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# Design and Analysis of Microstrip Patch Antenna for 6G Millimeter-Wave Communication

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**Abstract**

The growing requirements of sixth-generation (6G) applications call for wireless communication systems, capable of delivering ultra-high speeds and substantial capacity, are critical for the successful implementation of 6G technology. To address this demand, a microstrip antenna was developed to operate within the 110 GHz to 120 GHz frequency range, with its performance meticulously evaluated using various patch materials, including copper. A comprehensive analysis of key antenna parameters was performed, leveraging Computer Simulation Technology (CST) Studio software for rigorous simulation and optimization tailored to 6G applications within this frequency spectrum. At 110 GHz, the proposed antenna exhibited exceptional performance metrics, including a directivity of 186.7 dB, a gain of 10.03 dBi, a radiation efficiency of 176.7 dB, a reflection coefficient of -12 dB, a total efficiency of -177 dB, and a voltage standing wave ratio (VSWR) between 1.5 and 2. At 120 GHz, similarly impressive results were achieved, with a directivity of 181.5 dB, a gain of 4.697 dBi, a radiation efficiency of -176.9 dB, a reflection coefficient ranging from -14 dB to -15 dB, a total efficiency of -177 dB, and a VSWR of 1.5. This research highlights the critical role of optimizing microstrip antenna designs for 6G millimeter-wave communication, offering valuable insights to propel advancements in next-generation wireless communication systems.

*Keywords*: 6G Applications; Antenna parameters; Microstrip antenna; Wireless communications.


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## 1. Introduction

In the context of 6G communications, antennas [1] play a crucial role as the link between the physical and digital worlds. With 6G striving for exceptional speed, capacity, and reliability, antennas are central to several key areas. Firstly, antennas designed for terahertz frequencies are essential for accessing the broad bandwidths necessary for ultra-fast data transmission in 6G networks. Furthermore, antenna arrays that support advanced techniques like beamforming and Massive Multiple Input, Multiple Output (MIMO) significantly

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improve spectral efficiency and network capacity, enhancing the user experience. Additionally, antennas offering extensive coverage and flexibility for multi-band, multi-mode operations ensure reliable connectivity in diverse environments and across various timeframes. Innovative antenna designs also contribute to energy-efficient transmission and reception, reducing the environmental footprint of 6G networks. Antennas optimized for emerging technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Augmented Reality (AR) devices enable smooth integration and reliable connectivity across different applications. Lastly, antennas with advanced security features play a vital role in strengthening network defenses and protecting user data. In summary, antennas are the backbone of 6G networks, driving progress in performance, efficiency, and user satisfaction, with their continued development and integration being key to unlocking the full potential of 6G technology.

Microstrip patch antennas [2], a type of printed antenna, are widely used in fields like wireless communications, satellite systems, and radar applications due to their lightweight, compact design and simple manufacturing process. Typically consisting of a radiating patch on top of a dielectric substrate and a ground plane beneath, these antennas are commonly made from conductive materials such as copper or gold and are often rectangular in shape. The design of microstrip patch antennas [3,4] requires careful attention to parameters such as operating frequency, bandwidth, gain, and radiation pattern, which are influenced by the patch's dimensions, geometry, and substrate thickness.

In 6G communication, microstrip patch antennas are considered essential components [5] due to their adaptability and simple design and manufacturing process. However, achieving high gain, directivity, and a low reflection coefficient remains a key challenge for effective communication. High reflection coefficients can lead to significant signal loss, which negatively affects system performance. To address this issue, various techniques have been developed to minimize reflection coefficients in microstrip patch antennas [6,7]. This paper presents a custom-designed antenna for 6G applications, optimized for high gain, directivity, and a low reflection coefficient within the frequency range of 110 GHz to 120 GHz. The proposed antenna exhibits promising characteristics for 6G communication, supporting efficient signal transmission and reception. Its simple design and manufacturing process further enhance its cost-effectiveness, making it an appealing choice for 6G technology implementation. As 6G technology promises remarkable advancements in speed, capacity, and latency, microstrip patch antennas, with their compact size, lightweight, and ease of production, are well-suited for wireless communication systems, particularly in portable devices. Despite their advantages, achieving high gain, directivity, and low reflection coefficient remains a significant challenge, directly impacting the efficiency of signal transmission and overall system performance. This paper addresses this challenge and contributes to the advancement of microstrip patch antennas for 6G communication systems.

This paper focuses on the development and optimization of a microstrip antenna for 6G applications, specifically within the 110 GHz to 120 GHz frequency range. The antenna's performance parameters, including directivity, gain, radiation efficiency, reflection coefficient, total efficiency, and voltage standing wave ratio (VSWR), were thoroughly analyzed and simulated using Computer Simulation Technology (CST) Studio software. The study aims to evaluate the antenna's suitability for meeting the high-speed and high-capacity demands of 6G technology at both 110 GHz and 120 GHz frequencies.

## 2. *Research Methodology*

The process of designing a microstrip patch antenna in CST Studio Software to achieve high gain, directivity, and low reflection follows a systematic approach [8-10]. The first step involves defining the frequency range between 110 GHz and 120 GHz. Attention is then given to selecting suitable materials for the antenna components. After that, the antenna is precisely designed with the necessary dimensions. Once the design is complete, a detailed simulation is carried out to evaluate the antenna's performance. The research workflow for this process is illustrated in Fig. 1.

