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PERFORMANCE ANALYSIS OF A RECTANGULAR SLOT MICROSTRIP PATCH ANTENNA

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A B S T R A C T

This paper analyzes the design and improvement of a small microstrip patch antenna for use in the 2.4 GHz ISM band. The research focuses on enhancing a conventional rectangular antenna by integrating a rectangular slot to enhance its performance. The study compares a base unslotted design with the modified geometry using a FR4 substrate and CST Studio Suite for modeling. The results show that the slot integration greatly increases operational resonance through a double tuning effect. This nearly doubles the impedance bandwidth from 50 MHz to 95 MHz. The modified design also has a better return loss of -21.599 dB. The change increases the directionality of the main lobe by shifting the frequency down to 2.31 GHz and lowering the gain to 5.16 dB. These results show that changes to the shape of the design can overcome conventional narrowband limitations, making it good for small IoT sensors and medical monitoring systems.

1. INTRODUCTION

The rapid growth of wireless communication and the growing need for small, efficient antennas have led to a demand for new designs that can work well in specific frequency ranges. The rise of wireless technologies and Internet of Things (IoT) devices have made the need for antenna solutions that make the best use of space and improve performance metrics like bandwidth and gain even greater (Banale et al., 2025; Mishra et al., 2021; Meena & Kannan, 2018; Alam et al., 2021; Varma et al., 2025). Traditional antenna designs often don't meet these needs, so we need to move towards more advanced designs (Pozar, 2012). This study investigates advanced microstrip patch antenna design strategies aimed at improving bandwidth and reflection coefficient (Mishra et al., 2021; Nahar & Rawat, 2021). Accordingly, the objective is to propose alternative approaches that address the inherent limitations of traditional designs.

Microstrip patch antennas remain one of the most viable options because they are cheap, easy to make, and have a flat shape. However, their narrow bandwidth and moderate gain limit their full potential in high performance systems. Many current solutions use complicated structures, costly dielectric materials, or multilayer designs that make manufacturing harder and more expensive. So, there is still a strong need for simple, useful, and effective ways to make antennas better without making them much harder to make or more expensive (Pozar, 2012; Herdiana, 2022).

This study addresses these challenges by introducing a compact rectangular microstrip patch antenna featuring a strategically positioned rectangular slot. The primary objective is to achieve broader impedance bandwidth and improved return loss while preserving a straightforward single layer design on a cost effective FR4 substrate.

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Detailed simulations conducted in CST Studio Suite enable systematic comparison between the slotted antenna and a conventional unslotted reference design. The results reveal significant enhancements in key performance parameters, underscoring the efficacy of this geometric modification.

The novelty of this work lies in achieving a balanced performance improvement using only a single rectangular slot, combined with careful analysis of waveguide port configuration for accurate simulation results. This approach offers a practical and easily reproducible solution suitable for real world IoT and wireless communication devices.

2. BACKGROUND

The concept of a microstrip patch antenna has played a major role in the development of the compact design for its application in Bluetooth at 2.4 GHz frequency. Many research works have been carried out on different methods of improving bandwidth and performance in microstrip patch antennas. Substrate materials are shown to be a key determinant of operating properties; some materials offer improved directivity properties that enable wider bandwidths. Moreover, geometrical optimization techniques have been demonstrated to be of great significance in obtaining desired antenna characteristics.

