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RADIALLY-DIRECTED MICROSTRIP PATCH ANTENNA FOR LIGHTWEIGHT MOBILE WIRELESS CONTROL

Ahmad Ilham Rokhul Fikri, Laurentius Kevin Hendinata*

Department of Nuclear Engineering and Engineering Physics, Universitas Gadjah Mada, Sleman, Daerah Istimewa Yogyakarta, 55281, Indonesia

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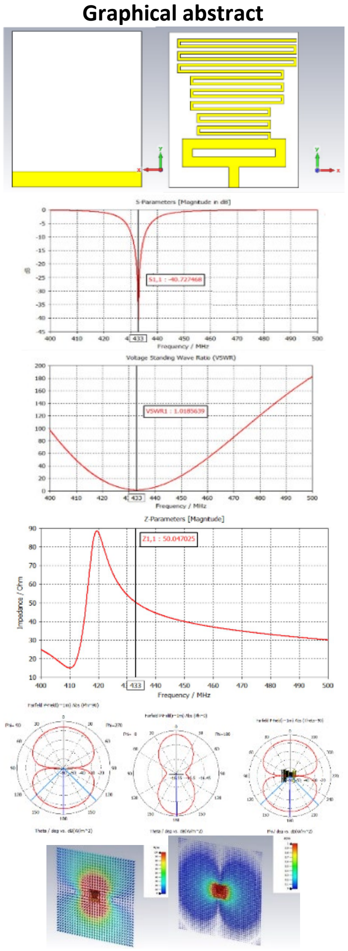
*Corresponding author
kevinhendinata@mail.ugm.ac.id

Graphical abstract



Abstract

In the realm of wireless communication, the continuous evolution driven by the rapid advancements in information technology over the past few decades has led to an ever-growing reliance on various digital technologies such as WiFi, GSM, LTE, IoT, 5G, and mmWave for communication connectivity. This technological expansion finds significant application in the transportation sector, where smart and automated systems demand efficient communication for enhanced efficiency, safety, and reliability, encompassing both vehicle-infrastructure interactions and broadband services. However, this progress poses challenges encompassing security, spectrum utilization, energy efficiency, and communication infrastructure. The critical role of antennas in enabling radio wave-based communication is evident, necessitating compact, integrated, and polarization-responsive designs with substantial bandwidth and high gain. Here, the microstrip patch antenna emerges as a solution, offering attributes like favorable return loss, high efficiency, and directional radiation patterns. The design, at dimensions of 50 mm × 60 mm within a single-layer FR-4 PCB of 1.4 mm thickness, undergoes simulations using CST Studio. The resultant data includes current signal output, gain, radiation pattern, and parameters for potential design optimization. Simulation findings indicate a resonant frequency of 433 MHz with an S11 value of -40.727 dB, a VSWR value of 1.018 at 433 MHz, and an impedance of 50.05 ohms. The radiation pattern showcases elevated gain radially and diminished axial gain, indicating optimal signal transmission perpendicular to its axis. Additionally, the analysis of electric (E) and magnetic (H) fields offers insights into the antenna's radiation characteristics. This work addresses challenges in modern wireless communication, providing a promising microstrip patch antenna solution supported by quantitative simulations, heralding the prospect of enhanced wireless control and communication in lightweight mobile applications.

Keywords: Microstrip patch antenna, CST Studio, reflection coefficient, VSWR, impedance, E-field, H-field, radiation pattern

1.0 INTRODUCTION

In the past three decades, wireless communication systems have witnessed substantial progress in tandem with the rapid evolution of information technology [1]. With the internet and the development of various digital technologies in recent years, wireless communication has become an important connection equipment and the main transmission medium, whether through WiFi, Global System for Mobile Communications (GSM), Long Term Evolution (LTE), Internet of Things, 5G, and millimeter wave (mmWave) [2].

The applications of wireless communication have proliferated across diverse sectors, including the transportation domain. In this context, wireless communication is pivotal for meeting the demands of intelligent and automated transportation systems [3], [4]. It facilitates critical communication between vehicles and infrastructure, enhancing efficiency, safety, and reliability. Moreover, it serves as the foundation for broadband connections in both cargo and passenger services.