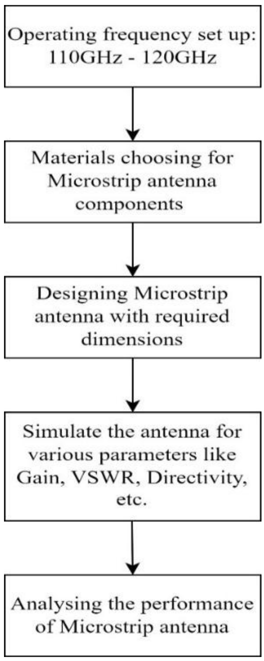


Fig. 1. Microstrip antenna design and simulation workflow.

### 2.1. *Design and composition of microstrip antenna components*

Designing a Microstrip Patch Antenna involves several critical components, each requiring specific materials to ensure optimal functionality [11,12]. The key components include the Ground, Substrate, Patch, and Feeds, with material selection playing a crucial role in their performance. Annealed copper, known for its excellent conductivity and durability, is commonly used for both the Ground and Patch. The Substrate, which provides the dielectric medium, is typically made of FR4, a material recognized for its dielectric properties despite its lossy nature. The Feeds, responsible for signal transmission to and from the antenna, also utilize annealed copper for its superior conductivity. The components of the microstrip antenna, along with their corresponding materials, are detailed in Table 1.

Table 1. Materials used for microstrip antenna components.

| Microstrip antenna components | Used Materials |
|---|---|
| Ground | Copper annealed |
| Substrate | FR4(loosy) |
| Patch | Copper annealed |
| Feed 1 | Copper annealed |
| Feed 2 | Copper annealed |

The microstrip antenna components have been constructed using the materials outlined in Table 1. Table 2 presents the detailed specifications of the microstrip antenna design, including dimensions such as height, length, width, and thickness, along with their respective measurements.

Table 2. Design specifications of the microstrip antenna.

| Antenna dimensions | Values (mm) |
|---|---|
| Height (h) | 1.6 |
| Length (L) | 34 |
| Thickness (t) | 0.0035 |
| Length of feed 1( $lf_1$) | 5 |
| Length of feed 2 ( $lf_2$ ) | 7 |
| Width (w) | 34 |
| Width of feed 1($Wf_1$) | 3 |
| Width of feed 2 ($Wf_2$ ) | 1 |
| Length of patch (lp) | 20 |
| Width of patch (wp) | 28 |

The microstrip antenna has been carefully developed according to the specifications outlined in Table 2.

***Ground*:** The ground plane plays a vital role in the performance of the microstrip patch antenna [13,14], acting as the reference plane for electromagnetic waves. In our design, a solid ground plane is placed beneath the patch antenna to provide a stable reference point and minimize radiation losses. Typically constructed from conductive materials like copper, the ground plane ensures electrical stability. The ground plane's placement beneath the antenna, along with its dimensions, is visually represented in Fig. 2, highlighting its integration into the overall antenna design.

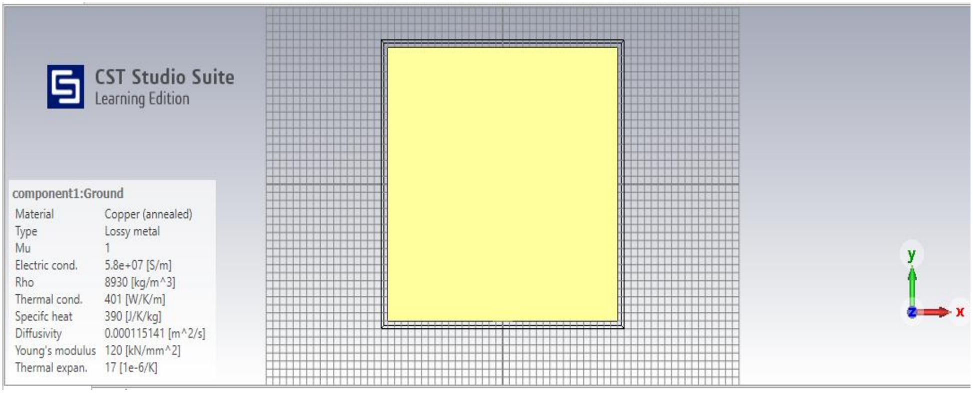

Fig. 2. Configuration of ground plane in microstrip antenna layout.

***Substrate:*** The choice of substrate is essential for optimizing the performance of the microstrip patch antenna, particularly for 6G applications. A dielectric substrate with specific characteristics is selected to ensure optimal antenna performance. Key factors such as the dielectric constant and thickness of the substrate are examined to achieve the desired impedance matching and radiation efficiency [15]. This analysis helps in assessing the antenna's key performance indicators, including reflection coefficient, bandwidth, and radiation pattern. The substrate selection and integration process are critical in determining the overall performance [16] and suitability of the microstrip patch antenna for 6G applications. In this design, FR4 (a lossy material) is used as the substrate, as shown in Fig. 3.

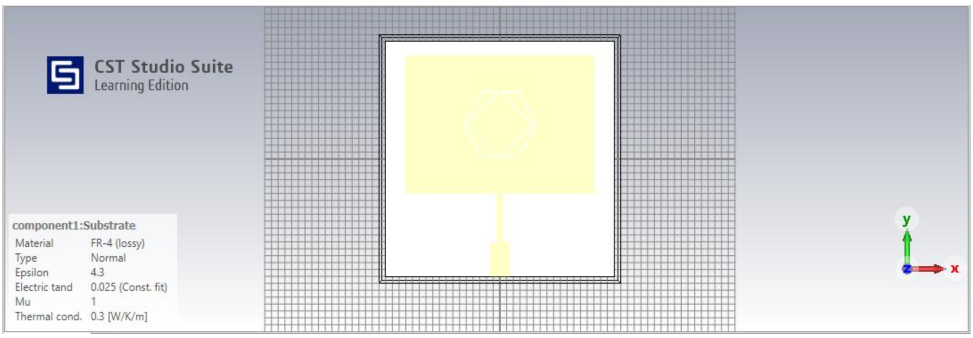

Fig. 3. Substrate material integration in microstrip antenna configuration.

