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ML Based Bandwidth Improvement of Microstrip Patch Antenna for Wi-Fi Application

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Abstract: One of the most common problems in microstrip patch antenna (MPA) design is the narrow bandwidth. Conventional optimisation approaches consume days of electromagnetic simulation time, that complicates this problem. This paper solves both problems for the 2.4 GHz Wi-Fi band. A rectangular MPA is designed by the transmission line equations and simulated in Ansys HFSS. Rectangular slot modifications were introduced pushing bandwidth from 59 MHz to 64 MHz and improving return loss from -17.58 dB to -26.48 dB. To go further without brute-force simulation, a Differential Evolution Genetic Algorithm for constrained parameter optimisation was coupled with an XGBoost surrogate model trained on 822 HFSS-generated parametric samples.The surrogate was able to simulate the HFSS results with 99.4% accuracy for the bandwidth and center frequency, while the optimisation time was reduced from hours to milliseconds. The optimised antenna was fabricated on FR-4 substrate and measured using the Rohde & Schwarz ZPH Cable and Antenna Analyser to validate the complete workflow. The fabricated prototype realised the return loss of −25.07 dB, VSWR of 1.10 and the measured bandwidth of 78 MHz at 2.42 GHz which is 32.2% improvement over the basic MPA and covers the whole IEEE 802.11b/g/n Wi-Fi ISM band. The methodology provides a practical, validated framework to engineers designing Wi-Fi and IoT antennas, leading to a significant reduction in design iteration time.

Keywords— Microstrip Patch Antenna, Bandwidth Enhancement, Machine Learning, XGBoost Model, Genetic Algorithm, HFSS, Fabrication, Wi-Fi

I. INTRODUCTION

A microstrip patch antenna (MPA) is a flat antenna with a metal patch that radiates on one side of a dielectric substrate and a ground plane on the other side. As shown in Fig. 1, a microstrip line is typically used to feed the patch. The performance of the antenna is affected by important factors such as the size of the patch, thickness of the substrate, and dielectric constant. MPAs are widely used in wireless communication systems such as Wi-Fi, satellite, and IoT applications, because they are small, light, and easy to integrate with electronic circuits. However, because they have built-in problems, such as narrow bandwidth and low gain, different enhancement methods must be used to improve their performance.

The demand for fast wireless communication is growing, especially for Wi-Fi systems at 2.4 GHz. This means that antennas need to be smaller, efficient and effective. The regular microstrip patch antennas are often used because of their low profile and ease of fabrication. However, their use is limited by the bandwidth. Some methods have been suggested to improve the bandwidth such as slotting or changing the structure but they often need long and complex optimisation processes. In this paper, a rectangular microstrip patch antenna has been designed, tested and verified using HFSS and MATLAB. Improved design with slot techniques and machine learning based optimisation. A Genetic Algorithm and an XGBoost surrogate model were used together to quickly determine the best design parameters.The proposed method enhances the bandwidth and overall efficiency of the antenna, making it suitable for modern wireless communication applications where reliability, efficiency and scalability are needed.

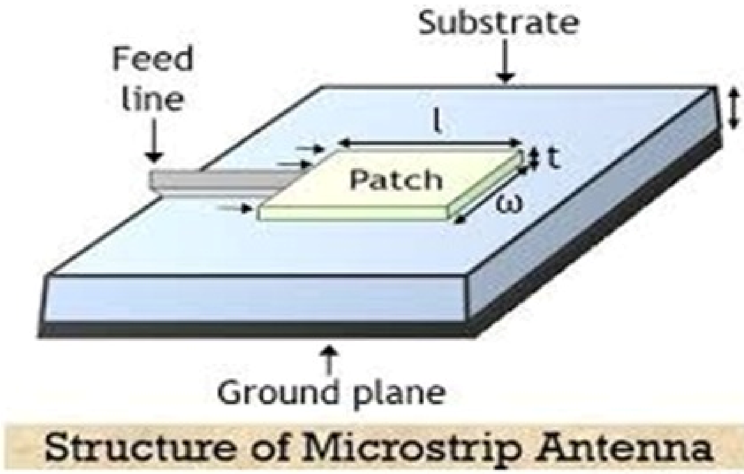

Fig. 1: Microstrip Patch Antenna Structure

II. LITERATURE REVIEW

Microstrip patch antennas (MPAs) have been widely investigated due to their compact structure, low cost of fabrication, and integration with modern wireless systems, especially the 2.4 GHz ISM band. The initial studies mainly concentrated on the effects of antenna geometry and substrate properties on performance. A comparative study of different patch shapes and substrate materials in [1] showed that parameters such as gain, return loss, and bandwidth vary significantly depending on design options. Similarly, the work in [2] presented the design and simulation of a 2.45 GHz microstrip patch antenna with acceptable radiation and impedance characteristics, confirming its suitability for wireless applications. Practical implementation issues are further discussed in [3], where the authors highlight the stable performance of antennas in realistic conditions. The study in [4] extended the application of microstrip antennas to GPS systems, focusing on their flexibility across various frequency bands.

