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Research Article

Performance Analysis of a 22 GHz Microstrip Patch Antenna for High-Frequency Wireless Systems

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Abstract:

The increasing need for high-frequency wireless applications, including satellite communications and radar systems, drives the demand for compact, high-performance antennas with efficient impedance matching, high gain, and stable radiation characteristics. However, traditional microstrip patch antennas often exhibit limitations such as poor impedance matching, polarization sensitivity, and undesirable side lobes, especially in the millimeter-wave spectrum.
This study presents the design and evaluation of a microstrip patch antenna optimized for approximately 22 GHz, incorporating structural and material enhancements to improve performance. The antenna's characteristics are analyzed in terms of Voltage Standing Wave Ratio (VSWR), gain, and S-parameters. The results show effective impedance matching within the 20.2–21.6 GHz range, achieving a minimum VSWR of 1.2034 at 21.4533 GHz. However, at 22.12 GHz, the VSWR rises to 4.5094, indicating impedance mismatch. To address this, modifications such as substrate optimization and impedance tuning are considered. Gain analysis demonstrates strong directional performance, with a peak gain of 5.5291 dB at 21.57 GHz. Moreover, S-parameter analysis confirms efficient impedance matching at 21.1733 GHz, with a reflection coefficient of -22.0036 dB, ensuring minimal signal loss.
The findings indicate that the proposed antenna is well-suited for high-frequency applications. However, additional refinements are required to enhance impedance matching at 22 GHz, reduce side lobes, and improve efficiency. Future research will focus on optimizing the substrate, refining the feed network, and implementing structural modifications to achieve superior broadband performance.

1. Introduction

The rapid advancement of wireless communication networks, particularly with the emergence of 5G technology, has driven the need for advanced antenna designs that can support higher capacity, improved reliability, and enhanced data rates. Among various antenna structures, microstrip patch antennas have gained significant attention due to their compatibility with integrated circuits, low profile, and ease of fabrication. However, designing an efficient patch antenna that operates across multiple frequency bands while maintaining stable circular polarization remains a challenge.
Circular polarization is highly desirable in modern communication systems as it enhances signal quality and resilience by mitigating polarization mismatches and minimizing the effects of multipath propagation. Additionally, with 5G technology spanning a broad frequency range—from sub-6 GHz to millimeter-wave (mmWave) bands—there is a growing demand for antennas capable of supporting triband operation, ensuring seamless communication across multiple frequency bands. This adaptability is crucial for enabling reliable, high-speed connectivity in next-generation wireless networks. Consequently, developing compact and efficient antenna designs that can meet these spectral requirements while maintaining stable performance remains a key focus in wireless communication research.

2. Methodology

With the increasing demand for high-frequency antennas, especially for millimeter-wave (mmWave) applications like satellite communications and radar systems, microstrip patch antennas have gained popularity due to their compact design, ease of fabrication, and integration capabilities. However, conventional rectangular patch antennas face challenges such as limited bandwidth, impedance mismatches, and efficiency reduction at higher frequencies. To address these limitations, this study proposes a circular microstrip patch antenna optimized for 22 GHz, aiming to enhance impedance matching, minimize reflection losses, and improve radiation characteristics.

The proposed design incorporates a circular patch with a central hole and symmetrical slot extensions, which contribute to bandwidth enhancement and impedance tuning. The antenna's performance is evaluated based on Voltage Standing Wave Ratio (VSWR), S-parameter (S11), and gain analysis, ensuring minimal signal loss while maintaining a stable radiation pattern. Additionally, the influence of the substrate material and feedline conFigureuration is examined to optimize overall efficiency. While effective impedance matching is achieved between 20.2 GHz and 21.6 GHz, further refinements are necessary for improved performance precisely at 22 GHz.

Structurally, the antenna consists of a circular microstrip patch printed on a dielectric substrate with a metallic ground plane. The central hole minimizes surface wave losses, thereby improving radiation efficiency, while slot extensions fine-tune the resonance characteristics. A low-loss dielectric material with an appropriate relative permittivity (εr) is selected to balance miniaturization and performance. The 1.6 mm substrate thickness ensures mechanical stability without significantly affecting radiation properties.

By integrating these design enhancements, the proposed antenna demonstrates strong potential for high-frequency applications. Future optimizations will focus on refining the feed network and substrate properties to further improve impedance matching at 22 GHz.