***Patch:*** The geometry of the patch is carefully selected, taking into account its shape, size, and substrate material to achieve the desired operating frequency and radiation properties [17]. The patch is precisely manufactured using standard printed circuit board (PCB) techniques, ensuring high quality and consistency throughout the process. After fabrication, the antenna undergoes experimental testing to verify its ability to attain a low reflection coefficient suitable for 6G applications [18]. The integration of the patch into the microstrip antenna is shown in Figure 4, with the patch material made of annealed copper.

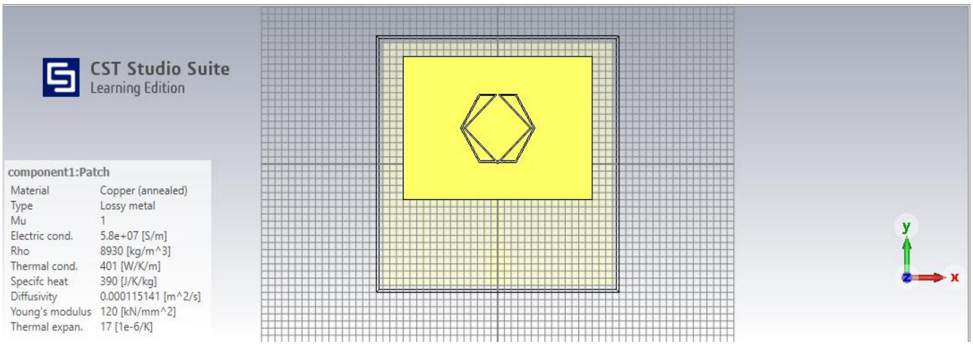

Fig. 4. Patch structure integration within microstrip antenna design.

***Feed 1:*** The design of Feed 1 for the microstrip patch antenna, tailored for 6G applications, was based on specific requirements, such as impedance matching and radiation pattern performance [19]. The geometry and dimensions of Feed 1 were precisely fine-tuned to meet these performance criteria. The optimization process involved adjusting key parameters like feed line width, length, and positioning through iterative refinements to minimize reflection coefficients and ensure efficient power transfer to the radiating element. The approach used for designing Feed 1 was aimed at enhancing the microstrip patch antenna's performance in 6G applications [20]. The integration of Feed 1 into the microstrip antenna is shown in Fig. 5, with annealed copper used as the material.

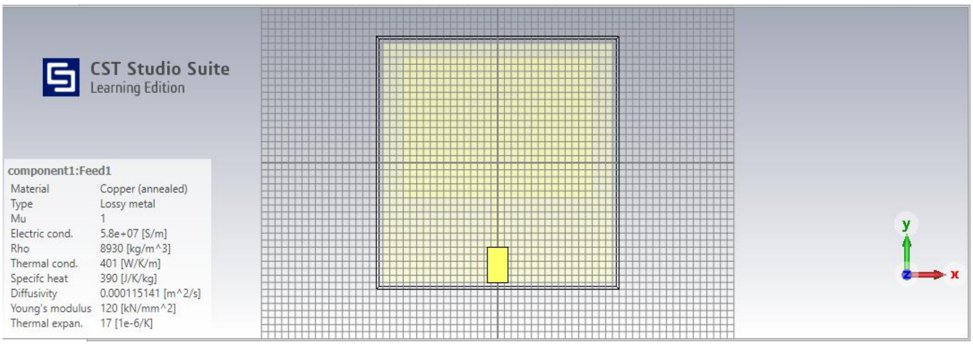

Fig. 5. Feed 1 Implementation in microstrip patch antenna configuration.

***Feed 2:*** In the design of microstrip antennas, "Feed 2" refers to the secondary feeding system used to excite the radiating element, such as the patch. It involves creating a connection point or signal source within the antenna to enable the transmission or reception of electromagnetic waves. The design and integration of Feed 2 are crucial, as they directly impact the antenna's impedance matching, radiation pattern, and overall performance [21]. The incorporation of Feed 2 into the microstrip antenna is shown in Fig. 6.

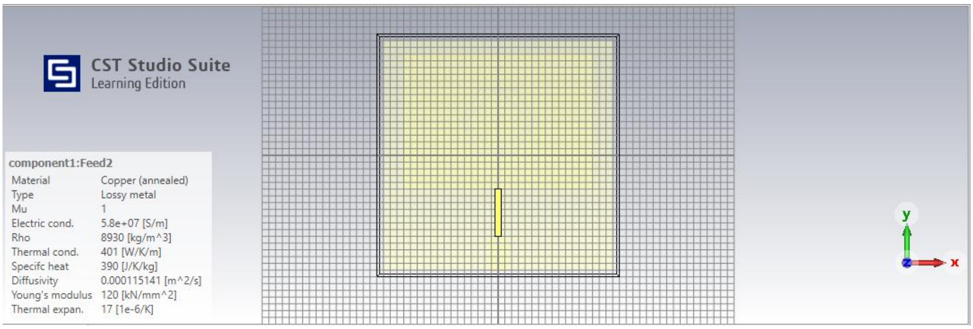


Fig. 6. Integration of the secondary feed in microstrip patch antenna.

