A 45-Degree Rotated Square Ring Frequency Selective Surface Structure for Broadband Matching Automotive Bumper

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Abstract

The reflections from a car's bumper significantly impact the performance of the automotive radar installed in the vehicle. This paper proposes a frequency selective surface (FSS) based matching layer designed on the inner surface of the car's bumper to reduce the reflections from it. The FSS matching layer is made from a periodically repeating 45-degree rotated square ring FSS structure. The proposed FSS structure provides a bandwidth of 5 GHz (76–81 GHz), effectively covering the entire automotive radar band. Further, to analyze the proposed FSS structure in the real-world scenario, a radar antenna is designed and placed behind a painted bumper with and without an FSS matching layer. It is found that the proposed FSS matching layer significantly improves the antenna performance compared to the stand-alone painted bumper.

1. Introduction

Self-driving cars have become a reality, thanks to the rapid advancement in sensor technologies like Radio Detection and Ranging (RADAR), Light Detection and Ranging (LiDAR), optical cameras, and ultrasonic sensors. Compared with the other sensor technologies, the radar sensor is the most efficient all-weather technology for driving automation applications [1]. Besides, radars also have a high range, much smaller form factor, and high-velocity resolution enabling high-precision target localization [2]. Because of these unique traits, radar has become an essential component in advanced driver assistance systems (ADASs) and automated driving systems (ADSs).

The radar sensors are utilized in various automotive applications like blind spot detection, lane change assistance, collision warning, adaptive cruise control, parking aid, pre-crash, etc. Based on the range and field-of-view, radars are classified into three categories: long-range radar (LRR), mid-range radar (MRR), and short-range radar (SRR) [3]. These automotive radar sensors operate in the 76–81 GHz frequency and are mounted behind different parts of the vehicle, such as the painted bumpers (as shown in Fig. 1). However, due to the high permittivity of the paint coatings, matching becomes challenging and, causes strong reflections. These unwanted reflections of radio waves from a car's bumper

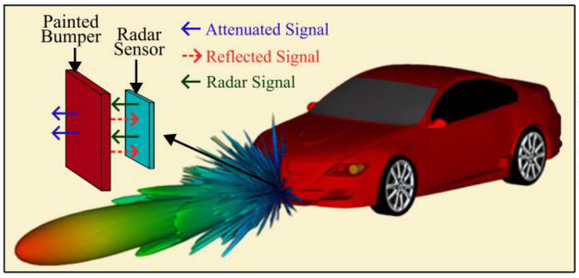

Figure 1. Illustration of an automotive installed radar behind a car's bumper.

significantly impact the performance of the automotive radar. Therefore, to improve the automotive radar performance, the reflections from the painted bumper need to be reduced.

In literature, various solutions have been presented to reduce these reflections, including optimizing the thickness of the bumper [4], and employing matching layers of dielectric material [5], metallics grids [6], rib profiles [7], and frequency selective surface (FSS) [8], [9] on the inner surface of the bumper. However, the works presenting FSS as a solution have disadvantages: 1) none of the presented FSS structures covers the complete automotive radar band, i.e., 76-81 GHz; 2) lacks analysis of performance for different incident angles; and, 3) do not adequately address the impact of the FSS on radar antenna gain. To address these shortcomings, this paper proposes a new type of FSS structure that covers the complete automotive radar band. Additionally, the reflection coefficients of the proposed FSS structures for different incident angles are presented. Furthermore, the impact of the FSS matching layer on the radar antenna placed behind a painted bumper is also analyzed.

2. Proposed FSS Structure

In this paper, the material properties of the bumper are $\varepsilon'_b = 2.86$, $tan\delta_b = 0.02$, with a thickness of 3.01 mm, and the properties of the paint layer are $\varepsilon'_p = 11.47$, $tan\delta_b = 0.022$ with a thickness of 0.12 mm. These material properties are considered a worst-case scenario for a painted bumper assembly as they present a

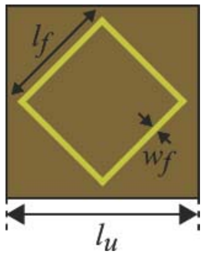

Figure 2. Proposed FSS Structure Unit cell.

challenging matching problem [8]. To address this, a 45-degree rotated square ring FSS structure (illustrated in Fig. 2) is proposed. The substrate material chosen for the FSS structure is 0.254 mm thick Rogers 5880 ($\varepsilon_s' = 2.2$ and $tan\delta_b = 0.0009$) with 0.017 mm copper cladding.

