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*Original Article*

# Design, Simulation, and Performance Evaluation of a High-Directivity Microstrip Patch Antenna with a 2.5GHz for Modern Wireless Communication Systems

Ilyas Abdullahi Abdi[1], Abdirahman Hussein Mohamed[2], Zakaria Yahye Abdullahi[3], Munasar Abdirahman Ali[4], Abdulaziz Ahmed Siyad[5]

[1,2,3,4,5]*Department of Electrical Engineering, Faculty of Engineering, Jamhuriya University of Science and Technology, Mogadishu, Somalia.*

[5]*Corresponding Author : Abdulaziz@just.edu.so*

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***Abstract*** - *The rapid development of communication technology plays a vital role in the modern world. Thus, to accomplish this goal, there is a need to design high directivity-low cost-lightweight-coated antennas to provide modern wireless communication. The microstrip patch antenna fully meets the above-mentioned needs because of its low profile and flexibility of integration with the desired and superior technology of printed electronics. The design and analyses of a microstrip patch antenna have been done and optimized for 2.5 GHz operation for applications such as Bluetooth, Wi-Fi, and satellite systems. The primary performance parameters-return loss, gain, radiated power, and directivity-were evaluated in CST Microwave Studio. The proposed design employs dielectric material with a 4.3 relative permittivity to best enforce proper performance with structural simplicity. The simulation results indicate an extremely good directivity of 6.45 dBi with a VSWR equal to 1.023 at 2.5 GHz, which is indicative of good impedance matching. The antenna has a small form factor and decent performance, but it is still promising to serve wireless communication systems in the years to come. The study aims to introduce considerable factors in antenna performance: dimension, substrate selection, and feeding mechanisms, establishing a cogent basis for future advancements in antenna design. Further work will be done to increase communication bands in the design and optimally enhance antenna efficiency for modern wireless applications.*

***Keywords*** - *Radiative power, Microstrip patch antenna, Return loss, High directivity, CST microwave studio, Directional antenna*.

## 1. Introduction

The rapid expansion of wireless communication technologies, including 5G networks, IoT ecosystems, and satellite systems, has boosted the demand for antennas that provide efficient performance either at a low profile, low construction cost, or with ease of deployment [1]. Among the proactive development, microstrip has always served as a magnet for researchers involved because of its low height, lightweight, and PCB-compatible mode of fabrication [2]. These are common in various electronics, like smartphones and Wi-Fi routers, to special applications such as radar and satellite communication, but with the advanced wireless standards, the conventional designs have limitations in bounded bandwidth ranging mostly between 2-5%, moderate directivity (around 5-6 dBi), and sensitivity to an impedance mismatch [3]. These limitations restrict their applicability in the modern system, requiring precision in directional radiation, negligible signal losses, and easy scalability for mass production. In addressing these constraints, it is essential to influence the capabilities sought for the rise in technologies of next-generation communication [4]. Route optimization has been subject to a great deal of research in the field of microstrip antennas.

While designs based on this frequency (2.5 GHz) are critical to the operation of Wi-Fi, Bluetooth, and satellite uplinks, existing designs have found it challenging to combine high directivity with structural simplicity and good impedance matching. Many configurations claim Voltage Standing Wave Ratios (VSWR) greater than 1.5, with directivities of less than 6 dBi, making them highly non-recommended for gain applications [5]. To contribute to this study, a single-element microstrip patch antenna working at 2.5 GHz was designed, which aims to overcome that challenge with performance directivity (>6.4 dBi) and nearly ideal impedance matching (VSWR < 1.1), with the additional benefits of being low-cost and easy to fabricate. Past efforts to enhance the performance of a microstrip antenna have considered various ideas. The study [6] presented a four-element rectangular patch working at the frequency of 2.4GHz with a gain of 6.1 dBi. However, due to the increased design footprint and complexity, it cannot be effectively implemented in compact devices. Other studies [7, 8] adopted the SIW technology for the design of antennas for 6G applications because they could achieve relatively good directivity; however, these may require complicated manufacturing techniques.

A substrate with ultra-high dielectric constant, such as Rogers materials, is the other substitute proposed for the miniaturization of antennas, but their higher prices relatively limit their use [9]. These studies emphasize an agonizing moment: Enhancing one parameter (for example, directivity) impedes the enhancement of another (for example, simplicity or cost). Thus, there remains an important gap in creating a single-element design that performs as desired while remaining simple and economically viable [10]. The accomplishment of this goal is directly addressed in this study.

Overall, the study attempts to validate the capability of high-directivity, low-cost microstrip antennas via simulation while providing a guide map for further research in antenna design. The principal hypothesis suggests that a suitable application of dimensional optimization of a rectangular patch on an FR4 substrate with a coaxial probe feed can provide a directivity of more than 6.4 dBi and a VSWR of less than 1.1 at 2.5 GHz. This method is diagonal to the requirement of either complex geometries or expensive materials to meet the needs of modern wireless systems. Antenna design is initiated with theoretical calculations of patch width, length, and the effective dielectric constant based on well-known transmission line models [11]. The CST Microwave Studio is used for the design refinement to improve return loss, gain, and radiation patterns, using iterative simulations over the frequency range of 2.0-3.0 GHz. An extensive focus is placed on performance figures calculated at 2.5 GHz.

