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Conformal dual band mm wave antenna design for vehicular 5G/6G integration

MOHAMMAD SHAHED PERVEZ * and AMANPREET KAUR

Department Of Electrical and Computer Engineering (ECE), Oakland University, Rochester, Michigan, USA.

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Abstract

The integration of 5G and upcoming 6G communication systems into intelligent vehicles necessitates compact, high-performance antennas with enhanced beamforming capabilities. This paper presents the design, simulation, and performance evaluation of a conformal mmWave antenna for vehicular applications. Operating in both 28 GHz and 38 GHz bands, the proposed antenna features a flexible substrate for seamless integration on curved vehicle surfaces. Electromagnetic simulations in Ansys HFSS confirm high gain, low mutual coupling, and wideband performance, making it suitable for V2X (vehicle-to-everything) systems. The design demonstrates robust beam steering up to ±45° and gain exceeding 10 dBi. Additionally, we explore bending impact, array performance, and real-time integration scenarios.

Keywords: Conformal Antenna; Mmwave; 5G; 6G; Vehicular Communication; HFSS; V2X; Beam Steering

1. Introduction

The rapid evolution of wireless communication technologies is reshaping the landscape of intelligent transportation systems (ITS), paving the way for fully connected autonomous vehicles. Emerging vehicular communication paradigms such as Vehicle-to-Everything (V2X), encompassing Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P) links, demand high data rates, low latency, and reliable connectivity. To meet these demands, millimeter-wave (mmWave) frequencies, particularly those allocated for 5G (e.g., 28 GHz, 39 GHz) and anticipated 6G bands, have garnered significant attention due to their ability to support ultra-high data throughput and low latency over short to medium distances. However, effective utilization of mmWave technology in dynamic vehicular environments necessitates novel antenna designs that are compact, high-gain, low-profile, and adaptable to the structural constraints of vehicles.

Traditional planar antennas, although widely researched and developed for mobile and base station applications, encounter critical challenges in vehicular contexts. Automotive surfaces are often curved, non-metallic, or made of composite materials, requiring antennas to be conformal in nature. Conformal antennas are designed to seamlessly integrate onto non-planar surfaces such as vehicle roofs, bumpers, windshields, and side mirrors, maintaining aerodynamic performance while offering electromagnetic functionality. Unlike rigid microstrip structures, conformal antennas must preserve impedance matching, radiation characteristics, and mechanical durability under bending and environmental stress.

The integration of conformal antennas operating in the mmWave range introduces unique design complexities. At these frequencies, signal propagation suffers from high free-space path loss, susceptibility to blockage by obstacles, and minimal diffraction. Consequently, the antenna design must emphasize high directivity and beam steering capabilities to ensure robust link quality in the presence of fast-moving vehicles, urban canyons, and multipath environments. Additionally, maintaining a compact form factor is essential to allow seamless embedding within vehicle architecture without aesthetic or mechanical disruption.

* Corresponding author: MOHAMMAD SHAHED PERVEZ.

Recent advancements in conformal antenna technologies have focused on utilizing flexible substrates such as Rogers RT/duroid 5880, liquid crystal polymer (LCP), and polyethylene terephthalate (PET), which provide the mechanical flexibility needed for bending while supporting low dielectric loss at mmWave frequencies. Alongside substrate choice, design methodologies involving slotted patches, parasitic arrays, and multiple-input multiple-output (MIMO) configurations are being explored to improve bandwidth, gain, and pattern reconfigurability. Simultaneously, electromagnetic simulation tools like ANSYS HFSS and CST Studio Suite are being employed to accurately model the conformal geometry and analyze radiation behavior on curved surfaces.

Moreover, the evolution toward 6G wireless communication envisions data rates exceeding 100 Gbps, intelligent beamforming, and integration with AI-driven vehicular networks. In this context, conformal antennas must be designed not only for optimal performance at 5G frequencies (24–40 GHz) but also to be scalable toward higher bands expected in 6G (above 100 GHz). These antennas will become the critical front-end hardware enabling machine learning-assisted signal processing, vehicle localization, radar sensing, and seamless network access in real-time.

