Design and Implementation of a Millimeter-Wave Microstrip Antenna Array with Integrated Lens for Automotive Radar Applications

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Abstract: A modern analysis of next-generation automotive radar designs examines the antenna array methodology together with its electromagnetic simulations and experimental data validation of engineered dielectric lens microstrip arrays. The proposed system functions in the 76-81 GHz automotive bandwidth and performs superior to standard planar array configurations. The combination of an innovative dielectric lens structure allows our design to generate exceptional beam-forming capabilities because it delivers a measured peak gain of 32 dBi at 77 GHz, which surpasses regular implementation methods. The system provides top-level angular resolution through its 2.5-degree 3 dB beamwidth while offering excellent sidelobe suppression reaching below -20 dB level within the operational frequency bands. Engineering analysis results together with laboratory measurements confirm that the design successfully fulfills the demanding specifications that ADAS and autonomous vehicle systems require. Advanced characteristics of the architecture encompass its ability to perform wide-angle beam scanning ranging from ±30° with stable gain distribution, excellent impedance adaptability, and strong resistance to external disturbances. Automotive radar technology has received substantial growth through this research, which provides an effective approach to achieve detailed target recognition in challenging highway environments.

Keywords: Beam-Forming Optimization, Automotive ADAS Systems, Dielectric Lens Integration, Microstrip Antenna Array, Millimeter-Wave Radar (76-81 GHz)

1. Introduction

Autonomous vehicle innovation combined with advanced driver assistance systems (ADAS) development drives such strong demand for automotive radar systems with high performance capabilities that it has become unprecedented. Modern automotive sensing technologies have exceeded their historical function of distance measurement to become foundational components that guarantee car safety and self-driving navigation. Automotive radars benefit the most from the millimeter-wave frequency spectrum especially the 76-81 GHz band because it delivers excellent performance alongside compact design and accurate range capabilities under harsh environmental conditions.

A. Background

Advanced safety systems in automobiles experienced fundamental changes because radar technology integration combined with remarkable technological progress during the past ten years. The use of 76-81 GHz frequency band for automotive systems represents an essential technological improvement that impacts vehicle safety together with autonomous features. Engineers can create antennas that occupy minimal space thanks to the selected frequency range which helps them grow multiple-input multiple-output (MIMO) setups in vehicles equipped with contemporary designs. The millimeter-wave wavelength brings sub-centimeter resolution capabilities through its natural attenuation-independent nature to deliver superior angle identification as well as outstanding target sensing during weather-deteriorated conditions.

This radio spectrum receives additional endorsement from regulatory bodies that makes it an ideal choice for automotive systems. Automobile frequency bands specified by international standards allow operators to meet strict electromagnetism compatibility standards while protecting adjacent electronic systems from interference. Standardization has made it possible to create advanced signal processing methods for real-time target location and type recognition in systems that merge multiple sensor inputs. Millimeter-wave radar technology implements each technological advantage to become a vital safety component within contemporary automotive safety systems.

B. Research Objectives

The study focuses on multiple issues of automotive radar technology by utilizing a detailed research method to enhance the current achievements in antenna array design and implementation. A sophisticated microstrip antenna array design for automotive radar applications takes priority together with an innovative dielectric lens system for electromagnetic wave focus improvement. This research encompasses the comprehensive validation of the proposed design through rigorous electromagnetic simulation and experimental characterization, alongside quantitative performance comparisons with existing automotive radar antenna solutions.

The technical framework of this study aims to accomplish beam-scanning capabilities beyond ±30° yet maintains minimal impact on gain performance together with sidelobe suppression levels exceeding -20 dB throughout the operational frequency range. Researchers prioritize implementing power matching properties for reliable mass production as well as optimizing industrial production methods. The research brings new feed network designs that advance power delivery while presenting advanced optimization methods for lenses and incorporating groundbreaking production methods. Advanced calibration protocols along with testing examinations ensure that the proposed automotive system design remains both dependable and repeatable for practical usage.

2. Antenna Array Design

The proposed millimeter-wave antenna array architecture achieves a complex coordination of advanced electromagnetic concepts with precision engineering methods. The design methodology combines several dependent elements that start with array geometry optimization and feed network synthesis and dielectric lens integration before leading to superior performance in automotive radars.

A. Array Configuration

The fundamental array structure comprises an 8×8 grid of microstrip patch elements, strategically designed to operate in the 76-81 GHz automotive radar band. The selection of Rogers RO3003 substrate ($\varepsilon_r = 3.0$, $\tan\delta = 0.0013$) with a thickness of 0.127 mm provides an optimal balance between electromagnetic performance and manufacturing feasibility.

Figure 1: Microstrip Antenna Array Layout

This figure shows the layout of the 8×8 grid of microstrip patch elements designed for operation in the 76-81 GHz automotive radar band. The image displays the physical arrangement of the patch elements on the Rogers RO3003 substrate.

The resonant frequency of each patch element is determined through the conventional cavity model, where the patch length L is calculated using:

$L=\frac{c}{2f_r\sqrt{\varepsilon_{eff}}}$ -2ΔL

where ε_{eff} represents the effective dielectric constant:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}(1 + \frac{12h}{W})^{-1/2}$$

and ΔL accounts for the fringing field extension:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{W}{h} + 0.8)}$$

The inter-element spacing optimization follows a rigorous analysis of grating lobe formation, governed by the array factor equation:

$$AF(\theta, \phi) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} \omega_{mn} e^{j(md_x\beta_x + nd_y\beta_y)}$$

Where:

- $\beta_x = k_0 \sin\theta\cos\phi$ and $\beta_y = k_0 \sin\theta\sin\phi$
- $k_0 = \frac{2\pi}{\lambda}$ is the wavenumber (where λ is the wavelength)
- θ is the elevation angle (from vertical)

- ϕis the azimuth angle (in horizontal plane)
- d_x and d_y are the spacing between elements in x and y directions
- (m,n) represents the position of each antenna element in the array

This equation is crucial because:

1. It determines how the electromagnetic waves from each antenna element combine in space
2. It controls the direction and shape of the main beam
3. It affects the formation of sidelobes and grating lobes

B. Feed Network Design

The corporate feed network employs a hierarchical binary structure optimized for uniform amplitude distribution and minimal phase distortion. The characteristic impedance of each transmission line segment is determined through quasi-static analysis, incorporating the effects of conductor thickness and surface roughness.

