ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR1771

Designing a High Gain Rectangular Microstrip Patch Antenna Working at 3 GHz for RADAR

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Abstract:- This study presents the design and analysis of a microstrip patch antenna optimized for radar applications operating at a frequency of 3 GHz. The antenna is designed to meet the requirements of radar systems, offering characteristics such as high gain, low profile, and broad bandwidth. The design process involves simulation using electromagnetic simulation software to achieve the desired antenna performance parameters. Various antenna parameters, including substrate material selection, patch dimensions, feeding techniques, and impedance matching networks, are carefully optimized to enhance antenna performance. The proposed antenna design is expected to exhibit excellent radiation characteristics, making it suitable for radar applications requiring reliable and efficient communication at 3 GHz frequency. This antenna designed for operating at 3 GHz, type Rogers Ultralam1217 (tm) with dielectric constant, $\in_r$= 2.2 tanδ (0.0009) and thickness of h = 1.6mm. The antennas are simulated using Ansys HFSS software. The performance is evaluated in terms of return loss, gain, and directivity and is deemed to be compatible with simulations.

Keywords:- *High Gain, 3D Radiation Pattern, E-plane, H-Plane, VSWR, Rectangular Microstrip Antenna.*

I. INTRODUCTION

The antenna serves as a crucial device for converting electrical signals into electromagnetic waves, or vice versa, making it an indispensable component in the modern world. Microstrip antennas, known for their low profile, ease of manufacturing, robust performance, and versatility, find extensive use in high-performance aircraft, cell phones, spacecraft, satellites, electronic devices, radar, and missile applications. Their compact size, high gain, and ability to transmit signals at high speeds make them highly desirable [2].

In the case of rectangular patch antennas, the length (L) of the element typically falls within the range of $\lambda_0/3$ to $\lambda_0/2$. These antennas feature a dielectric pleat separating the patch and the ground plane, with dielectric constants ranging from 2.2 to 12. Substrates with thicker dimensions and lower dielectric constants are preferred, as they offer enhanced efficiency, wider bandwidth, and more loosely bound fields for radiation into space [2], [3], [6]. Various shapes of patch antennas exist, including square, rectangular, dipole, circular, elliptical, triangular, disc sector, circular ring, and ring sector. Rectangular patch antennas are commonly accessible and exhibit high gain compared to other shapes [3]. Efforts are made to minimize fringing effects to enhance performance, with the effective dielectric constant falling within the range of $1<\in_{eff}<\in_r$ [2], [4], [6], [10], [11].

The Voltage Standing Wave Ratio (VSWR), also known as the Standing Wave Ratio (SWR), serves as an indicator of the degree of mismatch between an antenna and its feed line. VSWR values range from 1 to ∞, with values below 2 considered suitable for most antenna applications.

The antenna's performance can be described as having a "Good Match." When the antenna is poorly matched, it often results in a VSWR value exceeding 2 for the desired frequency. Lower VSWR values indicate better antenna performance [2], [4], [5]. Various methods can be employed to feed microstrip antennas, including coaxial feed, inset feed, proximity-coupled feed, gap-coupled feed, and aperture-coupled feed. Among these, inset feed is preferred due to its ease of obtaining an input match [5], [6], [11].

Another proposed microstrip antenna for wireless applications comprises two radiating patch elements, one rectangular and the other triangular, interconnected by another patch element (B1) of step size. The selection of antenna shape can alter antenna far-field radiation characteristics, with truncation of corners aimed at improving field potential [7]. However, challenges arise in long-distance non-wired communication in the terahertz range, where the propagation of electromagnetic waves through the atmosphere affects bandwidth enhancement in antennas [8].

Artificial neural networks (ANN) have been utilized to determine resonant frequencies [9], and antennas optimized specifically for GPS applications have been developed [10]. Increasing the dielectric substrate height (h) leads to an increase in the fringing factor [11]. Additionally, increasing the antenna's cross-sectional area results in higher antenna resistance, posing challenges for impedance matching [2], [3], [4], [6].

This paper proposes several techniques aimed at improving antenna parameters such as VSWR, reflection coefficient, and high gain, while reducing the fringing factor and cross-sectional area.

