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Design and Analysis of Dual-Band Microstrip Patch Antennas for Wireless Communication Applications

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Abstract

Three dual-band microstrip patch antennas operating at 1.8 GHz and 2.1 GHz, 1.8 GHz, and 2.5 GHz, and 2.1 GHz and 2.5 GHz are designed and analyzed in this article. These frequency bands are important for Wi-Fi, LTE, and GSM, among other wireless communication applications. The suggested antennas' compact size and multiband performance make them perfect for incorporation into RFID technologies, Internet of Things (IoT) devices, and mobile communication systems. The antenna designs utilize a Fr4 substrate due to its low dielectric constant (4.4) and low loss tangent, ensuring reduced signal loss and enhanced performance at high frequencies. The antennas are lightweight and small, measuring 80*80 mm overall and 1.65 mm in thickness. This makes them ideal for modern communication equipment with little space. The developed antennas offer excellent impedance matching across all desired frequency bands, as demonstrated by the simulation results. Values below −10 dB at each operating frequency are indicated by the S-parameter results, specifically, the reflection coefficient (S11), indicating minimum reflection and effective power transmission. These features show how effective the antennas are and how well they perform with multiband applications like Wi-Fi, cellular networks, and Internet of Things connectivity.

Keywords

Microstrip Patch Antenna, Tri-Band Antenna, Wireless Communication GSM, Long-Term Evolution, Wi-Fi, IoT, Impedance Matching, S-Parameters, Reflection Coefficient, Radiation Pattern, FR4 Substrate, Multiband Operation

1. Introduction

In today's fast-paced world, the demand for efficient and versatile antenna designs has reached unprecedented levels, driven by the rapid evolution of wireless communication technologies [1]-[3]. As users increasingly rely on seamless connectivity and high-speed data transmission for a wide array of applications—from mobile communication to the Internet of Things (IoT)—the need for antennas that can operate effectively across multiple frequency bands has become critical [4]-[7]. This research delves into the design and analysis of three dual-band microstrip patch antennas, each specifically tuned to operate at essential frequency combinations: 1.8 GHz and 2.1 GHz, 1.8 GHz and 2.5 GHz, and 2.1 GHz and 2.5 GHz. The relevance of these frequency bands is significant in the context of contemporary communication standards. The 1.8 GHz band serves as a cornerstone for GSM (Global System for Mobile Communications), which facilitates voice calls and basic mobile data services. In contrast, the 2.1 GHz band is predominantly utilized for LTE (Long-Term Evolution), enabling high-speed data transfers essential for activities such as video streaming and online gaming. Additionally, the 2.5 GHz band is commonly associated with Wi-Fi, providing robust wireless connectivity for various consumer electronics, including smartphones, tablets, and smart home devices.

The implications of these antennas extend beyond mere technical specifications; they play a vital role in various application domains. For example, integrating such antennas into mobile devices can significantly enhance connectivity in urban environments, where signal strength may fluctuate due to obstructions and interference. The dual-band capability allows users to seamlessly switch between GSM and LTE, ensuring a stable connection no matter the service being utilized.

Moreover, the growing prevalence of IoT devices emphasizes the need for versatile antenna solutions capable of handling multiple communication protocols [6]-[8]. As smart homes and interconnected devices become commonplace, antennas that can operate across multiple frequency bands are essential for facilitating communication among these devices. This research aims to address that need by developing antennas capable of supporting various protocols and standards used in IoT applications. Performance evaluation for each antenna is conducted through comprehensive simulations that analyze reflection coefficients and overall efficiency. By examining S-parameters, particularly the S11 reflection coefficient, the study offers insights into how effectively each antenna can operate within its designated frequency bands. The simulation results reveal clear dips in the reflection coefficient at the targeted frequencies, confirming the effectiveness of the design strategies employed. The potential applications of these antennas reach far beyond mobile communication and Wi-Fi. Their dual-band capabilities make them suitable for various industries, including healthcare, automotive, and industrial automation. In healthcare, for instance, reliable wireless communication is essential for remote patient monitoring and telemedicine services. Antennas that effectively operate in both GSM and LTE bands can significantly enhance communication between medical devices and healthcare providers, ensuring timely and accurate data transmission.

In the automotive sector, as vehicles become increasingly connected, the need for dependable communication systems is more critical than ever. Antennas designed for dual-band operation can support vehicle-to-everything (V2X) communication, allowing vehicles to exchange information with other vehicles and infrastructure to improve safety and efficiency on the roads. Industrial automation is another area where dual-band antennas can play a crucial role. As factories adopt smart technologies and IoT solutions, the necessity for seamless communication between devices and systems grows. Antennas capable of operating across multiple frequency bands provide the flexibility needed to support a variety of industrial applications, from real-time monitoring to automated control systems.

2. Design of the Antenna

2.1. Antenna 1

The proposed antenna is printed on a FR4 substrate with a thickness of 1.65 mm, as shown in Figure 1. With a dielectric constant of about 4.4, the FR4 substrate is a popular and reasonably priced material. Because of this dielectric constant, the antenna can function effectively at the desired frequency ranges and still be small. To modify the current distribution on the patch surface and enable the antenna to resonate at two different frequencies, the design includes slots inside the patch that are carefully introduced. The antenna's physical size is efficiently decreased by the slots without sacrificing its functionality. By generating extra resonance modes, these slots also contribute to increased bandwidth, enabling the antenna to function at both 1.8 GHz and 2.1 GHz with adequate bandwidth for each frequency.

GSM applications use the 1.8 GHz frequency band, while LTE communication systems use the 2.1 GHz frequency band. This is the configuration of the first antenna. Rectangular microstrip patches, which are popular for their simplicity, low profile, and ease of manufacture, are typically employed as the radiating element in planar structures. This antenna type is no exception. To ensure optimal impedance matching and reduce signal reflection, it is fed through a 50-ohm transmission line. This results in increased performance and efficiency.

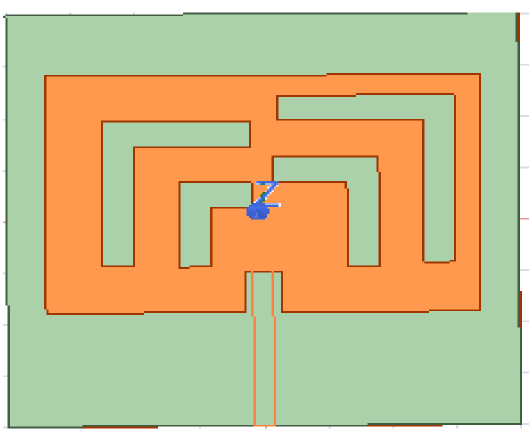

Figure 1. Proposed antenna 1.

