

Performance of Rectangular Micro-Strip Notch Antenna for RF Energy Harvesting Applications

Niketan Kumar Mishra^{1,2*} & Sanjay Kumar Sharma¹

¹Department of Electronics and Communication Engineering, University Institute of Technology, Rajiv Gandhi Proudhyogiki Vishwavidyalaya, Bhopal, Madhya Pradesh 462 033, India

²Department of Electronics and communication Engineering, Lakshmi Narain College of Technology & Science, Kalchuri Nagar, Raisen Road, Madhya Pradesh, India - 462022

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An enhanced bandwidth and performance for Wi-Fi applications was achieved through the design and optimization of a notched rectangle microstrip patch antenna in this work. A transmission line model was used in the CST STUDIO SUITE to develop an inset-fed microstrip rectangle patch antenna that would guarantee correct matching of impedance with the microstrip communication line. One of the crucial elements determining the antenna's physical properties, which in turn affected its ideal performance, was the substrate material. Radiation efficiency and impedance matching were the main objectives of this design, which was completed with careful consideration for the patch's size and feed placement. An extensive analysis was conducted on the antenna's key performance parameters, including efficiency, Voltage Standing Wave Ratio (VSWR), far-field radiation patterns, and return loss. The results for return loss demonstrated very good impedance matching, and the far-field radiation pattern demonstrated extremely good directivity with an effective proportion of energy. The return loss study showed a significant reduction at 2.275 GHz, while the VSWR data confirmed a nearly perfect match at the target frequency of 2.45 GHz. With a main lobe gain of 11.1 dB and a peak radiation efficiency of 90% at the design frequency, it is an excellent choice for applications involving the harvesting of radio frequency energy from ambient sources such as Wi-Fi, GSM, UMTS, and LTE signals. The chosen frequencies of 2.275 GHz and 2.45 GHz were selected to optimize impedance matching and enhance the antenna's performance for Wi-Fi and other RF energy harvesting applications, ensuring efficient energy capture and utilization. This work emphasizes the antenna's increased capabilities and provides a workable solution, as well as new applications for contemporary wireless communication systems.

Keywords: Energy harvesting, Radio frequency, Rectangular micro strip patch antenna, Transmission line model, Wireless communication

Introduction

Green power comes from Radio Frequency (RF) energy harvesting that offers a sustainable alternative to batteries for wireless sensors. It converts RF signals emitted by a transmitter into electrical energy, providing a power source for smart devices as shown in Fig. 1. This method, particularly in IoT-oriented networks, can meet energy needs for transmitting operations, sensing, processing, or rudimentary communication. The use of radio signals utilizing a frequency range of 3 kHz to 3 GHz is gaining popularity in various domains.¹ RF energy collection and radiative transferring power wirelessly is key methods for enabling battery-free, sustainable wireless networks. Antennas designed for RF energy

harvesting can effectively capture energy from a variety of ambient sources, including GSM-900 (850–910 MHz), GSM-1800 (1850–1900 MHz), UMTS (2150–2200 MHz), LTE (750–800 MHz), and Wi-Fi (2.4–2.45 GHz), among others. The effectiveness of these antennas hinges on key design factors such as impedance matching, gain, directivity, and bandwidth. While the ambient RF energy density is typically low, ranging from 0.2 nW/cm² to 1 W/cm², advanced antenna and rectenna designs are

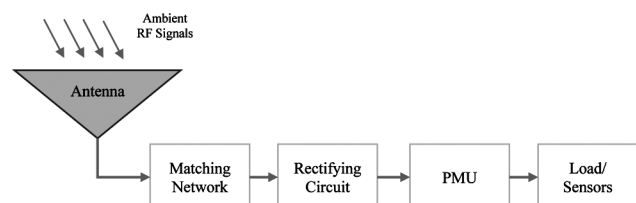


Fig. 1 — Radio-frequency (R-F) energy harvesting system

*Author for Correspondence

E-mail: niketanmishra14@gmail.com

enhancing the feasibility of RF energy harvesting for powering low-power devices in both indoor and outdoor environments. Rectifying antennas significantly impact harvesting efficiency, varying power output by orders of magnitude.² RF energy harvesting converts electromagnetic field energy into electrical energy, using a system comprising rectification circuit, adapter network, along with the receiving antenna. Radiative WPT transmits power to receiver via electromagnetic waves.³ Aim of all antenna energy harvesting projects has been to provide intelligent applications with highly efficient transmitted power and low-cost antenna device design. The following could be used to outline the primary benefits of EH: preserving the right to use it should the devices run on a small amount of power and lengthen the battery's end life.⁴

Microstrip antenna research has seen significant advancements over the past decades due to their low profile, ease of manufacturing, and cost-effectiveness. Numerical techniques, including radiating techniques, offer a wide range of applications due to their affordability and versatility in various computational environments. These advancements have extended microstrip antenna applications into fields such as telecommunications, automotive, aerospace, and biomedicine.⁵ Mobile data rates are significantly increasing, necessitating increased bandwidths for managing heavy data traffic, especially in the millimeter wave band.