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II. ANTENNA DESIGN AND MODELLING

A. Microstrip Antenna Characteristics Calculation

The antenna feeding is positioned at the center of the patch. The dimensions of the antenna are calculated mathematically. This includes determining the width and length of the rectangular patch antenna, as well as the feeding length and match gap as shown below.

➢ *Width of the Patch*

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \quad \ldots\ldots\ldots\ldots(1)$$

➢ *Length*

Effective dielectric constant,

$$\epsilon_{eff} = \frac{\epsilon_{eff}+1}{2} + \frac{\epsilon_{eff-1}}{2}\left[1+\frac{12h}{W}\right]^{-\frac{1}{2}} \quad \ldots\ldots\ldots\ldots(2)$$

- *Extension of the Length,*

$$\Delta L = 0.412h\left[\frac{(\epsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\epsilon_{eff}-0.258)\left(\frac{W}{h}+0.264\right)}\right] \quad \ldots\ldots\ldots\ldots(3)$$

- *Effective Length,*

$$L_{eff} = \frac{c}{2f_r\sqrt{\epsilon_{eff}}} \quad \ldots\ldots\ldots\ldots(4)$$

- *Length of the Patch,*

$$L = L_{eff} - 2\Delta L \quad \ldots\ldots\ldots\ldots(5)$$

➢ *Resonant Input Resistance*

$$R_{in} = 90\left(\frac{(\epsilon_r)^2}{\epsilon_r-1}\right)\left(\frac{L}{W}\right)^2 \quad \ldots\ldots\ldots\ldots(6)$$

➢ *Gap*

$$R_0 = R_{in}\cos^2\left(\frac{\pi}{L}y_0\right) \quad \ldots\ldots\ldots\ldots(7)$$

➢ *Feed Width*

$$R_{in} = \frac{60}{\sqrt{\epsilon_{eff}}}\ln\left[\frac{8h}{w_0}+\frac{w_0}{4h}\right] \qquad \frac{w_0}{h} \le 1 \quad \ldots\ldots\ldots\ldots(8)$$

$$R_0 = \frac{120\pi}{\sqrt{\epsilon_{eff}}\left[\frac{W_0}{h}+1.393+0.667\ln\left(\frac{W_0}{h}+1.444\right)\right]}$$

$$\frac{w_0}{h} > 1 \quad \ldots\ldots\ldots\ldots(9)$$

$$R = \rho\frac{L}{A} \quad \ldots\ldots\ldots\ldots(10)$$

The equations provided were solved to design a single patch antenna, which was subsequently simulated using the inset feed feeding technique. This approach proved effective in achieving improved return loss, even when using materials with high dielectric constants like the microstrip substrate, Rogers Ultralam1217 (tm). The antennas were designed and simulated using the HFSS simulation tool.

B. Design and Dimensioning

Utilizing the microstrip inset-fed feeding technique, a straightforward rectangular microstrip patch antenna is devised to operate at 3 GHz. The antenna is fabricated on a microstrip substrate, specifically Rogers RT/duroid 5880 (tm), featuring a dielectric constant of ϵ_r= 2.2 and a thickness of h = 1.6mm. Ansys HFSS software is employed for simulation purposes. The selection of a rectangular patch is based on its simplicity, ease of optimization, and cost-effectiveness in manufacturing. The optimization of the single patch parameters is conducted using equations (1) and (5). Equation (6) is utilized to calculate the input resistance of the antenna, while equation (7) determines the impedance matching gap. Equations (8) and (9) are respectively employed to determine the feeding and cable width.