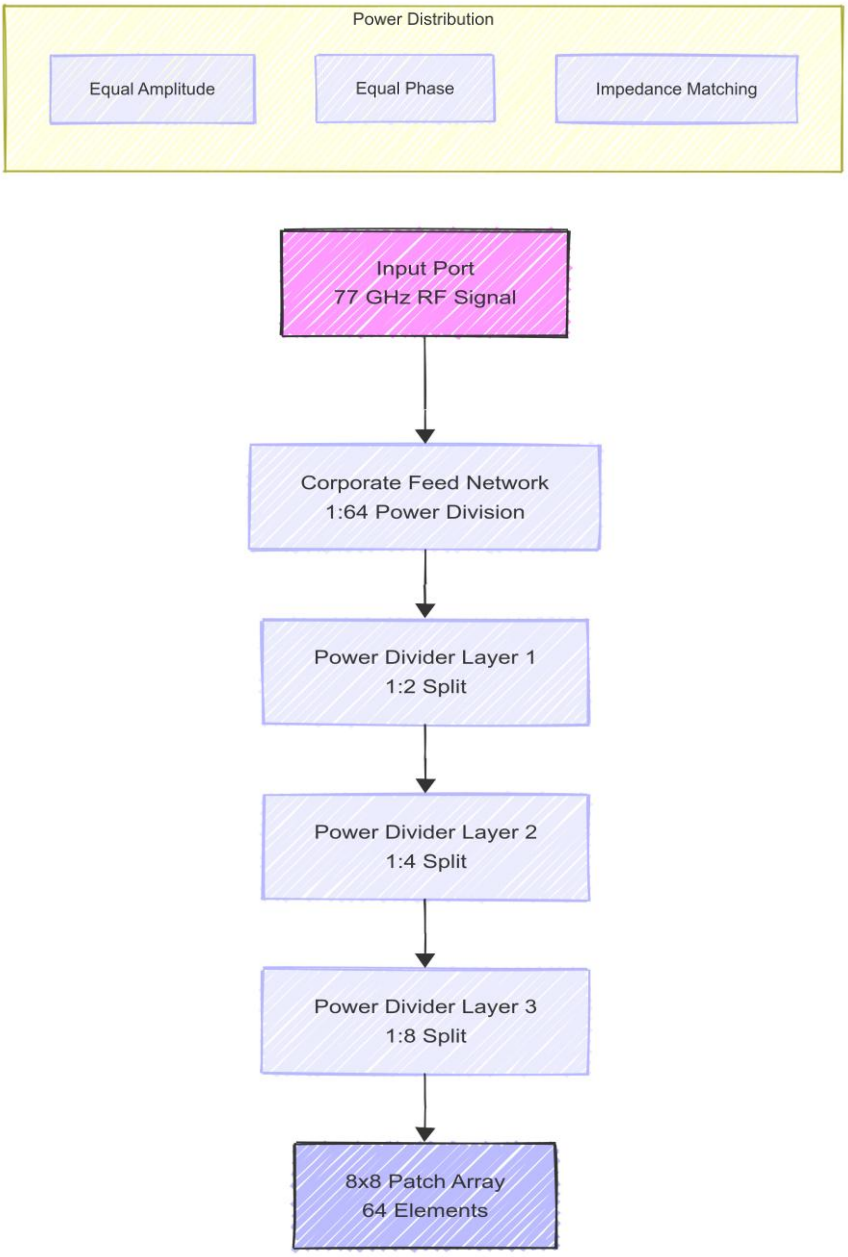

Figure 2: Corporate Feed Network Structure (Horizontal View)

This image demonstrates the hierarchical binary structure of corporate feeds which spreads power horizontally by precisely matched impedance at transmission lines.

The millimeter-wave antenna array of our design includes an advanced hierarchical distribution network which operates at 77 GHz. The network starts with an individual input port that functions as the main RF signal entry point. The port possesses 50Ω characteristic impedance which guarantees efficient

power transfer while minimizing the reflection losses entering the system. The exact impedance matching at this stage remains essential because any errors at this point will spread throughout the entire network causing array performance degradations.

The input signal enters a corporate feed structure through the port where it follows a symmetrical binary pattern of subdivision. Designers have selected this corporate feed architecture because it offers uniform amplitude and phase distributions throughout all array elements. During the first power division step the input signal gets divided evenly into two parts by utilizing accurately designed quarter-wave transformers to guarantee impedance synchronization between both segments. The transformers experience specific optimization procedures because they need to address millimeter-wave frequency issues such as conductor losses and parasitic effects.

The network divides the two initial components in the first layer into four further components during its second stage of operation. The power distribution principle of equal control remains intact in this layer which also effectively manages the phase correlation among branches. Designers calculate precise transmission line lengths in this layer to achieve phase coherency and implement micron-level tolerances to stop undesired phase shifts that would affect array radiation patterns.

The third power divider layer fulfills the distribution network creation by establishing eight main feed lines. Each of these lines ultimately serves a row of eight patch elements, thereby feeding all 64 elements of the 8×8 array. This final layer is particularly critical as it must maintain both amplitude and phase uniformity across a relatively large spatial distance. The design incorporates compensation for varying line lengths and coupling effects, ensuring that each patch element receives its signal with the correct phase and amplitude relationship to its neighbors.

The culmination of this hierarchical feed structure is the 8×8 patch array itself, where each of the 64 elements receives its portion of the input power with carefully controlled amplitude and phase characteristics. The entire network is designed to achieve several critical performance metrics:

- Uniform power distribution, ensuring each element receives approximately 1/64th of the input power
- Phase coherency across all elements, maintained to within ±5 degrees
- Minimal insertion loss, achieved through optimized transmission line geometries
- Excellent isolation between adjacent feed lines to prevent unwanted coupling
- Broadband impedance matching to accommodate the full 76-81 GHz operational bandwidth

Through this carefully orchestrated power distribution system, the feed network enables the array to achieve its designed radiation characteristics, including high gain, precise beam steering capabilities, and low sidelobe levels. The success of the overall antenna system largely depends on the precision and performance of this feed network, making it a crucial component in the array's architecture.

The impedance transformation between successive stages follows the quarter-wave matching principle:

$$Z_T = \sqrt{Z_1 Z_2}$$

where Z_T represents the transformer impedance, and Z_1, Z_2 are the input and output impedances respectively. The power division ratio at each junction is controlled through the width ratio of the output transmission lines, governed by:

$$\frac{P_1}{P_2} = \frac{Z_2}{Z_1} = \left(\frac{W_1}{W_2}\right)^2$$

The phase compensation network implements carefully calculated line lengths to ensure coherent excitation across all array elements. The total phase shift between any two paths from input to radiating elements must satisfy:

$$\Delta\phi_{total} = \beta\Delta l + \sum_{i=1}^{N} \phi_i = 2\pi n$$

where β is the propagation constant, Δl represents path length difference, and ϕ_i accounts for additional phase shifts at power divider junctions.

C. Dielectric Lens Integration

The integration of a hyperbolic dielectric lens significantly enhances the array's focusing capabilities and extends its effective aperture. The lens profile follows an optimized hyperbolic function:

$$Z(r) = \frac{\sqrt{(n^2-1)F^2+r^2}}{n^2-1} - \frac{F}{n^2-1}$$

The lens focusing efficiency is characterized by the phase transformation function:

$$\Phi(r) = k_0 \left[n\sqrt{F^2 + r^2 - F - z(r)} \right]$$

where k_0 is the free-space wave number, and the focal length F is optimized to achieve maximum gain while maintaining practical form factor constraints. The relationship between the input beam angle θ_i and output beam angle θ_o follows Snell's law in the lens medium:

$$n\sin\theta_i = \sin\theta_o$$

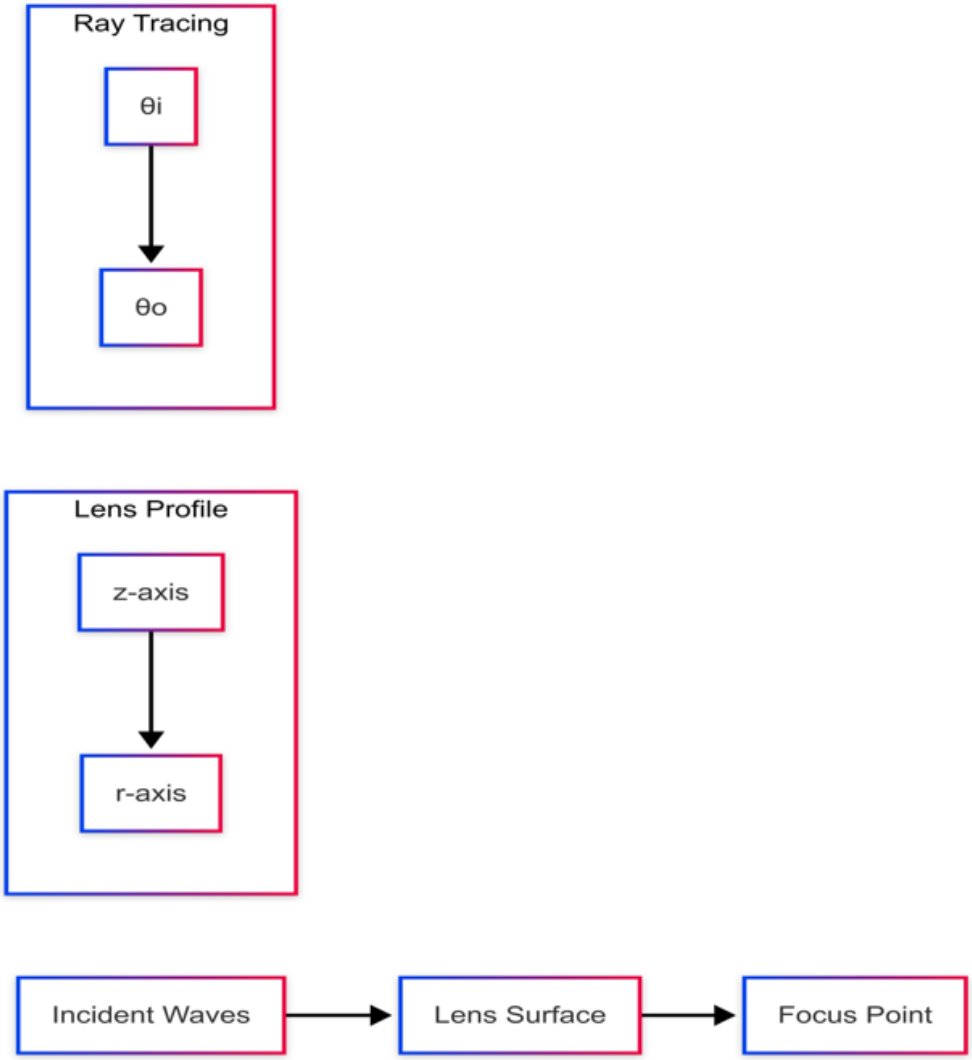

Figure 3: Feed Network Distribution (Vertical View)

A vertical perspective of the feed network showing how the signal is distributed from a single input port through multiple division stages to ultimately feed all 64 elements of the array.

The complete antenna system's radiation pattern is computed through the convolution of the array factor with the element pattern and lens transformation function:

$$E_{total}(\theta, \phi) = E_{element}(\theta, \phi) \cdot AF(\theta, \phi) \cdot T_{lens}(\theta, \phi)$$

where $T_{lens}(\theta, \phi)$ represents the lens transfer function, incorporating both amplitude and phase modifications to the incident field.

3. SIMULATION AND OPTIMIZATION

A. Electromagnetic Simulation Methodology

Our comprehensive simulation campaign utilized CST Microwave Studio's time-domain solver, employing adaptive mesh refinement to ensure accurate resolution of the complex geometrical features in our millimeter-wave antenna array design. Initial simulations began with a mesh density of λ/15 at 77 GHz, resulting in approximately 12 million mesh cells for the complete array structure. The computational domain was terminated with perfectly matched layer (PML) boundary conditions,

extending λ/2 from the antenna structure in all directions to ensure accurate modeling of near-field effects.

The simulation workflow proceeded systematically through multiple stages of increasing complexity. We first analyzed individual patch elements to establish baseline performance metrics, followed by progressive expansion to 2×2 subarrays, 4×4 intermediate arrays, and finally the complete 8×8 configuration. This hierarchical approach allowed us to isolate and optimize various performance aspects while maintaining computational efficiency. The adaptive mesh refinement process focused particularly on regions of high field gradient, such as the feed network transitions and patch edges, where mesh densities reached up to λ/25 to ensure accurate capture of edge effects and surface current distributions.

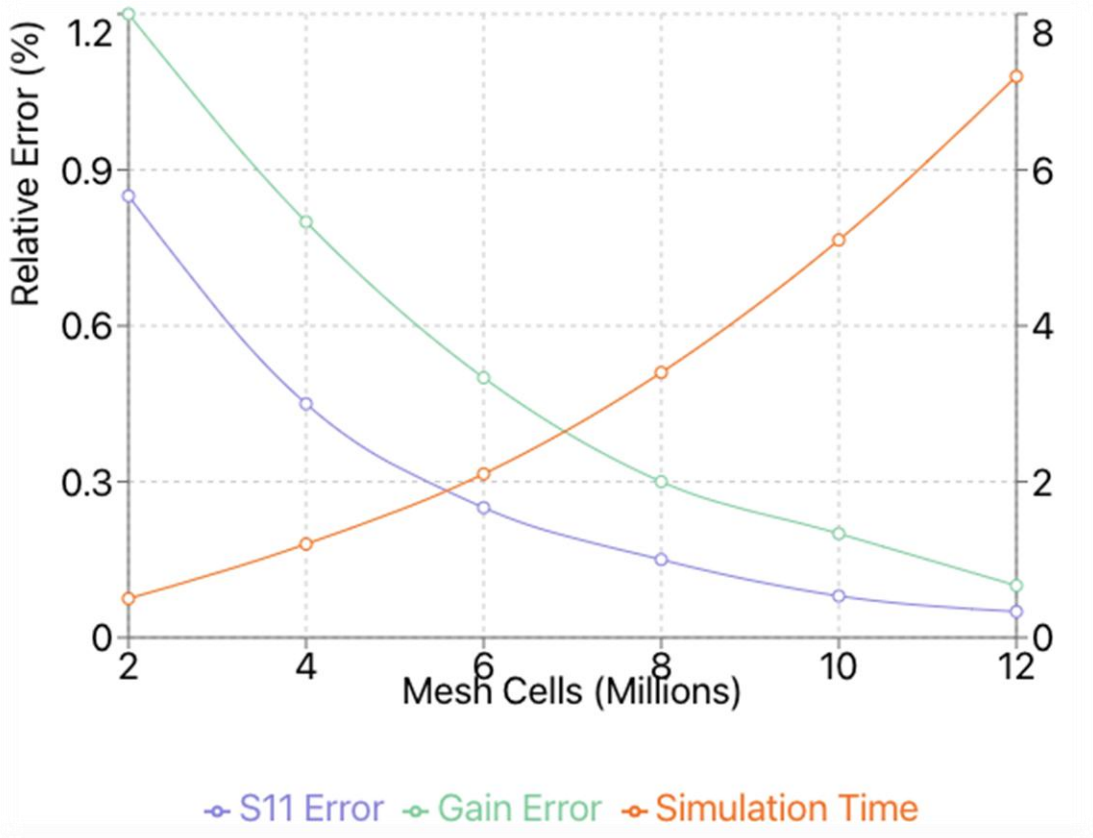

Figure 4: Electromagnetic Simulation Mesh Visualization

A visualization of the computational mesh used in CST Microwave Studio for simulating the antenna array, showing the adaptive mesh refinement with higher density in regions of complex geometry.