Frequency reconfigurable antennas have emerged as a viable solution for modern wireless devices, reducing costs and energy consumption.⁶ These antennas are pivotal in various technological innovations such as vehicles, motorcycles, and high-speed internet services. In today's world, smaller-sized communication technologies such as satellite phones, GPS, WLANs, and mobile phones rely heavily on these systems. Portable electronic devices like cell phones and laptops use microstrip patch antennas which, however, face challenges like bandwidth reduction with increased usage.⁷ The ongoing development of microstrip patches for wireless communication is crucial to accommodate the rising data demands of contemporary devices. The advent of 5G technology, utilizing broad signal bandwidths and high-frequency bands, aims to enhance network efficiency, coverage, and speed. Ultra-wideband (UWB) Microstrip Patch Antennas (MPAs) are gaining popularity due to their low

profile, cost-effectiveness, easy manufacturing, and overall good performance.⁸ A high-gain, flexible MPA has been developed, featuring a VSWR less than 2, 6–9 dBi gain, 82% efficiency, and a 300 MHz bandwidth for RF energy harvesting at 5 GHz. RF antennas with a pentagonal radiating patch and microstrip feeding technique are also incorporated for energy harvesting in the 2.33–2.57 GHz range, and a rectangular slot enhances impedance matching and gain. CST STUDIO SUITE was used to design this antenna, which operates near 2.45 GHz and has vertical slots for adjusting harmonic frequencies. The antenna achieves a peak gain of 8.02 dBi.⁹ Moreover, a cost-effective, transparent microstrip RF energy harvesting antenna made with AgHT-4 coated film, designed for 2.4 GHz, shows a return loss of –38.644 dB and a gain of 5.028 dBi. A printed rectenna with U-shaped slots was developed for RF energy harvesting at 2.45 GHz. It is powered by a symmetric 50 coplanar line and uses a rectangular patch. A 0.8 dBi peak gain and symmetrical radiation make this the smallest rectenna of its kind, making it an ideal candidate for low-power wireless sensor networks.¹⁰ Explorations in microstrip antenna design have examined the effects of microstrip slot placement and dielectric substrate thickness on performance metrics, demonstrating that thicker substrates reduce return loss and enhance gain.¹¹ An antenna array designed to exhibit resonant frequencies at 4.16 GHz, 3.38 GHz, 2.38 GHz, and 1.6 GHz showcases gains ranging from 2.48 to 7.66 dB.¹² Additionally, a rectenna antenna system has been developed to convert electromagnetic waves into direct voltage sources, operating at 2.4 GHz for WiFi signals. This system integrates a circular patch microstrip antenna with Schottky 2860 diodes and 1nF SMD capacitors in its rectifier circuit, achieving VSWR values of 1.11, 1.16, and 1.07, an impedance range of 51.1, 55.56, and 50.22, a bandwidth of 60 MHz, and return loss values of –26.29 dB.¹³

Further developments include a 3×4 circular polarization microstrip antenna patch array, operating at 2.45 GHz, designed for applications in the scientific, medical, and industrial fields. Printed on FR4 material, this compact antenna, measuring 22.7×13.5 cm, demonstrates strong performance with a directivity of 9.66 dBi at 2.45 GHz and a total efficiency of about 95.55%.¹⁴ For wireless energy harvesting applications at 2.45 GHz, a microstrip-fed spurious-free slant antenna array featuring a unique

design with a distorted ground structure and stubs has been created to minimize spurious responses, achieving a 19% return loss bandwidth and over 80% radiation efficiency.¹⁵

Performance evaluations of an inset feed rectangular microstrip patch antenna operating at 3 GHz reveal that adjustments in notch width and gap values significantly affect antenna performance.¹⁶ A modified version of the E-shaped microstrip antenna, featuring three unequal-length rectangular slots, has been proposed to reduce the resonance frequencies of higher-order modes such as TM₁₁ and TM₀₂, successfully achieving a bandwidth of over 450 MHz (>45%).⁽¹⁷⁾ This design provides a broadside radiation pattern across this bandwidth, with a peak broadside gain exceeding 8 dBi. It features high gain, wide bandwidth, and a low profile, with dimensions of 46.9 mm by 38.01 mm, offering a bandwidth of 115 MHz at 4.1 GHz and 90 MHz at 2.45 GHz. Equipped with Defected Ground Structures (DGS), the antenna showcases return losses of -27.5 dB at 4.1 GHz and -21.25 dB at 2.45 GHz, with gains of 6.70 dB and 6.80 dB respectively.¹⁸ A rectangular micro-strip antenna designed for TM₀₁₀ mode at 2.1 GHz, featuring narrow and inverted L-shaped slots, operates effectively at multiple frequencies, displaying excellent performance across specific frequencies from 2.9 GHz to 1.25 GHz.¹⁹

An in-depth analysis of the main resonant frequency of slot-loaded rectangular microstrip patch antennas through an analytical model has shown that the resonant frequencies closely follow expected harmonic patterns, mirroring the behaviour of a small strip antenna without a slot.²⁰ This synergy between theoretical models and practical measurements underscores the dynamic evolution of microstrip antenna technology, highlighting its potential for continued innovation and application in modern communications and technology sectors. These studies are relevant because they cover a diverse range of microstrip antenna designs and technologies that are closely related to RF energy harvesting and wireless communication applications, which are the primary focus of our work. Each study explores different aspects of antenna design, such as gain, bandwidth, and efficiency, which are critical performance metrics for RF energy harvesting.

Many of the recently published research studies are still working on different designs and configurations of MPAs in order to improve major