Over the past two decades, microstrip patch antennas have gained popularity in wireless communication due to their ability to meet the growing demand for low profile and lightweight radiators. Their compatibility with planar circuit technology has made them especially attractive for integration into modern compact devices. Extensive research has been done on these antennas for Bluetooth, Wi-Fi, and other IoT uses in the 2.4 GHz ISM band because this frequency range is license free and has a good balance between range and data rate (Arora et al., 2021; Mishra et al., 2021). The performance of a microstrip patch antenna is heavily affected by a few important factors, such as the type of substrate material, the shape of the patch, the feeding method, and the layout of the ground plane. Generally, substrate materials with a low dielectric constant and a low loss tangent give better bandwidth and radiation efficiency, but they also make the antenna bigger. High dielectric constant materials, on the other hand, help reduce antenna size, but they also usually make the bandwidth narrower and the efficiency lower. This trade-off has led to the study and analysis of hybrid substrates and diverse composite materials in recent years (Herdiana, 2022; Banale et al., 2025). Along with choosing the right materials, changing the shape of the antenna has become one of the best and cheapest ways to improve its performance. There has been extensive research on techniques like cutting slots of different shapes, adding notches, using defected ground structures (DGS), and adding parasitic elements. These changes change the current distribution on the patch, which then changes the resonant frequency, impedance bandwidth, and radiation characteristics. Many of these techniques have shown promise, but they often make the design more complicated or require precise fabrication, which can make production harder (Pozar, 2012; Nahar & Rawat, 2021).

2.1 Rectangular Patch Antenna

The rectangular patch antenna is one of the most commonly used types of microstrip patch antennas because it has a simple design, is easy to fabricate, and provides reliable performance. It is basically made of a metal patch printed on a dielectric substrate with a ground plane below it. This design efficiently supports the fundamental resonant mode and can be analysed using methods like the transmission line or cavity model (Paul et al., 2025). Due to these advantages, it is widely used in real world wireless systems.

Its popularity stems from the fact that the rectangular shape allows straightforward calculation of dimensions and predictable performance characteristics. The antenna is easy to integrate with the existing printed circuit boards and is very suitable for mass production. This configuration has been successfully implemented in many applications ranging from mobile communication devices to satellite systems and wireless local area networks in the years. It has been particularly appreciated by researchers for its low profile and light weight construction as well as its compatibility to different feeding techniques such as coaxial probe, microstrip line and aperture coupling (Pozar, 2012; Mishra et al., 2021). These features have made the rectangular patch a preferred choice for many compact wireless solutions where the space and cost are major constraints.

2.2 Disadvantages

The conventional microstrip antenna designs suffer from several limitations like narrow bandwidth, spurious radiation from feed, poor polarization purity, limited power handling capacity, and sensitivity to fabrication tolerances (Mishra et al., 2021; Tumakov et al., 2020; Alam et al., 2021). This has resulted in extensive research and development in microstrip antennas to overcome these limitations to meet the requirements of modern systems.

The narrow bandwidth, which is usually only 1–5% of the center frequency, is still the biggest problem. This makes it hard to use in applications that need to work over a wider frequency range. This problem is especially hard to solve in modern wireless systems that need to support more than one standard and faster data rates. Also, when thicker substrates are used, surface wave excitation in the substrate can lower radiation efficiency and change the radiation pattern. Fabrication tolerances are also very important. Even small changes in the size of the patch, the thickness of the substrate, or the position of the feed during manufacturing can cause big changes in the resonant frequency and impedance matching. (Herdiana, 2022; Arora et al., 2021).

These inherent limitations have been a reason for much research of different enhancement techniques. To overcome these challenges, many studies have explored changes in patch geometry, substrate materials and feeding arrangements. But improving one parameter often degrades another, leading to a complex design trade off that antenna engineers continue to resolve. With the trend of wireless communication towards smaller and multifunctional devices, it is more and more important to find simple but effective solutions to these drawbacks (Mishra et al., 2021; Banale et al., 2025).

2.3 Improvements

Some of the possible ways to improve the design of a standard microstrip patch antenna are to add slots or meandered structures to the patch to make it smaller, use inset feeding to get stable impedance matching, and use partial or defected ground planes to improve bandwidth and radiation characteristics (Mishra et al., 2021; Pozar, 2012; Tumakov et al., 2020; Meena & Kannan, 2018). To get better performance, you can change the shape and size of the patch antenna, such as making it round, square, or some other shape. These methods can help make the antenna work well with Bluetooth in a small, efficient, and dependable way.

