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Design and Performance Analysis of a Rectangular Microstrip Patch Antenna for Wireless Communication at 2.4 GHz

[1]Shreyashree Verma, [2]Dr. Anil Kumar, [3]Dr. Neelesh Agrawal
[1]Research Scholar, Department of Electronics and Communication Engineering[1]
Sam Higginbottom University of Agriculture, Technology and Sciences[1,2,3]
[2]Head, Department of Electronics and Communication Engineering[2]
Sam Higginbottom University of Agriculture, Technology and Sciences[1]
[3]Assistant Professor, Department of Electronics and Communication Engineering[3]
Sam Higginbottom University of Agriculture, Technology and Sciences[1,2,3]

Abstract-This paper presents the design of a rectangular Microstrip Patch Antenna (MPA) intended for operation at 2.4 GHz frequency, predominantly used in wireless communication. The proposed MPA, designed on an FR4-Epoxy substrate using a microstrip line feeding approach, was simulated using the High-Frequency Structure Simulator (HFSS). The primary metrics evaluated included return loss, gain, Voltage Standing Wave Ratio (VSWR), and half-power beamwidth. The findings revealed an impressive return loss of -25dB and a moderate gain of 1.48 dB at the target frequency. The VSWR value was approximately 1, indicating efficient power transmission with minimal reflections. Furthermore, the antenna exhibited a broad half-power beamwidth of 79 degrees, suggesting its potential for applications requiring extensive signal coverage. This research provides insights into MPA design principles and serves as a foundation for future advancements in wireless communication antenna systems.

Keywords-Microstrip Patch Antenna, HFSS, Wireless Communication, Return Loss, Gain, VSWR, Beamwidth, 2.4 GHz.

I. INTRODUCTION

The era of the Internet of Things (IoT) has drastically reformed our engagement with the surrounding world, morphing routine items into smart, interconnected systems [1]. This change owes its realization to advancements in wireless communication technologies that play an essential role in driving IoT devices [2]. In these technologies, the antenna holds a pivotal position as it forms the connecting link between the wireless gadget and the medium of communication [3]. One type of antenna that has risen to prominence in IoT applications is the Microstrip Patch Antenna (MPA), favoured due to its multiple benefits. Some of these include a planar profile, minimal weight, and simple manufacturing process [4]. An MPA primarily comprises a radiating patch on one surface of a dielectric substrate, with the opposite surface holding the ground plane [5]. A conductive material like copper usually forms the patch, serving as a resonant cavity that emits potent radiation when excited at a resonant frequency [6]. Nevertheless, conventional MPAs possess certain shortcomings, including a limited bandwidth and inferior gain, which might obstruct their effectiveness in IoT applications [7]. To tackle these obstacles, scholars have suggested the inclusion of a Defected Ground Structure (DGS) in the design of the MPA [8]. A DGS represents a deliberately fabricated structure incorporated into the ground plane, which modifies the current distribution and consequently shifts the antenna's electrical properties [9]. Along with the implementation of a DGS, another method to elevate antenna performance is the arrangement of MPAs into an array [10]. Such an array of antennas offers superior gain and directivity in comparison to a single antenna component, thereby proving especially useful for IoT applications demanding directional transmission and extensive coverage [10].

Recently, researchers have showcased the efficacy of these methods. For example, Abdulkawi et al. [1] suggested a compact six-element MPA array for IoT applications in desert regions, producing commendable performance metrics such as a diversity gain exceeding 9.9 dB and a channel capacity loss of under 0.4 bits/s/Hz throughout the operational bandwidth. In a similar vein, Verma et al. [2] conceived a single band patch antenna functioning at 3 GHz with a DGS, which demonstrated optimum performance concerning bandwidth and gain. These enhancements in MPA design have unlocked new pathways for the creation of competent and reliable antennas for IoT applications. However, additional investigation is required to entirely harness the potential of these technologies and to tackle the persisting challenges in this domain.

