Design and Analysis of a Dual-Band Microstrip Patch Antenna for Sub-6 GHz Applications

ABSTRACT

Aims: This paper sets out to explore the development, simulation, and analysis of a dual-band Microstrip patch antenna functioning at 3.32 GHz - 3.62 GHz and 4.72 GHz - 6.83 GHz, employing Ansys High-Frequency structure simulator (HFSS) software. The primary aim is to improve performance metrics such as bandwidth, gain (dB), and radiation efficiency to cater to applications requiring simultaneous operation at both frequency bands.

Study Design: The study entails the comprehensive design, simulation, and analysis of the dual-band Microstrip patch antenna using Ansys HFSS software. Design considerations are customized to optimize performance characteristics for efficient utilization in modern wireless communication systems.

Place and Duration of Study: Conducted within a simulated environment using Ansys HFSS software, the study's duration encompasses iterative design processes, simulation runs, and analysis phases aimed at refining the antenna design for optimal performance.

Methodology: The methodology involves iterative design refinement using Ansys HFSS software to enhance the dual-band Microstrip patch antenna. Parameters such as reflection coefficient (dB), gain (dB), radiation efficiency, VSWR, and relative permittivity are assessed at both at 3.32 GHz - 3.62 GHz and 4.72 GHz - 6.83 GHz frequencies to evaluate antenna performance.

Results: Evaluation of key parameters at both frequencies reveals positive attributes. At 3.32 GHz - 3.62 GHz the antenna demonstrates a reflection coefficient of -5 dB, a gain of 2.77 dB, a radiation efficiency of 0.7429, and a VSWR of 1.9299. Similarly, at 4.72 GHz - 6.83 GHz, corresponding values indicate a reflection coefficient of -20.5213 dB, a gain of 3.34 dB, a radiation efficiency of 0.7, and a VSWR of 1.2203.

Conclusion: The proposed dual-band Microstrip patch antenna, designed and analyzed using Ansys HFSS software, demonstrates promising potential for contemporary wireless communication applications requiring multi-frequency operations. The enhancements achieved in bandwidth, gain, and radiation pattern highlight its suitability for deployment in modern wireless communication systems.

Keywords: Ansys HFSS, Antenna Gain, Dual-Band Antenna, Microstrip Patch Antenna, Radiation Efficiency, Reflection Coefficient, Sub-6 GHz, Wireless Communications.

1. INTRODUCTION

The rapid expansion of wireless communication systems has drastically increased the need for compact, efficient, and versatile antenna designs capable of operating across multiple frequency bands. This requirement spans a variety of applications, such as WLAN, Bluetooth, satellite communication [1], and more. With the surge in wireless device usage, the demand for antennas that can effectively handle multiple communication standards and protocols within a compact form factor has become paramount.

Among the numerous antenna designs, the dual-band Microstrip patch antenna [2] has emerged as a particularly promising solution. These antennas offer several benefits, including their low profile, ease of fabrication, and ability to be integrated into various surfaces, making them ideal for modern communication systems that often require antennas to be embedded into portable and handheld devices [3].

The dual-band Microstrip patch antenna’s capability to operate at two distinct frequency bands provides considerable advantages for multi-frequency applications [4]. For example, in WLAN systems, it is crucial to support both the 2.4 GHz and 5 GHz bands to ensure device compatibility and effective network traffic management. Similarly, in satellite communication, operating at different frequency bands can improve the reliability and coverage of communication links.

Research and innovation in the area of dual-band Microstrip patch antennas are driven by the pursuit of enhanced bandwidth, improved efficiency, and reduced size [5,6]. Achieving these goals involves tackling several technical challenges, such as minimizing reflection coefficients, optimizing radiation patterns, and maximizing gain. Advanced simulation tools like Ansys HFSS software are essential in this process, enabling precise modelling and analysis of antenna designs.

This paper presents the design, simulation, and analysis of a dual-band Microstrip patch antenna operating at 3.32 GHz - 3.62 GHz and 4.72 GHz - 6.83 GHz using Ansys HFSS software. The selection of these frequencies is strategic, covering key bands used in various communication standards, including sub-6 GHz 5G applications. Our design aims to achieve performance enhancements in terms of bandwidth, gain, and radiation pattern, thereby meeting the diverse needs of contemporary wireless communication applications.

2. ANTENNA DESIGN

Designing an antenna to operate at dual frequencies [7], the microstrip configuration incorporates a rectangular patch with two slots on the substrate. Ensuring peak performance requires careful attention to a range of parameters, which include:

Operating Frequency(f_0)*:* The key frequency or frequencies at which the antenna functions, which are essential as they dictate the antenna's dimensions and resonant behaviour of the antenna. The operating frequencies are set at 3.6 GHz and 5.25 GHz.

Substrate Material: The substrate, made from FR-4 Epoxy and measuring 1.6 mm in thickness (h) with a relative permittivity (ε_r) of 4.4, significantly influence the microstrip antenna's electrical properties, including impedance matching, bandwidth, and radiation efficiency. Its dimensions, with length (L_s) 70mm and width (W_s) at 60 mm, determine the physical layout of the antenna. Together with the substrate's properties, these dimensions affect parameters like resonant frequency and radiation pattern. Designers utilize these substrate dimensions to compute the microstrip patch antenna's dimensions, optimizing them to meet desired performance characteristics. Ultimately, these substrate dimensions are pivotal constraints, guiding designers in achieving specific performance goals and objectives.