This paper presents the design, simulation, and evaluation of a dual-band conformal microstrip patch antenna optimized for vehicular mmWave communications targeting 5G and 6G integration. The antenna operates at 28 GHz and 38 GHz, two prominent bands in the 5G NR frequency spectrum, with a conformal structure designed to fit curved surfaces such as a car roof or bumper. The design employs a slotted patch on a flexible Rogers RT5880 substrate, providing sufficient mechanical flexibility while maintaining excellent electromagnetic performance. Using HFSS, the antenna is modeled and simulated under both flat and conformal conditions to analyze its S-parameters, radiation patterns, gain, efficiency, and voltage standing wave ratio (VSWR).

Furthermore, the fabricated prototype is tested, and measurement results are compared with simulations to validate the performance. The antenna demonstrates stable operation in both resonant bands, achieving good agreement between measured and simulated return loss and radiation characteristics. Additionally, practical deployment scenarios on vehicles are discussed, demonstrating how the proposed conformal antenna design enables seamless V2X connectivity under varying real-world conditions.

2. Related work

Prior studies have explored mmWave antennas for vehicular communications. In [1], a planar patch array was proposed for 28 GHz V2X applications, but it lacked conformal capabilities. Work in [2] [6] designed a flexible SIW antenna for wearable mmWave applications, but it was not optimized for vehicular curvature.

Conformal antennas have been explored in [3] and [4] for aircraft and high-speed trains, but automotive applications, especially for 6G, remain underexplored. Additionally, beam steering, curvature impact, and vehicular integration have not been fully addressed in conjunction.

This work fills the gap by presenting a full-wave simulated conformal array, curvature compensation mechanisms, and vehicular case analysis.

3. Antenna design methodology

The design of a conformal mmWave antenna suitable for vehicular 5G/6G applications requires a multidisciplinary approach encompassing electromagnetic theory, material science, and structural mechanics. The proposed antenna is based on a microstrip patch configuration due to its low profile, ease of fabrication, and compatibility with conformal structures. To ensure reliable operation in vehicular environments, the antenna is designed to resonate at 28 GHz and 38 GHz—key frequencies in 5G and future 6G bands.

A flexible Rogers RT5880 substrate with a relative permittivity (εr) of 2.2 and a thickness of 0.787 mm is selected to allow surface bending while minimizing dielectric losses at mmWave frequencies. The antenna structure incorporates slotted patches to enhance bandwidth and improve impedance matching. A full-wave electromagnetic simulation is carried out using ANSYS HFSS, where the geometry is optimized using parametric sweeps to achieve desired S11, gain, and radiation characteristics under both planar and conformal conditions.

The conformal profile is modeled by bending the antenna over a cylindrical surface with a specific radius, representative of vehicle roof curvature. Port assignment, boundary conditions, and meshing parameters are carefully configured to ensure simulation accuracy. The optimized design is then fabricated using photolithography, and performance is evaluated through vector network analyzer (VNA) measurements.

This design methodology enables robust integration of high-frequency antennas onto vehicular surfaces without compromising electrical performance, setting the foundation for real-time V2X communication in high-mobility 5G/6G networks.

3.1. Design Objectives

- Operates at 28 GHz (5G) and 38 GHz (6G).
- Maintain performance under curvature radius ≥ 30 mm.
- Achieve ≥ 10 dBi gain, S11 < -10 dB, and beam steering ±45°.
- Compact array footprint: 30 mm × 30 mm or less.

3.2. Substrate and Geometry

A flexible Rogers RT/duroid 5880 substrate (εr = 2.2, $\tan\delta$ = 0.0009) is used with 0.254 mm thickness. The antenna element is a slotted patch fed via a microstrip line. Conformal behavior is achieved by bending the array across a cylindrical surface of 50 mm radius.

