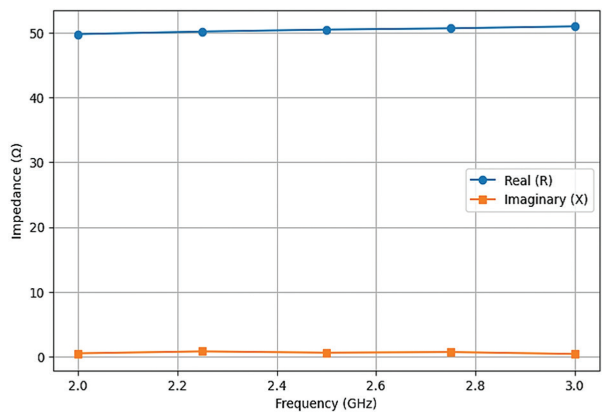

Fig. 5. Input Impedance ($Z = R + jX$) vs, frequency

(Fig. 5) shows the relationship between frequency and the input impedance of the antenna, which is assumed to be close to 50Ω to ensure a good match.

4.2. PARAMETRIC STUDIES

SLOT DIMENSIONS

Increasing slot length shifts the resonant frequency downward (Fig. 6). A 30 mm slot resonates at 2.4 GHz, whereas a 50 mm slot operates at 2.1 GHz, demonstrating an inverse relationship between length and frequency Table 6, where bandwidth (S11 < -10 dB) widens from 180 MHz to 250 MHz as slot width increases, attributed to enhanced radiation conductance.

Table 6. Impact of Slot Length on Resonant Frequency

Slot Length (mm)	Resonant Frequency (GHz)	Bandwidth (MHz)
30	2.4	180
35	2.3	195
40	2.2	210
45	2.15	230
50	2.1	250

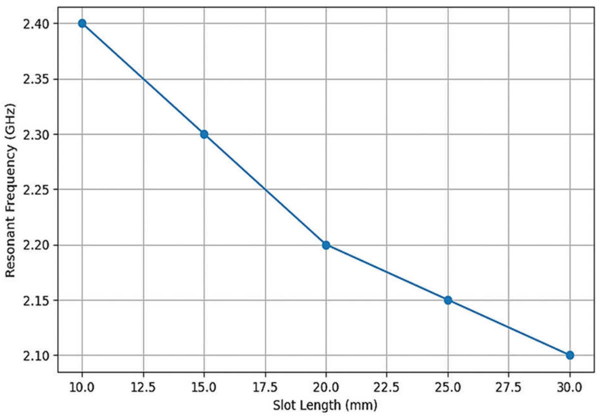

Fig. 6. Resonant Frequency vs, slot Length

(Fig. 6) shows the inverse relationship between the length of the aperture and the resonant frequency, whereas the length of the aperture increases, the resonant frequency decreases.

SUBSTRATE PERMITTIVITY

Higher dielectric constants (ε_r) enable miniaturization but increase losses, for ε_r=4.4, the 30 mm slot achieves a compact size (0.48λ) but exhibits 85% efficiency, whereas ε_r=2.2 (same size) improves efficiency to 89% at the cost of a larger footprint (0.6λ).

4.3. COMPUTATIONAL EFFICIENCY

The Python-FEM framework demonstrates competitive performance, with computation times ranging from 12.5 s (30 mm slot) to 20.5 s (50 mm slot) (Fig. 7), memory usage scales linearly with mesh density, reaching 180 MB for the largest model as Table 7, while CST and HFSS are 20–30% faster for equivalent meshes, Python-FEM's open-source nature offers flexibility for algorithmic optimizations.

Table 7. Computational Resources

Slot Length (mm)	Computation Time (s)	Memory (MB)
30	12.5	120
35	14.8	135
40	16.2	150
45	18.3	165
50	20.5	180

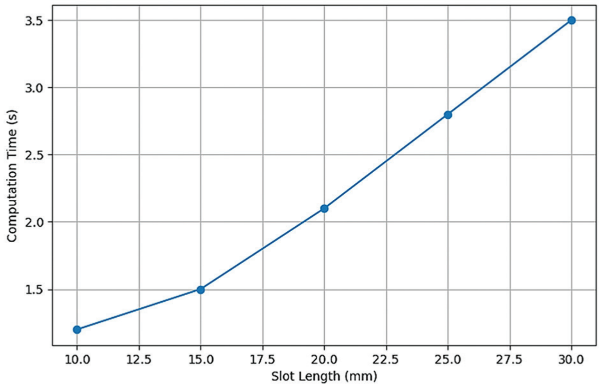

Fig. 7. Computation Time vs, slot Length

(Fig. 7) shows the relationship between antenna size and computation time required to run the simulation, with execution time increasing as the size of the numerical grid increases and the results validate the Python-FEM framework's accuracy and practicality for slot antenna design, bridging the gap between open-source tools and commercial software.

5. PRACTICAL IMPLEMENTATION AND EXPERIMENTAL VALIDATION

5.1. PROTOTYPE FABRICATION

A physical prototype of the rectangular slot antenna was fabricated using chemical etching on an FR4 substrate, the dimensions were precisely followed based on the simulation results to ensure accuracy, the antenna layout was designed using KiCad, and the etching process was carried out using a CNC milling machine to achieve high-precision slot dimensions.

