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Original Article

Design and Analysis of a Dual-Band CPW-Fed Flexible Split Ring Resonator Circular Microstrip Antenna for Wireless Wearable Devices

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Abstract - *This paper presents the design and analysis of a flexible circular microstrip antenna with a coplanar waveguide for use in a wearable wireless health monitoring system. The antenna applies a Split Ring Resonator (SRR) in place of a traditional monopole patch, which allows two different resonant frequencies to be generated. The antenna is built on a flexible paper substrate with a dielectric constant of 3.55, and it is enclosed in a circular trim that facilitates application on a patient's chest. The antenna also allows for remote monitoring because it operates on two different frequencies: 2.4 GHz for Wi-Fi and 3.4 GHz for WLAN. The metrics for performance are satisfactory in both frequency bands. At 2.4 GHz, the antenna has a gain of 4.3 dB, directivity of 4.43 dB, radiation efficiency of 17.21dB and Voltage Standing Wave Ratio (VSWR) of 1.33. At 3.4 GHz, a gain of 6.44 dB, directivity of 4.58 dB, a VSWR of 1.29, and radiation efficiency of 15.98 dB. This evidence suggests that the antenna can be used for health monitoring systems since it provides good wireless connectivity for wearable devices. The study aids in a location feature that can help further progress in this area by showing how flexible antenna designs can improve the comfort and functionality of wearable devices.*

Keywords - *Circular Microstrip, Coplanar Waveguide, Health Monitoring, Paper Substrate, Split Ring Resonator, Wearable devices.*

1. Introduction

With the development of health monitoring devices that are worn on the body, antennas have become prominent in medicine. The devices are enabled by advanced antenna technologies, which facilitate communication between patients and healthcare service providers [1]. For continuous monitoring of the patient's health, flexible antennas using the Coplanar Waveguide (CPW) structure are very effective because of their comfort and usefulness [2]. Technology that is worn on the body [3] assists doctors in monitoring patients' vital signs, including heartbeats, body temperature, and oxygen concentrations, without any difficulty. These devices cannot function effectively without antennas, which are crucial for wirelessly sending data to the health systems. Medical action is possible even when the patients are not physically in the health centres, hence enhancing the health outcomes of patients. Chronic patients, as well as old aged patients who need continuous monitoring, can benefit from this technology. Moreover, antennas are critical in telemedicine as they support remote consultation and follow-up with patients [4] living in regions where healthcare services are lacking.

Recent advancements in biomedical devices, especially body-centric communication technologies [5], have greatly improved healthcare provision by facilitating increased connectivity among patients, medical practitioners, and relatives. Remote monitoring systems are one such advancement, with patients being able to receive uninterrupted care at home, consequently cutting the high healthcare expenses related to hospitalization. The use of multiband antennas makes it more flexible so that devices can be connected on different protocols and networks, which is critical for consistent communication in wearable health applications [6].

Circular microstrip antennas, which have circular radiating elements, are becoming increasingly popular as a result of their small size and omnidirectional radiation [7]. The circular shape guarantees a symmetrical current distribution and, hence, increased bandwidth and efficiency compared to rectangular antennas. The antennas are optimally suited for use in broad coverage applications such as mobile and satellite communications and other wireless systems [8]. Their thin form factor enables them to be integrated into handheld and wearable devices and be used in many different settings [9].

Even with these benefits, current wearable antenna structures suffer from limitations in sustaining high performance and ensuring flexibility, miniaturization, and stable operation over multiple frequency bands. Most traditional antennas are either rigid to be integrated into wearable systems easily or functional over limited frequency bands, limiting their use in multiband communication systems. Balancing mechanical robustness, electromagnetic performance, and multiband functionality is a key research lacuna in wearable antenna design.

This work presents a conformable, thin-profile CPW-fed circular microstrip antenna featuring an SRR configuration. It provides dual-frequency operation at 2.45 GHz and 3.4 GHz in response to Wi-Fi and WLAN communication needs. Electromagnetic parameters such as gain and reflection coefficient show top-notch performance with an omnidirectional radiation pattern at both frequencies, offering a robust wireless connection. The incorporation of soft materials like plastic, paper, or textiles increases wearable flexibility. Through its ability to enhance the comfort and function of wearable medical devices, this study helps to advance next-generation wearable health monitoring technology.

2. Literature Review

The integration and design of antennas in medical devices have been the focus of much research, with emphasis on key areas like size, efficiency, and biocompatibility. According to Rajesh Kumar, G. Venkat Babu, and N. Raju (2020) [10], miniaturization of antennas is important for their smooth integration into medical devices, while biocompatibility is important to avoid reactions in patients. Numerous studies reinforce these design considerations as the incorporation of antennas in medical devices grows more crucial for monitoring and treating patients. One major concern during the design process is preserving antenna performance when brought close to or in contact with biological tissues. Reji and Manimegalai (2019) [11] highlighted this feature by providing a dual-band antenna for the medical field, with its efficacy substantiated through the wearability experiment on various tissues, and reinforcing the advantage in flexibility small size antennas provide on direct placement against the body. Also, Upreti (2021) [12] explored the application of flexible materials such as Polyethylene Terephthalate, which have good performance in free space and close to the human body, an important consideration in wireless body area networks.

Although there have been improvements in antenna technology, the integration of antennas into medical systems still has issues, particularly in terms of reliable wireless data telemetry. Topsakal (2009) [13] mentioned the challenges of creating antennas for medical devices, pointing out that most current designs are still very much in the simulation phase, with actual implementation still in development. Creating reliable implantable RF systems that make continuous data transmission a certainty without interference is a major research challenge. Likewise, Lemaître-Auger, Tedjini, and Andriamiharivolarnena (2018) [14] emphasized long-term safety and reliability when integrating antennas close to the human body, highlighting that antennas must be capable of performing over long times without any adverse effects on the health of patients.

Wearable antennas are increasingly being incorporated into different healthcare technologies, enhancing medical treatment and monitoring technologies. Prudhvi Nadh, Madhav, and Siva Kumar (2019) [15] observed that wearable antennas are utilized in vital sign monitoring, including ECG telemetry and blood glucose levels, as well as drug delivery systems. The ease of integration of the antennas into medical devices allows constant monitoring of patients, enhancing the quality of care. Secondly, patient tracking is accomplished by wearable antennas. López-Soriano and Parrón (2015) [16] designed a wristband UHF European band (865-868 MHz) antenna to track patients at a read distance of up to 2 meters, suitable in small environments such as hospitals. Conway and Scanlon (2022) [17] further created a UWB antenna to be employed for microwave imaging purposes to detect tumours, leveraging the integration with fabrics to ensure both comfort and ease of functionality.

Performance-wise, wearable antennas are always optimized in terms of higher efficiency, gain, and bandwidth, especially near the human body. Jacob, Salama, Abbas, and Liyanapathirana (2021) [18] discussed a range of different wearable antenna types and highlighted miniaturization techniques and polarization approaches as essential aspects for efficient functioning in the presence of the human body. Gain and radiation efficiency are two of the main performance parameters crucial to determining antenna performance. Abdulrahman S. M. Alqadami et al. (2019) [19] presented a 9.8 dB realized gain and 60% radiation efficiency with the assurance of keeping the specific absorption rate (SAR) within safety limits for on-body communication. Moreover, Khajeh-Khalili, Shahriari, and Haghshenas (2020) [20] proved that triple transmission lines could greatly improve the gain and bandwidth of wearable antennas with dual-band performance in the frequency bands of 1.7–2.5 GHz and 5.4–5.95 GHz, which are appropriate for medical communication systems.