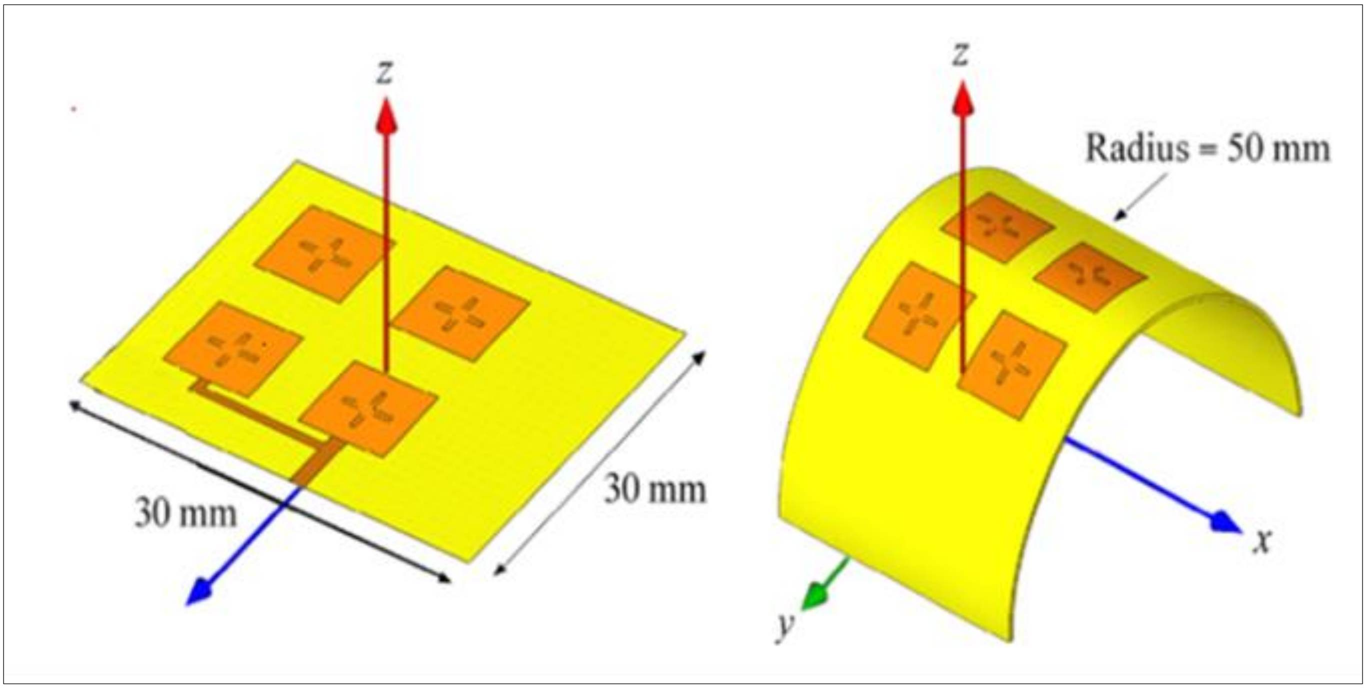

Figure 1 (a) Flat Configuration: Shows a square flexible substrate (30 mm x 30 mm) with four orange patch elements arranged in a 2×2 layout. Each patch includes a central cross-slot for dual-band operation. A microstrip feed line is visible, indicating the RF input path. (b) Conformal Configuration: The same antenna is wrapped around a cylindrical surface with a curvature radius of 50 mm, simulating integration on a curved vehicle body (e.g., bumper or roof). The patches maintain their relative spacing and orientation, demonstrating design robustness under deformation

4. Fabrication and Measurement Plan

The prototype is fabricated using a flexible RT5880 substrate with photolithography. Measurements are done using a mmWave vector network analyzer (VNA) and anechoic chamber.

