A HYBRID STRUCTURE OF FREQUENCY SELECTIVE SURFACE AND MAGNETIC ABSORBING SALISBURY SCREEN FOR WIDEBAND RADAR CROSS SECTION REDUCTION

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Abstract

This article presents a novel hybrid physical mechanism that combines frequency selective surface (FSS) and Salisbury-type absorption to create a structure that can reduce the radar cross section (RCS) over a wide frequency range. The proposed design integrates a lossy sheet composed of a magnetic absorbing material (MAM) with a traditional Salisbury screen and a FSS of a T-ring resonator. The Salisbury screen effectively absorbs incoming waves when illuminated by a plane wave with normal incidence. Furthermore, the integration of a T-ring resonator generates high-order reflection beams, thereby enabling the selection of absorption band. Simulation results demonstrate that the proposed structure enables tunable RCS reduction between 2 and 18 GHz under various conditions with normal incidence. The combination of broadband absorption mechanism with frequency selective resonance allows to construct a perfect structure both in terms of bandwidth and frequency selection of absorption.

Keywords: *Radar cross section; frequency selective surface; Salisbury screen.*

1. Introduction

Passive radar cross section (RCS) reduction techniques, which rely on the design and use of specialized materials and geometries to reduce the reflected signal, have received significant attention in recent years due to their widespread applications in both military and civilian areas. Numerous approaches have been used for RCS reduction such as shape optimization, Salisbury screens [1, 2], Jaumann absorbers [3], resistive frequency selective surfaces (FSS) [4, 5], and ferrite-based metamaterials [6-8]. For wideband RCS reduction, there have also been a lot of metamaterial absorbers [9, 10]. The alternative RCS reduction method uses curved geometries to divert the reflected wave in directions away from the radar receivers [11, 12]. Recently, some metasurfaces can perform phase modulation, altering the electromagnetic scattering characteristics of objects while minimally manipulating their geometric properties, has garnered substantial attention [13-17]. A group of structures known as random metasurfaces has reportedly achieved backscattering RCS reduction [10, 18]. To effectively control the metasurface's

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scattering, a general metasurface coding technique [19] is proposed and widely used [20-22]. The metasurface, however, can only excite a clear phase difference within a certain range of substrate thickness. This makes it difficult for RCS reduction metasurfaces to thin out and expand their useful frequency range [22].

Furthermore, many real-world RCS reduction solutions involve a combination of various techniques to achieve the desired level of stealth and target signature reduction. The effectiveness of each method depends on the specific application, the operating frequency of the radar system, and the environmental conditions in which the target operates.

Salisbury screen techniques stand as an effective and integral component within the realm of RCS reduction technology. In essence, a typical Salisbury screen is composed of a single continuous resistive sheet positioned a quarter-wavelength above a conducting plate [18]. Though this design is straightforward and easy to fabricate, it generally exhibits a narrow absorption bandwidth. As an improvement to Salisbury screen for a broader absorption bandwidth, Jaumann absorber was later proposed to utilize multiple resistive sheets and spacers, albeit at the expense of increased overall thickness and angle of incidence sensitivity. On the other hand, FSS techniques offer several advantages in RCS reduction such as high-resolution selectivity, lightweight, angle of incidence insensitivity, and customizability. However, FSS techniques also come with some unresolvable disadvantages, namely, complicated fabrication for broader absorbing bandwidth and large-scale surfaces, undesirable effects of mutual interference between multiple FSS structures in proximity and environmental sensitivity. Despite these disadvantages, the improved Salisbury screen as well as FSS remains a valuable RCS reduction technique, especially when they are combined to effectively address their inherent limitations.

In this article, we propose a novel hybrid structure that exploits the advantages of a Salisbury-type magnetic absorber with a FSS, culminating in a significant reduction of RCS across an expansive frequency spectrum. To address the heavyweight and the sensitivity to incident angles inherent in the Salisbury-type magnetic absorber, we introduce a solution in the form of a resistive FSS, featuring conductive and resistive patterns on a single substrate backed by a ground plane. This proposed design enables the realization of broadband absorption while simultaneously maintaining a compact thickness and angle of incidence insensitivity. A FSS is created by integrating the T-ring resonant rings in a plane in a symmetrical arrangement. The overall structure's resonant frequency is chosen by adding or removing resonant rings. The RCS reduction bandwidth of the combined superinterface is significantly extended compared to that of the MAM superinterface, according to the simulated results, which shows an RCS reduction of less than -25 dB over the entire 2 - 18 GHz frequency range. This study illustrates the potential advantages of combining different RCS reduction mechanisms in order to create a thin-thick broadband RCS reduction superstructure that still allows for absorption frequency.