performance parameters such as return loss, bandwidth, and isolation, as shown in Table 1. Despite all these efforts, there are still huge gaps that exist, particularly concerning the optimization of microstrip antennas for RF energy harvesting. Previous work on microstrip antennas has been aimed at maximum efficiency and throughput in practical applications; issues specific to RF energy harvesting remain neglected. This work seeks to address this by optimizing the performance evaluation of a rectangular microstrip notch antenna design, with special targeting of RF energy harvesting, and as such will bridge an important gap in this area of current research. The motivation for choosing a notch design in a Rectangular Microstrip Patch (RMP) antenna lies in its ability to enhance impedance matching, which reduces return losses and increases total efficiency, and to broaden the operational bandwidth by altering current distribution. Additionally, notches provide fine control over resonant frequencies and can improve gain by influencing the radiation pattern and current paths. The research will leverage advanced simulation tools and refined design techniques to boost the antenna's efficiency and bandwidth, with an aim of bridging the gap. Moreover, the primary objective of this research is to boost the antenna's efficiency and bandwidth which is slated to be achieved through rigorous comparative analysis and bandwidth assessment using sophisticated design methods and cutting-edge modeling technologies. To evaluate the effectiveness and adaptability of the proposed antenna across various wireless scenarios, the study includes in-depth performance analysis in comparison with traditional antenna designs. Furthermore, the impact of different substrate materials, notch configurations, and feed techniques on the general performance of MPAs has been hardly explored. The scalability of these designs for broader applications, including Industrial, Scientific, Medical (ISM) sectors, and emerging 5G technologies, remains to be understood. The present work will try to fill these gaps through comprehensive analysis using a new RMP antenna design with a notch for bandwidth and performance enhancement, which shall be applicable to a wide range of modern wireless communication systems. This design is necessary because it enhances the efficiency and effectiveness of RF energy harvesting by improving impedance matching and radiation

Table 1 — Comparative Analysis of Microstrip Patch Antenna Designs and Their Performance Metrics across Various Studies

Antenna Type	Key Features	Frequency Range	Bandwidth	Notable Performance Metrics	Applications
High-gain, low-profile microstrip array antenna ⁷	Low side lobes, high gain, flexible design	5 GHz	300 MHz	VSWR < 2, Gain 6–9 dBi, 82% efficiency	RF energy harvesting
Single band RF antenna ⁸	Pentagonal radiating patch, microstrip feeding, rectangular slot	2.33–2.57 GHz	240 MHz	Gain 8.02 dBi, Omni-directional radiation	Energy harvesting
Rectangular geometry microstrip antenna ⁹	Vertical slots influence harmonic frequencies	2.34 GHz	—	Difference in resonance frequency: 0.06 GHz	RF energy harvesting
Transparent microstrip RF energy harvesting antenna ¹⁰	Transparent material, AgHT-4 coated film	2.4 GHz	—	Return loss: –38.644 dB, Gain: 5.028 dBi	Cost-friendly smart energy technology
Compact printed rectenna ¹¹	Rectangular patch with U-shaped slots, symmetric 50 coplanar line	2.45 GHz	—	Peak gain: 0.8 dBi, Nearly symmetrical radiation	Ambient RF energy harvesting
Microstrip antenna with ARLON AD450 substrate ¹²	Influence of substrate thickness and slot placement	Various resonant frequencies around 1.6 GHz, 2.38 GHz	—	Gain: 2.48–7.66 dB	RF energy harvesting
Circular patch microstrip antenna ¹³	Schottky diodes, 1nF smd capacitors in rectifier circuit	2.4 GHz	60 MHz	Return loss: –26.29 dB, VSWR: 1.11–1.07	WiFi signal energy harvesting
3×4 circular polarization microstrip antenna patch array ¹⁴	FR4 substrate, compact size	2.45 GHz	—	Directivity: 9.66 dBi, Axial ratio: 1.69 dB, Efficiency: 95.55%	ISM band applications
Microstrip-fed spurious free slant antenna array ¹⁵	Distorted ground structure and stubs to suppress spurious responses	2.45 GHz	—	19% return loss bandwidth, > 80% radiation efficiency	Wireless energy harvesting
Inset feed rectangular microstrip patch antenna ¹⁶	FR-4 substrate, suitable for ISM sectors	3 GHz	—	Return loss varies with notch gap, Resonant frequency: 2.944–2.978 GHz	ISM applications
Broadband rectangular microstrip antenna with unequal length slots ¹⁸	Broadside radiation pattern, high gain	2.45 GHz, 4.1 GHz	450 MHz	Gain > 8 dBi, Return losses: -21.25 dB (2.45 GHz), -27.5 dB (4.1 GHz)	Broadband applications
<i>Proposed Rectangular Microstrip Notch Antenna</i>	<i>RF Energy Harvesting, Aperture area - 17.86 cm²</i>	<i>2.400 to 2.483 GHz</i>	<i>2.275 GHz</i>	<i>Peak gain > 11 dB, Efficiency 90%</i>	<i>Wi-fi applications</i>

efficiency. It offers better performance in terms of bandwidth and directivity compared to existing antenna designs in Table 1, making it more suitable for modern wireless communication systems.

Material and Methods

Theoretical Background of Rectangular Micro-Strip Patch Antennas (RMPA)

Electromagnetic waves are frequently transmitted into space during wireless transmission with the use of an MPA. The ground, substrate, patch, and feed are the four essential components of an MPA.²¹ The range of uses of microstrip antennas is constantly expanding, despite their extensive development. The area of communications that is wireless is one of these. Microstrip rectangular patch antenna enhances directivity by removing the e-shaped patch and using a rectangular patch, transforming the omni-direction

antenna into a directional antenna, thereby improving return loss and bandwidth in feed line multiple frequency operations.²² It is possible to optimize micro strip notch antennas for high efficiency RF energy to electrical power conversion. Through meticulous antenna structure design with complementary circuitry, maximum power transmission is possible, improving the total efficiency of energy harvesting. Micro strip notch antennas may be produced in large quantities at a relatively reasonable cost because of its planar construction and compliance with common fabrication procedures. They may be mass-deployed profitably in a variety of energy collecting applications because to their scalability. Energy may be collected from a variety of RF sources using micro strip notch antennas since they can be made to

function in several frequency bands. This versatility makes them suitable for diverse environments and applications. Overall, the design and optimization of micro their adaptability renders them appropriate for a wide range of settings and uses. Strip notch antennas are necessary to increase the effectiveness of and effectiveness of RF energy harvesting devices, resulting in it possible for wireless devices to run on their own and for Internet of Things ecosystems.

