Mikailalsys Journal of
Advanced Engineering International

e-ISSN : 3046-9694
p-ISSN : 3046-8914

Index : Harvard, Boston, Sydney University, Dimensions, Lens, Scilit, Semantic, Google, etc

https://doi.org/10.58578/MJAEI.v3i2.9125

Design and Analysis of Rectangular and Circular Microstrip Patch Antennas for 2.45 GHz ISM-Band Applications

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Article Info:

Submitted:	Revised:	Accepted:	Published:
Feb 1, 2026	Apr 29, 2026	May 11, 2026	May 16, 2026

Abstract

This paper presents the design, parametric analysis, and comparative evaluation of rectangular and circular microstrip patch antennas operating at 2.45 GHz in the industrial, scientific, and medical (ISM) band for wireless communication applications. Both antenna configurations were fabricated on a low-cost FR-4 dielectric substrate (εr = 4.5, thickness = 1.6 mm) to ensure compatibility with standard printed circuit board (PCB) manufacturing processes. The rectangular patch was designed with dimensions of 38.5 mm × 29.2 mm, while the circular patch had a radius of 16.42 mm; both were optimized using cavity-model formulations and closed-form analytical equations. A 50-Ω microstrip feed line with a width of 2.88 mm was employed for impedance matching. Comprehensive parametric studies were conducted to examine the influence of geometric parameters on resonance frequency, bandwidth, and radiation characteristics. The simulation results demonstrate that both antennas achieve satisfactory impedance matching, with $S_{11} < -10$ dB at the target frequency. The rectangular configuration produces a directional radiation pattern suitable

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for point-to-point links, whereas the circular design provides near-omnidirectional coverage with potential for circular polarization. Comparative analysis against four recent literature designs indicates that the proposed antennas achieve competitive performance in terms of compactness, fabrication simplicity, and cost-effectiveness without requiring complex modifications such as slots or parasitic elements. The study concludes that rectangular and circular microstrip patch antennas fabricated on FR-4 substrates offer practical, low-profile, and integrable solutions for WLAN, IoT, and biomedical applications requiring compact and cost-effective antenna structures.

Keywords: Antenna Design; Impedance Matching; ISM Band; Microstrip Patch Antenna; Wireless Communication Systems

INTRODUCTION

Modern wireless communication systems have become increasingly reliant on antennas for the effective transmission and reception of electromagnetic waves. Among the diverse range of antenna types, microstrip patch antennas have captured substantial interest due to several advantageous features they offer (Saeed & Nwajana, 2023). These antennas are characterized by their compact size, low profile, ease of fabrication, and compatibility with printed circuit board (PCB) technologies, making them particularly suitable for modern electronic devices. Microstrip patch antennas are typically designed in two common shapes: rectangular and circular. Each shape has its own unique set of advantages, which has led to extensive research and development efforts aimed at optimizing its performance (Das et al., 2022). The rectangular patch antenna is often favored for its straightforward design and well-understood radiation characteristics, while the circular patch antenna is noted for its circularly polarized radiation pattern, which can be beneficial in certain applications.

Both types of microstrip patch antennas have found a wide range of applications across various fields, including telecommunications, satellite communication, and mobile devices, among others. Their versatility and effectiveness make them ideal for applications where space is limited and performance is crucial. In this design introduction, we will delve deeper into the key characteristics that define microstrip rectangular and circular patch antennas (Lad et al., 2023). We will also explore vital design considerations that engineers must take into account when developing these antennas. Furthermore, we will discuss relevant research contributions that have advanced our understanding of microstrip patch antennas, ultimately highlighting their importance in the evolving landscape of wireless communication technology (Yahya et al., 2023).

Array Antennas

Many applications require radiation characteristics that may not be achievable with a single radiating element. However, it may be possible for an aggregate of radiating elements, arranged both electrically and geometrically as an array, to produce the desired characteristics. radiation characteristics. The arrangement of the array may be such that the radiation from the elements adds up to give a radiation maximum in a particular direction or directions, a minimum in others, or otherwise as desired.

