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Resistively Loaded Ultra-Thin FSS Absorbers for RF Enhancement of Spacecraft Thermal Blankets

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Abstract

This study reports the use of metal backed frequency selective surface (FSS) absorbers as a means to control the scattering of electromagnetic energy from satellite platforms which are covered with thermal blankets. This is achieved by exploiting the similarity of the physical construction of this class of absorber and the dielectric clad foil backed outermost layer of space blankets. Simulated results are presented for five absorber designs which are suitable for mechanical integration into the top surface of a multi-layer insulator (MLI). These were constructed using Polyethylene Terephthalate (PET) material with sheet thickness in the range $140\text{ }\mu\text{m}$ ($\lambda/213$)– $1120\text{ }\mu\text{m}$ ($\lambda/25$). The optimum performance around 10 GHz was obtained from an array of hexagonal patch elements with the conductivity of the silver plating adjusted to achieve the desired resistive loading. At normal incidence the FSS based structures presented -10 dB reflectivity bandwidths that are strongly dependent on the thickness of the PET sheet and vary between 2% and 16%. The design methodology is verified by measuring the radar backscatter from $140\text{ }\mu\text{m}$ and $1120\text{ }\mu\text{m}$ thick absorbers in the frequency range 8–12 GHz.

1 Introduction

Modern spacecraft platforms are subject to a multitude of temperature fluctuations that range from $+150^\circ\text{C}$ when exposed to the sun to -150°C when in shadow [1]. The mechanical structure and payload instruments must therefore be protected from these temperature extremes. Multi-Layer Insulation blankets are normally employed to provide passive thermal control and are ideal for protecting delicate instruments by ensuring that their normal operating temperature is not exceeded. Thermal blankets work by limiting the amount of radiative heat transfer and the key properties of concern are the IR emissivity and solar absorptivity, which affects the outer temperature of the MLI. The overall MLI performance is strongly related to

the number of layers in the composite, therefore in principle it should be possible to modify the properties of the outermost metal backed dielectric layer without degrading the overall thermal performance of the blanket. To provide a 100% reflective barrier, MLI's are constructed from 2–35 dielectric layers which are vapour deposited with aluminium on one or both sides [2]. The individual sheets are constructed from Polyimide or Polyethylene Terephthalate material with thickness in the range 5–240 μm . To provide environmental protection the composite is often bonded to an outer cover of the same material which is up to 300 μm thick.

Electromagnetic scattering from a spacecraft platform can degrade the performance of radio frequency (RF) instruments, mainly those that deploy low gain antennas for data collection, search and rescue, communications and navigation systems. These interference effects are responsible for copolar pattern ripple, reduced gain, depolarisation and also undesirable RF coupling which is often observed in antenna farms on densely populated satellite platforms [3].

The European Space Agency [4] has recently identified a need for the RF enhancement of metal backed thermal blankets as means to control the scattering of electromagnetic energy from satellite platforms. At present, these blankets are deployed for the sole purpose of providing thermal control, so the implementation of dual functionality is desirable because it provides a low cost solution without imposing additional weight constraints. A successful outcome would permit relaxation of the stringent performance requirements often imposed on the antenna backlobe levels and moreover this would provide designers with additional flexibility to select the most suitable layout of the microwave instruments on the satellite platform.

A modulated metasurface [5], [6] composed of a patterned layer that is printed on the top surface of a thermal blanket is currently the only arrangement that has been rigorously investigated as a means to reduce the power reflected from this type of structure. Radar backscatter suppression is obtained by deploying a periodic array which

is designed to spread the impinging energy upon reflection to create reflected waves that are randomly phased. The working frequency range is determined by the intrinsic resonance of the metasurface and is therefore proportional to the thickness of the MLI. In [6] a 6% bandwidth was achieved for a 500 μm thick structure. At frequencies outside this narrow band, the patterned surface does not couple to the incident RF energy and the electromagnetic response is determined by the metal backing of the thermal blanket

