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# DESIGN, ANALYSIS, AND FABRICATION OF A HOLOGRAPHIC METASURFACE ANTENNA FOR HIGH FREQUENCY APPLICATIONS

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**Abstract**
Holographic metasurface antennas (HMAs) have gained significant attention for their ability to achieve dynamic beam steering, high gain, and compact integration in high-frequency communication systems. This paper presents the design, analysis, and fabrication of a holographic metasurface antenna operating at the 24 GHz frequency band, targeting applications such as automotive radar, wireless communications, and satellite links. The proposed antenna employs a metasurface layer to manipulate electromagnetic wavefronts based on holographic principles, enabling efficient beamforming and reduced sidelobe levels. Full-wave electromagnetic simulations are conducted to optimize the metasurface structure, ensuring enhanced radiation efficiency and wide-angle beam scanning. A prototype is fabricated using PCB-based manufacturing techniques, and its performance is experimentally validated. Measurement results demonstrate a high-gain radiation pattern, effective beam steering capabilities, and improved efficiency, making the proposed HMA a promising candidate for next-generation high-frequency communication systems.

**Keywords**: Holographic EM Modulation, Reconfigurable Meta surfaces, Millimeter-Wave Beam forming, 24 GHz Antenna, Adaptive Wavefront Control, Smart Radar Arrays, High-Precision EM Engineering, Low-Profile Antenna Design, Dynamic Phase Modulation.

## 1. Introduction

The increasing demand for high-frequency antennas with efficient beam forming and compact integration has driven research into advanced antenna technologies. Traditional phased arrays, while effective, are costly and power-intensive. Holographic meta surface antennas (HMAs) provide an alternative by leveraging engineered meta surfaces to achieve precise wave front control, enabling dynamic beam steering with reduced complexity. This paper presents the design, simulation, fabrication, and validation of a 24 GHz holographic meta surface antenna, utilizing a Rogers RT/Duroid substrate for enhanced performance. The proposed antenna is optimized for applications in automotive radar, satellite communications, and next-generation wireless networks. Full-wave simulations refine the antenna's radiation characteristics, and a prototype is fabricated using PCB-based techniques. Experimental results confirm high directivity, low side lobe levels, and wide beam-scanning capability. The paper is structured as follows: Section II details the design methodology, Section III presents simulation results, Section IV discusses fabrication and measurements, and Section V concludes with key findings and future directions.

## 2. Antenna Performance Requirements

*2.1 Key Performance Parameters*
For optimal operation at 24 GHz, the following antenna parameters are critical:
Gain and Directivity – High gain (>10 dBi) is required to ensure strong signal transmission and reception over long distances. Directive beam shaping is essential for focused radiation.
Bandwidth – A sufficient fractional bandwidth (≥ 500 MHz) ensures stable performance over a range of frequencies, allowing compatibility with communication standards.
Radiation Efficiency – Low dielectric and conductor losses are crucial, requiring materials like Rogers RT/Duroid 5880, which has a low loss tangent ($\tan \delta = 0.0009$).

Beam Steering Capability – Dynamic beamforming enhances adaptability in applications like automotive radar and satellite tracking. Impedance Matching – The antenna must maintain a return loss (S11) below -10 dB to ensure minimal signal reflection and efficient power transfer.

*2.2 Environmental and Material Considerations*

The choice of materials and environmental factors impact antenna performance at 24 GHz:
Substrate Selection – Rogers RT/Duroid 5880 is chosen for its low dielectric loss, stable performance at high frequencies, and thermal stability, which is crucial for high-frequency applications.
Fabrication Constraints – Achieving precise metasurface patterns requires high-resolution. photolithography or PCB fabrication techniques to minimize fabrication-induced losses.
Atmospheric Attenuation – At 24 GHz, mmWave signals experience higher atmospheric absorption, necessitating high-efficiency designs to compensate for signal degradation.
Thermal and Mechanical Stability – Materials must withstand thermal expansion and mechanical stress, especially in automotive and aerospace environments.

**3. Methodology**

The methodology for designing the 24 GHz Holographic Meta surface Antenna (HMA) involves a structured approach, integrating theoretical modeling, full-wave simulations, and experimental validation. The antenna is designed to achieve dynamic beam forming, high gain, and low loss using meta surface-based wave front manipulation techniques.

