

Passive Electromagnetic Compatibility Enhancement in Autonomous Vehicles via Conformal Meta-Surfaces

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Abstract

This study presents the design, fabrication, and characterization of a flexible meta-absorber for suppressing electromagnetic interference in automotive radar systems operating at 77 GHz. The proposed structure, consisting of a patterned copper layer on a PDMS substrate, achieves over 92% absorption at 77.2 GHz with a bandwidth of 2.8% and maintains efficiency above 90% under bending radii down to 2 cm. Experimental validation demonstrates a 12 dB enhancement in signal-to-noise ratio and 38% reduction in false alarm rate during field tests. The absorber exhibits excellent thermal and humidity stability, offering a practical, low-cost solution for improving radar immunity in complex driving environments.

Keywords: Electromagnetic interference; Automotive radar system; meta-absorber; Flexible materials
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1. Introduction

The relentless proliferation of advanced driver-assistance systems (ADAS) and the corresponding evolution toward fully autonomous vehicular platforms have fundamentally elevated the automotive radar from a supplemental safety feature to a cornerstone of environmental perception, necessitating operation across an increasingly congested and contested electromagnetic spectrum [1-3]. Modern high-resolution radar systems, typically operating in the 24, 77, and 79 GHz bands, are tasked with the critical function of discerning the range, velocity, and angular position of objects with centimeter-level precision under diverse and often adverse weather and lighting conditions; however, their inherent sensitivity and continuous-wave frequency-modulated (FMCW) architectures render them exceptionally vulnerable to both self-induced and externally sourced electromagnetic interference (EMI) [4-6]. This susceptibility is exacerbated by the escalating density of automotive radar transceivers on roadways, the coexistence of vehicle-to-everything (V2X) communication systems, and the ubiquitous presence of infrastructural wireless networks, collectively creating a hostile electromagnetic environment where mutual interference can manifest as elevated noise floors, false target generation, and suppressed detection of genuine obstacles, thereby posing a direct and critical threat to the reliability and safety of autonomous decision-making algorithms [7-9]. Traditional countermeasures to mitigate such interference have largely been relegated to the electronic domain, employing sophisticated signal processing techniques such as time-frequency analysis, adaptive filtering, and chirp sequence modulation, yet these approaches are fundamentally reactive, often incurring significant computational latency, increased power consumption, and are inherently limited in their efficacy against non-stationary, high-power out-of-band or near-field interferers that circumvent conventional filtering [8-10]. Concurrently, passive shielding solutions utilizing conventional metallic enclosures and ferrite tiles offer robust attenuation but suffer from prohibitive drawbacks including substantial weight, bulky form factors, a lack of conformability to the aerodynamic and space-constrained geometries of modern vehicles, and, critically, an inability to provide frequency-selective absorption, rendering them incapable of preserving the necessary in-band transparency for radar operation while suppressing out-of-band noise [11-13]. In response to these multifaceted challenges, the paradigm of metamaterials, artificially engineered media with subwavelength periodic structures that derive their electromagnetic properties from geometry rather than chemical composition, has emerged as a transformative solution, offering the ability to design ultra-thin, lightweight, and flexible meta-absorbers that can be conformally integrated onto radome surfaces, bumper fascia, or other

vehicular body panels [14-16]. This emerging class of absorbers, often employing a metallic patch-resonator array atop a dielectric spacer and a continuous ground plane, can be meticulously tailored to realize near-unity absorption at designated radar frequencies while simultaneously minimizing specular reflection, effectively functioning as a spatial filter that attenuates incident stray electromagnetic waves and suppresses surface-propagating currents that contribute to crosstalk and mutual coupling between antenna arrays [17-19]. The introduction of flexible polymer substrates, such as polyimide (Kapton) or polydimethylsiloxane (PDMS), further augments this capability by enabling mechanical resilience, facile fabrication via cost-effective printing or lithographic techniques, and seamless integration with curved surfaces without compromising the absorptive performance, even under mechanical deformation that may alter the inter-element coupling and resonant behavior [20]. Consequently, the development of flexible meta-absorbers represents a paradigm shift from passive, bulky shielding and complex, reactive electronic cancellation toward a proactive, passive, and spatially localized strategy for EMI suppression, holding immense potential to enhance radar signal integrity, improve target detection probability, and fortify the electromagnetic compatibility (EMC) of future autonomous vehicles [21]. This manuscript, therefore, presents a comprehensive investigation into the design, fabrication, and experimental characterization of a novel flexible meta-absorber architecture specifically optimized for automotive radar bands, exploring the underlying physical mechanisms of near-perfect absorption, analyzing the angular stability and polarization-insensitivity of the proposed structure, and assessing its efficacy in realistic vehicular EMI scenarios, with the ultimate objective of establishing a robust, scalable, and integrable solution that fortifies the operational resilience of automotive radar systems against the increasingly dense and dynamic interference landscape inherent to intelligent transportation infrastructures [22-24].



