In-band radar cross-section reduction of the slot array antennas by RAM-based frequency selective surfaces

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**Abstract**

A method for reducing radar cross-section (RCS) of the slot array antenna by utilising the radar absorbing material, while preserving the radiation performance simultaneously, is proposed and discussed. The scheme is based on the implementation of the multilayer frequency selective surface-radar-absorbing material (RAM) capable of operation over a wide frequency band. The use of radar absorbing material on an antenna’s radiation screen causes a change in surface current, resulting in the radiation pattern of the antenna. Therefore, by designing the coating pattern of the radar absorbent material as a substrate and a capacitive patch as a unit cell on the antenna board, the reduction of 19 dB RCS at X-band and minimum antenna gain loss (3dB) is achieved. To demonstrate the proposed solution, a 30-cm diameter slot array antenna, which is considered as a test case, is coated by RAM and radar cross section reduction (RCSR) is dramatically accomplished over a frequency band ranging from 8 to 12 GHz. It is worth mentioning that the obtained RCSR at 9.4 GHz is as much as 19 dB. Subsequently, the proposed method can be a candidate for reduction of RCS in slot array antennas, considering the remarkable RCSR and acceptable effect on radiation characteristics.

**1 | INTRODUCTION**

Today, antenna radar cross-section reduction (RCSR) has become one of the critical issues in the field of stealth technology. To reduce the radar cross-section (RCS) of the antennas outside the frequency band, they can use radomes with band-pass specifications [1] or frequency selective surfaces (FSSs) plates in front of the antenna [2], [3], which acts in the antenna working band. The wave passes through it with the minimum loss and outside the band, by shielding the antenna and reducing the mono-static RCS, the filtering behaviour can be realised by the use of the FSS [4]. The problem with this methodology is that the in-band RCS of antennas does not reduce significantly [5]. Consequently, to reduce the RCS of antennas in their frequency bands, techniques such as radar-absorbent materials or FSSs are used [6]. For example, in [7] and [8], artificial magnetic conductors (AMC) with perfect electric conductors (PEC) have been used to reduce the in-band RCS, as well as to improve the antenna specifications in a slotted waveguide based on passive cancellation.

In [9], the reflection characteristics of an AMC composite sheet were reviewed and designed to reduce RCS in a wide band. Similarly, in [10], for a metal surface, an inhomogeneous AMC array reduces the RCS of it in a wide band. These studies, as mentioned earlier, attempt to reduce the antenna’s mono-static RCS by changing the direction of its reflection wave with the phase shift of the individual elements, suggesting the increase of its bi-static RCS. Nevertheless, radar absorber, can generate losses and convert electromagnetic wave into the heat, in order to prevent the reflection of the wave to other positions, which is an appropriate option for use for reducing the mono- and bi-static RCS in the antennas.

In Section 2, using radar absorber coating, the RCS reduction of the slotted array antenna is evaluated. In the third section, using a circuit model analysis, a unit cell is designed to reduce the thickness of the coating employed in Section 2. In Section 4, based on the unit cell utilised in Section 3, the two-layer FSS-radar-absorbing material (RAM) for coating on the slot array antenna is designed. The design is then applied to an array antenna, is constructed to compare with the simulation results and is evaluated in the anechoic chamber. Afterwards, in
Section 5, the results obtained in Section 4 are evaluated, compared and analysed.

2 | RCS REDUCTION OF RAM-COATED SLOT ANTENNA

As mentioned in the first section, RAMs can be used to reduce the radar cross section of the array antenna.

Although this method has the potential to reduce the antenna RCS, it can change the antenna propagation characteristics due to the undesirable destruction of the surface current on the plate of antenna.

For example, a previously designed slot array antenna is considered. The diameter of the antenna and its area are 30 cm and 0.071 square metres, respectively, and the number of slots is 112. Also its aperture efficiency including taper efficiency is 64%. The antenna consists of an input single slot waveguide, multiple branchline waveguides with broad wall radiating slots and a main waveguide to feed the branch waveguides through a series of inclined coupling slots.