3. Simulations and Results

The simulations are performed using the electromagnetic (EM) simulation software CST Microwave Studio. To demonstrate the bandwidth performance of the FSS matching layer with the painted bumper, the reflection data is generated by exciting a unit cell of dimensions $l_u \times l_u$ using incident plane waves via a Floquet port. Furthermore, all the geometrical parameters of the proposed FSS structure are optimized to operate at the automotive radar band, i.e., 76–81 GHz. The obtained geometrical parameters are l_u = 2.4 mm, l_f = 1.5 mm, and w_f = 0.06 mm. Fig. 3 shows the bandwidth performance of the painted bumper with and without the proposed FSS structure. It can be seen that the bandwidth for the painted bumper assembly is only 3.99 GHz, while for the painted bumper with the proposed FSS structure is 5 GHz (76–81 GHz), covering the entire automotive radar band. Also, the minimum reflection observed for the painted bumper is only –11.53 dB, whereas the best matching is observed in the proposed structure case with a minimum reflection of –31.5 dB. Additionally, a parametric study has been performed to understand the effect of the geometrical parameters of the FSS structure on its bandwidth performance. Fig. 4 shows the parametric study of the geometrical parameters, wherein it can be observed that for the parameter l_u = 2.41 mm or l_f = 1.6 mm, more bandwidth can be achieved. However, in such cases, the reflections will increase. Further, the reflection coefficient of the painted bumper with and without the FSS structure for different incident angles within the automotive radar band is also studied and plotted in Fig. 5. It can be observed from the figure that the reflection coefficient for the proposed structure stays below –10 dB up to θ=25° at 78.5 GHz. However, for the painted bumper case, it stays below –10 dB only up to a maximum of θ=20°.

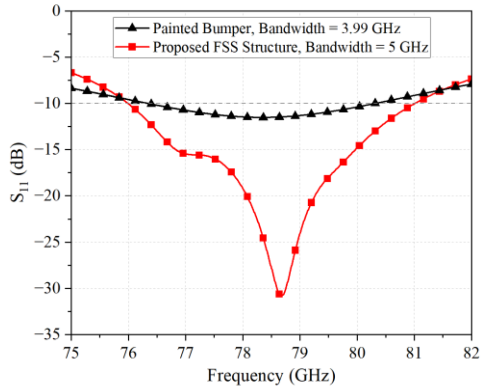

Figure 3. Bandwidth performance of the stand-alone painted bumper and painted bmper with proposed FSS structure.

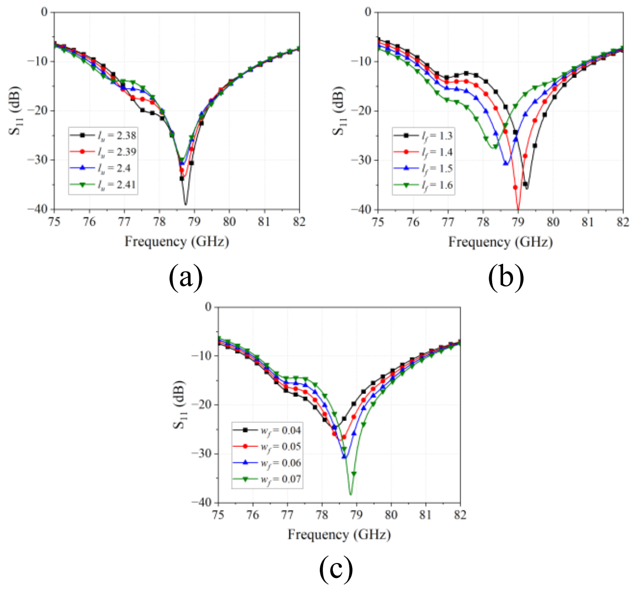

Figure 4. Effect of the geometrical parameters of the proposed FSS structure on its bandwidth performance (a) l_u (b) l_f (c) w_f (all the parameters are in mm).

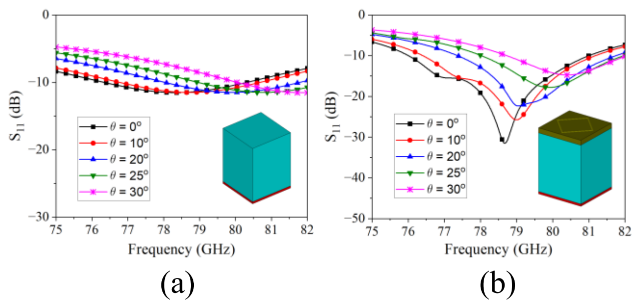

Figure 5. Reflection coefficient for different incident angles (a) Painted bumper, (b) Painted bumper with proposed FSS structure.