Despite these benefits, MPAs are inherently limited by narrow bandwidth, restricting their performance in contemporary communications systems. To solve this problem, various bandwidth enhancement techniques have been proposed. In [5], methods such as slot incorporation, substrate modification, and impedance matching improvements were investigated, showing a significant increase in bandwidth. However, these traditional approaches often involve repetitive simulations and manual parameter adjustment, making the design process time-consuming and less efficient.

To overcome these limitations, recent research has increasingly integrated machine learning (ML) techniques into antenna design. ML-based optimization was applied to a 5G sub-band antenna in [6], showing improved design efficiency and reduced computation effort. A broader view of ML-assisted antenna design was given in [7], where the opportunities and challenges of ML incorporation into electromagnetic design were considered. Similarly, [8] showed how ML models can accurately predict antenna performance metrics, reducing reliance on time-consuming full-wave simulations.

Surrogate-based optimization methods represent another important development. In [9], a surrogate model was used for multi-band antenna design, achieving faster optimization while maintaining acceptable accuracy. The work of [10] further demonstrated the efficacy of ML-based optimization for inset-fed patch antennas, especially for 5G applications. Moreover, [11] proposed a predictive model based on ML approaches to estimate antenna parameters, significantly reducing iterative design procedures. Beyond conventional antenna structures, AI techniques are also being explored in advanced electromagnetics: [12] used AI-based strategies for intelligent metamaterial design, and [13] presented deep learning models for ultra-wideband (UWB) antenna design. The majority of these studies are grounded in the fundamental principles discussed in [14], which provides the theoretical background for microstrip antenna analysis and synthesis. The literature demonstrates a clear transition toward intelligent data-driven techniques that improve efficiency, accuracy, and scalability in modern wireless applications.

III. PROPOSED METHODOLOGY

The proposed method improves the bandwidth of a microstrip patch antenna (MPA) for 2.4 GHz Wi-Fi applications using a hybrid machine learning approach.

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First, a rectangular MPA was designed using transmission line equations and simulated in HFSS. Slot techniques were used to achieve the first bandwidth improvement. A dataset was created by varying parameters such as patch dimensions, substrate height, dielectric constant, slot size, and feed position. The performance metrics, including return loss, bandwidth, gain, and VSWR, were obtained through simulations. An XGBoost surrogate model was trained to capture the nonlinear relationships between the parameters and performance. A Genetic Algorithm (GA) was then applied for optimization, with the model serving as a fitness function. The optimized design was validated in HFSS and showed improved performance across all metrics.

TABLE I
ANTENNA PARAMETERS

Parameter	Formula/Description	Value	Unit
Lp	Patch Length	28.21	mm
Wp	Patch Width	39.85	mm
h	Substrate Height	1.6	mm
Lg	Lp + (6 × h)	37.81	mm
Wg	Wp + (6 × h)	49.45	mm
Wi	Inset Width	3	mm
Li	Inset Length	9.55	mm
Lf	Li + (Lg/2) – (Lp/2)	14.35	mm
Wf	Feed Width	2.4	mm
SL	Slot Length	4.92	mm
SW	Slot Width	2	mm
SH	Slot Height	13.19	mm