***Port assignment for the antenna:*** The microstrip patch antenna, designed for 6G applications, utilizes a single-port configuration to streamline the feeding process and enhance impedance matching [22]. This setup is essential for minimizing reflection coefficients, especially in the high-frequency bands associated with 6G networks [23]. The implementation of this configuration within the antenna design is shown in Fig. 7.

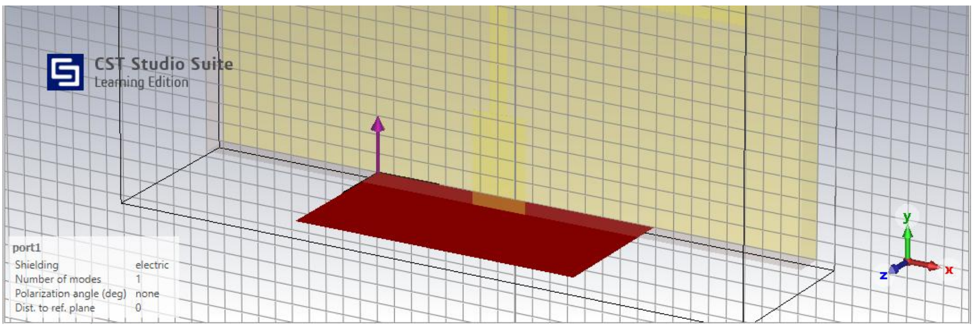


Fig. 7. Deployment of single port configuration in microstrip antenna design.

## 2.2. *Proposed microstrip antenna design*

The development of a microstrip patch antenna system involves the integration of several essential components that ensure its proper functioning. These include the ground plane, which serves as the reference for electromagnetic waves; the substrate material, providing both structural support and dielectric properties; the patch element, responsible for transmitting or receiving signals; and the feeding mechanisms, Feed 1 and Feed 2, which facilitate the transfer of signals to and from the patch [24].

After carefully integrating these components, they collectively form the intricate structure of the antenna system. This integration process involves the precise positioning and alignment of each component to optimize performance and fulfil the required specifications. The resulting configuration of the antenna system is illustrated in Figure 8, offering a detailed overview of how these components are interconnected. Figure 8 not only shows the physical arrangement of the antenna elements but also represents the culmination of extensive design and engineering efforts aimed at developing an efficient and functional microstrip patch antenna system.

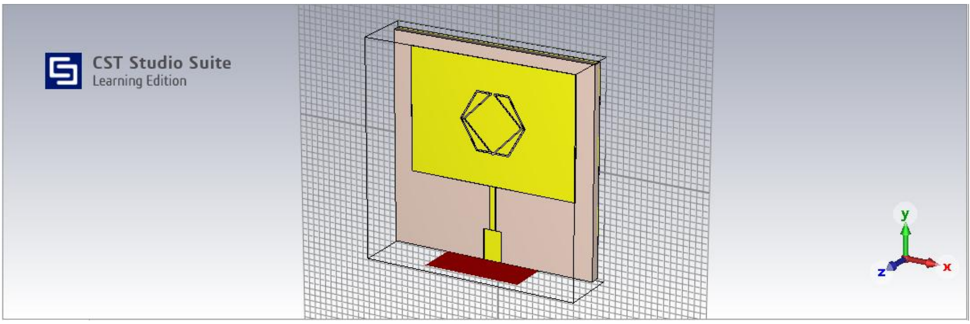

Fig. 8. Design of the proposed microstrip antenna.

When designing the antenna, it is essential to follow specific dimensional constraints along the X, Y, and Z axes, denoted by Xmin, Xmax, Ymin, Ymax, Zmin, and Zmax. These dimensions are defined based on the components utilized and the values outlined in Table 3. Adhering to these specifications ensures accurate alignment and optimal performance of the antenna design.

Table 3. Spatial dimensions of the designed microstrip antenna.

| Microstrip Antenna Components | 3D-Dimensional boundaries | | | | | |
|---|---|---|---|---|---|---|
| | Xmin | Xmax | Ymini | Ymax | Zmini | Zmax |
| Ground | - w/2 | - w/2 | $-L/2$ | $L/2$ | 0 | t |
| Substrate | - w/2 | - w/2 | $-L/2$ | $L/2$ | t | t + h |
| Feed 1 | $-Wf_1/2$ | $-Wf_1/2$ | $-L/2$ | $-L/2 + lf_1$ | t + h | 2t + h |
| Feed 2 | $-Wf_2/2$ | $-Wf_2/2$ | $-L/2 + lf_1$ | $-L/2 + lf_1+lf_2$ | t + h | 2t + h |
| Patch | - wp/2 | - wp/2 | $-L/2 + lf_1+lf_2$ | $-L/2 + lf_1+lf_2+lp$ | t + h | 2t + h |

The microstrip antenna, designed using CST Studio software, is simulated and assessed for parameters like gain, directivity, radiation efficiency, VSWR, and reflection coefficient, with a focus on the frequency range of 110 GHz to 120 GHz for 6G applications.