Microstrip Rectangular Patch Antennas

Microstrip rectangular patch antennas have a ground plane on one side and a thin metallic patch printed on the other side of a dielectric substrate. They have a number of benefits, including simplicity in fabrication, affordability, and compatibility with integrated circuit technologies. A broad variety of design options are available thanks to the rectangular shape, which enables modifications to the dimensions for performance characteristics, including resonance frequency, bandwidth, and radiation pattern. The substrate material, dielectric constant, patch size, feeding strategies, and ground plane selection are just a few of the factors that must be properly taken into account while designing a microstrip rectangular patch antenna (Barnas Simanjuntak et al., 2021). These design characteristics affect how well the antenna performs, and optimisation techniques are used to meet the required specifications. The literature has suggested several design techniques, such as analytical models, numerical simulations, and optimisation algorithms.

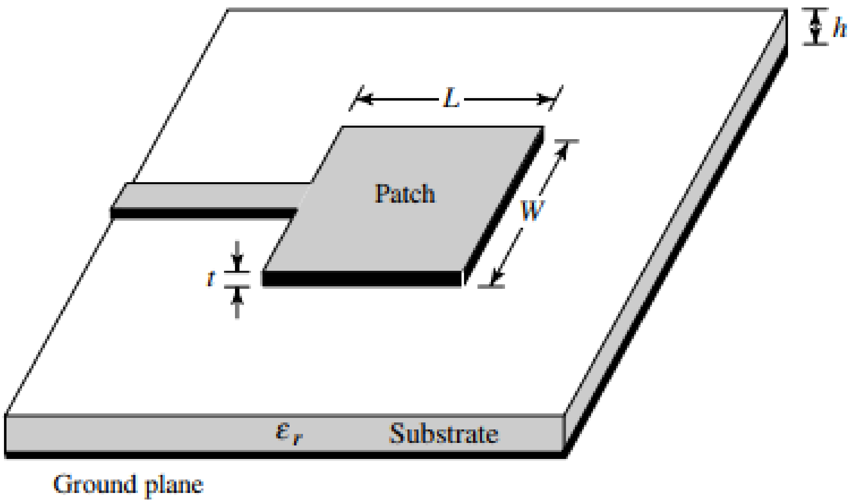

Figure 1: Rectangular Patch Antenna Architecture (Joshi & Sharma, 2024)

Microstrip rectangular patch antenna design and optimisation have received a lot of scientific attention. A revolutionary design methodology based on a genetic algorithm was put out by the author (Maurya et al., 2014) to increase the gain and bandwidth of a rectangular patch antenna. A distinct investigation, in (Anto Bennet et al., 2019), examined the impact of various feeding strategies on the functionality of a rectangular patch antenna, and recommended a small design appropriate for wireless communication applications.

A. Microstrip Circular Patch Antennas

Circular metallic patches are printed on dielectric substrates to form the basis of microstrip circular patch antennas, which also have a ground plane on the other side. Unique benefits of circular patches include their omnidirectional radiation patterns, small size, and straightforward construction. These antennas are best suited for uses that call for widespread coverage or circularly polarised radiation (Bansal, 2008).

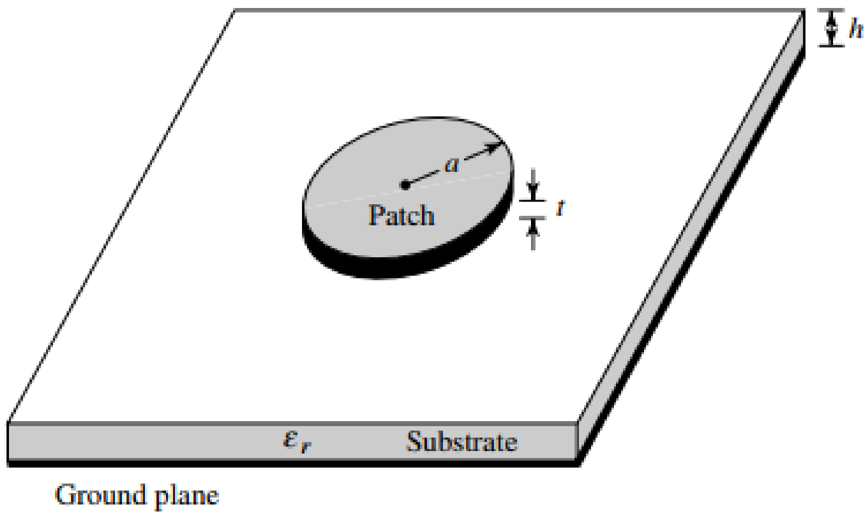

Figure 2: Circular Patch Antenna Architecture (Joshi & Sharma, 2024)

When creating a microstrip circular patch antenna, it is important to optimise factors including the circular patch's radius, substrate material, dielectric constant, and feeding method (Singh & Pattnaik, 2018). Compared to other antenna geometries, the circular shape offers inherent symmetry, simplifying the design process. Different design strategies have been put forth by researchers to improve the functionality of microstrip circular patch antennas (Mukta et al., 2021).

