WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Design and Simulation of a Rectangular Microstrip Patch Antenna using FR4 Substrate for Satellite Communication and IoT Device Applications

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A B S T R A C T

In this study, the design and simulation of an innovative single element inset fed Rectangular Microstrip Patch (RMPA) Antenna for Satellite communications, GPS systems and IoT devices is presented. The proposed antenna design used an operating frequency of 2.3 GHz, a FR-4 substrate with dielectric constant of 4.40 mm, and a substrate height of 1.6 mm. All the performance parameters such as return loss, bandwidth, VSWR, gain, directivity, beam width and radiation efficiency were analysed and investigated using Computer Simulation Technology (CST) studio suit v. 24. The simulation results revealed that the designed antenna resonated at 2.3 GHz, with a return loss of -21.296 dBi, narrow bandwidth of 39.1 MHz, VSWR of 1.188, maximum gain of 6.58 dBi, minimum gain of -23.4 dBi, directivity of 7.86 dBi, and a beam width of 88.1o. The antenna achieved 83.7% efficiency. The significant difference between the maximum and minimum gains of the novel designed RMPA indicates a highly directional antenna which makes it useful in applications where energy is needed to be concentrated in one direction like Satellite communication and IoT while minimizing energy in others to avoid interference or wasted power.

Keywords: IoT, Microstrip patch, Substrate, CST, Gain, VSWR.

1.0 Introduction

The wireless communication system is an imperative component of Internet of Things (IoT) framework, serving as a bridge for bidirectional connection for data gathering and control message conveyance for effective data application hence, wireless techniques has short range of IoT band and consume a lot of power [1]. Microstrip patch antennas have become extremely useful because they can be directly printed on the circuit board, which in turn makes the machine compact in size and weight. They can be easily fabricated and hence have wide range of applications in mobile communication, satellite communication, and even in GPS as they offer ease in tracking vehicles and devices. Wireless communication services have been increasing at a very fast rate in current years [2], and the need for compact and multifunctional wireless communication systems has spurred the development of antennas with small size [3]. With the increasing number of wireless users and limited available bandwidth, wireless service providers are always trying hard to optimize their network for larger capacity and improved quality coverage, as to satisfy the mobility need of users [4]. This surge has led the field of antenna engineering to constantly evolve, and accommodate the users need for wideband, low-cost, miniaturized and easily integrated antennas. Amongst the various types of antennas that include wire antennas and reflector antennas, microstrip patch antennas are the most popular, versatile, and easy to fabricate antennas (Hala, 2010). In this study, a RMPA using FR-4 as substrate is designed, simulated and investigated with CST studio suit 2024 at 2.3 GHz operating frequency with 1.6 mm substrate thickness.

2.0 Review of Related Works

Quite a lot of researchers have reported on design and simulation of microstrip patch antenna. These research works employed diverse design procedures, topologies and electromagnetic simulators to achieve better antenna performance.

Maneesh Rajput (2014) proposes the design of a hexagonal patch antenna for L(1.8 GHz)-band applications. The material used is Glass Epoxy (dielectric constant 4.2 and loss tangent 0.0012). The width and length of the patch was selected as 64mm and 52mm respectively. The return loss was shown as -22 dB and – 27 dB for simulation (IE3D software) and hardware respectively [5].

Sumanpreet Kaur Sidhu (2015) reported the designed microstrip patch antennas with six different shapes. Antennas were designed with Rogers RT/Duroid 5880 material and simulated using HFSS software. Of these, circular patch (Radius 30mm) and Hexagonal patch (side: 35 mm) have return loss of -16.50 dB and -22 dB respectively for Bandwidth around 1 GHz [6].

Sonali Somvanshi (2017) reported the designed a Rounded Bow tie antenna with flexible polyimide substrate having 4.3 dielectric constant at 2.5 GHz and simulated using HFSS software. The length and width of the patch are 86mm and 28.2mm respectively. The return loss and VSWR were shown as -24.82 dB and 1.25 respectively [7].

