Rectangular Microstrip Patch Antenna for Wi-Fi Applications at 2.4-2.483 GHz using FR4 and RT/Duroid Substrate

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ABSTRACT

This work presents a novel architecture of a 2.4–2.483 GHz resonant rectangular microstrip patch antenna (RMPA), appropriate for Wi-Fi applications. HFSS tool is used to design the antenna utilizing FR-4 Epoxy and RT/Duroid substrate, both of which have 1.6 mm thickness and 4.4 and 2.2 dielectric constants, respectively. The frequency at which the planned antenna operates is 2.4415 GHz, which is shared by both substrates. The FR4 and RT/Duroid substrate simulation results are shown and contrasted. Resonant frequency, gain, VSWR, and directivity are among the antenna metrics that are enhanced in the RT/Duroid substrate as compared to FR4 substrate. These improvements range from 2.4207 GHz to 2.4576 GHz, 2.5977 dB to 4.4429 dB, 1.23 to 1.3, and 6.019 dB to 6.2722 dB, respectively. Furthermore, for both substrates that are appropriate for Wi-Fi applications, the return loss is less than 10dB.

Keywords— FR4-epoxy, RMPA, RT/Duroid, S-parameter, VSWR.

I. INTRODUCTION

In communication systems, wireless communication technology is becoming more and more ubiquitous [1]. Wi-Fi is a crucial part of the contemporary internet-connected world since it permits wireless communication between devices and offers wireless internet access [2]. Wi-Fi transmits and receives data using the IEEE 802.11 standard and functions in the 2.4 GHz–6 GHz frequency range [3]. Microstrip patch antennas are broadly operated in wireless communication systems due to their ease of integration with microstrip technology, low profile, cheap cost, and lightweight, compact design [4, 5]. Because of its straightforward design, the microstrip patch antenna is among the best promising antennas. The structure is made up of a substrate ground plane on one side and a patch that radiates on the other [6]. Several geometries, including rectangular, square, circular, elliptical, triangular, yearly ring, and pentagon, are observed in microstrip patch antennae [7]. However, because they are easier to adjust to and need a shorter design process, the most prevalent shapes are rectangular, triangular, round, and elliptical. Because rectangular patch antennas work better with array configurations, researchers employ them.

However, the microstrip patch antenna has significant drawbacks, including low gain and efficiency, low frequency of 2.400-2.483 GHz, and limited bandwidth, which is linked to tolerance issues [8]. The antenna is designed on two substrates, FR4 and RT/Duroid, and its performance is compared with two dielectric materials. In the suggested antenna design, a rectangular patch antenna with a ground plane on one side is fed via a 50-ohm coaxial cable. The ground plane's dimensions and the patches are tuned to reach a frequency of 2.4415 GHz. In order to achieve the best possible impedance matching and radiation pattern, the design additionally takes the substrate's thickness and dielectric constant into account. The antenna is designed and optimized using HFSS software. Evaluation is done on performance metrics such gain, return loss, directionality, VSWR, reflection coefficient, and bandwidth. This study discusses the design and optimization of microstrip patch antennas for Wi-Fi applications. A comparison of several substrates makes it easier to determine which material is best for a particular application. The impact of different parameters on the antenna structure is shown in the next section. Sections 3 and 4 then offer the antenna design process and the analysis of the comparative simulation results. The conclusion is the last section of this work..

II. ANTENNA DESIGN AND METHODOLOGY

A. Designing parameter

Power handling capacity, bandwidth, and impedance are all impacted by the feed position. The location of the feed must be changed by impedance mismatching. To raise this parameter, several techniques are applied. Several feeding methods, including coaxial probe, microstrip line, aperture coupled, and proximity coupled, can change the substrate's thickness and width [9]. Various feeding methods could be used to attain high gain [10]. Equation (1) represents the impedance.

$$Z = \frac{V}{I} \quad (1)$$

The patch antenna's center is where the current (I) is at its highest. At the patch's edge, it decreases and becomes zero. It appears to be λ⁄2, or a half-wavelength. Most often, we employ the fundamental mode TM10, where (L=λ⁄2) and m=1 and n=0. The impedance is zero at the patch's center and rises as it approaches the end point. Thus, we feed between L⁄4 and (L)⁄6. For a wide band antenna, the feed location begins with (L)⁄4, and for a narrow band antenna, with (L)⁄6. In most cases, we supply the antenna at 50 Ω input impedance. As anticipated, we can maximize the input impedance between 50 and 60, as well as between (L) 4 and (L) 6. We obtain zero impedance at center (L⁄2). So, the input impedance can be optimized to 50 Ω, approximately between $L/4$ and $L/6$.