METHODS

This section outlines the methodology used to analyze microstrip rectangular and circular patch antennas. The approach taken is systematic and detailed, ensuring a comprehensive examination of the antenna designs and their performance characteristics. The rectangular patch antenna dimensions are calculated based on the desired frequency and substrate material. The circular patch antenna is designed similarly, taking into account the geometric differences. Both antennas are modeled using CST Microwave Studio.

Rectangular Patch Antenna Configuration

The rectangular patch antenna design is presented in **Figure 3**, which includes both a schematic layout and a three-dimensional structural view. The antenna consists of three fundamental layers: a conducting radiating patch on the top surface, an FR-4 substrate in the middle, and a conducting ground plane on the bottom surface. The rectangular patch serves as the main radiating element, where radiation occurs primarily due to fringing electric fields along the patch edges. The rectangular geometry is preferred in many applications due to its design simplicity and ease of controlling resonant frequency through patch length and width optimization. The 3D view further demonstrates the physical placement of the patch on the substrate, emphasizing the planar nature of the antenna structure and its suitability for compact wireless communication systems.

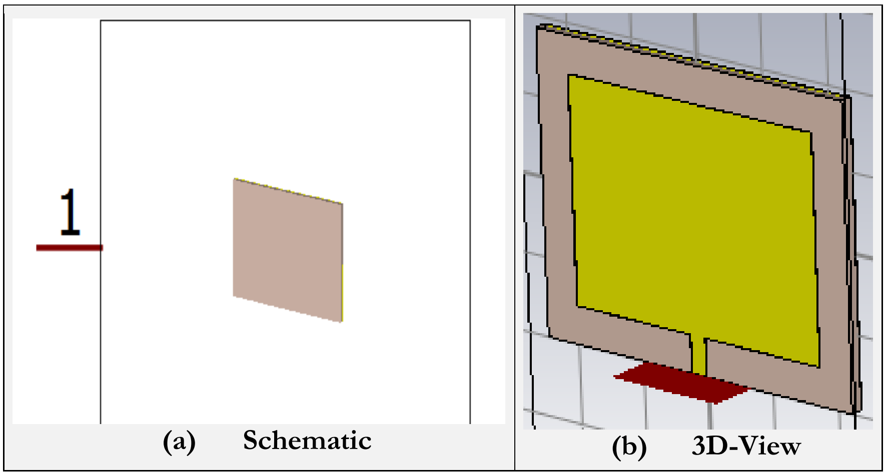

Figure 3: Microstrip Rectangular Patch Antenna

Circular Patch Antenna Configuration

The configuration of the circular patch antenna is depicted in Figure 4, which includes both a schematic and a 3D representation. Like the rectangular patch structure, the circular patch antenna features a radiating conductor printed on the upper layer of the FR-4 substrate, with a continuous ground plane located beneath. The circular patch geometry provides enhanced symmetry in current distribution compared to rectangular designs, potentially leading to more uniform radiation characteristics depending on the excitation mode. In circular microstrip antennas, the resonant behavior is primarily determined by the patch radius. This structure accommodates various transverse magnetic modes that can be utilized to meet specific requirements for polarization and bandwidth.

The proposed circular microstrip patch antenna has been designed using CST Studio Suite 2015 software. After completing the design, the antenna can be simulated within the software to estimate its real-world performance. For the antenna design, it is assumed that the dielectric constant of the substrate (ε_r), the resonant frequency (fr in GHz), and the height of the substrate (h in mm) are known. Subsequently, a set of simplified cavity model equations is employed to calculate the design parameters for the circular microstrip patch antenna (Mukta et al., 2021).

$\boldsymbol{a = \frac{F}{[1 + \frac{2h}{\pi F \varepsilon_r}(In\left\{\frac{\pi F}{2h}\right\} + 1.7726]^{1/2}}}$	(1)

Where $F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}}$ in GHz

Note: $h\ must\ measured\ in\ cm.$

Given: $h = 1.6\ mm \cong 0.16\ cm$,

Solving for ‘a’ into equation (3) when F is calculated as 1.691, and a = 1.642 cm (16.42 mm).

As a result, this geometry is often regarded as advantageous for applications that demand a compact size and stable radiation patterns.