3.0 Methodology

This paper intends to design and simulate a single rectangular microstrip patch antenna for Satellite communications and IoT devices. To realize this, the choice of simulating software, design specifications and parameter (dimension) calculations to achieve a light weighted RMPA is considered as follows:

(a) Choice of Antenna Simulation Software

In this study, the CST studio suit 2024 software is preferred for design and simulation, as it is based on the Finite Element Method (FEM) techniques. CST is Ideal for wideband antenna designs and fast transient analysis, such as impulse response and broadband scattering. It also combines multiple solvers to handle complex antenna systems, like an array inside an enclosure.

(b) Design Procedure

The following stages were involved in the process to realize the design and simulation of RMPA:

(i) Specifying the frequency of operation (f_r) (ii) Select a suitable dielectric substrate (iii) Select on the substrate height (h) (iv) Calculate the appropriate patch dimensions (v) Select a feeding method

Table 1. Design specifications of RMPA

Parameter	f_r	ε_r	Substrate	$h\ (mm)$	Feeding technique
Specification	2.3 GHz	4.4	FR-4	1.6	Inset-fed

(c) Design Specification

Step 1: Calculation of the Patch width (W)

The width (W) of the microstrip patch is calculated based on the transmission line model equation given as [8],

$$W = \frac{c}{2f_r\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{1}$$

Substituting: $f_r = 2.30 \times 10^9\ Hz, c = 3 \times 10^8\ ms^{-1},\ h = 1.6\ mm\ \ and\ \varepsilon_r = 4.4.$

$$\therefore W \approx 41\ mm$$

Step 2. Design of effective dielectric constant, ϵ_{eff}

The effective dielectric constant $\boldsymbol{\epsilon_{eff}}$ introduced to account for the fringing and the wave propagation in the line. It is obtained as [9],

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-0.5} \tag{2}$$

Substituting $h = 1.6\ mm\ \ and\ \varepsilon_r = 4.4, W = 41\ mm$

$$\epsilon_{eff} \approx 4.07\ mm$$

Step 3. Calculation of Effective length (L_{eff})

The effective length of the patch is calculated from [10] as:

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \tag{3}$$

$$L_{eff} = 36.85\ mm$$

Step 4. Calculation of Length extension (Δl)

The patch length extension is obtained from [10] as:

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

$$\Delta l\ = 1.39\ mm$$

Step 5. Estimation of Actual length (L)

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

$$L \approx 34.00\ mm$$

Step 6. Design of Ground plane dimensions

The length of the ground (Lg) and width of ground plane Wg were computed as follows:

$$L_g = 6h + l \tag{6}$$

$$W_g = 6h + w \tag{7}$$

$L_g \approx 43.7\ mm,\ W_g \approx 50.5\ mm$

Step 7(a). Design of Feed length (L_f)

The feed lengt**h** is the section of the microstrip transmission line extending from the coaxial connector (or waveguide) to the inset feed point on the patch. The length should be optimized to minimize impedance mismatch and losses [12]. It is determined as follows:

$$\lambda_g = \frac{c}{f_r\sqrt{\varepsilon_{eff}}} \tag{8}$$

$$\lambda_g \approx 72.2\ mm$$

A standard feedline is given by

$$L_f = \frac{\lambda_g}{4} \approx 18\ mm$$

Step 7(b). Design of Feedline width (W_f)

The feedline width for a 50 Ω impedance is given by [12],

$$W_f = \frac{c}{2f_r\sqrt{\varepsilon_r + 1}} \tag{9}$$

$$W_f \approx 3\ mm$$

Step7(c). Design of inset fed depth (y_0)