1) Slots: Adding slots is one of the popular methods for reducing the size of a rectangular microstrip patch antenna. By etching slots of different shapes (rectangular, circular, U shaped, etc.) into the patch, the effective path of the current is increased (Mishra et al., 2021; Tumakov et al., 2020). This helps to lower the resonant frequency while keeping the overall antenna size compact. Depending on the slot's shape and position, it can also be used to achieve dual band or multiband operation.

2) Meanders: Meander lines or meander patches are another technique for antenna miniaturization. Here, the current path is folded into a smaller area, which increases the electrical length of the patch without making its physical size bigger. This approach is especially useful for designing antennas in portable and wearable devices, where space is limited but the antenna still needs to resonate at a required frequency, like 2.4 GHz.

3) Inset Feeds: Inset feeding is a commonly used technique to improve impedance matching in microstrip patch antennas (Pozar, 2012; Meena & Kannan, 2018). Instead of connecting the feed line at the edge of the patch, it is inserted at a specific point inside the patch. The location is carefully chosen so that the input impedance of the patch matches the characteristic impedance of the feed line, which is usually 50 ohms. This reduces return loss and improves antenna efficiency without making major changes to the patch design.

3. ANTENNA EQUATIONS

The design of a rectangular microstrip patch antenna relies on several classical equations that define its dimensions and performance parameters (Pozar, 2012). These equations are derived from cavity model analysis and transmission line theory.

- Width (W):

$$W = \frac{c}{2f_0\sqrt{\frac{\epsilon_r+1}{2}}} \tag{1}$$

where c is the speed of light in free space, f0 is the resonant frequency, and εr is the dielectric constant of the substrate.

- Effective Dielectric Constant (εeff):

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

where h is the height of the substrate.

- Effective Length (Leff):

$$L_{eff} = \frac{c}{2f_0\sqrt{\epsilon_{eff}}} \tag{3}$$

- Length Extension (ΔL):

$$\Delta L = 0.412h \cdot \frac{\left(\epsilon_{eff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\epsilon_{eff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{4}$$

- Actual Length of the Patch (L):

$$L = L_{eff} - 2\Delta L \tag{5}$$

4. METHODOLOGY

This section discusses the simulation setup, meshing, and effect of waveguide port dimensions. Followed by the approach of selecting substrate materials, antenna geometry, and design parameter to achieve the desired operating frequency and improved antenna characteristics.

4.1 Software Overview

The compact patch antenna is then simulated by using CST Studio Suite by Dassault Systèmes. It is a powerful platform for precise modeling of the electromagnetic properties at the frequency of 2.4 GHz. This software allows for an in-depth analysis of many design variables to ensure the antenna performs to the required performance specifications. To improve the computational efficiency while maintaining result fidelity, boundary conditions and mesh are carefully set up. The selection of boundary conditions is of great influence on the computation of an open space environment, thus minimizing reflections that might lead to inaccurate results. Further, optimized mesh configurations can be used to accurately resolve the field distributions over the antenna surface, allowing efficient design iterations that ultimately lead to bandwidth and gain modifications. Such rigorous attention to detail when setting up a simulation is necessary to ensure that consistent and reliable results will be able to inform downstream design improvements.

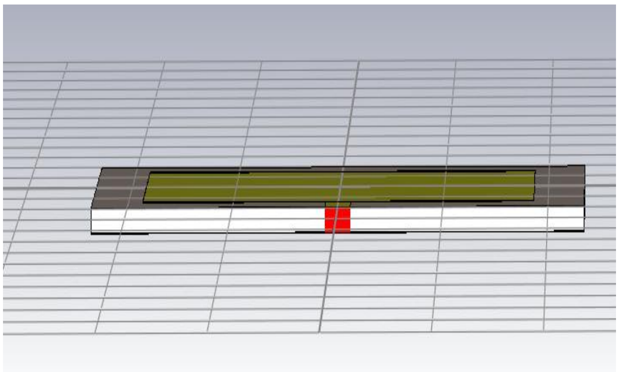
4.2 Substrate Material

Of all substrate materials, FR4 was chosen as the substrate material in the compact patch antenna design, as it was motivated by the good blend of electrical and other mechanical properties (Mishra et al., 2021; Meena & Kannan, 2018; Alam et al., 2021). FR4, with a relative dielectric constant of approximately 4.4 and a low loss tangent, provides a stable resonance and facilitates efficient signal transmission in applications operating within the ISM band. In addition, FR4 provides significant mechanical strength and affordability, which contributes to the miniaturization and useful manufacturability of the antenna – achieved benefits in the integration of modern wireless devices.