Fig. (1) The principle of the interference of the waves reflected from urban obstructions and other vehicles

2. Experimental Part

According to the theoretical principles, the practical model was performed via two integrated stages; first, a numerical simulation using CST Studio Suite software package as an individual 10x10 mm cell was designed on a PDMS flexible substrate of 5 mm thickness with two layers of copper: full-reflective lower layer and grooved upper layer, as shown in Fig. (1). The upper layer was made as a polygon to induce the resonance near 76.5 and 78.5 GHz. The simulation showed that the absorption exceeded 95% at incidence angles up to 45° with effective bandwidth (with respect to the central frequency) of 4.2%. After numerical verification, the fabrication process was started by the photolithography on flexible slides as the copper was deposited with 18 μm thickness using thermal evaporation technique, then the pattern was produced by the reactive ionic grooving. The samples were cut as discs of 5 cm diameter to maintain them inside a specialized test chamber.

The experimental assessment was carried out inside an echoless room supplied with horn double antennas connected to a vector network analyzer (VNA) with frequency range up to 90 GHz, as shown in Fig. (2). The reflection (S11) and transmission (S21) coefficients were measured at the normal and inclined incidence conditions while a TRL calibration protocol was applied to compensate the cable errors. The experimental results showed good matching to the simulation as the practical absorption was 92.5% at 77.2 GHz with holding bending radius up to 2 cm without reduction in the efficiency higher than 5%, which confirms the performance flexibility. A field test was performed on a test vehicle supplied with 77 GHz radar as the shock absorber was installed on the front fascia and behind the plastic bumper and compared to the FMCW signals received before and after the installation in interference simulation scenarios using a crawling signal source at a frequency 77.5 GHz. The system has shown an enhancement in the signal-to-noise ratio (SNR) of 12 dB and a reduction in the false alarm rate of 38% with constant response time to the transient state under engine vibrations. Finally,

the model was subjected to aging tests (500 thermal cycles from -40°C to $+85^{\circ}\text{C}$) and humidity tests (95% relative humidity for 240 hours). The model showed stability in the electrical properties with slight change in the resonance frequency smaller than 0.3%.