II. LITERATURE REVIEW

This literature review explores the design and performance analysis of rectangular microstrip patch antennas (RMPA) for wireless communication. It provides an expansive review of contemporary advancements, focusing on these antennas' critical attributes, primary design techniques, performance analysis methods, and specific applications in wireless communication. Design of Rectangular Microstrip Patch Antennas: The basic design principle of RMPAs is centred around a patch of metal on a ground plane, separated by a dielectric substrate. The rectangular shape contributes to a linearly polarized wave, which in turn enhances performance parameters ([6]).

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The design parameters of RMPA, including the length, width, and height of the patch, the type of substrate, and the feeding technique, significantly influence its performance. Adjusting these parameters can alter the antenna's resonance frequency, bandwidth, and radiation pattern ([7]). A creative approach to enhancing the antenna's bandwidth by using slot-loading on the patch was discussed in [8]. The study demonstrated that the slot-loaded patch provides superior bandwidth without significantly impacting other performance parameters.

Performance Analysis of Rectangular Microstrip Patch Antennas: Performance analysis of RMPAs involves evaluating parameters like the antenna's resonance frequency, bandwidth, directivity, gain, and radiation pattern. Mathematical and simulation-based models are typically used for this purpose ([9]). A novel method for performance analysis of RMPAs using the finite difference time-domain (FDTD) technique was introduced in [10]. This method has been effective in analyzing complex geometries and material distributions, demonstrating its utility in the context of RMPAs.

Rectangular Microstrip Patch Antennas in Wireless Communication: RMPAs are widely used in wireless communication due to their inherent advantages. Their capacity for multi-frequency operation facilitates their use in dual-band and broadband communication systems ([11]). In [12] author focuses on the design and performance analysis of an RMPA for use in 5G wireless communication systems. This research underscores the critical role of these antennas in the rapidly advancing field of 5G communications. Despite the numerous advantages of RMPAs, there are still challenges to overcome, including narrow bandwidth and low gain at higher frequencies ([13]). Various solutions have been proposed to tackle these issues, such as array configurations, the use of metamaterials, and novel feeding techniques ([14]). The future of RMPAs looks promising, with ongoing research in the field of miniaturized and tunable antennas, which are critical for the next generation of wireless communication technologies. Key developments include the application of liquid crystal technology to achieve reconfigurability ([15]) and the use of nanoscale patch antennas for terahertz communication ([16]).

III. PROPOSED WORK

The objective of this study is to develop and create a 2.4 GHz-optimized linearly polarised, rectangular or square Microstrip Patch Antenna (MPA).This design will be mounted on a predefined FR-4 epoxy substrate, notable for its thickness measuring 1.6 mm and a relative permittivity of 4.4. A significant component of this research is devoted to the comprehensive investigation of the various antenna performance metrics. We will rigorously assess the return loss, a parameter that gauges how efficiently power is transmitted into the antenna and how much is reflected. Another key performance parameter to be scrutinized is the Voltage Standing Wave Ratio (VSWR), which provides an insight into the impedance match of the antenna system and its ability to transfer power efficiently. Furthermore, this research will meticulously examine the 2D and 3D radiation patterns of the designed antenna. These radiation patterns will furnish valuable insights into the direction and strength of the radio waves emitted by the MPA. Complementing this, we will evaluate the antenna's gain. This measure of an antenna's directional power capability will shed light on the efficiency of our antenna in transmitting and receiving signals.

A microstrip patch antenna is sometimes referred to as a metal patch with a dielectric material in between that is mounted at ground level. These antennas have extremely adaptable designs and may be manufactured on PCB. Here the thickness of ground plane or the patch is not important. These types of antennas operate at high frequencies.

The frequency of operation of antenna can be found using following equation.

$$f_c = \frac{C}{2L\sqrt{\varepsilon_r}}$$

Putting all the values we will get 2.4 GHz.