Patch Design: The patch design is fundamental in microstrip antenna design [8], as it acts as the primary radiating component. Usually, a microstrip transmission line feeds the patch, and the location of this feed point affects both the antenna's radiation pattern and impedance matching. Designers commonly utilize simulation tools or analytical techniques to fine-tune the patch dimensions and feedline setup to fulfil particular performance criteria. In summary, the patch design significantly influences the microstrip antenna's effectiveness and adaptability across different applications [9].

The dimensions of the patch in a microstrip antenna are crucial, with the primary dimensions typically considered in patch design being as follows.

Patch Width (W_p): The patch width impacts both the antenna's input impedance and bandwidth, usually resulting in a broader bandwidth with a wider patch [10,11]. Its calculation is derived from Equation 1, yielding a patch width value of 25.33 mm.

$$W_p = \frac{C}{2f_0}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Where,

C is Velocity of light,
f_0 is desired Resonant frequency,
ε_r is the relative permittivity of the substrate.

Patch Length (L_p): The patch length is a crucial parameter, typically set to approximately half the wavelength ($\lambda/2$) within the dielectric medium. This measurement is determined using Equation 2 provided as.

$$L_p = \frac{C}{2f_0\sqrt{\varepsilon_{eff}}} - 2\,\Delta\mathrm{L} \tag{2}$$

Where,

ε_{eff} is effective dielectric constant of an antenna
$\Delta\mathrm{L}$ is patch length extension

To calculate the patch length, the effective dielectric constant of an antenna and the patch length extension need to be determined. These values are calculated using the formulas provided in equations 3 and 4.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\left(\frac{h}{w_p}\right)\right]^{-\frac{1}{2}} \tag{3}$$

Where,

h is substrate thickness
w_p is patch width

$$\Delta\mathrm{L} = \mathrm{h}{*}0.412\left[\frac{(\varepsilon_{eff}+0.3)\left(\left(\frac{W_p}{h}\right)+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\left(\frac{W_p}{h}\right)-0.8\right)}\right] \tag{4}$$

The calculated values of ε_{eff} and ΔL are 3.982 and 0.733 mm, respectively. These values are substituted into Equation 2 to determine the length of the patch, resulting in an obtained value of 19.414 mm.

Feed line: The feed line within a microstrip antenna [12] setup plays a pivotal role in efficiently transmitting RF signals from the input source to the radiating element. It comes in various forms, such as microstrip transmission lines, coaxial cables, and waveguides, selected based on factors like operational frequency and design requirements. Critical attributes of the feed line include proper impedance matching, minimal losses, and isolation to uphold peak antenna performance [13]. In this microstrip antenna design, the feed line is typically realized as a microstrip transmission line with a 50Ω characteristic impedance, where its dimensions, including width, length, and placement relative to the radiating element, are carefully tailored. In essence, the feed line's optimization is key to enhancing the antenna's efficiency in RF signal transmission and radiation characteristics.

The width of the feed line is determined using the equation provided in Equation 5 as follows:

$$W_f = \frac{8h}{\exp(Z_o\sqrt{\varepsilon_r+1.41})-1.25} \quad (5)$$

Where,

Z_o is Characteristic impedance

After inputting the values of substrate thickness and characteristic impedance into the equation, the derived width of the feedline is confirmed to be 3mm.

Table 1 presents a comprehensive list of the parameters essential for designing the proposed dual band Microstrip antenna.

Table-1: Design Parameters for Dual band Microstrip antenna

Antenna Parameters	Values
Substrate thickness(h)	1.6 mm
Length of substrate(L_s)	70 mm
Width of substrate(W_s)	60 mm
Relative Permittivity(ε_r)	4.4
Width of Patch(W_p)	25.33 mm
Length of Patch(L_p)	19.414 mm
Characteristic impedance(Z_o)	50 ohms
Width of feedline(W_f)	3 mm

Utilizing the specified design parameters as input, a dual-band microstrip antenna is meticulously crafted through the utilization of HFSS simulation software. Following the construction, an exhaustive evaluation of the antenna's performance metrics, encompassing S-Parameters, gain radiation efficiency, and VSWR is conducted. The culmination of this process is visually represented in Figure-1, which illustrates the finalized design of the antenna.