Sudharsanam, Sesha and K.G. Shanthi (2023) [21] presented that Ultra Wide Band(UWB) flexible antennas have also been a good candidate for Wireless Body Area Networks(WBAN) purposes. Patch and fractal antennas are especially appropriate for wearable applications because of their conformability to the human body, low profile, good flexibility, and ease of fabrication. It addresses some flexible antenna design challenges like material selection, substrate properties, and fabrication techniques. The article enhances understanding of the challenges and opportunities in the development of flexible antennas for WBAN applications. Addressing the increasing demand for wireless healthcare solutions necessitates ongoing research on the advancement of flexible UWB antennas for WBAN systems.

Afroz et al. (2024) [22] discussed the fabrication and measurement features of a thin, flexible, wideband printed antenna and briefly compared it with a standard copper tape antenna. The research revealed high conformity between simulation and measurement results, confirming the accuracy of the fabrication and measurement process. A bending analysis was also performed to test the performance of the antenna when deformed, proving that it is still in good working condition even when bent.

The design requirements, integration issues, and applications of wearable antennas in healthcare, as well as the developments in performance enhancement, are highlighted. With ongoing research overcoming existing constraints, wearable antennas will increasingly contribute to the future of medical technology, opening up new avenues for patient monitoring and treatment.

3. Antenna Design

The antenna structure comprises a circular microstrip geometry integrated with Split Ring Resonator(SRR) elements employing Coplanar Waveguide (CPW) feeding [23] to attain dual-band operation. It focuses on compactness and flexibility and thus is well suited for hassle-free integration into wearable technology.

3.1. Split Ring Resonator

A Split Ring Resonator (SRR) is a metamaterial structure. Due to its unusual electromagnetic features, the SRR has become more important in the design of an antenna. It is essentially a split ring with one gap in a metallic ring; this allows the SRR to take on resonant characteristics that can be quite fine-tuned by the dimensions of the resonator and the width of the gap [24]. This ring is made of metal and is designed using materials like copper or gold, which supports the passage of electric current when exposed to electromagnetic fields. The resonance enables the SRR to store and release electromagnetic energy effectively, hence making it suitable for applications in multiband cases.

The SRR works like an LC circuit, with both capacitance and inductance taking central roles in its resonant activity:

Inductance (L): When the current passes through the ring of conductive material, it creates a magnetic field similar to an inductor. The bigger the ring, the higher the inductance, which affects the SRR's resonant frequency.

Capacitance (C): The gaps in the ring act as capacitors by storing electrical charge and creating an electric field. The gap size, number of gaps, and ring dimensions determine the overall capacitance, allowing the SRR's resonant frequency to be finely adjusted based on its physical configuration.

SRR resonant frequency(f) is determined by Equation 1 expressed as:

$$f = \frac{c}{2\pi\sqrt{LC}} \qquad (1)$$

Where,

c is the speed of light,
L is inductance and
C is capacitance

The performance of a Split Ring Resonator (SRR) is largely dependent on its geometric parameters, including the outer radius, inner radius, and gap width. These dimensions can be adjusted to target certain resonant frequencies specifically. In this design of the antenna, two SRRs of different radii are used to enable operation at two different frequencies, as shown in Figure 1. By using SRRs of different sizes, each resonator can be tuned to resonate at frequencies corresponding to their geometric parameters.

The initial SRR, with a greater radius, is designed for operation at lower frequencies. Its structure allows for effective interaction with electromagnetic waves at this frequency, making it highly effective in applications requiring a broader range and wider coverage. The second SRR, with a smaller radius, is designed to resonate at a higher frequency. Such arrangement is most valuable for purposes of better bandwidth and efficiency since it usually sustains better data and signal transfer capabilities at higher frequencies.

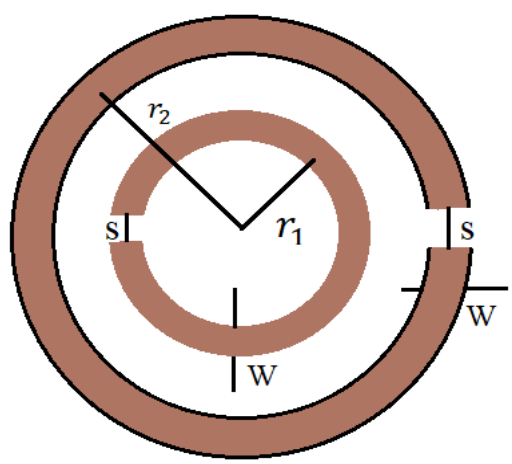

Fig. 1 Structure of split ring resonator

The typical loop lengths L_1 and L_2 of the effective lengths of the conducting loops responsible for the resonant property of the SRR are defined by Equations 2 and 3. They are computed as each loop's total circumference minus a gap (S) by the respective radii r_1 and r_2 of their loops as:

$$L_1 = 2\pi * r_1 - S \quad (2)$$

$$L_2 = 2\pi * r_2 - S \quad (3)$$

Where,

L_1 is the average loop length of a smaller metallic ring,

L_2 is the average loop length of a larger metallic ring,

r_1 is radii of smaller metallic ring,

r_2 is radii larger metallic ring,

S is a split or Gap of a Metallic ring

The resonant frequencies of every loop f_1 and f_2 are calculated on the basis of half-wavelength resonance. According to this principle, resonance occurs when the physical length of the loop is half the wavelength of the electromagnetic wave. Mathematically, this relation is expressed by equation 4 and 5 as:

$$f_1 = \frac{c}{2L_1\sqrt{\varepsilon_{eff}}} \quad (4)$$

$$f_2 = \frac{c}{2L_2\sqrt{\varepsilon_{eff}}} \quad (5)$$

Where,

c is the speed of light,

f_1 is the resonant frequency of smaller metallic ring,

f_2 is the resonant frequency of the larger metallic ring

The gaps in the ring are responsible for determining the resonant behavior of the ring. One gap allows the SRR to support resonant modes by enabling electromagnetic energy to flow around the loop. This break in the current flow promotes the creation of electric and magnetic fields that enhance resonance. Two gaps introduce more complex resonant modes and allow the SRR to support multiple resonant frequencies. Both the gaps affect the effective inductance and capacitance of the loop, which are essential parameters in determining the resonant frequency.

Embedding two SRRs in an antenna design enhances its multiband ability, which is efficient enough for operation at numerous frequency bands. The specific electromagnetic properties of SRRs contribute to successful energy storage and discharge, making them essential elements for contemporary wireless communications and wearable technologies. Their potential to govern electromagnetic behaviour is behind the production of small-sized, flexible, and high-capacity antennas responding to the shifting needs of modern-day technological evolution.

3.2. Proposed Antenna Design

The key focus lies in selecting proper materials, finding key design parameters, and employing SRR methodologies to implement multiband capability [25]. Simulation of the performance of the antenna is conducted by utilizing state-of-the-art electromagnetic simulation software like HFSS.

The strategy spans every step in the design cycle to enable the antenna to meet the rigorous standards of wireless wearable devices, such as flexibility, low profile, and multi-frequency capability for communicating within frequencies like Wi-Fi and Bluetooth.

3.2.1. Material Selection

In order to design an antenna, the right choice of substrate material is imperative to ensure performance and longevity [26].

For this design, PREPERM paper, made available by the Premix Group, was utilized owing to its printability, mechanical strength, low profile, and flexibility. It has a dielectric constant of 3.55 and a loss tangent of 0.005, giving it the right blend of manufacturability and high performance. The substrate was made 0.15 mm thick to ensure the necessary flexibility, which enables the antenna to conform easily to body shapes without compromising its electromagnetic performance.