An inset-fed microstrip line feed **is** employed in this design, with the feed depth denoted as y_0**.** The feed point must be positioned at a location on the patch where the input impedance (Z_0) is 50 Ω at the resonant frequency. The resonant input edge resistance (Zi) of the rectangular patch is determined using an online microstrip patch antenna calculator [12]**,** yielding Zi = 197 **Ω**. Consequently, the inset feed depth (y_0) is calculated following the method outlined by [9] **[12]**as:

$$y_0 = \frac{L}{\pi} cos^{-1}\sqrt{Z_0/Z_{in}} \tag{10}$$

Substituting the value of $L = 34\ mm$, $Z_{in} = 197\ \Omega$ and $Z_0 = 50\ \Omega$. Therefore, $y_0 \approx 11\ mm$

Step 7(d). Design of inset feed gap Gp

The feed gap in millimeters is computed according to an equation given in [9] as:

$$Gp = \frac{4.65 \times 10^{-18} \times c \times f_r}{\sqrt{2\varepsilon_{ref}}} \tag{11}$$

$$Gp = 1.12\ mm$$

The geometry of the proposed **i**nset-fed RMPA**,** based on the calculated design parameters, is illustrated in **Fig. 1.**

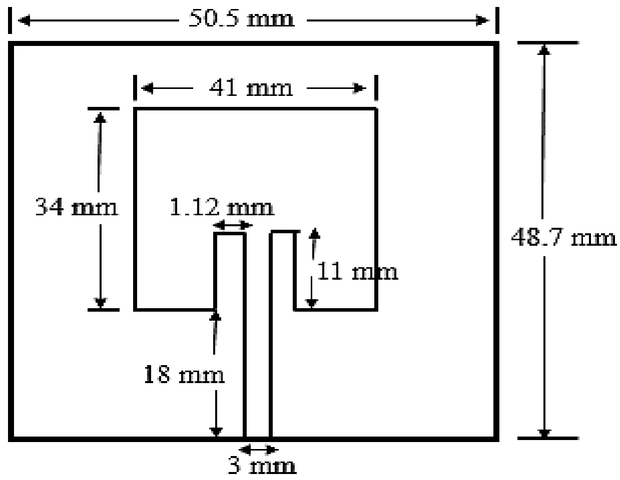

Fig. 1. Design of Microstrip patch Antenna (Theoretical)

Table 2. Dimensions of design parameters

Parameters	Values
(a) Patch dimensions	
Patch with (W)	41.00
Patch length (L)	34.00
Substrate height (h)	1.60
(b) Ground plane dimensions	
Ground plane length (L_g)	43.70
Ground plane width (W_g)	50.50
(c) Dimensions of feedline	
Feed line length (L_f)	18.00
Feed line width (W_f)	3.00
Inset depth (y_0)	11.00
Inset feedgap (Gp)	1.12

The proposed RMPA operating at 2.3 GHz following the design procedure mentioned above is shown in Fig.2. The major simulation results (i.e. return loss, gain, directivity, bandwidth, radiation patterns) of the designed RMPA are given in this section.

4.0 Results and Discussion

The proposed RMPA operating at 2.3 GHz following the design procedure mentioned above is shown in Fig.2. The major simulation results (i.e. return loss, gain, directivity, bandwidth, radiation patterns) of the designed RMPA are given in this section.

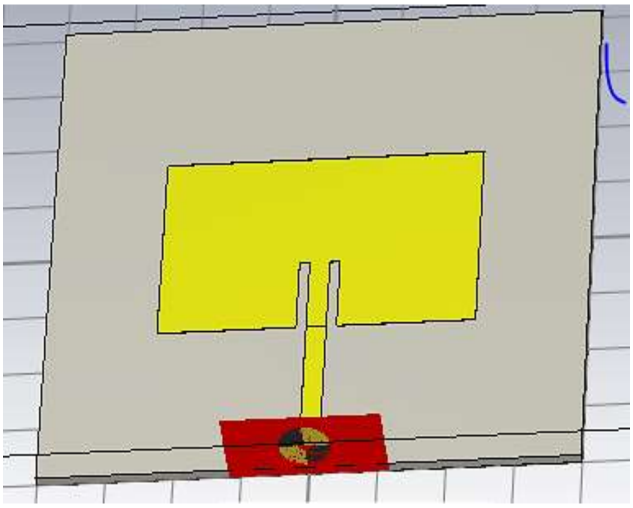

Fig. 2. The proposed RMPA modelled in CST.

