A thin radar-infrared stealth-compatible structure: Design, fabrication, and characterization*

Tian Hao(田 浩)[a], Liu Hai-Tao(刘海韬)[a)b)], and Cheng Hai-Feng(程海峰)[a)†]

[a] Science and Technology on Advanced Ceramic Fibers and Composites Laboratory, College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China

[b] Science and Technology on Scramjet Laboratory, College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China

(Received 26 June 2013; revised manuscript received 26 July 2013; published online 10 December 2013)

A thin radar-infrared stealth-compatible structure with reflectivity below −10 dB in the whole radar X wave band and infrared emissivity less than 0.3 in the infrared region of 8 μm–14 μm is reported. The designed stealth-compatible structure consists of metallic frequency selective surface (MFSS), resistive frequency selective surface (RFSS), and metal backing from the top down, and it is only 2.1-mm thick. The MFSS is made up of some divided low infrared emissivity metal copper films, and the RFSS consists of a capacitive array of square resistive patches. They are placed close together, working as an admittance sheet because of a mutual influence between them, and the equivalent admittance sheet greatly reduces the thickness of the whole structure. The proposed stealth-compatible structure is verified both by simulations and by experimental results. These results indicate that our proposed stealth-compatible structure has potential applications in stealth fields.

Keywords: radar-infrared stealth-compatible structure, absorbing property, infrared emissivity

PACS: 52.25.Os, 68.35.bt, 42.25.Bs **DOI:** 10.1088/1674-1056/23/2/025201

1. Introduction

With the development of advanced detectors and precision guidance technology, once armaments are detected in a war, their fate is to be destroyed, especially aircraft, ships, helicopters, and missiles. Stealth or low observability technology is one of the main electronic countermeasures used to make military hardware less detectable. It appears to be urgently needed and has attracted much attention all over the world.[1–3] Stealth material technology is the principal means for actualizing stealth performance if the shape of the armament cannot be further modified.[4] So, it is an important direction of development and has great military value.

In modern systems of reconnaissance and guidance, radar and infrared multi-band detection and dual-mode homing guidance techniques are becoming mainstream, so the most important research in stealth material technology is aimed at compatible stealth functionality in infrared and radar bands. However, radar adsorbing materials require a high absorptivity and low reflectivity, while infrared stealth materials demand a lower emissivity.[5,6] It is very difficult to give a material both high absorptivity and low emissivity. Yet there is a big frequency difference between infrared wavelengths and radar wavelengths, so it seems possible to design and fabricate a new material or structure with both excellent absorption in the radar wave band and low emissivity in the infrared wave band. Wang *et al.*[7] successfully fabricated an ordered mesoporous C–Al_2O_3 nanocomposite with a maximum reflection loss of −15.3 dB, and at bandwidths lower than −10 dB it is 7.4 GHz, with a thickness of 3 mm in 0.5 GHz–18 GHz, whereas its infrared emissivity can reach 0.46 in the wavelength range from 8 μm to 14 μm. Le Chen *et al.*[8] prepared a sort of $Sm_{0.5}Sr_{0.5}Co_{1-x}Fe_xO_3$ ($0 \leq x \leq 0.5$, SSCF) with perovskite-type structure by conventional solid-state reaction as a microwave and infrared multi-functional material. The infrared emissivity of SSCF can be tailored from 0.29 to 0.54 as the content of Fe is increased from 0 to 0.5, and optimal absorption can be achieved and the microwave loss peak is 29.33 dB for an $x = 0.1$ sample. However, to the best of our knowledge, experimental results on the design of a radar-infrared stealth-compatible structure are rarely reported. Hence, our manuscript is of considerable interest.

In the present study, we report a new, thin, and lightweight radar-infrared stealth-compatible structure, which consists of metallic frequency selective surface (MFSS), resistive frequency selective surface (RFSS), and metal backing from the top down, which is only 2.1-mm thick. The designed stealth-compatible structure exhibits an excellent radar adsorption property and a lower infrared emissivity in the wavelength range between 8 μm and 14 μm.

2. Foundation consideration and design

To make an ideal radar absorbing structure, the reflection coefficient should be as low as possible so that the radar wave can enter the structure with the maximum intensity, which

*Project supported by the National Natural Science Foundation of China (Grant No. 51202291).