Effective transmission and reception of data through radio wave wireless communication necessitate the use of antennas [5]. In providing a gateway for the transmission and reception of radio signals, antennas play an important role in both base stations and mobile terminals.

However, the realm of wireless communication is not without challenges, encompassing aspects such as security, privacy, optimal resource and spectrum utilization, communication infrastructure, and energy efficiency [6]. Some of these challenges arise, one of which is the characteristics and type of antenna used [7]. The utilization of larger antennas can amplify the load on data transmission. Moreover, as communication systems grow more intricate, the demand for antennas that are compact, seamlessly integrable with radio frequency circuits, responsive to specific polarizations, possess broad bandwidth, and offer high gain, becomes imperative [8]. Thus, further design is needed to obtain an effective antenna for this radio communication function. Here, the microstrip patch antenna is proposed as a solution to increase the effectiveness of this radio communication. The microstrip patch antenna has characteristics that provide good return loss, high efficiency and directional radiation pattern [9]. The basic configuration of the microstrip patch antenna is illustrated in Figure 1.

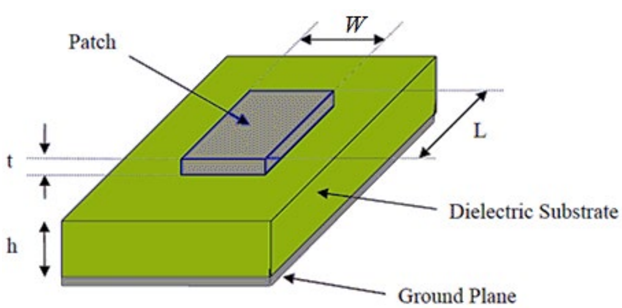


Figure 1 Basic configuration of the microstrip patch antenna [10], [11].

However, there are challenges in the development of the microstrip patch antenna, as it struggles to find the best geometry to carry out its communication function. In order to solve this challenge, a number of different designs have been carried out, with the main goal to create an antenna with high performance. This paper will provide a detailed explanation of the microstrip patch antenna's design to achieving high-performance results. Through the simulation model, the behavior of the antenna will be thoroughly examined, and its ability to overcome the challenges faced during development will be shown.

2.0 MATERIALS AND METHODS

2.1 Antenna Design

Wireless communication over long distances often relies on frequencies within the high frequency (HF)/ very-high frequency (VHF)/ultra-high frequency (UHF) range. These frequencies are preferred due to their ability to maintain stable signals over extended distances and their capability to reflect off the ionosphere [12].

Within HF/VHF/UHF communication, two common types of antennas are utilized: the dipole and monopole antennas. A dipole antenna consists of two conductors for transmitting or receiving radio frequency energy, with a center-fed driven element [13]. On the other hand, a monopole antenna is a simpler version that employs only half of the dipole's structure [14].

In terms of dimensions, the length of a dipole antenna is determined by half the wavelength (λ) of the signal being used, while for monopole antennas, it's just a quarter of the wavelength. Refer to Figure 2 for the visual representation of the dipole and monopole antenna structures.

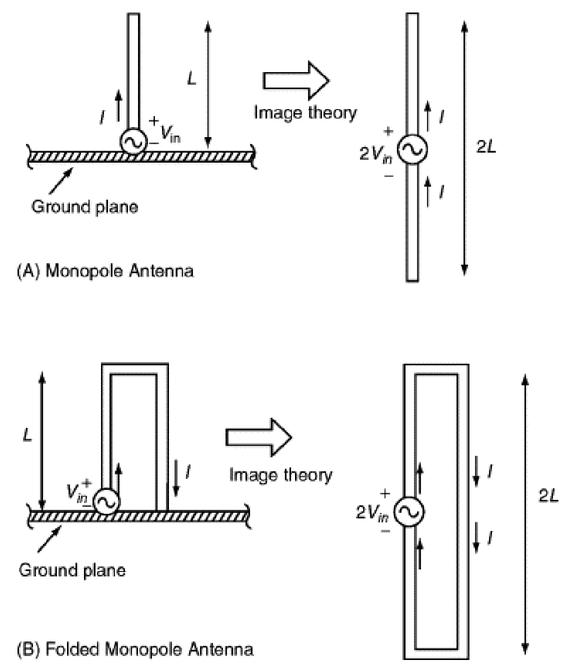
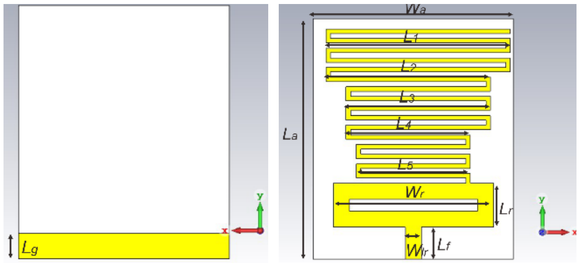