We must thicken the substrate in order to lower the surface wave radiation. According to Equation (2), the bandwidth is dependent on the substrate's thickness.

$$Bandwidth \propto \frac{h}{\lambda_0} \quad (2)$$

Where h is the substrate's thickness or height and λ_0 is the wavelength of open space. Wavelength decreases with frequency increase, increasing bandwidth (BW). Increasing the value of h has a limit. Equation 3 provides the relationship between h and λ_0.

$$h \leq \frac{0.3\lambda_0}{2\pi\sqrt{\varepsilon_r}} \quad (3)$$

The transmission line method can be used to calculate the antenna parameters. The formulae to find different parameters of a rectangular patch antenna are mathematically expressed as per Table I [8, 12, 13].

In Table I, the highest frequency is f_h, the lowest frequency is f_l, the patch width is W_p, velocity of light is C, the resonance frequency is f_0, the substrate dielectric constant is ε_r, the substrate effective dielectric constant is ε_{reff}, the height of the substrate is h, the patch effective length is L_{eff}, due to fringing field effect the extension length is $2\Delta L$, the patch length is L_p, the ground plane length is L_g, the substrate length is L_s, the substrate width is W_s, the ground plane width is W_g, the patch input impedance is Z_{in}, the conductance of transmission line model is G_1, the feed line width is W_f, the feed line length is L_f, the depth of cut is d, the width of cut is W_c, the radiation box length is L_r, the radiation box width is W_r, the radiation box height is H_r, the guided wavelength is λ_g, the wavelength of free space is λ_0. A typical RMPA structure with its parameters is presented in Fig. 1.

TABLE I. FORMULAE TO FIND THE PARAMETERS OF A RECTANGULAR PATCH ANTENNA.

Parameter	Formula
center frequency	$(F_h - F_l)/2$
Width of the Patch (Wp)	$\dfrac{C}{2f_0\sqrt{\dfrac{\varepsilon_r+1}{2}}}$
Effective dielectric constant (ε_{reff})	$\dfrac{\varepsilon_r+1}{2}+\dfrac{\varepsilon_r-1}{2}\left[1+\dfrac{10h}{w_p}\right]^{-\frac{1}{2}}$
Effective length (L_{eff})	$\dfrac{C}{2f_0\sqrt{\varepsilon_{reff}}}$

length extension (ΔL)	$\frac{h}{\sqrt{\varepsilon_{reff}}}$
Actual Patch Length (Lp):	$L_{eff} - 2\Delta L$
dimensions of the ground and the substance	$L_g = L_s = 6h + L_p, W_g = W_s = 6h + W_p$
Input Impedance (Z_{in})	$Z_{in} = \frac{1}{2G_1}, G_1 = \frac{1}{120}\frac{W_p}{\lambda_0}$
Width and length of feed line	$w_f = \frac{7.48h}{e^{Z_0\frac{e_{reff}+1.414}{87}}}, L_f = \frac{L_g}{2}$
Value of Depth and Width of the Cut	$Z_0 = Z_{in}cos^2\left(\frac{\pi d}{L_p}\right), W_c = W_f + 2\Delta L$
Radiation Box	$L_r = \frac{\lambda_g}{3} + L_g, W_r = \frac{\lambda_g}{3} + W_g, H_r = \frac{\lambda_g}{3} + h, \lambda_g = \frac{\lambda_0}{e_{reff}}$

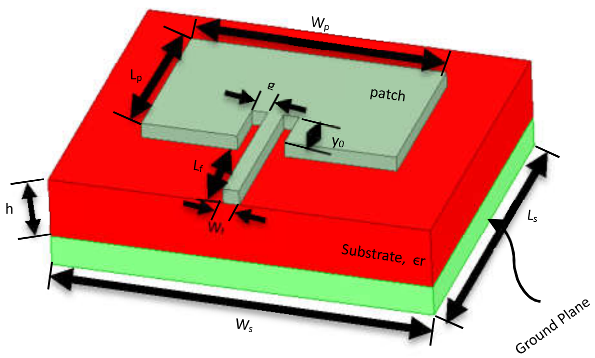

Fig. 1. RMPA structure [9]

B. *Design Specifcation*

The design of proposed antennas on FR4 and RT/Duroid substrate are represented in Fig. 2 and Fig. 3 using the dimensions mentioned in Table 2.