It is possible to analyze a straightforward Rp, Lp, and Cp are combined parallel into an oval microstrip patch antennas. Wherein Rp, Lp, & Cp are defined as:-

$$C_p = \frac{\epsilon_e \epsilon_0 L W}{2h} \cos^{-2} \left(\frac{\pi x_0}{L} \right) \quad \dots (1)$$

$$L_p = \frac{1}{\omega^2 C_p} \quad \dots (2)$$

$$R_p = \frac{Q_r}{\omega C_p} \quad \dots (3)$$

where, x₀ denotes the setting of the feed point along the length of a patch, h indicates the backing material's thickness, L, W, and h

$$Q_r = \frac{c \sqrt{\epsilon_e}}{f h} \quad \dots (4)$$

where, ϵ_e represents the effective permittivity of the medium, which can be calculated from eq; c represents the light's velocity; and f represents the intended frequency Eq. (5).

$$\epsilon_e = \frac{\epsilon_{r+1} + \epsilon_{r-1}}{2} \left(1 + \frac{10h}{W} \right) - 1/2 \quad \dots (5)$$

where, ϵ_r is the backing material's comparative permittivity.

The suggested antenna's radiation pattern is computed using a rectangular patch method as¹⁹

$$E(\theta) = \frac{-jk_0 W V e^{-jk_0 r}}{\pi r} \cos(kh \cos \theta) \sin \left(\frac{k_0 W \sin \theta \sin \phi}{2} \right) \times \cos \left(\frac{k_0 l}{2} \sin \theta \sin \phi \right) \cos \phi \quad \left(0 \leq \theta \leq \frac{\pi}{2} \right) \quad \dots (6)$$

$$E(\phi) = \frac{-jk_0 W V e^{-jk_0 r}}{\pi r} \cos(kh \cos \theta) \frac{\sin \left(\frac{k_0 W}{2} \sin \theta \sin \phi \right)}{\frac{k_0 W}{2} \sin \theta \sin \phi} \times \cos \left(\frac{k_0 l}{2} \sin \theta \sin \phi \right) \cos \phi \sin \phi \quad \left(0 \leq \theta \leq \frac{\pi}{2} \right) \quad \dots (7)$$

where, r represents a radius to any given location and j denotes it's radiated voltage.

$$k = k_0 \sqrt{\epsilon_r} \quad \dots (8)$$

$$k_o = \frac{2\pi}{\gamma} \quad \dots (9)$$

The length, breadth, feed point placement, substrate thickness, and effective permittivity of the medium all affect the capacitance of the antenna. The capacitance and operating frequency determine the inductance. The quality factor Qr, which is influenced by capacitance, light speed, design frequency, and effective permittivity, is correlated with resistance. The corresponding permittivity of the substrate material and the physical dimensions of the antenna are used to compute the effective permittivity. Analyzing the antenna as a rectangular patch yields the suggested antenna's radiation pattern it considers the waveform number, the distance to any location, and the projecting edge voltage. These formulas explain the electric field distribution in terms of the substance or physical characteristics of the antenna. The transmission line model was integral to the design process, as it provided a theoretical foundation for analyzing and optimizing the antenna's impedance matching and resonance characteristics. By modeling the microstrip patch as a transmission line, we were able to calculate parameters such as characteristic impedance, reflection coefficients, and input impedance, which guided the design decisions.

Role of Notches in Antenna Performance

The selection and optimization of frequency bands play a critical role in RF energy harvesting, as they ensure efficient capture of energy from existing RF sources. Advanced techniques are needed to optimize the antenna's efficiency and improve the conversion performance. Antenna parameters like size and shape and substrate material become key aspects of the effectiveness of energy harvesting systems. Optimization methods for microstrip notch antennas include analytical, numerical, and experimental techniques that should strive for desired performance metrics. Effective tuning of the parameters is thus crucial to maximizing both power conversion efficiency and bandwidth. Moreover, approaches to multi-objective optimization can be used to reconcile conflicting design metrics, for instance, efficiency, bandwidth, and compactness. The overview of microstrip notch antenna structure is shown in Fig. 2.

The fundamental component of any communication system is an antenna, which serves as a constant factor in transmitting and receiving signals.²³ In such systems,