2. Structure design

The configuration proposed for the reduction of RCS is illustrated in Fig. 1. It consists of a FSS and a conventional Salisbury screen. Traditional Salisbury screen in which the lossy sheet is made of a $Mn_{0.5}Zn_{0.5}Fe_2O_4$ and PANI particles radar absorbing materials [23]. The hybrid structure incorporates a pair of printed wideband FSS elements, characterized by an array of co-planar T-ring resonant components, configured in a circular arrangement (Fig. 2). When integrated atop a grounded dielectric substrate, the resulting structure serves as a resonant cavity that effectively absorbs electromagnetic waves at specific resonant frequencies.

The geometrical attributes of an arbitrary T-ring resonator are defined by several parameters: the width of the horizontal base, denoted as d_1, the width of the horizontal ceiling, designated as d_2, the length of the lower vertical bar, indicated as r_1, and the length of the upper vertical bar, denoted as r_2. These parameters collectively govern the geometric configuration of arbitrary T-ring resonators, affording flexibility in tailoring resonant frequencies.

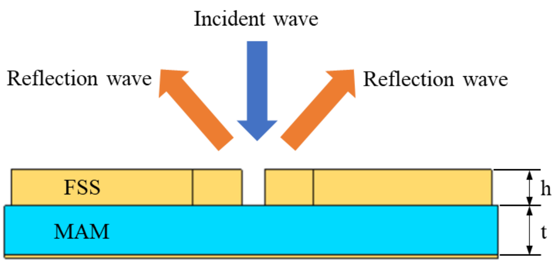

Fig. 1. A general schematic diagram of RCS design.

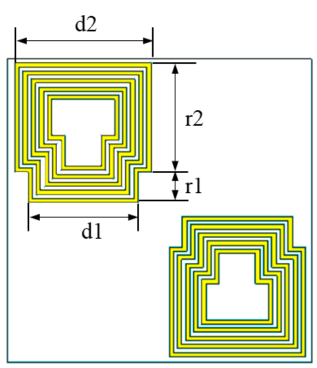

Fig. 2. Fundamental T-ring resonator.

The atypical, asymmetric T-ring configuration contributes to a significant reduction in mutual coupling, which traditionally poses a dominant interference among proximally positioned resonators. The structure of the MAM is a sheet of lossy Salisbury screen backed by a metal plate. Utilizing a Salisbury screen can further absorb the incoming wave to suppress the backward scattering wave and achieve RCS reduction across a relatively broad frequency band. A full wave simulation, utilizing CST electromagnetic simulation software, is conducted to assess and optimize the metasurface performance. This computational analysis delves into the reflective attributes of the proposed structural design, thereby providing insights into its efficacy and operational characteristics.

3. Simulation results

Figure 3 presents the simulated RCS reduction results for various FSS configurations. Among the potential configurations, the chosen frequency-selective structure encompasses an assembly of five complete resonating loops, while the other two structures exhibit deficiencies of one and three resonating loops, respectively. It is evident that the fully structured configuration generates five distinct resonant points corresponding to frequencies of 6.8 GHz, 8.3 GHz, 9.8 GHz, 11.7 GHz, and 14.6 GHz. The structure with a single missing loop manifests four resonant points at frequencies of 7.5 GHz, 9.9 GHz, 11.6 GHz, and 14.5 GHz. The three-loop deficient structure creates two resonant points at the frequencies of 13.45 GHz and 15.6 GHz.

These obtained results facilitate the formulation of structures characterized by varying the number of resonant points and their corresponding frequencies. In other words, these findings enable us to solve the problem of filtering frequencies suitable for radar systems based on specific real-world requirements.