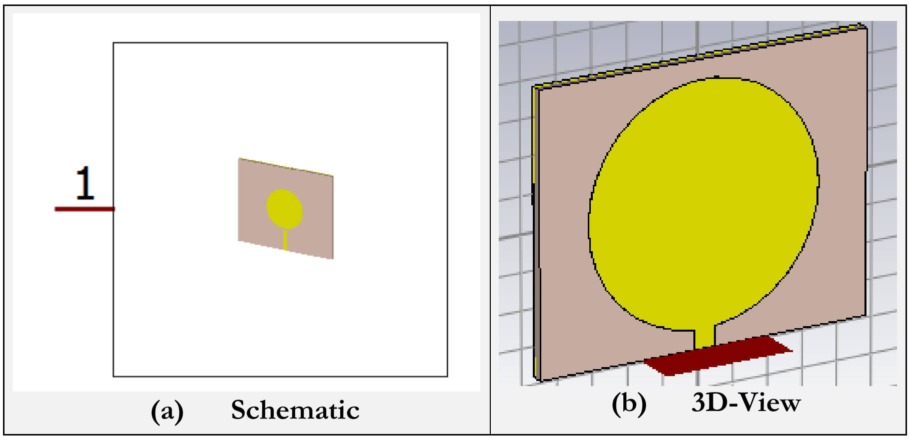

Figure 4: Microstrip Circular Patch Antenna

Ground Plane and Substrate Dimensioning

To achieve optimal electromagnetic field distribution and minimize performance degradation caused by edge diffraction, the antenna's ground plane and substrate were intentionally designed to extend beyond the radiating patch. This design consideration is crucial in microstrip antenna modeling, as an inadequate ground plane size can result in undesirable coupling, impedance mismatches, and shifts in resonant frequency. The antenna presented in this paper is designed on a double layer of 1.6 mm height (*h*) FR-4 substrates, having 4.5 dielectric constant (ϵr), with a resonant frequency of 2.45 GHz. The proposed antennas comprise a rectangular and circular patch. Figures 1 & 2 presents designed of a rectangular and a circular patch antenna.

A model of antenna architecture was developed using a circular and rectangular microstrip planar antenna, based on the following closed-form equation. (Bansal, 2008; Maurya et al., 2014):

$$\boldsymbol{Ws = Wg = 6h + Wp} \tag{2}$$

$$\boldsymbol{Ls = Lg = 6h + Lp} \tag{3}$$

Where the parameters are represented by the abbreviations Ws, Wg, and Wp, Ls, Lg, and Lp are the widths and the lengths of the substrate, ground, and patch, respectively.

RESULTS

This section presents the measured geometrical parameters of the fabricated microstrip patch antenna. These dimensions define the physical structure of the antenna and serve as the basis for evaluating its electromagnetic performance in the subsequent analysis.

Table 1: Parameters

Parameters	Symbol	Measured (mm)
Width of Substrate/ ground	Ws/Wg	46.6
Length of Substrate/ ground	Ls/Lg	38
Thickness of Substrate	Hs	1.6
Width of Patch	Wp	38.5
Length of Patch	Lp	29.2
Thickness of Patch/ground	tp/tg	0.035
Width of Feedline	Wf	2.88

Reflection Coefficient (S_{11}) Performance Analysis

The impedance matching performance of the proposed circular microstrip patch antenna was evaluated using the simulated reflection coefficient parameter S_{11}.

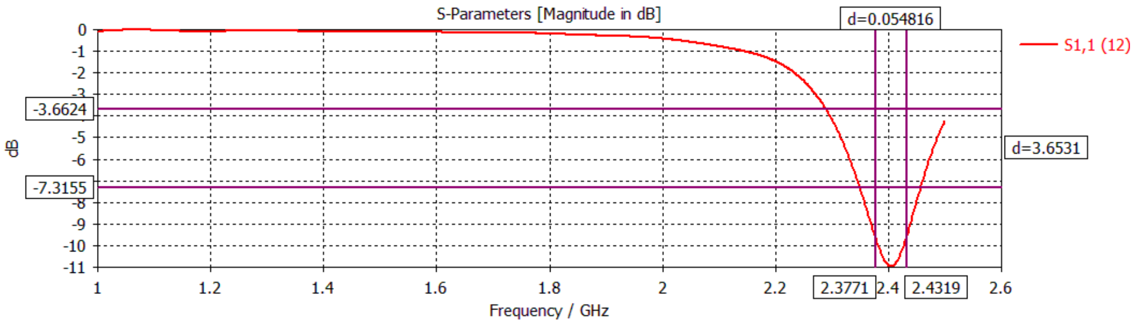

Figure 5: Microstrip Circular Patch Antenna

Figure 5 illustrates the magnitude of S_{11} (dB) over the frequency range from 1 GHz to 2.6 GHz. The reflection coefficient response indicates that the antenna achieves a clear resonance within the targeted ISM band region.