This section outlines the step-by-step approach used in designing the metasurface structure, optimizing antenna parameters, fabricating the prototype, and conducting performance evaluations.

3.1 Antenna Design Approach

*3.1.1 Existing System Limitations*
The design of high-frequency antennas, particularly at 24 GHz, presents several challenges:
Narrow Bandwidth: Conventional antennas suffer from limited operational bandwidth, restricting their efficiency in broadband applications.
High Side Lobe Levels (SLL): Traditional designs exhibit unwanted radiation, leading to reduced directivity and signal interference.
Limited Beam Steering: Phased arrays require bulky and power-consuming phase shifters for beam forming.
Substrate Losses: Many conventional substrates introduce excessive losses, requiring advanced materials like Rogers RT/Duroid 5880 for optimal performance.

*3.1.2 Proposed System*
The design methodology follows a multi-stage approach: Antenna Design Approach (AV)
Establishing theoretical models for holographic beam forming. Selecting a low-loss, high-frequency substrate (Rogers RT/Duroid 5880) for optimal performance. Designing a meta surface layer with sub wave length resonators to achieve phase modulation.

*3.1.3 Meta surface Configuration and Element Design*
Developing unit cells with precise phase shift control for efficient beam steering. Optimizing the metasurface layout using holographic impedance modulation techniques. Ensuring the design supports broadband operation and linear polarization.

*3.1.4 Simulation and Optimization*
Conducting full-wave simulations in Ansys HFSS to refine antenna parameters. Optimizing return loss (S11 < -10 dB), gain enhancement, and radiation efficiency. Studying surface current distributions to validate impedance matching and power distribution.

*3.1.5 Fabrication and Experimental Validation*

Fabricating the antenna using high-precision PCB milling. Characterizing the antenna with Vector Network Analyzer (VNA) measurements for S-parameters. Measuring radiation patterns, gain, and beam steering performance in an anechoic chamber.

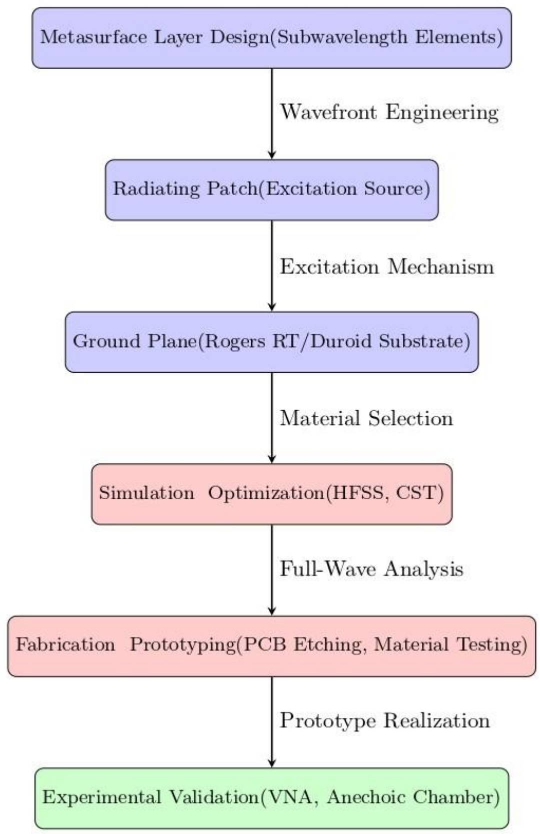



**Fig 1.** Block Diagram Multi Stage Approach

The design, simulation, fabrication, and testing methodology for the proposed 24 GHz holographic metasurface antenna (HMA) is illustrated in Figure1. The workflow consists of multiple stages, from conceptual design to experimental validation, ensuring an optimized and functional antenna system.

*3.1.6 Metasurface Layer Design (Subwavelength Elements)*

The metasurface layer consists of subwavelength resonant elements, designed to manipulate the electromagnetic (EM) wavefront efficiently. These elements are arranged in a holographic pattern to facilitate beam steering and wavefront shaping.

Key Considerations: Phase distribution, resonant frequency tuning, and element spacing.
Design Tools: Theoretical modelling and numerical simulations. Radiating Patch (Excitation Source)
A patch antenna is employed as the excitation source, coupling energy into the meta surface layer. This ensures effective wave propagation across the designed surface.