2.2. Antenna 2

Designed to function at 1.8 GHz, which is mostly utilized for GSM communication, and 2.5 GHz, which is a shared band for Wi-Fi and certain LTE applications, is the second antenna (**Figure 2**). Once more, a rectangular patch antenna is the fundamental component, supplied by a transmission line with a 50 ohm impedance. To reduce losses and optimize the power emitted by the antenna, the feed ensures that the impedance matching is optimal. The design, like the original antenna, is printed on a 1.65 mm thick FR4 substrate. It can operate at both frequency bands thanks to its 4.4 dielectric constant.

Also, this antenna has patches with carefully positioned slots. The slots have two functions: they increase the bandwidth for each operational frequency and aid in the antenna's resonance at two different frequencies. The slots in this instance are intended to resonate at 2.5 GHz and 1.8 GHz. In addition to providing extra channels for current distribution, the slot structures enable the antenna to function in the Wi-Fi band (2.4/2.5 GHz) and support GSM communication (1.8 GHz). Multi-band functioning of this kind is perfect for gadgets like wireless routers, tablets, and smartphones that need to be able to transmit data as well as communicate.

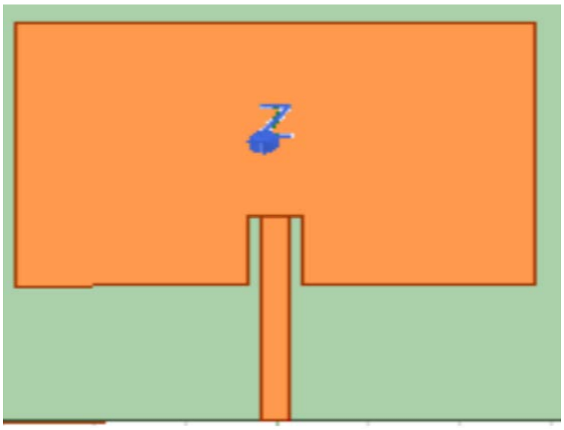

Figure 2. Proposed antenna 2.

2.3. Antenna 3

The third antenna is designed to operate at 2.1 GHz, primarily for LTE applications, and 2.5 GHz for Wi-Fi. Like the previous designs, it's based on a rectangular microstrip patch antenna, which is fed through a 50-ohm impedance line. The antenna is printed on an FR4 substrate, with a thickness of 1.65 mm and a dielectric constant of 4.4, ensuring a good balance between performance and compact size (**Figure 3**). Slots in the patch allow for dual-band operation at 2.5 GHz and 2.1 GHz with this antenna arrangement. These slots increase bandwidth and operational efficiency by facilitating resonance at both frequencies. The design optimally matches the impedance and supports both bands by providing two different current routes on the surface. S-parameter measurements, which reveal S11 values below −10 dB, indicating effective power transmission with low reflection, provide evidence of this.

The 2.1 GHz and 2.5 GHz frequencies are essential for contemporary LTE and Wi-Fi applications. This dual-band capability not only broadens the antenna's versatility but also makes it an excellent fit for a range of devices, including smartphones, tablets, and wireless routers. The ability to support high-speed Wi-Fi data transfers alongside stable LTE connections is a significant advantage. Furthermore, the compact design is well-suited for devices with limited space, ensuring high performance across multiple frequency bands. Overall, this antenna represents a reliable and efficient solution for modern mobile and wireless applications.

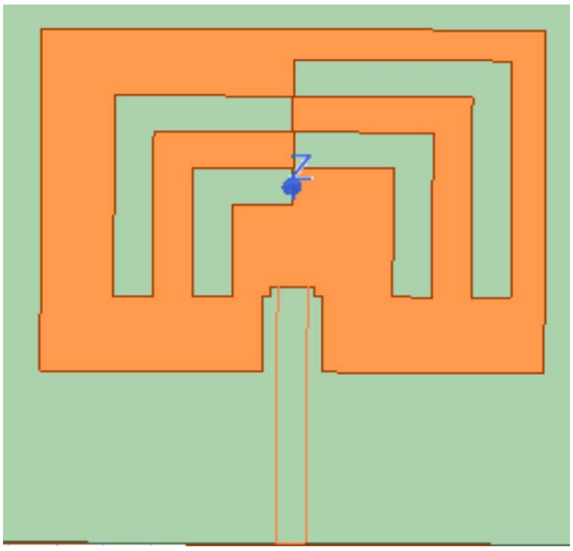

Figure 3. Proposed antenna 3.

2.4. Multi-Band Antenna

The proposed antenna design is a tri-band antenna, printed on an FR4 substrate with a thickness of 1.65 mm and a dielectric constant of 4.4, just like the reference antenna (**Figure 4**). This substrate choice allows the antenna to maintain a compact size while achieving effective performance across the desired frequency bands. The key innovation in this design lies in the intricate slot structure within the patch, which reduces the antenna's overall size and introduces multiple resonance modes.

These slots contribute to the tri-band operation by altering the current distribution across the surface, thus enabling the antenna to resonate at three distinct frequencies. The design ensures broad bandwidth coverage while maintaining optimal impedance matching through a 50-ohm transmission line, enhancing both performance and efficiency. This tri-band antenna is a versatile solution for various applications, further expanding the functionality of the original design while keeping the form factor compact.

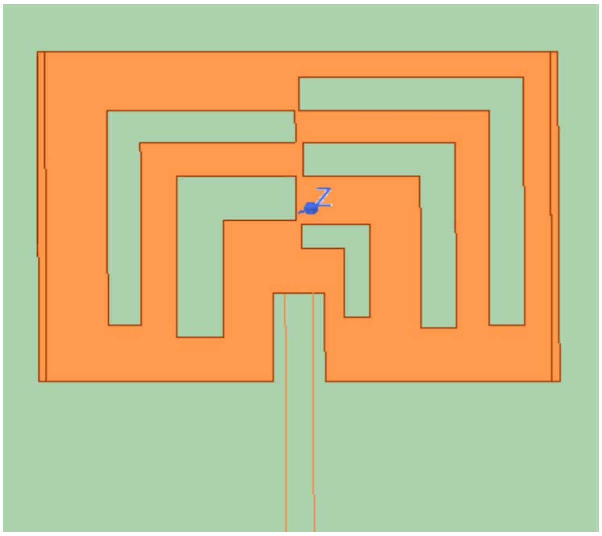

Figure 4. Proposed multi-band antenna.