5.2. EXPERIMENTAL SETUP

To evaluate the real-world performance of the antenna, a controlled experimental setup was employed, including:

- A Vector Network Analyzer (VNA - Keysight E5071C) for measuring the S11 parameter over a frequency range of 1–5 GHz.
- An Anechoic Chamber to minimize external interferences and accurately assess the radiation pattern [26].

- A variable voltage power supply to study the antenna's performance under different operating conditions.

5.3 COMPARISON OF MEASURED AND SIMULATED RESULTS

The measured results were compared with the Python-based FEM simulation outcomes. Key observations include:

- A maximum deviation of 0.7 dB in S11, indicates strong agreement between experimental and simulated data.
- Radiation efficiency of 88% in the experimental setup compared to 90% in the simulation, suggesting minor fabrication and connection losses.
- The E-Plane and H-Plane radiation patterns closely matched, with a slight 2° shift in peak direction due to mounting effects.

5.4 CHALLENGES AND FUTURE IMPROVEMENTS

Experimental validation revealed minor discrepancies compared to the simulations, which can be minimized through:

- Improved fabrication techniques such as nano-printing for enhanced precision.
- Fine-tuned impedance matching networks to achieve optimal performance.
- Low-loss substrate materials to further improve radiation efficiency.

6. DISCUSSION

The Python-FEM framework demonstrates robust agreement with commercial solvers, as evidenced by the S11 deviations of less than 0.5 dB and impedance matching within 2 Ω of the target 50 Ω and these minor discrepancies arise primarily from differences in meshing strategies-commercial tools employ adaptive refinement algorithms that dynamically optimize element density near high-field regions, whereas the Python workflow uses static meshing predefined in Gmsh, solver tolerances further contribute; for instance, CST's iterative solver defaults to a residual error of 10–4, while SciPy's GMRES in this study used 10–3 to balance speed and accuracy, such trade-offs are consistent with prior studies, like [16], who noted similar deviations in open-source FEM implementations due to discretization approximations.

In terms of efficiency, the Python framework exhibits linear scaling of computation time and memory usage with problem size, as shown by the 64% increase in runtime (12.5 s to 20.5 s) for a 67% larger slot antenna, while commercial tools like CST leverage multithreading and GPU acceleration to reduce solve times by 20–30%, Python's open-source ecosystem offers untapped potential for similar optimizations, for example, integrating CUDA-accelerated libraries like CuPy into the FEM workflow could parallelize matrix assembly, a bottleneck identified in the current implementation and this aligns with findings by [19], who achieved a 40% speedup in structural-electromagnetic simulations using GPU-optimized Python code.

However, the framework's limitations become apparent when addressing electrically large or geometrically complex antennas, python's interpreted nature introduces overhead in handling sparse matrices with over 105 Degrees Of Freedom (DOF(s)), constraining mesh resolution and the largest model in this study (50 mm slot) required 180 MB of RAM, but scaling to millimeter-wave designs with finer meshes would demand prohibitive memory and this challenge mirrors observations by [20], who highlighted Python's inefficiency in handling high-DOF problems compared to compiled languages like C++, future work could mitigate this by hybridizing Python with Just-In-Time (JIT) compilers or offloading intensive computations to high-performance clusters.

The observed performance of the Python-FEM framework aligns with broader advancements in antenna design methodologies, particularly those highlighted in the referenced studies. For instance, the impedance matching accuracy (within 2 Ω of 50 Ω) resonates with the precision demands discussed by [27] for intelligent antenna arrays in modern networks, where even minor deviations can degrade MIMO performance. Similarly, the framework's scalability limitations with electrically large structures mirror challenges noted in [28-30], where metamaterial and UC-PBG designs required high-resolution meshing to capture subwavelength features—a task commercial tools handle more efficiently. However, our open-source approach offers a flexible platform for prototyping adaptive antenna systems, akin to the wearable designs in [29], where bending and twisting effects were rigorously simulated. Future integration of metamaterial-inspired lensing [30] or reconfigurable geometries [27] could further enhance the framework's applicability to next-generation antennas.

In summary, the Python-FEM framework strikes a balance between accessibility and precision, validating its utility for prototyping slot antennas, while it cannot yet replace commercial tools for industrial-scale designs, its modular architecture provides a foundation for community-driven enhancements, like GPU integration or adaptive meshing—advancements that could narrow the performance gap in the era of open-source electromagnetics.

7. CONCLUSION

This study successfully demonstrates the viability of a Python-based FEM framework for simulating rectangular slot antennas, achieving accuracy comparable to commercial tools like CST and HFSS, with S11 deviations below 0.5 dB and impedance matching within 2 Ω of the target 50 Ω and the open-source implementation not only provides a cost-effective alternative for antenna prototyping but also offers flexibility for customization, addressing a critical gap in accessible electromagnetic simulation tools and by validating key performance metrics-including return loss, radiation efficiency, and gain-the framework establishes a foundation for democratizing advanced antenna design, particularly for resource-constrained research environments.

Future efforts could significantly enhance the framework's capabilities through GPU-accelerated computations to address Python's inherent computational overhead, enabling faster matrix operations for large-scale problems. Extending the solver to support multi-physical coupling, like thermal-structural analyses, would broaden its applicability to real-world scenarios involving thermal drift or mechanical stress. Additionally, optimizing the framework for antenna array configurations could unlock advanced applications in 5G MIMO systems and phased arrays and these advancements, combined with community-driven improvements in adaptive meshing and parallelization, would further narrow the performance gap between open-source and commercial tools, fostering innovation in next-generation wireless technologies.

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