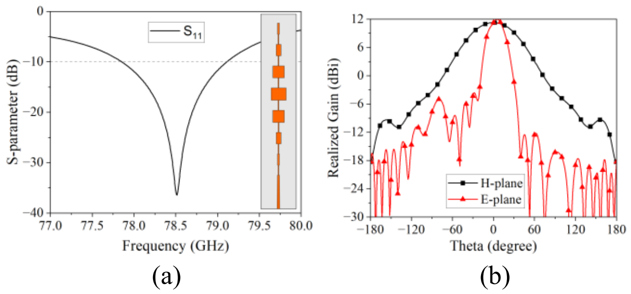

Figure 6. (a) S-parameter of the designed antenna (Inset: geometry of the series-fed radar antenna). (b) Azimuth and elevation patterns of the radar antenna.

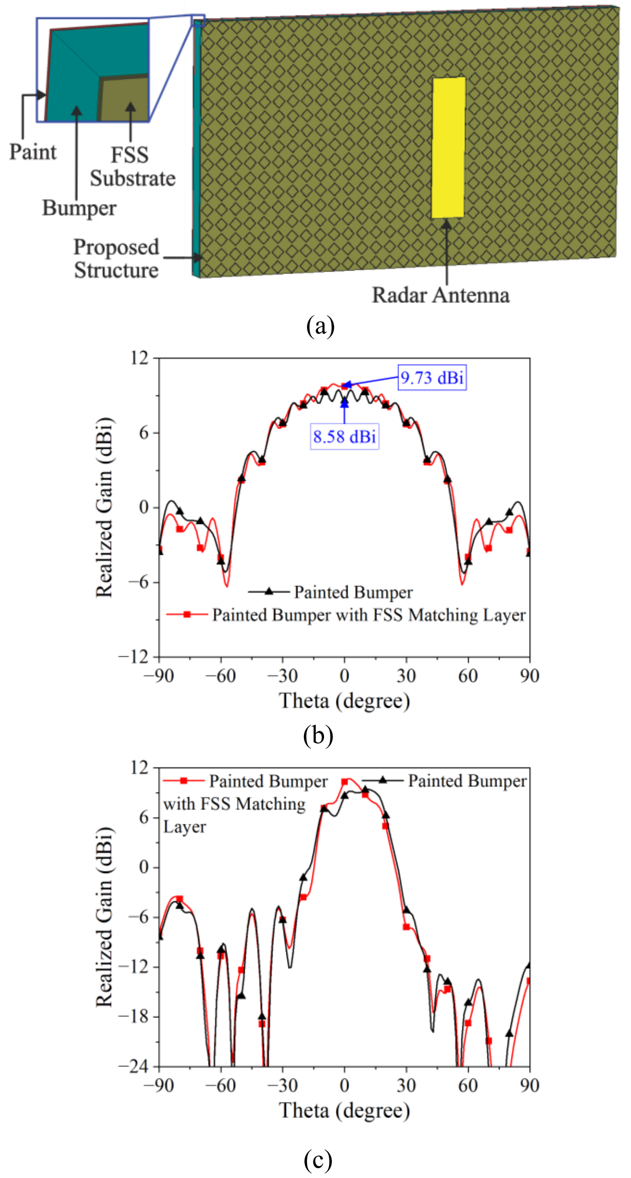

Figure 7. (a) Radar antenna behind the painted bumper with the proposed FSS matching layer. (b) Azimuth gain patterns of the painted bumper with and without FSS matching layer. (c) Elevation gain patterns of the painted bumper with and without FSS matching layer.

To analyze the proposed FSS structure in the real-world scenario, a radar antenna [10] is designed to operate at 78.5 GHz on an RT5800LZ substrate (dielectric constant = 2, loss tangent = 0.0021, thickness = 0.25 mm) and is placed 15 mm behind a 70 mm × 40 mm painted bumper with and without the FSS matching layer. Fig. 6 shows the S-parameter and azimuth and elevation gain patterns of the series-fed radar antenna, along with its geometry. Fig. 7(a) shows the radar antenna behind a painted bumper with the proposed FSS matching layer. Additionally, the simulated azimuth and elevation gain patterns for the painted bumper with and without FSS matching layers are illustrated in Fig. 7(b) and Fig. 7(c), respectively. It is found that the radar antenna gain decreases from 11.26 dBi to 8.58 dBi at θ=0° after placing it behind the painted bumper. However, the gain improves to 9.73 dBi after applying the proposed FSS matching layer on the inner surface of the painted bumper, leading to an improvement in gain of 1.15 dB.