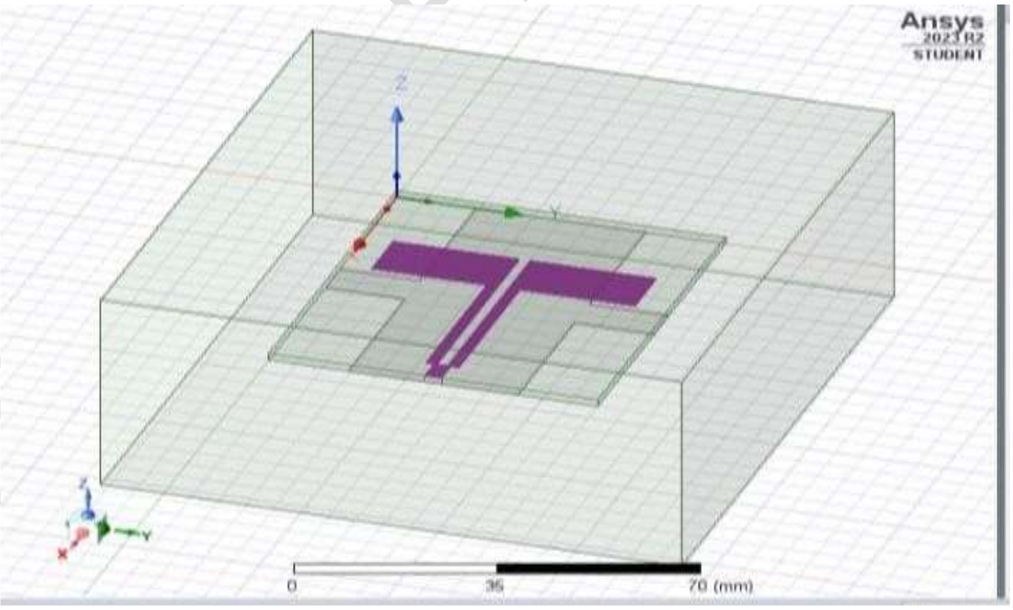


Figure 1: Dual-band Microstrip Antenna design

2.1 Antenna Parameters

Antenna parameters are crucial characteristics that determine an antenna's performance and functionality. Understanding these parameters is essential for designing and deploying antennas in various applications, including communications, broadcasting, and radar systems [14,15]. The proposed antenna design is evaluated based on the following key parameters:

Gain: Antenna gain denotes an antenna's capacity to concentrate electromagnetic radiation toward a specific direction compared to an isotropic radiator. It's typically measured in dBi and hinges on factors like the antenna's design and positioning. While high gain antennas are indispensable for long-range communication, they might offer narrower coverage. A thorough grasp of antenna gain is essential for optimizing communication and sensing systems.

Radiation Efficiency: Radiation efficiency evaluates how well an antenna transforms input power into useful electromagnetic radiation. It's represented as a percentage and is influenced by antenna design, materials used, and surrounding conditions. Maximizing radiation efficiency is key for enhancing antenna performance, enabling effective signal transmission or reception across diverse applications.

Voltage Standing Wave Ratio: In antenna design, VSWR (Voltage Standing Wave Ratio) is crucial for evaluating how well the antenna matches with the transmission line. Low VSWR means efficient power transfer, while high VSWR indicates poor matching, resulting in signal loss and reduced efficiency. Engineers aim to minimize VSWR across different frequencies to optimize antenna performance and reliability in communication systems.

Scattering(s) Parameters: In the field of antenna design, S-parameters, also referred to as scattering parameters, are fundamental for thoroughly assessing and refining antenna performance. Among these parameters, S_{11} holds particular importance as it directly evaluates the reflection coefficient at the antenna input, indicating the degree of impedance matching with the power source. When S_{11} values are notably diminished, typically below -10 dB, it indicates an optimal state of impedance matching. Essentially, this means that the antenna efficiently channels most of the incoming power for radiation, rather than reflecting it back. This alignment is essential for ensuring maximal power transfer and the effective operation of the antenna system.

Return Loss: Return loss serves as a gauge for the quantity of signal power reflected back by a component or system due to impedance disparities. It measures the disparity between the incoming power and the reflected power [16]. A high return loss denotes efficient absorption or transmission of the incident power by the component or antenna, with minimal reflection. Conversely, a low return loss indicates substantial power reflection, typically signalling inadequate impedance matching or other discrepancies within the system. It is calculated using scattering parameters, with the corresponding formula represented by equation 6 as:

$$Return\ loss\ (dB)\ =\ -20\ log_{10}(|S_{11}|) \tag{6}$$

Where,

$|S_{11}|$ is magnitude of the S_{11} parameter

3. RESULTS AND DISCUSSIONS

To evaluate the performance of the proposed antenna configuration, the HFSS simulation software was employed for numerical analysis and the optimization of geometrical parameters. After numerous experimental iterations, the parameters were meticulously adjusted. The analysis of the designed dual-band microstrip antenna produced various antenna parameters, as shown in the following figures.

The scattering parameters for the antenna are displayed in Figures 2 and 3, illustrating its performance at frequencies of 3.32 GHz - 3.62 GHz and 4.72 GHz - 6.83 GHz respectively.