## 3. Results and Discussion

The simulated results for the gain, directivity, radiation efficiency, VSWR, reflection coefficient, and other parameters of the designed microstrip antenna within the 110 GHz to 120 GHz frequency range are provided below:

The gain distribution simulation results at 110 GHz and 120 GHz are shown in Figs. 9 and 10, respectively

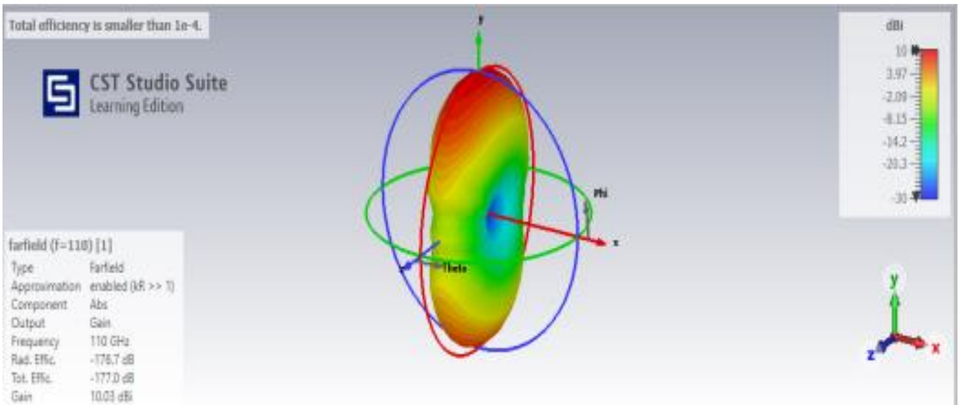


Fig. 9. Gain distribution of microstrip antenna at 110 GHz frequency.

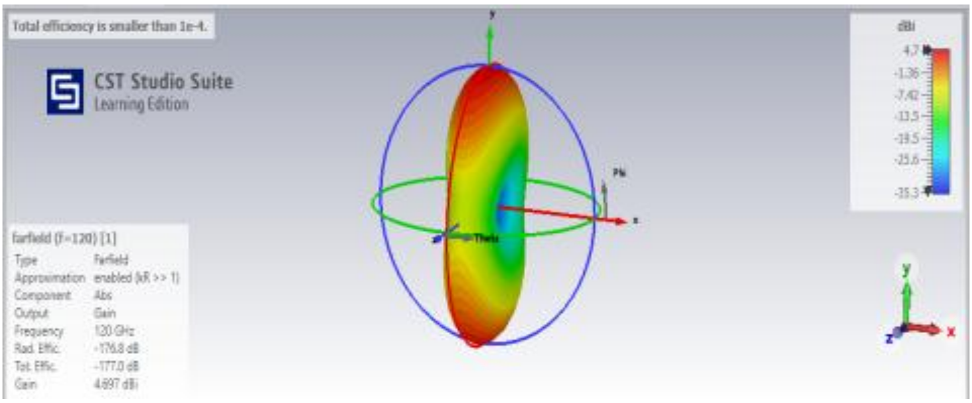


Fig. 10. Gain distribution of microstrip antenna at 120 GHz frequency.

The results show a significant increase in signal amplification in the desired direction, indicating the antenna's effectiveness in strengthening the signal. At 110 GHz, the antenna achieves a gain of 10.03 dBi, while at 120 GHz, it reaches 4.697 dBi. These results are essential for establishing reliable communication in 6G networks. The antenna's optimized design, including the compact structure and hexagonal slot, enhances energy concentration, which is crucial for improving directivity and coverage in high-frequency applications.

The directivity analysis of the microstrip patch antenna demonstrates its capability to focus radiation in a specific direction, as illustrated in Figs. 11 and 12 for frequencies of 110 GHz and 120 GHz, respectively.

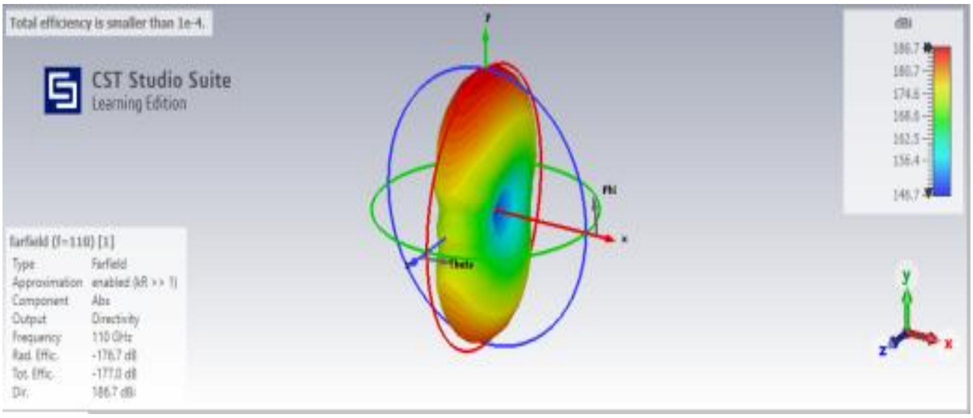


Fig. 11. Directivity of microstrip antenna at 110 GHz frequency.

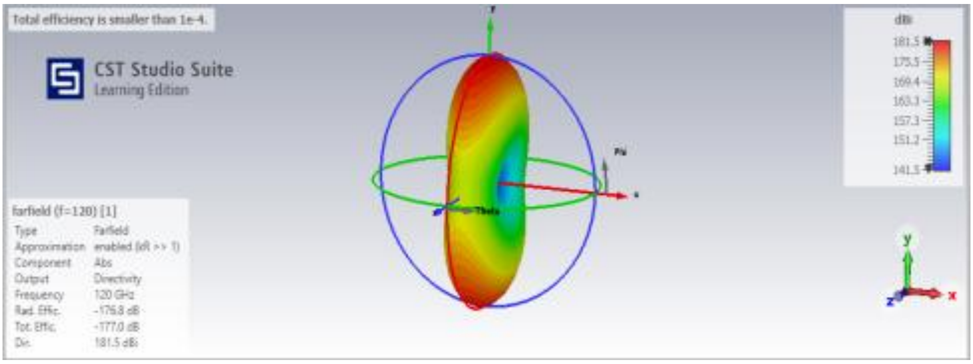


Fig. 12. Directivity of microstrip antenna at 120 GHz frequency.