The ground plane plays a vital role in ensuring proper radiation characteristics by preventing unwanted reflections and surface wave propagation. To excite the antenna efficiently, a microstrip feedline is employed, with optimized dimensions for maximum power transfer and minimal reflection losses. The overall antenna structure is carefully designed to achieve stable directional radiation, making it suitable for high-frequency communication systems where precise beamforming and polarization control are required. The specific dimensions of the antenna, including patch width (W), patch length (L), feedline width (Wf), feedline length (Lf), and slot extension length (Ns), are chosen to optimize performance while maintaining a compact footprint.

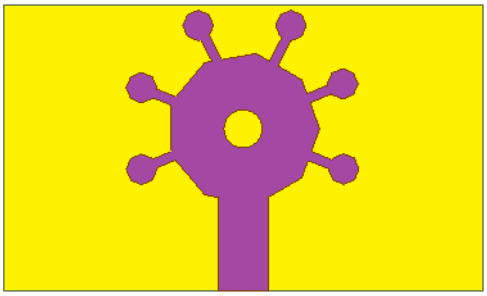

Figure 1. a) *Top View of Antenna*

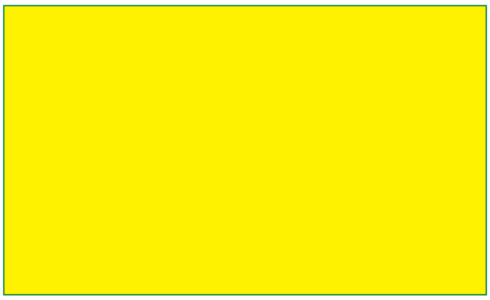

Figure 1. b) *Ground Plane of Antenna*

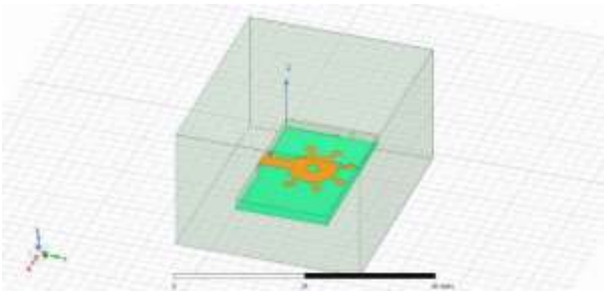

Figure 2. *Design of proposed anteena*

The finalized antenna design, as illustrated in the Figure 2 and Figure 3, incorporates a well-balanced combination of substrate selection, slot geometry adjustments, and feedline optimization to achieve superior impedance matching. These refinements collectively contribute to the minimized return loss, improved gain, and stable radiation pattern across the targeted frequency range.

Table1. *design parameters for the antenna*

Name	Value	Unit
W	25	mm
L	15	mm
Wf	2.6	mm
Lf	5	mm
T	1.6	mm
Ns	9	mm
Fw	-0.5	mm

Figure 3. a) *Length of the Anteena (From Top View and bottom view)*

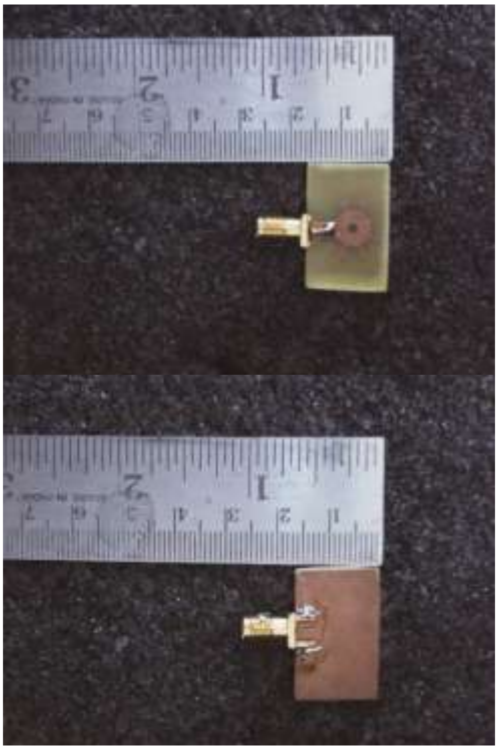

Figure 3. b) *Width of the Anteena (From Top View and bottom view)*

The working principle of the proposed circular microstrip patch antenna is based on resonance and radiation of electromagnetic waves. When the antenna is excited using a microstrip feedline, surface currents are induced on the patch and ground plane, leading to the generation of an electromagnetic field. The circular patch, combined with the central hole and slot extensions, influences the current distribution, thereby controlling the resonance frequency and radiation characteristics. The radiating edges of the circular patch act as active radiators, while the central hole helps in reducing surface wave losses, leading to enhanced directivity and efficiency.