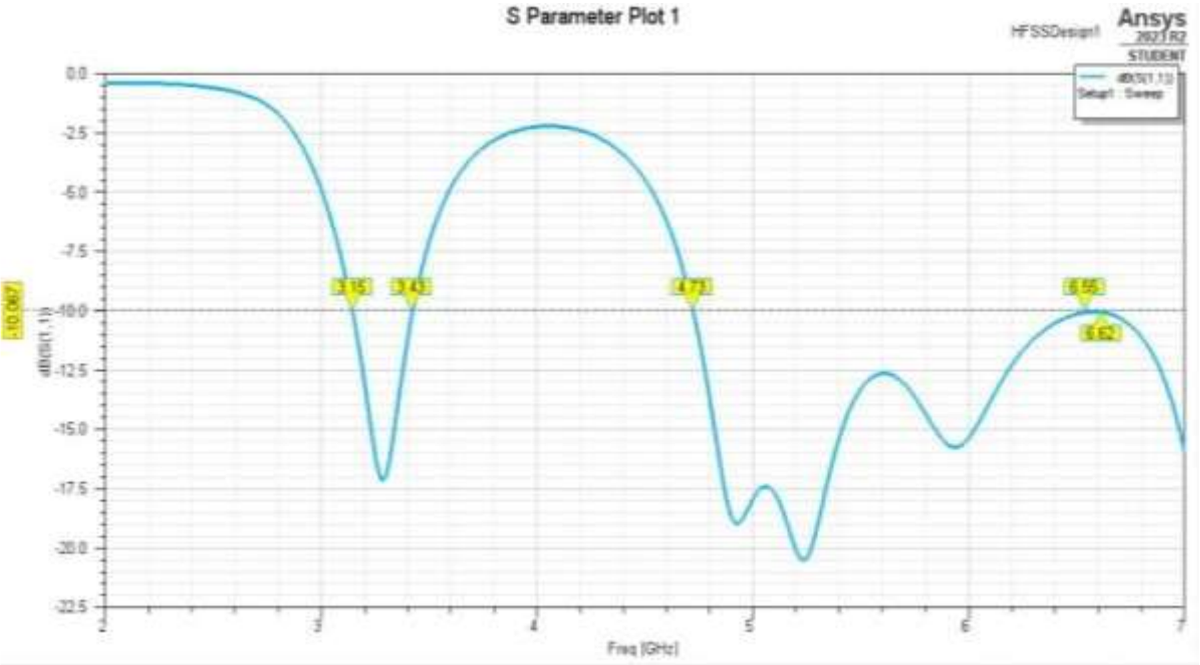
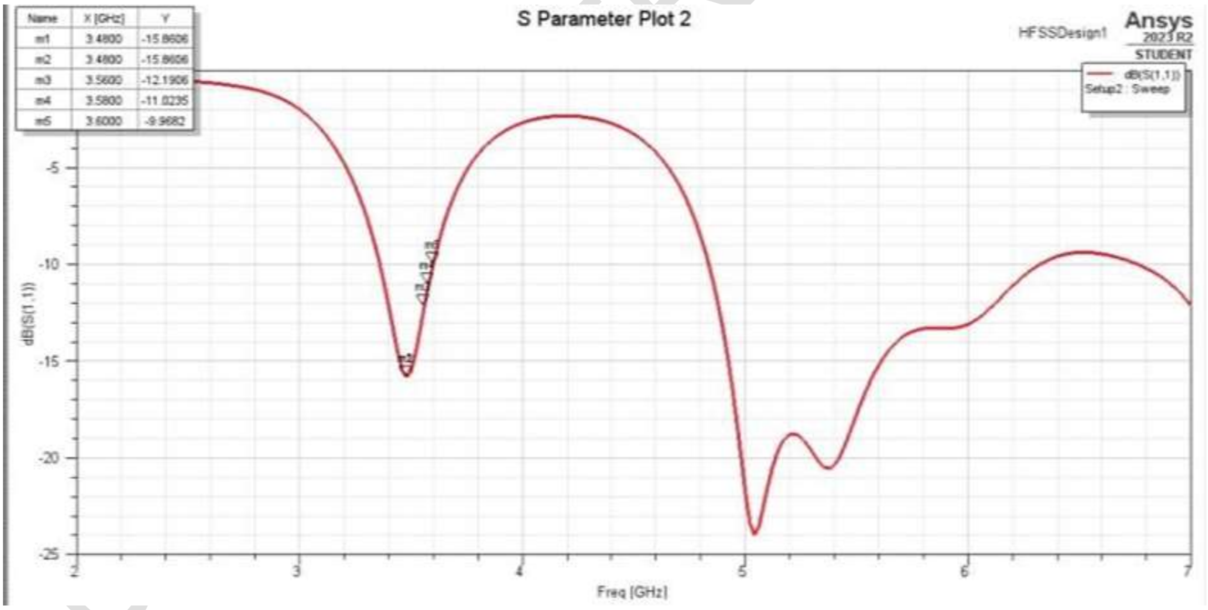


Figure 2: Scattering Parameters for the designed antenna at 3.6 GHz frequency



Name	X [GHz]	Y
m1	3.4800	-15.8606
m2	3.4800	-15.8606
m3	3.5600	-12.1906
m4	3.5800	-11.0235
m5	3.6000	-9.9682

Figure 3: Scattering Parameters for the designed antenna at 5.25 GHz frequency

The figures reveal that at 3.6 GHz, the scattering parameter stands at -5 dB, indicating a moderate level of reflection in the antenna system. This results in a moderate reduction in signal strength due to this reflection. However, at 5.25 GHz, the scattering parameter drops notably to -20.52 dB, suggesting significantly less reflection. This implies that a smaller portion of the incident energy is being reflected away at this frequency, leading to less signal loss. Essentially, the lower scattering parameter value at 5.25 GHz indicates a reduced level of reflection compared to 3.6 GHz, which is advantageous as it means more of the incident energy is utilized or absorbed by the antenna system, rather than being reflected away.