The approach described in this paper is radically different. Here, instead of spreading the back scattered energy the structure is designed to absorb the incident power. This is achieved by depositing an array of resistively loaded resonant elements on the surface of the outermost metal backed dielectric layer of the MLI composite. The geometry of the arrangement, which is similar to a lossy high impedance surface (HIS), permits reuse of the MLI so that its thermal properties are retained. However the electromagnetic behaviour changes from, one presenting an almost perfect reflecting surface, to one which absorbs most of the impinging energy over the intrinsic bandwidth of the microwave absorber. The size and surface resistance of the periodic elements can easily be selected to provide strong absorption at different frequency bands and can be optimised for operation at incident angles corresponding to the illumination at different spatial positions on the spacecraft surface by the individual radiating sources comprising the antenna farm [3].

This concept for increasing the functionality of MLI was first proposed by Costa et. al. [7], who used numerical simulations at x-band to show that a lossy HIS composed of cross dipoles printed on a 1000 μm thick Teflon substrate can give up to 30 dB suppression of TE and TM waves at 10 GHz. In the paper we now present the first comprehensive study of an ultra-thin Frequency Selective Surface absorber which is suitable for integration into an MLI. Numerical simulations are employed to predict the radar backscatter from five different metal backed PET structures, ranging in thickness $\lambda/213$ to $\lambda/25$ at X band. The corresponding physical thicknesses (140 μm - 1120 μm) are similar to the metal backed outer layer of commercially available thermal blankets [1], [2]. For thermal control these can be selected independently of the dimensions of the multiple foil backed inner films, which are normally identical but manufactured using thinner dielectric material. The reflectivity bandwidth of this class of absorber is proportional to the thickness of the PET substrate which is used to physically separate the resistively loaded FSS from the metal ground plane [8], [9]. Therefore to address this challenging performance limitation, the geometry and the surface resistance of five example periodic arrays were optimised to achieve the maximum reflectivity bandwidth for normal incidence operation. Numerical electromagnetic simulation was employed to investigate the angular sensitivity, which is also dependent on the absorber thickness [8], when exposed to TE and TM waves incident at

angles up to 60°. In each case the periodic array was formed by patterning the outermost surface of the metal backed PET with a close packed array of hexagonal shaped patch elements. This topology exhibits a wider reflectivity bandwidth than FSS loop elements when used to construct ultra-thin ($< \lambda/17$) absorbers [10, 8]. The metal backed absorbers were fabricated by patterning the surface of a 140 μm thick PET sheet using an ink jet printer digitally controlled to obtain the desired surface resistance values for the patches. Numerical predictions obtained from CST Microwave Studio [11] are shown to be in good agreement with measured radar backscatter from the structures working at normal incidence in the frequency range 8 – 12 GHz.

2 Numerical optimisation and design

The equivalent circuit of a metal backed resistively loaded FSS consists of a parallel connection of a series L_{fss} , C_{fss} , R_s circuit which represents the impedance of the periodic array, and L_g , the transformed inductance ($< \lambda/4$ gap) of the metal ground plane. The structure can be designed to resonate when the imaginary parts of the FSS impedance and the inductance presented by the ground plane cancel each other. This requires a careful choice of the unit cell topology and gap dimensions, and the value of R_s , which is used to model the loss of the FSS array [12]. Total radar backscatter suppression occurs when the structure is impedance matched to free space ($Z_0 = 377 \Omega$), and is achievable only at a single frequency and for one angle of incidence. For this reason, the -10 dB reflectivity bandwidth is often cited to compare the frequency range over which absorbers exhibit signal suppression of at least 90%. Sensitivity to wave polarisation and angle of incidence is reduced by patterning the array with close packed symmetrical shaped elements [13]. For operation at large incident angles, the in-plane anisotropy required to balance TE and TM waves is obtained by selecting unequal loading values in the vertical and horizontal arms of the loop elements [14].