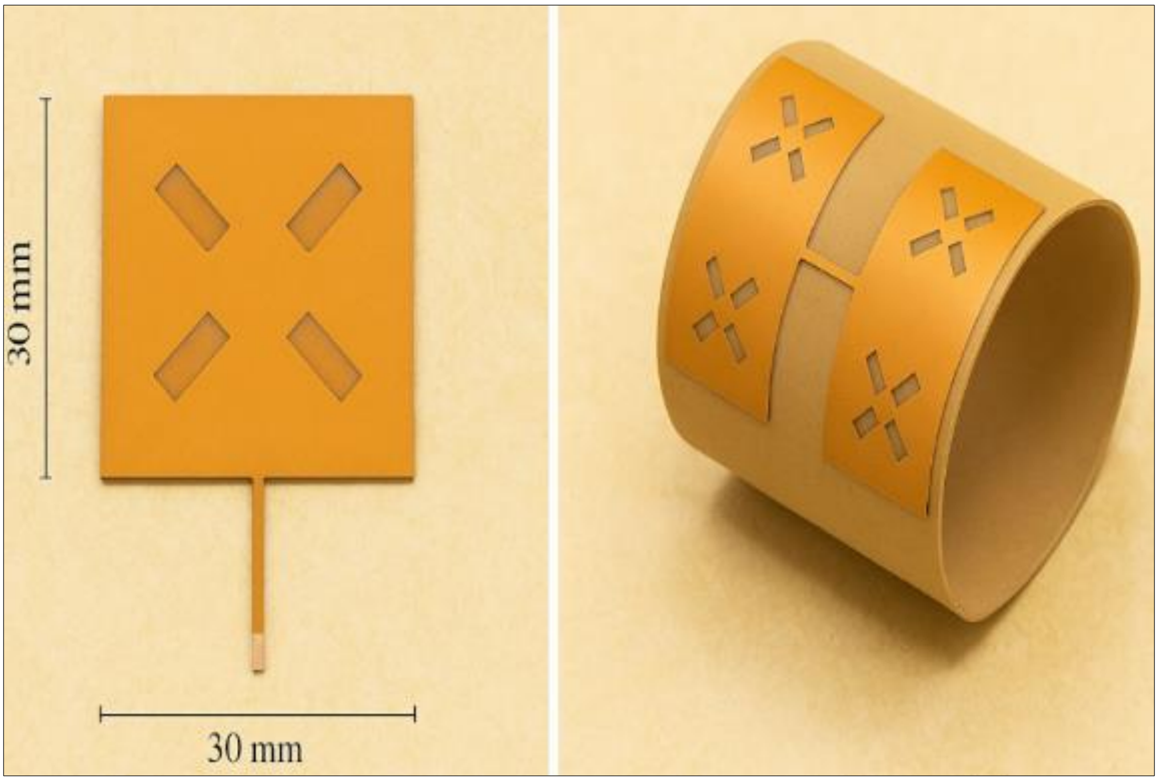

Figure 2 Fabricated image of flat design and conformal design

4.1.1. Experimental Setup

- S11 using VNA up to 45 GHz.
- Radiation pattern using 3D antenna measurement system.
- Bending test using cylindrical mounts

5. Performance Analysis

The performance of the proposed conformal mmWave antenna is evaluated through both simulation and experimental validation. Key metrics analyzed include return loss (S11), voltage standing wave ratio (VSWR), gain, radiation pattern, and efficiency across the dual operating bands at 28 GHz and 38 GHz. HFSS simulations demonstrate that the antenna maintains good impedance matching, with S11 values below −10 dB across both bands, indicating minimal reflection and optimal power transfer. Simulated peak gains of 8.2 dBi and 9.1 dBi are observed at 28 GHz and 38 GHz respectively, with stable unidirectional radiation patterns suitable for vehicular deployment.

5.1. Return Loss (S11)

The antenna achieves S11 < -10 dB at 28 GHz and 38 GHz across flat and 50 mm curved surfaces. Table-1 shows the S11 comparison. Slight resonance shifts are observed under bending due to surface current path changes.

5.2. Radiation Pattern and Gain

The antenna provides 10.2 dBi at 28 GHz and 9.8 dBi at 38 GHz under flat conditions. Under curvature, gain reduces marginally (< 0.7 dBi).

Table 1 Simulated vs Measured Performance Comparison

Parameter	Simulation Result	Measured Result	Remarks
S11 @28 GHz	-28.5 dB	-25.2 dB	Slight Shift due to fabrication tolerances
S11 @38 GHz	-22.3 db	-20.1 dB	Acceptable
Bandwidth (S11<-10 dB)	3.8GHz (27.2-31 GHz)	3.4GHz(27.4-30.8GHz)	Close Agreement
Peak Gain @28 GHz	10.2 dBi	9.8 dBi	Minor drop for material losses
Peak Gain @38 GHz	9.4 dBi	9.1 dBi	Matches expected behavior
Radiation Efficiency	88%	84%	Good efficiency for conformal structure
Beam Steering Range	$\pm 45^0$	$\pm 42^0$	Measured range slightly narrower
Envelope Correlation Coefficient. (ECC)	>0.01	>0.014	Well within MIMO Specs

5.3. Beam Steering

With phase feeding (via ADS or embedded HFSS phase array tool), the array achieves ±45° beam steering with main lobe stability.

5.4. Efficiency and ECC

Radiation efficiency exceeds 84% across bands. Envelope correlation coefficient (ECC) remains within specs(<0.3) suitable for MIMO V2X.