- The antenna design uses FR4 epoxy and RT/Duroid, which have dielectric constants of 4.4 and 2.2, respectively. To achieve more radiated power, improved efficiency, and a wide bandwidth, the design employs a low dielectric constant.
- The frequency range that is being used is 2.400 – 2.4830 GHz.
- The thickness or height of the dielectric substrate is taken as 1.6 mm.
- The antenna uses different materials in different layers. Various dielectric materials are used in substrate layer. Patch, ground plane, and feed line of rectangular microstrip patch antennas are prepared with copper.
- For FR4 Epoxy, f_c=2.4415 GHz, h= 1.6mm, ε_r=4.4 and for RT/Duroid, f_c=2.4415 GHz, h= 1.6 mm, ε_r=2.2 are considered.

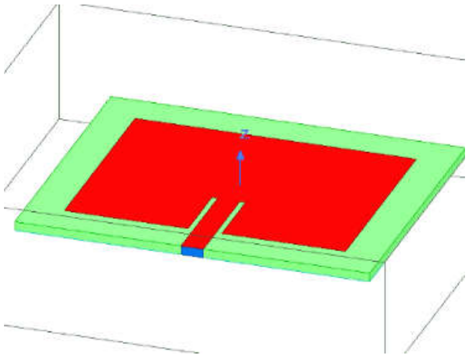

Fig. 2 Rectangular Microstrip Antenna Design Using FR4 Epoxy Substrate

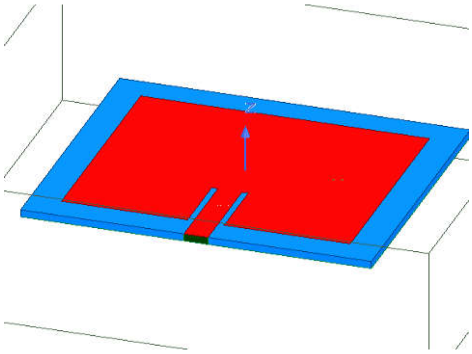

Fig. 3 Rectangular Microstrip Antenna Design Using RT/Duroid Substrate

Table II DIMENSIONS OF RMPA USING FR4 EPOXY.

Parameter	FR4 Epoxy (Value in mm)	RT Duroid (Value in mm)
ε_{eff}	4.126	2.11
W_p	38	48
L_p	28.64	40
W_g	48	58
L_g	39	50
W_r	69	86
f_c	2.4415	2.4415
W_f	3	4
L_f	19.5	25
Z_{in}	194.55 Ω	166.66 Ω
d	9.71	12.707
W_c	5	6
L_r	60	78
H_r	20	30

III. METHODOLOGY ADOPTED

The RMPA is designed using different dielectric materials with appropriate dielectric constant to compare their performance. Our primary goal is to achieve better operating frequency. So FR4 epoxy and RT/Duroid substrates were selected. Then the dimensions of RMPA were calculated using the formulae of Table 1. Ansys HFSS software was used to design, simulate, and analyze the RMPA. After the design is completed it is validated. The design is simulated with no issues and the parameters like S-parameter, VSWR, Gain, Directivity, and Efficiency are calculated. It was then compared with the theoretical values till the approximate matching of values. In the final step we analyze and conclude the superior substrate to design RMPA for Wi-Fi application.

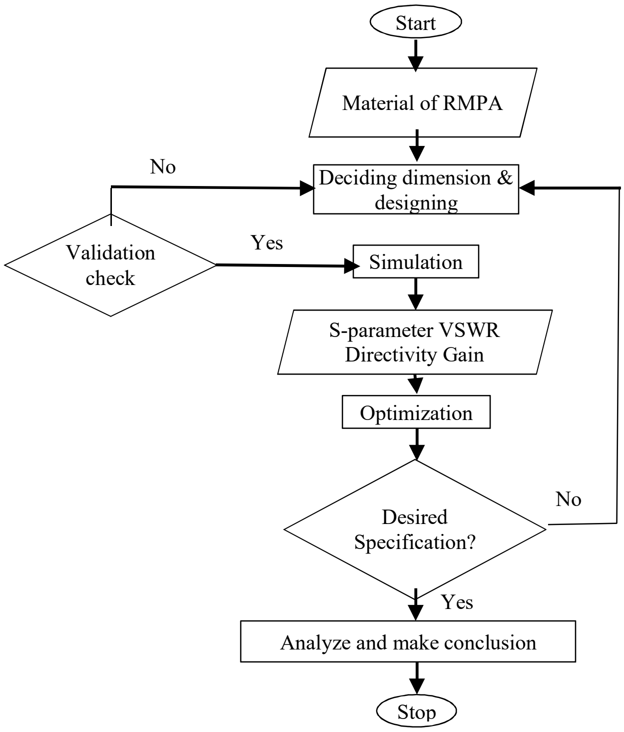

Fig. 4 Research methodology flow chart for designing a RMPA structure in HFSS [14]