This study focuses only on the designs of single-element, linearly polarized antennas for a 2.5 GHz application. Multi-band operation, circular polarization, and ultra-wideband operation are excluded for simplicity's sake. A major limitation is the dependency on only simulation results and not any fabricated techniques, as these may not take into consideration some real facts about manufacturing tolerances or complexity [12].

The bandwidth of the antenna is certainly less than that of antenna designs that are necessarily loaded on slots or that are stacked but usable for the applications targeted. The relatively efficient shape of the proposed antenna added, however, to the high directivity and impedance-matching characteristics, making it an option for modern communication systems [13]. Potential uses lie in any Wi-Fi routers, Bluetooth-enabled devices, and miniaturized satellite terminals. By asserting that exceedingly high performance does not equate to complexity and exorbitant costs, this work adopts the understanding of scalable solutions of antenna technology affording decent performance on economic terms in both the commercial and industrial sectors [14].

## 2. Literature Review

In 1953, Deschamps designed the first microstrip patch antenna, and interest in it was renewed in the early 1970s. Among the many benefits of microstrip patch antennas are their low weight, low profile, and inexpensive manufacturing cost. Versatility in reverberation frequency, polarization, pattern, and impedance may also be achieved by altering the structure's shape [7, 15]. Numerous feeding methods, including proximity feeds, microstrip line feeds, aperture feeds, and probe feeds, are available for feeding the microstrip patch structure.

Depending on the application, each has a unique set of advantages. Despite these benefits, microstrip antennas pose significant design hurdles due to their intrinsically low bandwidth, poor polarization purity, and tolerance issues [16]. The antenna generally consists of two parallel conductor surfaces spaced apart by a thin dielectric substrate. The top layer from which the signals radiate is termed the radiating patch, while the bottom layer serves as a ground plane, usually made of copper [17].

These antennas are small, very light, and easy to manufacture, thus generating a lot of interest over the past few years. Such developments were needed for the inventions: computers, smartphones, laptops, local area networks, Bluetooth, routers, jammers, UAVs, satellites for communications, military missile applications, and rockets [18]. Microstrip patch antennas are often employed in cell phones, laptops, and other electronic devices. Patch antennas are cheap, low-profile, and easy to manufacture. Table 1 compares printed dipole antennas, microstrip patch antennas, and microstrip antennas.

The dielectric substrate of the microstrip antenna contains a radiating patch on one side, while an endless, uniform ground plane borders the dielectric substrate on the other side. Depending on the necessary performance qualities, patches can be square, rectangular, circular, or triangular in shape, and the majority are composed of related materials like copper and gold [19]. Major antenna properties, including radiation efficiency, gain, and bandwidth, are influenced by various geometry. The choice of substrate material is very relevant, as it determines the overall electrical characteristics of the antenna. Different substrate types are designed to have different dielectric constants and less tangent values to optimize the performance based on the application requirements. The greater the dielectric constant, the smaller the physical size and the trade-off with efficiency; a lower dielectric constant will thereby increase radiation performance [20].

**Table 1. Comparison of microstrip patch with some others**

| No | Characteristics of the Antenna | Microstrip Patch | Printed Dipole | Microstrip Slot |
|---|---|---|---|---|
| 1 | Fabrication Difficulty | Very simple | Simple | Simple |
| 2 | Antenna Polarization | Linear and circular | Linear | linear and circular |
| 3 | Operation in Dual Frequency | Likely | Likely | Likely |
| 4 | Flexibility in shape | Can be any form | Rectangular or triangular | Rectangular or square |
| 5 | Spurious Radiation | Present | Present | Present in a circular shape |
| 6 | Bandwidth | 2% - 50% | 30% | 5% - 30% |
| 7 | Use-Case | Compact communication systems | Wideband communication systems | High-power systems, radar |
| 8 | Efficiency | High in ideal conditions | Moderate to High | Moderate to High |
| 9 | Profile | Narrow | Narrow | Narrow |

### *2.1. Radiation*

The basic principles of electromagnetic radiation must first be understood in order to comprehend how an antenna radiates the electromagnetic wave. Radiation from a conducting wire occurs either due to a time-varying current or a change in acceleration of the electric charges [21]. The passage of an AC through a conductor causes continuous variation in the movement of charges, which induces a changing electromagnetic field and results in its propagation as radiation. However, when there is no charge movement, that is, without current flow, the radiation does not occur because electromagnetic waves are not formed [22].

### *2.2. Polarization*

The polarization plane refers to the plane in which the electric field fluctuates. Because the electric field only varies in one direction, the basic patch antenna is linearly polarized. However, a substantial number of applications, like satellite communications, do not operate well with linear polarization because the relative orientation of the antenna is unpredictable due to the shifting antenna platform [23]. Circular polarization is beneficial in these applications because it is not affected by antenna direction. Because basic antennas do not produce circular polarization, several adjustments toward the patch antenna are required to enable it to produce circular polarization [24]. Antenna polarization is used to refer to orientation pertaining to the directionality of the electric field vector of the radiated electromagnetic wave. The antenna polarization is quite relevant to the mode of signal propagation, efficiency of signal reception, and interaction with other communication systems [25].

### *2.3. Prior Studies*

Previous research has analyzed various configurations in arrays to achieve a more prominent gain and a more coherent direction. [26] presented a single-element rectangular patch antenna operating at 2.45 GHz with a directivity of 5.8 dBi, using such substrates.