4. Conclusion

This paper proposes an FSS matching layer to reduce reflections and improve transmission from the car's bumper. The FSS matching layer is made from a periodically repeating 45-degree rotated square ring FSS structure. It is found from the floquet port analysis that the—1) The bandwidth for the painted bumper assembly is only 3.99 GHz, while for the painted bumper with the proposed FSS structure is 5 GHz (76–81 GHz), covering the entire automotive radar band. 2) The minimum reflection observed for the painted bumper is only –11.53 dB, whereas the best matching is observed in the proposed FSS structure case with a minimum reflection of –31.5 dB. 3) The bandwidth can be further increased by varying l_f and l_u; however, there is a tradeoff with the minimum reflections. 4) The reflection coefficient for the proposed structure stays below –10 dB up to θ=25° at 78.5 GHz, whereas, for the painted bumper case, it stays below –10 dB only up to a maximum of θ=20°. Furthermore, to analyze the proposed FSS structure in the real-world scenario, a radar antenna is designed and placed behind a painted bumper with and without an FSS matching layer. It is found that the radar antenna gain decreases from 11.26 dBi to 8.58 dBi at θ=0° after placing it behind the painted bumper. However, the gain improves to 9.73 dBi after applying the proposed FSS matching layer on the inner surface of the painted bumper, leading to an improvement in gain of 1.15 dB. It is concluded that the proposed FSS matching layer exhibits better transmission than the stand-alone painted bumper, which is much needed for future-generation autonomous vehicles.

7. References

1. Y. Xiao, F. Norouzian, E. G. Hoare, E. Marchetti, M. Gashinova and M. Cherniakov, "Modeling and Experiment Verification of Transmissivity of Low-THz

Radar Signal Through Vehicle Infrastructure," in *IEEE Sensors Journal*, vol. 20, no. 15, pp. 8483-8496, 1 Aug.1, 2020.

2. K. Ramasubramanian and K. Ramaiah, "Moving from legacy 24 ghz to state-of-the art 77-ghz radar," *ATZelektronics worldwide*, vol. 13, pp. 46-49, 2018.

3. M. Al Henawy and M. Schneider, "Integrated antennas in eWLB packages for 77 GHz and 79 GHz automotive radar sensors," *2011 41st European Microwave Conference*, Manchester, UK, 2011, pp. 1312-1315.

4. N. Modi, B. M. Kumar, J. C. Dash and J. Mukherjee, "Study of the Bumper Thickness and its Placement for Automotive Radar Applications," *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI)*, Denver, CO, USA, 2022, pp. 772-773.

5. N. Modi, B. M. Kumar and J. Mukherjee, "Design of Wideband and Wide-Angle Matching Bumper to Improve Automotive Radar Performance," *in IEEE Sensors Letters*, vol. 8, no. 5, pp. 1-4, May 2024, Art no. 6005304.

6. F. Pfeiffer and E. M. Biebl, "Inductive Compensation of High-Permittivity Coatings on Automobile Long-Range Radar Radomes," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 11, pp. 2627-2632, Nov. 2009.

7. F. Fitzek and R. H. Rasshofer, "Automotive Radome Design - Reflection Reduction of Stratified Media," in *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1076-1079, 2009.

8. F. Fitzek, R. H. Raßhofer and E. M. Biebl, "Broadband matching of high-permittivity coatings with frequency selective surfaces," *2011 German Microwave Conference*, Darmstadt, Germany, 2011, pp. 1-4.

9. Huanlei Chen, Libo Huang and Meisong Tong, "Frequency selective surface in millimeter-wave automotive radar radome applications," *2016 Progress in Electromagnetic Research Symposium (PIERS)*, Shanghai, 2016, pp. 3199-3202.

10. J. C. Dash, D. Sarkar and Y. Antar, "Design of Series-fed Patch Array with Modified Binomial Coefficients for MIMO Radar Application," *2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI)*, Singapore, Singapore, 2021, pp. 1027-1028.