IV. RESULT AND ANALYSIS

The performance of RMPA is analyzed through S-parameter, gain, and directivity for both FR4 and RT/Duroid substrates.

A. Return Loss

The reflection coefficient is obtained by the load impedance at the end of the transmission line (Z_L) and the characteristic impedance of the line (Z_0) as per Eq. (4) [11]. Return loss is high when the reflection coefficient is low.

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (4)$$

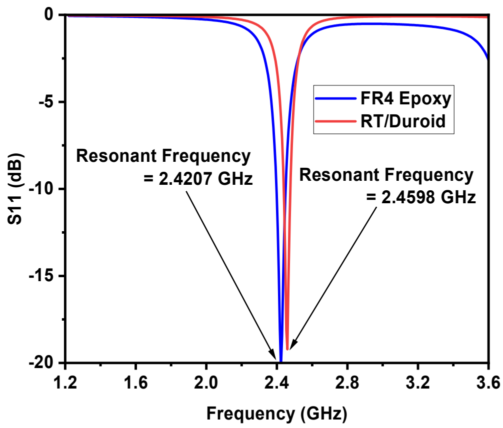

Fig. 5 Comparative S-Parameter plot for antenna designed using FR4 Epoxy and RT/Duroid substrate.

Also referred to as the return loss or reflection coefficient, S-parameter controls the power reflected from the antenna's patch port. The antenna performs better and matches better when reflection coefficient is lower. Perfect matching is indicated by a reflection coefficient value of 0, and perfect mismatching is shown by a reflection coefficient value of 1. The bandwidth can be computed using a return loss plot. The return loss is represented by S11 parameter. Figure 5 depicts the simulation outcome of the designed antenna's return loss versus frequency on FR4 Epoxy and RT/Duroid substrates. Good impedance matching is indicated by return losses of -20 dB for FR4 Epoxy and -18 dB for RT/Duroid at the resonance frequency of 2.4415 GHz.

B. Voltage Standing Wave Ratio (VSWR)

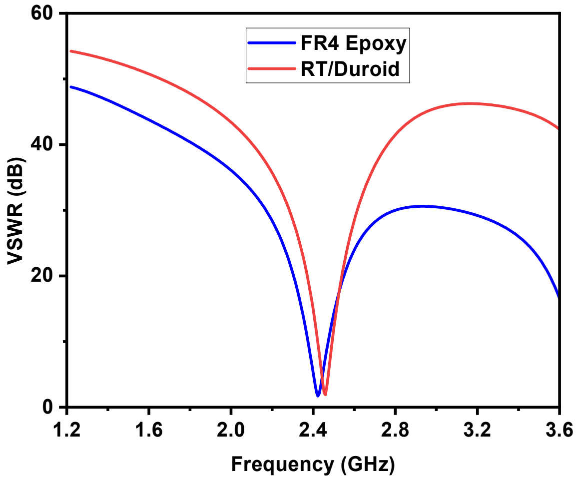

Fig. 6 VSWR comparisons for antenna designed using FR4 Epoxy and RT/Duroid substrate

Reflection coefficient (S11) for FR4 Epoxy, RT/Duroid substrates, respectively, is -19.73dB at 2.4207GHz and -19.5459dB at 2.4598GHz, as shown in Fig. 5. The suggested antenna has a lesser return loss than the one built in Reference [15]. The ratio of the greatest voltage (V_{max}) to the minimum voltage (V_{min}) is known as the voltage standing wave ratio (VSWR). For optimal performance, the VSWR value should be almost equal to 1, with a maximum limit of 2 allowed [14]. The range of VSWR is 1 to ∞. The VSWR performance vs frequency comparison for an antenna built with RT/Duroid and FR4 Epoxy substrate is displayed in Fig. 6. For the FR4 epoxy substrate, a VSWR of 1.23 is obtained at a resonance frequency of 2.4207GHz. At a resonance frequency of 2.4576GHz, a significantly improved VSWR of 1.3 is achieved for RT/Duriod. The resulting VSWR value is superior than that of a manufactured antenna that is comparable and can be found in the literature [17].