This aspect makes it very appropriate for wearable applications, such as remote monitoring systems. The electromagnetic performance of the designed antenna was simulated and studied using full-wave analysis in HFSS to ensure the antenna's performance meets the desired standards.

3.2.2 Design parameters

The given parameters and dimensions are vital to the design of the antenna, relating to different necessary components. The following are detailed descriptions of each parameter:

Width of the Feedline(W_f)

It is used to join the antenna to the outside circuit for the transmission of energy. Being 2 mm wide, it plays a central role in impedance matching and the efficiency of signal transmission between the antenna and the feed network.

Width of the Copper Trace(W_{cu})

Copper trace is the conduction path of the antenna for transmission and reception of signals. 3.2 mm trace width determines the electrical conductivity and, thus, the antenna's performance.

Gap between the First SRR(X_{fed})and Feedline

A 5 mm gap is maintained between the first Split Ring Resonator (SRR) and feedline, as it is extremely crucial in order to establish electromagnetic coupling between them. The gap influences the resonant characteristics of the antenna as well as the transmission characteristics of the antenna at specific frequencies.

Width of the CPW Feed Structure(X_{cpw})

CPW feed structure [27] consists of a centre strip placed between two grounds. Having a total width of 16 mm, it also serves a significant function in maintaining impedance and the feedline-antenna interaction influencing signal propagation and impedance matching.

Substrate Width (X_{sub})

The 18 mm wide substrate provides mechanical support to the antenna structure and affects its dielectric properties, frequency response, and efficiency.

Radius of the Substrate (R_{sub})

The radius of the circular substrate of 27 mm determines the area where the antenna elements are. Its radius directly affects the working frequency and the spatial character of the radiation pattern.

Radius of the CPW-fed Circular Patch Area (R_{cpw})

This area is the centre radiating patch that is fed by the CPW feedline. The patch radius at 26 mm defines the resonant characteristic of the antenna and its operating frequency.

Radius of the Feed Element(R_{fed})

The radius of the feed element is 17 mm, and it indicates the area over which energy is supplied to the antenna system. It also specifies the coupling efficiency and bandwidth of the antenna.

Radius of the First Split Ring Resonator (R_{srr1})

The first Split Ring Resonator (SRR), a 16 mm metal ring, helps to introduce some resonance properties. This is an extremely critical parameter in adjusting the resonant frequencies of the antenna so that it can work for more than a single band.

Second Split Ring Resonator (R_{srr2}) Radius

The second SRR is the inverted one and serves to facilitate multiband operation.

The second and smaller SRR, with a radius of 13 mm, provides a second resonant frequency for the antenna, increasing its ability to operate in two frequency bands.

The dimensions of the listed design parameters in Table 1 also contribute significantly towards increasing the performance of the antenna since signal propagation is ensured by CPW feed structure, SRRs ensure multiband nature, and substrate and feedline dimensions ensure impedance matching and overall bandwidth.

Table 1. Design parameters of Proposed antenna

Parameter	Value (mm)
Width of the Feedline(W_f)	2
Width of the copper trace(W_{cu})	3.2
Gap between the feedline and the first SRR(X_{fed})	5
Width of the CPW Feed Structure(X_{cpw})	16
Width of the Substrate (X_{sub})	18
Radius of the Substrate (R_{sub})	27
Radius of the CPW-fed Circular Patch Area (R_{cpw})	26
Radius of the Feed Element(R_{fed})	17
Radius of the First Split Ring Resonator (R_{srr1})	16
Radius of the Second Split Ring Resonator (R_{srr2})	13

3.2.3. Designed Antenna

The antenna is designed in HFSS software by incorporating the parameters as described in Table 1, with two Split Ring Resonators (SRRs) and a Coplanar Waveguide (CPW) fed [28] circular patch.

The design is especially beneficial for wearable purposes because it provides efficient signal transmission along with a compact size. The proposed antenna is shown in Figure 2.

The design parameters are carefully selected to balance performance and size constraints common to wearable technology [31]. The low-profile and lightweight design enables easy wearing, making it simple to integrate into clothing or accessories.

This novel design not only improves user experience but also ensures end-to-end reliable communication in a variety of environments, making it suitable for health monitoring, fitness tracking, and other wearable applications.

The antenna has a central circular metal patch, which is a typical element in microstrip antennas [29-30] due to its omnidirectional radiation capability. The antenna is small in size and, hence, well adapted to wearable devices.

The central circular patch is also encompassed by split ring resonators, which enable the antenna to support dual-band or multiband operation. The arrangement of the SRRs enables the antenna to resonate at multiple frequencies, thus making the antenna well-adapted to various wireless applications, including Wi-Fi and Bluetooth.

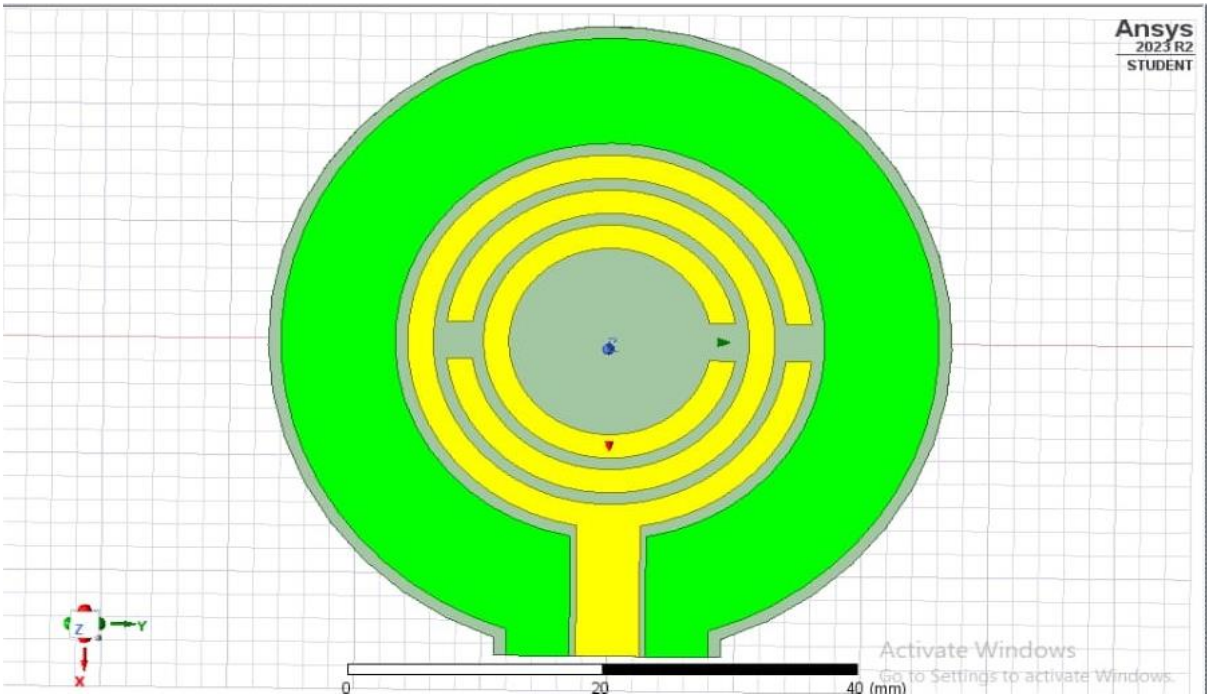

Fig. 2 Designed dual band circular microstrip antenna

This design uses a Coplanar Waveguide (CPW) feeding mechanism. CPW is preferred because it offers wide bandwidth, increased impedance matching, and simplicity of fabrication. CPW also fosters flexibility and is, hence, convenient for wearable antennas that need low-profile and adjustable structures. The substrate placed below the antenna patch offers mechanical strength and influences the overall electrical response. Made flexible, it is optimized for wearable devices. Moreover, the ground plane is helpful for effective radiation and impedance matching.