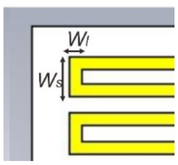
Figure 2 Structure of monopole and dipole antenna [14].

Various antenna types have been developed to fit within limited spaces, with the microstrip patch antenna standing out as an example. This antenna design involves a radiating patch affixed to one side of a dielectric substrate (with a permittivity of ≤10), accompanied by a ground plane on the opposite side [15]. Microstrip patch antenna consist of a very thin ($0\ t \ll \lambda$, where λ is the free-space wavelength), metallic strip (patch) placed a small fraction of a wavelength $h \ll \lambda$, usually $0.003\lambda_o \le h \le 0.05\lambda$ above a ground plane [16].

Differently shaped patches have been used to increase the return loss, resonant frequency, and antenna bandwidth. In the proposed design, microstrip patch antenna has dimensions of 50 mm × 60 mm. This antenna is designed on FR-4 single layer PCB with the thickness 1.4 mm with a dielectric constant value of 4.3.

A visual representation of how this antenna is configured can be observed in Figure 3. The antenna will be placed in one side of FR-4 layer, while the other layer will become the partial ground plane of the antenna.





Parameter	Values
L_a	60.0 mm
W_a	50.0 mm
L_g	6.0 mm
L_1	46.0 mm
L_2	41.0 mm
L_3	37.0 mm
L_4	32.0 mm
L_5	28.4 mm
W_l	1.1 mm
W_s	1.3 mm

Figure 3 Detailed dimension of the presented microstrip patch antenna.

According to Figure 3, the yellow-colored strip refers to the antenna element in the design. The antenna element is made of copper, which is a commonly used material for printed circuit board (PCB) manufacturing. The choice of materials used for the design was based on availability and ease of access.

The antenna structure was designed with the aim of being cost-effective and easy to fabricate using simple materials such as a PCB board. Compared to other antennas with similar frequency ranges, this antenna structure is smaller in size, making it more suitable for certain applications where space is a constraint.

2.2 Modelling

The proposed antenna was subjected to numerical simulation using the frequency domain solver in the CST Studio Suite simulation tool. CST Studio is a program used to simulate electromagnetic fields based on finite integration methods for patch antenna analysis, and enables fast and accurate analysis of HF devices such as antennas, filters, couplers, planar and multilayer structures as well as SI and EMC effects [17]. The objective of this simulation was to extract the antenna's current signal output, inclusive of metrics such as gain, radiation pattern, and other parameters that can guide further design optimization.

The simulation covered a frequency range of 400 MHz to 500 MHz to analyze the performance metrics such as reflection coefficient, voltage standing wave ratio (VSWR), radiation patterns, and impedance. The results of the simulation were analyzed, where a parametric analysis of the S11 magnitude was carried out. This scrutiny revealed that the proposed antenna exhibited an exceptional level of performance, notably resonating at the 433 MHz frequency band. This frequency selection aligns with specific application requirements, underlining the antenna's suitability for wireless scenarios that necessitate superior and efficient performance.

3.0 RESULT AND ANALYSIS

The design and modeling of microstrip patch antennas encompassed a series of numerical investigations aimed at gauging the antenna's performance. To encapsulate, the numerical simulations conducted on the antenna demonstrated its remarkable capabilities and its potential to serve as a suitable answer for diverse wireless applications. The results of the simulation and analysis are described as follows.

3.1 Reflection Coefficient

The antenna performance as a function of the reflection coefficient S11 of the designed microstrip patch antenna is shown in Figure 4.