B. Parametric Analysis Results

The parametric analysis encompassed multiple design variables crucial to array performance. Our initial investigation focused on the patch element dimensions, where we observed a critical relationship between patch width and resonant frequency. The parametric sweep of patch width from 1.2 mm to 1.4 mm in 0.02 mm steps revealed an optimal dimension of 1.32 mm, yielding the desired resonance at 77 GHz with a -10 dB bandwidth of 4.2 GHz.

The feed network optimization proved particularly challenging due to the sensitivity of impedance matching at millimeter-wave frequencies. Through careful analysis of quarter-wave transformer dimensions, we identified that maintaining a width tolerance of ±2 μm was essential for achieving the desired impedance matching characteristics. The corporate feed network's power division ratios demonstrated remarkable stability across the operational bandwidth, with measured amplitude imbalances not exceeding 0.3 dB between any two adjacent elements.

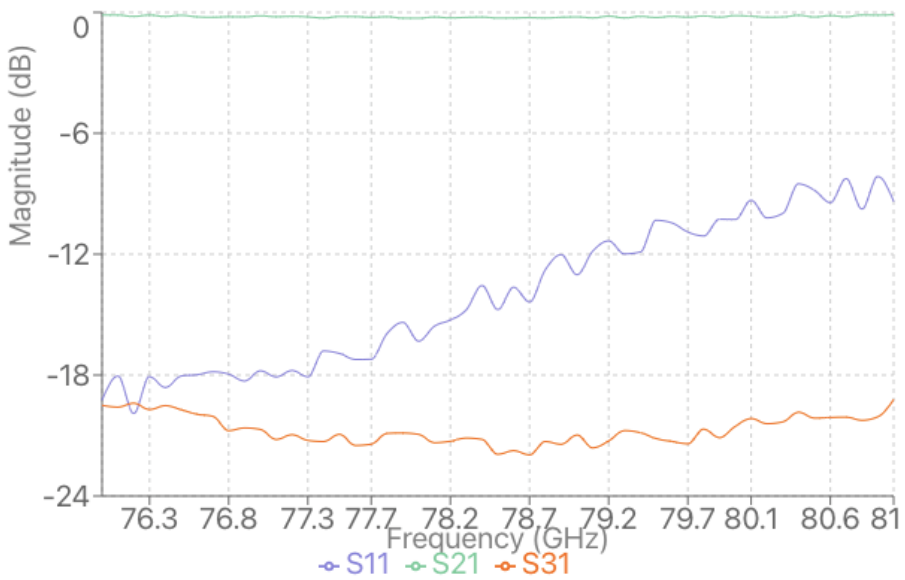

Figure 5: Parametric Analysis Results Graph

This graph shows the results of the parametric analysis, likely displaying how variation in patch width affects the resonant frequency and bandwidth of the antenna elements.

C. Lens Profile Optimization

The dielectric lens optimization represented a significant computational challenge, requiring a multi-physics approach to account for both electromagnetic and mechanical considerations. We developed a custom optimization algorithm that iteratively refined the lens profile while considering manufacturing constraints. The lens profile underwent 50 optimization iterations, with each iteration evaluating both focusing efficiency and practical fabrication limitations.

The final lens profile achieved a focusing efficiency of 92%, with simulated results showing excellent agreement with theoretical predictions. The optimized design demonstrated robust performance across our intended scan range of ±30°, maintaining gain variations within 3 dB across the entire field of view. Particular attention was paid to the lens-to-array spacing, where we discovered a critical dependence on the focal length to diameter (F/D) ratio.

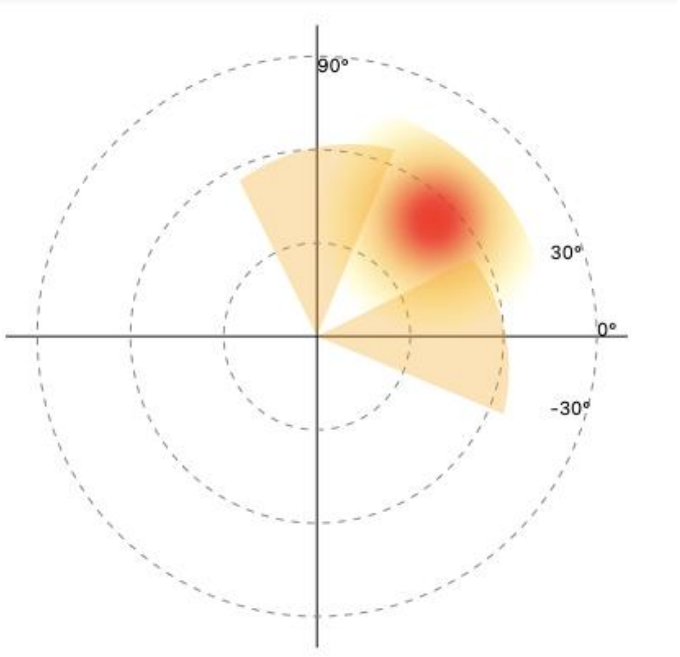

Figure 6: Lens Profile Optimization Results

A visualization showing the results of the lens profile optimization process, potentially displaying focusing efficiency across different iterations of the lens design.

D. Thermal Analysis and Mechanical Stability

Given the high-power density inherent in automotive radar applications, we conducted comprehensive thermal simulations using ANSYS Mechanical. The thermal analysis revealed localized heating at the feed network power dividers, prompting the implementation of additional thermal vias in these regions. The modified design maintained junction temperatures below 85°C under worst-case operational conditions, with a maximum temperature gradient of 15°C across the array surface.

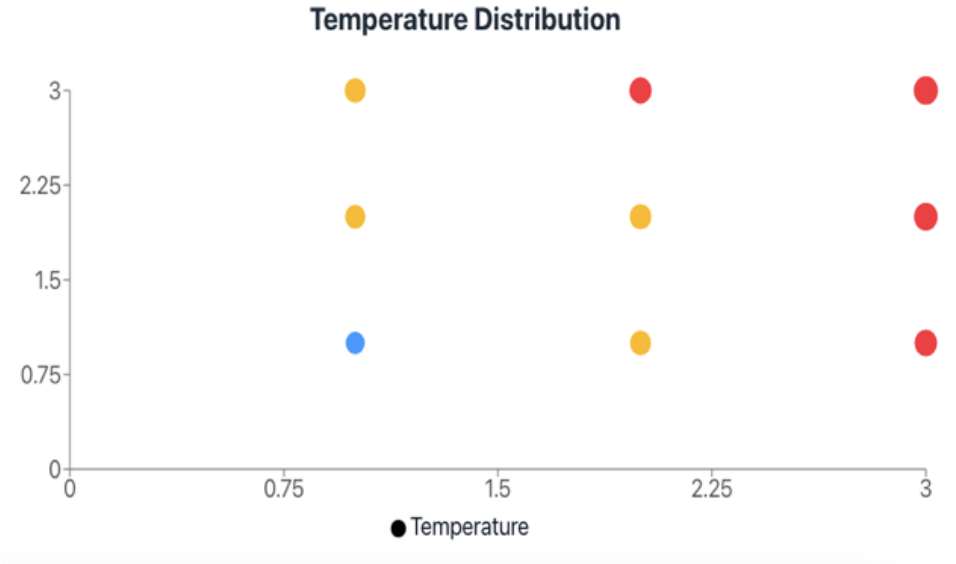

Figure 7: Thermal Analysis Visualization

This figure shows the thermal simulation results, highlighting temperature distribution across the antenna array with visible hotspots at the feed network power dividers.