The summary of the simulation results is presented as follows:

(i) Return loss (S11) and Bandwidth

The simulation results confirm the accuracy of the parameter. The base value of -10 dB is ideal for mobile and wireless applications. The antenna is properly tuned to the desired frequency for optimal performance. Figure 3 illustrates various S-parameter values, with the best recorded value being -21.296 dB. As shown in Figure 4, the antenna operates at 2.30 GHz, where the return loss is measured at -21.296 dB. The value obtained **(**-21.296 dB) implies that, only about **0.75%** of the power is reflected, while **99.25%** is transmitted into the antenna for radiation. This value is considered excellent, as it surpasses the -10 dB threshold for a well-designed microstrip patch antenna, ensuring minimal power reflection from the antenna to the source input port.

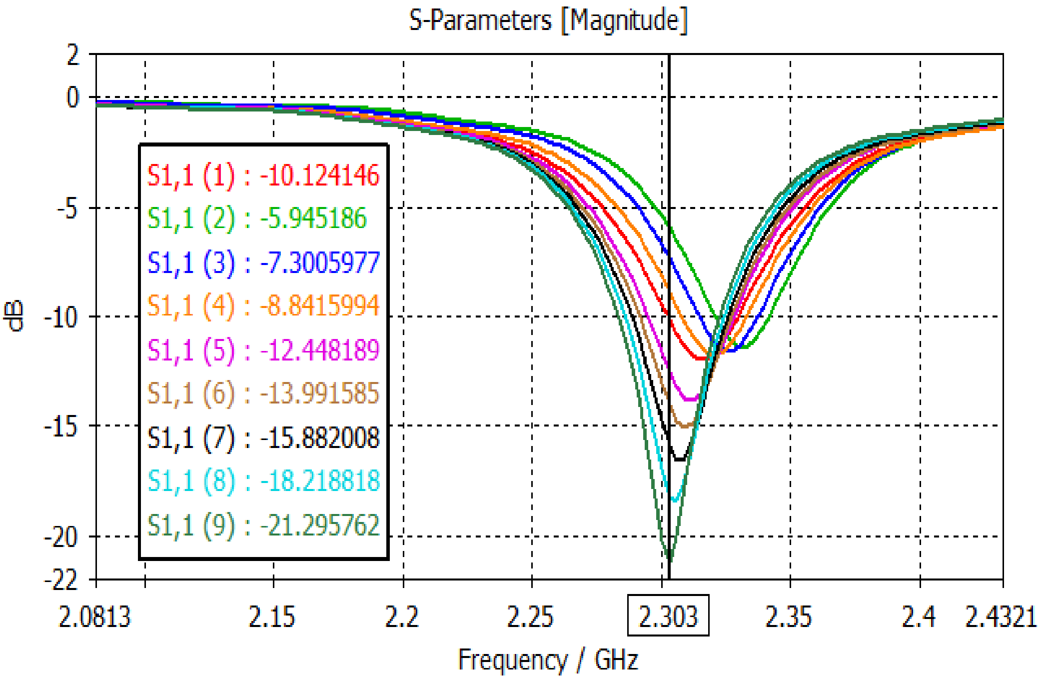

Fig. 3. Graph of Return loss of gap inset feed against frequency

In Figure 4, the return loss (dB) versus frequency plot shows that the proposed microstrip patch antenna achieves a return loss of -21.296 dB at its resonant frequency of 2.303 GHz. The bandwidth of an antenna refers to the frequency range over which it can effectively transmit and receive energy. The antenna's bandwidth was determined by measuring the separation between two points at -10 dB, located at 2.2836 GHz and 2.3227 GHz, respectively. As illustrated in Figure 4, the resulting bandwidth is 0.0391 GHz. This relatively narrow bandwidth is characteristic of microstrip antennas, particularly when employing a high-dielectric-constant material like FR4. Despite its limited bandwidth, the antenna remains suitable for specific communication applications where frequency stability is essential.

