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Comparison of FSS Topologies for Maximising the Bandwidth of Ultra-Thin Microwave Absorbers

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Abstract—The maximum obtainable reflectivity bandwidth is compared for circuit analogue absorbers patterned with two different types of frequency selective surface (FSS). Metal backed resistively loaded FSS designs with thickness in the range of $\lambda/18$ to $\lambda/14$, were investigated to identify the crossover point below which the bandwidth of structures patterned with nested loops is narrower than a much simpler arrangement consisting of an array of patch elements. The results show that the deployment of a multi-resonant loop FSS, which are widely used to enhance the bandwidth of this class of microwave absorber, is undesirable below a threshold thickness where it is impossible to merge the individual absorption bands resulting from the nested loops. Numerical simulations are compared with radar backscatter measurements that were performed at normal incidence over the frequency range 7-14 GHz.

Index Terms—frequency selective surfaces, FSS, microwave absorbers.

I. INTRODUCTION

The deployment of thin microwave absorbers based on lossy metal backed FSS is desirable for electromagnetic cloaking of metal objects such as wind turbine blades and land, air and space vehicle platforms. For these applications, several critical design drivers are imposed on surface treatments which are required to reduce radar signature. These include robustness, minimisation, and the physical thickness to ensure no degradation of the aerodynamic performance of the host platform. The first reported planar absorber, the $\lambda/4$ thick Salisbury screen [1], exhibits a $-10\text{dB}$ reflectivity bandwidth of about 77%, but this can be increased to 117% by inserting a resistive FSS between the outermost 377 $\Omega$ square sheet and the ground plane [2]. However, this arrangement is too cumbersome for the above applications, and an alternative solution based on resistively loaded high impedance surfaces is preferable when the bandwidth requirements are less stringent. These thinner structures are composed of periodic arrays of patch elements placed above a metal ground plane. Resistive loading can be implemented by either integrating lumped resistors [3] into the periodic elements, patterning the FSS with a low conductivity metal [4] or by inserting a lossy substrate [5] in the gap between the FSS and the ground plane. The bandwidth is proportional to the absorber thickness but it can be enhanced by carefully selecting the geometry of the FSS pattern in conjunction with the resistance values.

This design strategy has been used to create high performance thin ($< \lambda/4$) absorbers by employing multi resonant FSS with two or more unequal size elements in each unit cell [3], [6], [7]. These generate discreet absorption bands at different frequencies which can be merged by a suitable choice of the physical dimensions and surface resistance values to obtain a $-10 \text{dB}$ reflectivity bandwidth well beyond the value that is available from a single resonance structure. For example, in [6] the authors reported the design and measurement of a 3 mm thick resistively loaded quadruple hexagonal loop absorber which exhibits 90% signal suppression over a bandwidth of 108% between 7.8 - 24.0 GHz, (thickness range $\lambda/12.25 - \lambda/4$). Numerical simulations show that a larger bandwidth (136%) is obtainable from a more complex unit cell topology formed by nesting four square loops and a center patch, with a different surface reflection resistivity for each of the five features [7]. However, although this technique is useful for enhancing the bandwidth of thin absorbers, it is not possible to merge the high $Q$ reflectivity nulls generated by the individual loops when the absorber is below a threshold electrical thickness. For these structures a better performance can be obtained using less complex FSS designs with unit cells composed of a single shaped patch element [8]. This threshold value, and a comparison of the bandwidths obtainable from ultra-thin absorber designs based on these two FSS topologies, has to our knowledge never been reported in the open literature.