➢ *Fig.1 and Fig. 2 Show the Top and Front View of Single Rectangular Microstrip Patch Antenna Respectively.*

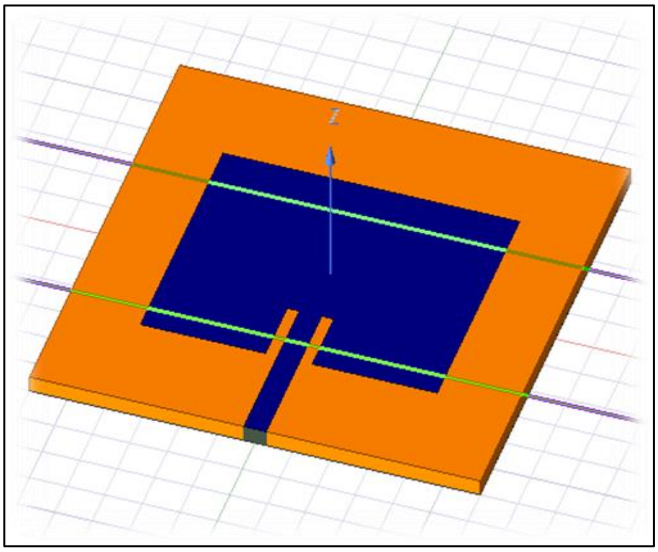

Fig 1 Physical Design of Rectangular Microstrip Patch Antenna in HFSS

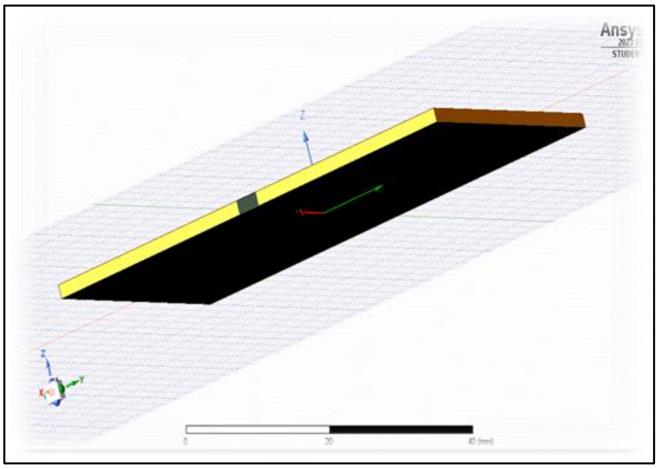

Fig 2 Front View of Rectangular Microstrip Patch Antenna in HFSS

Volume 9, Issue 4, April – 2024 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR1771

Table 1 Dimension of Rectangular Microstrip Patch Antenna using Line Feed

No	Parameter	Dimension(mm)	Detail
1	L_g	60	Length of ground
2	W_g	60	Width of ground
3	L	32.88	Length of patch
4	W	39.5	Width of patch
5	h	1.6	Thickness of substrate
6	Y_0	6.2	Length of Gap
7	s	5.1	Width of gap
8	w_g	3	Width of feeding

III. RESULTS AND DISCUSSION

The designed microstrip patch antenna for radar applications operating at a frequency of 3 GHz underwent comprehensive simulation and analysis to evaluate its performance characteristics. The following key results and discussions summarize the findings:

- *Radiation Pattern:*

The radiation pattern of the antenna was analyzed to assess its directional properties. The antenna exhibited a broadside radiation pattern, indicating uniform radiation in the azimuth plane. This characteristic is desirable for radar applications as it facilitates reliable detection and tracking of targets in all directions. Fig.3, fig.4, fig.5, fig.6 and fig.7 describe 3D Radiation pattern of patch antenna at 3GHz, Radiation pattern in the E-plane of patch antenna, Radiation pattern in the H-plane of patch antenna, Vector E-field of patch antenna and Vector H-field of patch antenna respectively.