Key Considerations: Impedance matching, radiation efficiency, and feed mechanism. Ground Plane (Rogers RT/Duroid Substrate). A low-loss substrate (Rogers RT/Duroid) is chosen to enhance efficiency and minimize dielectric losses at 24 GHz. The ground plane provides a reference conductor for stable radiation.

Material Choice: High dielectric constant for compact design and low tangent loss for minimal attenuation. Simulation & Optimization (HFSS, CST). The design undergoes extensive simulation using Ansys HFSS and CST Microwave Studio, ensuring optimized performance in terms of: S-parameters (Return Loss, VSWR), Radiation Pattern and Beamforming Characteristics Gain, Directivity, and Efficiency Optimization.

*3.1.7 Fabrication & Prototyping (PCB Etching, Material Testing)*

The optimized antenna layout is fabricated using PCB etching techniques, and the metasurface elements are precisely patterned on the substrate. This stage also involves material characterization for validation.

Experimental Validation (VNA, Anechoic Chamber)

The fabricated prototype is tested in an anechoic chamber to measure real-world performance. A Vector Network Analyzer (VNA) is used to validate: Resonant Frequency Matching , Antenna Gain & Radiation Efficiency, Beamforming & Scattering Parameter Validation.

For the design, fabrication, and testing of the meta surface antenna, various hardware components are required. Below is a breakdown of the key components, their specifications, and the justification for their selection Table 1.

**Table 1.** Required Hardware Components

| Components | Model / Material | Specification / Function | Justification |
|---|---|---|---|
| Substrate Material | Rogers RT5880, Duroid 6010 | Dielectric Constant (εr): 2.2 (RT5880),10.2(Duroid 6010) Thickness: 0.5 mm – 1.6 mm Loss Tangent: 0.0009 (RT5880), 0.0023 (Duroid 6010) | Low loss tangent ensures minimal signal attenuation. High-frequency stability for microwave and mm-wave applications. Suitable for 5G, satellite communication, and radar applications. |
| Patch & Ground Plane | Copper | Conductivity: $5.8 \times 10^7$ S/m Thickness: 17μm – 35μm | Provides efficient signal transmission with minimal resistance. Used for both radiating patch and ground plane. Standard material in PCB-based meta surface antennas. |
| Simulation & Optimization Tools | -- | Software Used: HFSS, MATLAB | HFSS provides precise full-wave electromagnetic analysis. Essential for optimizing unit cell design and beam forming properties. |
| Vector Network Analyzer | Keysight E5071C | Frequency Range: 10 MHz – 20 GHz (or higher) Dynamic Range: 120 dB Measurement: S-parameters (S11, S21, S12, S22) | Required for characterizing return loss, insertion loss, and impedance matching. High accuracy in RF and microwave frequency measurements. Supports real-time testing of fabricated meta surface antenna. |
| Anechoic Chamber | -- | Size: 2m × 2m × 2m (compact setup for high-frequency antennas)Absorber Type: RF pyramidal absorbers Measurement Range: 1 GHz – 40 GHz | Provides an interference-free environment for radiation pattern measurement. Eliminates reflections for precise gain and beam forming analysis. Ensures accurate far-field antenna testing. |
| PCB Fabrication Setup | -- | Etching Process: Laser Etching Substrate Handling: CNC milling machine for precision Alignment Precision: ±10μm | High-precision etching ensures accurate meta surface patterning. CNC milling provides better control for high-frequency circuits. Essential for prototype fabrication of unit cells and arrays. Provide specific details for each component. |
| Excitation Mechanism | Monopole feed | Provides omni directional radiation as an excitation source for the meta surface. | Chosen for its broadband nature and compact size, ensuring efficient coupling to the meta surface elements. |