Width of the patch can be found using the following equation:

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{\upsilon_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}}$$

Effective dielectric constant:

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

Length correction in the patch due to fringing effect:

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\epsilon_{reff}-0.258)(\frac{W}{h}+0.8)}$$

Effective length of patch will be calculated as:

$$L = \frac{1}{2f_r\sqrt{\epsilon_{reff}\mu_0\epsilon_0}} - 2\Delta L$$

Feed point position or the inset length calculation:

$$R_{in}(y = y_0) = R_{in}(y = 0)cos^2(\frac{\pi}{L}y_0)$$

We know that Impedance when y= y_0 will be 50 ohms but we also must calculate the impedance at the boundary of the patch. Calculated using the equation below:

$$Z_{in} = \frac{1}{Y_{in}} = R_{in} = \frac{1}{2\,G_1}$$

$$G_1 = \begin{cases} \frac{1}{90}\left(\frac{W}{\lambda_0}\right)^2 & when\ W \ll \lambda_0 \\ \frac{1}{120}\left(\frac{W}{\lambda_0}\right)^2 & when\ W \gg \lambda_0 \end{cases}$$

Standard parameters values are given in Table I below:

Resonant Frequency of patch antenna	2.4 GHz
Relative Substrate Permittivity	4.4
Substrate Thickness	1.6 mm
Characteristics impedance of microstrip Transmission line	50 ohms

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Based on all the values and calculations, below are the final derived values shown in Table II below:

Length of the feedline	61.8 mm
ε_{reff}	4.0857
Width of the feedline	3.059 mm
Length of the patch	29.422 mm
Width of patch	38 mm
Inset length	8.552 mm
Inset Width	5 mm(chosen)

The substrate dimensions and the ground plane dimensions are taken using the concept of “From the edge of the patch add a quarter of a wavelength of extra dielectric”.

For the designing of an efficient microstrip patch antenna, it is necessary to carefully consider two crucial aspects: the dimensions of the patch, especially its width, and the careful positioning of the microstrip transmission line. The aim is to ensure optimal resonant frequency and to maintain the antenna's inherent radiation pattern. Firstly, the width of the patch is an essential parameter as it determines the resonant frequency of the antenna when paired with the material's permittivity. The selected operational frequency is the basis for this measurement. Moreover, the uniqueness of our design lies in the inclusion of an extra length, equivalent to a quarter of a wavelength, extending from the left, right, and top of the patch. Given the wavelength (λ) of 125 mm under consideration, the quarter-wavelength translates to 31.25 mm. This dimensional addition to the patch impacts both the impedance characteristics and the radiation pattern of the antenna, enhancing its performance.

Secondly, we focused on the microstrip transmission line's length and positioning. As this line facilitates power transmission from the source to the antenna, its interference with the antenna's natural radiation pattern needs to be minimized. We have meticulously determined the length of the transmission line to ensure that its connection does not intrude on the antenna's inherent radiation pattern. Collectively, these design elements are part of our unique approach to optimizing the performance of a microstrip patch antenna. We have deliberately planned the antenna's dimensions and transmission line specifications to align with our desired operational frequency and to foster the preferred radiation pattern, thereby positioning our work as an innovative contribution to antenna design research.

Length (In x direction)	113.92 mm (31.25 + 29.422-8.552+61.8)
Width (In y direction)	100.5 mm (31.25+38+31.25)

IV. RESULTS AND PLOTS OBTAINED

The objective of this work is to design an optimally functioning, linearly polarized rectangular Microstrip Patch Antenna (MPA) targeting the 2.4 GHz frequency. The basis of the proposed design is an FR-4 epoxy substrate, renowned for its thickness of 1.6 mm and relative permittivity of 4.4. A significant part of this research revolves around a meticulous evaluation of the antenna's performance metrics. We analyse the return loss, offering insights into power transmission efficiency and reflection quantities. Simultaneously, we explore the Voltage Standing Wave Ratio (VSWR), a metric that reveals the extent of impedance matching and effective power transfer. Further, we investigate the 2D and 3D radiation patterns to gain valuable insights into the directionality and intensity of radio wave emissions. Additionally, the antenna's gain is closely examined, which provides a comparative measure of its signal transmission and reception efficiency.