In this paper CST Microwave Studio has been employed to optimize the performances of hexagonal shape loop and patch based FSS absorbers with thickness in the range $\lambda/18 - \lambda/14$, this is a narrowed range down based on the work reported in [9], where the author calculates a limit for the thickness of broadband electromagnetic absorbers. In addition to computing the maximum reflectivity bandwidths of the 6 structures, the work identifies the preferred FSS topology which should be used to create ultra-thin absorbers, based on the design thickness. The numerical simulations are compared with measured results at normal incidence over the frequency range 7 - 14 GHz.
II. PRINCIPLE OF OPERATION

The principle of operation of a FSS absorber is based on a lossy high impedance surface which is composed of a periodic array placed above a grounded dielectric slab. In the work reported in this paper, energy loss is obtained by printing the periodic arrays with metals that exhibit a surface resistance value which is slightly lower than the bulk material. The thin substrate material also exhibits inherent energy dissipation which is quantified by the loss tangent. The equivalent circuit of the structure consists of a parallel connection of the FSS impedance and the transformed impedance of the metal plate which is placed behind the periodic array. The ground plane presents an inductance ($L_{GP}$) when the structure is $< \lambda/4$ thick, and the FSS imaginary impedance is represented by either a capacitance for patch elements or a series of parallel LC circuits, one for each loop of a nested arrangement, as shown in Fig. 1. Resonance occurs at the frequency where the imaginary parts of the FSS impedance and the inductance presented by the ground plane cancel each other [10]. By selecting the value of $R$ which is used to represent the FSS dissipation loss in the equivalent circuit model, it is possible to match the structure to the impedance of free space (377 $\Omega$) and thereby maximize radar backscatter suppression [8].

III. NUMERICAL PREDICTIONS

To investigate the widest -10 dB reflectivity bandwidth obtainable from patch and loop FSS absorber topologies, we have computed the scattering coefficients from structures constructed of three different physical layers in the CST build model. The resistively loaded elements are patterned on a 140 $\mu$m thick dielectric substrate which has the same physical thickness and electrical properties ($\epsilon_r = 2.9$, $\tan \delta = 0.025$) as PET based Novele IJ-220 sheets [11]. This substrate was used to manufacture the prototype absorbers presented in section IV. For each arrangement the gap between the metal ground plane and the FSS sheet was filled with a lossless foam layer with $\epsilon_r = 1.05$ in order to emulate Rohacell material [12]. By applying appropriate boundary conditions, a single 3D unit cell was used to model infinite size periodic structures with plane waves impinging on the surface at normal incidence. Fig. 2a shows an exploded view of the composite structure and Fig. 2b and 2c illustrate the hexagonal patch and nested loop FSS topologies studied, where the diamond shape in the centre represents the unit cell box used in the simulations.

Absorbers constructed with hexagonal shaped patch elements exhibit broader bandwidths than square patches [11]. This is attributed to the larger surface area and the two additional coupling edges which simultaneously increase the capacitance and decrease the inductance [8] in the equivalent circuit model. Similarly, the reflectivity bandwidth obtained from hexagonal loops is larger than square shaped elements because of the higher packing density of the unit cells [6]. The numerical simulations were performed with the aim of optimizing the physical geometry and metal conductivity to obtain the maximum possible -10 dB reflectivity bandwidth centered at about 10 GHz.

Table I summarises the physical dimensions and surface resistance ($R_s$) values for each of the six different loop and patch based FSS absorbers investigated. $T$ is the electrical thickness of the absorber, $w$ is the width of the loops, $p$ is the periodicity for both topologies, $s$ is the space between the loops, $D_1$ is the internal diagonal of the external loop (or

![Fig. 1: Absorbers equivalent circuits. (a) Single loop or patch FSS; (b) Nested loops FSS.](image)

![Fig. 2: Geometry of the two FSS based absorbers](image)
Table I: Unit cell dimensions and surface resistivity of the two FSS absorber topologies.