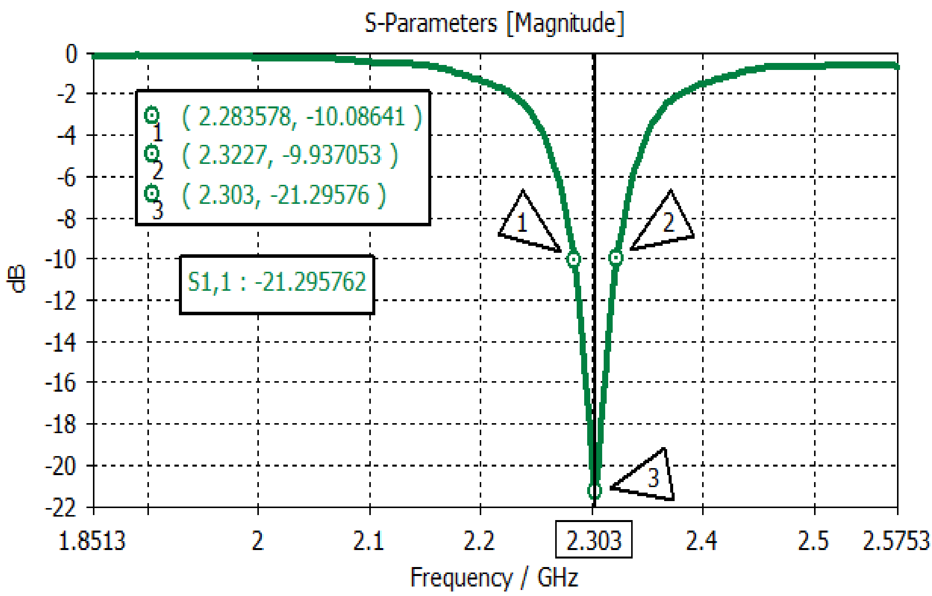

Fig. 4. Simulation of Return loss against frequency.

(ii) Voltage Standing Wave Ratio (VSWR)

The VSWR reflects how well the antenna's impedance matches the characteristic impedance of the feedline, typically 50 Ω. Figure 5 presents a plot of the simulated VSWR for the designed patch antenna across different frequencies. The proposed rectangular microstrip patch antenna (RMPA) achieves a VSWR of 1.1885 at its resonant frequency of 2.303 GHz. Subsequently, the VSWR value is less than 2, it falls within the acceptable range for efficient antenna performance. A VSWR between 1 and 2 is generally preferred for optimal antenna operation [10]. From the reflection coefficient given as,

$$\Gamma = \frac{VSWR - 1}{VSWR + 1} = 0.0866$$

The value of Γ obtained is 0.0866, this implies that, only 8.66% of the power is reflected, while 91.34% of the power is transmitted into the antenna.