The return loss can be calculated from the scattering parameter value using equation 6. At 3.6 GHz, where the return loss is approximately -13.98 dB, it indicates moderate reflection. However, at 5.25 GHz, with a return loss of about -26.24 dB, significantly less reflection is evident. This suggests that more of the incident energy is efficiently transmitted or absorbed by the antenna system at 5.25 GHz compared to 3.6 GHz, resulting in improved performance in reducing reflections.

Figures 4 and 5 showcase the radiation efficiency of the antenna, demonstrating its effectiveness at 3.32 GHz - 3.62 GHz and 4.72 GHz - 6.83 GHz frequencies, respectively.

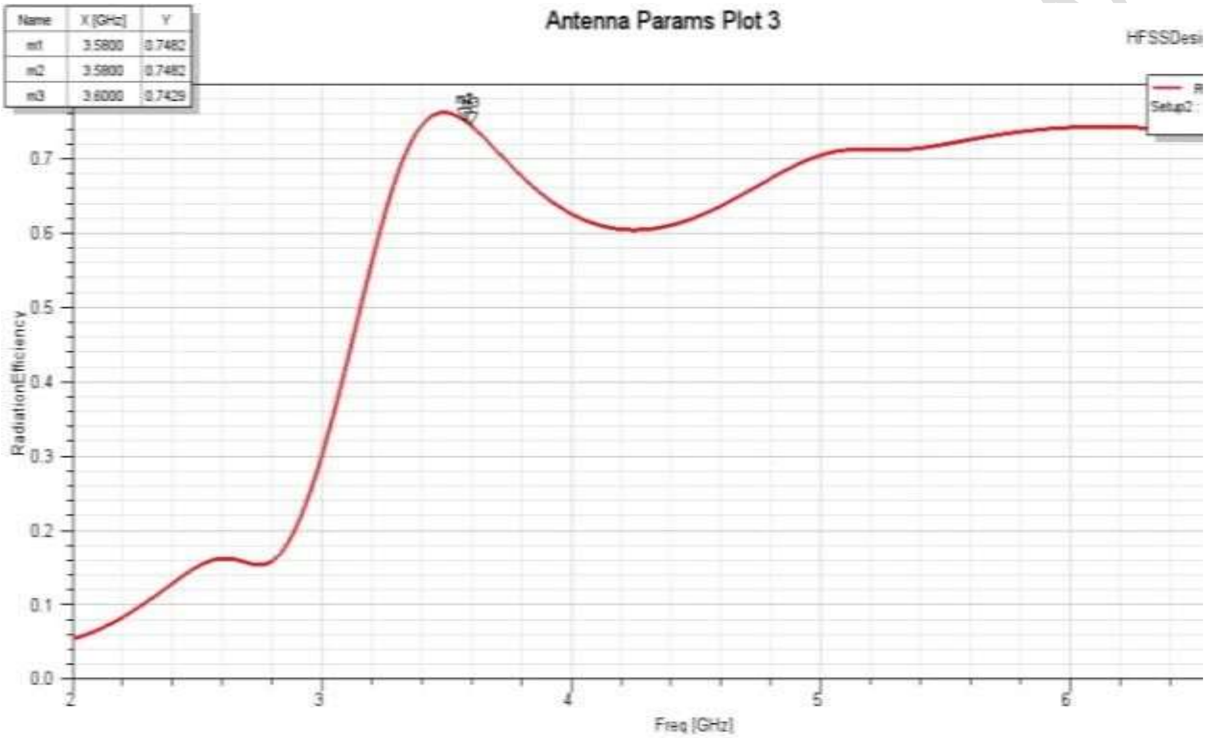


Figure 4: Radiation efficiency for the designed antenna at 3.6GHz frequency

The figures reveal that at 3.6 GHz, the antenna demonstrates a radiation efficiency of 74.2%, meaning that 74.2% of the input power is effectively converted into radiated electromagnetic waves. Similarly, at 5.25 GHz, the radiation efficiency is measured at 69.96%, indicating that 69.96% of the input power is efficiently radiated by the antenna at this frequency. These findings underscore the antenna's effectiveness in converting input power into radiated electromagnetic energy, with a slightly higher efficiency observed at 3.6 GHz compared to 5.25 GHz.