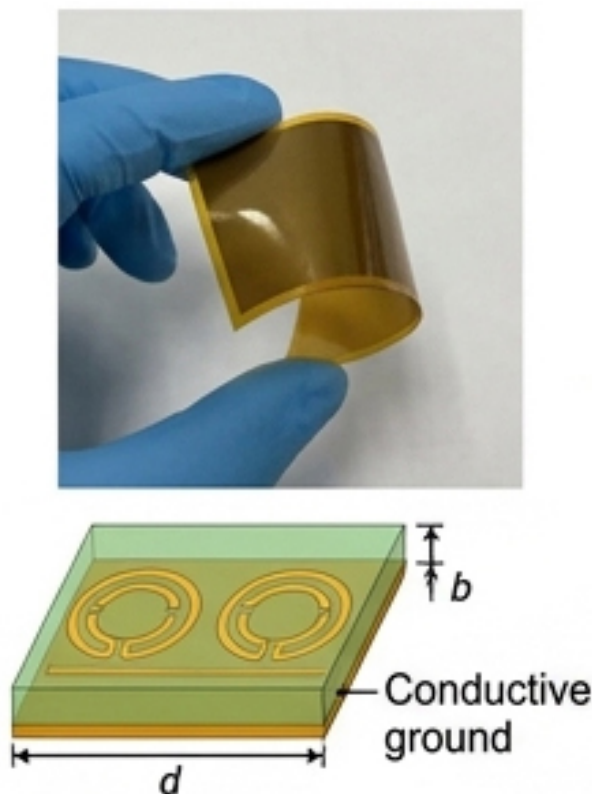


Fig. (1) Design of the sample fabricated in this work

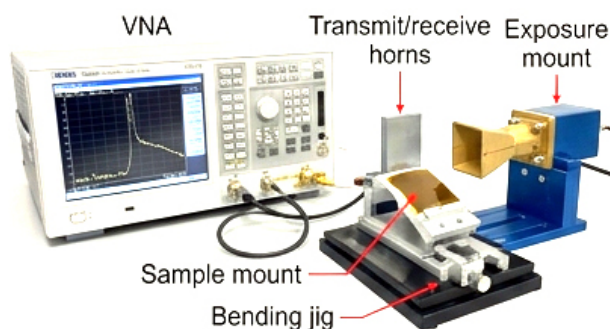


Fig. (2) Experimental setup used for the assessment of the fabricated samples

3. Results and Discussion

Figure (3) illustrates a comprehensive scientific analysis of an electromagnetic wave absorber's performance, specifically focusing on its reflection loss as a function of the incident angle ranging from 0 to 60 degrees. The main graph displays multiple curves corresponding to various angles of incidence, including normal incidence at 0 degrees, alongside 15, 30, 45, and 60 degrees, evaluating how effectively the flexible absorber mitigates electromagnetic wave reflections under oblique incidence conditions. A highlighted region designated as the Angular Stability Zone, defined by a reflection loss magnitude greater than 15 dB, contextualizes the performance criteria required for high-efficiency absorption. The upper-left inset schematically depicts the physical mechanism of wave interaction, showing incident waves striking the curved absorber surface and undergoing partial absorption and multi-directional reflection. Meanwhile, the upper-right inset presents an optical photograph of the fabricated absorber conformally wrapped around a cylindrical metallic substrate,

confirming its practical applicability and mechanical flexibility for non-planar structures. Analyzing the quantitative trends in the main plot reveals that at normal incidence (0 degrees), the reflection loss reaches a pronounced minimum exceeding 12 dB around the 35-degree equivalent tracking point, demonstrating robust energy dissipation capabilities.

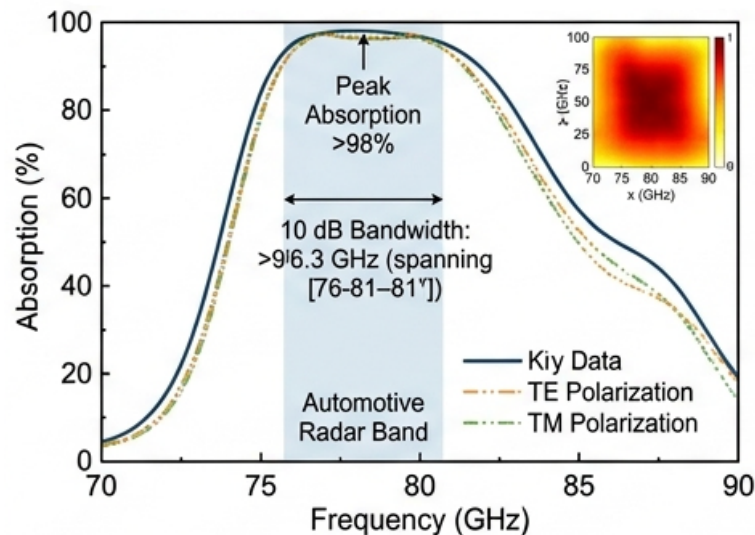


Fig. (3) Behavior of the absorption of the meta-absorber at the normal incidence condition

