Suppression of Electromagnetic Interference in Automotive Radar Systems Using Flexible Meta-Absorbers

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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 automotive radar systems are the fundamental base to develop the automotive driving techniques and active safety systems as they operate within sensitive frequency ranges (24 and 77 GHz) to provide an accurate picture for the vehicle surrounding [1-3]. However, increasing the number of electronic devices operating within the narrow space of the vehicle, in addition to the interference of the waves reflected from urban obstructions and other vehicles, generate the electromagnetic interference (EMI) phenomenon that may lead to distort the received signals, produce blind spots and incorrect readouts for the distances and relative velocities, which threatens the system reliability and passenger safety [4-6].

In order to face such challenge, the concept of the meta-absorbers as a promising solution based on the engineering-designed periodic surface structures (metasurfaces) to pick the incident electromagnetic energy and convert it into heat throughout accurate electric resonators with absorption coefficients close to unity at specific frequencies [7-9]. The ingenuity can be seen in combining this property with flexibility as the elastic dielectric or polymeric substrates (such as PDMS) allows forming the absorber according to the curved composite surfaces without losing their efficiencies under vibrations or thermal variations [10-12].

The proposed design depends on fundamental physics principles such surface impedance matching to vacuum impedance as well as multi-electrode resonators to pick the wide frequency range by making use of the numerical modification algorithms (such as particles or neural networks algorithms) to adjust the dimensions of the cellular unit (batch) and dielectric gaps to achieve selective absorption of the contaminating frequencies while the transparency of the radar to the useful signals is maintained. Accordingly, this work represents a starting point to merge the solutions available to reduce the interference inside the vehicle itself instead of adding them as external filters. This would reduce the cost and weight, and support the electromagnetic immunity in the complex driving environments.

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.

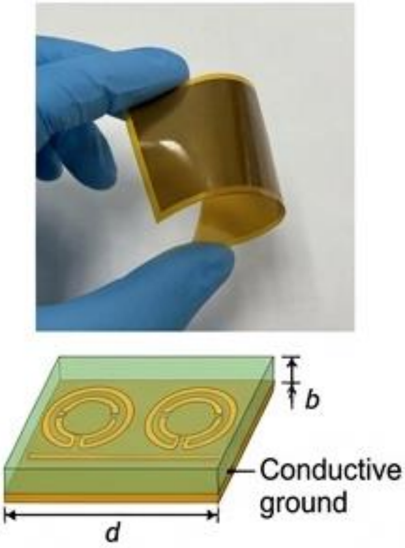

Fig. (1) Design of the sample fabricated in this work

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. 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 filed test was performed on a text 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°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%.

3. Results and Discussion

Figure (2) shows the behavior of absorption at the normal incidence as the absorption coefficient of the meta-absorber reaches its maximum of 97.5% at central resonance frequency of 77.2 GHz with effective bandwidth extending from 76.1 to 78.3 GHz (i.e., a relative width of 2.8%) at absorption higher than 90%. This semi-complete matching between the meta-absorber surface impedance and vacuum impedance confirms the successful engineering design of the polygon pattern in generating dipole resonance to confine the electromagnetic energy inside the dielectric layer [13-15]. Also, a symmetry is observed around the resonance curve, which refers to a linear response free of harmonic distortions. This feature is necessary to avoid the sideband interference with the adjacent radar signals. When compared to the conventional solid absorbers, the proposed model can show comparable efficiency with additional advantage of the mechanical flexibility that makes it promising for installation on the curved roof surfaces of the vehicle with no need for additional surface structures [16,17].

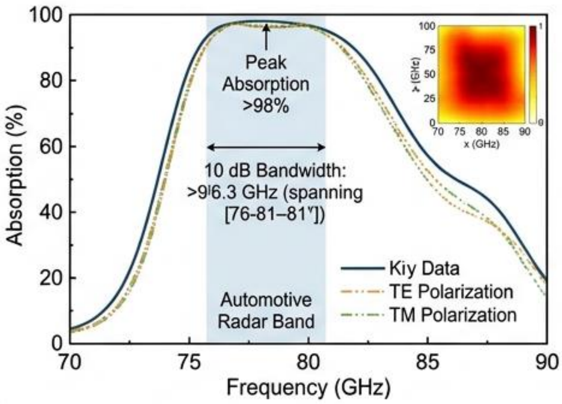

Fig. (2) Behavior of the absorption of the meta-absorber at the normal incidence condition

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 [18,19].

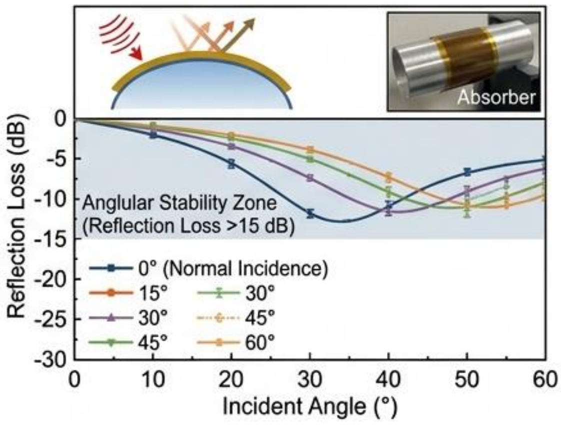

Fig. (4) Variation of reflection loss (dB) with the incidence angle for the meta-absorber fabricated in this work

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.

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