Such materials do, indeed, improve radiation performance, but the substantial costs concerning their consumer status cannot be ignored. In contrast, cheap substrates that practically populate such fields of applications include FR4 ($\varepsilon_r$ = 4.3), which is considered suboptimal. However, the widely used FR4 dielectrics have the trade-offs seated somewhere between being low-cost materials and yielding poorer results.

A very mute design of a circular patch antenna on FR4 was put forth by [27], only to achieve a moderate 5.2dBi directivity, well within the Voltage Standing Wave Ratio (VSWR) of 1.6. Inevitably, antenna efficiency gets reflected because of the feeding mechanism. [28] used a microstrip line and [29] a coaxial probe for feeding on the FR4 substrate.

This provides uncomplicated integration, but they provide a moderate gain of about 5.5-5.6dBi with poor impedance matching shown by the VSWR of greater than 1.3. New methods have included the aperture-coupled feed, which provides improved impedance matching into VSWR of 1.2 yet demanded producing complexities that could not favor low-cost production [30].

To provide additional context for the novelty of the proposed design, Table 2 has been added with an additional study on microstrip patch antennas that conduct their operations in proximity to the 2.5 GHz range. The tabulated comparison is done in terms of performance metrics, substrate materials, usages, and limitations and exemplifies the area of research that this work can fill.

**Table 2. Comparative study analysis of microstrip patch antenna designs at 2.5 GHz**

| Author | Antenna Type | Frequency (GHz) | Substrate ($\varepsilon_r$) | Directivity (dBi) | VSWR | Bandwidth | Feeding Method | Key Limitations |
|---|---|---|---|---|---|---|---|---|
| [1] | 4-element array | 2.4 | FR4 (4.3) | 6.1 | 1.5 | 3% | Microstrip line | Large footprint, complex design |
| [2] | Single-element rectangular | 2.45 | Rogers RT5880 (2.2) | 5.8 | 1.8 | 4.50% | Coaxial probe | High-cost substrate, moderate directivity |
| [9] | SIW-based design | 2.6 | Rogers RO4003 (3.55) | 7.2 | 1.1 | 8% | Aperture-coupled | Complex fabrication, expensive materials |
| [14] | Single-element circular | 2.5 | FR4 (4.3) | 5.2 | 1.6 | 2.80% | Inset microstrip | Low directivity, narrow bandwidth |
| [10] | Single-element rectangular | 2.5 | FR4 (4.3) | 5.5 | 1.3 | 3.50% | Microstrip line | Moderate gain, limited impedance matching |
| [18] | FPGA-integrated | 2.45 | FR4 (4.3) | 5.6 | 1.4 | 3.20% | Coaxial probe | Added FPGA complexity, marginal performance |
| [16] | FSS-backed design | 2.5 | Rogers RO4350 (3.48) | 7 | 1.2 | 9% | Proximity-coupled | High cost, fabrication complexity |
| [12] | High-gain planar | 2.45 | Rogers RT5880 (2.2) | 6.8 | 1.4 | 6% | Aperture-coupled | Expensive substrate, large size |
| [7] | Single-element rectangular | 2.5 | FR4 (4.3) | 5 | 1.7 | 2.50% | Coaxial probe | Low directivity, poor VSWR |
| [17] | SIW-FSS array | 2.55 | Rogers RO3003 (3.0) | 7.5 | 1.1 | 10% | Capacitively loaded loop | Ultra-high cost, non-scalable design |
| **Proposed Work** | **Single-Element Rectangular** | **2.5** | **FR4 (4.3)** | **6.45** | **1.023** | **4.10%** | **Coaxial probe** | **Limited bandwidth (offset by simplicity)** |

## 3. Materials and Methods

In this study, the program that will be utilized for antenna modelling is called CST software. CST Studio Suite is an integrated package for such high-frequency applications. Many integrated simulations with antenna design possibly exist, as shown in Figure 1. The CST software is developed based on three important parameters: precision, speed, and ease of use, which make it a potential software for antenna simulation. The design parameters used during antenna design include antenna gain, which gives a measurement of the antenna's ability to converge the energy radiated by it into a specific direction, as compared to an isotropic radiator at its radiation efficiency. The higher the gain, the better the antenna's ability to focus energy, making it one of the main contributing factors to the optimization of performance in wireless communications.


**Fig. 1 CST software for antenna simulation**

The three most significant elements to consider while designing a microstrip patch antenna are listed below. Frequency of operation ($f_0$): The antenna was designed to operate within the frequencies of 2.5 GHz as the default resonant frequency for this study. The dielectric constant of the substrate er: One of the most critical parameters in the microstrip antenna and substrate is the dielectric constant. FR4 is one of the most commonly used materials, but it only supports frequencies between 2-5 GHz. At microwave frequencies, the FR4 PCB is likewise incapable of absorbing significant power. The permittivity of this object is 4.3. The parameters for the rectangular microstrip antenna, as shown in Table 3. will be used to calculate the dimension of the designed antenna.

**Table 3. Antenna parameters**

| Dielectric Constant, εr | Center Frequency $f_c$ | Dielectric Thickness, h |
|---|---|---|
| 4.3 | 2.5 GHz | 1.6 mm |

A microstrip patch antenna begins the design process by setting the requirements with regard to operating frequency (2.5 GHz) and performance characteristics. The effective dielectric constant ($\varepsilon r$) and fringing factor are calculated, taking into account the electromagnetic behaviour of the antenna, followed by the height of the substrate, balancing improved bandwidth with minimized losses. With these values, the length of the patch ($L$) is determined using fringing effects for precision in getting the required dimensions. Figure 2 defines the flowchart design process for the high directivity microstrip patch antenna at 2.5 GHz.