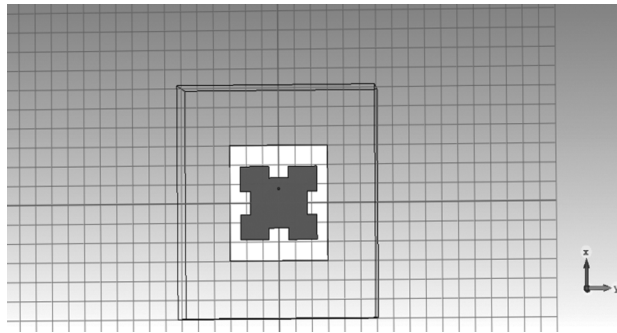


Fig. 2 — Overview of microstrip notch antenna

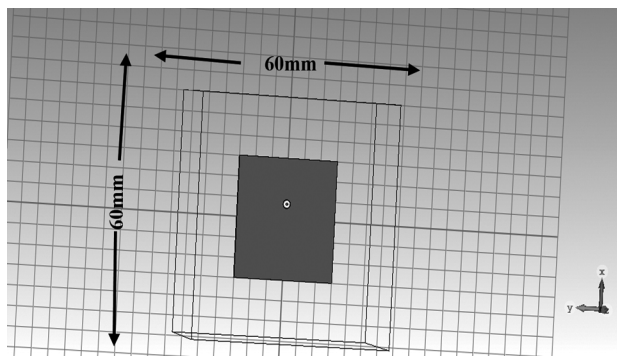


Fig. 3 — Layout of rectangular microstrip patch antenna

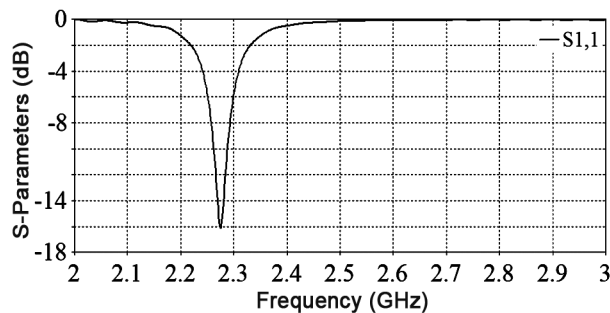


Fig. 4 — Return loss (S11) profile of a microstrip patch antenna at 2.45 GHz

ground planes are commonly employed, but stacking them can lead to increased bulkiness and difficulty in production and alignment, particularly with patch antennas.²⁴ Patch antennas have garnered considerable attention due to their compact design and suitability for various applications, including satellite communication, missile guidance, and mobile communication systems. However, stacking ground planes can exacerbate issues related to bulkiness and alignment, prompting the exploration of alternative approaches. Varying ground plane designs present a promising solution to address these challenges, offering improved communication system performance and flexibility.²⁵ Given the limited space available in

mobile devices, integrating wireless antennas poses a significant challenge. Hence, there is a growing need to optimize antenna design and structure to maximize functionality within the constraints of compact device form factors.

Specifications and Dimensions of the Proposed Antenna

The objective of a developing a notch in an RMP antenna is to increase its bandwidth. During the design phase, a transmission line model is used on CST STUDIO SUIT. To address the concern regarding the methodology, in this study CST STUDIO SUITE is used to design the antenna, focusing on optimizing critical parameters such as patch dimensions, feed placement, and substrate material. These parameters are selected based on their impact on impedance matching and radiation efficiency. For instance, the substrate material was chosen for its dielectric properties to ensure effective signal transmission, while the dimensions of the patch and feed placement were adjusted to achieve the desired resonance frequency and enhance overall performance. When designing an antenna on CST software, controlling environmental factors is crucial for accurate results. This includes setting appropriate boundary conditions, defining the frequency range, optimizing mesh size, accurately modeling material properties, considering radiation patterns, accounting for interference, and including nearby structures.

For precise match the spacing of a 50A tiny broadcast range, an inset-fed stripes rectangle antenna with patching was designed. Fig. 3 shows the structure of the planned microstrip patch antenna. Selecting an acceptable substrate is the first step of creating a rectangle. The microstrip Array (RMPA) is featuring a recess and Wlan usage with a 2.400–2.483 MHz wavelength range. The chosen substrate FR4 has a thickness (h) of 0.16 cm, a losses tangential ($\tan\delta$) of 0.001, with an apparent permittivity (ϵ_r) of 2.32. The chosen substrate was selected based on its specific dielectric properties, such as dielectric constant and loss tangent, which are critical in determining the antenna's impedance matching, bandwidth, and overall efficiency. The substrate's thickness and material composition were also considered to minimize signal loss and enhance radiation performance. The presence of a notch has significant effects on the physical parameters of an RMP.

A rectangular microstrip patch antenna layout with designated dimensions is depicted technically in

Table 2 — Dimensions of proposed antenna

Parameter	Value
Frequency	2.45 GHz
Frequency Range	2.400 to 2.483 GHz
Substrate ϵ_r	2.32
Substrate Thickness (h)	0.16 cm
Loss Tangent ($\tan\delta$)	0.001
Patch Width (W)	4.7 cm (47 mm)
Patch Length (L)	3.8 cm
Feed Position (x)	7.5
Substrate Length	6 cm
Substrate Width	6 cm
Feed Type	Co-axial feed
Aperture Area	17.86 cm ²

Fig. 4. The patch dimensions are calculated to achieve the desired frequency; the width (W) of the patch is 4.7 cm (47 mm) and the length (L) is 3.8 cm. The feed position for the coaxial feed is set at $x = 7.5$ to optimize the impedance matching. The substrate dimensions are chosen to be 6 cm in both length and width to ensure proper antenna performance and to accommodate the patch and feed structure. These dimensions are crucial for determining the antenna's resonant frequency and bandwidth. Table 2 provides the dimension of the proposed antenna.

The aperture of this antenna, which refers to the physical dimensions of the radiating patch, can be calculated by multiplying the width and length of the patch. Therefore, the aperture area of the proposed antenna is $4.7 \times 3.8 = 17.86 \text{ cm}^2$. This aperture area is a critical parameter as it defines the radiating surface responsible for the antenna's performance.

Results and Discussion

Assessment of Near Fields Emission with Return Loss

The foundation for contemporary mobile phone networks is micro-strip patch antennas, which are highly valued for their small size and suitability for printed circuit board production processes. These antennas work well in certain band frequencies by emitting guided waves from a metallic patch positioned in a solid substrate. Two important performance measures are studied in the field of antennas design: The degree of the antenna's and transmission line are resistance lined up, or return loss, and the far-field radiation pattern, which describes the distribution of radiated energy in space. The former ensures that the antenna transmits or receives the maximum possible power without significant as well as the far-field radiation pattern,