3. Results of the Antenna

S-parameters for all antenna designs were carefully simulated to evaluate the S11, or reflection coefficient, over the designated frequency ranges. The accompanying graphs show the results, which show clear falls below −10 dB, suggesting effective performance at the desired frequencies. A thorough examination of each antenna is provided below.

3.1. Antenna 01 Results

3.1.1. The Reflection Coefficient

The simulation results for the first antenna reveal two significant dips in the reflection coefficient at 1.8 GHz and 2.1 GHz, as shown in Figure 5. These frequencies are vital for GSM and LTE applications, which are essential in today's mobile communications landscape. The dip at 1.8 GHz corresponds to the GSM frequency band, where mobile devices depend on effective signal transmission for voice calls and basic data services. The second dip at 2.1 GHz relates to LTE services, which greatly enhance data transfer speeds and enable advanced features like video streaming and mobile broadband.

Certain components that are integrated into the antenna's design help it function well in both frequency bands. The patch's incorporated slots are essential for producing a variety of resonance modes, which aid in the antenna's efficient coupling at both frequencies. Furthermore, the antenna's optimized dimensions allow it to maintain its tiny size, which facilitates easy integration into a range of mobile devices without compromising performance. Importantly, the S11 results show values below −10 dB, indicating excellent impedance matching. This is crucial because good impedance matching minimizes reflection losses, which can negatively affect signal quality and overall efficiency. By maintaining low S11 values across both bands, the antenna ensures that it can transmit and receive signals with minimal interruptions, leading to a more reliable communication experience.

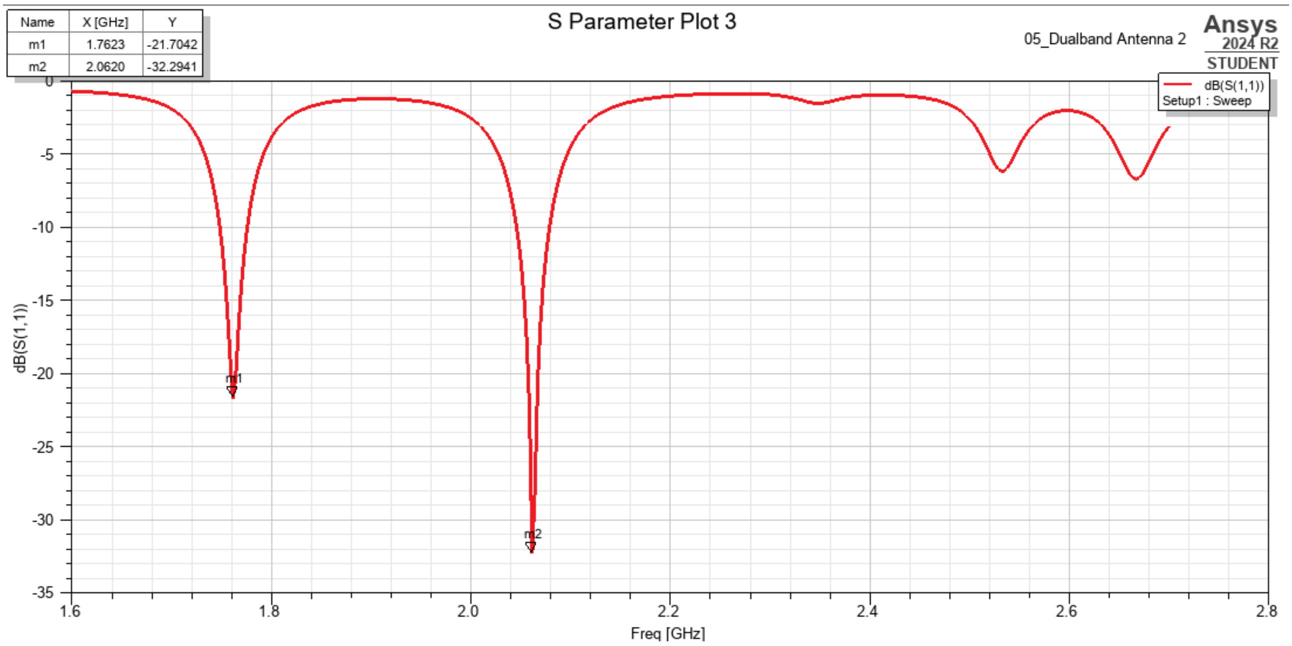

Figure 5. Reflection coefficient of antenna 1.

3.1.2. 2D Radiation Pattern

The 2D radiation pattern shows the antenna's directional characteristics, illustrating how it radiates power across different angles. Figure 6 demonstrates a dual-lobed pattern, indicating bidirectional radiation. The gain variations across angles reveal areas of strong and weak radiation, critical for understanding antenna coverage.

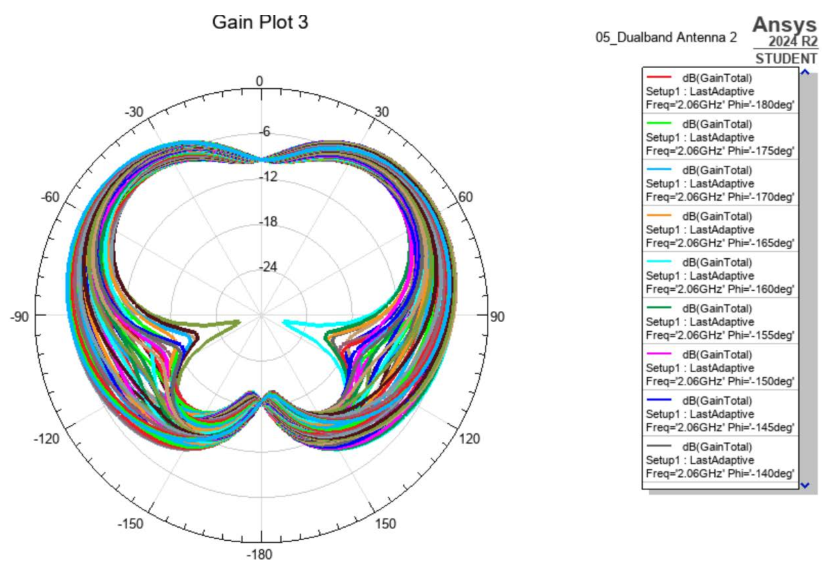

Figure 6. 2D radiation pattern of antenna 1.

3.1.3. 3D Radiation Pattern and Gain Plot

The 3D radiation pattern and gain plot depict the overall radiation efficiency and directionality shown in Figure 7. The spherical shape with higher gain at the center indicates focused radiation in the desired direction. The color scale shows gain variations, assisting in visualizing the antenna's effective radiated power across space.