<table>
<thead>
<tr>
<th>$T$</th>
<th>Hex. patch dimensions</th>
<th>Hex. loops diagonals</th>
<th>Hex. loops dimensions</th>
<th>Hex. Patch $R_s$ vs Hex. Loop $R_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda/18$</td>
<td>$D_1 = 3.0$ mm, $p = 5.4$ mm</td>
<td>$D_1 = 3.9$ mm</td>
<td>$w = 0.5$ mm, $s = 0.2$ mm</td>
<td>$R_s = 80\Omega/\text{sq}$ vs $R_s = 4.5\Omega/\text{sq}$</td>
</tr>
<tr>
<td>$\lambda/15$</td>
<td>$D_1 = 2.9$ mm, $p = 5.2$ mm</td>
<td>$D_1 = 3.9$ mm</td>
<td>$w = 0.5$ mm, $s = 0.2$ mm</td>
<td>$R_s = 57\Omega/\text{sq}$ vs $R_s = 4.45\Omega/\text{sq}$</td>
</tr>
<tr>
<td>$\lambda/14$</td>
<td>$D_1 = 2.9$ mm, $p = 5.2$ mm</td>
<td>$D_1 = 3.9$ mm</td>
<td>$w = 0.5$ mm, $s = 0.2$ mm</td>
<td>$R_s = 80\Omega/\text{sq}$ vs $R_s = 7\Omega/\text{sq}$</td>
</tr>
</tbody>
</table>

Table II: Simulated reflectivity bandwidth and FOM for two FSS absorbers.

<table>
<thead>
<tr>
<th>$T$</th>
<th>Hexagonal patch FOM / FBW%</th>
<th>Hexagonal loops FOM / FBW%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda/18$</td>
<td>470 / 27%</td>
<td>195 / 11%</td>
</tr>
<tr>
<td>$\lambda/15$</td>
<td>478 / 31%</td>
<td>608 / 40%</td>
</tr>
<tr>
<td>$\lambda/14$</td>
<td>497 / 38%</td>
<td>643 / 46%</td>
</tr>
</tbody>
</table>

Fig. 3: Simulated reflectivity bandwidth of the two FSS absorbers at normal incidence working at a center frequency of about 10 GHz for thicknesses in the range $1.64 \text{ mm}$ ($\lambda/18$) 2.14 mm ($\lambda/14$).

Fig. 4: Predicted maximum reflection loss versus fractional reflection bandwidth - 2.14 mm ($\lambda/4$) thick hexagonal FSS absorber, maximum FBW 38%.

The simulated reflectivity bandwidth of the two optimised absorber topologies is depicted in Fig. 3, where it is shown that the crossover point is predicted to be approximately 1.89 mm ($\lambda/15$). Below this threshold thickness, it is not possible to merge the individual absorption resonances that are generated by the nested loops and a better performance is obtained from the patch based topologies which are much easier to design. This is illustrated in Fig. 3 which shows reflection loss plots for three cases, one below ( 1.64 mm, $\lambda/18$) and the other two above ( 1.89 mm, $\lambda/15$) the threshold absorber thickness. Above the threshold thickness the two loops generate individual absorption bands which are merged to give a wider fractional bandwidth (FBW) than absorbers based on patch elements.

Table II summarizes the -10 dB reflection bandwidths and the Figure of Merit (FOM), which is defined as the bandwidth divided by the physical thickness normalized to the center operating frequency, for each of the absorber designs studied. This FOM is a very useful tool with which to evaluate the performance of microwave absorbers because it takes into account the design frequency and the physical thickness of the structure. For reference a classical quarter wavelength thick Salisbury screen [13] has a FOM of 300, and with the exception of the $\lambda/18$ thick absorber using the loop topology, all the other structures studied exhibit a FOM considerably higher than 300.

As a general observation the minimum reflection loss in most cases was found to be lower than 25 dB, and our computations show that a near perfect impedance match to free-space must be sacrificed to maximise the fractional bandwidth of this class of absorber. This is contrast to the design methodology often reported in the literature where value of the resistor is carefully adjusted in the computer model, to maximise the depth of the reflectivity null at resonance. The relationship between the fractional bandwidth and maximum radar backscatter suppression is illustrated in Fig. 4 for the case of a $\lambda/14$ thick hexagonal patch FSS absorber.

The resistive loading required to suppress radar backscatter is proportional to the thickness of the absorber [11]. However, there is a level of tolerance in how much the surface resistance may vary, such that the bandwidth and energy absorption are not significantly affected [11].