At 110 GHz, the antenna demonstrates a directivity of 186.7 dB, and at 120 GHz, it shows 181.5 dB, both key factors for ensuring effective communication in 6G environments. The antenna's design, particularly its planar structure and feed line optimization, plays a significant role in enhancing directivity, which improves coverage and reliability for high-frequency communication systems.

Fig. 13 shows the Voltage Standing Wave Ratio(VSWR) values across the 110 GHz to 120 GHz range, with results of 1.5 to 2 at 110 GHz and 1.5 at 120 GHz. These low values indicate excellent impedance matching and minimal signal reflection, aligning with the design goal of achieving a low reflection coefficient. This ensures effective energy transfer between the antenna feed and radiating element, minimizing signal loss and improving performance in 6G applications.

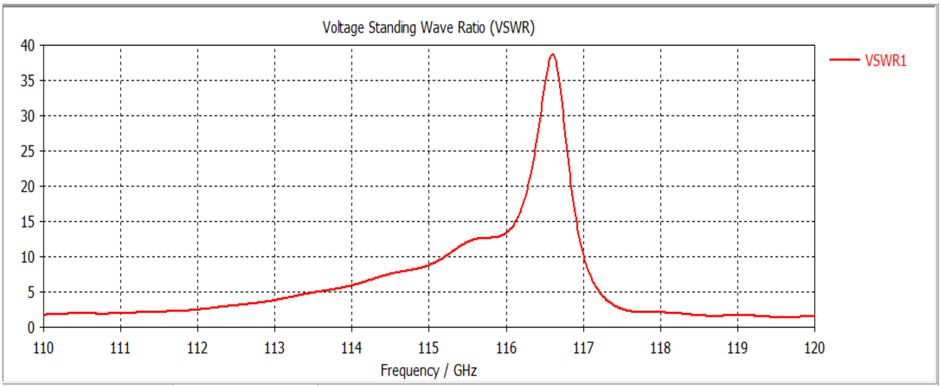

Fig. 13. Voltage standing wave ratio of microstrip antenna across 110 GHz to 120 GHz frequency.

Fig. 14 provides a visual representation of the reflection coefficient characteristics of the custom-designed microstrip patch antenna. The reflection coefficient was measured at -12 dB at 110 GHz and between -14 dB and -15 dB at 120 GHz, confirming the antenna's low reflection and optimal signal transmission. The antenna's design, with a well-calibrated microstrip patch and material selection, plays a crucial role in reducing signal reflection, which enhances overall efficiency, particularly in 6G systems.

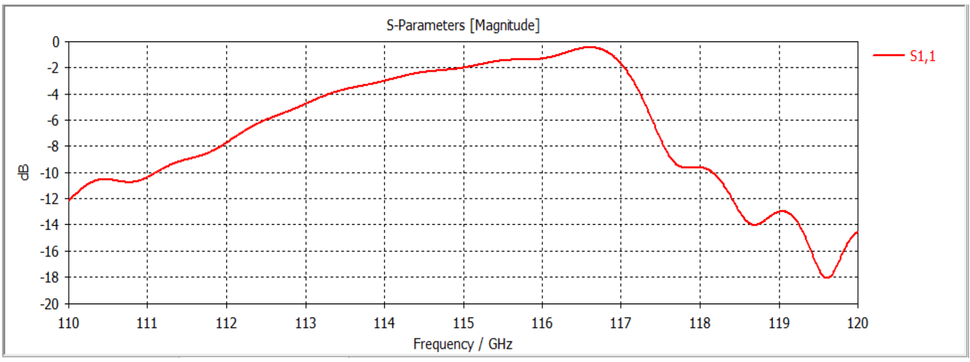

Fig. 14. Reflection coefficient characteristics of the antenna at 110 GHz and 120 GHz frequency.

The radiation efficiency of the microstrip patch antenna design was analyzed to assess its capacity to convert input power into radiated energy. As shown in Fig. 15, this evaluation covered the frequency range pertinent to 6G applications. The results demonstrated a notable improvement in radiation efficiency, especially within the targeted frequency bands. Specifically, the radiation efficiency measured -176.7 dB at 110 GHz and -176.9 dB at 120 GHz. This enhancement underscores the antenna design's effectiveness in reducing energy losses and optimizing radiation output, crucial for ensuring reliable communication in 6G networks.

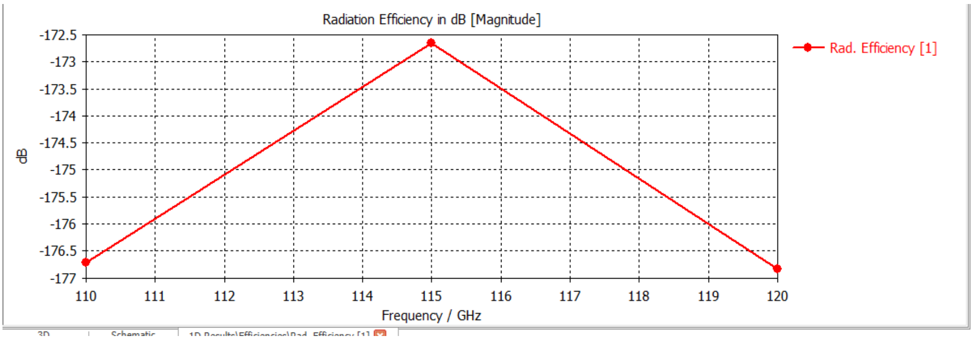


Fig. 15. Radiation efficiency of microstrip antenna at 110 and 120 GHz frequency.