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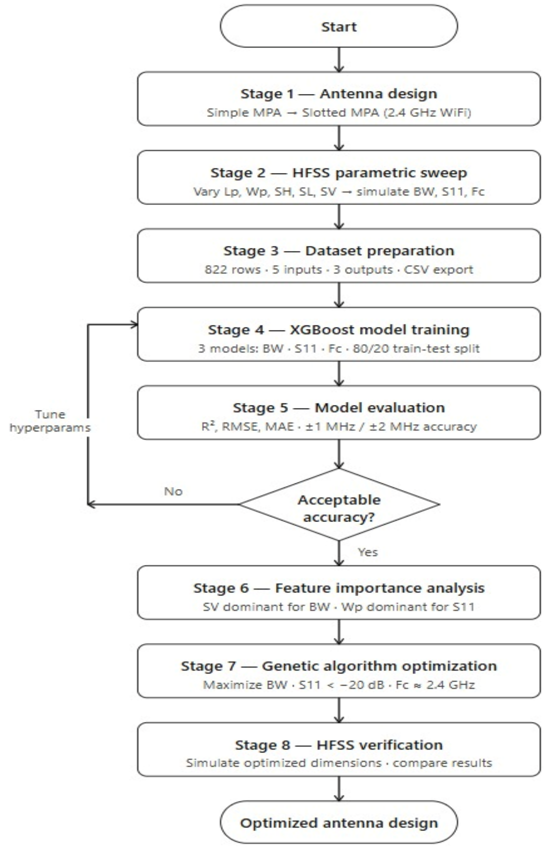
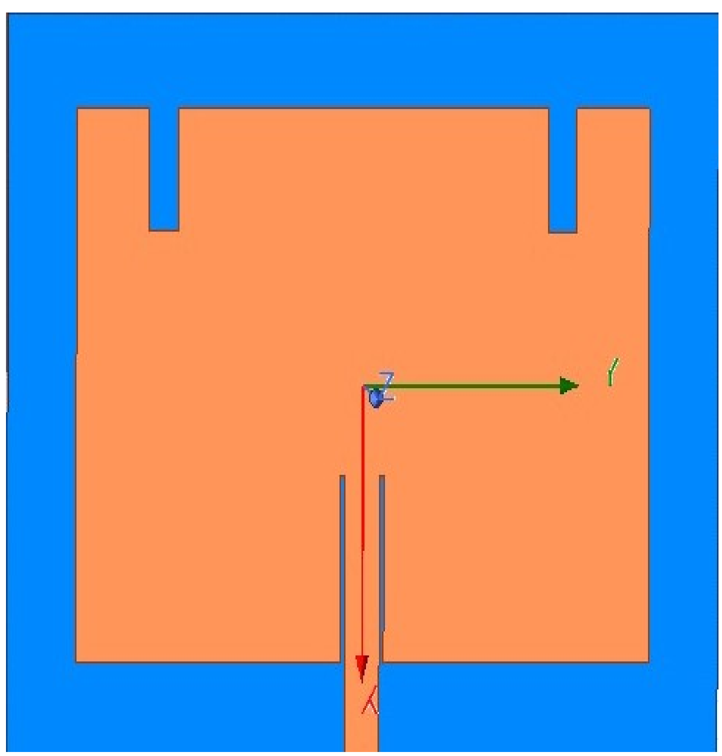


Fig. 2: Methodology Flow Chart



.Fig. 3: Final Design of Rectangular Slotted MPA

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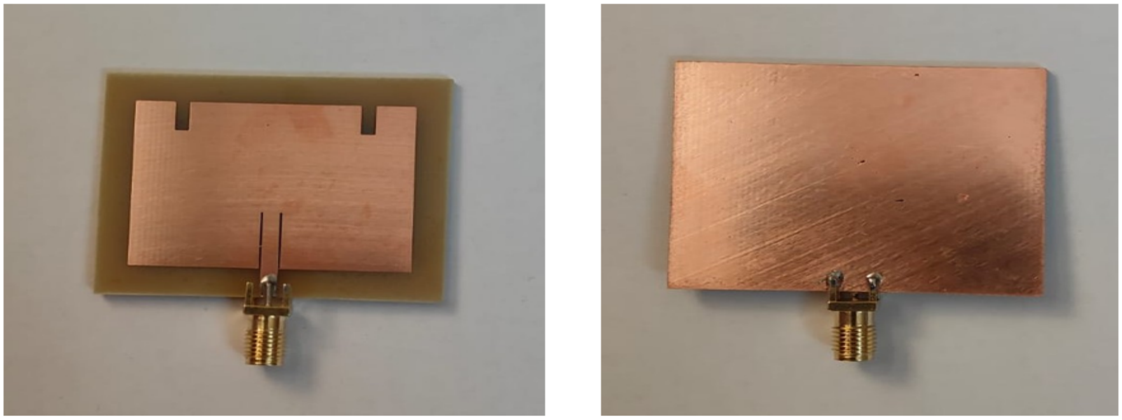

Fig. 4. Fabricated Antenna on FR-4 Substrate

IV. RESULTS AND DISCUSSION

The performance of the proposed microstrip patch antenna was evaluated through simulation, machine learning-based optimization, and physical fabrication. The results were examined in terms of bandwidth, return loss, and overall design efficiency. The regular rectangular patch antenna has a bandwidth of 59 MHz with a return loss of −17.58 dB at 2.391 GHz. When slots are added, the bandwidth improves to 64 MHz and the return loss also improves to −26.48 dB at 2.43 GHz.This shows that making changes to the structure of the microstrip patch antenna improves its performance.

Performance improved further with the ML-based optimization approach. The XGBoost surrogate model accurately predicts how the MPA will behave, and the Genetic Algorithm identifies optimal design parameters. The optimized MPA exhibits improved bandwidth and impedance matching compared with both the basic and slotted designs. S11 versus frequency plots confirm a clear resonance and a wider bandwidth. The proposed method also reduces simulation time from hours to milliseconds, making the design process substantially more efficient.