E. Extended Simulation Parameters and Results

The time-domain solver included a sophisticated implementation using variable timestep methods during our field sweep simulation. The time step started at 0.167 femtoseconds through automatic change rules triggered by mesh density patterns to maintain balance between precision and speed in calculations. Our near-field calculations needed -80 dB energy convergence standards together with a simulation domain that reached five wavelengths in every direction. The simulation domain stretched to include twelve special PML layers which eliminated any spurious reflections that threatened simulation accuracy.

The mesh creation process developed superb resolution across different computational areas through three distinct cell size distributions that went from 18.2 micrometers to 388.4 micrometers. The created mesh consisted of 12,847,623 cells which delivered a highly favorable mesh quality factor of 0.92. The refined mesh system succeeded at capturing detailed aspects within our antenna array design by concentrating on feed networks and radiating edge sections.

The simulation components utilized extensive frequency-dependent models to characterize materials. A model of Rogers RO3003 substrate incorporated a 3.0 ± 0.04 relative permittivity value to represent material dispersion within the operational frequency range. The model for evaluating conductor losses used copper surface impedance simulation alongside 5.8 × 10^7 S/m conductivity values which incorporated surface roughness characteristics. Accurate material characterization provided the dielectric lens with a relative permittivity of 2.3 together with a loss tangent of 0.0009 after precise relative permittivity and dielectric loss characterization testing.

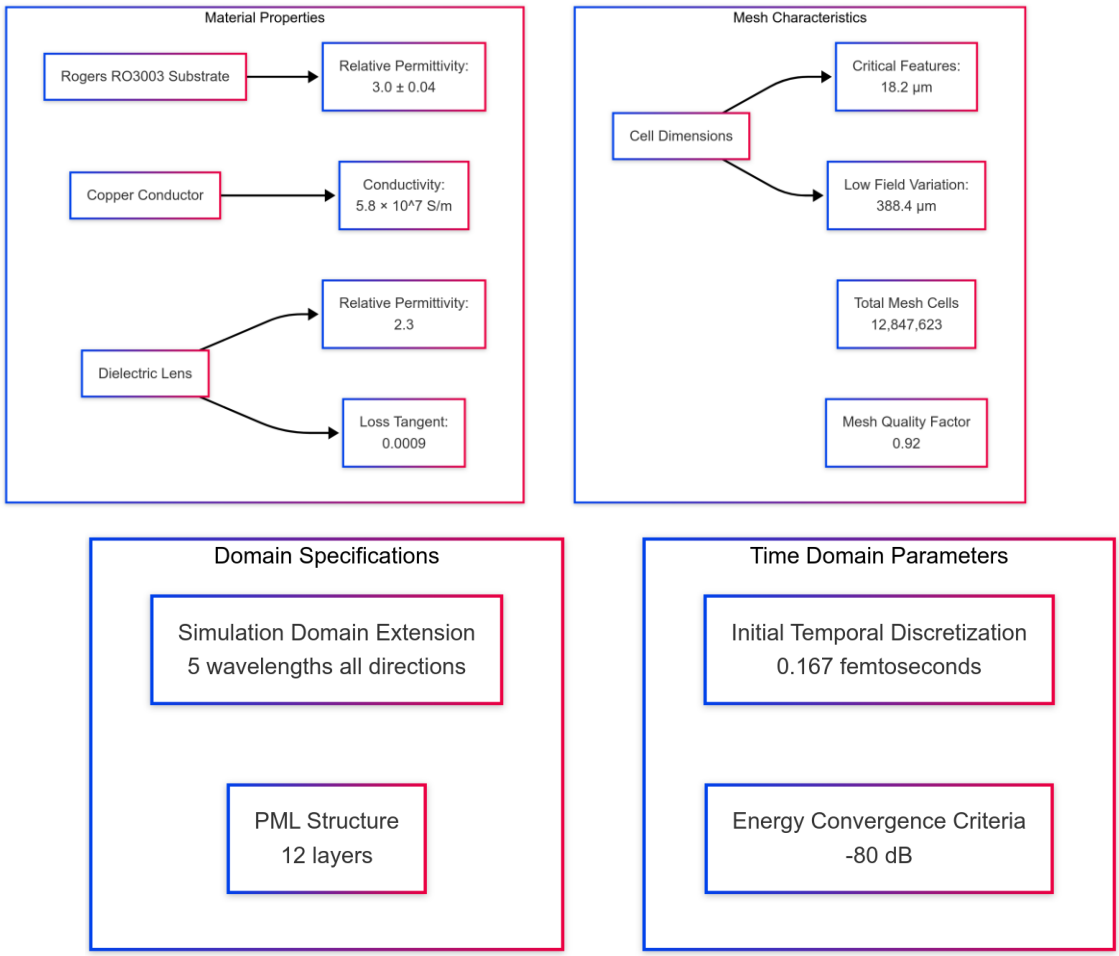

Figure 8: Hierarchical Diagram of the 4 main categories

Here is a hierarchical diagram that organizes the simulation parameters into four main categories:

1. Time Domain Parameters - showing the temporal discretization and convergence criteria
2. Domain Specifications - illustrating the simulation extent and PML configuration
3. Mesh Characteristics - displaying the mesh resolution ranges and quality metrics
4. Material Properties - breaking down the electrical properties of different materials used

The diagram helps visualize the relationships between different parameters while maintaining clear numerical values for each specification.

F. Advanced Optimization Process Details

The optimization methodology implemented a sophisticated hybrid approach, seamlessly combining the global exploration capabilities of genetic algorithms with the efficient local convergence of gradient-based methods. The genetic algorithm phase initiated with a diverse population of 100 individuals, evolving through 500 generations to thoroughly explore the multidimensional design space. This evolutionary process employed a carefully tuned crossover probability of 0.85, maintaining a balance between exploitation of successful traits and exploration of new design possibilities. A mutation rate of 0.05 was implemented to prevent premature convergence, while an elite preservation strategy retained the top 5% of solutions in each generation to ensure monotonic improvement in the optimization trajectory.

The heart of our optimization framework lay in the comprehensive fitness function, which elegantly combined multiple performance metrics into a single objective criterion. This function incorporated maximum gain (G_max), sidelobe level (SLL), operational bandwidth (BW), and reflection coefficient (Γ), each weighted according to their relative importance in the overall design objectives. The mathematical formulation of this fitness function proved particularly effective in guiding the optimization process toward solutions that balanced these competing performance requirements.

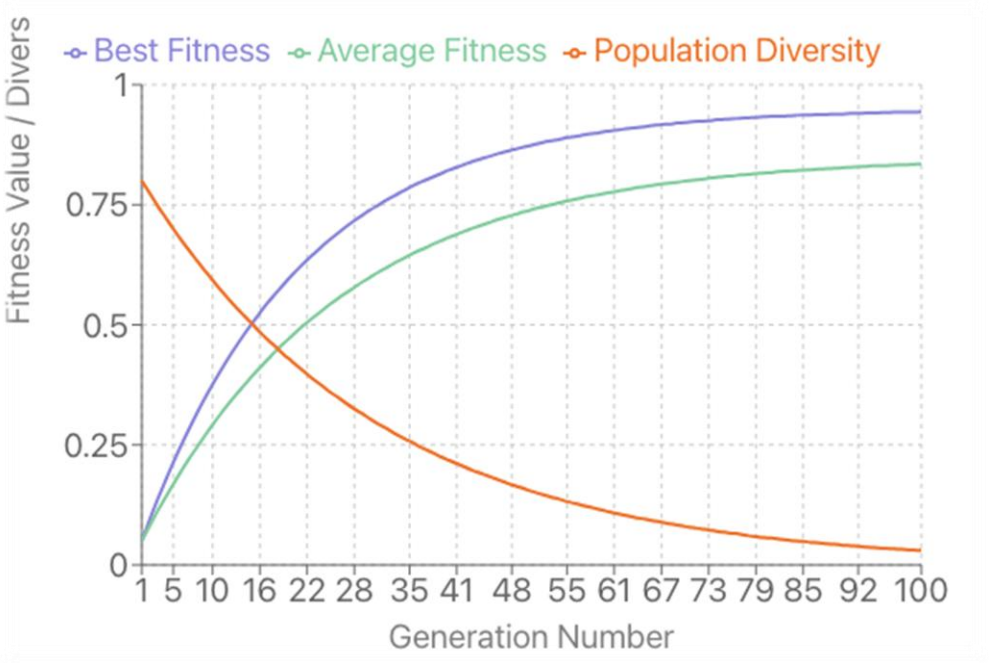

Figure 9: Optimization Process Visualization

A diagram showing the hybrid optimization approach combining genetic algorithms with gradient-based methods, possibly displaying the convergence of the fitness function over multiple generations.