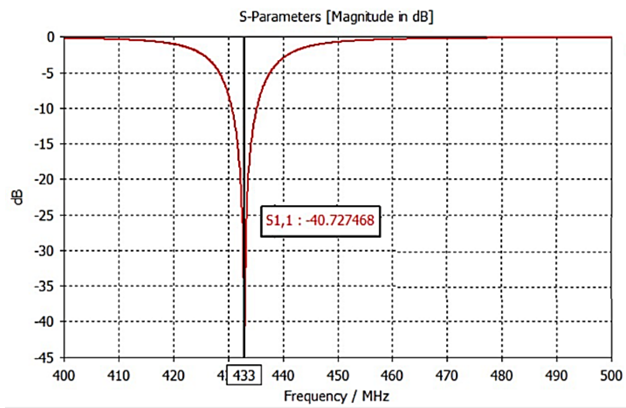


Figure 4 Simulated and measured reflection coefficient S11 of the proposed antenna.

The simulation results indicate that the resonant frequency of the microstrip patch antenna is 433 MHz. This means that the antenna is most efficient at transmitting and receiving electromagnetic energy at this frequency. Additionally, the statement notes that the value of S11 is -40.727 dB, which is a measure of how much energy is reflected back from the antenna to the transmission line.

The fact that the value of S11 is less than -10 dB (i.e., S11 < -10 dB) indicates that the antenna is performing well for radio communication [18], [19]. In general, a reflection coefficient of less than -10 dB is considered to be a good performance for an antenna, as it indicates that the majority of the energy from the transmission line is being effectively transferred to the antenna without significant reflection back to the line. This is important for achieving efficient signal transmission and reception in radio communication systems [20].

3.2 Voltage Standing Wave Ratio (VSWR)

VSWR is a crucial parameter in determining the efficiency of radio communication system. VSWR value is determined from the ratio of the maximum and minimum voltage amplitude of the wave in transmission line [21]. The simulated VSWR value from this proposed model is shown in Figure 5.

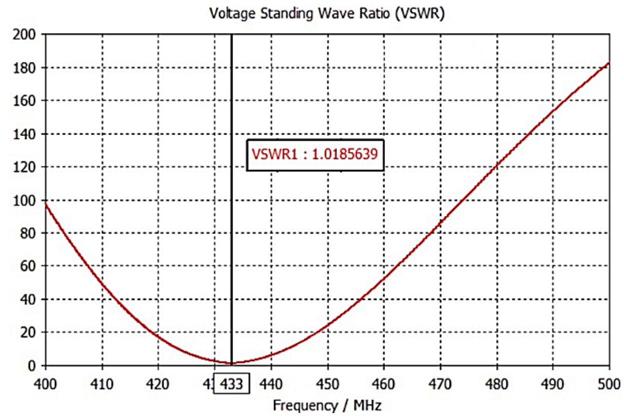


Figure 5. Simulated and measured VSWR of the proposed antenna.

The simulation results indicate that the proposed antenna has a VSWR value of 1.018 at a frequency of 433 MHz. This is considered to be a good VSWR value because the lower the VSWR value is, the better the impedance match between the antenna and the transmission line. A VSWR value of 1 indicates a perfect impedance match, while higher values indicate a poorer match [22], [23]. A VSWR value of 1.018 is considered to be quite good because it is very close to 1, indicative of a near-perfect match between the transmission line and the load, thereby reflecting optimal energy transfer efficiency in the microstrip patch antenna system.

3.3 Impedance

A good impedance match between the antenna and the system is important because it allows for efficient transfer of energy between the antenna and the system, which is essential for achieving good performance in radio communication systems [24]–[26]. This is achieved using impedance matching networks such as baluns, transformers, and matching circuits. Proper impedance matching is critical for optimal performance in various antenna applications.