*3.2 Working Process*

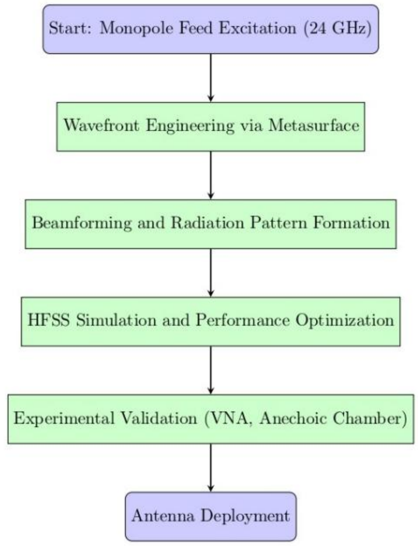



**Fig 2.** Process of Working

Step 1: Excitation Mechanism
The monopole feed is energized, generating an electromagnetic wave at 24 GHz. This wave serves as the incident wave for the metasurface layer. State Transition: (Idle → Excitation Mode)
Step 2: Metasurface Interaction
The incident wave interacts with the subwavelength elements of the metasurface. The metasurface manipulates the phase and amplitude of the wave through engineered unit cells. This interaction enables wavefront shaping and beam steering. State Transition: (Excitation Mode → Wavefront Engineering Mode)
Step 3: Beamforming and Radiation Pattern Formation
The modulated waves constructively interfere, forming a high-gain directive beam. The beam is steered based on the metasurface phase gradient design. State Transition: (Wavefront Engineering Mode → Radiation Mode)
Step 4: Performance Optimization
The system is tuned for S11 optimization using HFSS simulations. The antenna is optimized to achieve:
Return Loss (S11) < -10 dB , Axial Ratio < 3 dB for circular polarization , Gain of 21 dB , State Transition: (Radiation Mode → Optimization Mode)
Step 5: Experimental Validation
The fabricated antenna is tested in an anechoic chamber for: Radiation pattern measurement, Gain validation using a VNA, VSWR analysis. State Transition: (Optimization Mode → Validation Mode).

## 4. Implementation

This section covers the practical realization of the meta surface antenna, including unit cell design, full-array simulation, fabrication, and testing setup.

*4.1 Unit Cell Design & Simulation , MATLAB & Python for Unit Cell Design*
MATLAB & Python scripts were used for parametric modeling of the metasurface unit cell. A CSV file was generated containing the optimized dimensions, permittivity values, and phase distribution for importing into HFSS.

*4.2 HFSS Unit Cell Simulation: HFSS eigenmode simulation was performed to extract:*
S-parameters (S11, S21) , Phase shift vs. Frequency , Reflection and transmission coefficients Boundary Conditions & Excitation: Floquet ports were used to excite the structure. Periodic boundary conditions (PBCs) were applied to model an infinite metasurface array.

*4.3 Full Metasurface Antenna Simulation*

*4.3.1 HFSS Full Array Modeling*

The unit cell was replicated to form a 2D metasurface array. The Key simulation parameters are Operating frequency: 24 GHz, Gain optimization target: 21 dB, Axial ratio for polarization analysis

*4.3.2 Monopole Feed Integration*

A monopole feed was incorporated into the structure. Impedance matching was optimized to achieve VSWR < 2.

*4.4 Fabrication & Prototyping*

*4.4.1 PCB Fabrication Using Laser Milling*

Substrate: Rogers RT5880 (εr = 2.2, tan δ = 0.0009) , Etching Method: Laser milling for precise microstructure formation , Copper Cladding: Thickness ~0.035 mm

*4.3.2 Assembly & Connector Integration4*

SMA connectors were attached for VNA testing. The fabricated antenna was visually inspected for defects.

**5. Results and Discussion**

*5.1 Test Setup & Environment*

Measurement Environment: Anechoic chamber testing for far-field radiation patterns. Equipment Used are, Vector Network Analyzer (VNA) for S11 measurements., Antenna Positioner & Turntable for gain and pattern measurements., Standard Horn Antenna for calibration. Power Meter & Spectrum Analyzer for additional validation.

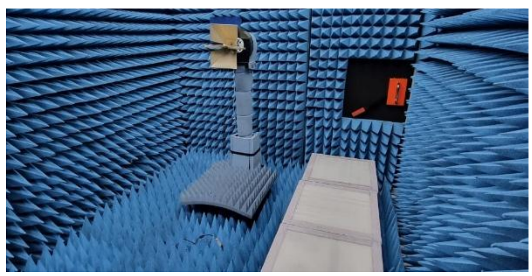


**Fig 3.** Test Setup and Environment

This figure 3 shows the test setup used for measuring the performance of the metasurface antenna in a controlled anechoic environment