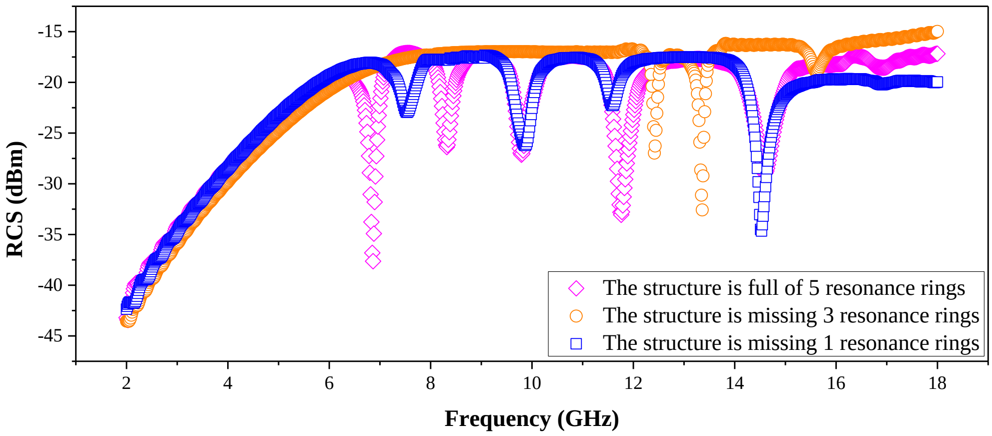

Fig. 3. RCS response for structures with different number of resonant rings.

Figure 4 shows the simulation results of RCS reduction performance. The FSS configuration, as previously shown, manifests 5 distinct frequency resonance points. The RCS reduction reaches less than -15 dB over the entire frequency range from 2 to 18 GHz. For the complete structure of the FSS and the Salisbury shield, two RCS-reduced peaks are generated at 8.7 GHz and in the vicinity of 14.2 GHz; of particular note is the absorption peak of -57 dB. The RCS reduction is less than -25 dB over the entire studied frequency range. The results also show that the FSS structure gives the advantage of frequency selectivity while the full structure gives the absorption width of the whole frequency band.

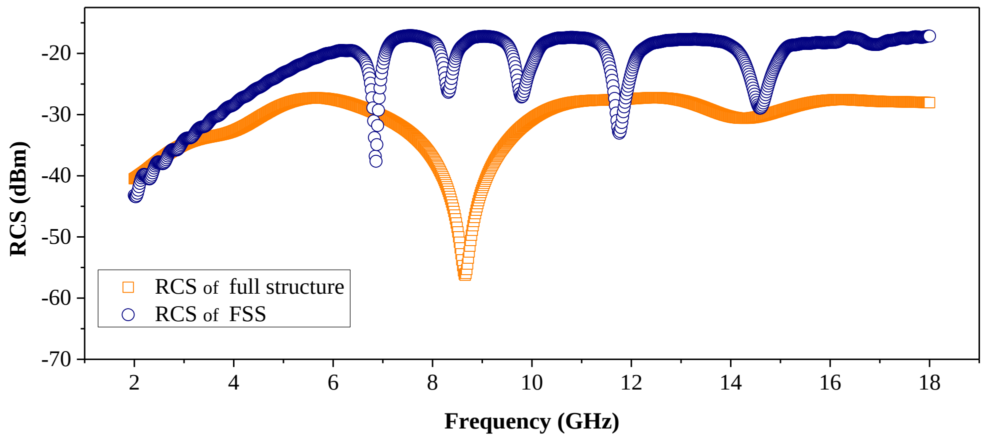

Fig. 4. RCS response for structures with different number of resonant rings.

The monostatic RCS results of the proposed structure under θ-polarized incident plane wave are shown in Fig. 5. The incident angles of $\varphi = 0°, 30°, 60°,$ and $90°$ at frequency 9 GHz are investigated. As shown in Fig. 5a, the monostatic RCS for incident angles of $\varphi = 0°$, the maximum reduction is -64 dB at $\theta = 60°$. Similarly, the results in Fig. 5b shows that the maximum RCS reduction is -42 dB at $\theta = 50°$. For angles $\varphi = 60°, 90°$, the result does not exhibit any significant difference (Fig. 5(c, d)).

The maximum RCS reduction reached -43 dB at angle $\theta = 80°$. Although our main focus is the RCS reduction of the proposed structure under θ-polarized incidence, it is also necessary to investigate its RCS under φ-polarized plane wave incidence (Fig. 6). Obviously, RCS reduction can be observed for incident angles of $\theta = 30°$ and $\theta = 60°$. It should be emphasized that for any angle, the RCS reduction corresponding to $\varphi = 0°$ is -37 dB. This is the most important value because radar detects targets from very distant positions, so it can be considered that they perform detection target below the angle $\theta = 0°$.