The introduction of slot extensions plays a crucial role in fine-tuning the impedance matching by altering the effective electrical length of the antenna. This modification enables the antenna to operate efficiently at high frequencies, ensuring that maximum power is radiated with minimal reflection losses. The selection of an appropriate substrate material further enhances performance by minimizing dielectric losses and improving radiation efficiency. The ground plane, positioned on the opposite side of the substrate, provides a reflecting surface that aids in shaping the radiation pattern while preventing unwanted signal dispersion.

3. Results and Discussion

Figure 4 reveals a directional radiation pattern with noticeable variations based on the azimuth angle (Theta) and orientation (Phi). The maximum gain of 3.0170 dB is observed at Theta = 60° for Phi = 90° (green curve), while a gain of 2.6487 dB occurs at Theta = 290° for Phi = 0° (red curve). The radiation pattern features multiple lobes, indicating focused signal transmission in specific directions, along with deep nulls where the gain drops below -20 dB.

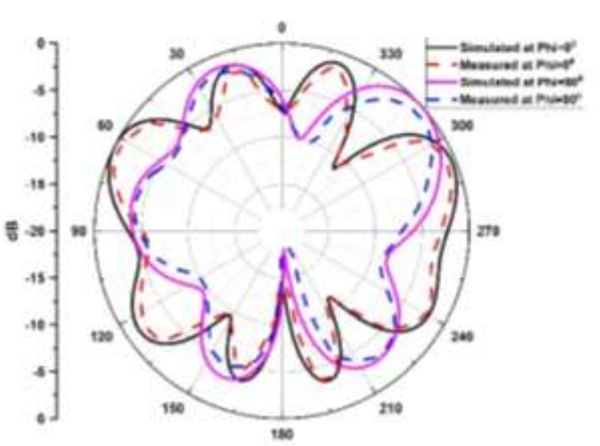

Figure 4. *Gain plot of the antenna at 20.22 GHz*

These characteristics indicate that the antenna is well-suited for applications requiring directional performance, such as radar and high-frequency communication systems. The disparity between Phi = 0° and Phi = 90° highlights polarization sensitivity, meaning the antenna's orientation significantly affects its performance. The observed anisotropy in the radiation pattern further supports its suitability for scenarios where precise directional gain is essential. However, the presence of side lobes and nulls suggests that careful placement is necessary to minimize interference and maximize efficiency.

Overall, the antenna exhibits strong performance at 20.22 GHz, with gain values and radiation characteristics aligning with typical high-frequency directional antennas. Further optimization may help reduce side lobes and enhance overall efficiency.

At 21.57 GHz as shown in Figure 5, the antenna's gain pattern exhibits directional characteristics with peak performance varying based on orientation. For Phi = 0°, the highest gain of 5.5291 dB occurs at Theta = 30°, whereas for Phi = 90°, a slightly lower gain of 5.4012 dB is observed at Theta = 26°. The radiation pattern reveals a lobed structure with deep nulls, indicating strong directionality. The noticeable difference between the two orientations highlights polarization sensitivity, meaning gain varies with antenna orientation. This feature makes it suitable for applications requiring high directivity and polarization-dependent performance, such as radar or advanced communication systems. The relatively high gain at this frequency ensures efficient operation. However, the presence of side lobes and nulls necessitates careful alignment to optimize signal strength and reduce interference. Overall, the antenna demonstrates stable performance within a narrow angular range, making it a viable option for applications requiring controlled radiation patterns.

The S11 plot as shown in Figure 6 reveals the antenna's impedance matching and resonance behavior. The best matching occurs at 21.1733 GHz with a -22.0036 dB reflection coefficient, ensuring minimal power loss. Secondary resonances at 21.4400 GHz (-23.2500 dB) and 23.1044 GHz (-14.9081 dB) confirm additional operational frequencies. At 29.0978 GHz, a -9.3927 dB reflection coefficient suggests reduced efficiency at higher frequencies. The narrow bandwidth around resonances makes this antenna ideal for precision applications like satellite communications and radar systems. However, increased reflections at off-resonant frequencies indicate the need for further design optimization to enhance broadband performance.