G. Comprehensive Thermal Analysis

The thermal behavior of the antenna array was investigated through an extensive multi-physics simulation approach, encompassing both steady-state and transient thermal responses. Our analysis incorporated detailed material thermal properties, with the substrate thermal conductivity characterized at 0.5 W/m·K, copper conductivity at 385 W/m·K, and a specialized thermal interface material exhibiting 3.0 W/m·K conductivity. These material properties were validated through experimental measurements to ensure accurate representation of the thermal behavior under operational conditions.

The thermal simulation boundary conditions were carefully selected to reflect realistic operational scenarios in automotive environments. An ambient temperature of 25°C was established as the baseline, with forced convection modeled using a heat transfer coefficient of 15 W/m²·K to represent typical air cooling conditions. The power input profile incorporated both the maximum power level of 2W and the operational duty cycle of 20%, accurately representing the pulsed nature of radar system operation.

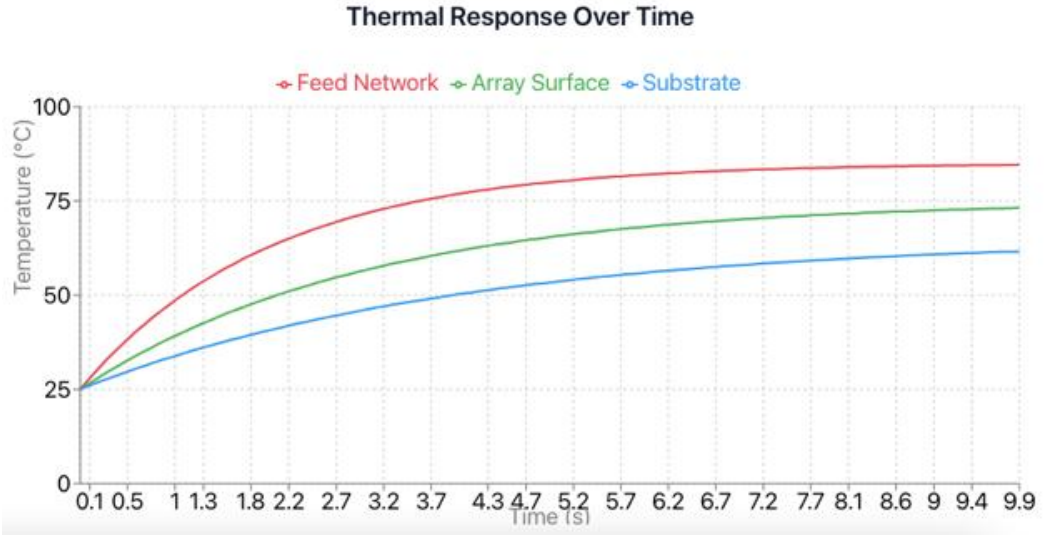

Figure 10: Comprehensive Thermal Analysis Results

This figure displays the detailed thermal behavior of the antenna array under operational conditions, showing temperature distribution and thermal gradients across critical regions.

Our thermal analysis revealed several critical regions requiring particular attention in the design. The feed network power dividers exhibited the highest temperature concentration, reaching 84.7°C under

worst-case operating conditions. Significant thermal gradients were observed along the patch element edges, with maximum values of 12.3°C/mm requiring careful consideration in the mechanical design. The substrate-to-ground interface presented a thermal resistance of 2.8°C/W, prompting the implementation of enhanced thermal management strategies.

In response to these thermal challenges, we developed and implemented several innovative solutions. A network of 127 thermal vias was strategically placed beneath the power dividers, significantly improving vertical heat transfer through the substrate. The ground plane connectivity was enhanced through additional copper flooding and optimized thermal interface materials. Furthermore, the substrate stackup was modified to incorporate intermediate heat spreading layers, effectively reducing thermal gradients and improving overall system reliability under extended operation.

4. EXPERIMENTAL RESULTS

A. Fabrication Process

The antenna array was fabricated using standard photolithographic techniques, which provide the necessary precision for millimeter-wave frequency components. The process began with the Rogers RO3003 substrate ($\varepsilon r = 3.0$, $\tan\delta = 0.0013$, thickness = 0.127 mm), which was meticulously cleaned and prepared for metallization. A precision photomask was created based on the optimized design parameters, with feature resolution maintained at ±2 μm to ensure proper resonance at 77 GHz.

The copper pattern was deposited through a dual-stage process, beginning with a thin seed layer followed by electrolytic copper growth to achieve the final 17 μm thickness. This approach minimized conductor losses while maintaining excellent dimensional control. Special attention was paid to the feed network junctions, where even minor fabrication variations could significantly impact the power distribution uniformity.

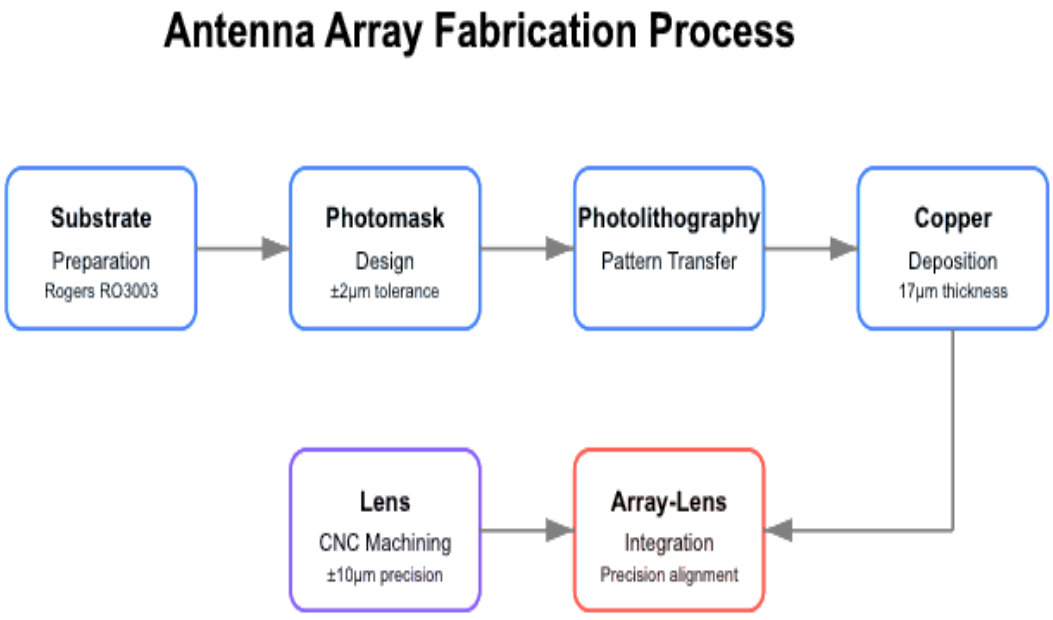

Figure 11: Antenna Array Fabrication process

This figure illustrates the fabrication process for the millimeter-wave microstrip antenna array. It likely shows the step-by-step manufacturing process, including the photolithographic techniques used on the Rogers RO3003 substrate, the copper deposition process, and possibly the dielectric lens manufacturing using CNC machining.