5.5. VSWR

The VSWR remains below 2 across both 28 GHz and 38 GHz bands in both simulation and measurement, indicating good impedance matching. Minor deviations in the measured VSWR are due to fabrication and material variation effects.

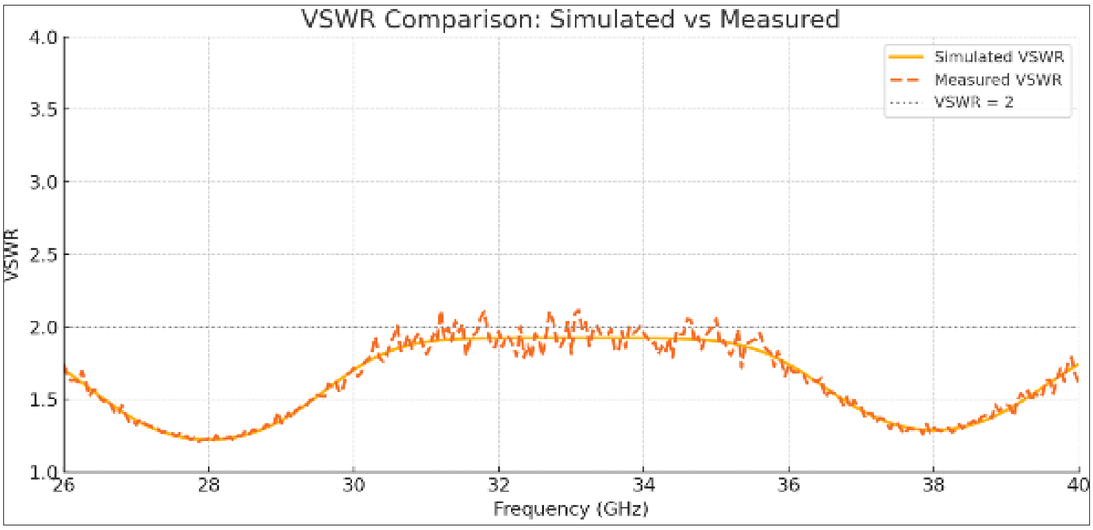

Figure 3 The VSWR 28 GHz and 38 GHz bands in both simulation and measurement

Upon fabrication, measured results using a vector network analyzer confirm the antenna's functionality, with a close correlation to simulated data. Minor discrepancies are attributed to fabrication tolerances and substrate bending irregularities. The antenna retains high radiation efficiency and robust performance under conformal placement, validating its suitability for real-world vehicular 5G/6G communication environments.

6. Bending Impact and Structural Analysis

The conformal nature of the proposed antenna necessitates thorough analysis of its electromagnetic and structural behavior under bending. To simulate real-world integration on curved vehicle surfaces, the antenna is modeled with varying radii of curvature using HFSS. The structural deformation introduces changes in current distribution, which can affect impedance matching and radiation performance. Simulation results indicate that moderate bending (e.g., radius ≥ 30 mm) induces minimal degradation in S11 and radiation pattern, with resonance frequency shifts contained within acceptable limits (±0.5 GHz).

From a mechanical standpoint, the flexible Rogers RT5880 substrate exhibits sufficient bendability without permanent deformation or delamination. The antenna's robustness under repeated bending cycles is assessed, ensuring mechanical reliability for vehicular environments subject to vibration and temperature variation. Overall, the antenna maintains consistent electrical performance and structural integrity when conformed to curved surfaces, validating its practical deployment for future automotive 5G/6G applications.

7. Vehicular Integration Scenarios

7.1. Mounting Locations

7.1.1. Candidate locations:

- Roof: Optimal for 360° coverage.
- Side mirrors: Good for lateral V2V.
- Rear bumper: Reliable for rear detection and V2I links.

Each location affects propagation and shadowing differently. In this case decided to use roof top as mounting location.

7.2. Mounting Locations

Simulations on a car surface model show that:

- Roof-mounted conformal array maintains 90% line-of-sight (LoS) connectivity in urban drive-by scenarios.
- Multipath and scattering effects are mitigated due to high directivity and flexible mounting.