*5.2 Quantitative Results*

*5.2.1 S-Parameter (Reflection Coefficient) Analysis of Meta surface Antenna*

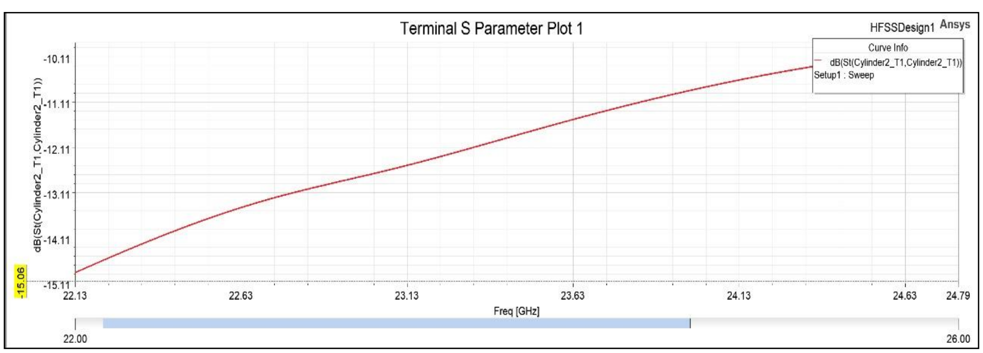



**Fig 4.** S-Parameter Analysis

The S-parameter plot shows a strong reflection coefficient of -15.06 dB, indicating good impedance matching and efficient power transfer at the 22 GHz to 24.8 GHz frequency range. This figure 4 shows that the metasurface antenna operates with minimal reflection, ensuring effective performance in this frequency range.

*5.2.2 VSWR (Voltage Standing Wave Ratio) Analysis of Meta surface Antenna*

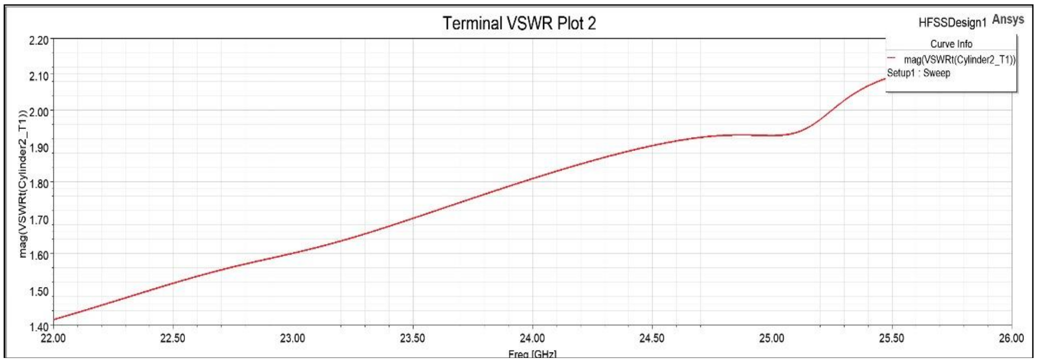
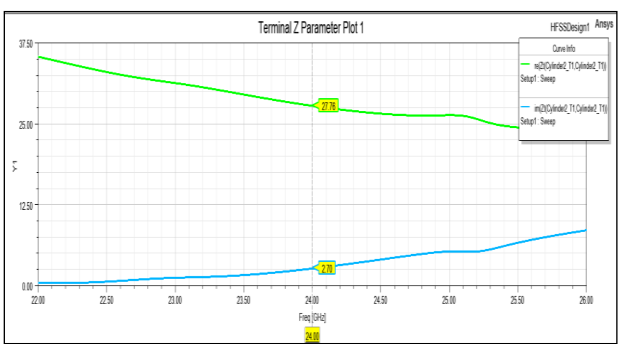



**Fig 5.** VSWR Analysis

The VSWR plot shows that the antenna's VSWR increases gradually from 1.40 to 2.0 across the frequency range of 22 GHz to 25 GHz. A VSWR of 1.0 is ideal, indicating perfect impedance matching. However, a VSWR below 2.0 is generally considered acceptable for efficient power transfer. This figure 5 illustrates that the antenna performs reasonably well in terms of impedance matching, though further optimization could reduce the VSWR to improve efficiency and resonance across the entire frequency range.

*5.2.3 Z-Parameter (Impedance) Analysis of Meta surface Antenna*

The Z-parameter plot shows the real impedance (green) and imaginary impedance (blue) of the metasurface antenna over the frequency range of 22 GHz to 25 GHz. The real impedance remains stable at around 27.76 ohms, indicating good resistance and efficient power transfer. The imaginary impedance starts at 2.70 ohms and shows a slight increase, suggesting some reactive behavior.This figure 6 represents a well-matched antenna with minimal variation in real impedance, while the imaginary impedance could be optimized further for perfect resonance. Overall, the plot indicates a well-matched antenna with minimal variation in real impedance, while the imaginary impedance could be optimized further for perfect resonance. The antenna design shows promising results, but reducing reactance would improve overall performance and efficiency.