The antenna, designed as above, is analyzed for various important parameters that altogether ascertain its performance in real-life applications. S-parameters determine the impedance matching, whereas VSWR determines power transmission efficiency. Gain calculates the directionality of the radio frequency energy, and directivity tells us how concentrated the radiated energy is. Radiation efficiency also tells us how efficiently the input power is being converted to radiated energy. These determinations are required to optimize the antenna for diverse applications.

4. Results and Discussion

Dual-band circular microstrip antenna was conceived and modelled via CST Studio Suite to allow the electromagnetic analysis properly for its functioning at 2.4 GHz and 3.6 GHz as desired by modern wireless communications. Substrate material, the geometry of the patch, and the mechanism of the feeding were established as part of the simulation to accomplish effective dual-band functioning. Finite Element Method (FEM) was used to perform full-wave analysis with exact results for gain, directivity, radiation efficiency, VSWR, and radiation patterns.

The substrate material was chosen according to its dielectric characteristics to reduce losses and improve performance at the desired frequencies. Patch size and feeding position were tuned utilizing parametric sweeps to resonate in the specified bands. The excitation was done by a waveguide port, with impedance matching achieved and boundary conditions specified as open (radiation) to achieve free-space conditions well.

Meshing was optimized with adaptive methods to achieve computational efficiency and accuracy. The simulation results were confirmed by comparing the results from different iterations to be consistent. The systematic approach allows for reproducibility and verification of the performance of the antenna for compatibility with Wi-Fi and WLAN devices.

4.1. Gain Performance

The Gain of the designed antenna at the interested frequencies is shown in Figure 3 and Figure 4. Figure 3 shows the antenna to achieve a gain of approximately 4.3 dB at 2.4 GHz and 4.4 dB at 3.4 GHz, showing a similar performance at the two frequencies. Figure 4 indicates a gain of around 6.4 dB for 3.4 GHz, indicating better efficiency at this frequency. Other than the target frequencies, the gain reduces considerably with a rapid decline in non-designated bands, a measure of optimization of the antenna to 2.4 GHz and 3.4 GHz frequencies.