VSWR can be calculated as per Eq. (9) [13],

$$VSWR = \frac{V_{max}}{V_{min}} \quad (5)$$

It can be easily shown that VSWR is related to the load reflection coefficient Γ as per Eq. (10) [13],

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \quad (6)$$

C. Bandwidth

Bandwidth is inversely proportional to the dielectric constant ε_r. So that bandwidth can be calculated as per Eq. (7) [13],

$$BW = \frac{377\pi}{3Z_0\sqrt{\varepsilon_r}} \quad (7)$$

An antenna's bandwidth is the range through which a gain variation of no more than one or two dB is possible. Here, the return loss and VSWR of an antenna serve to determine its bandwidth. Since VSWR is correlated with the reflection coefficient, the frequency range over which it is less than or equal to two is referred to as the bandwidth. VSWR=2 is obtained when the reflection coefficient is 0.333. This means that the power reflected is 11.1% and the reflection coefficient is 0.333. An antenna designed for FR4 Epoxy substrate has a bandwidth % of 1.7, while an antenna developed for RT/Duroid substrate has a bandwidth percentage of 2.2, which is a higher proportion than that of FR4 Epoxy substrate.

D. Gain

The comparison results of the gain of the designed antenna are discussed in Fig. 7. A gain of 2.5977dB for FR4 Epoxy at a resonance frequency of 2.4207GHz and a better gain equal to 4.4429dB for RT/Duroid at a resonance frequency of 2.4576GHz are obtained.

With the decrease in ε_r, length, width, fringing field, and aperture area increases. Because of the larger aperture area, more gain is obtained. With an increase in the fringing field, more bandwidth is obtained. As per antenna theory, the relation between the gain (G) of the antenna and antenna aperture (A_e) is as per eq. (8) [9],

$$G = \eta A_e \frac{4\pi}{\lambda^2} \qquad (8)$$

The relation between gain and directivity is as per Eq. (9) [13],

$$G = \eta D \qquad (9)$$

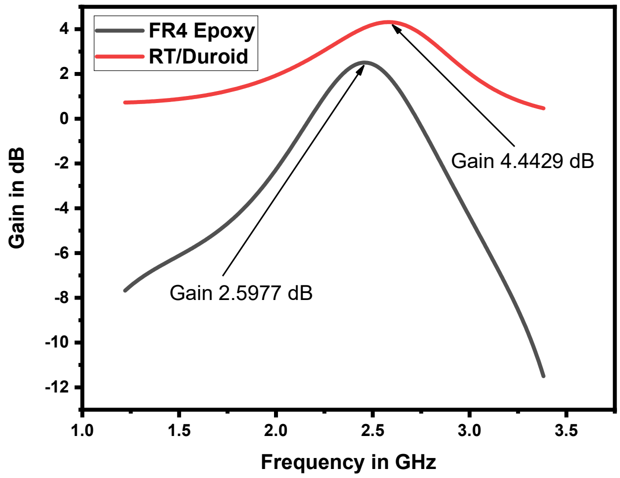

Fig. 7 Gain comparisons for an antenna designed using FR4 Epoxy and RT/Duroid substrate

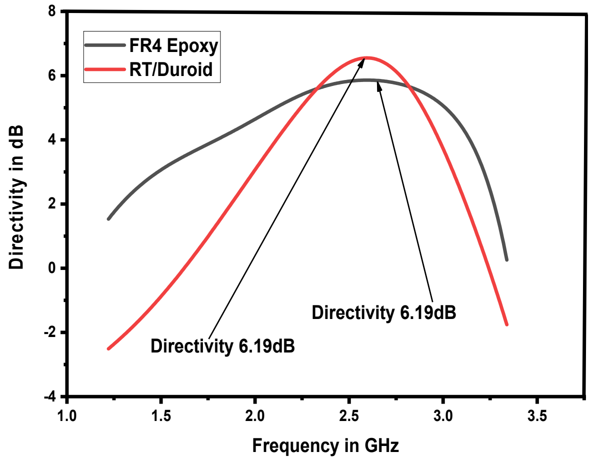

Fig. 8 Directivity comparisons for antenna designed using FR4 Epoxy and RT/Duroid substrate

E. Directivity

The directivity of an antenna can be calculated from the half-power beam width in H-plane and E-plane. Fig. 8 shows a directivity comparison for an antenna designed using two substrates at resonance frequency. The directivity of 6.019 dB for FR4 Epoxy substrate at the resonance frequency of 2.4207GHz and the directivity equal to 6.2722 dB for RT/Duroid at the resonance frequency 2. 4576GHz are obtained. So RT/Duroid substrate results in good directivity as compared to FR4 Epoxy substrate.