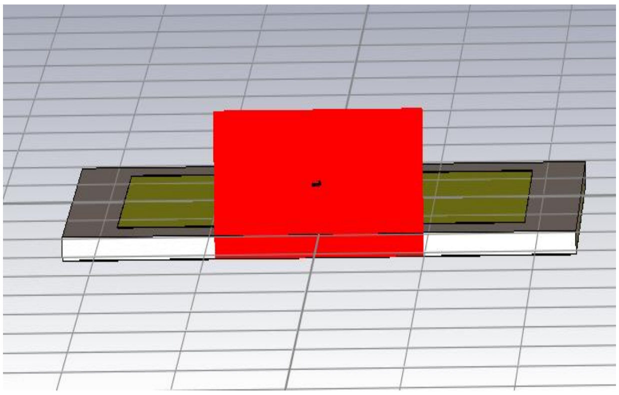
Other high-performance substrates such as Rogers RT/duroid or Taconic TLY offer lower dielectric losses and more stable permittivity over frequency, which can improve antenna efficiency; however, these materials are substantially more expensive and are less readily available, making them less suitable for cost sensitive compact designs.

4.3 Effect of Waveguide Port Dimensions

To investigate the effect of waveguide port sizing on calculated input matching, two port configurations were tested for the edge fed reference antenna. First, a minimal aperture ("small port") that precisely covered only the feed conductor cross section where, Ymin = Ymax = Zmax = 0 and Zmin = SH (refer Fig. 1 (a)) was used. This configuration produced poor and unstable S-parameter results because the port did not enclose the near fields associated with the stripline and substrate. Second, the aperture was increased using an extension coefficient(k) where, Ymin = Ymax = Zmax = k*SH and Zmin = SH (refer Fig. 1 (b)). The port fully captured the dominant mode and produced stable, physically realistic S11 and impedance results. The extension coefficient therefore represents how many times the substrate height the port aperture spans, and it controls whether the solver can form the correct guided mode field at the port plane. While a larger aperture increases the mesh size and the chance of exciting higher order modes, limiting the port to the fundamental mode and choosing moderate extension values gives much improved and reproducible S-parameter behavior. For inset fed designs we still prefer a discrete port (lumped) for lower memory cost, but for clean edge fed comparisons the extension coefficient approach to waveguide port sizing is a robust, reproducible method.



(a) Small Waveguide Port



(b) Big Waveguide Port

Figure 1. Different dimensions of waveguide ports

4.4 Base Design Parameters

The base design (refer Fig. 2) utilizes an FR4 substrate with thickness of 1.6 mm and the copper thickness 0.035 mm.

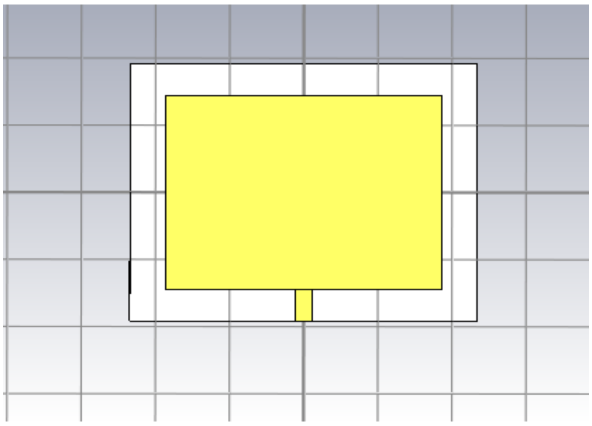


Figure 2. Base Design 3D model

The antenna dimensions were precisely calculated and optimized to ensure that it resonates at the required frequency, which is a critical step to achieve a high performance and reliable wireless communication system. Using the formulas mentioned in the previous section, the various values for the design are summarized in Table 1.