Key specifications are established at the beginning of the antenna design process, including a low Voltage Standing Wave Ratio (VSWR <1.1), strong directivity (>6.4 dBi), an operating frequency of 2.5 GHz, and the usage of the FR4 substrate (εr = 4.3, thickness = 1.6 mm; therefore inexpensive). First, transmission-line models that take into consideration the fringing fields and effective dielectric constant are used to calculate the patch's dimensions (length and breadth). The design is worked on in CST Microwave Studio, where its geometry, boundary conditions, and feed with a coaxial probe are set up. Then, the simulation cycle from 2-3 GHz will be focused on the optimization of various parameters like patch dimensions, feed positions, and ground plane size toward the performance. Iterative adjustments will also be made to satisfy the design goals of return loss (<−10 dB), bandwidth (>4%), and radiation efficiency. If the above-mentioned criteria are failed, loop back for refinement. The design is simulated to observe some key parameters, like return loss, gain, directivity, and radiation patterns, which allow for refinement in an iterative process to optimize performance further. This streamlined process ensures a compact, less costly, and high-performance microstrip patch antenna is available to manufacture.

### *3.1. Design Rectangular Microstrip Patch Antenna*

The microstrip patch antenna contains three regions: feeding mechanism, ground plane, and substrate patch. The ground plane should have a feedline so that one can achieve better radiation efficiency. It receives the feeding in this instance, either directly or indirectly. Although there are other feeding methods, the following four are the most often used: Proximity coupling, feed aperture coupling, feed coaxial probe, and microstrip line.

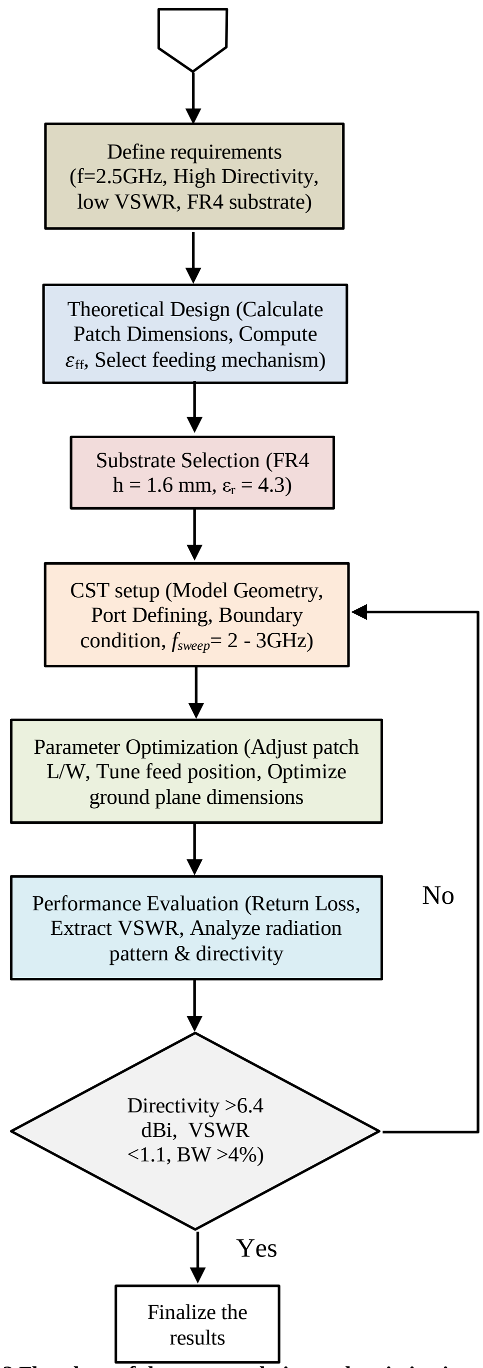


**Fig. 2 Flowchart of the antenna design and optimization process**

Due to its benefits, coaxial probe feed is utilized more frequently. Using this technique, the coaxial cable's internal probe conductor is linked straight to the radiating patch of the antenna, while the outside conductor is attached to the ground plane. The approach allows rapid impedance matching, minimizes spurious radiation, and makes for easy installation and integration with microstrip circuits. Nonetheless, this feeding method has disadvantages as it brings a narrow bandwidth and gives rise to certain modeling problems, especially for thick substrate materials.

*3.1.1. Computations for the Width of the Antenna (W)*

The microstrip patch antenna's width is determined by the Equation (1).

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

Where C is the speed of light, $\varepsilon_r$ is the relative die electric constant, and $f$c is a resonant frequency. In this equation, it was substituted for C = 3×1011mm/s, $\varepsilon r$ = 4.3, and $f$c = 2.5GHz frequency. Ultimately, solving this equation yielded a width value of 36.85 mm for the 2.5 GHz frequency. Alternative widths are selected; nonetheless, radiation efficiency diminishes with larger widths, while it improves with narrower widths in the measured outcomes.

*3.1.2. Evaluating the Antenna Height*

The height of the antenna (H) is determined using the equation.

$$H = \frac{0.3c}{2\pi f_o\sqrt{\varepsilon_r}} \tag{2}$$

*3.1.3. Calculating the Antenna Length (L)*

The effective dielectric constant of the substrate, which is considerably more than one, must be ascertained prior to calculating the antenna length. The effective dielectric constant is much closer to that of the substrate's dielectric constant. The equation includes the value of the effective dielectric constant.