This structure is simulated in CST Studio software and $S_{11}$. Gain, RCS and surface current are plotted in Figure 1. For simulation, time domain method of CST software is used.

Figure 1(a) shows that the designed antenna has a maximum matching criterion at 9.4 GHz and has a bandwidth of 250 MHz. Additionally, there is the main lobe with 27.5 dBi gain, 3 dB beamwidth of 6.7 degrees and side-lobe level of −12.9 dB in the antenna gain diagram at this frequency (Figure 1(b)). Figure 1(c) demonstrates the RCS of the antenna at a frequency of 9.4 GHz and 0–90 degrees of sweep angle. Consequently, RCS of slot antenna at bore sight is 17.9 dBSm, 3 dB beamwidth is 3.2 degrees and side-lobe level is 17.8 dB at 9.4 GHz frequency. The surface current generated by the plane wave radiation on the antenna plate is shown in Figure 1(d). As it is clear, there is the highest surface flow around the slots. Accordingly, the surface current formed on the radiation plate, which is the radiating agent, will be disrupted if the area around the slots is covered with radar absorbent material.

Now, to minimise the destructive effects on the current, the points with higher densities are identified based on the surface current pattern of the antenna, and the electromagnetic absorber is formed in a way that is not placed around these areas.

The distribution of the current at these points should not be disrupted since these points mostly determine the main radiation characteristic of the antenna. Therefore, an initial shape of the absorbent coating pattern is designed accordingly, as showed in Figure 2.

For this purpose, a RAM with its electromagnetic properties as shown in Figure 3 is used. The relative complex

**Figure 1** Simulation results of slot array antenna (a) $S_{11}$ parameter at X-band frequencies, (b) realised gain in dBi vs. angle, (c) antenna radar cross-section in dBSm vs. angle and (d) Surface current on plate of the antenna at 9.4 GHz frequency
F I G U R E 2 Radar-absorbing material coating pattern according to the surface current of the slot antenna

F I G U R E 3 Measurement results of relative permittivities and permeabilities of the proposed radar absorbing material coating at X-band frequencies

F I G U R E 4 Comparison of (a) realised gain in dBi and (b) radar cross-section in dBsm for the uncoated antenna, antenna coated with radar absorbing material and antenna with optimised coating layer at 9.4 GHz frequency

The next step is to improve the absorbent layer properties, including optimum thickness to achieve the maximum RCS reduction. Thus, the parameters of $t$ (thickness), $a$ and $b$ are extracted by changing the thickness parameter as well as the absorbent dimensions shown in Figure 2 and optimisation by the genetic algorithm. This is done by the optimisation section of the CST Studio software. After optimising, it is found that the coating thickness is 2.7 mm and the values of $a$ and $b$ achieved are 21 and 5.2 mm, respectively. In Figure 4, the realised gain (a) and RCS (b) of the uncoated antenna, coated antenna with RAM and an optimised coating plan on the antenna plate are compared.

Figure 4(a) illustrates the slot antenna gain, which is 27.5 dBi after coating with RAM and thickness of 2.7 mm decreases to 14.9 dB and becomes equal to 12.6 dBi. In addition, the antenna RCS will be reduced from 17.9 to −7.7 dBsm. Although coating with the RAM of thickness of 2.7 mm reduces the RCS of antenna by 25.6 dB, the decrease in radiation properties is not desirable. According to the findings in Figure 4, optimising the dimensions of the radar absorber coating on the radiating surface of the slot antenna results in a bore-sight gain of 23.6 dBi, which is 3.9 dB less than that of the uncoated case. This decrement in gain is acceptable with respect to the reduction of RCS to 11.4 dBsm.

Moreover, the weight of the absorber-coated antenna and its optimised type is 696 and 116 gr, respectively. So, optimising the coating design in addition to improving the radiation properties of the coated antenna will result in a weight reduction of about 83%.