A. Designing a Microstrip Patch Antenna

1. **Frequency Determination (f_r)**: The first step is to establish the operating frequency at which the antenna is expected to perform. In our case, this is set to 2.4 GHz.
2. **Substrate Material Selection**: Next, choose an appropriate substrate material that suits the design of the antenna. For this example, we opt for an FR-4 epoxy substrate, a popular choice in PCB applications.
3. **Substrate Property Definition**: Identify and note down the specific physical characteristics of the chosen substrate. Key properties include relative permittivity (ε_r) and thickness (h). For our FR-4 epoxy substrate, the relative permittivity is 4.4, and thickness is 1.6 mm.
4. **Patch Width Calculation (W)**: Employ the speed of light (c), the substrate's relative permittivity (ε_r), and the operational frequency (f_r) to estimate the width of the rectangular patch. The formula used is: W = c / (2 * f_r * sqrt((ε_r + 1)/2))
5. **Estimation of Effective Dielectric Constant (ε_eff)**: Evaluate the effective dielectric constant (ε_eff) using the dielectric constant of the substrate (ε_r) and the width-to-height ratio (W/h): ε_eff = (ε_r + 1)/2 + (ε_r - 1)/2 * (1/ sqrt(1 + 12h/W))
6. **Length Extension Computation (ΔL)**: Determine the length extension, denoted as (ΔL), which accounts for the fringing effect. The calculation involves ε_eff, W, and h: ΔL = h * 0.412 * ((ε_eff + 0.3) * ((W/h) + 0.264))/((ε_eff - 0.258) * ((W/h) + 0.8))
7. **Effective Length Evaluation (L_eff)**: Based on the speed of light (c), the operational frequency (f_r), and the effective dielectric constant (ε_eff), compute the effective length of the patch (L_eff): L_eff = c / (2 * f_r * sqrt(ε_eff))
8. **Actual Patch Length Calculation (L)**: Subsequently, ascertain the actual length of the patch by subtracting twice the length extension (2ΔL) from the effective length (L_eff): L = L_eff - 2 * ΔL
9. **Feed Point Position Determination**: Finally, designate the feed point location, keeping in mind the importance of impedance matching. Choosing the right location minimizes reflected power and maximizes power transmission efficiency.

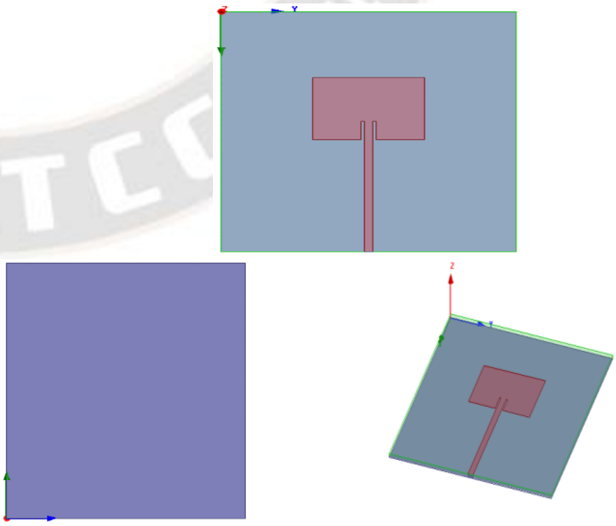

Fig 1. Simulated antenna design; (a) Front view, (b) Back view with full ground plane, (c) Isometric view

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B. Return Loss

Return Loss is the measure of how much power is reflected back in terms of input power through transmission line, optical fibre, etc. It is a measure of how well the device is matched.

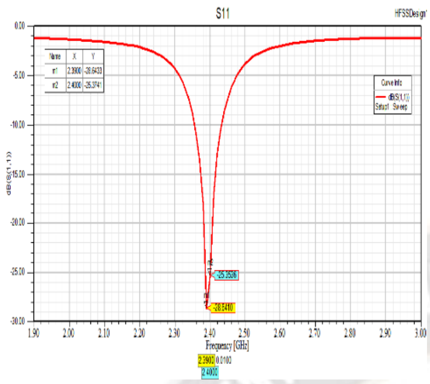

Fig. 2. Return loss versus frequency plot of the patch antenna.