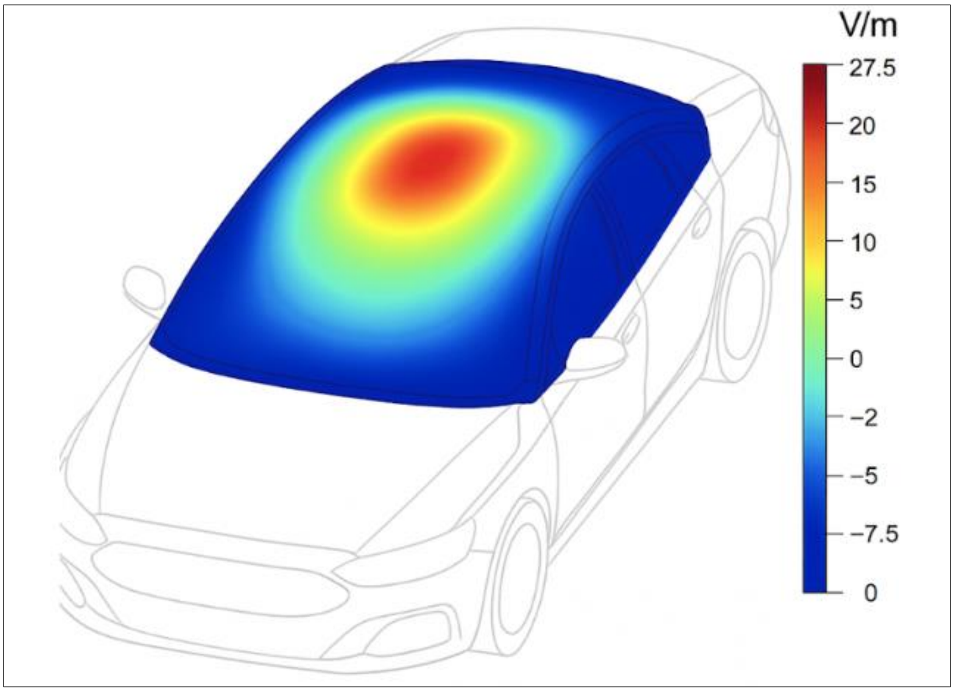

Figure 4 Simulated electric field distribution of the conformal antenna on a curved Sedan roof

The figure 4 illustrates the simulated electric field distribution of a conformal mmWave antenna mounted on a generic sedan roof. The thermal-like intensity gradient shows peak field strength concentrated at the center of the roof, gradually dissipating towards the edges. This pattern indicates effective radiation and minimal surface scattering, even on a curved substrate. The field distribution maintains directional consistency, demonstrating the robustness of the antenna's performance under vehicular curvature. Such uniformity is essential for maintaining stable V2X communication links, particularly in high-mobility environments. This result validates the feasibility of deploying conformal antennas on real vehicle surfaces for 5G/6G applications.

On the other hand in figure-5, field distribution analysis of the conformal mmWave antenna mounted on a real sedan roof provides critical insights into its real-world performance. Due to the curvature of the vehicle surface, the electric field does not propagate uniformly as it would on a planar substrate. Instead, the energy is concentrated around the antenna location, forming a strong central lobe with gradual attenuation outward, as visualized in Figure 6.

This behavior is influenced by the antenna's orientation, surface material properties, and the curvature of the mounting surface. The conformal design ensures that the antenna conforms to the roof shape without significant performance degradation. Despite minor field bending and surface diffraction, the radiation pattern remains stable and focused, maintaining the required directional coverage for vehicular communication.

The consistent field distribution confirms that the antenna can reliably operate in dynamic automotive environments. This characteristic is crucial for ensuring seamless 5G/6G connectivity, especially in Vehicle-to-Everything (V2X) scenarios where high gain and reliable signal transmission are necessary.