Table 1. Calculated Microstrip Patch Antenna Dimensions

Parameter	Value (mm)
Substrate thickness	1.6
Copper thickness	0.035
Patch width	37.3
Patch length	28.8
Substrate length	38.4
Substrate width	46.9
Ground plane length	38.4
Ground plane width	46.9
Feed line width (50 Ω)	2.4
Feed line length	4.8

4.5 Modified Design Parameters

For the modified design (refer Fig. 3), the same substrate is used with $\varepsilon_r = 4.4$. Certain modifications in the patch's dimensions have been introduced in order to increase stability and reliability. A slotted patch configuration was used in order to further refine the efficiency of the antenna (Mishra et al., 2021; Tumakov et al., 2020). Table 2 includes the precise patch as well as slot measurements:

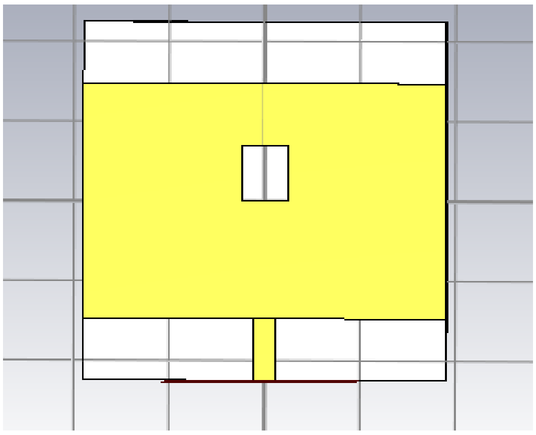


Figure 3. Modified Design 3D model

Table 2. Modified Microstrip Patch Antenna Dimensions

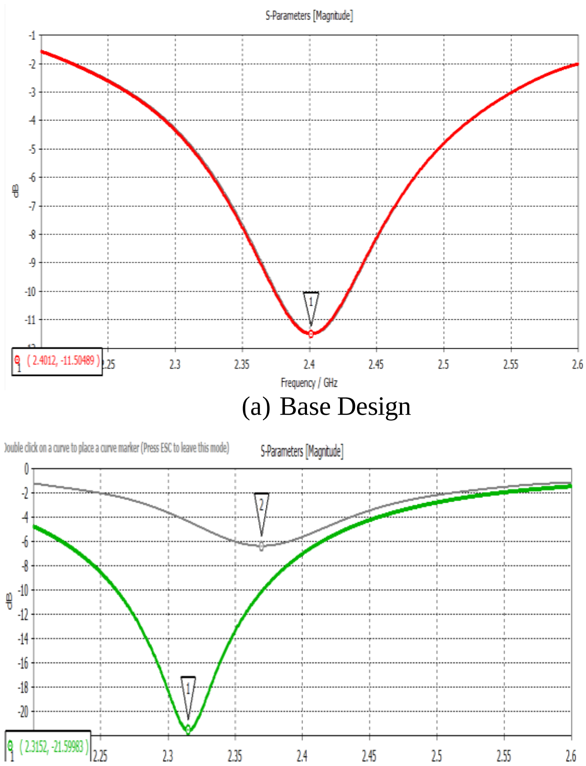
Parameter	Value (mm)
Substrate thickness	1.6
Copper thickness	0.035
Patch width	38
Patch length	29.5
Substrate length	45
Substrate width	38
Ground plane length	45
Ground plane width	38
Feed line width (50 Ω)	2.4
Feed line length	7.75
Rectangular slot width	2.4
Rectangular slot length	7