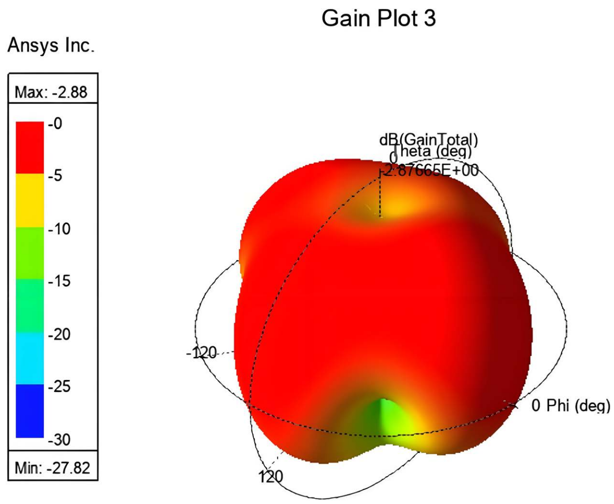

Figure 7. 3D radiation pattern and gain plot of antenna 1.

3.1.4. Current Distribution

The current distribution map highlights regions of varying current intensity on the antenna's surface (Figure 8). Red areas denote high current, leading to strong radiation, while blue areas represent low current, indicating less efficient radiation. This distribution helps evaluate the antenna's resonant behavior and efficiency at specific frequencies.

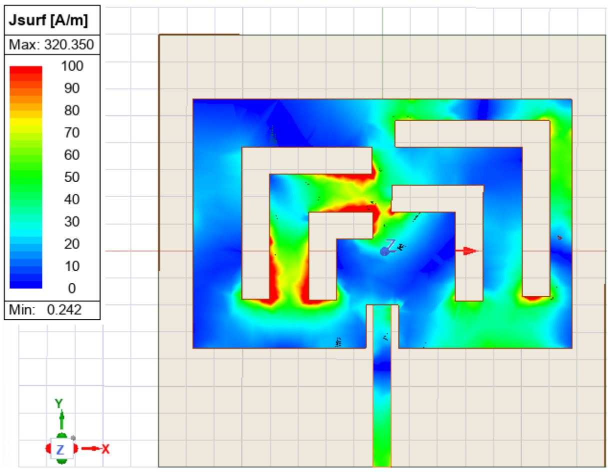

Figure 8. Current distribution of antenna 1.

3.2. Antenna 02 Results

3.2.1. The Reflection Coefficient

Significant drops in the reflection coefficient are seen in the S-parameter study of the second antenna at 1.8 GHz and 2.5 GHz, which are crucial frequencies for GSM and Wi-Fi applications (Figure 9). The GSM standards-compliant dip at 1.8

GHz guarantees dependable phone and data connection, while the Wi-Fi frequency band is the focus of the dip at 2.5 GHz, which is essential for high-speed internet access in a variety of devices. Advanced design methods are used in this antenna to maximize performance at both frequencies. The incorporation of slots into the patch improves surface current management and multiplies the resonance frequency of the antenna. With the help of this function, which increases overall efficiency and expands the operational bandwidth, laptops, tablets, and cellphones may all connect seamlessly. This antenna design is also perfect for incorporation into consumer devices, where space is frequently at a premium, due to its small form factor. Its dual-band functionality gives devices the flexibility and performance needed in today's connected world, enabling them to function well in a variety of networking contexts.

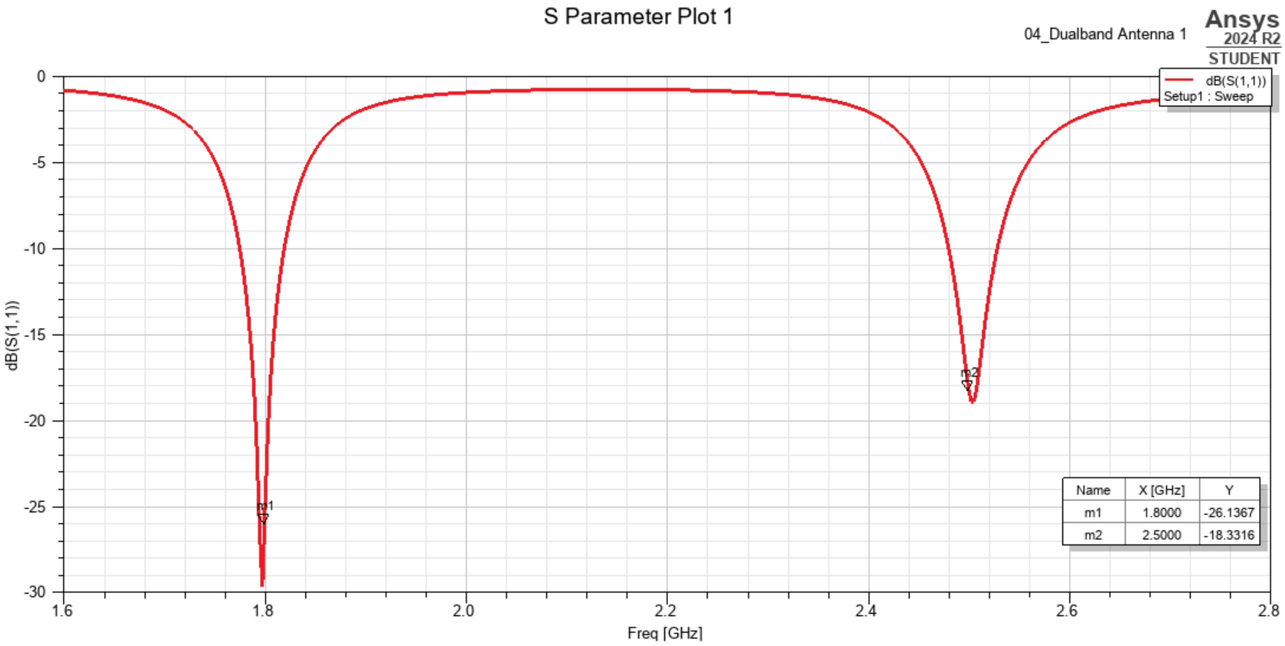

Figure 9. Reflection coefficient of an.

3.2.2. 2D Radiation Pattern

The 2D radiation pattern (**Figure 10**) shows a bidirectional radiation pattern, with two prominent lobes indicating radiation concentrated at ±90˚. The maximum gain reaches −0.14 dB, as shown on the scale. This suggests that while the antenna radiates effectively in these directions, the overall gain is relatively low, indicating suboptimal radiation efficiency.