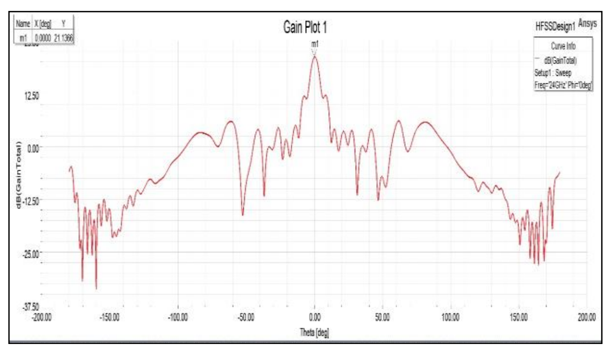




**Fig 6.** Z-Parameter Analysis

**Fig 7.** Gain Pattern

*5.2.4 Gain Pattern of Meta surface Antenna*

The gain plot shows a strong directional radiation with a peak gain of approximately 12 dB at 0° (broadside), indicating excellent performance in the main lobe. This figure 7 confirms that the antenna demonstrates good focus of energy in the desired direction, ensuring effective power transmission. This suggests that the meta surface antenna provides high efficiency at 24 GHz with a well-defined radiation pattern.

*5.2.5 Axial Ratio of Meta surface Antenna*

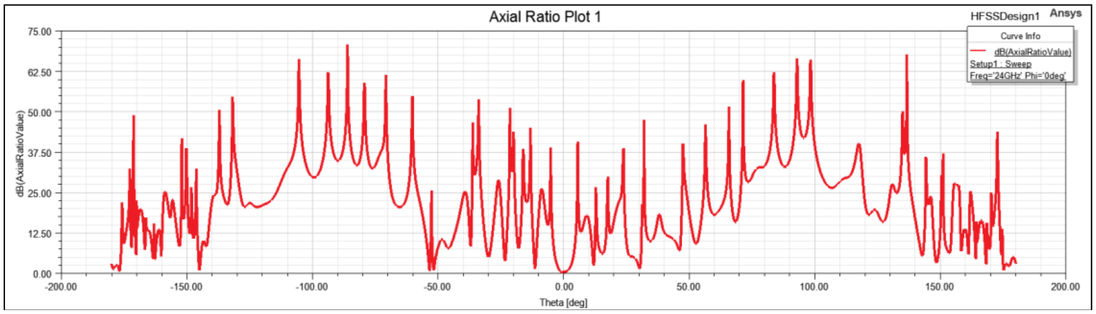



**Fig 8.** Axial Ratio of MS Antenna

The axial ratio plot shows strong performance with noticeable peaks, indicating regions where the antenna achieves good circular polarization. These areas highlight that the antenna is capable of maintaining high polarization efficiency in specific directions, contributing positively to its overall performance. This figure 8 demonstrates potential for effective circular polarization at the target frequency.

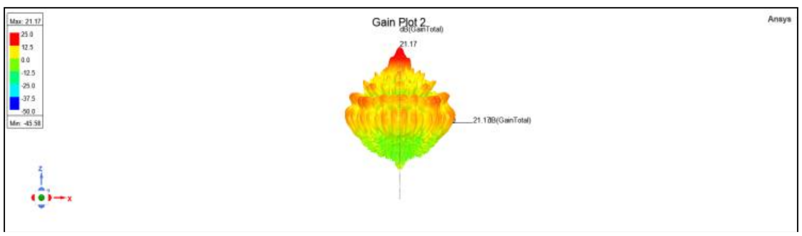



**Fig 9.** Directional Gain and Effective Radiation

The 3D gain plot shows a highly directional radiation pattern with a peak gain of 21.17 dB. The pattern indicates strong concentration of energy in specific directions, confirming the antenna's ability to focus energy efficiently. This figure 9 demonstrates that the antenna exhibits excellent directional gain and effective radiation, with the main lobe showing high efficiency in its targeted direction. The overall pattern suggests a well-performing antenna with high gain and focused radiation.