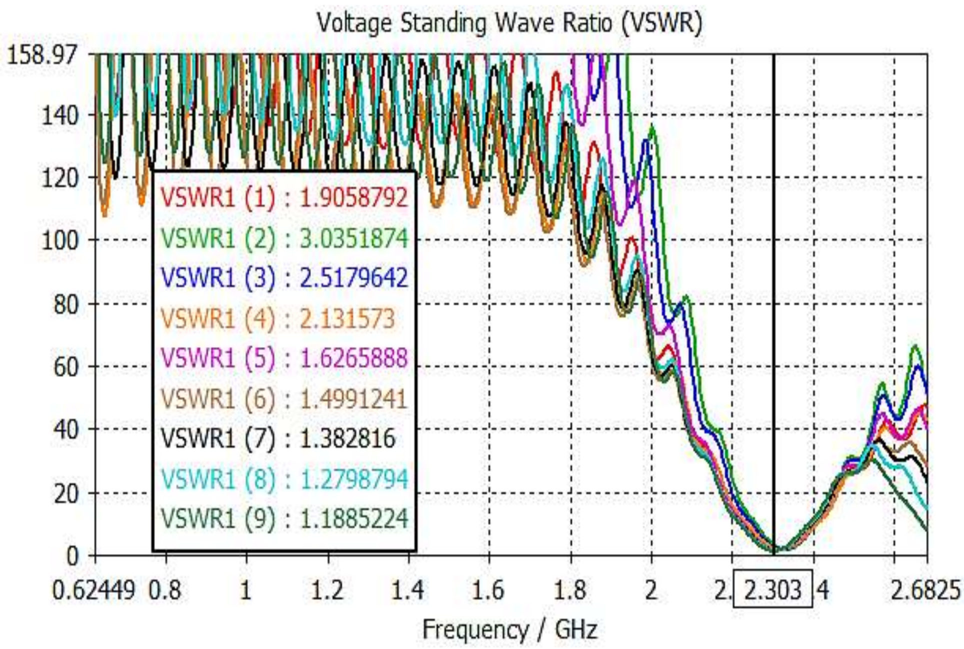

Fig. 5. Graph of VSWR against frequency

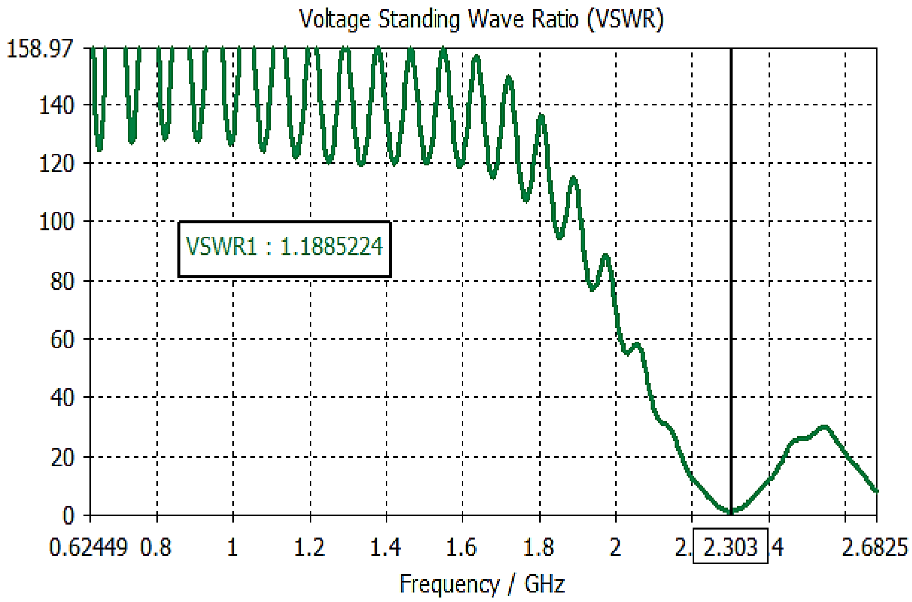

Fig. 6. Graph of VSWR against frequency at 2.3 GHz

(iv) Gain

As depicts in figure 7, the microstrip patch antenna achieves a maximum gain of 6.58 dBi and a minimum gain of -23.4 dBi**,** which has significant implications for its performance and radiation characteristics. The relatively high maximum gain indicates that the antenna is moderately directive**,** efficiently radiating energy in a preferred direction, which is beneficial for applications requiring focused signal transmission, such as Satellite communications and IoT networks. In contrast, the minimum gain of -23.4 dBi suggests that the antenna exhibits deep nulls in certain directions**,** meaning that radiation is significantly suppressed in those areas due to destructive interference or the ground plane's influence. This strong directionality ensures that most of the radiated power is concentrated in the desired direction while reducing interference in unwanted directions. Overall, the gain variation confirms that the antenna is well-suited for applications requiring directional radiation**,** ensuring reliable performance with minimal energy wastage in unintended areas.