3.2.3. 3D Radiation Pattern and Gain Plot

The current distribution plot shows minimal current density across most of the antenna surface, with the highest current near the feedline reaching 55 A/m (in red), as shown in **Figure 11**. The dominance of blue areas indicates low current density over the rest of the antenna, which correlates with the low overall radiation efficiency and reduced gain.

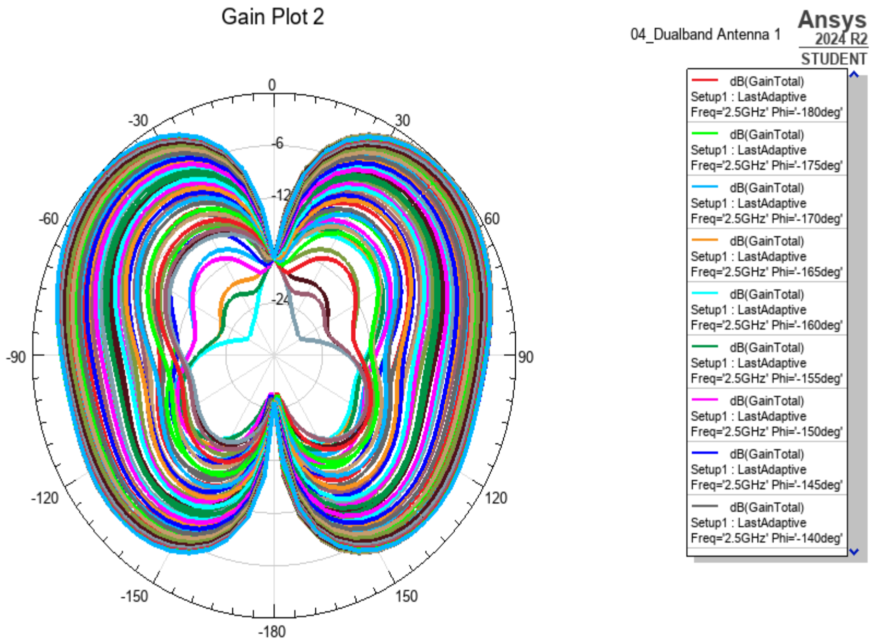

Figure 10. 2D radiation pattern of antenna 2.

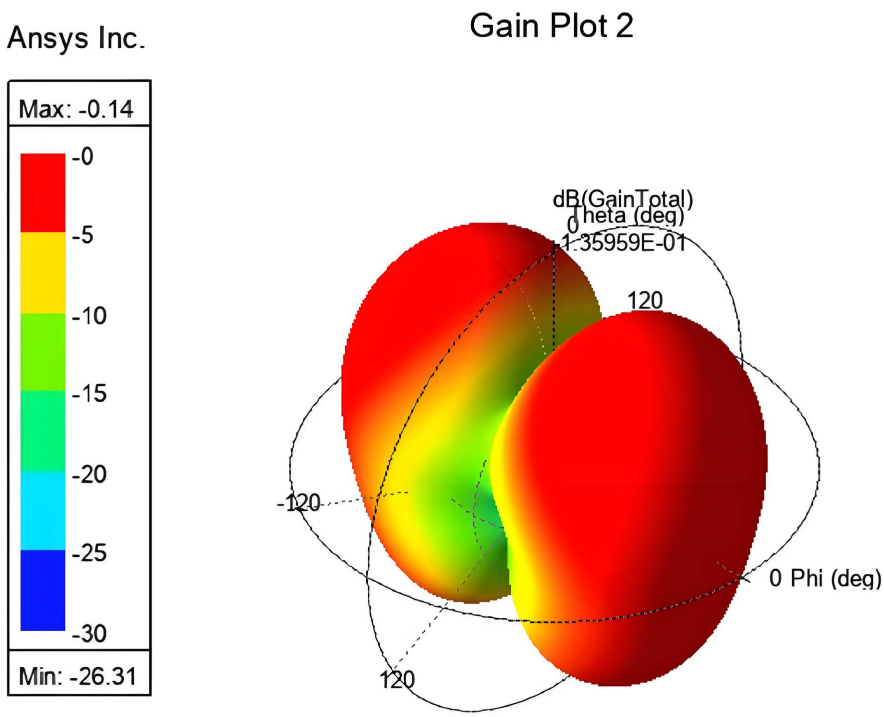

Figure 11. 3D radiation pattern and gain plot of antenna 2.

3.2.4. Current Distribution

The 3D radiation pattern confirms the gain's maximum value of −0.14 dB, showing a weakly directional radiation profile (**Figure 12**). The lobes focus the radiation along two opposite directions, but the low gain suggests that the antenna is not performing efficiently, likely due to design constraints or impedance mismatches at this frequency.

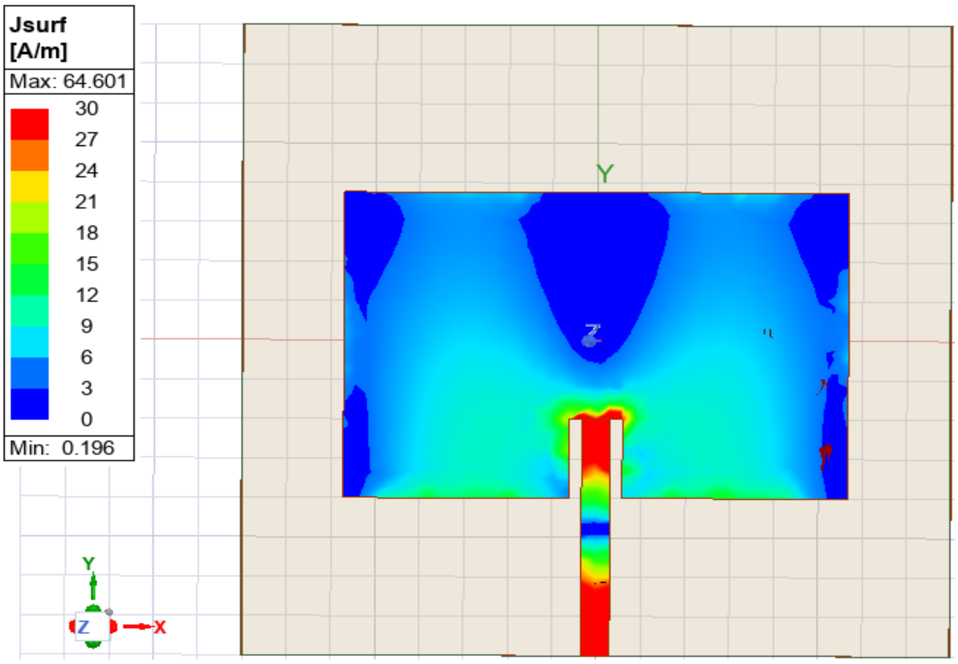

Figure 12. Current distribution of antenna 2.