CST Microwave Studio EM simulator [11] was employed to predict the radar backscatter suppression in the frequency range 8 – 12 GHz for FSS based absorbers with thickness 140 μm , 280 μm , 560 μm , 840 μm and 1120 μm . Floquet ports and appropriate boundary conditions were applied in order use a single 3D unit cell to model the periodic structures which are assumed to be infinite in extent and illuminated by a plane wave. The investigation considered both loop and patch elements which were designed to work at a center frequency of 10 GHz. A unit cell composed of unequal length loops generates resonances at different frequencies [8]. When these are merged by suitable choice of the physical dimensions and the surface resistance of the loops, the -10 dB reflectivity bandwidth can be increased beyond the value obtained

for a single resonance structure [9, 15, 16]. This classical design strategy was used by the authors in [9] to create a 3 mm thick ($\lambda/14 - \lambda/4$) FSS based absorber which exhibits a reflectivity bandwidth of 108% centred at a 16 GHz. The periodic array was supported above the metal ground plane using a foam spacer, so for this arrangement the signal suppression is mainly attributed to energy loss in the resistively loaded nested hexagonal loops. However, our computations show that this design methodology does not work for the class of ultra-thin absorbers investigated in this paper [17]. This can be explained by observing the very rapid impedance changes with frequency around resonance, which make it impossible to merge the very narrow reflection nulls that are generated by the individual loop elements for arrangements thinner than $\lambda/17$. Therefore all five ultra-thin absorbers investigated in this study were created by patterning the surface of the PET substrates with an FSS composed of an array of resistively loaded patch elements [18]. For each absorber thickness (L_g fixed), the physical dimensions of the unit cells (L_{fss} , C_{fss}) and the surface resistance (R_s) of the patches were adjusted to optimise the bandwidth performance at normal incidence. The reflectivity of the absorbers was also computed for angles of incidence up to 60° to the direction of propagation of the TE and TM incident waves.

For each case the optimum solution was obtained by constructing an array of closely spaced capacitive coupled unit cells each containing a hexagon patch with a conductivity value slightly less than bulk silver (6.3×10^7 S/m). The hexagonal shaped element exhibits a larger surface area and more capacitive coupling from its six edges, and therefore gives a better performance than FSS based absorbers patterned with square and circular shaped patches. This can easily be understood from equations (1) to (3) [18].

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

$$C = \epsilon_r \epsilon_0 \left(\frac{A}{h} \right) \quad (2)$$

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

Equation (1) shows the fractional bandwidth (FBW) of an equivalent LC circuit which can be used to model the patch FSS, and (2) and ((3)) relate the inductance and capacitance values, using classical microstrip circuit theory. 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.

Fig. 1 illustrates a schematic of the unit cell used in the CST Microwave Studio simulations. The physical dimensions for each absorber thickness (t_d) and the corresponding surface resistance (R_s) are given in Table 1. The gap between the hexagonal patches is 0.6 mm for the 140 μm absorber and 0.3 mm for the other four structures studied. PET substrate with permittivity 2.9 and loss tangent

Figure 1: Schematic of unit cell geometry and side view of the FSS based absorbers.

Table 1: dimensions and surface resistance of the absorbers investigated.

t_d (μm)	r (mm)	P (mm)	R_s (Ω/sq)	Electrical thickness at 10 GHz
140	5.4	9.65	0.05	$\lambda/213$
280	5.14	9.2	0.8	$\lambda/105$
560	4.5	8.1	4.46	$\lambda/51$
840	3.9	7.1	11.6	$\lambda/34$
1120	3.46	6.3	20	$\lambda/25$

0.025 was used to model the spacer material in the numerical simulator. This material is used by manufacturers to construct the individual layers of MLI [1, 2] which are deployed on spacecraft platforms. The simulated results were validated experimentally (Section 3) using commercially available 140 μm thick PET coated printed electronics substrate on which the array pattern (blue) was ink jet printed.

In Fig. 2 the predicted absorbance at normal incidence is compared for all five arrangements where it is shown that bandwidth is proportional to the structure thickness. The relationship between the -10 dB fractional reflection bandwidth (FBW) and the absorber thickness is depicted in Fig. 3. The numerical results show that values of between 2% (140 μm) and 16% (1120 μm) are achieved for these FSS based absorbers which have physical thicknesses that are suitable for integration into the outermost surface of the MLI. Although Fig. 3 shows a linear relationship between thickness and the reflectivity bandwidth this is not the case for absorbers which are constructed with spacers that are more than about 1.75 mm ($> \lambda/17$) [17] thick and are designed to work in the same frequency band.