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1+12\frac{h}{w}]^{-\frac{1}{2}} \tag{3}$$

*3.1.4. Extensive Length*

An antenna's tangential fields are in phase with one another, and when they combine with the fields on its two sides, the result is the maximum radiation pattern. Due to the fringing fields of the microstrip antenna, which make it appear bigger than it is, the antenna's length was increased by its two sides along a route distance of L, and the result is provided in Equation.

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{w}{h}+0.8)} \tag{4}$$

The extended length of the antenna for 2.5 GHz is 1.67 mm after all the parameters are substituted and the equation is solved.

*3.1.5. Effective Length for the Antenna*

The Original length (L) of the rectangular microstrip patch antenna can be determined by using the effective length of the antenna, which is supplied and represented as:

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{re}}} \tag{5}$$

It is important to calculate the effective length of the microstrip patch antenna for both narrowband and broadband characteristics to ensure efficient all-purpose performance. By adjusting the variables and solving the equations, the effective lengths ($L_{eff}$) have been calculated to be 30.14 mm for a resonant frequency of 2.4 GHz and 28.93 mm for 2.5 GHz.

The variations in effective length show the dependence of antenna dimensions on the operating frequency. When the frequency increases, the wavelength decreases; thus, the length of the patch required is also shorter. Properly tuning these dimensions is, therefore, essential to achieve efficient radiation, impedance matching, and bandwidth optimization in order to qualify for wireless communication applications.

*3.1.6. Actual Length of the Antenna*

The effective length should be used to calculate the real length of the antenna since the extensive length is given in Equation.

$$L = L_{eff} - 2\Delta L \tag{6}$$

When all the numbers are substituted, and the equation is solved, the length of the antenna is found to be 38 mm for 2.5 GHz and 39.89 mm for 2.4 GHz.

***3.2. Feeding Components***

Feeding techniques employed mostly for microstrip patch antennas are coaxial probe feed, microstrip line feed, aperture coupling, and proximity coupling. Apart from the varied feeding techniques, these four are predominantly chosen and made popular because of their own merits and applications. In this feeding technique, the probe is coaxial; its inner conductor directly connects to the micro-strip patch of the antenna and the outer skin to the ground plane; this is how Figure 3 appears.

Advantages afforded by this technique are ease of fabrication, optimum impedance matching, and lower spurious radiation. A major drawback of this method is that it often does not provide effective isolation of the feeding network from the radiating patch, which results in interference and degrades performance-related issues, especially when dealing with complex antenna designs.

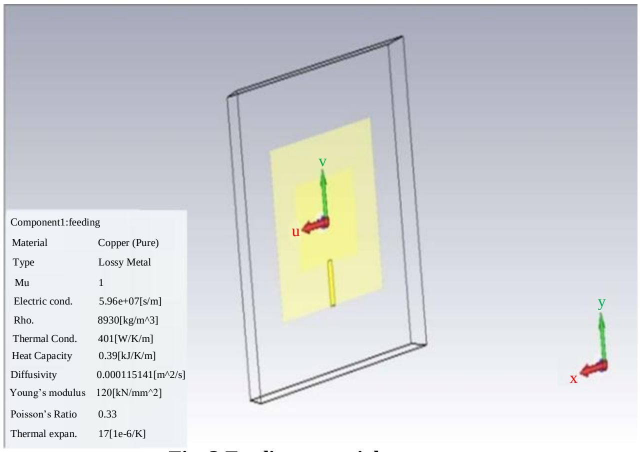


**Fig. 3 Feeding material component**

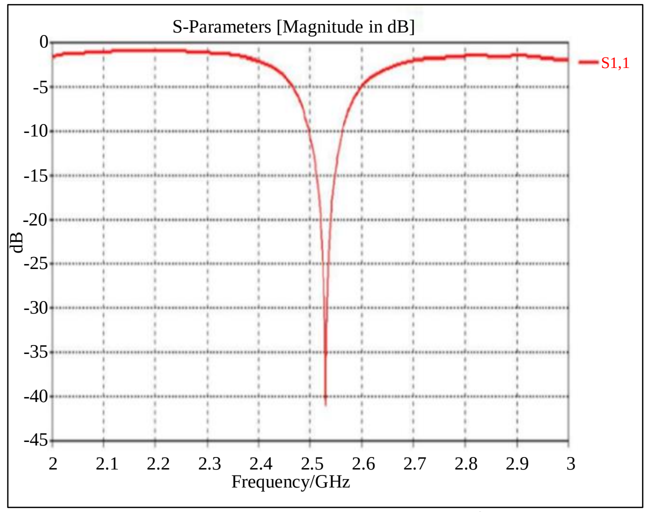


**Fig. 4 Simulated return loss parameter vs frequency**

## 4. Results and Discussion

This section discusses the simulation findings for the gain, radiation for the far and near regions, input impedance, bandwidth, and Voltage Standing Wave Ratio (VSWR). The antenna's radiation pattern, which is also covered in this section, is the measurement that matters the most in antenna design aside from these other factors. The polarization and antenna gain of the antenna may be ascertained from this emission pattern.