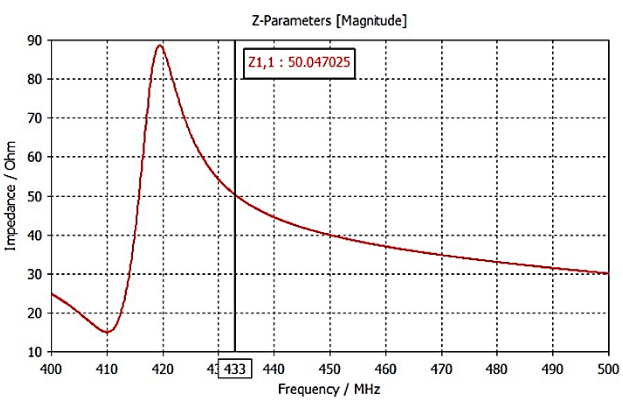


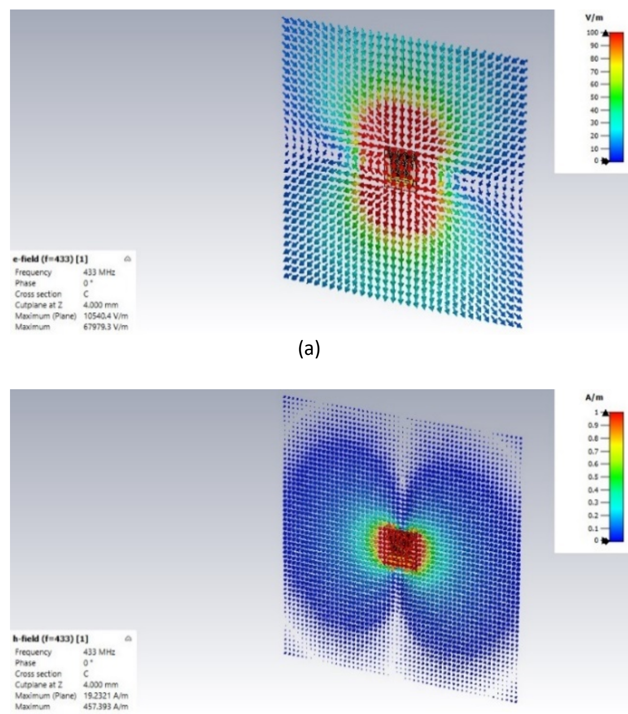
Figure 6 Simulated and measured impedance of the proposed antenna.

In the proposed antenna design, impedance values are simulated and shown in Figure 6. The simulation results show that the impedance value is 50.05 ohms. Impedance is the measure of opposition that an electrical circuit presents to the flow of current when a voltage is applied, and in the case of antennas, the impedance is an important parameter to ensure that the antenna can efficiently transfer power to and from the transmission line.

A commonly used standard impedance for antennas is 50 ohms [27], [28]. When a simulated antenna impedance measures at 50.05 ohms, it's very close to the standard value, which suggests it can work optimally. It's important to know that antennas are designed to work well within a range of impedance values around 50 ohms. The small deviation in measured impedance, like 50.05 ohms, is well within the acceptable limits in antenna engineering. In real-world situations, slight changes in impedance, like the measured 50.05 ohms, can happen due to manufacturing, the environment, or design features. These small differences are usually fine and won't significantly affect the antenna's performance.

3.4 Electric and Magnetic Field Analysis

Analysis of the electric (E) and magnetic (H) fields is important for optimizing the design of antennas, as it provides crucial insights into their radiation patterns, polarization characteristics, and efficiency. In the context of microstrip patch antennas, the typical E and H fields exhibit a concentrated pattern around the patch area, with E-fields primarily confined between the patch and the ground plane, while the H-fields circulate around the edges of the patch. This field distribution is vital for microstrip patch antennas as it directly influences the radiation pattern and polarization. The E and H field at 433 MHz from this proposed antenna is shown in Figure 7.



(a)

(b)

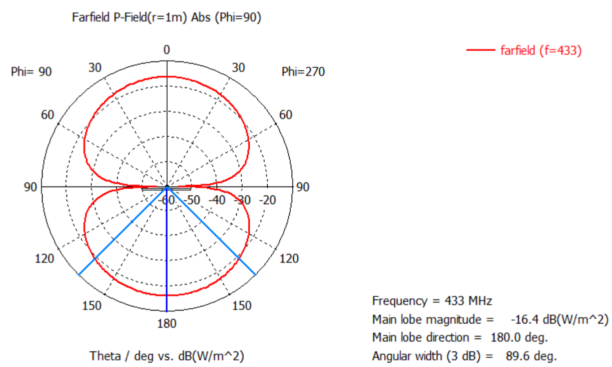
Figure 7 Field analysis of the proposed antenna (a) electric (E-field) and (b) magnetic (H-field).