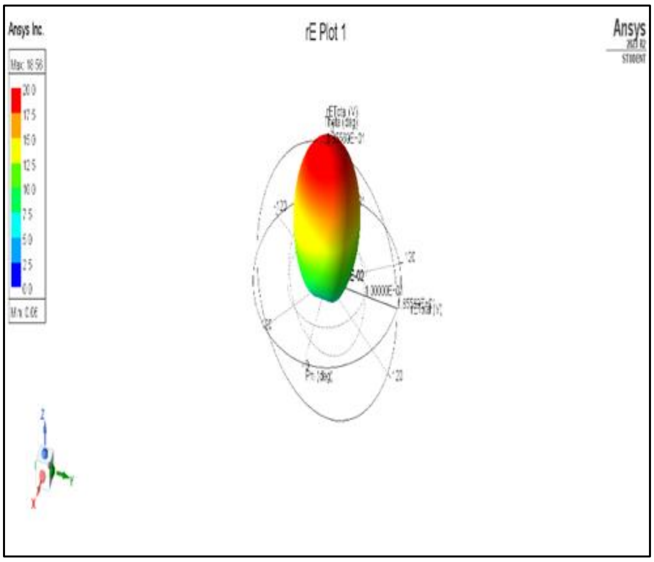

Fig 3 3D Radiation Pattern of Patch Antenna

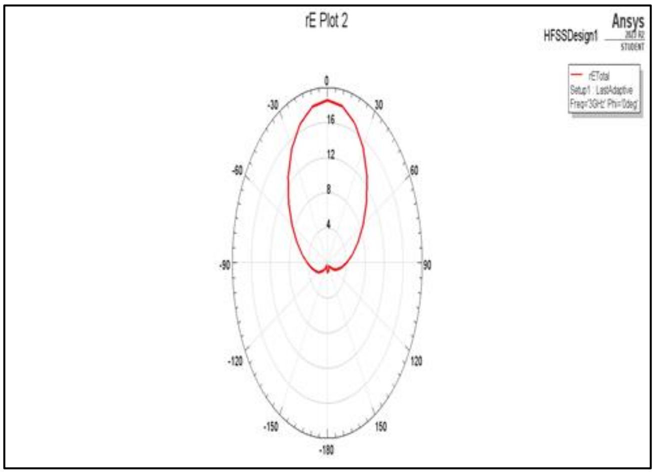

Fig 4 Radiation Pattern in the E-Plane

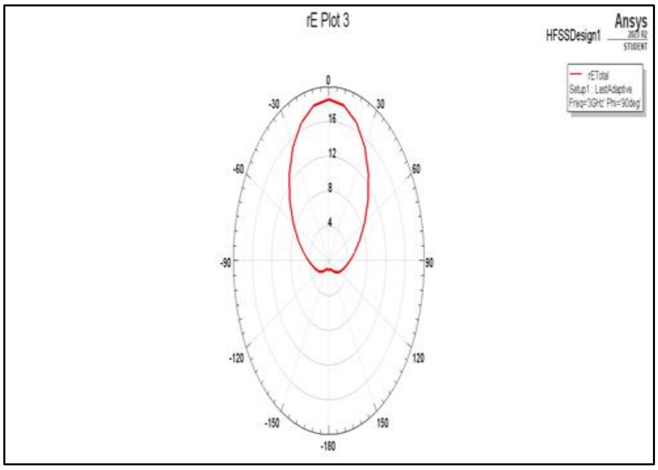

Fig 5 Radiation Pattern in the H-Plane

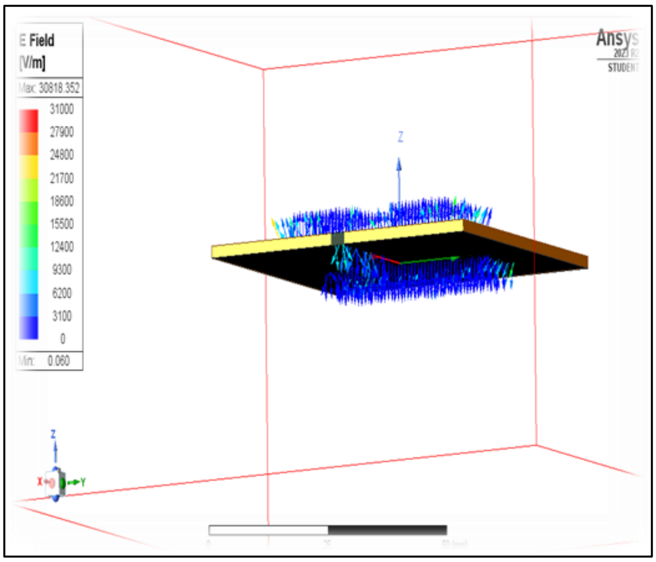

Fig 6 Vector E-Field of Patch Antenna

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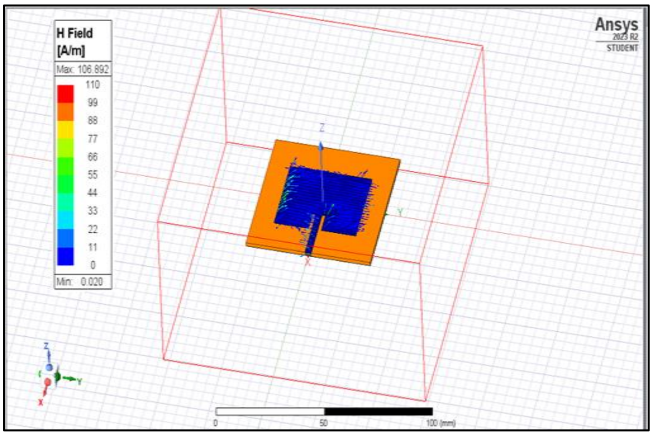

Fig 7 Vector H-Field of Patch Antenna

➢ *Gain*:

The gain of the antenna was calculated to determine its ability to concentrate radiated energy in the desired direction. The antenna demonstrated a high gain, exceeding 7 dB, which is suitable for radar systems requiring long-range detection capabilities