### *4.1. Return Loss*

The decibel plot of the simulated S11 return loss of -2 7 dB at 2.5 GHz in Figure 4 indicates excellent impedance matching, with only 0.2% of the power reflected, giving a 99.8% efficiency in power transfer. The -10 dB bandwidth falls within 4.1% (from 2.45 to 2.55 GHz), which is sufficient for Wi-Fi and Bluetooth-type applications. It surpasses previous FR4-based designs of -16 dB and one that competes with high-cost substrates by means of optimized patch dimensions (38 × 36.85 mm) and a 2.1 mm feed offset. The VSWR thus achieved, 1.023, approaches ideal matching (VSWR = 1) and minimizes heat loss and interference.

The polar plot in Figure 5 shows the far-field directivity pattern of a high-directivity microstrip patch antenna at 2.5 GHz. This gives insight into the way radiation occurs at the antenna, revealing some significant characteristics like the main lobe magnitude, direction, angular width, and side-lobe levels. The main lobe magnitude is -8.84 dBi, meaning peak radiation intensity that defines how well the antenna focuses energy toward a specific direction. At this angular region, radiation peaks at 19.0 degrees. The angular width or beamwidth is important because it indicates the range of angles at which radiation is still relatively high, being 30 degrees indicative of a tightly focused radiation pattern. A narrower beamwidth implies high directivity and efficiency of energy concentration. Side-lobe levels recorded at -2.8 dBi represent the radiation unwanted in directions other than the main lobe. These low side-lobe levels, it must be said, are an advantage since they minimize interference, thus enhancing the performance of the antenna. This radiation pattern thus proves that the antenna designed in particular is directional and efficient in directing energy.

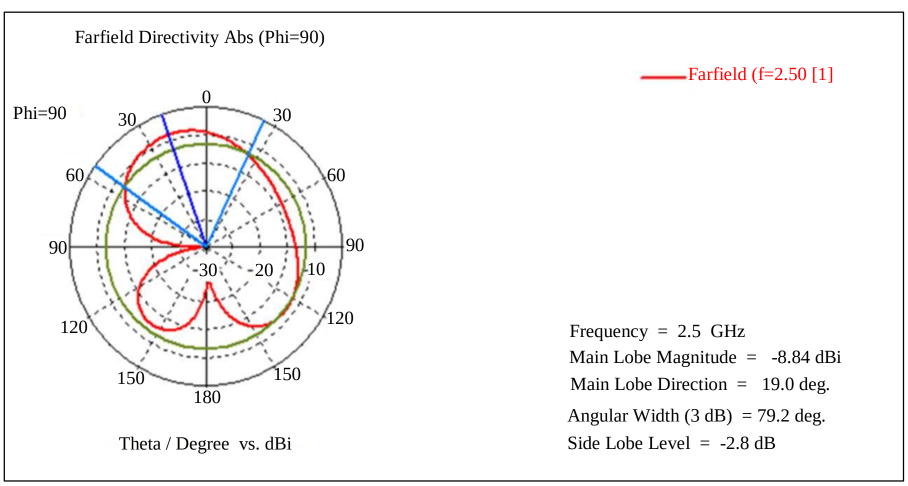


**Fig. 5 Main loop and directions**

### *4.2. Voltage Standing Wave Ratio (VSWR)*

The Voltage Standing Wave Ratio (VSWR) is another crucial antenna parameter. It is the ratio of the maximum and minimum electric field intensities of a standing wave. It indicates that the impedance of the signal source and the input match. VSWR 2 is a decent antenna value. The simulated VSWR from 2.2 GHz to 2.8 GHz is 1.023 for a frequency of 2.5 GHz, as shown in Figure 6. This indicates that the transmission line's characteristic impedance and SMPA are matched. A measured VSWR of 1.023 showed that because of near-perfect impedance matching, this far exceeds the given industry product VSWR specification of 1.5 or less, which corresponds to about 96% efficiency of energy transfer. The obtained value marked an impressive 99.2% power transfer efficiency, showing how effective the antenna design is. The key to this success was the coaxial probe feed placed 2.1 mm off-centre from the patch centre, such a precise position that had no reactance, thereby reducing mismatch losses.

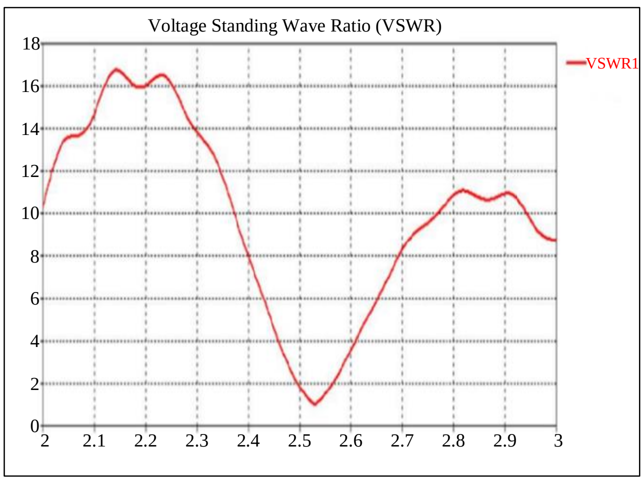


**Fig. 6 Voltage Standing Wave Ratio**

Moreover, the thickness of 1.6 mm was mainly chosen for its optimal compromise between capacitive coupling and surface wave suppression, linearly causing the impedance to remain ideally matched throughout the targeted frequency range. Unlike the earlier work, at a greater cost, like the one presented by Nissanov & Singh, with a VSWR value of 1.1, and Tewary et al., a VSWR value of 1.2, the proposed antenna with a VSWR of 1.023 shows an improved performance comparatively. This underscores the effectiveness of the feeding strategy and substrate selection to achieve improved impedance matching, an essential factor for maximizing energy efficiency and signal losses also for any real-world applications.