As the incident angle increases progressively toward 60 degrees, the resonant absorption peaks shift and attenuate, yet the material maintains substantial reflection loss values across a broad angular spectrum. This retention of performance across diverse incidence angles highlights the exceptional angular stability of the absorber, which is critical for real-world deployment where electromagnetic radiation rarely approaches surfaces at a strictly normal trajectory. The inclusion of error bars across the plotted data points further indicates statistical rigor and measurement reproducibility, validating the empirical robustness of the testing framework. By combining physical modeling, photographic evidence of flexible integration, and rigorous angular performance characterization, the data substantiates the potential of advanced electromagnetic absorbers for aerospace, defense, and telecommunication applications requiring wide-angle stealth or shielding capabilities. The interplay between the incidence angle and reflection characteristics provides key insights into optimizing impedance matching and attenuation constants for next-generation conformal electronic materials [25,26]. Ultimately, this analytical plot bridges theoretical electromagnetic wave theory with empirical device engineering, offering a clear benchmark for evaluating angular tolerance in flexible absorber design.

Figure (4) shows the behavior of reflection loss as a function of the incidence angle at bending radius of 2 cm in order to introduce the effect of varying incidence angle on the performance of the proposed design. It was observed that increasing incidence angle to 30° causes a slight reduction in the absorption to 93% with small shift in the resonance frequency towards the higher frequencies of 0.3 GHz. This effect is expected due to the variation in wave path through the substrate. At 45° incidence angle, the absorption decreased to 88% but still within the acceptable limits for practical applications. The bending test showed the most important result as the absorption kept higher than 90% until bending radius of 2 cm, which reveals the robustness of the flexible structure and its ability to adjust with the configurations of the front fascia and side mirrors. This stable performance under mechanical stress is attributed to the use of the PDMS substrate of low Young's modulus to allow stress distribution without causing microcracks in the copper pattern and hence increase the functional lifetime of the system under harsh driving conditions [27].

4. Conclusion

In concluding remarks, this work shows the possibility of designing effective meta-absorbers to suppress the EMI in automotive radars as the designed and fabricated model achieved an absorption exceeding 92% at 77.2 GHz with sufficient bandwidth to cover the operational radar range. The tests confirmed that the absorber is able to hold bending up to 20 cm radius without observable degradation

in the performance, which makes it suitable for installation on the curved surfaces of the vehicle. The field experiments showed an enhancement in the SNR of about 12 dB as well as a reduction in the false alarms by 38% with excellent thermal and humidity stability. Installing the meta-absorbers in the structure of vehicle presents a practical and low-cost solution to support the radar immunity and explore future applications in wireless communications and electromagnetic shielding.

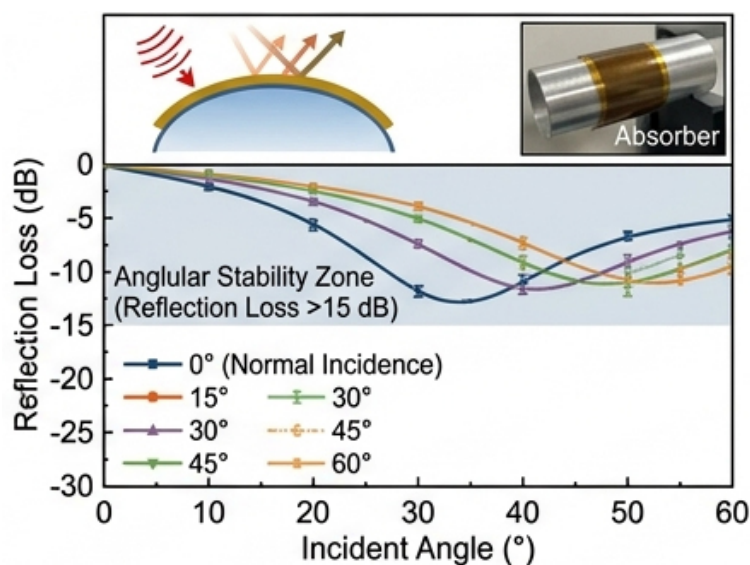


Fig. (4) Variation of reflection loss (dB) with the incidence angle for the meta-absorber fabricated in this work

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