However, this amount of thickness used for RAM may cause problems for antenna movements. As a result, using frequency selective surfaces will reduce the RAM thickness and, thus, decrease the weight of the antenna.
3 | RAM IMPROVEMENT BY FSSs

It was observed in the preceding section that, in order to optimise the absorbent RCS reduction, its thickness must be equal to 2.7 mm. One of the methods that can be applied to reduce the absorber thickness is the use of FSSs. Using RAM with a high dielectric coefficient as the FSS substrate can reduce substrate thickness. In other words, the higher the substrate \( \epsilon_r \) value of an FSS structure, the more decreased its thickness would be. Therefore, since the absorbent \( \epsilon_r \) is approximately 6, a low-thickness FSS absorber structure can be designed.

3.1 | Design of FSS

In the following section, we intend to design an FSS layer with respect to the absorber substrate specifications. For this purpose, the absorbent layer coated on the surface of the antenna, on which the FSS is located as shown by the circuit model in Figure 5. In this circuit model, the FSS is modelled as a series resistor and capacitor parallel to the transmission line due to the absorber layer.

If we want the coefficient of return loss \( (\Gamma) \) to be less than \(-10\) dB, then \( \Gamma \) and \( Y_s \) (input admittance of RAM substrate) in linear coordinate will be equal to:

\[
-1/3 < \Gamma < 1/3
\]

\[
Y_s = Y_0 \frac{1 - \Gamma}{1 + \Gamma}
\]

where \( Y_0 \) is free space admittance. Now to summarise the problem, we put the end of the absorber on a PEC and then compute the input admittance \( (Y) \). Hence, it is obtained from Equations (1) and (2).

\[
\frac{Y_0}{2} < Y_s < 2Y_0
\]

Input admittance of the modelled FSS-RAM structure is given in Equation (4), where \( \gamma \) is calculated in Equation (5). The admittance of the substrate on the metal plate is calculated to obtain the appropriate thickness of the absorber, based on Equations (4) and (5) for different thicknesses in MATLAB software, is shown in Figure 6.

\[
Y_{in} = Y_{fs} + Y_s = Y_{fs} + Y_0 \coth(\gamma t)
\]

\[
\gamma = \alpha + j\beta = j\omega \sqrt{\epsilon_0\mu_0(\epsilon' - j\epsilon')(\mu' - j\mu)}
\]
According to Equation (3), for $\Gamma_t$ to be less than $-10$ dB, $Y_t$ should range from 1.3 to 5.3 in milli Siemens. In conformity with Figure 6, the thickness required for the absorbent substrate to achieve impedance matching at the frequency of 8.5 to 11 GHz equals 1 mm.

After the impedance matching of the real part of the substrate, we have to neutralise the imaginary part of impedance using FSSs. As indicated, the behaviour of $Y_t$ is inductive. Consequently, based on the equation $Y_{in} = Y_{fa} + Y_p$, the imaginary part of $Y_{in}$ is required to be zero to adapt the impedance to the free space, so $Y_{fa}$ must have a capacitive behaviour. Therefore, we need to use a structure that satisfies this behaviour at X-band frequencies. One of the most famous FSS structures with almost capacitive behaviour is called capacitive patch.

For example, a unit cell with $5 \text{ mm} \times 5 \text{ mm}$ total dimensions and patch dimensions mentioned in Figure 7 is simulated in CST Studio software and the admittance diagram is shown. As indicated in Figure 7, the imaginary part of the simulated patch has a positive value, indicating that this unit cell with a frequency of 8–12 GHz and these dimensions can play a capacitive role. For practical reasons, unit cell is mounted on a thin substrate of FR-4 with the thickness of 0.25 mm so that unit cell can be effectively mounted on the absorber. As shown in Figure 7, the real part of this unit cell is quite small and close to zero. This is due to the relatively small thickness of the FR-4 substrate and indicates that it will not have a significant impact on the transmission model in Figure 5.

The unit cell dimensions are extracted by optimisation in CST Studio software using the genetic algorithm to adjust the capacitance value. The optimised unit cell dimensions are shown in Figure 7. The designed unit cell coated on the absorber substrate with its calculated admittance is given in Figure 8.