†Corresponding author. E-mail: chfcfc@163.com

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generally requires a high input resistance — optimally the input resistance should be quite close to the free-space intrinsic impedance of air. On the other hand, the radar wave entering the structure should be absorbed maximally.[9,10] In our previous research,[11–14] a high-impedance surface is investigated as one effective approach to realize excellent radar absorption. Its structure has resistive patches periodically arranged on a dielectric slab with a back metal.

To get a desirable infrared camouflage effect, according to the Stefan–Boltzmann equation:

$$M = \varepsilon\sigma T^4, \tag{1}$$

where M is the infrared radiative intensity, ε is the infrared emissivity of the surface, σ is the Stefan–Boltzmann constant, and T is the absolute temperature. There are two feasible approaches to reducing infrared radiative intensity: 1) controlling the temperature of the body; 2) decreasing the infrared emissivity of the surface.[15] Generally, low infrared emissivity metals, such as silver, copper, aluminum, gold, and platinum, are good candidate materials for infrared camouflage.[16,17] However, a gapless sheet of metal film totally reflects the radar wave band, which is disadvantageous for radar adsorption since the radar wave cannot enter the structure.

Low infrared emissivity metal films are used to fabricate a two-dimensional periodic array of conducting patches; that is, MFSS, and its dimension parameters, such as lattice type, element spacing, etc., can be adjusted appropriately. When the element size is quite different from the resonant dimensions, the MFSS screen is essentially transparent to incident radar waves.[18–20] More importantly, the infrared emissivity of MFSS is not much greater than that of a gapless sheet of low infrared emissivity metal film.

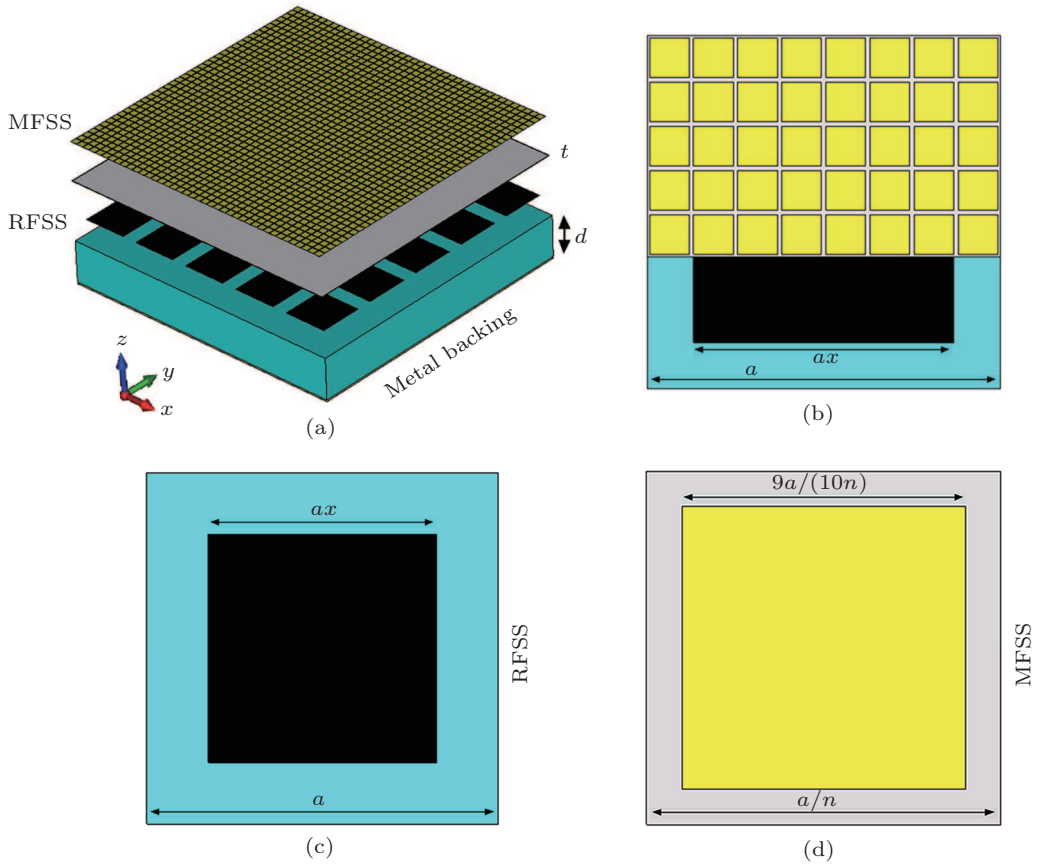


Fig. 1. (color online) (a) Three-dimensional view of the radar-infrared stealth-compatible structure, $d = 1.968$ mm, $t = 0.08$ mm. (b) Front view of the unit cell of the radar-infrared stealth-compatible structure, $a = 13.811$ mm, $x = 0.738$. (c) Front view of the unit cell of the RFSS. The square resistance of the capacitive resistive patches is 150 Ω/□. (d) Front view of a unit cell of MFSS, $n = 8$.