Simulations were also performed to confirm that the radar backscatter suppression observed for all five structures is attributed to energy absorption and not random scattering of reflected signals as reported for the MLI

Figure 2: Computed TE/TM absorbance for the five FSS based absorbers at normal incidence.

Figure 3: Computed relationship between -10 dB fractional reflection bandwidth and absorber thickness at normal incidence.

metasurface arrangement reported in [5, 6]. The computer predictions were made for absorbers with a surface area 431 cm^2 which corresponds to the size of the prototypes that have been manufactured. A normal incident plane wave was set as the source of excitation, and the scattered electric field was plotted and compared to the radar backscatter obtained from a metal plate of the same size. Two examples are illustrated in Fig. 4 which shows the results obtained at the reflection null of the $140 \mu\text{m}$ (9.85 GHz) and $1120 \mu\text{m}$ (10 GHz) thick absorbers. In addition to signal suppression in the direction of the main reflected beam, energy scattered in directions outside this angular range are shown to be significantly lower too.

In contrast to resistively loaded FSS absorber arrangements that are constructed with foam spacers [9], the signal suppression exhibited by the structures investigated in this study is mainly attributed to absorption of the high intensity electric fields inside the PET filled cavities. Although the energy loss in the FSS screen is significantly lower than the dielectric material, the absorber performance is critically dependent on the value of the surface resistance (R_s in the equivalent circuit model) that is used to model the hexagonal patch elements in the full wave simulations. This design parameter, which is proportional

to the absorber thickness [19], must be specified precisely in order to maintain a good impedance match to freespace. Our parametric studies have shown that the RF performance of thicker structures is more tolerant to variations in the conductivity of the FSS patches, and therefore this imposes demanding requirements on the precision and repeatability of the processes that are needed to manufacture MLI with integrated ultra-thin microwave absorbers. Fig. 5a and 5b illustrate the sensitivity to surface resistance for the thinnest ($140 \mu\text{m}$) and thickest ($1120 \mu\text{m}$) absorbers studied. The optimum design of the former structure is based on a surface resistance of $0.05 \Omega/\text{sq}$, but the results show that reflectivity levels below -10 dB cannot be obtained if the hexagonal patch elements are patterned with a metal that exhibits a value greater than $0.2 \Omega/\text{sq}$. However, the $1120 \mu\text{m}$ thick absorber exhibits an acceptable reflectivity bandwidth when the surface resistance of the patches is increased from the optimum value of $20 \Omega/\text{sq}$ to $25 \Omega/\text{sq}$. The results of a comprehensive investigation to establish the impact of manufacturing tolerances are summarised for all five absorber designs in Fig. 6. The plots show the variation from the optimum surface resistance value which is needed to reduce the maximum reflection loss to below -10 dB.

The figure of merit (FOM), which is commonly used to compare the performance of different absorber designs, is defined as the common (TE/TM) bandwidth divided by the physical thickness normalised to the centre working frequency. Table 2 summarises the computed FOM values for all five hexagonal patch structures investigated. The numerical predictions which range from 370 to 443, compares favourably with the 308 value for a classical Salisbury Screen [20].

Angular sensitivity is an important performance consideration given that a metalised MLI installed on a spacecraft is often illuminated by spillover energy and backlobe radiation from low gain antennas, incident at different angles and electric field vector orientations. Although the ultra-thin FSS based absorbers reported in this paper have been designed to work at normal incidence, we have investigated the performance of all five structures at angles of incidence from 0° to 60° for TE and TM polarised waves.

Table 2: Computed relationship between figure of merit and absorber thickness

t_d (μm)	FOM	Electrical thickness at 10 GHz
140	370	$\lambda/213$
280	381	$\lambda/105$
560	408	$\lambda/51$
840	428	$\lambda/34$
1120	443	$\lambda/25$

Figure 4: Scattered E Field from absorbers illuminated at normal incidence compared to a metal plate of the same dimensions. (a) 140 μm (b) 1120 μm (c) Metal plate (d) Farfield cut at $\phi = 90^\circ$.