5. SIMULATED RESULTS AND ANALYSIS

5.1 Return Loss (S11)

Return loss, represented by the S11 parameter, serves as a critical metric that quantitatively shows how much of the input power gets reflected back from the antenna because of impedance mismatch between the transmission line and the radiating element (Arora et al., 2021; Pozar, 2012). A value less than -10 dB is generally considered an industry standard benchmark for good performance, since it indicates that over 90% of the incident power is successfully radiated into free space instead of being reflected back toward the source. The characteristic of the base design, as illustrated in Fig. 4(a), exhibits a particularly sharp and localized resonance with a minimum value of approximately -11.504 dB.

While this specific value comfortably meets the typical engineering requirement for an acceptable impedance match, defined as S11 < -10 dB, the pronounced steepness and high Q-factor of the curve clearly indicate a relatively narrow operational bandwidth that may be sensitive to environmental shifts.



(a) Base Design

(b) Modified Design

Figure 4. Comparison of S11

In marked contrast, the modified design shown in Fig. 4(b), which strategically incorporates a rectangular slot within the patch geometry, fundamentally alters the antenna's electromagnetic frequency response. The physical presence of the slot acts as a secondary coupled resonator. This physical phenomenon, widely known in microwave engineering as double tuning, is clearly evident in the S11 plot as a significantly broadened and more robust resonance profile. This design modification works effectively by creating a distinct second resonance that electromagnetically interacts with the primary mode, thereby expanding the antenna's total impedance bandwidth to successfully overcome the inherent narrow band limitations and rigid constraints of the base design.

However, it is important to note that the structural addition of the slot also had the consequence of shifting the antenna's overall frequency range downward. While the initial base design is perfectly centred within the 2.4 GHz Bluetooth band, the modified design's deepest resonance of -21.599 dB occurs at a lower frequency of approximately 2.31 GHz. As a result, its highest performing operational region is not perfectly centred within the standard frequency range required for high-speed Bluetooth applications, suggesting a need for further optimization of the slot dimensions

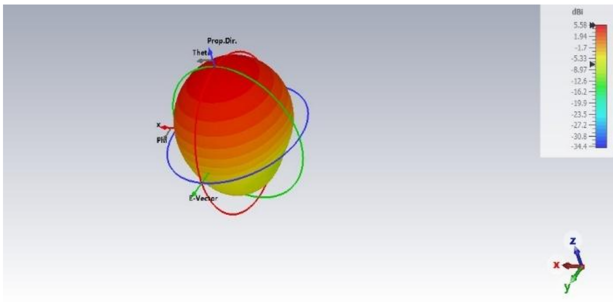
5.2 Bandwidth Analysis

The impedance bandwidth is the range of frequencies where the return loss stays below -10 dB, ensuring stable antenna performance. From the S11 curves in Fig. 4, the modified design represents a better performing antenna with a significantly wider bandwidth (Mishra et al., 2021; Alam et al., 2021; Al-Hiti et al., 2025; Nahar & Rawat, 2021). The base design exhibits a narrow bandwidth of only 50 MHz, with its S11 remaining below -10 dB from approximately 2.38 GHz to 2.43 GHz. In contrast, the modified design demonstrates a substantial improvement, achieving a much wider bandwidth of approximately 95 MHz. Its S11 stays below -10 dB from approximately 2.28 GHz to 2.375 GHz. This enhancement is a direct result of the design modifications, which successfully broadened the antenna's operational frequency range.