Based on the preceding analysis, the radar-infrared stealth-compatible structure designed in this work consists of MFSS, RFSS, and metal backing from the top down, as shown in Fig. 1(a). The MFSS and RFSS are placed close together and separated with a metallic ground plane as a dielectric layer. The front view of the radar-infrared stealth-compatible structure is shown in Fig. 1(b). The yellow areas represent the metallic frequency selective surface, which can be made up of some mesoporous metal films with low infrared emissivity, such as silver, copper, gold, and platinum. The gray areas

represent an ultrathin dielectric slab of FR-4, which has a permittivity of 4.4 and a loss tangent of 0.02. The thickness of the FR-4 is only 0.08 mm. The single unit cell of the RFSS is illustrated in Fig. 1(c). RFSS consists of a capacitive array of square resistive patches placed on the top of a 1.968-mm-thick metal-backed commercial E-glass fabric/epoxy composite substrate (the blue areas). The substrate has a permittivity of 5.7 and a tangential loss of 0.02, and the metal backing was modeled as an 18-μm thick silver film with a frequency independent conductivity of 5.8×10^7 S/m. The front view of the unit cell of the MFSS is shown in Fig. 1(d). The n represents the cell periodicity ratio of the RFSS and MFSS.

We performed numerical simulations of our design by CST Microwave Studio software using the standard finite difference time domain (FDTD) method. In the simulations, periodic boundary conditions are set in both the x-axis and y-axis directions. In the z-axis direction, one port is added above the absorber surface for the TEM wave normal incidence, and an electric boundary is set at the substrate bottom to model the backing metal. Since our designed stealth-compatible structure substrate is metal-backed, the transmission is zero and, thus, the absorption can be determined only by the reflection response. Here, the reflectivity is used to characterize the microwave absorption properties of our compatible stealth structure. Subsequently, the structure parameters of the stealth-compatible structure are optimized to minimize the reflectance in X-band, the obtained geometric parameters are listed in the caption of Fig. 1. The calculated and optimized result is shown in Fig. 2. As is shown, two distinct absorption apexes are located around 9.1 GHz and 11.7 GHz, respectively. The reflectivity in the whole X-band is below −10 dB.

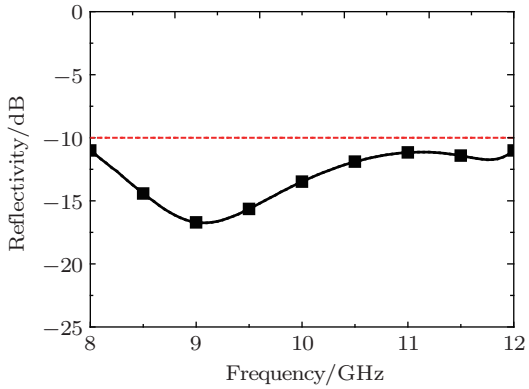


Fig. 2. (color online) Optimized reflectivity of the designed radar-infrared stealth-compatible structure.

3. Experimental verifications and discussion

To confirm the simulation and design results, a 180 mm×180 mm sample was fabricated with the dimensions shown in the caption of Fig. 1. The MFSS was prepared by the PCB techniques using an FR-4 slab (the thickness of the slab is 0.1 mm), one side of which is covered with copper, the thickness of the copper is about 15 μm. The RFSS was fabricated by printing the resistive patches on a grounded substrate of E-glass fabric/epoxy composite (the thickness of the grounded substrate is 1.968 mm) via the silk-screen technique. Afterwards, the MFSS and RFSS were pasted together. The photograph of the fabricated radar-infrared stealth-compatible structure is shown in Fig. 3.