Fig. 16 provides a visual representation of the antenna's total efficiency. The total efficiency of the antenna was found to be -177 dB at both 110 GHz and 120 GHz. These results highlight the improvements in overall efficiency due to the antenna's optimized design, which reduces losses and maximizes radiation. This performance supports the antenna's suitability for high-performance 6G applications that require low-loss, high-efficiency components

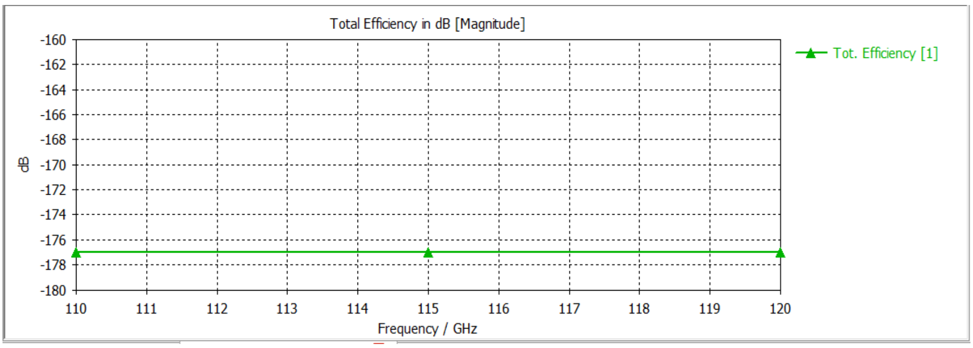


Fig. 16. Total efficiency of microstrip antenna at 110 and 120 GHz frequency.

Fig. 17 shows the metal loss in the copper material, with measurements of 0.00034 at 110 GHz and no loss detected at 120 GHz. These findings highlight the importance of minimizing metal losses for maintaining low reflection coefficients and optimal impedance matching. The low metal loss at 120 GHz demonstrates the antenna's capability to preserve energy, ensuring maximum efficiency for 6G communication systems.

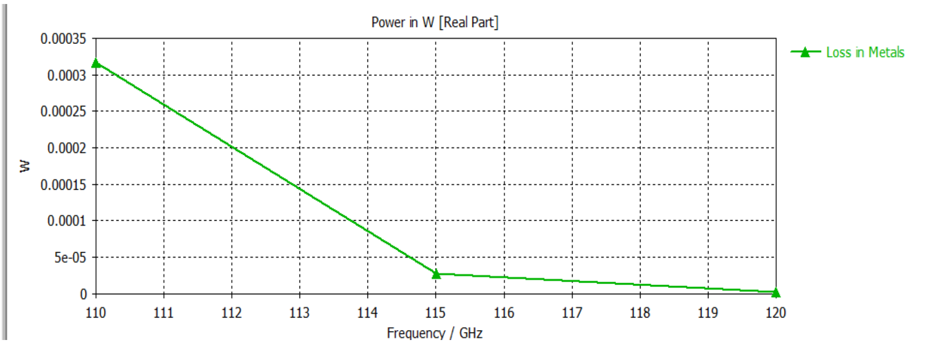


Fig. 17. Metal loss in copper material of microstrip antenna at 110 and 120 GHz frequency.

Fig. 18 illustrates the volume loss in the FR4 material, with values of 0.195 at 110 GHz and 0.005 at 120 GHz. The reduction in volume loss at 120 GHz shows the effectiveness of the design adjustments made during fabrication, which were essential in maintaining a low reflection coefficient and ensuring the antenna met the requirements for 6G communication systems.

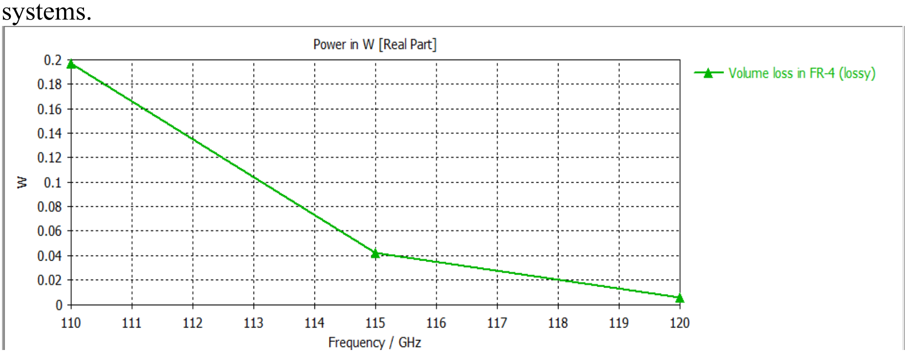


Fig. 18. Volume loss in FR4 lossy material of microstrip antenna at 110 and 120 GHz frequency.

The volume loss mainly results from dielectric effects, with corresponding dielectric loss tangent (tan δ) values of 0.2 and 0.01, respectively. The sharp decline in both volume and dielectric losses at 120 GHz reflects the success of the design improvements applied during fabrication. These optimizations were essential for enhancing impedance matching and reducing signal reflection, thereby aligning the antenna's performance with the demanding standards of 6G communication systems.