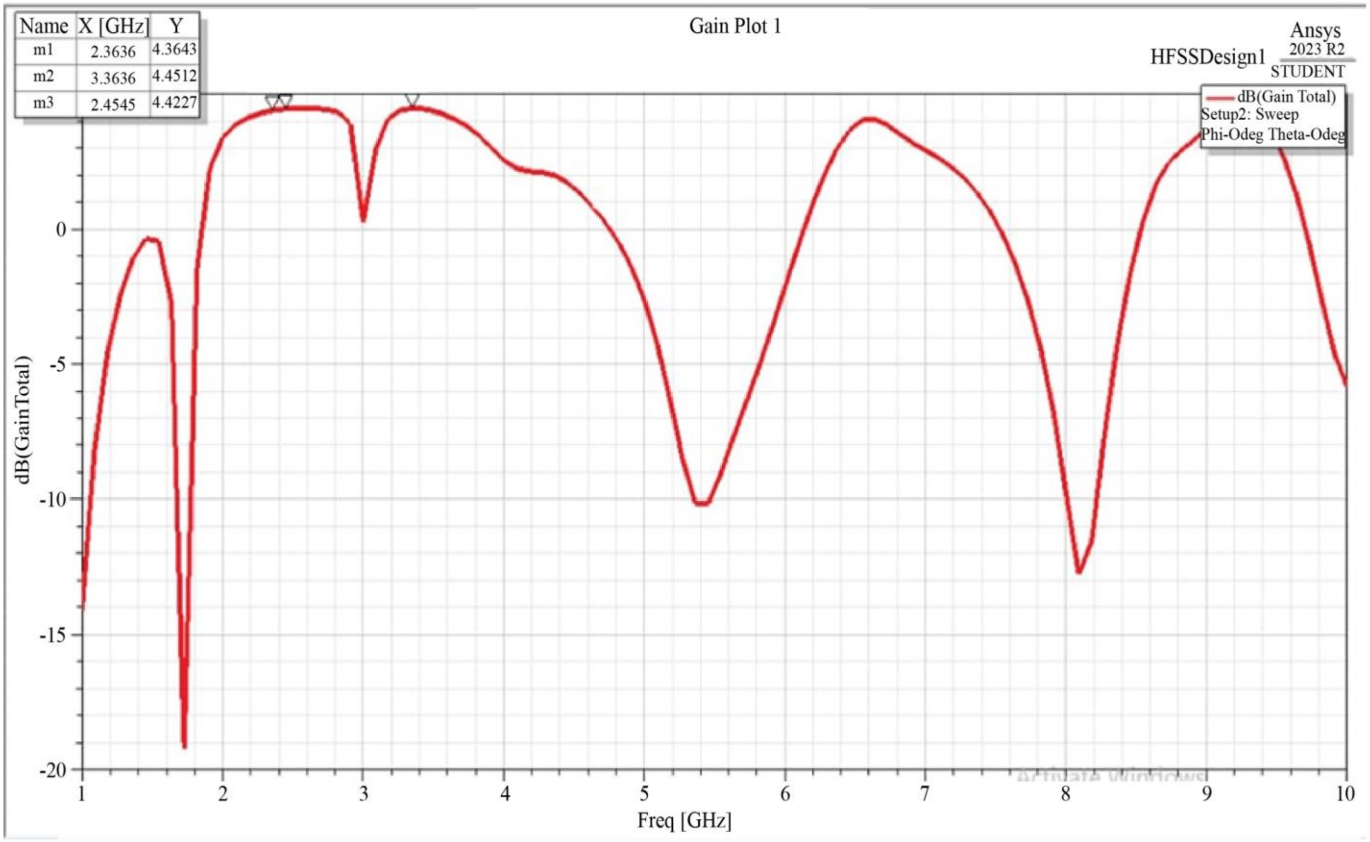

Fig. 3 Gain of Dual band circular microstrip antenna at 2.4GHz

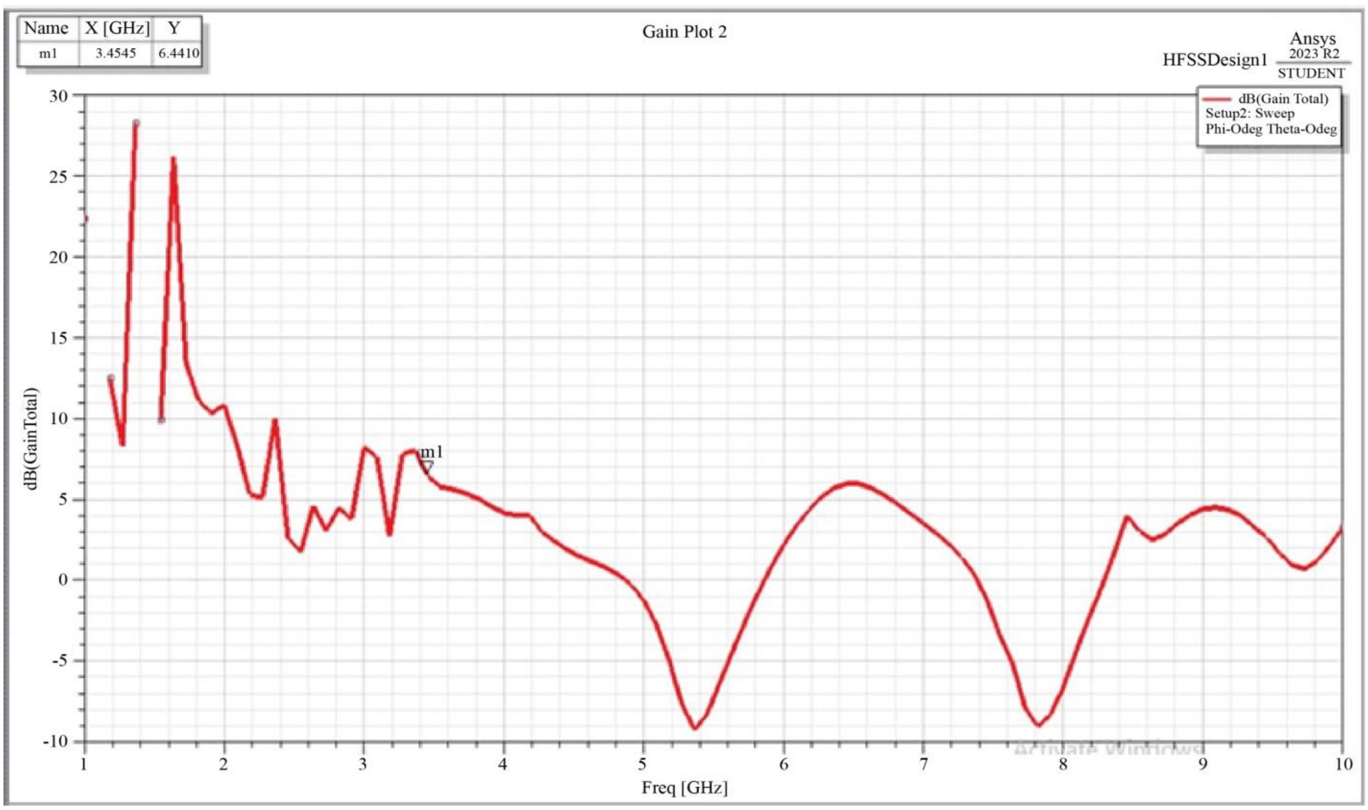

Fig. 4 Gain of Dual band circular microstrip antenna at 3.4GHz

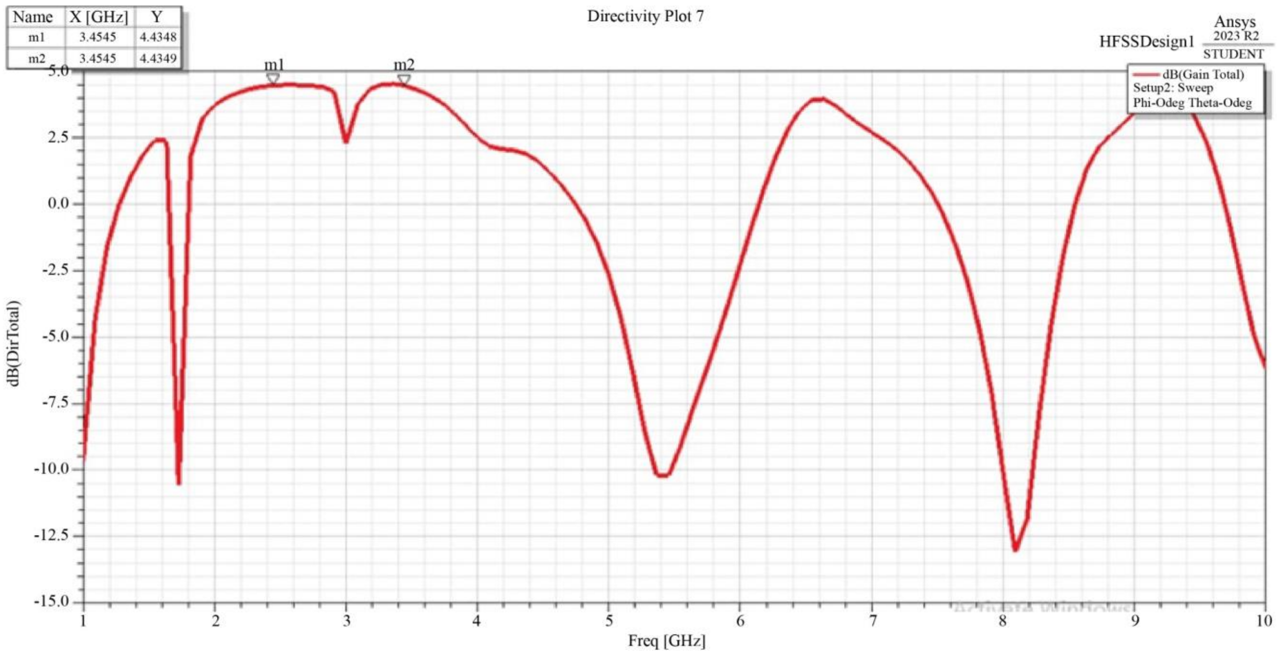

Fig. 5 Directivity of Dual Band Circular Microstrip antenna at 2.4GHz

4.2. Directivity Performance

The Directivity of the antenna as designed at the desired frequencies is presented in Figure 5 and Figure 6. From Figure 5, the antenna has a directivity of 4.43 dB at 2.4 GHz, demonstrating good performance and effective energy radiation at frequency. This value is good for applications like Wi-Fi and Bluetooth, where high directivity is useful to improve communication in desired directions.

From Figure 5, the directivity at 3.4 GHz is 4.41 dB, which is very close to that at 2.4 GHz. This shows that the antenna is also suitable for use at 3.4 GHz and can be a good candidate for use in applications such as 5G or WiMAX. The comparable directivity values at both frequencies show the effective design of the antenna for dual-band operation. The small difference between 2.4 GHz and 3.4 GHz indicates that the antenna is optimized for even performance in both bands.