TABLE III COMPARISON BETWEEN RT/DUROID & FR4 EPOXY.

Parameters	FR4 Epoxy	RT/Duroid
Resonance Frequency (f_r) (GHz)	2.4207	2.4576
Return Loss (dB)	-19.73	-19.5459
Reflection Coefficient	0.1032	0.1274
VSWR	1.23	1.3

Gain (dB)	2.5977	4.4429
Directivity (dB)	6.019	6.2722
Dielectric Constant	4.4	2.2
Bandwidth (%)	1.7	2.2
Frequency Error $\left(\frac{fc-fr}{fc}100\right)$	0.85%	0.65%

Table III compares different parameters based on the two substrates FR4 epoxy and RT/Duroid. It can be observed from the table that, the resonance frequency, reflection coefficient, VSWR, gain, directivity, and the bandwidth corresponding to an RMPA designed by using RT/Duroid substrate give better performance as compared to an antenna designed by using FR4 substrate. Directivity can be calculated by using Eq. (10) [13].

$$D = A_e \frac{4\pi}{\lambda^2} \tag{10}$$

F. *Efficiency*

The power given to the antenna divided by the power it radiates defines an antenna's efficiency. Most of the power present at the antenna's input is radiated by a high-efficiency antenna. When an impedance mismatch occurs, a low-efficiency antenna loses most of its power. A great feature of an antenna is that its efficiency remains the same whether it is being used as a broadcast or receiver antenna. It is expressed as a ratio with a range of 0 to 1. Fig. 9 demonstrates the comparison of the efficiency of an antenna for FR4 epoxy and RT/Duroid substrates. The efficiency of FR4 epoxy is 46.32%, whereas RT/Duroid has a better efficiency equal to 95%. From Fig. 10, the maximum gain of the designed antenna is 2.46 dB for FR4 epoxy and comparatively better 6.02 dB for RT/Duroid. In the recommended antenna, the gain and efficiency are higher than the antenna fabricated in Ref. [15].

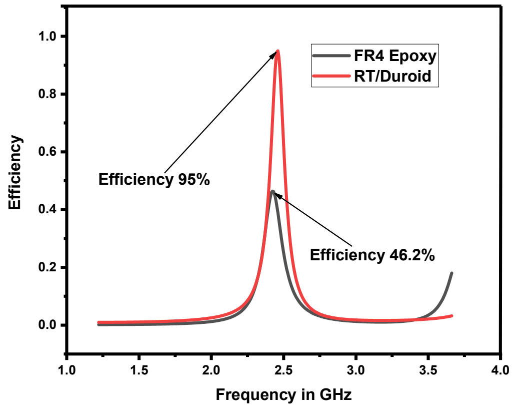

Fig. 9 Efficiency comparisons for antenna designed using FR4 Epoxy and RT/Duroid substrate

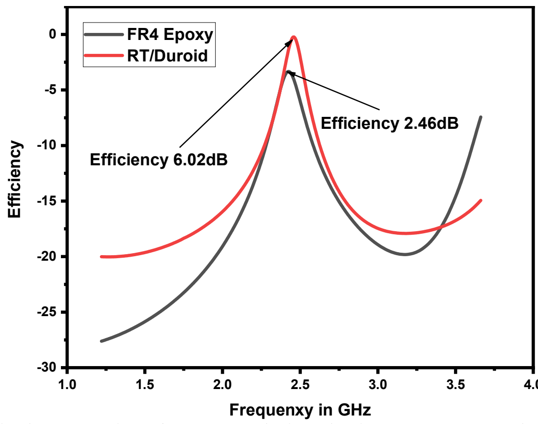

Fig. 10 Efficiency in dB comparison for antenna designed using FR4 Epoxy and RT/Duroid substrate.