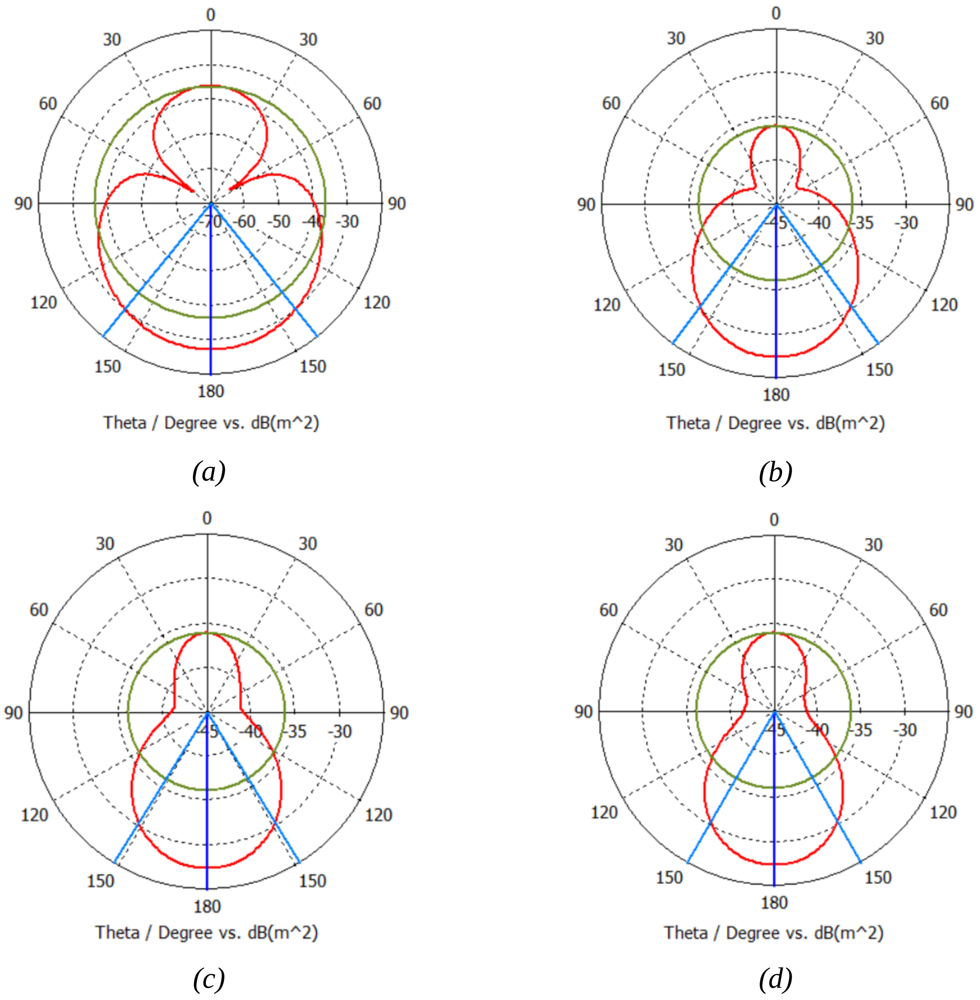

Fig. 5. Monostatic RCS for φ = 0° (a), 30° (b), 60° (c), and 90° (d) under θ-polarized incidence.

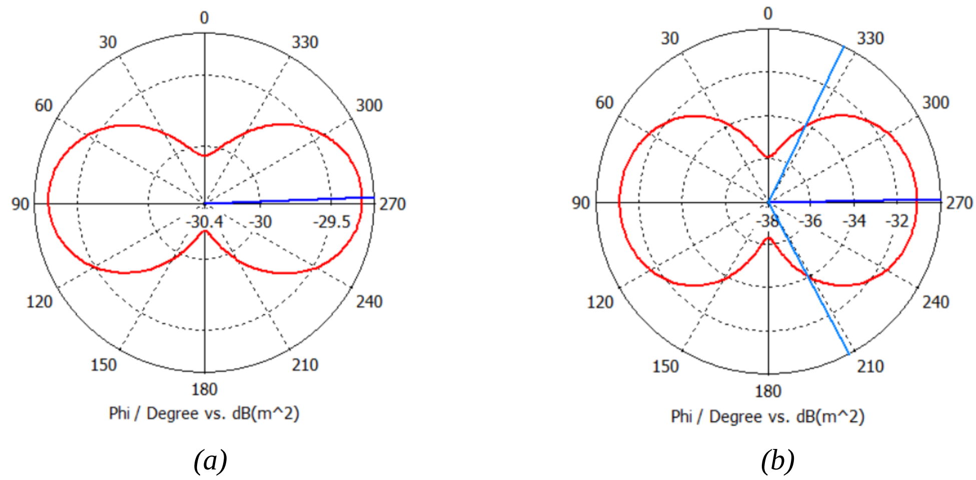

Fig. 6. Monostatic RCS for θ = 30° (a) and 60° (b) under φ-polarized incidence.