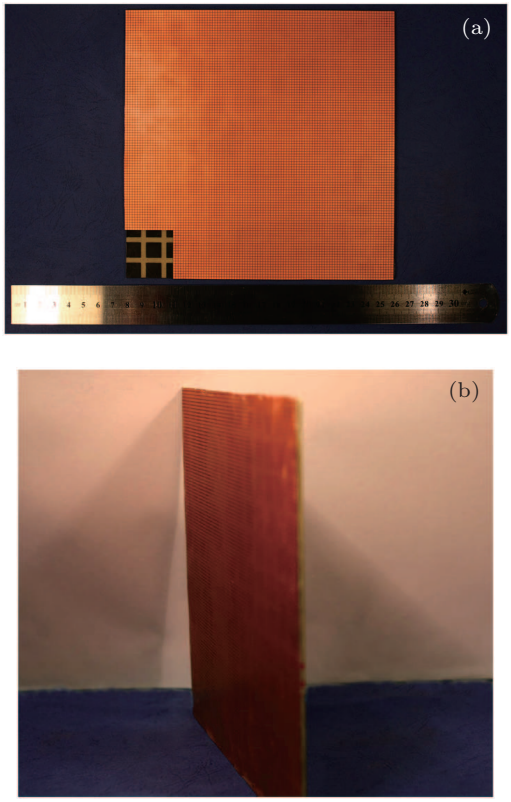


Fig. 3. (color online) Photograph of the fabricated radar-infrared stealth-compatible structure: (a) front view, and (b) side view.

The reflectivity of the radar-infrared stealth-compatible structure samples was measured with the free-space reflection method in a microwave anechoic chamber. A vector network analyzer Agilent 8720ET and two linear polarized horn antennas were used to transmit TEM waves in the range of 8 GHz–12 GHz (X-band) onto the sample and receive the reflected signals. The sample was placed on a metal plate to eliminate the transmission itself from the measurements, and its location was far enough from the horn antennas — the incidence can be recognized as normal to the sample. The measured reflection as a function of the frequency is displayed in Fig. 4. As is shown, the experimental result (black curve) is nearly consistent with the designed performance (red curve). The slight blue shift of the absorption frequency compared to the simulation results can reasonably be ascribed to fabrication tolerances, such as the location deviations of the MFSS and RFSS.

Both the simulation and experimental results indicate that the proposed stealth-compatible structure offers an excellent absorbing property in the radar X-band.

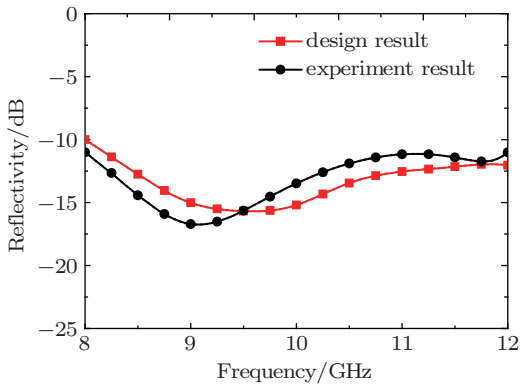


Fig. 4. (color online) Comparison of the reflectivity of the radar-infrared compatible stealth structure between experimental (black curve) and simulated (red curve) results.

The absorbing mechanism of the proposed compatible stealth structure can be explained by its equivalent circuit model. Since the MFSS and RFSS are closely placed together, and the two films are thin enough compared to the radar wavelength, the closely placed MFSS and RFSS can be regarded as an admittance sheet for the incident radar wave, the admittance of the sheet has frequency dependence because of the mutual influence between the films.[21]

Figure 5 shows the equivalent circuit of the wave absorber, where B_{c1} is the susceptance of MFSS, B_{c2} and G_r are the susceptance and conductance of RFSS, respectively. $Y_s(= G_s + jB_s)$ is the surface admittance of the admittance sheet, and Y_{in} is the input admittance seen from the front of the wave absorber. Lastly, Y_d is the admittance of the grounded dielectric substrate, and Y_0 is the admittance in vacuum. Incidentally, it is expected that G_s and B_s would be changed from B_{c1}, B_{c2}, and G_r. Note that each admittance of the sheet (MFSS and RFSS) differs from that of the films due to the mutual influence between the films. G_s increases with frequency because the electromotive force in proportion to change of current is generated by mutual induction between the films. B_s is larger than B_c because of capacitance between the films.[21,22]