A. Parameter Study of the Antenna

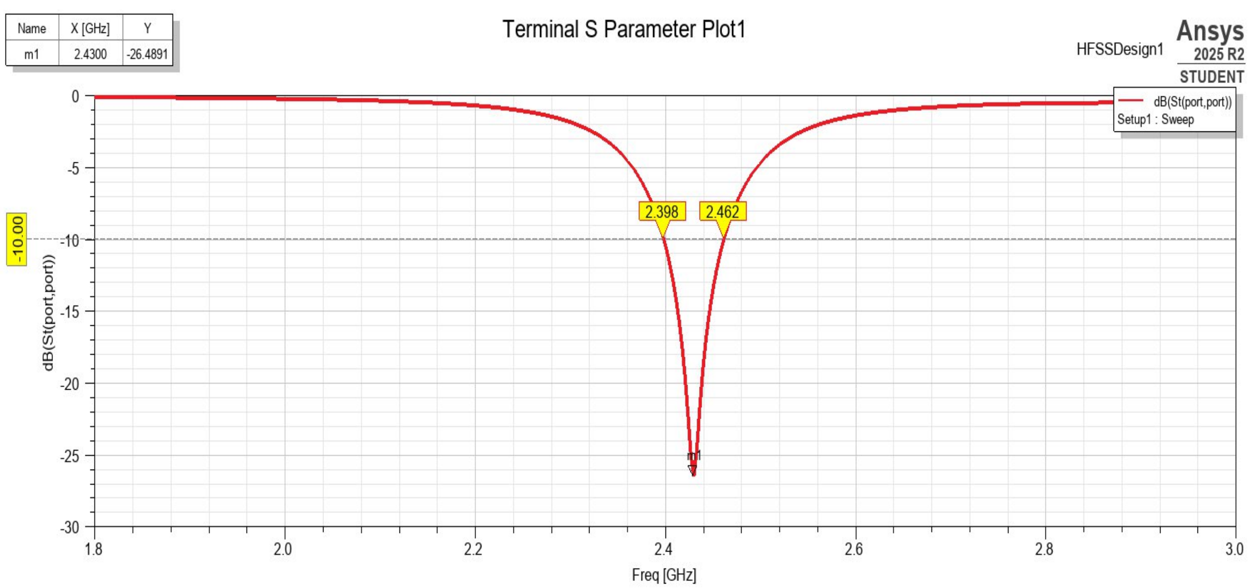

Fig. 5: S11 Curve

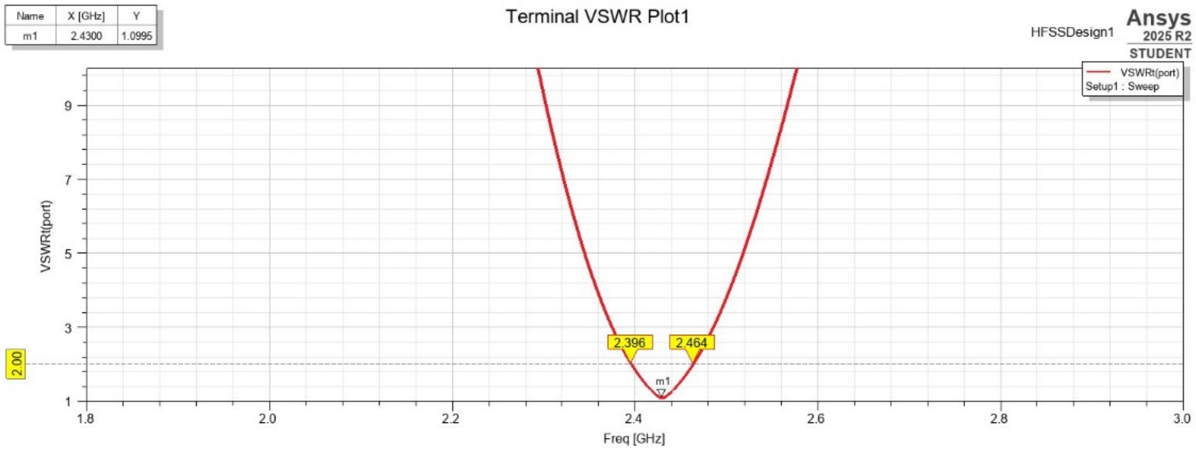

Fig. 6: VSWR Plot

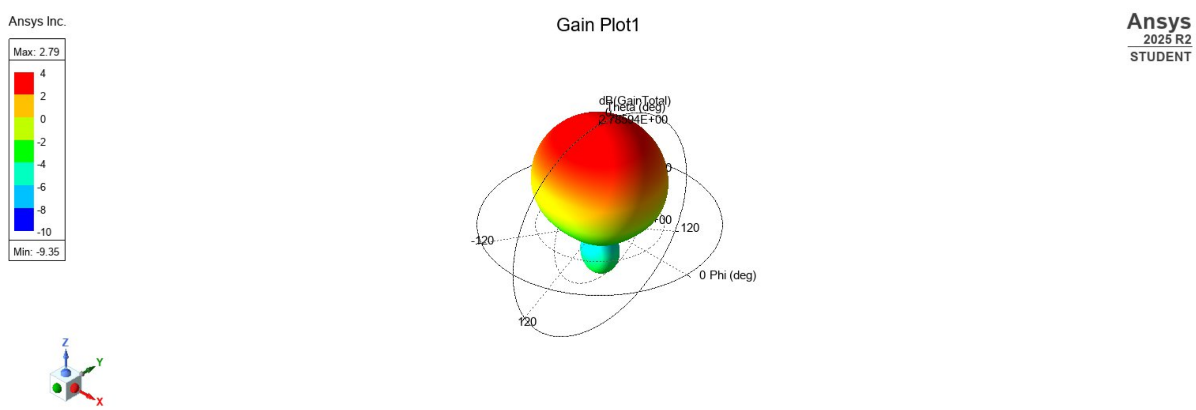

Fig. 7: Gain Plot

B. Results of Algorithms

An XGBoost surrogate model and Genetic Algorithm (GA) were used to optimize the proposed antenna. The bandwidth (BW) model obtained an R^2 score of 0.0813 and an RMSE of 1.0552 MHz, and 93.9% of the predictions were within ±2 MHz.

The best values for the parameters were Lp = 28.2137 mm, Wp = 39.8533 mm, SH = 13.1968 mm, SL = 4.9200 mm, and SV = 14.1147 mm. The expected performance was 64.40 MHz bandwidth, −20.14 dB return loss and 2.4331 GHz resonant frequency. The results are satisfied with the design requirements and show the proposed method is effective for the Wi-Fi applications.

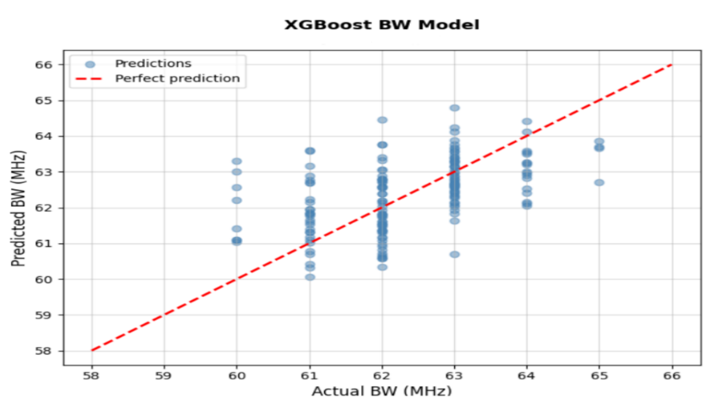

Fig. 8. XGBoost Bandwidth Surrogate Model: Predicted vs. Actual BW

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TABLE II
ML PREDICTION VS. HFSS RESULT

Parameter	Predicted	HFSS	Accuracy
BW (MHz)	64.40	64.00	99.4%
Fc (GHz)	2.4331	2.43	99.4%
S11 (dB)	−20.14	−26.48	76.05%

C. Fabricated Antenna — VNA Results

The optimized slotted microstrip patch antenna was fabricated on FR-4 substrate and its RF performance was measured by Rohde & Schwarz ZPH Cable and Antenna Analyzer. The antenna under test was connected to the analyzer with the help of a coaxial SMA connector. Before measurement a full SOL (Short-Open-Load) calibration was carried out to minimise the systematic errors. The measurement is done in the frequency range 2.3 GHz to 2.6 GHz with 201 data points, covering the entire 2.4 GHz ISM band.

C.1 Return Loss (S11):

Fig. 9 Measured S11 magnitude versus frequency. A clear resonant dip is observed at the center frequency of 2.42 GHz (M1) at which the return loss is −25.07 dB which confirms the excellent energy transfer into the antenna with minimal reflection. The −10 dB bandwidth markers show an upper edge at 2.448 GHz (M2) and a lower edge at 2.37 GHz (M3), giving a measured impedance bandwidth of 78 MHz. This bandwidth covers the IEEE 802.11b/g/n Wi-Fi ISM band (2.4–2.4835 GHz). The measured resonant frequency of 2.42 GHz is within 0.83 % of the HFSS simulated resonant frequency of 2.43 GHz, which confirms the accuracy of the simulation model.