G. *Radiation Pattern*

The antenna's radiation pattern displays the amount of energy it is emitting. There are several types of radiation patterns, such as 3D and 2D lobes formed by radiation. The antenna's radiation patterns are shown in Fig. 11 and 12 respectively. The nature of designed antennas is unidirectional and the top of the patch has maximum radiation. The maximum power is at the main lobe and it is pointed over the patch. The radiation pattern depicted in Fig. 11 and 12 reveals that, very small radiation from antennas is directed towards the angle 90° and very large directed towards the angle 0°. Hence the forward-to-backward power radiation (FBR) ratio is limited. The radiation pattern of an antenna, which shows amount and direction of radiation it emits or receives from electromagnetic waves, is normal to the radiation distribution on its surface [4].

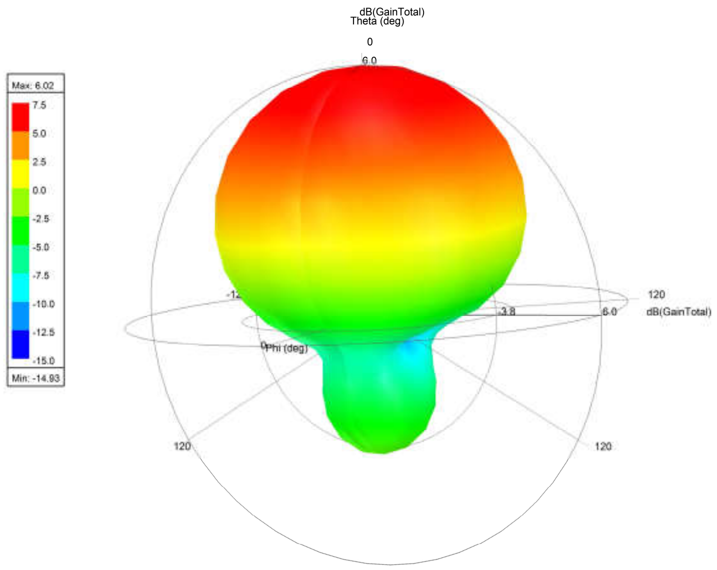

Fig. 11. 3D Radiation Pattern of RT/Duroid

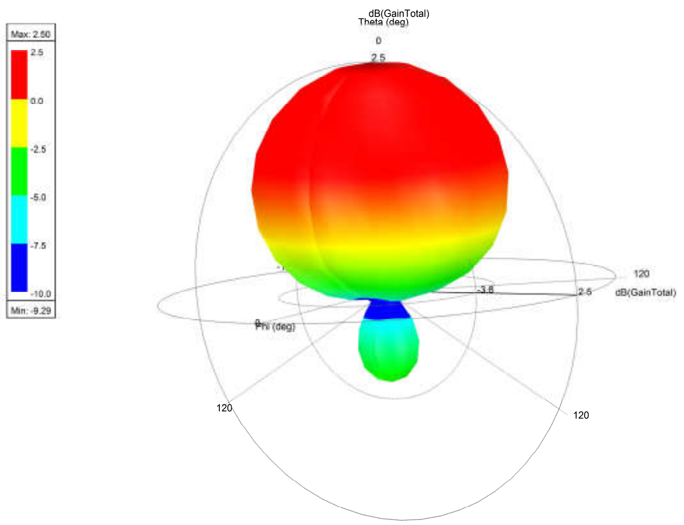

Fig. 12. 3D Radiation Pattern of FR4 Epoxy

V. CONCLUSION

In this article, two different substrates, FR4 epoxy and RT/Duroid, are used to develop RMPA with coaxial feed. The constructed antenna is found to resonate at two distinct frequencies, and over all frequencies, the return loss is less than -20 dB. S11, VSWR, Directivity, and Gain between RT/Duroid and FR4 Epoxy are examined and contrasted. We found that the RT/Duroid substrate had a gain of more than 3 dB, which is sufficient for the antenna to function as intended. The antenna's design makes it appropriate for Wi-Fi uses. Using different patch and slot shapes can increase every metric, including return loss, reflection coefficient, VSWR, gain, directivity, and bandwidth.

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No funding was received for this work.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Availability of data and material

The data used to support this study are included in the article. No supplementary materials.

Compliance with ethical standards

This article does not contain any studies with human or animal subjects.

REFERENCES

[1]. Z. -Y. Wu and M. Ismail, "Generalized RIS Tile Exclusion Strategy for Indoor mm Wave Channels Under Concept Drift," IEEE Transactions on Wireless Communications, 2024. doi: 10.1109/TWC.2024.3402267.