The H-field, represented by the magnetic field strength, shows the pattern as a function of the antenna's spatial coordinates. It can be seen that there is a gradual decrease in H-field strength as we traverse from negative to positive values along the X-axis. This indicates the anticipated attenuation in magnetic field intensity, providing the potential for a controlled and predictable dispersion of the magnetic field around the antenna structure. Also, the electric field strength, represented by the E-field, provides a distribution pattern in relation to the spatial coordinates. Fluctuations in E-field intensity along the X-axis indicate the dynamic nature of the electric field surrounding the microstrip patch antenna. From the coordinated analysis of these field distributions, it can explain the electromagnetic performance.

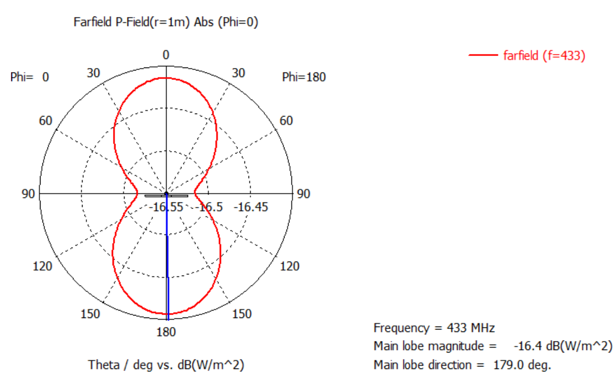
3.5 Radiation Patterns

Radiation patterns refer to the directional distribution of electromagnetic energy radiated by an antenna in free space. The radiation pattern of an antenna is determined by the geometry and electrical properties of the antenna, as well as its operating frequency [29], [30].

Radiation patterns are typically represented graphically using polar plots or three-dimensional plots, which show the intensity of the radiated electromagnetic energy as a function of angle and distance from the antenna [31]–[33]. The shape and directionality of the radiation pattern can vary greatly depending on the type of antenna and its orientation, as well as the presence of any reflecting or absorbing objects in the vicinity of the antenna. In the proposed antenna design, the radiation pattern is obtained as shown in Figure 8, at phi 90°, phi 0° and theta 90°.



(a)



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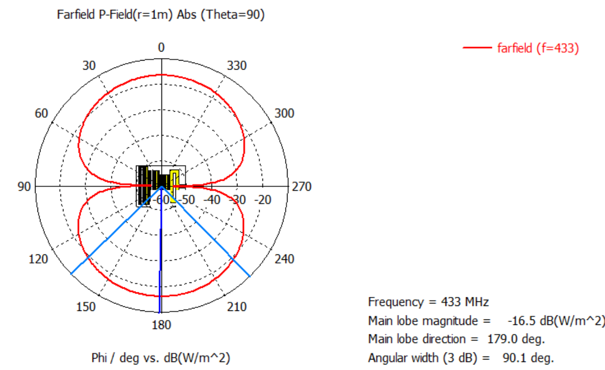

(c)

Figure 8 2D radiation patterns of proposed antenna at (a) phi 90° (b) phi 0°, and (c) theta 90°.

Angles of phi 90°, phi 0°, and theta 90° were thoughtfully selected due to their ability to unveil distinct operational aspects of the antenna. Phi 90°, perpendicular to the antenna's main axis, reveals lateral radiation characteristics, showcasing its efficiency in emitting energy parallel to the ground. Phi 0°, encompassing the main axis, highlights vertical signal transmission potential. Meanwhile, theta 90°, bisecting the main axis and perpendicular to the ground, demonstrates radial radiation prowess, illustrating horizontal energy dispersion.

Simulation results display the farfield radiation pattern, showing variations in gain across directions. These areas of differing gain could indicate the antenna's aptitude for radiating energy in specific directions or receiving energy from certain angles. Understanding this variation is crucial for optimizing performance for particular applications.