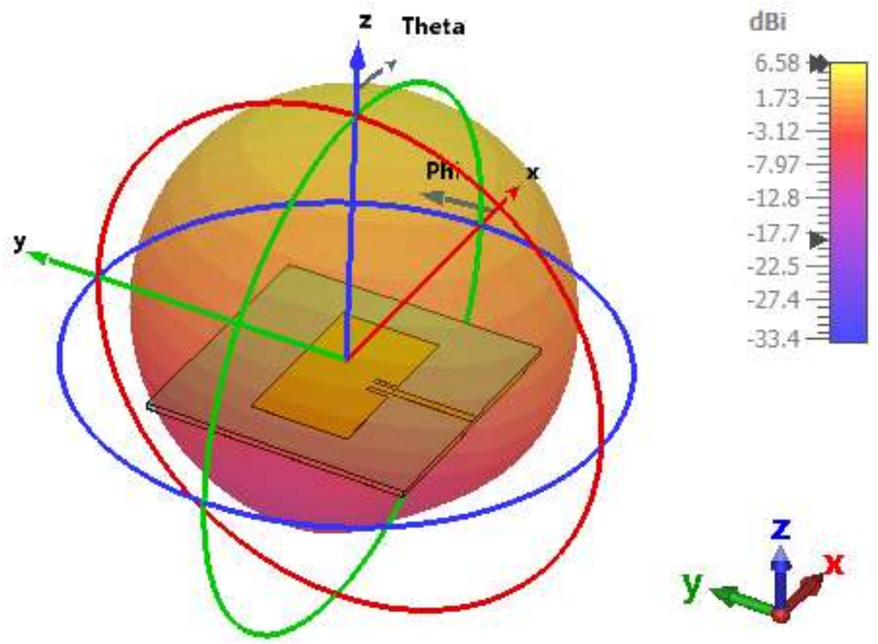

Fig 7. 3D model of a RPMA with color-coded gain

(v) Far field Directivity

As presented in Fig. 8, the designed microstrip patch antenna exhibits a main lobe magnitude of 7.06 dBi**,** indicating strong directional radiation, with its main lobe direction at 4°, suggesting a slight tilt from the broadside direction, which may be due to feed positioning or substrate properties but remains within an acceptable range. The angular width (3 dB beamwidth) of 88.1° shows that the antenna provides a moderate trade-off between directivity and coverage, making it suitable for applications where a broader service area is required while maintaining efficient radiation. Additionally, the sidelobe level of -16.8 dB signifies effective suppression of unwanted radiation, reducing interference and improving overall antenna performance. A lower sidelobe level enhances signal clarity, making the antenna well-suited for applications requiring high signal-to-noise ratio (SNR)**,** such as IoT and satellite systems**.** Overall, these characteristics confirm that the antenna achieves efficient radiation, minimal interference, and balanced directivity**,** making it an excellent choice for communication systems requiring focused energy transmission with controlled beamwidth and low sidelobe interference**.**