From the equivalent circuit in Fig. 5, Y_{in} can be considered as a parallel connection of Y_s and Y_d as in the following equation:

$$Y_{in} = Y_s + Y_d. \tag{2}$$

Then, the Y_d can be obtained from the transmission line method:

$$Y_d = -j\frac{Y_0}{\sqrt{\frac{1}{\varepsilon_r}}\tan\left(\frac{2\pi d}{\lambda}\cdot\sqrt{\varepsilon_r}\right)} \tag{3}$$

By using Eqs. (2) and (3) with $Y_s = G_s + jB_s$, the Y_{in} can be evaluated as follows:

$$Y_{in} = G_s + jB_s - j\frac{Y_0}{\sqrt{\frac{1}{\varepsilon_r}}\tan\left(\frac{2\pi d}{\lambda}\cdot\sqrt{\varepsilon_r}\right)}. \tag{4}$$

For achieving the matching condition and obtaining optimal absorbing property, Y_{in} should be defined as $Y_{in} = Y_0$. Likewise, the considered wave absorber is a resonant structure and, thus, the absorption frequency can be easily derived by imposing the equivalent susceptance $\mathrm{Im}\{Y_{in}\} = 0$.[23,24] Accordingly, the equation (4) and $Y_{in} = Y_0$ show that the matching frequency depends on d and B_s, and the reflection value depends on G_s. Moreover, the shapes and sizes of the unit cells influence the values of B_s. The lumped conductance G_s is also related to the surface conductance G_r of the RFSS. Therefore, adjusting the structural parameters of the stealth-compatible structure appropriately can obtain the minimum reflectance in the whole X-band. In addition, it is also shown that the structure would be thinner when B_s becomes large. So, it is easy to understand that the total thickness of the stealth-compatible structure is only about 2.1 mm.

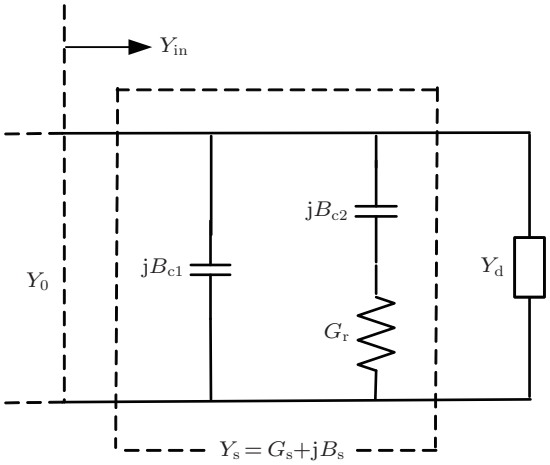


Fig. 5. Equivalent circuit of the compatible stealth structure shown in Fig. 1.

The distribution of the power loss density of the compatible stealth structure was calculated at different frequencies, as shown in Fig. 6. It is shown that the loss of divided copper films and the dielectric layers is relatively small and can be neglected, and the absorbed energy is dissipated mainly by the resistive patches of RFSS. Compared with the power loss density of the compatible stealth structure at three different frequencies, it is shown that the absorption is effective all over the whole X-band. The close proximity of MFSS and RFSS makes the impedance of the structure perfectly match that of free space, insuring the low reflection of the waves incident on the surface of the structure.