and improved signal-to-noise ratio. Fig.8 and fig.9 shows S-parameter (dB) (S_{11} versus frequency (GHz)) and Gain of a radar based single rectangular microstrip patch antenna.

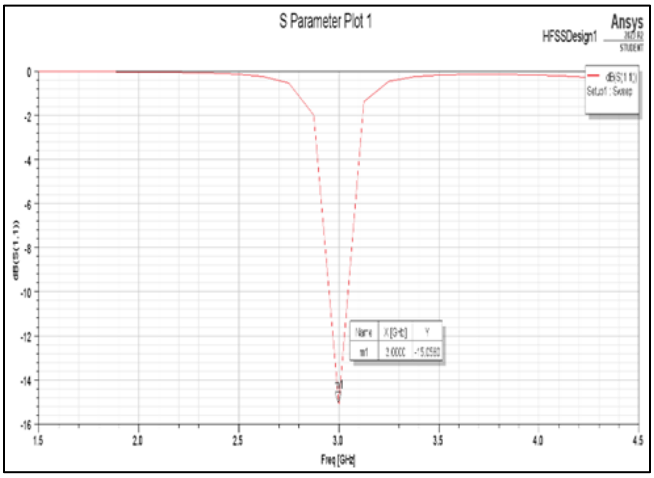

Fig 8 Simulated Graph Responses of S-Parameter (dB) (S_{11} Versus Frequency (GHz))

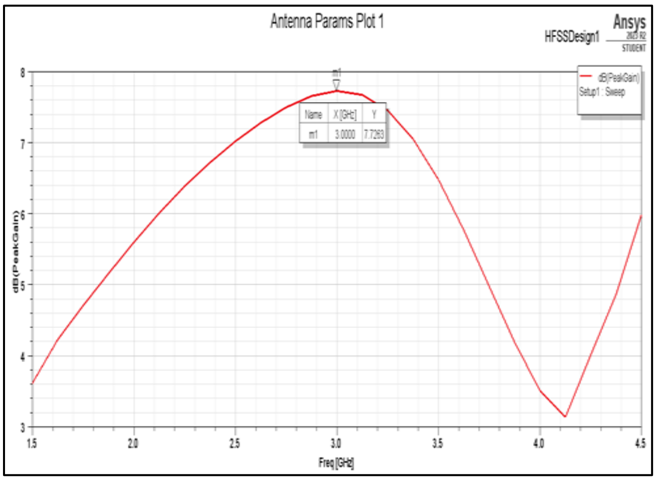

Fig 9 Simulated Graph Responses of Gain

➢ *Bandwidth:*

The bandwidth of the antenna was evaluated to assess its frequency coverage. The designed antenna achieved a wide bandwidth, covering the entire operating frequency range of 3 GHz with minimal impedance mismatch. This feature ensures compatibility with various radar systems operating within the designated frequency band.