Further insights into the distribution pattern are obtained through the 3D radiation pattern at 433 MHz, within the Ultra High Frequency (UHF) band, as shown in Figure 9. This frequency balance between signal propagation and interference management is advantageous for wireless applications. Its alignment with permissible unlicensed ranges like the ISM bands underscores its real-world relevance. This choice reflects the antenna's practical applicability and adherence to electromagnetic principles.

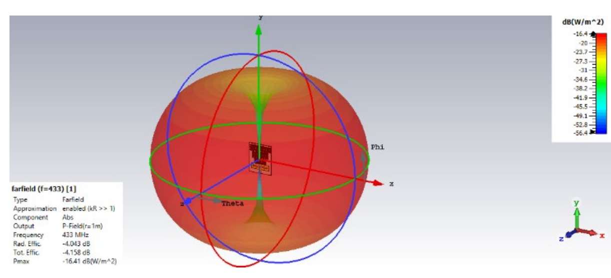

Figure 9 3D radiation pattern of proposed antenna at 433 MHz.

As in Figure 9, it is shown that the antenna's characteristic of exhibiting high gain in the radial direction while showcasing lower gain in the axial direction. This implies that the antenna is particularly efficient in transmitting signals in all directions perpendicular to its axis, as opposed to along its axis. Understanding this information is crucial in determining the most advantageous positioning of the antenna within a specific application, as it allows for the optimization of its performance. By thoroughly analyzing the far-field radiation pattern of the antenna, valuable insights can be gained regarding its behavior, enabling informed decisions to be made regarding its usage.

4.0 APPLICATION AND FUTURE PROSPECTS

The proposed microstrip patch antenna, characterized by its compact dimensions of 50 mm × 60 mm on a single-layer FR-4 PCB (1.4 mm thick), holds promising applications, particularly in the realm of lightweight and compact communication systems. The antenna's small form makes it particularly well-suited for integration into vehicles or Unmanned Aerial Vehicles (UAVs) where size and weight considerations are paramount. Notably, its compatibility with low-frequency VHF signals, specifically operating at 433 MHz, positions it as an ideal solution for applications demanding both reduced dimensions and ergonomic design, such as UAVs or other remote-controlled devices.

The 2D and 3D radiation patterns offer valuable insights into the antenna's functionality. The proficiency in emitting energy perpendicular to its axis, coupled with high radial gain and low axial gain, positions the microstrip patch antenna as an optimal choice for various wireless applications. Particularly noteworthy is its potential role in lightweight control systems, where the compact size and optimized performance characteristics derived from the aforementioned metrics contribute significantly to its advantages. There are various other studies that also support the use of microstrip patch antennas for lightweight application systems, as in [34]–[38].

Besides that, the future prospects of the proposed microstrip patch antenna are promising, particularly in advancing wireless communication technologies. Its compact size, efficient energy transfer capabilities, and near-perfect impedance matching at the resonant frequency of 433 MHz position it as a viable candidate for integration into emerging applications, such as Internet of Things (IoT) devices and small-scale unmanned aerial vehicles (UAVs). The antenna's optimized performance characteristics, as evidenced by controlled dispersion patterns and radiation profiles, contribute to its potential deployment in smart transportation systems and sensor networks. Furthermore, its compatibility with lightweight control systems underscores its versatility in diverse applications, paving the way for enhanced connectivity and reliable communication in the evolving landscape of wireless technologies.

5.0 CONCLUSION

The microstrip patch antenna, measuring 50 mm × 60 mm on a single-layer FR-4 PCB (1.4 mm thick), was thoroughly analyzed through CST Studio simulations. Results reveal a resonant frequency of 433 MHz with an S11 value of -40.727 dB, indicating efficient energy transfer. The VSWR of 1.018 at 433 MHz signifies a near-perfect impedance match, while the impedance of 50.05 ohms aligns with the standard 50-ohm value for antennas. Electric and magnetic field analyses exhibit controlled dispersion patterns at 433 MHz. 2D and 3D radiation patterns demonstrate the antenna's effectiveness in emitting energy perpendicular to its axis, with high radial gain and low axial gain. This quantitative assessment underscores the microstrip patch antenna's potential for diverse wireless applications.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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