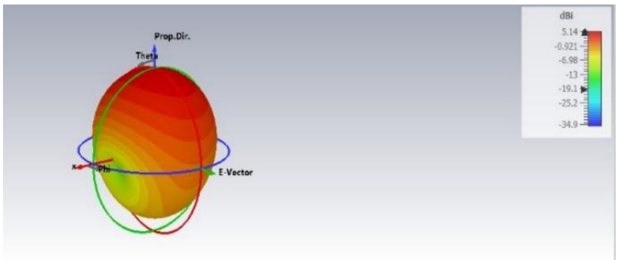
5.3 Radiation Pattern and Gain

The radiation pattern indicates how the power from an antenna spreads out in space, while the gain measures how well the antenna can direct that power. For systems like Bluetooth, a pattern that is nearly omnidirectional is often preferred for maintaining connectivity regardless of device orientation. The simple, unslotted design (see Fig. 5 (a)) exhibits a broad, quasi-hemispherical radiation pattern. This is characteristic of a standard microstrip patch antenna, which radiates from its edges and possesses lower directivity, resulting in a peak gain of 5.39 dB.

In contrast, the modified design, which incorporates a rectangular slot, fundamentally alters the surface current distribution on the patch (Alam et al., 2021). This strategic modification acts as a resonant element that reshapes the radiated field (see Fig. 5 (b)). The slot geometry concentrates the electromagnetic energy into a more focused and directional main lobe (Ahammed et al., 2025), suppressing radiation in undesired directions. While this modification increases the antenna's directivity, it results in a slightly lower peak gain of 5.16 dB. This trade-off between directivity and gain is an important design consideration, where the modified design prioritizes a more focused radiation for potential long range or point-to-point communication.



(a) Base Design



(b) Modified Design.

Figure 5. Comparison of Radiation Pattern and Gain

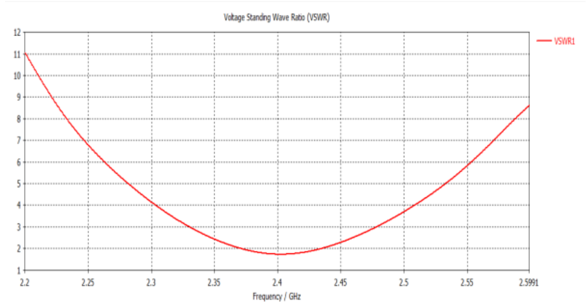
5.4 VSWR

Voltage Standing Wave Ratio (VSWR) is a crucial value that shows antenna efficiency in terms of matching to the feed line. A smaller VSWR implies more power transfer and minimal reflections, which is highly important when using an antenna. Overall, VSWR of 2:1 or less can be regarded as acceptable in practice (Paul et al., 2025; Pozar, 2012; Ahammed et al., 2025).

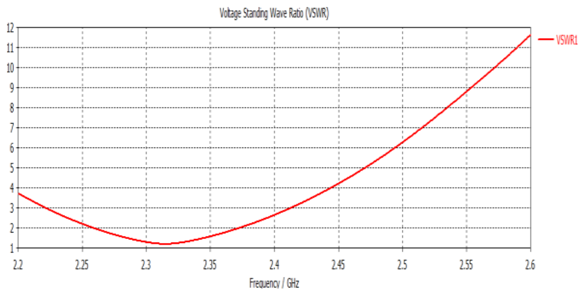
For base design, the VSWR is under 2:1 only within a very narrow band (refer Fig. 6 (a)). Beyond this range, VSWR increases rapidly beyond 2:1, which signifies that impedance is not matched well at other frequencies other than the resonant frequency.

Under the modified (slot integrated) structure, VSWR remains less than 2:1 in a broader band (refer Fig. 6 (b)). Nevertheless, the frequency points at which the VSWR is above the 2:1 level are still present, indicating irregular matching behaviour.

This variation exists since the rectangular shape of the slot in the modified design varies the surface current distribution in a complicated way. The slot adds more resonances and influences the coupling and radiated energy of the patch, which is no longer a smooth broadband enhancement but an unstable impedance match at specific frequencies.