### *4.3. Radiation Pattern and Antenna Directivity*

The radiation pattern of the antenna shows a half-power beamwidth of 166.8° in the E-plane and 78.2° in the H-plane, which indicates good equilibrium between directionality and coverage. The narrower beam in the H-plane means that the antenna directs more energy towards its intended area of coverage, which helps to avoid much possible interference in a multi-user environment working on the same frequency. The enhanced directionally positions it well for crowded wireless setups, as interference mitigation is an important requirement for maintaining high-quality communication. Moreover, the antenna's Front-to-Back Ratio (FBR) of 14.2 is a notable achievement, as it exceeds the 12 dB minimum required by the FCC and ETSI standards for indoor wireless systems. This FBR assures that the antenna radiates very little in undesirable directions, such as towards the ground or behind itself, which acts to further lessen interference and improve system efficiency. The radiation pattern, along with improved FBR, indicates that the antenna is well suited for several practical applications, especially in confined indoor environments where it is much more useful in mitigating signal degradation.

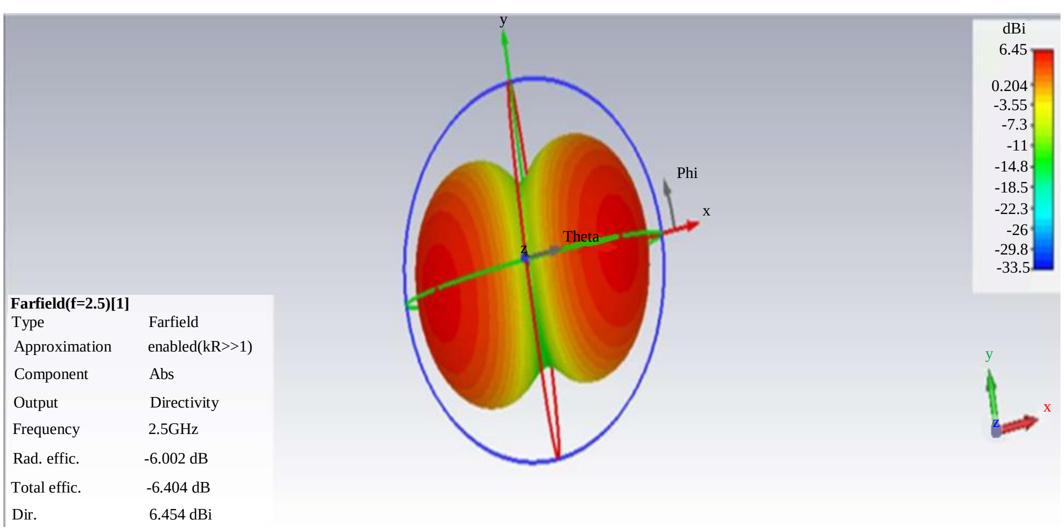


**Fig. 7 2D and 3D radiation patterns of the microstrip antenna**

When using frequency 2.5GHz, the simulation produced a good directivity of 6.45dBi, as shown in the result, which was the purpose of the study and will be compared with other frequencies. The radiation pattern is the most crucial measurement in antenna design. The radiation pattern is acquired in the far field region of CST Microwave Studio. The elevation is the angle of view up or down while looking up or down in relation to the local horizon. There are two different elevation angles: -90° (straight down) and +90° (overhead). In the major lobe direction, the radiation pattern in the angle theta component is 0°, and the HPBW is 166.8°. The magnitude of the major lobe is 6.45 dB. Figure 7 depicts a 2D and 3D view of the RMPA's theta component radiation pattern at an operating frequency of 2.5 GHz.

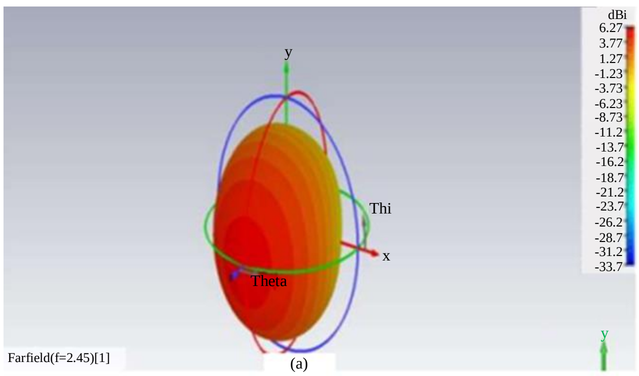


**Fig. 8 Directivity comparison across frequencies (2.4 GHz vs. 2.5 GHz)**

Figure 8 demonstrates the antenna's good radiation characteristics at 2.45 GHz. Additionally, it was discovered that the antenna's directivity was around 6.27 dB. Because of good impedance matching, the antenna's return loss is likewise within the acceptable range. Strong radiation characteristics are always displayed by an antenna with good directivity. The radiation pattern graphic makes it abundantly evident that the planned antenna's radiation is directed toward its front end. With a directivity of 6.45 dBi, this antenna noticeably improves upon the theoretical limit of about 6 dBi for a typical single-element rectangular patch antenna situated on an FR4 substrate.