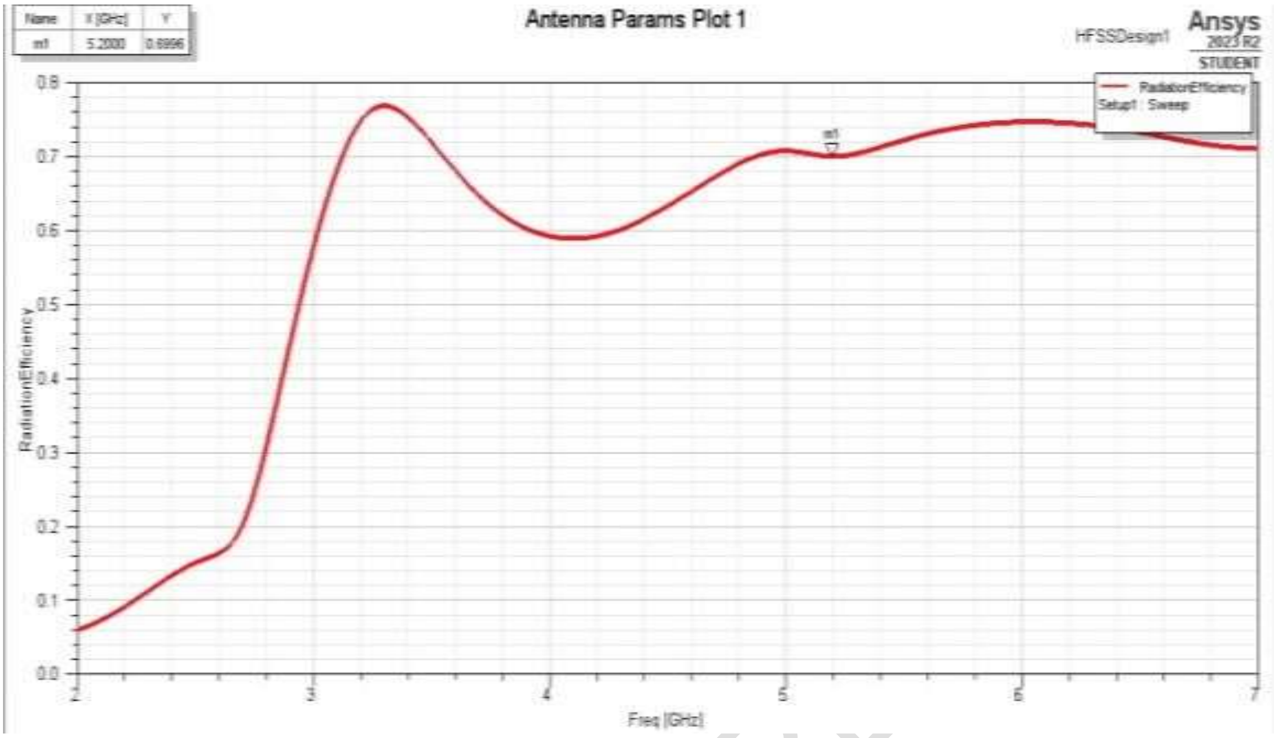


Figure 5: Radiation efficiency for the designed antenna at 5.25 GHz frequency

Figures 6 and 7 display the antenna's Gain, illustrating its performance at frequencies of 3.32 GHz - 3.62 GHz and 4.72 GHz - 6.83 GHz, respectively.