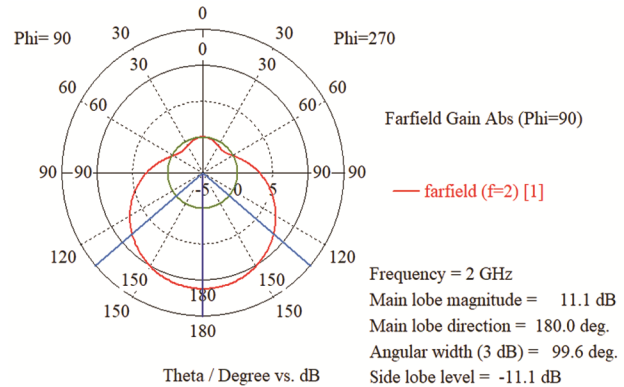


Fig. 5 — Polar radiation pattern of a 2 GHz microstrip patch antenna

which depicts how energy is distributed in space through radiation, reflections, whereas the latter determines the antenna's efficacy and orientation within its operating environment. In order to optimize the antenna's performance and achieve the lowest possible return loss, this study frequently entails modeling and measurement as well as a far-field pattern that complies with the particular needs of the system the antenna will be utilized.

The return loss (S11) of a micro strip patch antenna across a frequency range of 1 GHz to 4 GHz is displayed on the graph in Fig. 4. The antenna is best suited to the transmission line at 2.275 GHz, which is generally used for Wi-Fi applications, as shown by the significant drop at this frequency. The power reflected back from a Wi-Fi system component or device is measured at the return loss peak at 2.275 GHz, which indicates how well the component or device fits the impedance of the transmission line. A better match is indicated by a larger return loss, whereas a worse match is indicated by a lower loss. Reduced signal intensity, impedance mismatch, and other performance problems might result from this peak. The peak could also be purposeful or built into the design of the device. A high resistance matching is implied by the depth of the dip below -16 dB , which guarantees minimum signal reflection and maximum power transfer. The antenna's limited bandwidth is shown by the steep drop, and the 2.275 GHz frequency appears to be where it performs best. This performance attribute is essential for applications that need to operate at high efficiency in a certain frequency range.

The polar plot of the far-field radiation pattern for a microstrip patch antenna at 2.4 GHz is depicted in Fig. 5. The plot shows the gain of the antenna in

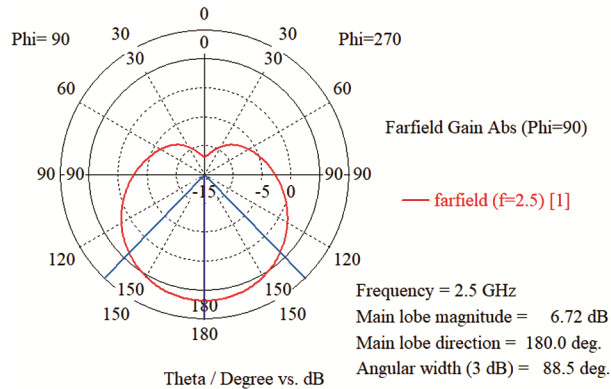


Fig. 6 — Far-field gain radiation pattern of a microstrip patch antenna at 2.5 GHz

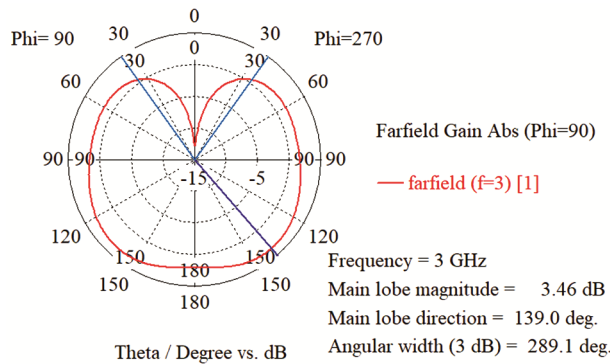


Fig. 7 — Far-field gain radiation pattern of a microstrip patch antenna at 3 GHz

various directions, with different curves representing different planes of phi (Φ) $-0, 90, 180,$ and 270 degrees. The main lobe, indicating the direction of the highest gain, is at 0 degrees on the theta (θ) axis, with a magnitude around 11.1 dB, suggesting that the antenna directs most energy forward. The main lobe direction coincides with the antenna's boresight. The angular width of the main lobe ($\theta = 3$ dB) is about 99.6 degrees, describing the beam's spread. Side lobe levels are at -11.1 dB, which are the peaks appearing at angles away from the main lobe, showing that the antenna emits some energy in non-preferred directions. These side lobes are lower in magnitude compared to the main lobe, which is desirable as it indicates that the antenna is efficiently focusing energy in the intended direction. This radiation pattern information is vital for understanding the antenna's coverage and directivity.

Polar plot of the far-field radiation pattern for an antenna at 2.5 GHz and radiation lobe is depicted in Fig. 6 with a peak gain of 6.72 dB, suggesting the antenna has a significant directional characteristic in

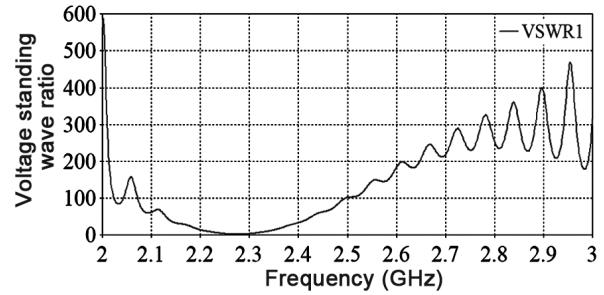


Fig. 8 — VSWR analysis across frequency range for a microstrip patch antenna

the plane of the main lobe. The 3 dB beam width is quite wide at 88.5 degrees, which indicates the antenna radiates over a large area, ideal for broad coverage. Side lobes are present at a level of -11.1 dB, considerably lower than the main lobe, implying effective directivity with less power radiated in unwanted directions

The polar plot of a far-field radiation pattern for an antenna at a frequency of 3 GHz, the pattern in Fig. 7 illustrates the gain of the antenna in decibels (dB) over various angles, with separate curves for different azimuthal angles (Φ). The main lobe is shown to have a peak gain of 3.46 dB, indicating that the antenna amplifies the signal in its main direction of radiation at 139.0 degree. The main lobe's beam width is around 289.1 degrees, representing a relatively broad radiation pattern. The side lobe level is at -11.1 dB, which is significantly lower than the main lobe's gain, showing the antenna's directivity and efficiency in the main lobe direction.

