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Design and fabrication of inkjet printed ultrathin FSS based microwave absorbers

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Abstract

This work reports the design and fabrication process used to create a new class of ultrathin inkjet printed microwave absorbers. The arrangement is composed of a lossy Frequency Selective Surface (FSS) placed above a ground plane to form a resistive High Impedance Surface (HIS). The thickness of the three absorbers investigated range from $\lambda/58$ to $\lambda/223$. These extremely thin structures present design and manufacturing challenges to achieve the desired energy absorption ($\geq 90\%$) over a useable (-10 dB) bandwidth. Numerical optimisation of the surface resistance and topology of the FSS pattern gives values of 7% ($\lambda/58$) and 1.5% ($\lambda/223$) for absorbers working at normal incidence. The digital settings used in a desktop ink jet printer to obtain the required surface resistance value of the metallised FSS patterns are obtained by curve fitting numerical simulations to experimentally obtained transmission coefficients.

1 Introduction

Microwave Radar Absorbing Materials (RAM) are deployed for applications that require electromagnetic cloaking of metal structures such as aircraft, land vehicles and wind turbines [1]. The aerodynamic performance of these platforms is of fundamental importance, therefore a critical design objective imposed on the RAM construction is the minimisation of the physical thickness and weight. However the operating bandwidth over which 90% (-10 dB) of the incident energy is absorbed, is proportional to the electrical thickness of the material. Therefore for applications where aerodynamic performance is important, it is necessary to create innovative design techniques based on the FSS patterned layer, to maximise the frequency range over which the structure provides sufficient radar backscatter suppression. For example in [2] and [3] the spectral reflection response of resistively loaded FSS with unit cells composed of nested hexagonal or square loops resonating at different frequencies are combined to exhibit wideband absorption. This technique is useful to design absorbers thicker than $\lambda/17$ [4], but not for the ultra-thin structures reported in this paper. Our computations show that for absorbers thinner than about $\lambda/25$, it is impossible to merge the high Q reflectivity nulls generated by the individual loops. In conjunction with

this observation, recently reported studies [5] on the bandwidth of very thin HIS, show that FSS unit cells composed of patch elements exhibit a wider reflectivity bandwidth than topologies based on single loops, and also crossed dipoles and other meandered features.

In [6], a requirement to enhance the RF performance of ultrathin thermal blankets deployed on spacecraft platforms was identified. Thermal blankets are composed of Multilayer Insulator (MLI) materials with up to 35 Kapton or PET dielectric layers each separated by a thin coating of aluminium or gold. The composite material exhibits high radar backscatter causing antenna gain ripple, undesirable coupling between payload instruments and also passive intermodulation (PIM) due to the non linearities present on the individual layers. In 2012 [7], a theoretical solution to mitigate reflections was proposed, using microwave absorbers positioned on the inner side of the spacecraft. More recently a different approach was presented in [8], which deploys a low loss HIS to create random scattering of the reflected energy thus preventing the focussing of unwanted signals in any given direction.

The work presented in this paper is an alternative and potentially better option for reducing radar backscatter from satellite platforms and other aerodynamic structures. A lossy HIS is created by patterning the top surface of the MLI with a resistive FSS which is separated by a dielectric spacer (PET or Kapton) from the first metalised layer of the structure. Ultrathin absorbers ranging in thickness from $\lambda/58$ to $\lambda/223$ at 10 GHz, corresponding to physical thickness of $140\text{ }\mu\text{m}$ and $560\text{ }\mu\text{m}$ were investigated. These are similar in value to the individual layer thicknesses of commercially available MLI [9]. For each case studied, the maximum reflectivity bandwidth was obtained using CST Microwave Studio by careful selection of the dimensions of the FSS pattern which is based on an array of closely spaced hexagonal patch elements, and the surface resistance of the printed features. We show that it is possible to employ an ink jet printer to pattern the hexagonal patch arrays and in conjunction control the surface resistance of the patch elements by choosing the digital settings to control the dot density of nano silver traces.

2 Simulation of ultrathin absorbers

As previously mentioned, an FSS design based on a resistively loaded patch element is predicted to yield the maximum reflectivity bandwidth. The reason for this behaviour can be under-

stood by inspection of Equations (1) to (3) [5].

$$\text{FBW} = R\sqrt{C/L}, \quad (1)$$

$$C = \epsilon_r \epsilon_0 (A/h), \quad (2)$$

$$L = l \frac{\mu_0}{4\pi} \ln \left\{ 1 + \frac{32h^2}{w^2} \left[1 + \sqrt{1 + \left(\frac{\pi w^2}{8h^2} \right)} \right] \right\}. \quad (3)$$

Equation (1) shows the fractional bandwidth of an equivalent LC which can be used to model the patch FSS, while Equations (2) and (3) relate the inductance and capacitance values, using microstrip circuit theory, to the geometry. l is the length of the line, h is the height of the substrate, w is the width of the element and A the area. If it is desirable to achieve the highest bandwidth, then it is important to increase the capacitance and decrease the inductance as much as possible. Hence a hexagonal patch FSS design is selected, since this has a larger surface area and two additional capacitive coupling edges than a square patch. The unit cell is depicted in Figure 1 with the dimensions normalised to electrical length for the 140 μm , 280 μm , and 560 μm absorbers.