3.3. Antenna 03

3.3.1. The Reflection Coefficient

The third antenna's S-parameter measurements (**Figure 13**) show notable reflection coefficients at 2.1 GHz and 2.5 GHz, indicating that it is suitable for LTE and Wi-Fi applications. For LTE networks, the 2.1 GHz frequency is especially important since it allows for fast data transfer and a variety of mobile services, such as online gaming, streaming videos, and downloading large files. Widely used for Wi-Fi, the 2.5 GHz band provides strong wireless networking capabilities and dependable and effective internet connectivity for devices.

To optimize performance at these frequencies, the antenna employs advanced design features. The strategic incorporation of slots within the patch enhances resonance, creating effective current pathways that improve functionality across both bands. This design not only supports dual-band operation but also maintains a compact form factor, making it suitable for integration into various devices, including smartphones, tablets, and other wireless communication equipment. The observed S11 values below −10 dB indicate excellent impedance matching, which is critical for minimizing reflection losses. Effective impedance matching maximizes power transfer, allowing the antenna to deliver strong and stable signals. This characteristic is particularly advantageous in environments where signal strength may vary, such as urban settings filled with obstacles.

3.3.2. 2D Radiation Pattern

The 2D radiation pattern (**Figure 14**) indicates a strong bidirectional radiation characteristic, with lobes prominently oriented in opposite directions along the azimuth plane. The maximum gain observed is −4.99 dB, as indicated in the color bar. This pattern demonstrates the antenna's directional behavior, though the low gain suggests limited radiation efficiency at this frequency.

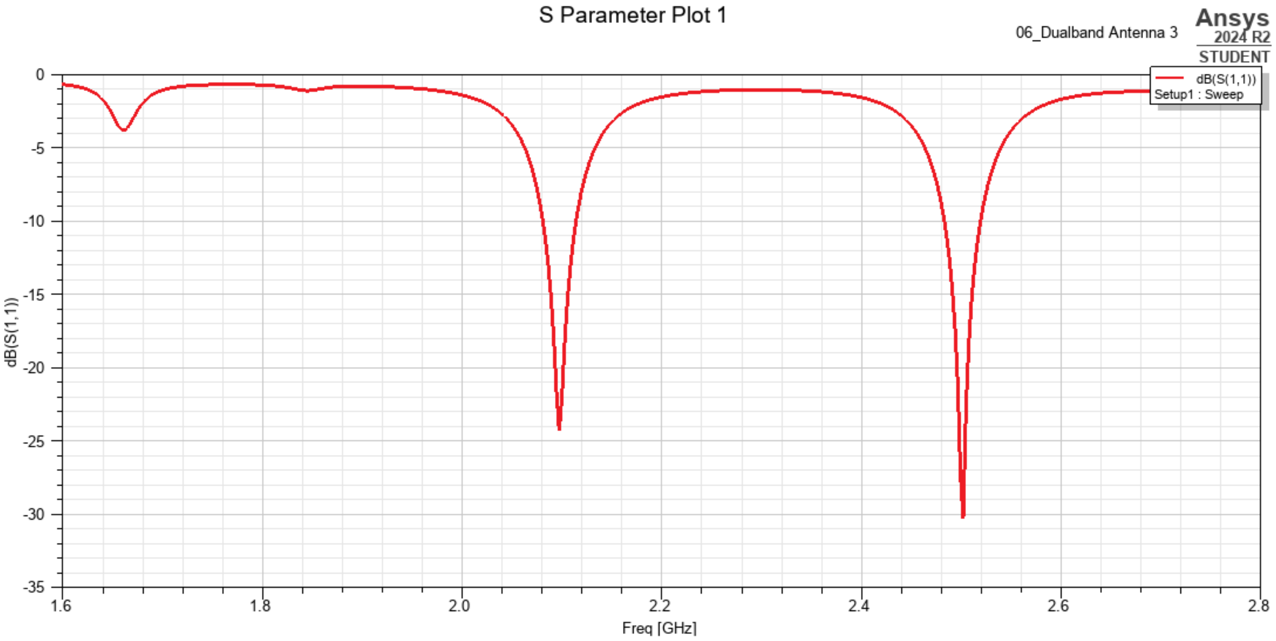

Figure 13. Reflection coefficient of antenna 3.

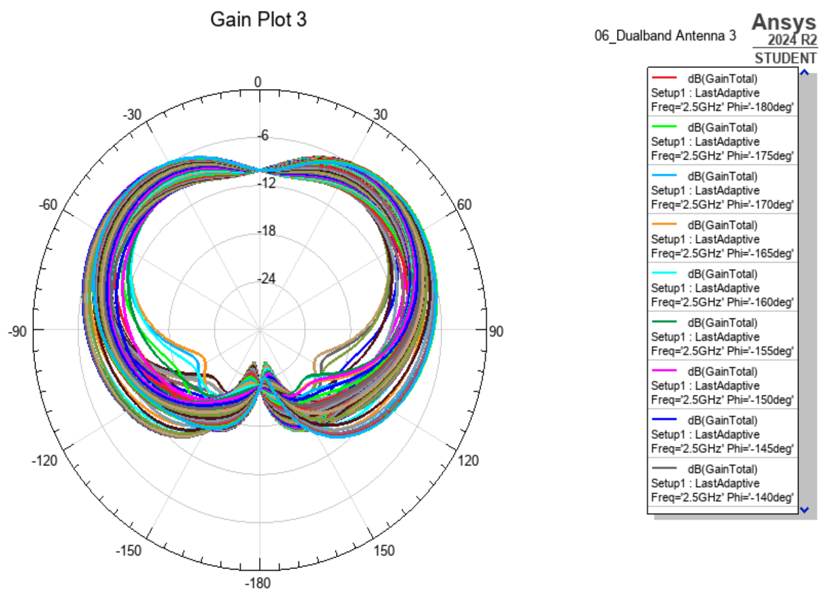

Figure 14. 2D radiation pattern of antenna 3.