VSWR Result and Power

Perfect impedance matching, or a full absorption of incident power by the antenna without any reflections, is indicated by a VSWR value of 1 A higher VSWR additionally results in a higher fraction of reflected power, which might cause signal deterioration and reduced efficiency. One important statistic for antenna tuning and optimization is the VSWR result. A number of characteristics, including antenna size and matching networks, are adjusted by designers, and feed combinations to reach the perfect VSWR value. VSWR results are shown in Fig. 8. The Voltage Standing Wave Ratio of an antenna system across a frequency range of 1 GHz to 4 GHz is shown on the graph in Fig. 8. A value of 1 represents optimal matching of impedance across the communication cable while the antenna and VSWR measures this. There is a noticeable peak on the graph somewhat

below 1.75 GHz, when the VSWR exceeds, signifying a serious impedance mismatch. The VSWR significantly decreases as it gets closer to 2.45 GHz, decreasing than an amount that is closer to 1, indicating a considerably better impedance match at this frequency. In the region where the majority of power is transmitted to or from the antenna with little reflection, the VSWR is rather steady after 2.45 GHz, staying below 2 for the duration of the frequency range. The power characteristics of a microstrip patch antenna operating in the 2.1693 GHz to 2.5106 GHz frequency range are shown in Fig. 9. The graph delineates several power parameters, represented by distinct colored lines: Loss in Dielectrics (Red line), Power Accepted (Green line), Power Outgoing all Ports (Blue line), Power Radiated (Orange line), and Power Stimulated (Pink line). Observing the graph, it's evident that the Power Stimulated remains consistent throughout the frequency spectrum.

Notably, the Power Accepted exhibits a pronounced peak at approximately 2.25 GHz, indicating this frequency as the resonance frequency where the antenna operates optimally. The Power Outgoing all Ports displays a similar trend to Power Accepted but starts to deviate beyond 2.35 GHz. Likewise, the Power Radiated peaks around 2.25 GHz, corresponding to the peak in Power Accepted. Conversely, the Loss in Dielectrics maintains a relatively low level across the entire frequency range. To evaluate the antenna's efficiency (η), the formula $\eta = \frac{P_{radiated}}{P_{accepted}}$ is employed. At the resonance frequency of approximately 2.25 GHz, with the approximate values obtained from the graph $P_{radiated} \approx 0.45$ W and Power Accepted $P_{accepted} \approx 0.50$ W), the efficiency (η) is computed as $\eta = 0.45/0.50 = 0.90$ or 90%. Hence, at the resonance frequency of 2.25 GHz, the antenna exhibits an efficiency of approximately 90%.

Efficiency

Radiation efficiency measures the portion of input power converted into radiation, while total efficiency accounts for all losses in the antenna system, providing a more comprehensive evaluation of performance. Both metrics are critical for designing and optimizing efficient antenna systems for various applications. The graph in Fig. 10, illustrates the radiation efficiency of an antenna in dB over a frequency range of 2.0 to 3.0 GHz. Radiation efficiency quantifies the percentage of power

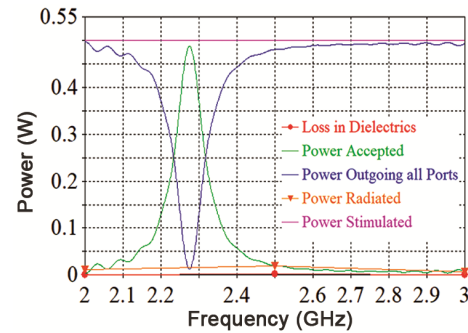


Fig. 9 — Power analysis for RMPA

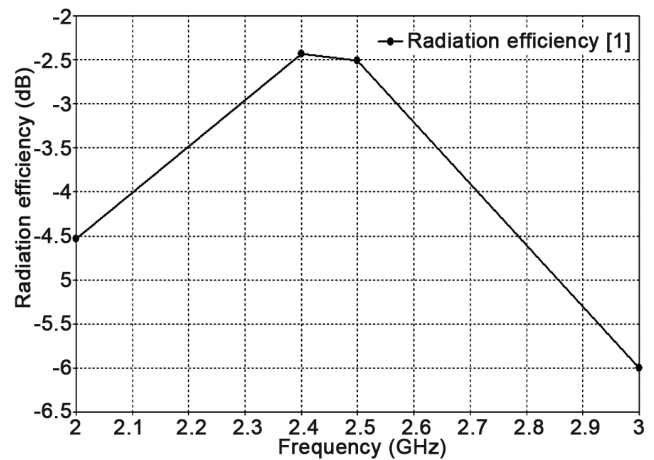


Fig. 10 — Radiation efficiency vs. frequency for a 2.45 GHz microstrip patch antenna

provided to the antenna that is actually radiated as opposed to being lost as heat or absorbed by the antenna structure. The plot shows the efficiency peaking at around 2.45 GHz, the center frequency for many wireless communication systems like Wi-Fi, suggesting the antenna is most effective at converting input power to radiated energy at this frequency. The efficiency drops off on either side of this peak, which is common as antennas are usually optimized for a specific frequency or band.