As presented in Figure 8(b), the imaginary part of the admittance of an optimised unit cell is $-3$ to $0.25$ in mS, which is a minimal amount, indicating relative impedance matching with the free space. Furthermore, the real part of the admittance of this unit cell is in the frequency range of 8–12 GHz between 4 and 5 mS and this satisfies the condition of Equation 3. The $S_{11}$ parameter of this structure is shown in Figure 9. Accordingly, the $S_{11}$ parameter of the unit cell from 8 to 10.7 GHz is less than $-10$ dB, suggesting that the proper matching is achieved in the mentioned frequency band.
do not change significantly with the coverage of the FSS-RAM structure on it.

Finally, the designed model is fabricated using a 1-mm absorbent coating as a substrate and the designed FSS as a superstrate; the whole assembly is coated onto the slot antenna’s surface. As depicted in Figure 10(b), the coating FSS-RAM, which can be explained by the periodic structure theory, has 24, 39, 48 and 57 cells in the y-direction and 1 or 2 cells in the x-direction. Since the surface current distribution is divided into the strong current area and the weak current area, this arrangement retains the strong current area to avoid the degradation of radiation characteristics. Gain and RCS parameters of this antenna are evaluated before and after covering the desired antenna in an anechoic chamber (Figure 11).

To allow the metal patches to be coated onto the RAM substrate, the FSS design is first printed on a 0.25-mm-thick printed circuit board with FR-4 material and then, the proposed thin layer is adhered to the RAM.

Figure 12 shows the measurement results of the slot antenna, which is compared with antenna coated with the designed FSS-RAM. Figure 12(a) demonstrates gain parameter at 8.5–12 GHz and Figure 12(b) indicates the reduction amount in RCS at 8.5–11.5 GHz. Based on the results of the measurement of the slot antenna in its working frequency band (8.9–9.8 GHz) after the designed FSS-RAM coverage, its gain is reduced to a maximum of 3 dB, which is acceptable due to the reduction of the RCS from 2 to 19 dB.

The importance of RCS reduction by this method is that the RCS cannot be reduced by applying the shielding of the radiating plate in this working frequency band (for example, by modifying the antenna radome in front of the antenna). The reason is, the application of band stop coating eliminates the

4 | APPLYING DESIGNED COATING TO SLOT ANTENNA SURFACE AND EXPERIMENTAL RESULTS

Using the coating design of Figure 2 and the unit cell designed in Section 3, an electromagnetic FSS is designed and its parameters are analysed by simulation. Figure 10 shows the radiation pattern and RCS of the improved antenna.

Results from Figure 10 show that RCS of slot antenna is reduced to 6.5 dBsm at bore-sight by coating the absorbent material with a thickness of 2.7 mm. Also, the antenna gain in its bore-sight is reduced by adding absorbent coatings up to a maximum of 3.9 dB. Following the coating of the FSS-RAM on the radiating plane of the antenna as shown in Figure 10, it can be seen that its RCS decreases by 19 dB and gain loss in the bore sight of the antenna does not exceed 3 dB. Figure 10 proves that the essential characteristics of the slot antenna, such as bore-sight gain, side-lobe level and 3 dB beamwidth,
radiation properties of the antenna. In other words, the most prominent feature of using this method is the reduction in the working frequency band of the antenna.

5 CONCLUSION

The authors have demonstrated that the RCS of a slot array antenna was reduced by using an absorber material and forming it based on the surface current distribution using FSS to control the absorber properties including thickness, bandwidth and absorption value. The RCS reduction of this method in the frequency band of 8.7–11 GHz was more than 19 dB, which was both inside and outside the working frequency band of the antenna. Furthermore, because of the absorber placement on the antenna, its gain was reduced by about 3 dB, which was acceptable given the advantage of an RCS reduction of 19 dB. The evaluated RCS reduction was verified by applying the design to a slot array antenna and measuring it in the anechoic chamber. Results confirmed the findings of the simulations.

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