IV. CONSTRUCTION AND EXPERIMENTAL VERIFICATION

Hexagonal patch and double loop FSS based absorbers with thickness 2.14 mm ($\lambda/14$), have been manufactured and the radar backscatter from each structure was measured at normal incidence to confirm the accuracy of the numerical simulations. For rapid prototyping, an Epson Stylus C88+ inkjet printer with a maximum DPI of 600 was configured to provide a single pass trace and operate with a single inkjet cartridge. This was digitally configured for black and white printing and best photo quality resolution with a dot density corresponding to the required surface resistances which are given in Table I [4], [11]. The doubly periodic arrays were patterned on the surface of a 140 $\mu$m thick PET based Novele II-220 substrate [14], using Metalon JS-B25HV Nano Silver ink [15] and cured at room temperature in the laboratory for
Table III: Mixture and RGB code used to manufacture the absorbers.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Mixture (ink:solvent)</th>
<th>RGB code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop - Mixture 1</td>
<td>1:5</td>
<td>25,25,25</td>
</tr>
<tr>
<td>Patch</td>
<td>1:7</td>
<td>24,24,24</td>
</tr>
</tbody>
</table>

Fig. 5: Computed (solid lines) and measured (dotted line) reflectivity plots at normal incidence. (a) Loop topology, (b) Patch topology

48 hours to ensure complete evaporation of the solvent. Table III summarises the ink/solvent volume ratio and the RGB settings used in the printer, where (0,0,0) defines the maximum obtainable ink dot density of 600 DPI.

The printed FSS sheets were glued to the surface of a Rohacell foam spacer backed by a copper plate using a 3M repositionable spray glue. A photograph of the two structures is given in Fig. 7. Time gated bi-static reflection measurements were made in an anechoic chamber relative to a 20x22 cm² metal plate that was placed 80 cm (> 26λ) from the aperture of a pair of 20 dB standard gain horns which cover the frequency range 7 - 14 GHz. The experimental reflectivity plots for the two FSS absorbers working at normal incidence are shown in Fig. 5. These are compared with simulations based on the nominal design dimensions of the periodic array and the modelled surface resistance values given in Table I. In Fig. 5a the experimental results for the absorber based on FSS loops show an upward shift in the resonant frequency whereas for the FSS hexagonal patch topology (Fig. 5b), this is correctly centred at about 9.7 GHz, but in this case the radar backscatter suppression is lower than the values obtained from the predicted results.

To explain the differences between the computed and measured results, further investigations have been made using a TESA-VISIO 300 non-contact measurement machine, in order to obtain the physical dimensions and observe on a microscopic level the quality of the patterned elements. For the patch FSS, the gap between the elements was found to be about 10% smaller than the nominal design dimensions. Moreover Fig. 6b shows other limitations which occur when using a simple ink jet printer to pattern the FSS: a non-uniform metal edge profile and straight lines used to create the patterned array elements. The latter suggests that the surface resistance is not uniform across the surface of the patch and therefore may be slightly different from the desired value used in the numerical model. Further physical measurements made on a sample of the 2.14 mm (λ/4) FSS nested loops showed the inner and outer loop separation were 23% smaller than the nominal design values and the gap between the elements was 4.5% larger than the expected. This would explain the upward frequency shift observed in the measured results in Fig 5a.

V. CONCLUSION

In this study we have investigated the radar backscatter suppression properties obtained from two FSS topologies which are contending options for creating ultra-thin metal backed microwave absorbers for radar cross section reduction of aerodynamic platforms. Unit cells composed of resistively loaded nested loop elements are widely deployed to maximise the reflectivity bandwidth, however our results show that it is impossible to merge the discrete resonances that are generated by the individual loops when the structure is thinner than λ/15. Therefore ultra-thin electromagnetic absorbers below this threshold thickness should be designed using FSS arrays.
composed of resistively loaded patch elements. In addition to yielding a better electromagnetic performance in terms of the operating frequency range, the simpler pattern layout has significantly fewer structural design variables and therefore performance optimisation requires less computational resources and is much faster. Inkjet printing is a rapid and low cost solution for prototyping FSS based absorbers, but further work is required to overcome the limitations imposed on the dimensional accuracy and pattern quality which is needed for the operation of this class of ultra-thin absorber.

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