In addition, RCS was found to decrease in all directions, which is dictated by the MAM's broadband absorption mechanism. The maximum absorption peaks are caused by the resonance mechanism of the T-rings of the FSS. The combination of broadband absorption mechanism with frequency selective resonance allows to construct a perfect structure both in terms of bandwidth and frequency selection of absorption.

4. Conclusion

In summary, a combined physical mechanism has been utilized to reduce wideband RCS. By integrating a frequency-selective surface with a conventional Salisbury screen, both absorption loss and resonance loss are generated in our design. The frequency-selective surface structure can produce multiple high-order reflections, subsequently diverting the incident waves. The Salisbury screen can further absorb incoming wave energy. Our structure has been demonstrated to achieve a -25 dB reduction in RCS across the frequency range of 2 to 18 GHz. Moreover, the frequency-selective absorption can be achieved by varying the number of resonance rings. Our approach provides a novel method for reducing wideband RCS that is controllable and holds potential for advancements in radar stealth capabilities.

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References

[1] W. W. Salisbury, “Absorbent Body of Electromagnetic Waves”, U.S. Patent 2 599 944, 1952.

[2] Qiqige Wulan et al., “Salisbury screen absorbers using epsilon-nearzero substrate”, *Mater. Res. Express*, Vol. 8, 2021, 016406. DOI: 10.1088/2053-1591/abd8a1

[3] L. J. Du Toit, “The design of Jaumann absorbers”, *IEEE Antennas Propag. Mag.*, 36, pp. 17-25, 1994. DOI: 10.1109/74.370526

[4] Hanying Lv et al., “A Broadband Absorber with Resistive Frequency Selective Surface”, IEEE MTT-S International Wireless Symposium, 2020. DOI: 10.1109/IWS49314.2020.9360027

[5] G. I. Kiani et al., “Frequency Selective Surface Absorber Using Resistive Cross-Dipoles”, IEEE Antennas and Propagation Society International Symposium, 2006. DOI: 10.1109/APS.2006.1711555

[6] Yin Poo et al., “Experimental verification of a tunable left-handed material by bias magnetic fields”, *Appl. Phys. Lett.*, Vol. 96, 2010, 161902. DOI: 10.1063/1.3409120

[7] F. J. Rachford, D. N. Armstead, V. G. Harris & C. Vittoria, "Simulations of Ferrite-Dielectric-Wire Composite Negative Index Materials", *Phys. Rev. Lett.*, Vol. 99, 2007, 057202. DOI: 10.1103/PhysRevLett.99.057202

[8] Fang Xu et al., "Realization and modulation of negative permeability using an array of hexaferrite rods", *J. Phys. D: Appl. Phys.*, Vol. 42, 2009, 065416. DOI: 10.1088/0022-3727/42/6/065416

[9] Fei Ding et al., "Ultra-broadband microwave metamaterial absorber", *Applied Physics Letters*, Vol. 100, 2012, 103506. DOI: 10.1063/1.3692178

[10] Y. Li, Q. Cao, & Y. Wang, "Radar cross section reduction metasurfaces based on phase gradient and chessboard structure", *International Journal of RF and Microwave Computer-Aided Engineering*, Vol. 28, Iss. 7, 2018. DOI: 10.1002/mmce.21457

[11] E. F. Knott, *Radar Cross Section*. 2nd ed. Norwood, MA: Artech House, 1993.