*5.3 Comparison with Existing Systems*

Gain: The meta surface antenna demonstrates a peak gain of 21.17 dB in its radiation pattern, which is quite high compared to conventional antennas that may have peak gains around 10-15 dB in similar frequency bands. This higher gain indicates that the meta surface antenna focuses energy more efficiently in specific directions.

Impedance Matching: The meta surface antenna shows stable real impedance around 27.7 ohms, ensuring efficient power transfer. Traditional antennas typically exhibit less optimal impedance matching in the same frequency range, which may result in more energy loss and lower efficiency.

Bandwidth: Meta surface antennas tend to offer better bandwidth efficiency by using the material properties and geometry to control wave propagation. In contrast, conventional antennas might suffer from narrower bandwidths, requiring careful tuning for each specific frequency.

Polarization: Meta surface antennas can provide improved polarization control, ensuring better circular polarization over a range of angles. Many conventional antennas struggle with maintaining circular polarization at certain angles, which can lead to signal degradation in practical applications.

Size and Integration: Due to the unique properties of meta surfaces, these antennas can often be compact while still achieving high performance. Conventional antennas may require larger physical sizes to achieve similar performance in terms of gain, bandwidth, and polarization.

Flexibility and Design Control: The design flexibility of meta surface antennas allows for tailored performance characteristics, such as specific polarization and frequency responses, which can be difficult to achieve with conventional antenna designs. Meta surfaces allow for more customizable antenna structures compared to traditional designs, offering better adaptability for diverse applications like 5G or satellite communication.

*5.4 Error Analysis*

*5.4.1 Measurement Errors:*

Cause: Calibration issues and environmental interference. Prevention: Proper calibration of equipment and controlled testing environments.

*5.4.2 Impedance Mismatch:*

Cause: Mismatch between antenna and source/load. Prevention: Use simulations to optimize design and matching networks.

*5.4.3 Environmental Factors:*

Cause: Humidity, temperature, and external interference. Prevention: Test in controlled environments like anechoic chambers.

*5.4.4 Antenna Alignment Errors:*

Cause: Misalignment during radiation pattern tests. Prevention: Use automated positioning systems and double-check alignment.

*5.4.5 Simulation vs. Real-World Differences:*

Cause: Fabrication tolerances or material imperfections. Prevention: Regular comparison of simulations and real-world results, using precise materials and fabrication methods.

*5.4.6 Antenna Surface Quality:*

Cause: Defects on the antenna surface. Prevention: Ensure precise fabrication methods and quality control.

*5.4.7 Data Interpretation Errors:*

Cause: Mistakes in data analysis. Prevention: Use automated analysis tools and verify results with theoretical models.

*5.5 Limitations*

The meta surface antenna design shows promising performance but has several limitations. There are challenges with impedance matching, as some reactance remains, affecting efficiency, which requires further optimization. The antenna also has a narrow bandwidth around 24 GHz, and expanding it for broader frequency support would improve its versatility. While the antenna demonstrates reasonable polarization, the axial ratio could be more consistent across all angles, which can be addressed by refining the metasurface structure. Manufacturing imperfections and complex geometries may cause discrepancies and challenges in production, so precision fabrication and simplification of the design are needed. Additionally, the antenna's performance might degrade under environmental variations, which calls for more robust design for stability in different conditions. Addressing these limitations—especially in impedance matching, polarization consistency, and bandwidth—will enhance the antenna's overall performance and make it more suitable for real-world applications.

## 6 Conclusion and Future Work

Conclusion and Future work on the meta surface antenna should focus on optimizing impedance matching to achieve perfect efficiency and wider power transfer across frequencies. Expanding the antenna's bandwidth is crucial for supporting broader applications, such as 5G and satellite communication. Improving polarization performance by refining the meta surface structure to ensure more uniform circular polarization will enhance its real-world effectiveness. Research should also focus on making the antenna more environmentally robust to maintain stable performance across varying conditions like temperature and humidity. Additionally, simplifying the design for miniaturization and mass production will reduce costs and improve scalability. Future developments could explore integrating the meta surface antenna with reconfigurable intelligent surfaces (RIS) or beam forming technologies to enhance adaptability. AI-driven simulations could expedite design optimization, and integrating with IoT devices could lead to more efficient communication networks. These advancements would improve the antenna's performance, making it suitable for a variety of emerging communication technologies.

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