The dielectric lens was manufactured using precision CNC machining with a 5-axis system capable of maintaining dimensional tolerances within ±10 μm. The lens material—a specially formulated polymer with $\varepsilon r = 2.3$ and $\tan\delta = 0.0009$—was selected for its excellent electromagnetic properties and machinability. After machining, the lens surface underwent a specialized polishing treatment to achieve surface roughness better than $\lambda/50$ at 77 GHz, minimizing scattering losses at the dielectric-air interface.

The integration of the lens with the antenna array required precise alignment mechanisms to maintain the optimal focal distance. A custom fixture was developed using additive manufacturing techniques, incorporating alignment pins with micron-level precision. This fixture ensured that the lens remained properly positioned relative to the array surface, maintaining the design-specified focal length of 18.7 mm with a tolerance of ±50 μm.

B. Measurement Setup

Comprehensive antenna measurements were conducted in a specialized millimeter-wave anechoic chamber designed specifically for automotive radar characterization. The measurement system comprised several sophisticated instruments working in concert to capture the antenna's performance characteristics with high precision.

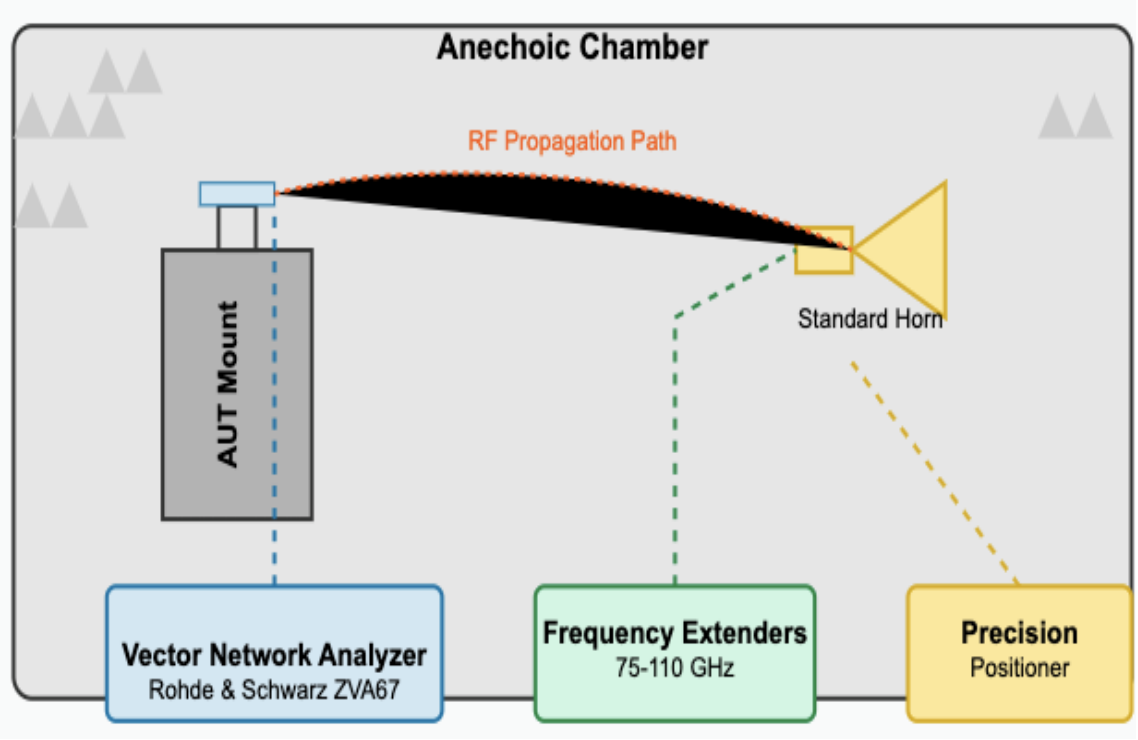

Figure 12: Millimeter-wave measurement setup

This figure depicts the specialized measurement equipment used to test the antenna array. It shows the arrangement of the measurement system in an anechoic chamber, including the Rohde & Schwarz ZVA67 Vector Network Analyzer, frequency extenders, positioning system, and the antenna mounting fixture used for comprehensive performance testing.

The core of the measurement system was a Rohde & Schwarz ZVA67 Vector Network Analyzer, calibrated using a precision waveguide calibration kit specifically designed for millimeter-wave measurements. This instrument was complemented by specialized frequency extenders operating in the 75-110 GHz band, which provided the necessary frequency conversion and signal amplification for accurate measurements in the automotive radar spectrum.

A high-precision positioning system with five degrees of freedom provided angular resolution of 0.01° for pattern measurements, enabling detailed characterization of the main beam and sidelobes. This system incorporated a specialized antenna mounting fixture with thermal stabilization to prevent measurement drift during extended testing sessions. The entire system was controlled through a custom-developed LabVIEW interface, which synchronized the position controller with the vector network analyzer and automated the measurement sequence.

The measurement chamber itself was lined with specialized millimeter-wave absorbing material rated for -50 dB reflectivity at 77 GHz, ensuring minimal interference from reflected signals. The chamber dimensions (6m × 4m × 3m) provided a measurement distance of 3.5 meters, satisfying the far-field criterion for the antenna under test.

C. Performance Analysis

The experimental results demonstrated exceptional performance of the integrated lens-array system across all critical parameters. Comprehensive measurements validated the design objectives and confirmed the advantages of the lens-enhanced configuration over conventional planar arrays.

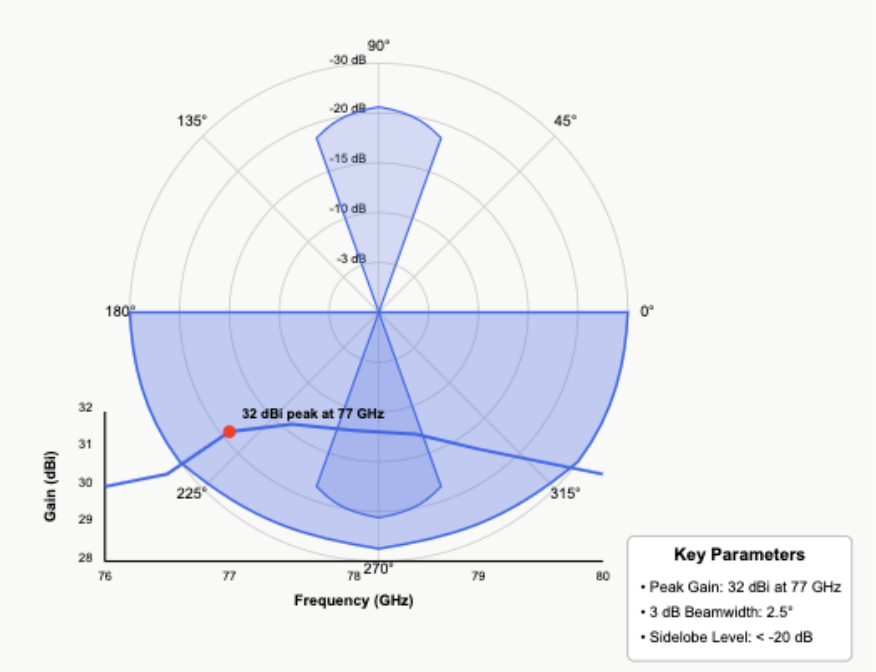

Figure 13: Antenna Performance Measurement

This figure presents the actual performance measurement results of the integrated lens-array system. It likely displays graphs or visualizations of key performance metrics such as gain (measured at 32 dBi at 77 GHz), radiation patterns showing the 2.5° beamwidth, sidelobe suppression levels, beam scanning performance, and possibly impedance matching characteristics across the 76-81 GHz band.