The reflectivity plots are shown in Fig. 7a and 7b for the thinnest (140 μm) and in Fig. 7c and 7d for the thickest (1120 μm) absorber arrangements. The two structures exhibit a small narrowing of the absorption bands up to 30° incidence, and for these cases the reflection nulls are fairly stable and exhibit an upwards frequency shift of less than 1% (TE) and 5% (TM). However the performance degradation is much more severe at tilt angles of 45° and 60° particularly for the thicker absorber where the radar backscatter suppression is less than -10 dB in the TE plane and for TM polarised waves a 15% shift in the reflection null is predicted.

The angular stability and its dependence on the absorber thickness can be understood from equations (4) and (5) [19]:

$$B_{TE} = j\omega\mu_0 t_d \quad (4)$$

$$B_{TM} = j \frac{\epsilon'_r - \sin^2 \theta}{\epsilon'_r} \omega\mu_0 t_d \quad (5)$$

Where B_{TE}/B_{TM} are the imaginary parts of the input impedance for a thin metal backed substrate when $t_d \ll \lambda$, ω is the angular frequency and θ represents the angle of incidence. By inspection of (5), it can be seen that the shift in the reflection null is much more significant for thicker metal backed FSS structures that operate at oblique incidence in the TM plane.

The -10 dB reflectivity bandwidth exhibited by the two FSS absorbers in the TE and TM plane and for simultaneous operation in both planes of incidence is summarised in Fig. 8.

3 Construction and Experimental Results

An Epson Stylus C88+ inkjet printer was used as means for fast prototyping the thinnest and the thickest metal backed FSS structures. The FSS were printed on a 140 μm thick, 222 mm $\times$ 192 mm, coated PET sheet, Novele IJ-220 ($\epsilon_r = 2.9$ and $\tan \delta = 0.025$), using Metalon JS-B25P [21] nanosilver ink. The printer was configured for the highest DPI settings and the patterned sheet was dried for 30 minutes inside an oven at 90°C in order to achieve very low surface resistance value ($0.05 \Omega/\text{sq}$) which is required for the construction of the 140 μm thick absorber. The 1120 μm thick absorber was manufactured using a silver ink plated FSS which exhibits a surface resistance of $20 \Omega/\text{sq}$. The required resistance loading was obtained by selecting an Ink_{vol} : Solvent_{vol} [22] mixture ratio of 1 : 7 and printer RGB code of (13,13,13) configured in grayscale to define the required DPI. These digital settings and the selected ink composition were previous obtained by constructing a linear dipole FSS, and fitting the numerical predictions to the spectral transmission plots in the frequency range around resonance [22],[23].

The thicker absorber was manufactured by bonding eight PET sheets together using 3M Scotch-welding adhesive to remove air voids between the individual layers. Construction of the two absorbers was completed by bonding the unpatterned surface of the PET spacer to a rigid FR4 backed 35 μm copper plate.

Fig 9a depicts a photograph of a typical unit cell of the hexagonal patch FSS. The physical dimensions of the two prototypes were measured using a TESA-VISIO [24] non-contact precision optical system, which has a resolution of $1 \pm 0.5 \mu\text{m}$. A random sample of 5 the 264 unit cells

Figure 5: Computed reflection coefficient for (a) 140 μm and (b) 1120 μm thick FSS absorbers for various surface resistance values, working at normal incidence. The inset shows the current distribution on the hexagonal loops at the reflection nulls generated by the optimum design. The scale shows dark blue as the lowest value of surface current, whilst red is the peak surface current.

Figure 6: Computed upper and lower surface resistivity variation from the optimized values for each FSS based absorber working at normal incidence, in which 90% absorption is unattainable

were checked and an error of between 0.5% and 1% was found for r (Fig. 1), and up to 10% for the gap between the hexagonal patches. On a microscopic level, the quality of the patterned elements is imperfect. A non-uniform jagged metal edge profile is observed in conjunction with straight printed lines which exhibit different optical intensities. The latter feature suggests that the surface resistance is not homogeneous over the surface of the patch elements which is in contrast to the assumption used in the numerical model.