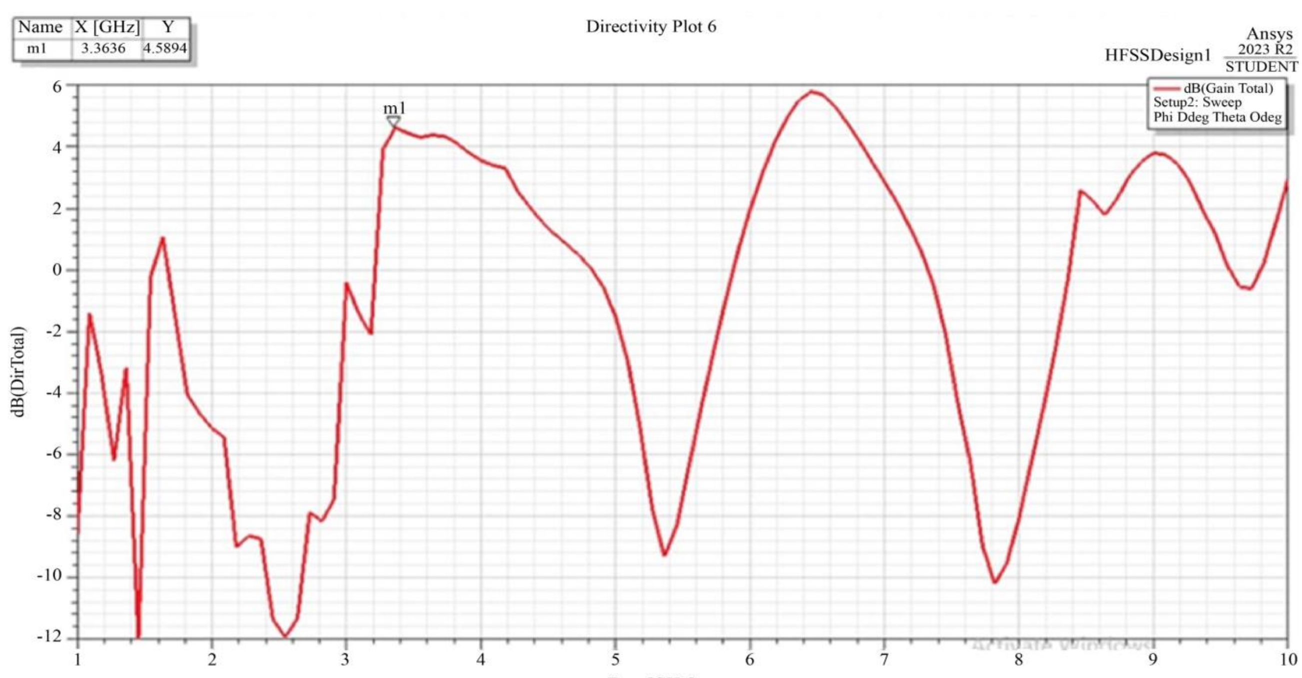

Fig. 6 Directivity of Dual Band Circular Microstrip antenna at 3.4GHz

From Figure 6, the directivity at 3.4 GHz is approximately 4.58 dB, which is an improved performance compared to the Figure 5 plot for this frequency. The oscillations between frequencies indicate some design trade-offs to facilitate multi-band operation.

4.3. Radiation Efficiency Performance

It computes the power radiated to input power ratio considering conductor resistance, dielectric characteristics, and surface wave losses. A low-loss substrate was selected to minimize dielectric loss, and the patch size and feeding mechanism were optimized for improved impedance matching. Simulation, using the Finite Element Method (FEM), confirmed high radiation efficiency across both frequency bands with applicability to Wi-Fi and WLAN applications with good and consistent results**.**

The radiation efficiency of the designed antenna at the specified frequencies is indicated in Figure 7. The efficiency for 2.4 GHz is approximately 17.21 dB, indicating higher performance with no power loss and effective energy radiation at this frequency.

At 3.4 GHz, the efficiency is around 15.98 dB, which is less than at 2.4 GHz but demonstrates the antenna to be compatible with operation at this frequency. Both at 2.4 GHz and 3.4 GHz, the antenna is optimized in radiation efficiency, demonstrating the optimization of the antenna for dual-band utilization.

The efficiency drops off at other frequencies slightly, as would be expected, because the design of the antenna is optimized primarily for these two bands.

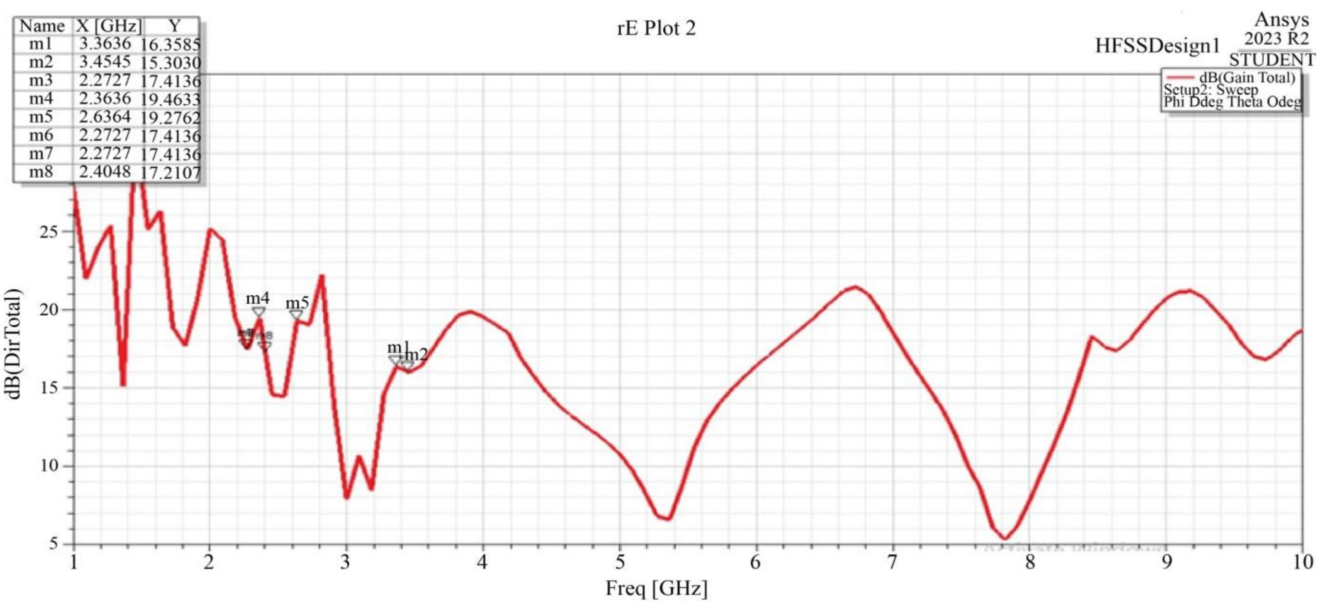

Fig. 7 Radiation Efficiency of Dual band circular microstrip antenna at 2.4 GHz and 3.4GHz

4.4. Radiation Pattern

Figure 8 and Figure 9 show the 2.4 GHz and 3.4 GHz antenna radiation patterns, reflecting the space distribution of radiated energy. These patterns are required to determine antenna performance and are usually given for two orthogonal planes, for instance, Phi = 0° (red line) and Phi = 90° (green line), as depicted in the figures.

From Figure 8, the pattern is bidirectional, with energy radiating in symmetric opposite directions. The areas of maximum radiation are shown by the lobes in the red and green traces, and areas of minimum or zero radiation by the nulls. The same bidirectional pattern is observed in both the orthogonal planes with minimal differences in gain, highlighting the directional character of the antenna.

At 2.4 GHz, the pattern demonstrates that the antenna is radiating energy very well in specific directions and, therefore, can be used in Wi-Fi and Bluetooth communication systems with this frequency.

The sizes of the lobes in each of the plots represent the gain in each direction. The uniformly distributed gain on the two planes reflects consistent performance in both directions.

From Figure 9, there is an asymmetric bidirectional pattern of the antenna with well-distinguished changes in gain with respect to radiation direction. The lobes represent the principal directions of high-energy radiation, and the nulls show areas with low radiation. The Phi = 0° plane has denser and stronger lobes than the Phi = 90° plane, exhibiting improved radiation efficiency along the latter direction.

At 3.4 GHz, radiation patterns highlight the capability of the antenna to radiate in specific directions with high efficiency, a critical aspect for application in 5G and other high-frequency systems where communication is necessary. The patterns show that the antenna is designed to support dual-polarization radiation, which enhances its performance in applications where smooth communication in specific directions is needed. The lobe length has a correlation with the gain in other directions, such that longer lobes correspond to greater radiative efficiency. The gain asymmetry between the two planes means that the antenna is optimized for specific directional and polarization requirements.

