Resistive Fractal FSS Based Thin and Broad Band Radar Absorber

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Abstract - A novel radar absorber (RA) using Hilbert curve fractal geometry from 4 to 12 GHz, is presented. The panel RA is analyzed using transmission line model and simulated using simulation HFSS™2014. The crucial resistive Frequency Selective Surface (FSS) based layer comprising the Hilbert curve fractal is designed as an electrically very thin microwave PCB and fabricated using conventional photolithographic technology. Monostatic RCS measurements on RA reveal better than 10 dB RCSR over the desired frequency bands. The simulated and measured results agree closely and are encouraging. The size of panel RA is (280 mm × 280 mm) and total thickness is 6.2 mm (thickness = 0.165 λ) and the weight is 210 g. The panel RA with its low weight and low profile can be easily up scaled for aircraft stealth applications.

Keywords -Circuit AnalogRA, FSS, RCS, RCSR, spacecloth

I. INTRODUCTION

Radar absorbers need to be designed for primary electromagnetic (EM) absorption requirements and developed as flight worthy radar absorbing structures (RAS) meeting non-congenial EM and multi disciplinary specifications. But wider radar absorption bandwidths and low thickness are conflicting requirements. The technology is classified and it becomes crucial that an indigenous capability be attained as the technology is classified due to its purported stealth usefulness for aircraft stealth applications.

Non-magnetic dielectric radar absorbers such as conventional Salisbury screen[2,3] radar absorbers are simple in construction and comprise of 377 Ohms/sq. resistive sheet – the spacecloth a quarter wavelength thick dielectric spacer backed conducting plane, whose Radar Cross Section (RCS) needs to be reduced. Although simple in construction, an accurate design of spacecloth for realizing the desired surface resistivity is not available in open literature. This lacuna in accurate design of spacecloth has been successfully addressed in our earlier paper [4] wherein novel spacecloths have been designed as square geometrical grid on infinitesimally thin dielectric substrates (thickness = 5 mils) with resistors at the center of each side of the square grid.

Larger bandwidths may be realized with Jaumann absorbers [5-6] which are multilayer Salisbury screens with multiple spacecloths designed for different surface resistivities each separated by quarter wavelength thick dielectric spacers, finally backed by the conducting ground plane. The multiple \(\frac{\lambda}{4}\) (λ is the wavelength) thickness of Jaumann absorber limit its usefulness for aircraft stealth applications.

In a continued quest for extended RCSR bandwidths with weight and thickness constraints, circuit analog (CA) radar absorbers have been pursued consistently in which the resistive layers- the spacecloths are replaced by frequency selective surfaces (FSS) FSS are periodic surfaces in two dimensions and offer more flexibility and control in the design to realize octave bandwidths with smaller thicknesses compared to Salisbury screen counterparts. But the challenge in the design of CA radar absorbers is the realization of resistive FSS as pure FSS does not absorb EM energy and can only be designed to act as spatial microwave filters[7] for application in the out-of-band Radar Cross Section Reduction (RCSR) of stealth antennas. The CA absorbers are also known as metamaterial absorbers [8-9] in which the resistive FSS is realized by incorporating lumped discrete resistors. The reduced reliability due to soldering related defects, prohibitively expensive microwave resistors, increased component count and assembly and most important, the parasitic effects limit the applicability of these designs for aircraft/Unmanned Air Vehicle (UAV) stealth.

In our earlier papers[10-12], we have successfully overcome the deleterious effects of lumped resistors by proposing novel concept of embedded passives (EP) resistors totally eliminating lumped discrete resistors wherein thousands of resistors can be incorporated into the FSS layer with no soldering at all, resulting in quantum increase in reliability. The EP resistors are designed using ECAD PCB layout design software and developed using conventional PCB fabrication facility without resorting to exotic chemicals. These designs result in improved performance and reliability and are suited for aircraft stealth applications.

In [13], a capacitive method for design of wide band radar absorbers is proposed wherein the resonating RLC circuits derived from FSS geometries (for e.g., double square loops etc.) are replaced by patches. The motivation for choosing such low pass FSS geometries stemmed from the fact that the dielectric spacer backed conducting ground plane with thickness \(<\frac{\lambda}{4}\) behaves as inductance and hence, the FSS layer needs to be designed to cancel this inductance by its capacitance. In [14], a dual polarized radar absorber is described and the paper is bereft of any hardware implementation or validating experimental results. In this paper, we present the design, full-wave analysis using the 3D EM simulation software HFSS, fabrication and RCS measurements of a low profile, single layer panel radar...
absorber with weight and thickness constraints. The dielectric profile of this absorber is similar to Salisbury screen, but with wide band RCSR characteristics combined with reduced thickness. The panel absorber is designed for an RCSR of 10 dBsm (typical) from 4 to 12 GHz. The total thickness of panel RA is 6.2 mm. and the weight is 210 g. In the following sections, the EM design and simulation is detailed, followed by PCB design and fabrication of the resistive FSS layer and final verification of design and simulation by RCS measurements in the microwave anechoic chamber.