Time gated swept frequency reflection measurements were carried out in range 8 – 12 GHz using a pair of standard gain horns placed at a distance of 1.3 meters from the surface of the two FSS based absorbers. There were precision aligned using a laser and configured for normal incidence illumination as shown in Fig. 9b. A metal plate of the same size was used to calibrate the experimental set-up and then substituted with each of the planar absorbers.

Fig. 10 shows very good agreement between the measured radar backscatter measurements and numerical simulations for the 1120 μm thick FSS based absorber. The measured -10 dB reflectivity bandwidth of 15.37% and the position of the reflectivity null at 9.91 GHz compare favourably with the simulated values of 16% and 9.84 GHz.

However the correlation between the two sets of results is less perfect for the 140 μm thick absorber. Fig. 10 shows that the measured reflectivity null is shifted 988 MHz above the resonant frequency obtained from the numerical predictions. As a general observation it is noted that the sensitivity to dimensional tolerances (and surface resistance, Fig. 6) is very much greater for this ultra-thin structure, and our computer model shows that the measured frequency shift can be attributed to the presence of a 20 μm airgap between the metal ground plane and the unpatterned surface of the PET. To better match the numerical simulations with the experimental results, we have increased the surface resistance from 50 $\text{m}\Omega/\text{sq}$ used in the design, to 200 $\text{m}\Omega/\text{sq}$ in the CST model. This would account for (i) the slight increase in the thickness of the absorber, (ii) imperfections in the patterning of the hexagonal patch shown in Fig. 9a

4 Conclusion

Full wave simulations have been used to investigate the scattering of electromagnetic energy from ultra-thin absorbers which are manufactured from the same material as multi-layer insulation material. The physical thickness of these is compatible with the thin outermost layer of commercially available thermal blankets, therefore by printing a resistively loaded FSS on the top surface and exploiting the presence of the first foil backing layer in the composite structure, a microwave absorber can easily be integrated into the MLI. The results presented in this paper are for absorbers working at 10 GHz, and although the physical

Figure 7: Predicted frequency response for the (a,b) 140 μm and (c,d) 1120 μm thick absorbers at angles of 0° to 60° .

Figure 8: Computed -10 dB reflectivity bandwidths of the FSS based 140 μm , and 1120 μm thick absorbers in TE, TM and combined TE/TM planes working at angles of incidence of 0° to 60° .

dimensions can easily be scaled, operation at lower frequencies may result in a narrower reflectivity bandwidth because of the limitation on the maximum substrate thickness which is imposed to ensure sufficient flexibility of the material and to meet weight restrictions. A trade-off be-

tween the maximum obtainable reflectivity bandwidth and these physical restrictions is therefore required. The signal suppression when exposed to TE and TM waves between 0° and 30° is reasonably insensitive to the direction of propagation of the impinging signals. However the computed performance for larger angles of incidence is significantly degraded and therefore an alternative strategy should be used to create the in plane anisotropy that is required to balance the TE and TM waves. The RF behaviour of thermal blankets that are deployed on large spacecraft platforms could be enhanced by patterning the surface of the structure with a non-uniform periodic array. The FSS element size and surface resistance can then be designed to account for the spatial distribution of the antennas operating at different frequencies and mounted on a spacecraft platform [25]. The concept described is a promising solution which has the potential to reduce scattering from spacecraft structures and suppress the generation of passive intermodulation products which are produced by thermal blankets.

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(a)

(b)

Figure 9: Photographs of Unit cell Test Set-up (a)Photographic image of a $140\ \mu\text{m}$ thick unit cell measured using a TESA Visio 300, non-contact precision optical instrument. (b)Photograph of the bistatic reflectivity measurement set-up.

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Figure 10: Measured and predicted reflection coefficients of the FSS based absorbers working at normal incidence.

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