[2]. H. Jiang, S. Chen, Z. Xiao, J. Hu, J. Liu and S. Dustdar, "Pa-Count: Passenger Counting in Vehicles Using Wi-Fi Signals," IEEE Transactions on Mobile Computing, vol. 23, no. 4, pp. 2684-2697, 2024.

[3]. Zhou Chen Fei , Nurulazlina Ramli, Permesh L. Jethi "Performance Analysis of Rectangular Microstrip Patch Antenna with Different Substrate Material at 2.4 GHz for WLAN Applications," International Conference on Space Science and Communication (IconSpace), pp. 23-24, 2021

[4]. R. A. Santos, H. S. Bernardo, D. H. Spadoti, G. S. da Rosa and R. A. Penchel, "Gain Enhancement and Sidelobe Level Reduction of Microstrip Patch Antenna Under Operation of TM50-Like Mode," in IEEE Open Journal of Antennas and Propagation, 2024.

[5]. Q. Wang, A. Sihvola and J. Qi, "A Novel Procedure To Hybridize The Folded Transmitarray and Fabry Perot Cavity With Low Antenna Profile and Flexible Design Frequency," IEEE Antennas and Wireless Propagation Letters, 2024. doi: 10.1109/LAWP.2024.3398076.

[6]. B. P Narendra, "Microstrip patch antenna design for GPS application using ADS software," Journal of Information, knowledge and Research in Electronic and Communication Engineering, Vol. 2, No. 2, pp. 475-478. 2013.

[7]. H. Werfelli, K. Tayari, M. Chaoui, M. Lahiani and H. Ghariani, "Design of rectangular microstrip patch antenna," IEEE International Conference on Advanced Technologies for Signal and Image Processing (ATSIP), pp. 798-803, 2016.

[8]. Vivek H, Panchatapa B, Sahadev R, Chakraborty P and Maity S, "Performance Analysis of Rectangular Patch Antenna for Different Substrate Heights" International Journal of Innovation Research in Electrical Electron Instrumentation Control Engineering, Vol. 2, No. 1, pp. 515-518, 2014.

[9]. Sarsamba M C and Yanamshetti R, "Micro strip antenna application for WiMAX, WLAN, mobile communication: A review" IEEE International Conference on Power, Control, Signals, and Instrumentation Engineering (ICPCSI), pp. 988-991, 2017.

[10]. Harshit Srivastava, Usha Tiwari "Design, Simulation & Analysis of Rectangular & Circular Microstrip Patch Antenna for Wireless Applications" International Journal of Recent Technology and Engineering, Vol. 8, No. 4, pp. 5078-5082, 2019.

[11]. Hasan R R, Islam M, Islam K S, Rahman M and Hasan M, "Designing and Analysis of Microstrip Patch Antenna for Wi-Fi Communication System Using Different Dielectric Materials" American Journal of Engineering Research, Vol. 4, No.10, pp. 118-126, 2015.

[12]. Wasiq S, Gupta S, Chandra V K and Varsheney V, "A review on different shapes of patch antennas" International Journal of Scientific Research and Management Sciences, vol. 2, pp. 59-65, 2015.

[13]. Balanis C A, "Antenna theory: analysis and design," John wiley & sons, 2016.

[14]. Rahmatia S, Fransiska D E, Pratama N I H, Wulandari P and Samijayani O N, "Designing dipole antenna for TV application and rectangular microstrip antenna working at 3 GHz for radar application" IEEE International Conference on Cyber and IT Service Management (CITSM)), pp. 1-6, 2017.

[15]. Md. Biplob Hossain and Md. Faruque Hossain "Design and Performance Analysis of a Tripleband Rectangular Slot Microstrip Patch Antenna for Wi-Fi, Wi-MAX and Satellite Applications" International Journal of Electronics and Telecommunications, Vol. 68, No. 2, pp. 217-222, 2022.

[16]. Vishwakarma A and Meda D K, "A Single Band E Shaped Microstrip Patch Antenna For WLAN Application using coaxial feed" IEEE International Conference on Communication Systems and Network Technologies (CSNT), pp. 10-13, 2021.

[17]. Sumathi A, Priyadarshini K Desai, "Design and fabrication of 2.4GHz rectangular patch antenna for Wi-fi application" Journal of University of Shanghai for Science and Technology, Vol. 23, no. 6, pp. 1218, 2021.