3.3.3. 3D Radiation Pattern and Gain Plot

The 3D radiation pattern further highlights the low gain of −4.99 dB, with radiation concentrated in a slightly directional lobe shown in **Figure 15**. The color gradient clearly visualizes areas of weak radiation, particularly in the negative gain regions, which correlates with the limited current distribution and highlights the antenna's inefficiencies at this operating frequency.

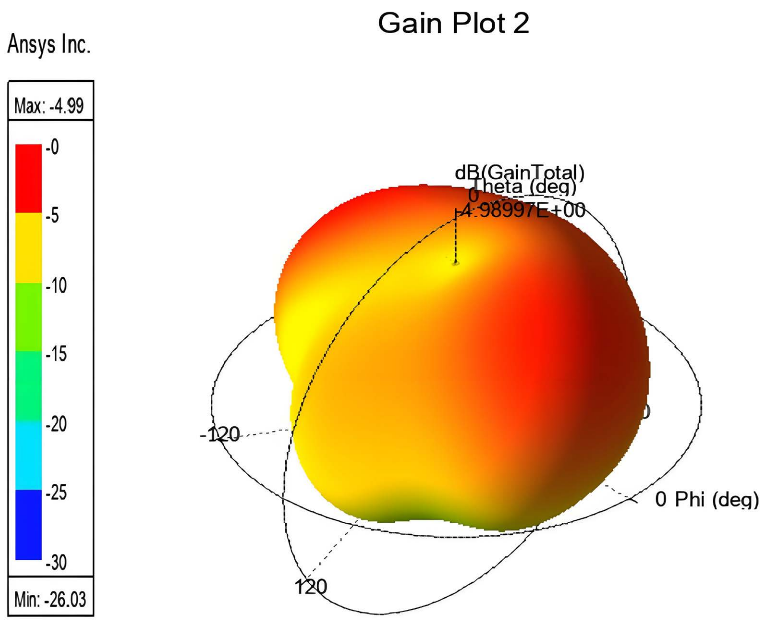

Figure 15. 3D radiation pattern and gain plot of antenna 3.

3.3.4. Current Distribution

The current distribution shows a maximum current density of 200 A/m in concentrated areas, particularly along the feedline and certain segments of the antenna, which are highlighted in red (Figure 16). The blue areas, representing low current density, cover the majority of the surface, indicating a less efficient current flow overall. This uneven current distribution is likely contributing to the reduced gain observed.

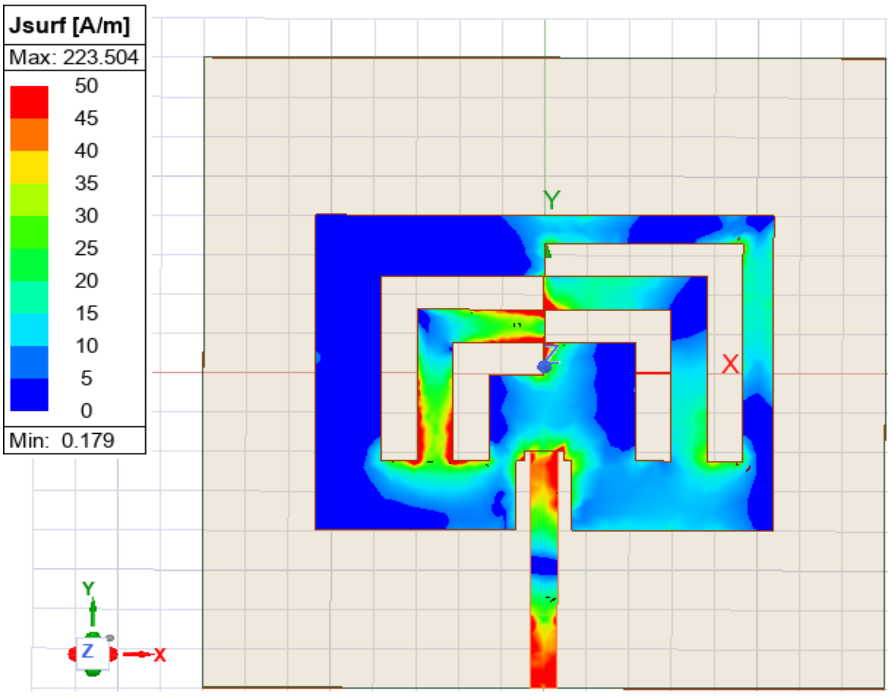

Figure 16. Current distribution of antenna 3.

3.4. Multi-Band Antenna Results

The results of the antenna design shown in Figure 17 are as follows:

S-Parameters: The S-parameter plot highlights that the antenna resonates at three frequency bands: 1.8 GHz, 2.1 GHz, and 2.5 GHz. Each of these bands exhibits a return loss below −10 dB, indicating good impedance matching and minimal signal reflection, thus ensuring efficient power transfer.