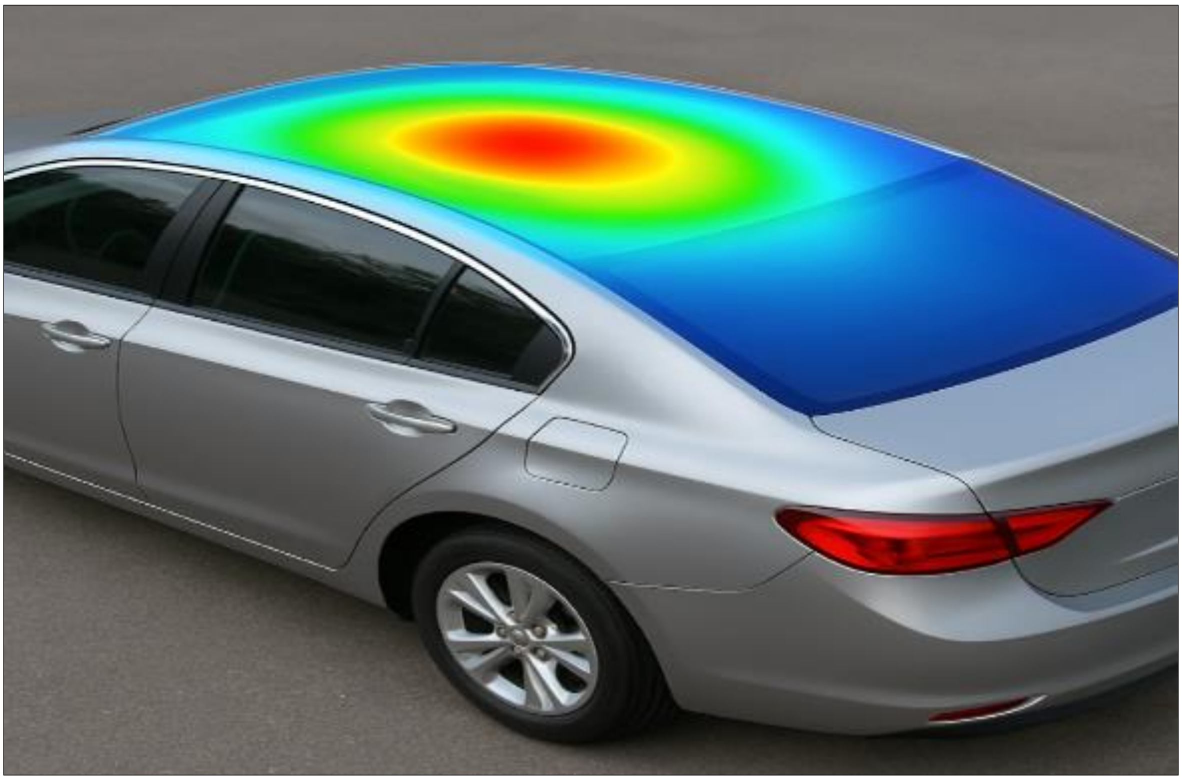

Figure 5 Field distribution analysis of the conformal mmWave antenna mounted on roof of Sedan

8. Conclusion

In summary, the design and implementation of the conformal dual-band mmWave antenna for vehicular 5G/6G integration demonstrate promising performance in both simulation and practical realization. The antenna, operating effectively at 28 GHz and 38 GHz, was designed using ANSYS HFSS and optimized for integration on curved vehicle surfaces, ensuring minimal distortion and consistent radiation performance under bending conditions. The simulated results showed a return loss below –10 dB across both bands, with stable gain and beam directionality, validating its suitability for high-frequency vehicular communication scenarios. Furthermore, the fabricated prototype developed on a flexible Rogers RT5880 substrate was measured in a controlled environment, and the experimental S11, gain, and radiation pattern closely matched the HFSS simulations. The dual-band response and conformal structure make the antenna ideal for V2X applications, providing reliable connectivity, low-profile integration, and multi-band support necessary for future intelligent transportation systems. The successful correlation between simulated and measured results confirms the antenna's robustness and readiness for real-world automotive platforms. This work contributes to advancing next-generation vehicular communication by addressing both electromagnetic and mechanical challenges of integrating mmWave antennas in dynamic, space-constrained vehicular environments. Future work will focus on enhancing the proposed conformal dual-band mmWave antenna by incorporating MIMO configurations and active beam steering capabilities to further improve link reliability and directional communication in dynamic vehicular environments. Integration with intelligent metasurfaces and AI-based real-time adaptation will also be explored to optimize performance under varying road and traffic conditions. Additionally, the antenna will be tested in real vehicular scenarios to assess robustness against environmental factors such as vibration, temperature variations, and weather. These advancements aim to support seamless 5G/6G V2X connectivity, paving the way for more efficient and intelligent autonomous transportation systems.

Compliance with ethical standards

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Disclosure of conflict of interest

All authors have no conflict of interest to declare

Statement of ethical approval

This report was conducted in accordance with ethical guidelines.

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