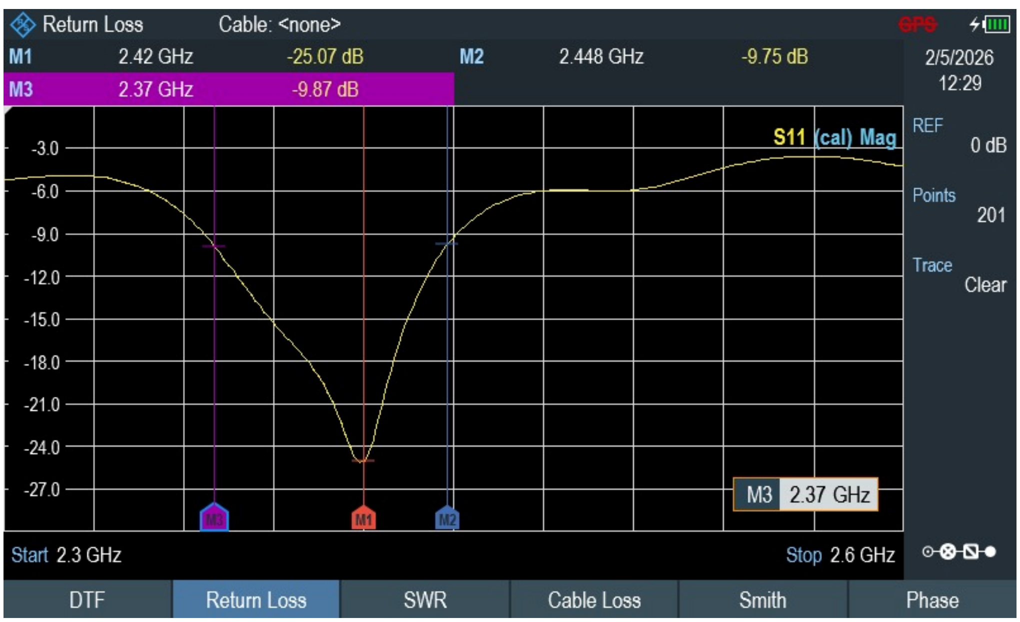

Fig. 9. Measured S11 vs. Frequency — Rohde & Schwarz ZPH Analyzer

C.2 VSWR:

Fig. 10 shows the measured VSWR versus frequency. The VSWR at the resonant frequency M1 (2.42 GHz) is 1.10, which is very close to the ideal value of 1.0, meaning the antenna and the 50 Ω feed system are almost perfectly impedance matched. The standard criterion of -10 dB bandwidth corresponds to VSWR ≤ 2.0. M2 at 2.448 GHz has VSWR = 1.96 and M3 at 2.37 GHz has VSWR = 1.98, both just within this threshold, fully consistent with the S11 band edges.

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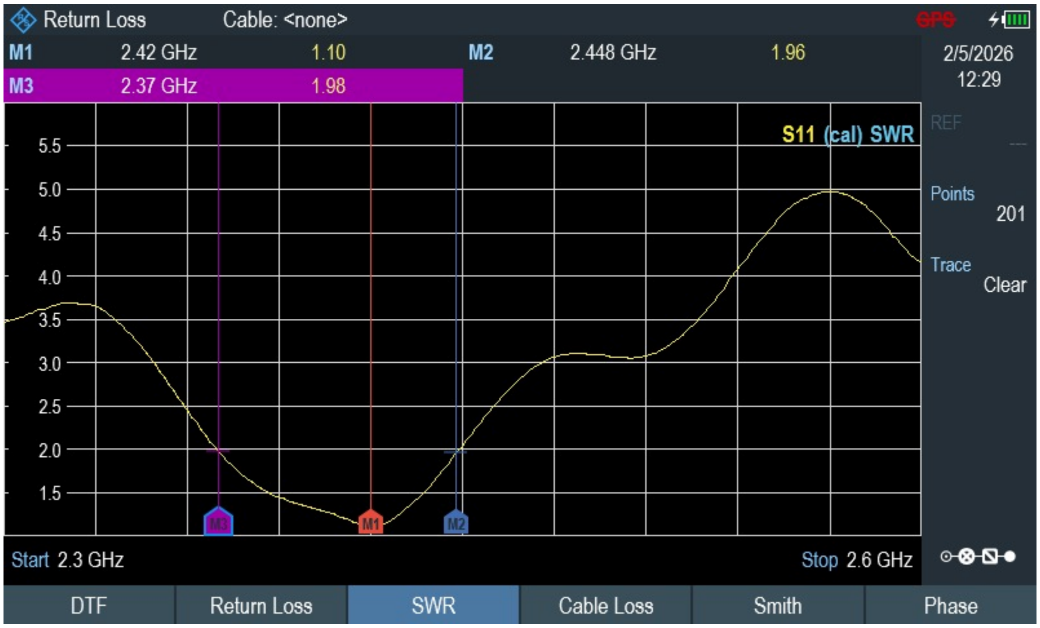