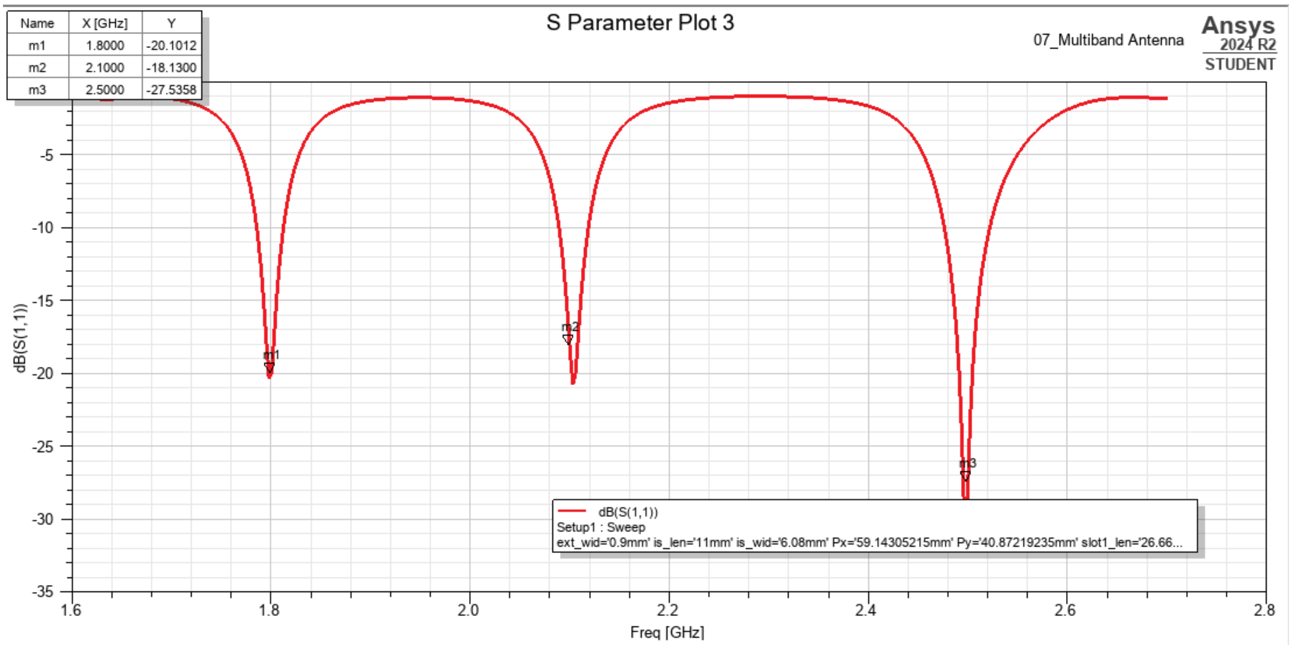

Figure 17. Reflection coefficient of multi-band antenna.

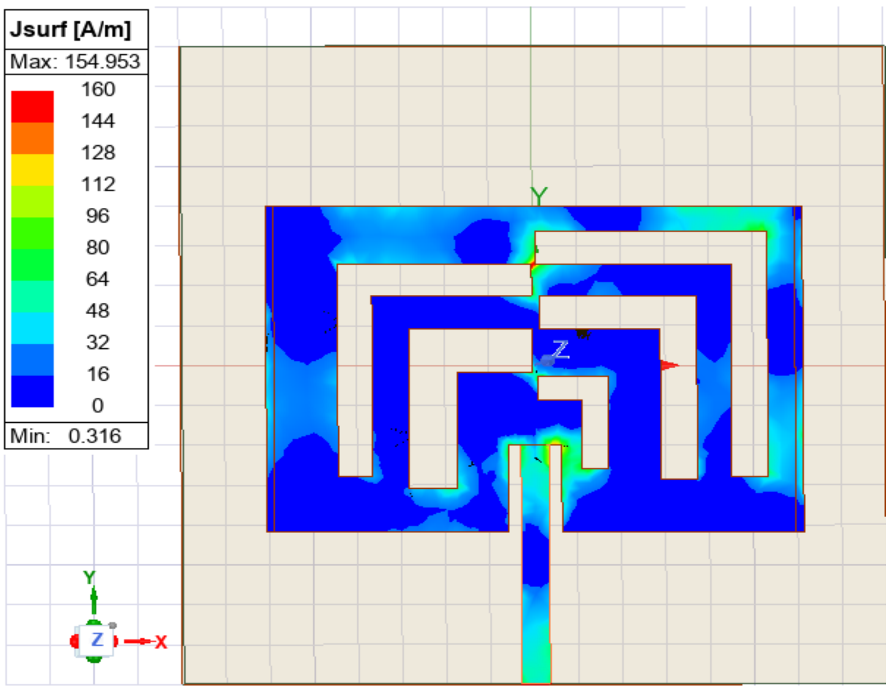

Figure 18. 3D radiation pattern and gain plot of multi-band antenna.

2D Radiation Pattern: The 2D radiation pattern exhibits a bidirectional pattern, typical of microstrip antennas. The gain plot shows stability across the frequency range, with the radiation focused in two major lobes.

3D Radiation Pattern (Figure 18): The 3D gain plot displays a relatively omnidirectional pattern with peak radiation in specific directions. The gain of the antenna is well-distributed, supporting its application in multi-band communication systems.

Current Distribution (Figure 19): The current distribution plot indicates the maximum current density on the patch, reaching a value of 154 A/m at resonant points. This demonstrates strong surface currents, which contribute to the effective radiation and performance of the antenna.

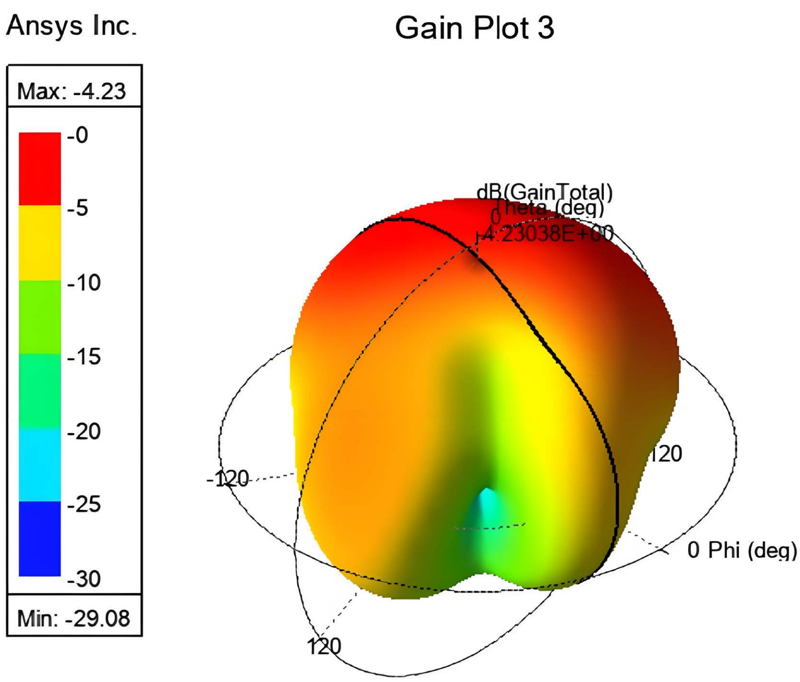

Figure 19. Current distribution of multi-band antennas.

4. Conclusion

The dual-band microstrip patch antennas developed in this research hold great promise for a variety of practical applications in wireless communication. Operating efficiently at critical frequency bands—1.8 GHz, 2.1 GHz, and 2.5 GHz—these antennas are well-suited for supporting essential services such as GSM for voice calls and basic data, LTE for high-speed internet access, and Wi-Fi for reliable wireless networking. Strong and adaptable connectivity solutions are more important than ever as the world of mobile devices and IoT technology continues to change. These antennas' small size and excellent performance make them perfect for incorporation into a variety of IoT devices, including tablets and smartphones. They allow customers to take advantage of smooth experiences with online gaming, video streaming, and rapid file transfers by guaranteeing steady connections.

Furthermore, because of their versatility in many communication contexts, they can efficiently support users in a range of scenarios, including busy cities and isolated places with spotty internet. These antennas signify significant developments in wireless communication technologies that not only improve user experience but also open up new avenues for future innovations and applications.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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