The simulation results for the reflection coefficient, radiation efficiency, total efficiency, gain, directivity, voltage standing wave ratio (VSWR), copper metal loss, volume loss in FR4 lossy material, and dielectric loss for the designed microstrip antenna within the frequency range of 110 GHz to 120 GHz are summarized in Table 4.

Table 4. Simulation results of the designed microstrip antenna at 110 GHz-120 GHz.

| Antenna Parameters | 110 GHz frequency | 120 GHz frequency |
|---|---|---|
| Reflection coefficient | -12 dB | -14 dB to -15 dB |

| | | |
|---|---|---|
| Radiation efficiency | -176.7 dB | -176.9 dB |
| Total efficiency | -177 dB | -177 dB |
| Gain | 10.03 dBi | 4.697 dBi |
| Directivity | 186.7 dB | 181.5 dB |
| VSWR | 1.5-2 | 1.5 |
| Metal loss in copper | 0.00034 | 0 |
| Volume loss in FR4 lossy | 0.195 | 0.005 |
| Loss in dielectrics | 0.2 | 0.01 |

The high directivity and efficiency observed at 110 GHz and 120 GHz are the result of a carefully crafted antenna design, as supported by existing literature on antenna technology. The antenna's microstrip structure, featuring a hexagonal slot in the radiating patch, a compact layout, and a precisely aligned feed line, is designed to direct radiation efficiently while minimizing dispersion. This is especially important for operation in millimeter-wave frequencies. The hexagonal slot plays a pivotal role in controlling the current distribution, helping focus the beam more effectively.

Additionally, the planar structure with a ground substrate reduces unwanted back radiation and surface wave losses, further improving the antenna's directivity. The choice of materials also enhances performance. Low metal losses in the copper layer and minimal dielectric losses in the FR4 substrate ensure that energy is radiated efficiently with minimal heat loss. The antenna also achieves good impedance matching, as reflected in the low VSWR, ensuring effective power transfer. Simulation results from CST Studio Suite validate these performance metrics, confirming that the combination of thoughtful design and low-loss materials is key to achieving strong performance in high-frequency applications such as 5G and millimeter-wave communications.

The results presented in this study are primarily based on simulations, providing valuable insights into the potential performance and behavior of the proposed design. Nevertheless, it is important to note that simulations may not account for all real-world variables and complexities. To ensure the design's practical applicability, future work should focus on experimental validation. This would help confirm the accuracy of the simulation results and evaluate the design's performance in real-world settings.

A comparison of the parameter results from our analysis with those from prior studies reveals several key differences, as shown in Table 5. Notably, our study demonstrates higher values for directivity, gain, radiation efficiency, and other parameters compared to the results from the referenced study. This indicates potential differences in the design or operational characteristics between the proposed microstrip antenna and the one examined in previous research.

Table 5. Performance comparison of the proposed and existing antenna designs.

| References | Operating Frequency (GHz) | Gain (dBi) | Directivity (dB) | Band width (GHz) | Applications |
|---|---|---|---|---|---|
| [25] | Sub-6 | 5.49 | 7.12 | 5.049 | 5G Communications |
| [26] | 28 | 7.6 | 7.67 | 1.38 | 5G Communications |

| | | | | | |
|---|---|---|---|---|---|
| [27] | 28 | 9.44 | -- | 0.51 | 5G Communications |
| [28] | 250 | 6.49 | -- | 8.25 | 6G Communications |
| Proposed antenna | 110-120 | 10.03 | 186.7 | 10 | 6G Communications |

The superior performance of the proposed microstrip antenna, when compared to previous studies, can be attributed to several key factors. Firstly, its optimized frequency range of 110-120 GHz is well-suited for 6G communications, providing higher frequencies that improve resolution and capacity. The antenna achieves a notably higher gain of 10.03 dBi and exceptional directivity of 186.7 dB, both of which enhance signal strength and efficiency. Furthermore, the antenna's 10 GHz bandwidth supports higher data transmission rates, surpassing the narrower bandwidths of antennas from previous research. Finally, the antenna is specifically designed for 6G applications, making it more suitable for next-generation communication systems compared to those designed for 5G.

## 5. Conclusion

This study emphasizes the critical role of customized microstrip patch antenna development for 6G applications. Through detailed design, optimization, and simulation using CST Studio software, significant improvements in key performance parameters essential for efficient communication at extremely high frequencies have been achieved. Notable advancements in gain, directivity, radiation efficiency, VSWR, and reflection coefficient within the targeted frequency range of 110 GHz to 120 GHz represent a substantial leap in meeting the stringent demands of 6G networks, ensuring effective signal transmission and reception across diverse communication environments.

Additionally, the progress in designing microstrip patch antennas optimized for high gain, directivity, and efficiency for 6G applications marks a significant milestone in wireless communication technology. The proposed antenna demonstrates remarkable effectiveness in reducing signal losses and enhancing signal strength, thus improving overall communication reliability and throughput. Its compact and lightweight design also makes it suitable for integration into various 6G-enabled devices, facilitating smooth connectivity and supporting the widespread adoption of 6G technology across multiple sectors.

Future research should focus on meeting the emerging demands of 6G networks, including enabling massive MIMO, beamforming, and ultra-dense deployments. Although this study offers important insights into the proposed antenna design, there is potential for further performance improvements by investigating advanced techniques. Specifically, methods such as adaptive beamforming, multi-band designs, and the use of metamaterials show great promise in enhancing antenna efficiency and versatility. These approaches will be explored in future studies to expand upon the current findings and address the evolving requirements of antenna technology.

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