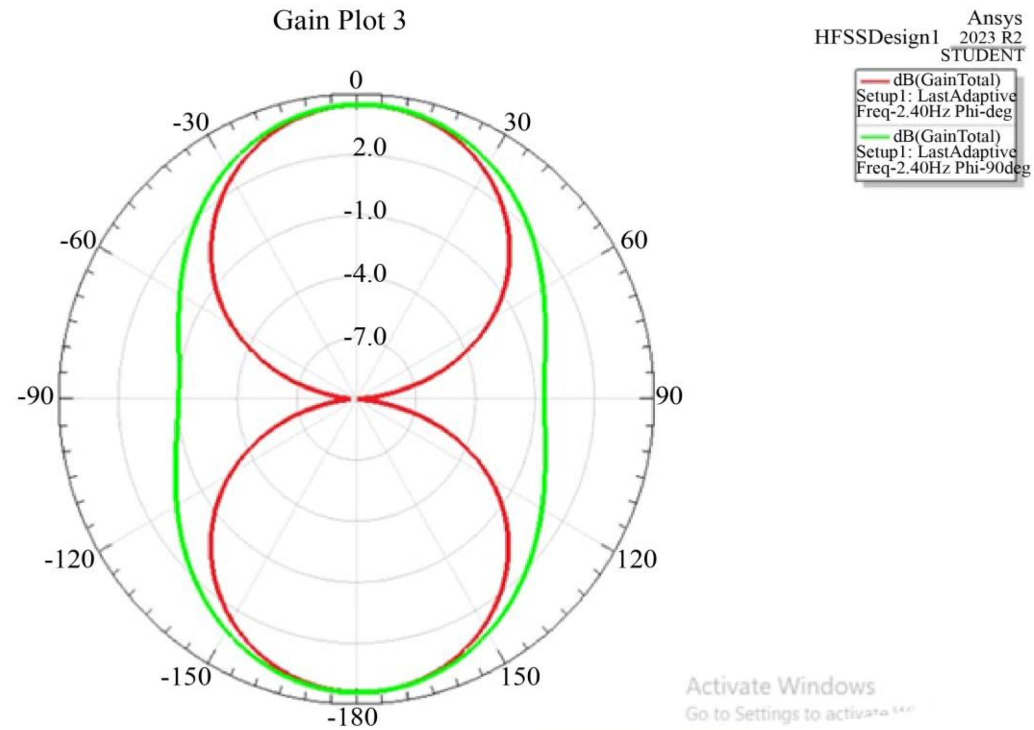

Fig. 8 Radiation Pattern of Dual band circular microstrip antenna at 2.4 GHz

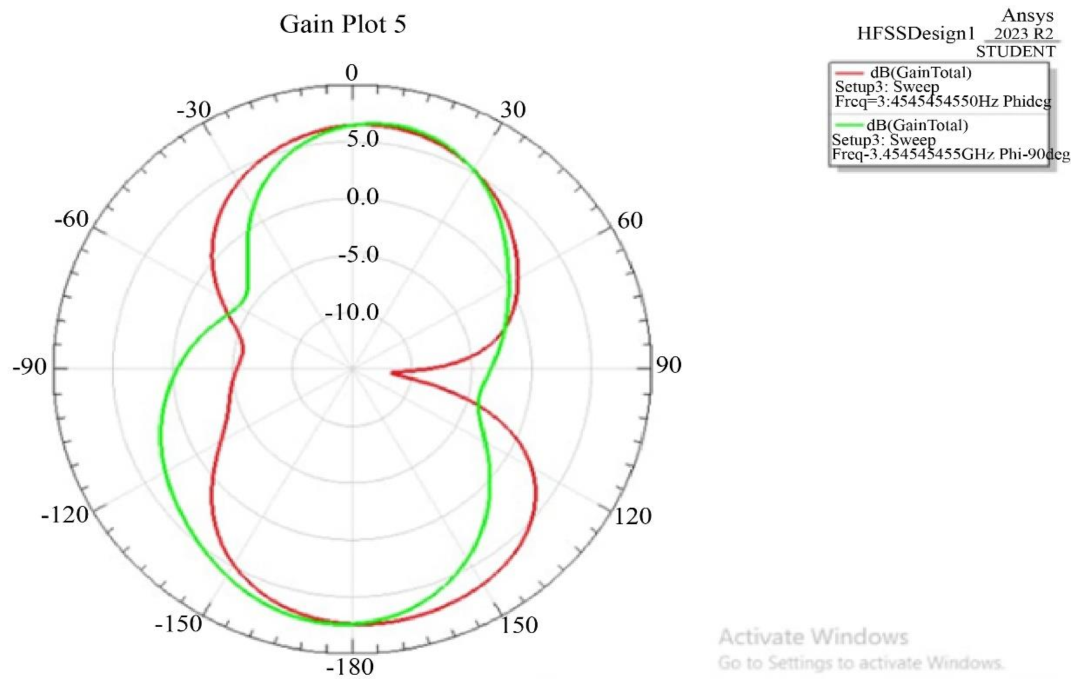

Fig. 9 Radiation Pattern of Dual band circular microstrip antenna at 3.4 GHz

4.5. VSWR Performance

Figure 10 shows the robust performance of the antenna at frequencies 2.4 GHz and 3.4 GHz from the low values of VSWR, which are 1.33 and 1.29 at these frequencies.

Low VSWR indicates a good impedance match between the antenna and transmission line, allowing good energy transfer with minimal reflection from the signal. This guarantees successful radiation of the energy, positioning the antenna at a good choice for these frequencies.

Performance at the 2.4 GHz frequency of the antenna is especially good since this is the frequency applied in wireless communication technologies like Wi-Fi and Bluetooth that need transmission of stable signals. Similarly, low VSWR at 3.4 GHz stands at 1.29, reiterating that the antenna would be suitable in the new-generation 5G applications where signal frequencies are very high, and signals require accurate impedance matching for maximum performance. Overall, the efficiency of the antenna in operating effectively at these frequencies makes it suitable for current and future wireless communication systems.