II. ELECTROMAGNETIC DESIGN

The dielectric profile of panel RA is given in Fig. 1 and comprises of 2nd order Hilbert fractal curve array FSS geometry. The top layer is the FSS layer as shown and is backed by the RF transparent dielectric spacer of thickness = 5.4 mm. The spacer used is Rohacel foam with an \( \varepsilon_r = 1.03 \) and \( \tan \delta = 0.0002 \). The dielectric spacer is backed by the conducting ground plane. The size of the panel RA is (280 x 280) mm.

![Fig. 1. Dielectric profile of panel RA.](image)

The thin and wide band RA is analysed for its performance in terms of transmission line model (TLM) and the equivalent circuit model is shown in Fig. 3. From Fig. 2 it is noted that the resistive Hilbert curve fractal FSS based textured layer is based on capacitive FSS and is a low-pass FSS type of element. The resistive FSS layer has surface impedance given by:

\[
Z_{FSS} = R_s + j \omega C_s
\]

The input impedance of a grounded dielectric slab behaves as an inductor until its thickness is lower than a quarter wavelength \([14]\) and its impedance is given by:

\[
Z_d = j\omega \varepsilon_r \tan(\beta d)
\]

The surface impedance of RA structure is given by a shunt connection between the lossy FSS impedance and the surface impedance of the PEC backed dielectric spacer. Using this approach, the free-space input impedance of RA for normal incidence is given by:

\[
\frac{Z_{in}}{Z_0} = \frac{Z_d}{Z_d + jZ_d \tan(\beta d)}
\]

where \( Z_d \) is the characteristic impedance of the PEC backed dielectric spacer, which behaves as an inductor (for sufficiently small thickness). \( Z_0 \) is the surface impedance of the FSS layer and \( \beta \) is the propagation constant of the spacer material.

The corresponding free-space reflection co-efficient, \( \rho \) of the absorber at normal incidence is given by

\[
\rho = \frac{(Z_{in} - Z_0)}{(Z_{in} + Z_0)}
\]

and reflectivity \( \Gamma \) by

\[
\Gamma = 20 \log_{10}(\rho)
\]

where, \( Z_0 \) represents the impedance of free space and is equal to 377 ohms.

The Hilbert fractal curve based FSS top layer acts as a capacitive sheet, and at resonance, the capacitance cancels the inductance of the dielectric backed conducting ground plane and the input resistance is matched to impedance of free space so that maximum absorption is obtained. For a dielectric RA, which is broadband and non-magnetic, minimum thickness constraint is given by Rozanov [16] as

\[
\lambda_{max} \leq \frac{172 d}{\Gamma_0}
\]

Where, \( \lambda_{max} \) is the wavelength at the lowest frequency, \( \Gamma_0 \) is the reflection coefficient in dB and \( d \) is the total thickness of RA. Hence, for desired RCSR and thickness, the lowest absorption frequency is constrained to a theoretical limit. Accordingly, the least thickness of a -10 dB wide-band dielectric RA such as proposed in this paper cannot be less than \((1/17.2)\) of the largest operating wavelength (at 4 GHz.) which is calculated to be 5.35 mm. The total thickness of RA proposed in this paper is 6.2 mm, and hence does not violate the fundamental design rules given in [16].

III. FULL-WAVE ANALYSIS USING HFSS SIMULATION SOFTWARE

Using the 3D EM simulation software HFSS 2014, the design is simulated to verify the performance. Based on Floquet’s theorem for periodic surfaces such as FSS, it suffices to simulate unit cell FSS geometry for analyzing the performance of RA. A unit cell Hilbert curve fractal FSS
based RA geometry model in HFSS is shown in Fig. 4.

The optimized simulation performance of RA from 4 to 12 GHz. with RCSR (typical) of 10 dB is shown in Fig. 5. Floquet’s port is used for excitation of the RA with periodic master and slave boundaries for the four sides of the unit cell, with de-embedding of the port. The unit cell is backed by the conducting ground plane which is modeled as PEC or perfect E boundary.

Fig. 4. Unit Cell resistive FSS based panel RA geometry model in HFSS.

The optimized input impedance plot of RA is shown in Fig. 6. The design is optimized to realize two resonances at 4.5 GHz. and 9.5 GHz. corresponding to the real part of input impedance of the grounded FSS layer which are 353 Ohms and 380 Ohms respectively, to achieve the desired RCSR bandwidth.

Fig. 5. Optimized simulation performance of panel RA.

The optimized design details of the unit cell FSS geometry is given in Fig. 7. This design is used for fabrication of the resistive FSS PCB layer of RA.

A. Parametric simulation studies

Parametric studies are carried out in HFSS to study the effects of variation in angles of incidence and effect of superstrate on RCSR performance of RA. Fig. 8 gives the simulation performance of RA for various angles of incidence (AOI) as witnessed in an airborne environment. It is observed that for an AOI of 30°, the worst degradation in RCSR of 8.5 dB is observed from 5.4 GHz. to 7.8 GHz.