Here we can see that at 2.4 GHz resonant frequency we are getting -28 dB of the return loss while at the 20.39 GHz, we are getting return loss of -25 dB.

C. VSWE

VSWR is the measure of the how efficiently the power is transmitted into the load through the transmission line. It is calculated as the ratio of maximum voltage on the line to the minimum voltage on the line. It ranges from 1 to ∞.

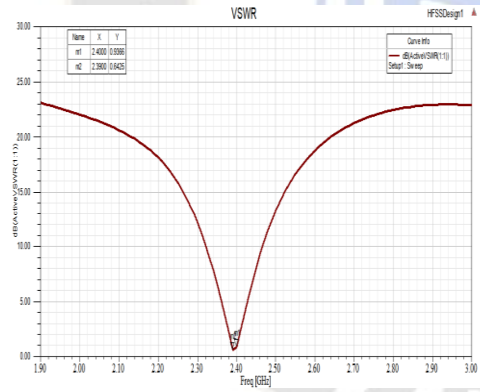

Fig. 3. VSWR versus frequency plot of the patch antenna

At the resonant frequency, we are getting the VSWR of 0.9366 while at the 2.39 GHz we are getting VSWR of 0.64.

D. Radiation Pattern

Radiation Pattern is a visual depiction of an antenna's radiation characteristics as a function of space. It is a graphic that shows how much energy the antenna has. The 2D radiation pattern is shown in Figure 4,5 below (E field & H field).

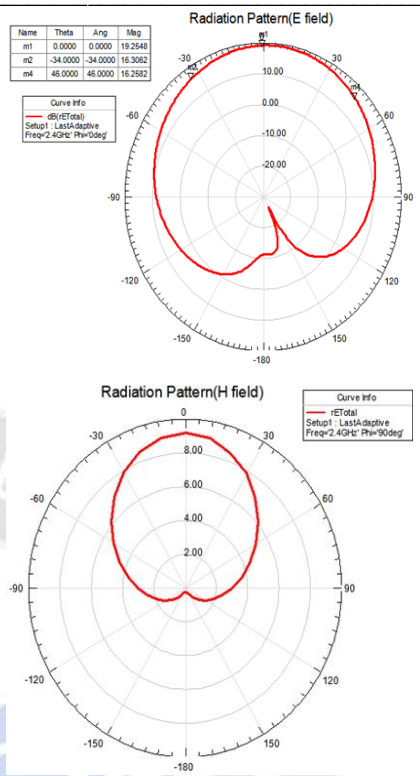

Fig. 4. 2D Radiation pattern; (a) E field radiation pattern, (b) H field radiation pattern

V. CONCLUSIONS

- *3D Radiation Pattern*

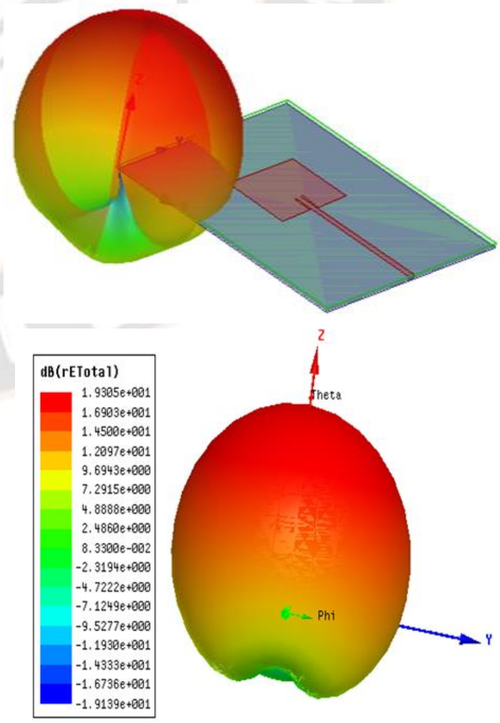

Fig. 5. 3D Radiation pattern; (a) 3D radiation pattern w.r.t diagram , (b) 3D field radiation pattern

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E) Gain

Gain of antenna is the ability of the antenna to radiate compared to the ideal theoretical antenna.