Radiation efficiency and total efficiency are critical parameters in the performance analysis of microstrip patch antennas. Radiation efficiency (η_r) measures how effectively an antenna converts input power into radiated power, defined as the ratio of radiated power (P_{rad}) to total input power (P_{input}). It is observed that the radiation efficiency is approximately -4.5 dB at 2.1 GHz, peaks at -2.5 dB around 2.5 GHz, and decreases to about -6.0 dB at 3 GHz, indicating optimal radiation at 2.5 GHz. Total efficiency (η_t), which includes radiation efficiency and losses due to impedance mismatch, is defined as $\eta_t = \eta_r \cdot (1 - |\Gamma|^2)$,

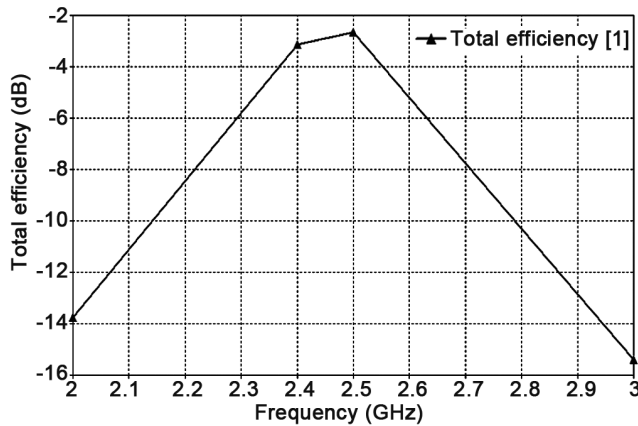


Fig. 11 — Total efficiency vs. frequency for a microstrip patch antenna

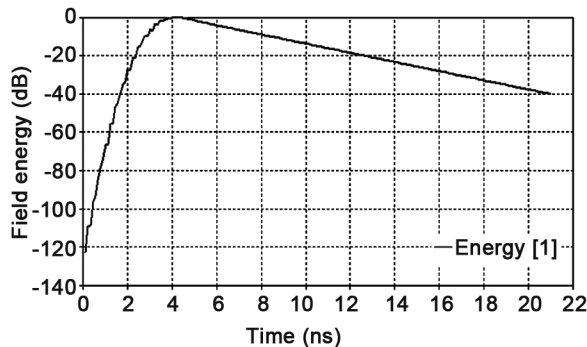


Fig. 12 — Transient field energy decay over time for an antenna system

where Γ is the reflection coefficient. It can be seen from Fig. 11 that total efficiency is about -16 dB at 2.1 GHz, peaks at -2 dB around 2.5 GHz, and drops to -15 dB at 3 GHz, highlighting significant losses and poorer impedance matching away from 2.5 GHz. These figures illustrate that the antenna performs optimally at 2.5 GHz, where both efficiencies are highest, indicating minimal losses and impedance mismatch. At frequencies away from this peak, the efficiencies decline, showing increased losses and impedance mismatch. Understanding these efficiencies is essential for designing and tuning antennas to achieve optimal performance at desired frequencies. An important factor to keep in mind when applying this antenna in systems like RF energy harvesting, where maximal energy transfer is necessary, is that its performance is highly wavelength-dependent. As the frequency goes farther from this point, its effectiveness drops rapidly.

Field Energy

The field energy graph is used to improve antenna designs, measure radiation properties, and assess

antenna performance and identify any possible problems, such as mismatched impedance, reflections, or unwanted coupling with adjacent structures. When conducting an antenna analysis, the field energy graph offers a clear visual depiction of the RF energy distribution surrounding the antenna. The visual aid can be used to gain important insights into radiation patterns, near-field behavior, polarization characteristics, frequency response, efficiency, and the overall performance of the antenna. Field energy decline with time is shown in Fig. 12 as a graph with energy in dB and time in nanoseconds (ns). It exhibits a sharp reduction in field energy in the first nanosecond, which is followed by a steadier decline over time. The study of an antenna's reaction to a pulse, which can be connected to the antenna's bandwidth and capacity for handling signals of various sounds, or the examination of rapid replies, like those seen in time-domain reflectometry, are common applications for this type of plot. A speedy release of the stored energy is indicated by the fast-early decay, but slower energy dissipation mechanisms inside the system may be indicated by the longer tail.

When using the transmission line model in CST STUDIO SUITE for designing the antenna, specific challenges encountered included accurately modeling the complex interactions between the antenna's physical geometry and the electromagnetic fields, which can lead to discrepancies between simulated and real-world performance. Ensuring precise impedance matching and minimizing parasitic effects such as unwanted resonances or surface waves were also challenging, as the transmission line model can sometimes oversimplify the antenna's behavior, necessitating iterative adjustments and validation with more comprehensive 3D simulations. Additionally, computational limitations and convergence issues may arise, particularly when dealing with intricate antenna structures or wide frequency ranges.

Conclusions

The notch-equipped Rectangular Microstrip Patch (RMP) antenna was developed for Wi-Fi applications in the 2.400–2.483 GHz band, focusing on improving performance and bandwidth. The insect-fed patch antenna aimed for ideal impedance matching with a 50Ω transmission line, with return loss (S_{11}) below -16 dB at 2.275 GHz, indicating good impedance. Far-field radiation analysis showed main lobe gain at 11.1 dB, while the VSWR matched well

at 2.45 GHz. Despite efficient design, limitations included reliance on specific substrates, a narrow bandwidth, and a focus solely on Wi-Fi. This antenna has potential applications beyond Wi-Fi, such as in biomedical implants or automotive systems, but these uses require further testing. Future iterations could employ technologies like AI, metamaterials, or beamforming to enhance versatility and effectiveness across broader applications, thereby addressing the current scope and performance limitations.

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