Figure 1: Schematic of the unit cell and electrical lengths.

The numerical computations were performed in CST Microwave Studio, where a unit cell was used for the boundary conditions and a Floquet port as the source of the incoming plane wave. For the substrate material, PET Novele IJ-220 ($\epsilon_r = 2.75$ and $\tan \delta = 0.035$) was chosen as it is one of the polymers that is often used to construct commercially available thermal blankets [9]. The simulations were performed with the aim of finding the best value for the surface resistance (R_s), which is a compromise between the energy absorption level and the Fractional Bandwidth (FBW), for an absorber working at normal incidence at a centre frequency of about 10 GHz. The optimal values of R_s obtained were 20 m Ω /sq, 300 m Ω /sq and 3.4 Ω /sq for the 140 μm , 280 μm and 560 μm thick absorbers, respectively. Figure 2 shows the absorptivity for each one of the designed absorbers. These values for the surface resistance agree with the theory presented in [10] which shows that R_s is

proportional to the absorber's thickness. Additionally, it is possible to see the FBW improvement when the absorber is made thicker.

Figure 2: Absorptivity values for the designed absorbers.

Table 1 summarises the simulated results for the three absorbers in terms of FBW and Figure of Merit (FOM), defined by Equation (4) [2]. The FOM is a very useful tool to evaluate the performance of FSS absorbers because it takes account of the FBW, operating frequency and physical thickness as shown in Equation (4).

$$\text{FOM} = \frac{\text{FBW} \times \lambda_c}{t}. \quad (4)$$

Where λ_c is the centre operating wavelength and t is the absorber thickness. The FBW is defined as the fractional band over which 90% of the energy is absorbed.

For example, for reference the classical Salisbury Screen [11] which is a $\lambda/4$ thick absorber has an FOM of 300 when designed for a perfect absorption at 10 GHz.

Thickness (μm)	Electric Thickness	FBW (%)	FOM
140	$\lambda/223$	1.5	340
280	$\lambda/116$	3.2	369
560	$\lambda/58$	6.9	407

Table 1: Summary of simulated results.

The simulation of a finite size structure was also performed in addition to the unit cell previously shown. Figure 3 depicts the 3D pattern for the two extreme cases (140 μm and 560 μm thick). These computer predictions were made for absorbers of surface area 431 cm^2 which corresponds to the size of the structures currently being manufactured. A normal incident plane wave was set as the source of excitation, and the scattered electric field was plotted. It is observed from Figure 3 (a) and (c), in band (9.6/9.1 GHz), that the scattered E-Field is much lower than the result obtained for the structure working at a frequency shifted (+6 GHz) from the absorption band, where the HIS behaves as a metal reflector. The actual values will be quantified in the next section. In addition, it is also noted that the sidelobe levels and energy scattered in directions beyond this angular region are significantly smaller in band than

Figure 3: Scattering behaviour for the $140\ \mu\text{m}$ (a) in band, (b) out of band and $560\ \mu\text{m}$ thick resistively loaded FSS absorbers (c) in band, (d) out of band.

Figure 4: Electric field behaviour for the $140\ \mu\text{m}$ (a,b) and $560\ \mu\text{m}$ (c,d) thick absorbers.

at out of band frequencies, thus confirming that the energy is suppressed by absorption and not random scattering.

In Figure 4 it is also possible to observe the E-Field distribution of the plane wave in and out of band (same frequencies as above) for both the $140\ \mu\text{m}$ and $560\ \mu\text{m}$ absorbers. The maximum scale is set to $1.87\ \text{dB}_{V/m}$. The electric field above the metal backing plate of the absorber is much more intense when the HIS behaves like a conductive plate (out of band).

3 RCS reduction of thermal blankets

The RCS reduction is a useful characteristic to be analysed since this is essentially a measure of the radar backscatter suppression. A Broadband Farfield Monitor has been set in CST

Figure 5: Predicted RCS of the three absorbers.

Figure 6: Scattered E-Field for the $140\ \mu\text{m}$ thick absorber.

Figure 7: Scattered E-Field for the $560\ \mu\text{m}$ thick absorber.

Microwave Studio, and the simulation performed using the Time Domain Solver. Figure 5 illustrates the calculated RCS in $\text{dB}_{V/m}$. The relation between RCS reduction and absorptivity can be confirmed by comparing the results with those depicted in Figure 2 for normal incidence operation

In terms of E-Field, Figures 6 and 7 quantify the reduction in the intensity of the electrical field over the forward hemisphere. In Figure 6, the E-Field decreases from $7\ \text{dB}_{V/m}$ to $-8.9\ \text{dB}_{V/m}$ with sidelobes not greater than $-22\ \text{dB}_{V/m}$. As for the $560\ \mu\text{m}$ thick absorber, Figure 7, the E-Field decreases from $6.4\ \text{dB}_{V/m}$ to $-13.4\ \text{dB}_{V/m}$ with sidelobes not greater than $-27\ \text{dB}_{V/m}$.