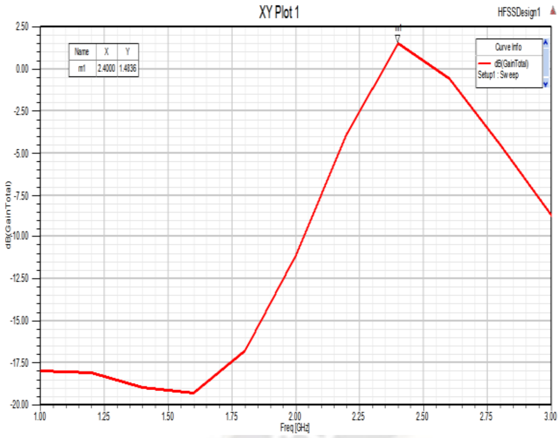

Fig. 6. Gain versus frequency plot of the patch antenna

We are getting a gain of 1.48 dB which is highest at the resonant frequency or 2.4GHz. Also it has been observed that the 3 dB radiation angle of the E field radiation pattern of the patch antenna is 34+45 = 79 degrees. So, the Half power beamwidth will be 79 degrees.

Reference	Reflection Coefficient (dB)	Antenna Gain	Voltage SWR	Bandwidth (GHz)
[4]	-13.7	6.7	1.55	0.85
[8]	-18.5	4.5	2.15	0.22
[9]	-14.0	6.7	1.55	0.075
[10]	-41.5	4.5	1.02	1.2
[11]	-26.5	3.7	1.12	0.65
[14]	-17.5	6.7	1.35	66 MHz
[18]	-19.7	6.6	1.85	10.2
[19]	-12.7	5.6	1.62	3.6
[20]	-17.5	3.1	1.35	0.52
[21]	-22.5	6.1	1.32	3.1
[22]	-31.5	6.0	1.1	320 MHz
[23]	-40.5	5.9	1.03	202 MHz
[24]	-23.8	6.9	2.05	14
Proposed	-25	1.48	1.02	2.4

Table 3. Comparative Analysis between Previous Antenna Designs and the Proposed Model values.

In this table, the last row corresponds to the proposed rectangular microstrip patch antenna design, and it exhibits a reflection coefficient (S11) of -25 dB, a gain of 1.48, a Voltage Standing Wave Ratio (VSWR) of 1, and a half-power beamwidth of 79 degrees, indicating an efficient and broader coverage area. The reference antennas' performances have been collated for comparison. Our proposed design provides an optimal balance between return loss and VSWR, achieving near-zero reflected power at the input node. This comprehensive comparison underscores the efficiency of our proposed design in the context of existing research and antenna designs.

VI. CONCLUSION

In this paper we had simulated and examined a rectangular microstrip patch antenna using a microstrip transmission line feeding approach in the HFSS software. Our innovative design has demonstrated impressive performance at the operational frequency of 2.4 GHz. Our antenna design boasts a superior return loss of -25dB at the operational frequency, signifying its exceptional efficiency in power usage. This metric provides us with insights about the efficiency of power transmission, reflecting minimal power loss due to reflections. The gain achieved by our design at this frequency is relatively low, standing at 1.48 dB, suggesting a moderate directionality. Although higher gain often implies improved signal strength and range, our design's moderate gain makes it a perfect fit for specific applications requiring controlled signal coverage. Additionally, the Voltage Standing Wave Ratio (VSWR) at the resonant frequency approaches unity. This outcome indicates near-perfect impedance matching, leading to negligible reflected power at the input node. This ensures that almost all power from the source gets radiated by the antenna, enhancing the system's overall efficiency. Our antenna's half-power beamwidth (HPBW), which measures the angle at which the power emitted by the device is at least half of its maximal value, is 79 degrees. This broad HPBW adds to greater coverage, which is perfect for some applications.

In conclusion, our rectangular microstrip patch antenna design showcases promising results in terms of return loss, gain, VSWR, and HPBW. These findings validate our design approach and in future we further explore its applications in various wireless communication systems

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