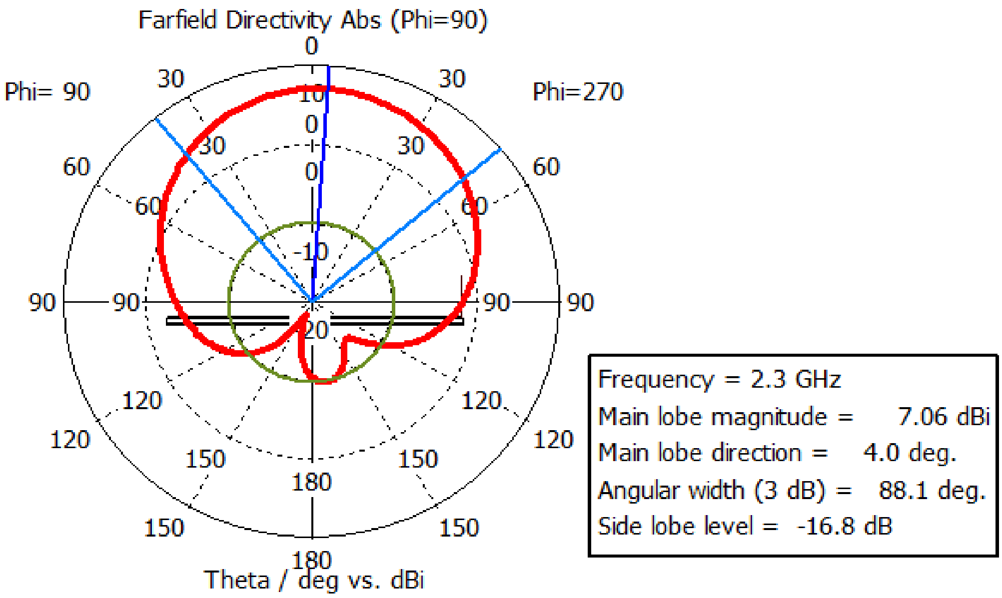

Fig. 8. .far field directicity

(vi) Radiation Efficiecy

The radiation efficiency of the proposed RMPA was found to be 83.7%**,** which is considered highly efficient for practical applications. This value is within the range of a typical 80-90% efficiency range reported by Alsager (2011) for most microstrip patch antennas, making the designed antenna a promising candidate for high-performance wireless communication systems.

Table 3 provides a summary of the simulation results for the designed RMPA**.** It presents the key performance parameters of the antenna, including resonant frequency, return loss **(S11),** VSWR, bandwidth, gain, directivity, half-power beamwidth (HPBW), and efficiency, offering a comprehensive evaluation of its characteristic.

Table 3. Summary of Simulation results

Parameters	Patch antenna with FR-4 substrate
S11	-21.296 dBi
VSWR	1.188
Bandwidth	39.1 MHz
Maximum gain	6.58 dBi
Minimum gain	-23.40dBi
Directivity	7.86 dBi
Antenna efficiency	83.7%
Reflection coefficient (**Γ**)	0.0866
Reflected power (**P_r**)	8.66%
Transmitted power (**P_T**)	91.34%

Conclusion

This research presents the design and simulation of a Rectangular microstrip patch antenna aimed at enhancing signal reception in Satellite communication, GPS systems, and Internet of Things devices**.** A novel single-element Rectangular Microstrip Patch Antenna (RMPA)**,** operating at 2.3 GHz**,** was successfully designed and simulated using CST studio suit (v.24) software**.** The antenna's key performance parameters, including return loss, bandwidth, VSWR, gain, directivity, beamwidth, and radiation efficiency**,** were analysed in the simulation. The results show that the proposed RMPA resonates at 2.3 GHz**,** achieving a return loss of -21.296 dB**,** a bandwidth of 39.1 MHz**,** a VSWR of 1.188**,** a maximum gain of 6.58 dB**i,** a minimum gain of -23.4 dBi, a directivity of 7.86 dBi**,** and an antenna efficiency of 83.7%**.** The significant difference between the maximum and minimum gains and the good results achieved by the novel designed RMPA indicates a highly directional antenna which makes it useful in applications where energy is needed to be concentrated in one direction like Satellite communication and IoT while minimizing energy in others to avoid interference or wasted power.

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