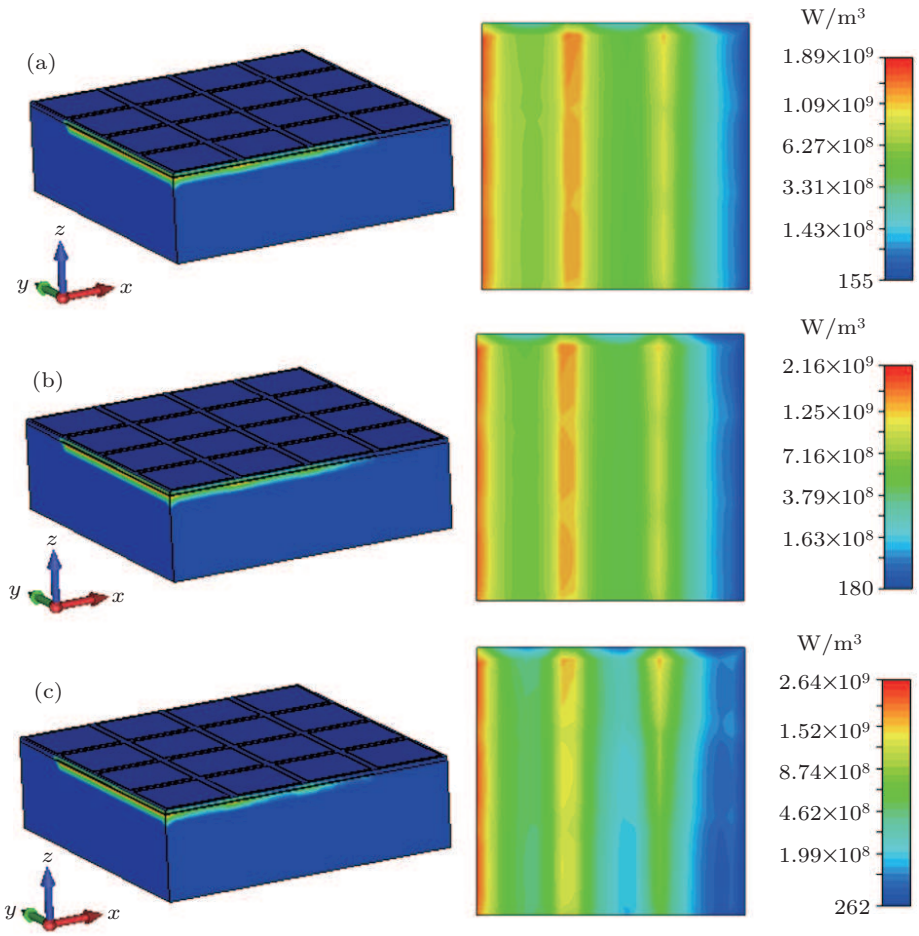


Fig. 6. (color online) Power loss density of the GHz wave in the stealth-compatible structure: a perspective view of a quarter of the unit cell at (a) 8 GHz, (b) 9.1 GHz, and (c) 11.7 GHz.

The infrared emissivity of the stealth-compatible structure at the wavelengths of 8 μm–14 μm was measured by using an IR-2 Infrared Emissometer (Shanghai Institute of Technological Physics of the Chinese Academy of Sciences). The final value was obtained by averaging over the data measured from ten different regions of the sample. After measurement, the infrared emissivity of the radar-infrared stealth-compatible structure is only 0.298 in the infrared region of 8 μm–14 μm.

For the infrared stealth properties, the infrared emissivity of the proposed stealth-compatible structure is mainly determined by the surface of the structure,[25]; that is, the condition of the MFSS. The infrared emissivity value of the MFSS is calculated by an empirical formula

$$\varepsilon = \varepsilon_{\mathrm{m}} S_{\mathrm{m}} + \varepsilon_{\mathrm{d}} S_{\mathrm{d}}, \tag{5}$$

where ε is the emissivity of the MFSS, ε_{m} is the emissivity of copper metal, and the measured value is about 0.09, ε_{d} is the emissivity of the medium FR-4 in a gap, and the value there is about 0.955 when the waveband is 8 μ–14 μm, S_{m} and S_{d} are the area percentages of the copper and medium FR-4 in a gap, respectively. According to Eq. (5) and Fig. 1(d), the calculated infrared emissivity value of MFSS is about 0.255, which is close to the experimental value.

To be clear, in a practical application, the exterior condition of the MFSS may be a high-temperature or oxidation environment. The metal will oxidize and generate oxide; whereupon, its infrared emissivity will increase considerably. On the other hand, if the metal film (only 15 μm) oxidizes completely, then the admittance characteristic of the absorber will also change; whereupon, the absorbing property will become worse. Because the exterior environment is so very important, it is necessary to give it deep consideration in future studies. Maybe, one would adopt gold or platinum instead of copper in a practical application.

4. Conclusions

A thin radar-infrared stealth-compatible structure, which contains MFSS, RFSS, and metal backing, was designed. A stealth-compatible structure with a reflectivity bandwidth of the whole X-band below −10 dB was obtained. Moreover, its infrared emissivity is less than 0.3 in the infrared region

of 8 μm–14 μm and its thickness is only 2.1 mm. The proposed stealth-compatible structure is verified both by simulations and by experimental results. These results indicate that our proposed stealth-compatible structure is a promising candidate for a multi-functional application with compatible camouflage capability for the radar and infrared bands.

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