The VSWR plot as shown in Figure 7 evaluates the impedance matching of the microstrip patch antenna from 19–25 GHz. The lowest VSWR of 1.2034 at 21.4533 GHz indicates optimal matching near the 22 GHz design frequency, with a secondary resonance at 20.2133 GHz (VSWR = 1.4134). However, higher values at 22.12 GHz (4.5094) and 23.6933 GHz (3.9666) signal poor matching at those points. The antenna performs well between 20.2–21.6 GHz but requires tuning to improve matching near 22 GHz. Adjustments like feed optimization or substrate modification can enhance performance across a broader range.

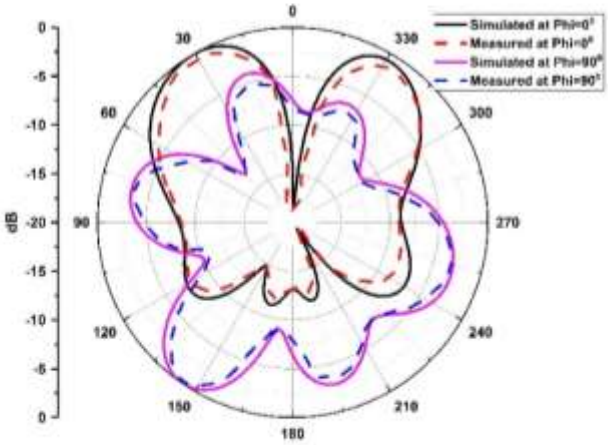

Figure 5. *Gain plot of the antenna at 21.57 GHz.*

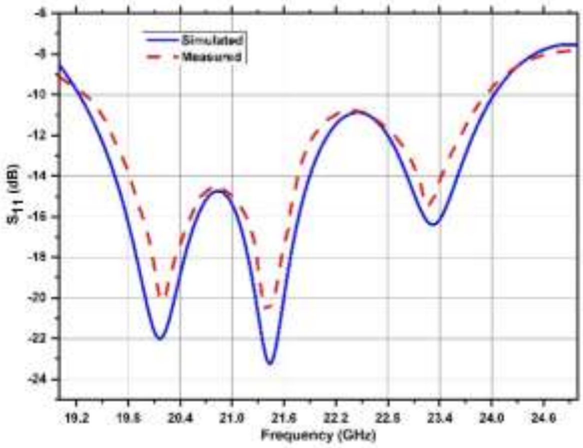

Figure 6. *The S-parameter plot (S11)*

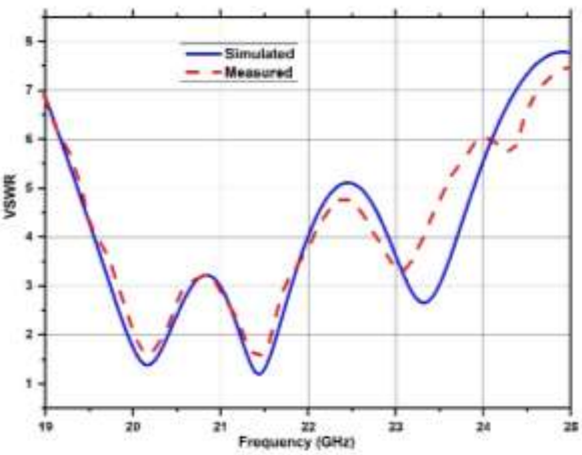

Figure 7. *VSWR plot*

4. Conclusion

The proposed microstrip patch antenna exhibits high-frequency performance, demonstrating strong gain, directional radiation, and effective impedance matching, making it suitable for radar, satellite communications, and high-frequency wireless systems. The gain analysis reveals peak values of 5.5291 dB at 21.57 GHz and 3.0170 dB at 20.22 GHz, confirming directional transmission with polarization sensitivity. The S11 and VSWR plots validate optimal impedance matching at 21.1733 GHz, but high VSWR at 22.12 GHz suggests the need for feed tuning and substrate optimization. The antenna's lobed radiation pattern necessitates precise alignment to reduce interference and enhance coverage. Its narrowband characteristics ensure high precision, but side-lobe reduction, bandwidth extension, and impedance adjustments could further improve performance. With design enhancements, this antenna can be optimized for next-generation communication, radar sensing, and advanced wireless applications requiring stable, high-gain operation.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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