Fig. 10. Measured VSWR vs. Frequency of the Fabricated Antenna

C.3 Input Impedance - Smith Chart:

The measured input impedance is plotted on the Smith Chart in Fig. 11. The measured impedance at the resonant frequency M1 (2.42 GHz) is 53.70 + j3.38 Ω which is very close to the center of Smith Chart (50 + j0 Ω reference). The small inductive component is attributed to fabrication tolerances and dielectric variation of FR-4 substrate. The impedance locus shows a well-behaved clockwise arc as the frequency increases from 2.3 GHz to 2.6 GHz, which is typical of a resonant patch antenna.

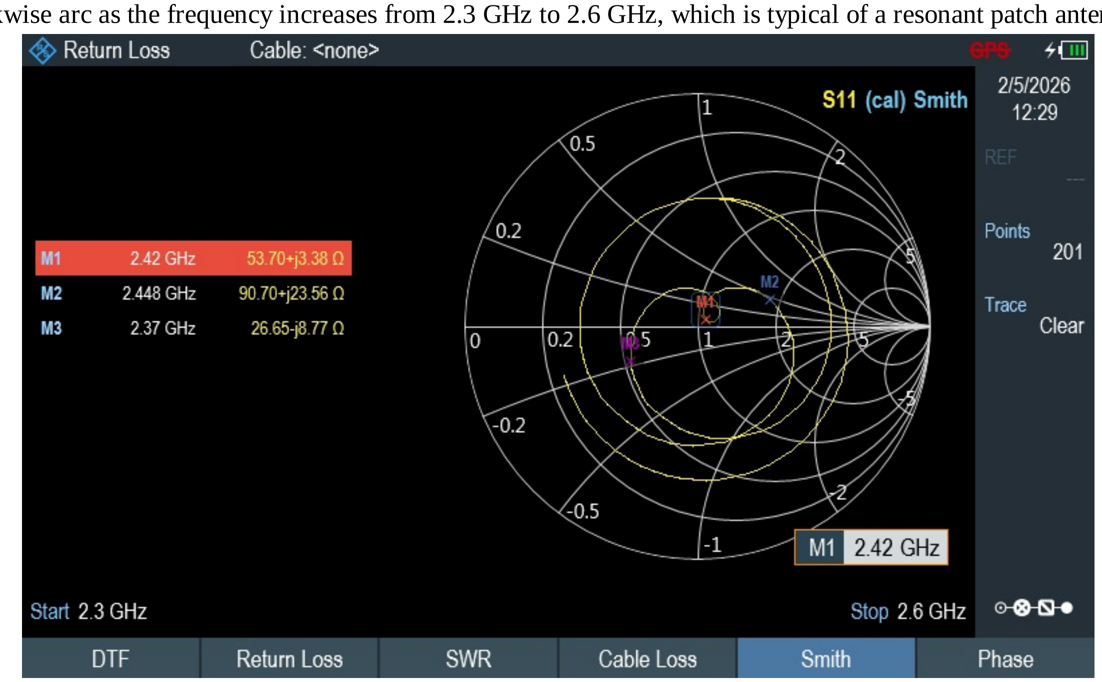

Fig. 11. Measured Smith Chart — Input Impedance of Fabricated Antenna.

C.4 Simulated vs. Measured Comparison:

Table III presents a direct comparison between the physically measured results and the HFSS simulation results. The fabricated antenna shows good agreement with simulation in all the important parameters.

The measured bandwidth of 78 MHz is higher than the simulated 64 MHz, which is a positive deviation due to minor geometry changes due to the fabrication and to the additional loss of the FR-4 substrate at 2.4 GHz that slightly broadens the resonance. The resonant frequency shifted only 10 MHz. The measured VSWR of 1.10 is very close to the simulated value of 1.09, which shows the reliability of the HFSS simulation model.