4 Fabrication of the FSS

Ink Jet printing of the three ultra-thin absorbers will be used to confirm the accuracy of the numerical simulations. An Epsilon Stylus C88+ with a maximum DPI of 600 was employed to pattern Metalon JS-B25HV Nano Silver ink [12] on the surface of a 140 μm thick Novele IJ-220 substrate [13], which is based on the same PET material that is used to construct MLI for spacecraft applications. The importance of selecting a suitable resistive loading factor in terms of the R_s value for the metallised hexagonal patches is illustrated in Figure 8 for each of the three absorbers. This parameter can be controlled by suitable choice of the digital settings available in the ink jet printer, however this must be established prior to manufacture. Thus, in order to fabricate the absorber with the correct electrical characteristics, a 8 mm $\times$ 16 mm dipole FSS with unit cell periodicity of 18 mm was designed to resonate at about 10 GHz and printed with different values of R_s by changing the RGB code using DipTrace software. When a very conductive FSS is to be printed, it is desirable that the nano silver ink particles are as dense as possible, which is defined as (0,0,0) in the RGB code, or pitch black. On the other hand, to obtain a more resistive FSS, the particles should not be as dense, thus the RGB code should increase towards (255,255,255), or white for an extreme case.

Multiple samples, for repeatability testing, of three FSS with identical size unit cells were printed with RGB codes of (0,0,0), (10,10,10), and (25,25,25). In Figure 8 it is shown that the surface resistance for the 140 μm thick absorber needs to be as low as 20 m Ω /sq to maximize bandwidth. To achieve this value of R_s , the most conductive FSS (RGB 0,0,0) was baked for 30 minutes at 100 $^\circ\text{C}$ in order to achieve the highest conductivity possible. On the other hand, the other samples were left to dry at room temperature in the laboratory for 48 hours to ensure complete evaporation of the solvent, and an identical structure of each one was also baked as for the sample with code (0,0,0).

Spectral transmission measurements were performed with the FSS placed in the aperture of a RAM covered screen. The two X-Band horn antennas were placed a distance 45 cm from the dipole array and connected to an Agilent PNA 8361C, as shown in Figure 9. The measured data was then compared to the simulations performed in CST Microwave Studio to estimate the value of the surface resistance. This method for obtaining much larger values of surface resistance, has been reported previously by the authors in [14].

Noteworthy is the fact that the measured data was post-processed in Matlab, where a Chebyshev window was applied in time domain to eliminate unwanted reflections and spill over, to obtain a smoother curve which is more suitable for comparison with the simulated data. Figures 10 to 12 show the measured results and data fitted using simulations obtained from CST Microwave Studio. The FSS ink jet printed using RGB code (0,0,0) has a R_s value around 30 m Ω /sq, which is close to the optimum design value for the 140 μm absorber; the sample (10,10,10) baked in the oven exhibits an R_s between 230

Figure 8: R_s tolerance for the three absorbers.

Figure 9: Photograph of the experimental setup.

m Ω /sq and 300 m Ω /sq, and is suitable for construction of the 280 μm absorber; and finally the air dried sample (25,25,25) exhibits a R_s between 2.8 Ω /sq and 3.5 Ω /sq, and is therefore suitable for printing the 560 μm thick absorber.

Figure 10: Computed surface resistance being compared to the fabricated FSS with the highest dot density RGB (0,0,0).

Figure 11: Computed surface resistance being compared to the fabricated FSS RGB (10,10,10), and dried in the oven.

Figure 12: Computed surface resistance being compared to the fabricated FSS RGB (25,25,25), and dried for 48h in the laboratory.

5 Conclusion

In this paper we presented the results of a study to obtain the maximum reflectivity bandwidth of ultra-thin resistively loaded microwave absorbers. These have physical dimensions similar to the metal backed cover layer of MLI which are employed to provide thermal control of spacecraft payloads. Numerical simulations show that radar backscatter suppression is obtained when the surface of the PET material is patterned with an array of closely spaced hexagonal patch elements. The importance of selecting the optimum surface resistance of the metal features was highlighted, and given that these structures are extremely thin, these values are much smaller than those presented in the literature for this class of absorber [2]. This highlights one of the main advantages of using inkjet printing to manufacture ultra-thin absorbers, because this technique permits better control of the conductivity of the FSS elements. By matching simulated results to measured transmission coefficients for FSS structures printed with different RGB codes, we were able to obtain the ink jet printer setting which give the desired surface resistance values for each of the three absorber designs. The reflectivity performance of the structures will shortly be measured and the results will be presented at the conference. To the best of the author's knowledge, this is the first time that an absorber as

thin as $\lambda/223$ has been studied in the literature, and with an FOM higher than 300, this is deemed to be a suitable strategy for enhancing the RF performance of thermal blankets.

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