(a) Base Design



(b) Modified Design

Figure 6. Comparison of VSWR

6. DISCUSSION

The simulation results clearly demonstrate that incorporating a single rectangular slot into the radiating patch generates a double resonance effect, which effectively overcomes the narrow bandwidth limitation inherent in conventional microstrip patch antennas. In the base design, a sharp resonance is observed at 2.4 GHz with an impedance bandwidth of only 50 MHz. Upon introducing the rectangular slot, the current distribution on the patch is suitably perturbed, allowing the coupling of a secondary resonant mode with the fundamental mode. This interaction significantly broadens the -10 dB return loss bandwidth to 95 MHz, nearly doubling the operational range while improving the minimum return loss to -21.599 dB. Although the modification causes a slight downward shift in resonant frequency to 2.31 GHz and a marginal reduction in peak gain from 5.39 dB to 5.16 dB, the radiation pattern becomes more directional, which may prove advantageous for many IoT applications requiring focused coverage.

These findings are consistent with recent trends observed in studies on slot loaded microstrip patch antennas (Zambak et al., 2023; ElAbbasi et al., 2025). Strategic placement of slots has been shown to excite additional resonant modes and improve bandwidth in several investigations. Similar sensitivity of resonant frequency to slot geometry has also been reported in parametric simulation studies (Mersani et al., 2025).

In comparison with previous works, the present design stands out due to its simplicity and practicality (Mishra et al., 2021; Zulmuqaddis & Setijadi, 2023). While many earlier studies have used complex slot geometries or costly substrates to achieve bandwidth enhancement, the proposed antenna delivers competitive performance using only a single rectangular slot on low-cost FR4 substrate. This approach also aligns with the emphasis on parametric optimization for reliable ISM band operation (Mersani et al., 2025).

The novel contribution of this work lies in achieving a balanced improvement in bandwidth and impedance matching while keeping the design simple and easy to fabricate. Unlike many existing solutions that rely on multiple or intricate slot configurations, the proposed single rectangular slot offers a practical and easily reproducible structure suitable for mass production. Furthermore, the detailed analysis of waveguide port sizing effects on simulation accuracy provides useful practical guidelines that are often overlooked (Pozar, 2012; Herdiana, 2022).

Nevertheless, some limitations should be acknowledged. The observed downward frequency shift and slight reduction in gain indicate scope for further optimization of slot dimensions and feed position. Future research should include prototype fabrication, experimental measurements, and detailed parametric studies to validate the simulated performance under real world conditions.

Overall, the results of this study confirm that even a simple geometric perturbation such as a rectangular slot can significantly enhance the performance of traditional microstrip patch antennas. This work contributes to the field by presenting a cost effective and practical design that bridges the gap between performance improvement and manufacturing simplicity for modern ISM band wireless applications.

7. CONCLUSION

This was a design and simulation analysis of a small patch microstrip antenna that can be applied in short range wireless networks and other applications. The base design features a minimum return loss (S11) of approximately -11.504 dB and a 50 MHz (2.38 GHz to 2.43 GHz) impedance bandwidth that meets fundamental performance requirements. A resonance range where VSWR is less than 2:1 is obtained, which implies that there is a tolerable impedance matching at the target frequency. The slot-integrated (optimized) design is shown with a better minimum S11 of -21.599 dB at a given frequency point and the nominal bandwidth extended to 95 MHz (2.28 GHz to 2.375 GHz). In conclusion, our design has superior performance in critical parameters like the return loss, VSWR and bandwidth compared to the basic model and thus can be used in compact IoT sensors and wireless communication gadgets among other uses. The frequency range 2.28-2.375 GHz that fits within the range of bandwidth achieved is applicable in applications of ZigBee, some Wi-Fi channels, wireless sensor networks, industrial telemetry systems, and low power communication devices in smart buildings or medical monitoring systems (Herdiana, 2022; Meena & Kannan, 2018). In this range, the modified design demonstrates a good performance as well as able to work reliably. Additional refinements are possible through slot geometry optimization, placement of feeds, and material choice to realize a more repeatable and predictable wideband response (Arora et al., 2021; Tumakov et al., 2020; Alam et al., 2021). This paper identifies the possibilities and constraints of fundamental geometric alterations in the design of microstrip patch antennas that will serve as a good basis to continue the development of efficient, stable and compact wireless solutions in the future.

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