TABLE III
SIMULATED VS. MEASURED RESULTS

Parameter	HFSS Simulated	Fabricated (Measured)	Deviation
Resonant Frequency (Fc)	2.43 GHz	2.42 GHz	−0.41%
Return Loss (S11)	−26.48 dB	−25.07 dB	+1.41 dB
VSWR	1.09	1.10	+0.01
Input Impedance	50 + j0 Ω (nominal)	53.70 + j3.38 Ω	Small inductive shift
Bandwidth (BW)	64 MHz	78 MHz	+14 MHz

V. CONCLUSION

In this work, we aimed to improve the MPA bandwidth for 2.4 GHz Wi-Fi without the trial and error that usually slows down antenna design. We did so in two steps: first, we added slots in a rectangular patch to push bandwidth from 59 MHz to 64 MHz and second, we replaced repeated HFSS runs with an XGBoost surrogate model coupled to a Genetic Algorithm. The optimised design resonated at 2.4331 GHz with a return loss of -26.48 dB, which is well within the target band. A limitation worth mentioning is the surrogate’s S11 prediction accuracy (76.05%), which was lower than its bandwidth and frequency accuracy. This was likely due to the return loss being more sensitive to fine geometric variations in the slot geometry.A natural next step would be reducing that gap, e.g. by adding more diverse training samples or by using a higher capacity model. More generally, the surrogate-GA framework is not specific to this antenna topology; we expect it to transfer fairly well to other patch geometries and frequency bands with some retraining effort.

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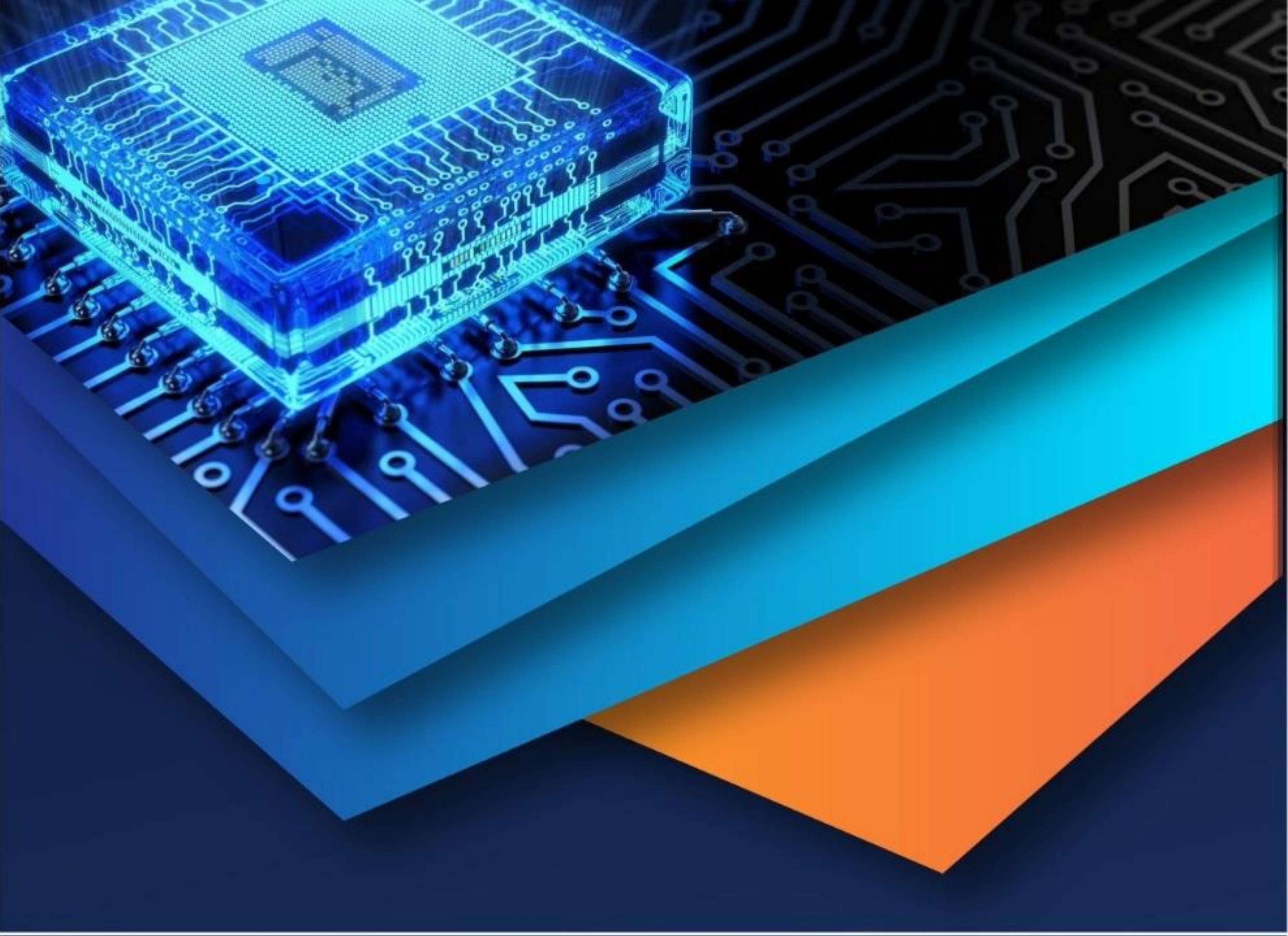

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