[12] W. Pan et al., "Combining the absorptive and radiative loss in metasurfaces for multi-spectral shaping of the electromagnetic scattering", *Sci. Rep.*, Vol. 6, 2016, 21462. DOI: 10.1038/srep21462

[13] Jiakun Song et al., "Broadband and tunable RCS Reduction using High-order Reflections and Salisbury-type absorption mechanisms", *Sci. Rep.*, Vol. 9, 2019, 9036. DOI: 10.1038/s41598-019-45501-8

[14] J. M. Zhao et al., "Achieving flexible low-scattering metasurface based on randomly distribution of meta-elements", *Opt. Express.*, Vol. 24, pp. 27849-27857, 2016. DOI: 10.1364/OE.24.027849

[15] W. Chen, C. A. Balanis and C. R. Birtcher, "Checkerboard EBG surfaces for wideband radar cross section reduction", *IEEE Trans. Antennas Propag.*, Vol. 63, pp. 2636-2645, 2015. DOI: 10.1109/TAP.2015.2414440

[16] C. Huang, W. Pan, X. Ma, and X. Luo, "Multi-spectral metasurface for different functional control of reflection waves", *Sci. Rep.*, Vol. 6, 2016, 23291. DOI: 10.1038/srep23291

[17] C. Huang, C. Ji, X. Wu, and X. Luo, "Combining FSS and EBG surface for high-efficiency transmission and low-scattering properties", *IEEE Trans. Antennas Propag.*, Vol. 66, pp. 1628-1632, 2018. DOI: 10.1109/TAP.2018.2790430

[18] B. Chambers, "Optimum design of a Salisbury screen radar absorber", *Electron. Lett.*, Vol. 30, pp. 1353-1354, 1994. DOI: 10.1049/el:19940896

[19] S. Liu, T. Cui, Q. Xu, D. Bao, L. Du, X. Wan et al., "Anisotropic coding metamaterials and their powerful manipulation of differently polarized terahertz waves", *Light-Sci. Appl.*, Vol. 5, 2016, e16076. DOI: 10.1038/lsa.2016.76

[20] H. Xu, S. Ma, X. Ling, X. Zhang, S. Tang, T. Cai et al., "Deterministic approach to achieve broadband polarization-independent diffusive scatterings based on metasurfaces", *ACS Photonics*, Vol. 5, pp. 1691-702, 2017. DOI: 10.1021/acsphotonics.7b01036

[21] M. J. Haji-Ahmadi, V. Nayyeri, M. Soleimani, O. M. Ramahi, "Pixelated checkerboard metasurface for ultra-wideband radar cross section reduction", *Sci. Rep.*, Vol. 7, 2017, 11437. DOI: 10.1038/s41598-017-11714-y

[22] Z. Zhou, K. Chen, J. Zhao, P. Chen, T. Jiang, B. Zhu et al., "Metasurface salisbury screen: achieving ultra-wideband microwave absorption", *Opt. Express*, Vol. 25, 2017, pp. 30241-30252. DOI: 10.1364/OE.25.030241

[23] Nguyễn Trần Hà, Trần Quang Đạt, Nguyễn Văn Toàn, Nguyễn Vũ Tùng, Đỗ Quốc Hùng, "Nghiên cứu tính chất hấp thụ sóng radar băng X của Composite $Mn_{0.5}Zn_{0.5}Fe_2O_4$ và PANI", *Tạp chí Khoa học và Kỹ thuật*, Số 179, 2016, tr. 194-201

CẤU TRÚC HỖN HỢP BỀ MẶT CHỌN LỌC TẦN SỐ VÀ MÀN CHẮN HẤP THỤ TỪ TÍNH ĐỂ GIẢM DIỆN TÍCH PHẢN XẠ HIỆU DỤNG SÓNG RA ĐA

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Tóm tắt: Bài báo trình bày phương pháp tổng hợp vật liệu dựa trên cơ chế vật lý kết hợp giữa bề mặt chọn lọc tần số (FSS) và màn chắn hấp thụ kiểu Salisbury để tạo ra một cấu trúc giảm diện tích phản xạ hiệu dụng (RCS) trên dải tần số rộng. Màn chắn truyền thống kiểu Salisbury sử dụng vật liệu hấp thụ từ tính và FSS gồm các bộ cộng hưởng vòng chữ T kết hợp. Màn chắn Salisbury hấp thụ hiệu quả các sóng ra đa. Cùng với đó, sự tích hợp của bộ cộng hưởng vòng chữ T tạo ra các chùm phản xạ bậc cao, do đó cho phép lựa chọn tần số hấp thụ. Kết quả mô phỏng chứng tỏ rằng cấu trúc được đề xuất cho phép giảm hiệu quả RCS trong toàn bộ dải tần số 2 đến 18 GHz với các góc tới khác nhau.

Từ khóa: *Diện tích phản xạ hiệu dụng; bề mặt chọn lọc tần số; màn chắn kiểu Salisbury.*

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