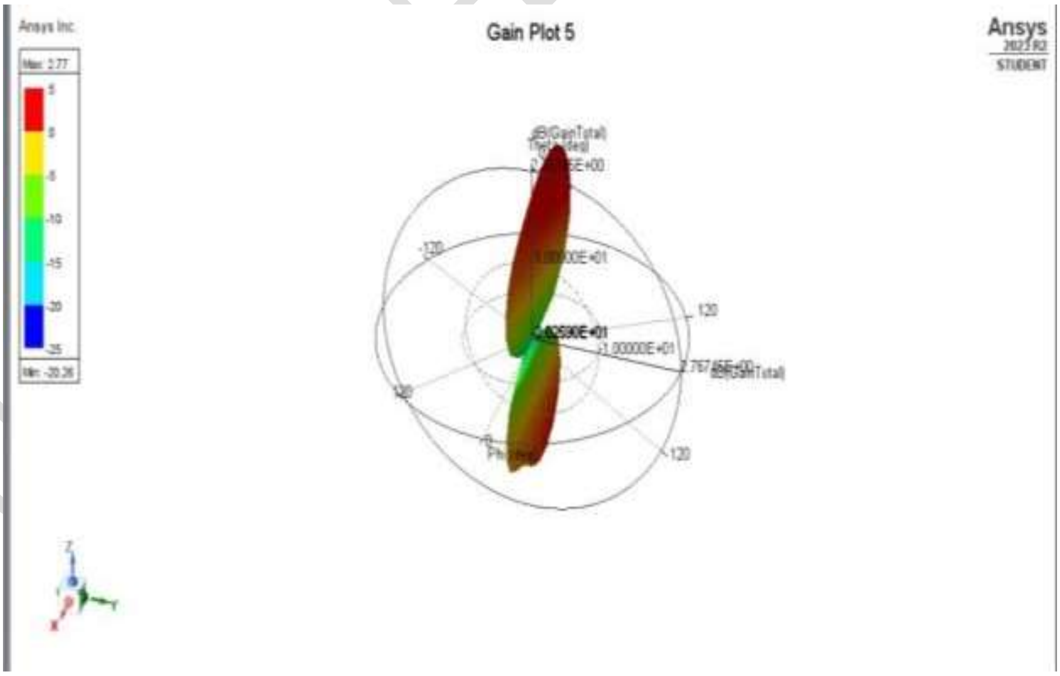


Figure 6: Gain for the designed antenna at 3.6 GHz frequency

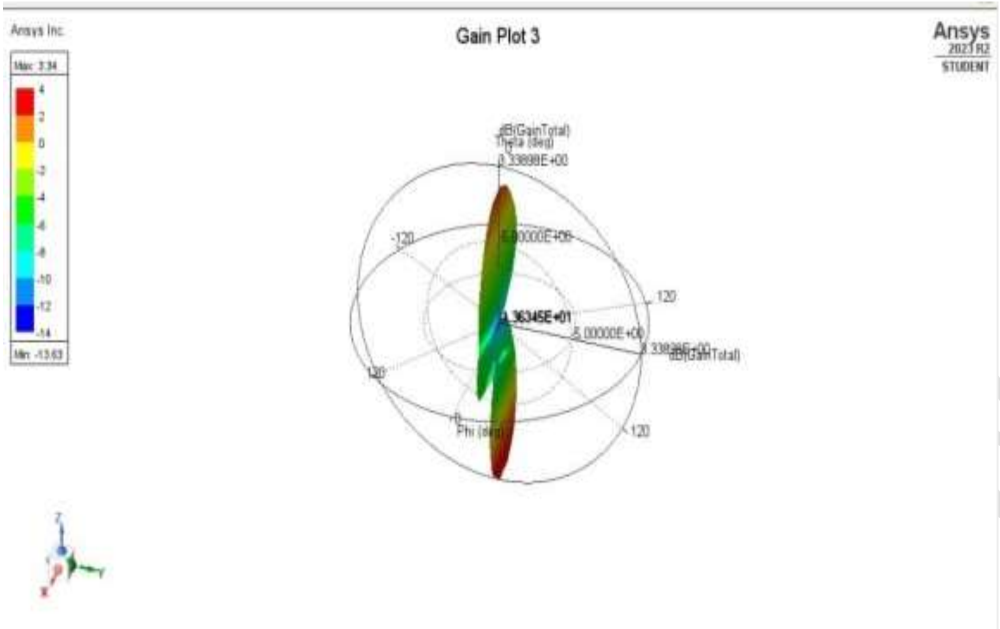
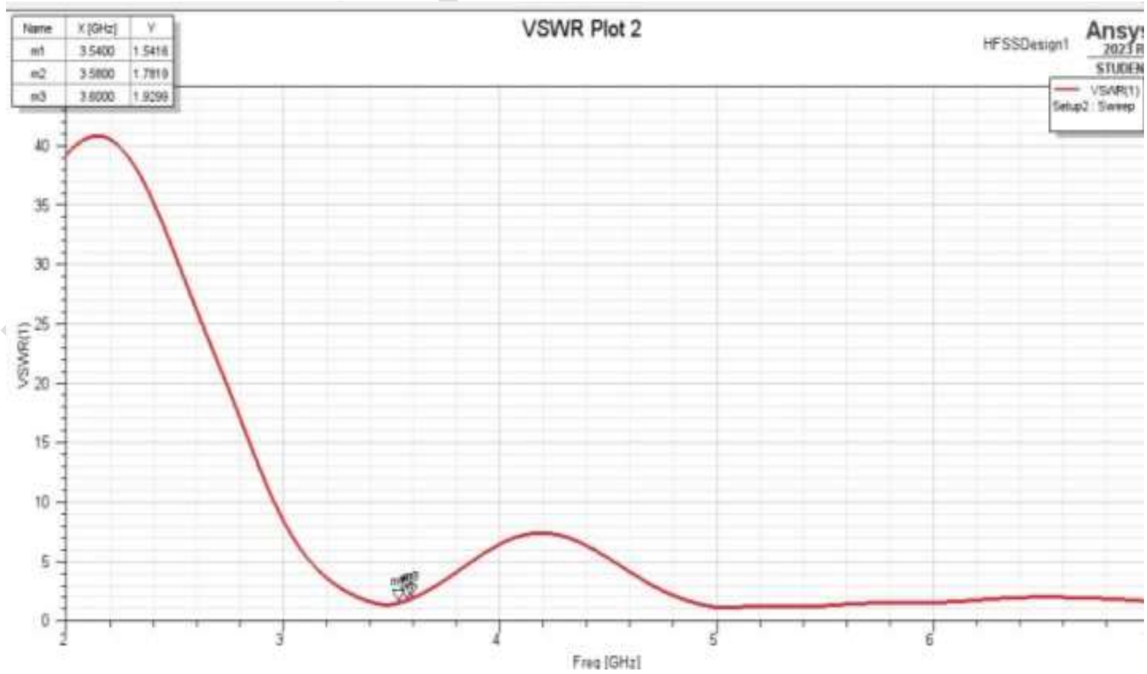


Figure 7: Gain for the designed antenna at 5.25 GHz frequency

The figures indicate that at 3.6 GHz, the antenna's gain is about 2.77 dBi, and at 5.25 GHz, it is approximately 3.34 dBi. These gain measurements imply that the antenna emits electromagnetic waves more effectively than an isotropic radiator, with a slightly greater emphasis on directionality seen at 5.25 GHz than at 3.6 GHz. This understanding of how the antenna concentrates radiation at varying frequencies is essential for assessing its performance.

Figures 8 and 9 depict the Voltage Standing Wave Ratio (VSWR), showcasing its performance at frequencies of 3.32 GHz - 3.62 GHz and 4.72 GHz - 6.83 GHz, respectively.