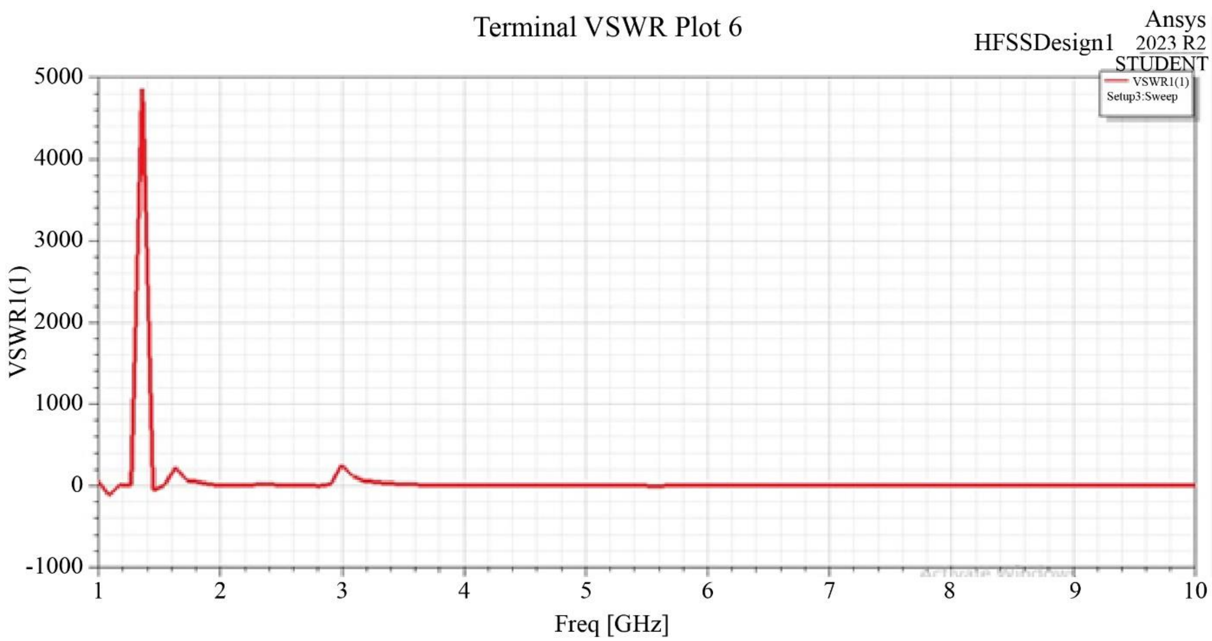

Fig. 10 Voltage Standing Wave Ratio of Dual band circular microstrip antenna

The simulated parameters of the dual-band circular microstrip patch antenna at 2.4 GHz and 3.4 GHz frequencies are given in Table 2.

Table 2. Simulation Results of Dual-Band Circular Microstrip Patch Antenna for 2.4 GHz and 3.4 GHz

Parameter	2.4GHz	3.4GHz
Gain	4.3dB	6.4dB
Directivity	4.43dB	4.58dB
Radiation efficiency	17.21dB	15.98dB
VSWR	1.33	1.29

The enhanced performance of the dual-band circular microstrip antenna lies in its design parameters, which are optimized to boost its efficiency for the desired frequencies. The geometrically designed geometry is stable and maintains gain and directivity, which makes the signal transmission and reception effective. The structure of the antenna avoids losses. Hence, it has high radiation efficiency and better impedance matching, as seen from the low VSWR values. In addition, the design efficiently suppresses unwanted radiation outside the specified bands, maximizing its performance for Wi-Fi, Bluetooth, and 5G applications. All these aspects together lead to better results in the simulation.

The radiation efficiency of the dual-band circular microstrip antenna has a direct application on the feasibility of the antenna for practical use, especially in medical communication systems. High radiation efficiency guarantees small power loss, which is paramount for wearable and implantable medical devices where energy should be minimized. The parameters of the performance of the antenna, such as gain, directivity, and VSWR, provide evidence of efficient radiation of energy and transmission of signals, which are prerequisites for stable and consistent wireless communication in patient monitoring systems.

In real-world applications, the low VSWR values guarantee maximum impedance matching, minimizing signal reflection and maximizing power transfer. This is particularly beneficial for biomedical devices, where ongoing data transfer becomes inevitable for patients' real-time monitoring.

Additionally, the bidirectional and asymmetric radiation patterns of the antenna at different frequencies enable versatile coverage, enhancing connectivity in varied patient settings. Its high 2.4 GHz directivity enables applications such as Bluetooth and Wi-Fi, while its 3.6 GHz capability can be used with upcoming 5G-enabled medical technology, enabling high-speed data streaming for remote diagnostics and telemedicine.

Choosing a low-loss substrate and optimized feeding mechanism further enhances the performance, with equal efficiency in both frequency bands. This prolongs battery life for portable medical equipment, avoiding periodic recharging and improving patient comfort. With stable radiation efficiency within defined frequencies, the antenna becomes an efficient option for next-generation medical wireless communication systems, with reliability, efficiency, and integration with future healthcare technology.

Table 3 provides a comparison between the proposed antenna design's simulated parameters and earlier works, pointing out the main improvements, including increased efficiency and better performance within specific frequency bands. The comparison also centres on other key measures, such as gain, which further highlight the advantages of the proposed design over the available alternatives.

The new antenna design has a reduced structure size with respect to earlier designs, and hence, it is suitable for applications that have space constraints. The compact size can be easily integrated into handheld devices, wearable devices, and small-scale communication systems without any performance compromise. Another unique aspect of the proposed antenna is the dual-band functionality. In contrast to the conventional single-band antennas, the proposed antenna sustains multiple communication technologies on two bands. Hence, it is more compatible and suitable with a wide variety of wireless systems.

Table 3. Parameter Comparison of Proposed antenna with previous designs

Ref.	Size (mm^3)	No. of bands	Frequency (GHz)	Gain (dB)	Application based bands
[32]	40 × 32 × 2	single	2.45	5.15	ISM
[33]	20 × 30 × 0.2	single	3.3	>2.2	5G
[34]	100 ×100 × 2	Dual	2.45 5.8	5.93 6.02	ISM
[35]	50 × 70 × 0.8	Dual	0.918 2.45	2.51 3.89	MICS ISM
[36]	80× 80 × 3.575	Dual	2.45 5.5/5.8	0.27 5.18/5.54	ISM WLAN
[37]	52× 52× 6.94	Dual	1.88 2.5	3.95 5.29	GPS Satellite communication
[38]	85 × 85 × 2	Dual	2.4 5.4 -	3.6 5.5	ISM/Wi-Fi 4G LTE
[39]	40 x 40 x 1.6	Dual	2.4 and 5.25	2.6 4.9	WLAN
Proposed	54 x 18 x 1.5	Dual	2.4 and 3.4	4.3 6.4	ISM, Wi-Fi, 4G LTE

The antenna has 4.3 dB and 6.4 dB gains, providing enhanced signal strength and efficiency. These increased gain figures help enhance overall performance, particularly in situations where strong signal reception and transmission are critical. With its dual-band architecture, the antenna can be applied to a range of applications, such as in ISM bands, Wi-Fi, and 4G LTE systems. This makes it applicable in a wide range of wireless technologies, from IoT devices to mobile communications systems, opening up its area of application.

The dual-band capabilities and increased gain levels (4.3 dB and 6.4 dB) provide increased performance with improved signal quality and range. This positions the antenna to perform better in long-range communication as well as in areas with signal issues.

The dual-band operation and increased gain guarantee that the antenna will be able to support future communication technologies. As wireless standards continue to advance, the proposed antenna will still offer efficient performance with long-term applicability compared to outdated, single-band antennas.

5. Conclusion

This article presents the design, simulation, and performance analysis of a dual-band circular microstrip patch antenna designed specifically for wearable device applications. The antenna was specially designed to operate at 2.4 GHz and 3.4 GHz, which are key frequency bands for contemporary wireless communication technologies such as Wi-Fi, Bluetooth, and 5G.

The simulation outcomes indicate that the antenna provides robust performance in various critical parameters. The gain in both frequencies guarantees stable signal intensity, which is crucial for wearable technology. The directivity is appropriate, meaning that the antenna transfers energy effectively and reduces interference, thus improving communication performance. Of particular note is the high radiation efficiency, which is an important benefit, indicating little power loss, and is particularly important for wearable devices that depend on long battery life. Also, the low VSWR at both frequencies ensures perfect impedance matching, with the antenna operating with maximum efficiency and minimum signal reflection.

The antenna is very effective for wearable devices, providing good communication with energy efficiency. The design strikes a good balance between performance and usability, making it suitable for wireless communication in small, power-limited environments.

Future research may continue to optimize the antenna's size and bandwidth and integrate it into even smaller wearable devices. The performance of the antenna may also be optimized to facilitate future high-speed data transfer and 5G networks. This design lays a solid ground for future wearable communication technology, providing reliable and efficient performance in real-world applications.

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