Reflection Coefficient (S_{11}) Performance of the Rectangular Patch Antenna

The impedance matching characteristics of the proposed rectangular microstrip patch antenna were evaluated using the simulated reflection coefficient $\boldsymbol{S_{11}}$.

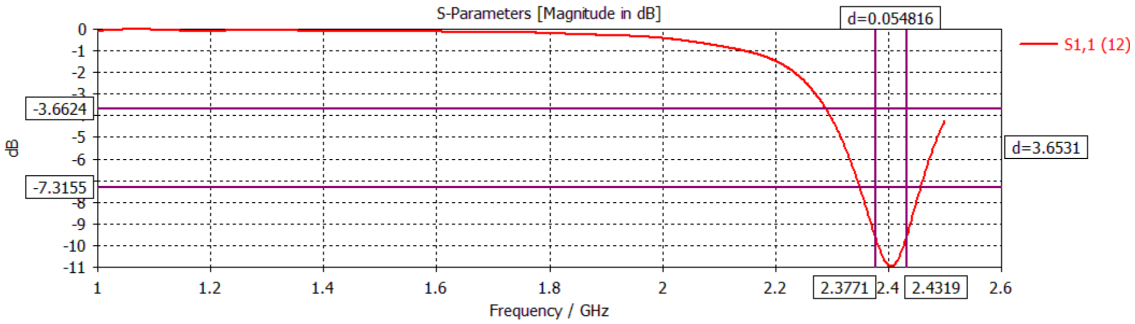

Figure 6: Rectangular S-Parameter

Figure 6 illustrates the magnitude of the $\boldsymbol{S_{11}}$ response in dB over the frequency range from 1 GHz to 2.6 GHz. The obtained results demonstrate that the antenna achieves resonance within the targeted 2.4 GHz ISM band region.

DISCUSSION

Figure 5 simulation results, the antenna exhibits its main resonant frequency at approximately 2.4 GHz, where the minimum return loss reaches nearly -11dB. This value confirms that the antenna achieves acceptable impedance matching, since the return loss satisfies the common design criterion of $(S_{11} < -10dB)$, implying that a significant portion of the input power is delivered to the radiating element rather than being reflected to the source. The impedance bandwidth of the antenna was determined using the standard -10 dB threshold. As indicated by the frequency markers in Figure 5, the antenna maintains S_{11} below -10 dB between 2.3771 GHz and 2.4319 GHz. Therefore, the achieved impedance bandwidth is calculated as:

BW = 2.4319 - 2.3771 = 0.0548 GHz

BW = 54.8 MHz

This bandwidth demonstrates that the antenna provides sufficient operational range for narrowband applications such as Bluetooth, Wi-Fi (IEEE 802.11b/g/n), and other ISM-based wireless systems operating around 2.4 GHz. Furthermore, the sharp resonance dip observed in the S_{11} response indicates a high-quality factor characteristic, which is typical of microstrip patch antennas fabricated on FR-4 substrates. While FR-4 introduces dielectric losses that may slightly reduce antenna efficiency compared to low-loss substrates, the achieved impedance response confirms that the proposed antenna structure remains practically viable for low-cost wireless communication designs. Therefore, the simulated S_{11} response verifies that the antenna design methodology successfully produced resonance within the desired operating band and achieved adequate impedance bandwidth for 2.4 GHz ISM applications.

CONCLUSION

This paper presented the design and comparative performance evaluation of rectangular and circular microstrip patch antennas operating at 2.45 GHz were analytically designed and numerically evaluated on an FR-4 substrate. Both configurations satisfied the −10 dB impedance matching criterion and achieved resonance within the ISM band, with the circular patch antenna providing an impedance bandwidth of 54.8 MHz. The key contribution is the validation of closed-form cavity-model equations as an efficient lowcomplexity design approach without geometric perturbations. Future work will address experimental validation, radiation efficiency assessment, and bandwidth enhancement for multi-band and reconfigurable wireless systems.

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