Name	X [GHz]	Y
m1	3.5400	1.5416
m2	3.5800	1.7819
m3	3.6000	1.9299

Figure 8: VSWR for the designed antenna at 3.6 GHz frequency

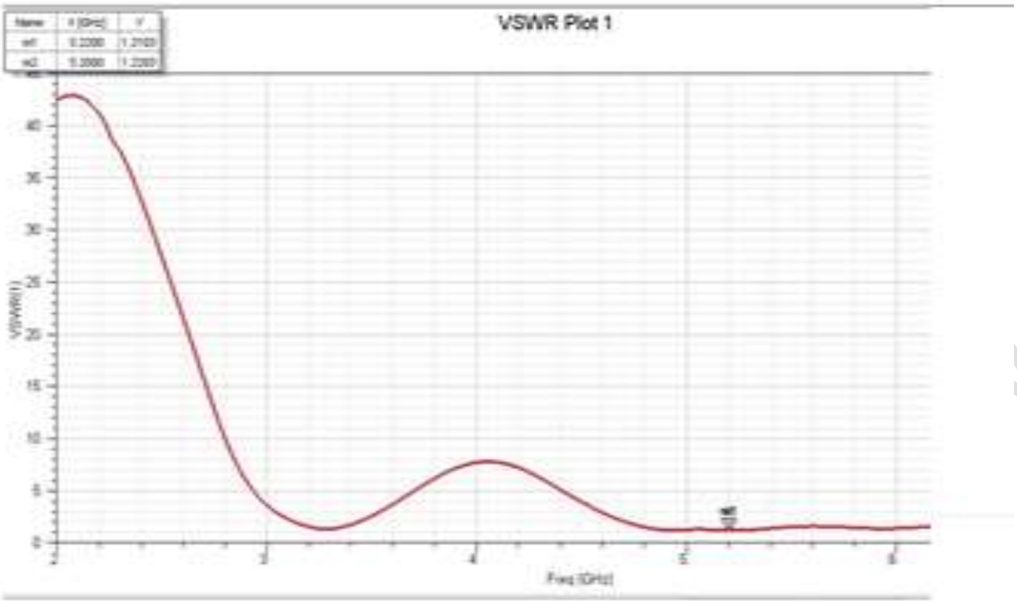


Figure 9: VSWR for the designed antenna at 5.25 GHz frequency

The figures reveal that at 3.6 GHz, the VSWR stands at 1.9299, indicating a higher level of power loss due to reflections, possibly indicating an impedance mismatch between the antenna and the transmission line. Conversely, at 5.25 GHz, the VSWR is lower at 1.2203, suggesting better impedance matching, resulting in improved power transfer efficiency and reduced signal loss. This disparity underscores the antenna's superior performance in power transfer at 5.25 GHz compared to 3.6 GHz.

A 50-ohm Microstrip line is used to feed the patch antenna, providing proper impedance matching for optimal performance. The simulation results indicate the bandwidths for the two distinct operating frequency bands. The first band, ranging from 3.32 GHz to 3.62 GHz, has a bandwidth of approximately 300 MHz.The second band, spanning from 4.72 GHz to 6.83 GHz, offers a bandwidth of about 2.11 GHz. These extensive bandwidths enable the antenna to function efficiently across both frequency ranges, making it suitable for various modern wireless communication applications.

The parameters obtained from the antenna simulation are presented in the following Table-2.

Table 2. Simulated parameters for designed Dual band Microstrip Patch antenna

Antenna Parameters	3.6 GHz frequency	5.25 GHz frequency
Scattering Parameters	- 5 dB	- 20.52 dB
Return loss	-13.98 dB	-26.24 dB
Radiation efficiency	74.2%	69.96%
Antenna Gain	2.77dBi	3.34dBi
VSWR	1.9299	1.2203
Bandwidth	300MHz (3.32 - 3.62 GHz)	2.11GHz (4.72 – 6.83 GHz)

4. CONCLUSION

The development, simulation, and analysis of the dual-band Microstrip patch antenna operating in two frequency bands, 3.32 GHz to 3.62 GHz and 4.72 GHz to 6.83 GHz, using Ansys High-Frequency Structure Simulator (HFSS) software have yielded promising results. The primary objective of enhancing performance metrics such as bandwidth, gain, and radiation efficiency for applications requiring simultaneous operation at both frequency bands has been successfully achieved.

In the first band, ranging from 3.32 GHz to 3.62 GHz, the antenna exhibits moderate reflection, as indicated by the scattering parameters and return loss measurements. Despite this, it demonstrates relatively high radiation efficiency and moderate gain. However, the VSWR suggests potential impedance mismatch, leading to increased power loss due to reflections.

In contrast, in the second band, spanning from 4.72 GHz to 6.83 GHz, the antenna shows significantly lower reflection, supported by lower scattering parameters and return loss values. This implies improved impedance matching and reduced power loss due to reflections. The radiation efficiency remains relatively high, while the gain slightly increases, indicating better directional focus of radiation. The lower VSWR at this frequency further confirms enhanced impedance matching and improved power transfer efficiency.

These findings highlight the importance of frequency optimization in antenna design. The transition from the lower to the higher frequency band demonstrates improved antenna performance, characterized by reduced reflection, enhanced impedance matching, and improved directional radiation focus. Such insights are invaluable for optimizing antenna designs for specific frequency applications, ensuring efficient and reliable performance in practical scenarios.

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