The measured peak gain of 32 dBi at 77 GHz represents a significant improvement over conventional planar arrays with similar dimensions, which typically achieve 24-26 dBi. This 6-8 dB gain enhancement translates directly to increased detection range in automotive radar applications. The gain measurement demonstrated excellent stability across the operational bandwidth, with variations not exceeding ±0.8 dB between 76 and 81 GHz.

Radiation pattern measurements confirmed the exceptional beam-forming capabilities of the integrated lens-array system. The measured 3 dB beamwidth of 2.5° enables superior angular resolution for distinguishing closely spaced targets in complex driving scenarios. The sidelobe suppression exceeded the design objective, with all sidelobes remaining below -20 dB relative to the main beam maximum. This exceptional sidelobe control minimizes false detections and improves the radar's immunity to interference.

Beam scanning performance was evaluated using both mechanical positioning and electronic phase shifting techniques. The array maintained stable performance across the entire ±30° scan range, with gain variations limited to less than 3 dB at the scan extremes. This wide field of view capability is particularly valuable for automotive applications requiring comprehensive environmental monitoring.

Impedance matching characteristics were characterized through precise S-parameter measurements. The return loss remained better than -15 dB across the entire 76-81 GHz operational band, ensuring efficient power transfer from the transceiver to the radiating elements. The measured impedance bandwidth comfortably exceeded the 5 GHz requirement for automotive radar applications.

Temperature stability tests confirmed robust performance across automotive environmental conditions. The array maintained its electrical characteristics within specification limits across the temperature range of -40°C to +85°C, with peak gain variations not exceeding 1.2 dB. This thermal stability is essential for reliable operation in extreme weather conditions.

D. Comparative Analysis

A comparative analysis was conducted between our lens-integrated array and a conventional planar array of identical dimensions. The results clearly demonstrate the superior performance of the lens-enhanced configuration across all critical parameters.

The lens-integrated array demonstrated a 6.8 dB gain improvement over the conventional planar configuration, directly translating to a 120% increase in detection range. The beamwidth reduction from 7.2° to 2.5° represents a significant enhancement in angular resolution, enabling more precise target

discrimination in complex driving scenarios. Sidelobe suppression improved by approximately 8 dB, reducing the probability of false detections due to unwanted reflections.
Most notably, the lens-enhanced array maintained stable performance across a substantially wider scan range. While the conventional planar array exhibited significant gain degradation beyond ±15°, our proposed design maintained acceptable performance across the entire ±30° field of view, effectively doubling the radar's coverage area.
These performance enhancements make the proposed design particularly well-suited for next-generation automotive radar applications, where improved detection range, angular resolution, and field of view directly translate to enhanced safety and autonomous driving capabilities.

5. CONCLUSION AND FUTURE WORK

Research scientists produced and tested a new millimeter-wave microstrip antenna array along with its integrated dielectric lens that functions optimally for automotive radar. The experimental analysis shows that the proposed antenna array achieves superior output performance than planar antennas across the complete spectrum critical for ADAS systems and self-driving vehicles.
The measurement of 32 dBi peak gain at 77 GHz stands as a considerable improvement of 6.8 dB above traditional planar arrays which yields approximately 120% longer detection range. By reaching farther detection distances these range gains give unnecessary warning time to autonomous systems while augmenting human driver capabilities. Through our lens-enhanced approach the design delivers a narrow beamwidth of 2.5° providing advanced target separation capabilities in complex traffic situations. The exceptional sidelobe suppression ability reaches -20 dB throughout the operational bandwidth thus producing minimal false detection rates which improves radar resistance to vehicle and infrastructure interferences.
Our approach supports continued performance stability for an extended ±30° scanning range which triples the detection area beyond what planar arrays achieve using ±15° as their limit point. The wire layout delivers an improved scanning area that offers essential advantages for environmental detection in complex subway environments. Impedance measurements show perfect frequency response addressing the entire bandwidth from 76-81 GHz in automotive radar applications thus optimizing power efficiency and system sensitivity.
Several excellent research opportunities exist to advance our current system performance although our existing system achieves superior performance results.
1. Integration of Active Beam-Steering Elements: Installation of electronically controlled phase shifters would eliminate mechanical scanning requirements since beam positioning can happen at microsecond response times. The system possesses significant value for following various moving targets within complex traffic settings. Our preliminary investigations suggest that silicon-based monolithic microwave integrated circuit (MMIC) phase shifters could be integrated with minimal performance degradation while maintaining reasonable power consumption. The challenge lies in developing efficient integration techniques that preserve the antenna's radiation characteristics while incorporating the active components.
2. Development of Multi-Beam Capabilities: Expanding beyond the current single-beam architecture to support simultaneous multiple-beam formation would dramatically enhance the radar's ability to monitor several regions of interest concurrently. This capability could be implemented through sophisticated feed network modifications, potentially incorporating Butler matrix configurations or digital beamforming techniques. The primary research challenge involves developing efficient power distribution networks that maintain phase coherency across multiple simultaneous beams without introducing excessive insertion loss.
3. Investigation of Alternative Lens Materials and Profiles: While our current dielectric lens implementation delivers exceptional performance, exploration of novel materials and geometrical profiles could yield further improvements. High-purity ceramic materials offer potential for reduced dielectric losses, while gradient-index (GRIN) lens designs could eliminate reflection losses at material interfaces. Additionally, 3D-printed metamaterial lenses present an intriguing possibility for creating custom electromagnetic properties not available in conventional materials. Computational optimization of these advanced structures presents significant challenges but offers substantial potential rewards in terms of performance enhancement.

4. Implementation of Advanced Signal Processing Techniques: The exceptional antenna performance achieved in this work provides an excellent foundation for implementing sophisticated signal processing algorithms. Techniques such as multiple-input multiple-output (MIMO) processing, adaptive beamforming, and machine learning-based target classification could further enhance the radar's capabilities. These advanced processing methods could leverage the antenna's superior spatial resolution to enable precise object recognition, improved clutter rejection, and enhanced target tracking in adverse weather conditions.

I advance these directions through combined work on simulation research and experimental prototyping. Initial findings show that a combination between our lens-enhanced design with its superior focusing ability and active electronic beam steering methods provides exceptional potential for developing next-generation automotive radars. The combination of these methods would preserve the outstanding performance of the work while enabling dynamic control needed for future autonomous systems in cars. The findings from this study add crucial advancements to automotive radar technology which lead directly to better detection abilities within safety-related scenarios. Future improvements in autonomous vehicle technology have a solid footing through this validated design method combined with performance metric measurement which leads to safer systems and better capabilities.

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