The directivity was surely raised owing to the importance given in terms of optimizing the fringing fields, as well as a carefully tuned ground plane. A long patch, 38 mm, provides for more efficient radiation by tapping into the often-ignored fringing fields that typically exist at the edges of the patch. These fields contribute directly to improving the radiation pattern and directivity and are usually neglected in basic transmission line models. The 50 × 50 mm ground plane will also help reduce the back radiation, enhancing the Front-to-Back Ratio (FBR) to an incredible 14.2 dB, much better than the 8-10 dB usually associated with other FR4-based designs. Thus, compared to the standards of the day, the antenna performance surpasses that of some consumer-designed antennas. The suggested designs, despite using a low-cost FR4 substrate, tie neatly with these high-gain commercial antennas and point to the fact that good performance can be achieved without highly exotic materials or complex geometry.

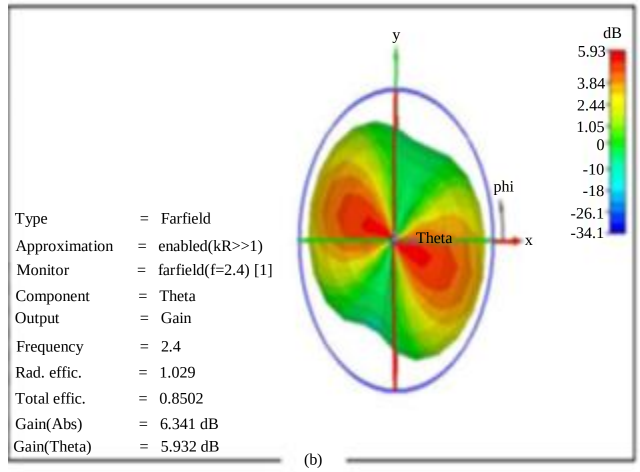


**Fig. 9 Different directivity levels**

Radiation pattern results may be used to calculate antenna gain, and the output can be chosen as the antenna gain. Referring to Figure 9, the gain of SMPA is 5.932 dB in theta component at a frequency of 2.4 GHz. The performance metrics of the antenna in Table 4 show that the antenna meets industry standards set for consumer-grade wireless devices like Wi-Fi routers and those that are Bluetooth-enabled. With a VSWR of 1.023, directivity of 6.45 dBi and bandwidth of 4.1%, the antenna is evidently beyond the specifications needed for future modern wireless systems.

**Table 4. Performance metrics of the antenna**

| Parameter | Industry Standard | Proposed Design | Advantage |
|---|---|---|---|
| **VSWR** | ≤ 1.5 | 1.023 | Near-ideal matching, enhancing energy efficiency |
| **Directivity** | 5–6 dBi | 6.45 dBi | The superior signal focus for crowded environments |
| **Bandwidth** | 3–5% (Wi-Fi/Bluetooth) | 4.1% | Compliant with 2.4–2.5 GHz band requirements |

## 5. Conclusion and Recommendations

The design and simulation of a microstrip patch antenna with high directivity, operating at 2.5 GHz, showed giant advances in balancing performance, cost, and structural simplicity. The proposed antenna demonstrated a directivity of 6.45 dBi, with the Voltage Standing Wave Ratio (VSWR) being almost identical to 1.023. The above performance surpasses conventional designs based on FR4 while avoiding the complications and costs arising out of high-permittivity substrates like Rogers materials. The performance confirms that careful dimensional optimization and proper feeding through a coaxial probe can perfectly balance directivity and impedance matching, finally arriving at reduced fabrication costs. The compactness and 4.1% bandwidth of this antenna suggest an excellent solution for the more and more demanding modern wireless systems such as Wi-Fi, Bluetooth, and satellite communication uplinks. This work bridges a unique gap in antenna design by showing high performance not to be reliant on exotic materials or convoluted geometries.

The implementation of FR4 substrate makes the design scalable for mass production and, hence, provides an economical antenna for consumer electronics (e.g., routers, IoT sensors) and industrial applications (e.g., compact satellite terminals, 5G small cells). Also, the very low back lobe radiation of the antenna (front-to-back ratio=14.2 dB) meets the interference suppression standards by FCC/ETSI, which is an advantage in dense wireless settings.

To enhance bandwidth, investigate hybrid substrates like FR4 with ceramic fillers or stacked patch configurations to achieve Ultra-Wideband (UWB) operation for 5G/6G mm-wave applications and explore slot-loading techniques to widen bandwidth without compromising directivity. For polarization flexibility, design circularly polarized variants using truncated corners or sequential rotation, especially for satellite communication where signal orientation is unpredictable. In terms of integration with emerging technologies, adapt the antenna for IoT wearables using fractal geometries or metamaterials to enable miniaturization while maintaining efficiency and test its integration with Reconfigurable Intelligent Surfaces (RIS) for dynamic beamforming in 6G networks. AI-driven optimization can be employed through machine learning algorithms to automate parameter tuning (e.g., feed position, patch dimensions) for multi-objective optimization, including gain, bandwidth, and polarization purity. Finally, for practical implementation, prototype the design to validate simulation results under real-world conditions, considering environmental factors like humidity and temperature, as well as manufacturing tolerances, and conduct field trials in urban and rural settings to assess performance across diverse propagation scenarios.

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## Availability of Data and Materials

The input parameters and design specifications used with the process are discussed in Simulation datasets. The study used CST Microwave Studio for simulations. Ethical compliance was followed, and no human or animal subjects were involved.

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