Superstrate requirements stem from structural requirements of RA for flight worthy applications as the resistive FSS layer cannot be exposed to the harsh outside environment. Fig. 9 gives the simulation plots with superstrate.

A commercially available microwave dielectric substrate with \( \varepsilon_r = 2.08 \) and thickness 5 mils with \( \tan\delta = 0.002 \) is used in simulation. It is observed that there is no degradation in RCSR performance of RA for scan angles from 0 to 20 degrees. With superstrate, the 8 dB RCSR bandwidth for 30° scan angle shrinks from its original 5.4 to 7.8 GHz. to 5.5 GHz. to 7.6 GHz.

Fig. 6. Tuning the input impedance of RA. The top curve is the input resistance plot and bottom curve is the reactance part.

Fig. 7. Design details of unit cell of Hilbert curve resistive FSS.

Fig. 8. Simulation performance of panel RA with various angles of incidence. AOI varied from 0 to 30°.
RADAR ABSORBER DEVELOPMENT AND RCS EXPERIMENTS

The resistive FSS layer is designed as an electrically thin PCB using FR4 dielectric substrate of thickness 0.8 mm, using the PCB design software Visula v. 2.3. A commercially available thin film based resistive sheet with surface resistivity of 100Ω/square is used for fabrication of PCB. Conventional PCB fabrication technology is used for fabrication of resistive FSS PCB. The FSS PCB layer is bonded to the Rohacel foam dielectric spacer of thickness 5.4 mms. using a double sided Fixon tape. The FSS backed foam layer is bonded to the conducting back plane comprising of an EM conducting, tin plated copper foil available in (1ft. × 1ft.) size rolls. A photograph of the panel RA is shown in Fig.10.

Monostatic RCS experiments are carried out on panel RA in the microwave anechoic chamber to verify the design and simulation. The panel RA’s securely placed on an RF transparent thermocol stand on a single axis positioner and rotated in Azimuth from 0 to 360°. The conducting backplane serves as reference with which the RCS readings from RA side are compared. High directivity standard gain horn antennas are used for transmission and reception. Continuously variable phase shifter and attenuator are used in the two coupled ports of directional couplers connected to the transmitting and receiving antenna for performing vectorial cancellation of the background at each measurement frequency. RCSR readings are taken with a frequency step size of 500 MHz from 4 to 12 GHz. Fig.11 shows a representative RCSR plot of panel RA at 8.7 GHz. From the plot, it is observed that an RCSR of -15 dB is obtained at 8.7 GHz. Experimental RCSR plots for panel RA are carried out for all other mentioned frequencies in C and X bands and are available.

DISCUSSION OF RESULTS

i. A wide band panel RA is described in this paper. The size of the panel RA is (280 mm × 280 mm). The RA is wide band with RCSR of 10 dB (typical) from 4 to 12 GHz. The thickness of RA is 6.2 mm (0.165 λ) and the weight is 210 g. This small thickness qualifies the Hilbert fractal FSS based RA as a thin The relative RCSR bandwidth given by $\frac{f_H}{f_L} = 3$, where $f_H = 12$ GHz and $f_L = 4$ GHz. The wide band panel RA is designed for vertical polarization. However, a higher order resistive Hilbert curve array FSS geometry with 90° rotational symmetry could be easily used for designing circularly polarized RA.

ii. Measured RCSR and simulated RCSR readings generally agree to the tune of +/- 1 dB. This is attributed to tight fabrication and assembly tolerances of panel RA.

iii. The thickness of wide band panel RA is 6.2 mm. This thickness qualifies the panel RA to be used for airborne stealth applications. Also, for airborne applications, a carbon fiber reinforced plastic (CFRP) can be used as conducting backplane of RA as it satisfies both EM and structural requirements. Rohacel foam is an airworthy material and this spacer can be bonded to the top FSS layer and the bottom CFRP layer by a wet layup process using conventional composite fabrication technology.

iv. Fig. 8 gives the simulation plot for various AOI as is encountered in an airborne environment. The RA performance is simulated for AOI varying from 0 to 30°. It is observed from Fig. that the RCSR performance does not degrade for AOI up to 20°. Hence, this RA can be used for AOI variation from 0 to 20° without any degradation in RCSR performance.

v. Fig. 9 shows the parametric simulation studies of using a superstrate layer on top of the FSS layer. In [6, 14], for a single layer RA such as the panel RA described in this paper, superstrate that can be used to improve the angular performance should have a dielectric constant given by

$$\varepsilon_r = 1 + \cos(\theta)$$

where, $\theta$ is the (maximum) angle of incidence. For AOI =
30°, εr = 1.866. Hence a commercially available substrate with εr = 2.08 is used in simulation.

VI. CONCLUSION

The radar absorber described in this paper with its RCSR of 10 dBsm from 4 to 12 GHz finds applications in airborne stealth with its low profile and reduced weight. The space filling property of fractals is utilized to design radar absorber which has significantly lower profile and footprint and the design can be easily up-scaled to design a flight-worthy subsystem with primary RCSR properties along with good structural characteristics.

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REFERENCES


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