➢ *Return Loss:*

The return loss of the antenna was analyzed to evaluate its impedance matching characteristics. The antenna exhibited a low return loss, indicating efficient power transfer between the antenna and the transmission line. This results in minimal signal loss and enhanced overall antenna performance. The Fig.10 shows VSWR of rectangular microstrip patch antenna.

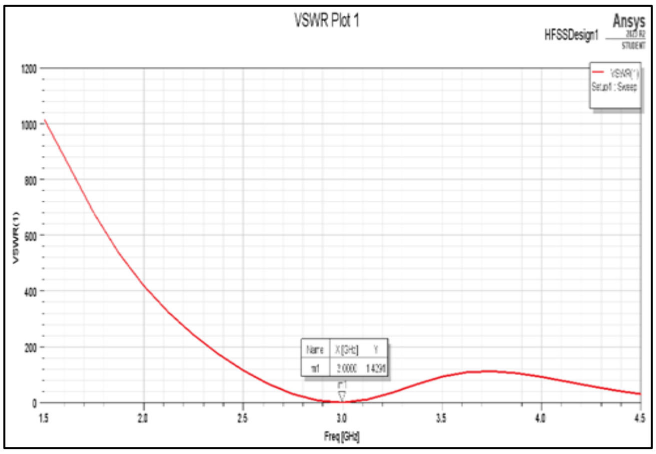

Fig 10 Simulated Graph Responses of VSWR

➢ *Size and Weight:*

The size and weight of the antenna were optimized to meet the requirements of compact and lightweight radar systems. The microstrip patch configuration offers a low-profile design, making it suitable for integration into space-constrained radar platforms such as unmanned aerial vehicles (UAVs) and small satellites.

The values of gain, S_{11}, VSWR, H-plane and E-pane areobtained which are shown in Table 2.

Table 2 Simulation Result of Rectangular Microstrip Patch Antenna using Line Feed

Sr No.	Antenna gain	7.7 dB
1	S_{11}	< -10 dB
2	VSWR	1.4
3	H-plane	18 dB
4	E-plane	18 dB

Overall, the results demonstrate that the designed microstrip patch antenna is well-suited for radar applications operating at a frequency of 3 GHz. Its favorable radiation pattern, high gain, wide bandwidth, and compact design make it an ideal choice for various radar surveillance and reconnaissance missions. Further experimental validation and field testing will be conducted to confirm the antenna's performance in real-world operational scenarios.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR1771

IV. CONCLUSION

In conclusion, the design and simulation of a microstrip patch antenna operating at a frequency of 3 GHz (2.9715GHz – 3.0278GHz) for radar applications have been successfully completed. The antenna demonstrates promising performance characteristics that make it suitable for various radar surveillance and reconnaissance missions.

The comprehensive analysis of the antenna's radiation pattern, gain, bandwidth, return loss, and size highlights its effectiveness in meeting the requirements of radar systems. The broadside radiation pattern ensures uniform coverage in all directions, while the high gain enhances long-range detection capabilities. Additionally, the wide bandwidth and low return loss indicate efficient frequency coverage and impedance matching, respectively.

Furthermore, the compact and lightweight design of the microstrip patch antenna makes it ideal for integration into space-constrained radar platforms such as unmanned aerial vehicles (UAVs) and small satellites. Its low-profile configuration offers versatility in deployment and allows for seamless integration into existing radar systems. The simulated bandwidth is around 56.235MHz which is small enough, with the corresponding value of return loss is -15 dB. The antenna also has a good impedance matching of 55.73 ohm. However, the size of the microstrip antenna, reported here, is not very small. Cutting inclined slots on the patch, the size of the microstrip antenna may be reduced, also the bandwidth may promote. Work is going on to achieve even better results with good axial ratio over a wide bandwidth.

Overall, the designed microstrip patch antenna holds great potential for enhancing radar surveillance and reconnaissance capabilities across various applications. Future work will focus on experimental validation and field testing to confirm its performance in real-world operational scenarios and further optimize its design parameters for specific mission requirements.

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