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Design and fabrication of an Ultra-Wideband Star-Shaped FSS Absorber with SMD Resistors

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Abstract—**In this paper, a novel circuit analog absorber based on Frequency Selective Surface (FSS) element loaded by only 8 Surface Mount Device (SMD) resistors has been designed, simulated, fabricated and measured. The proposed structure resulted in good 10dB absorption bandwidth about 107%, from 8.7GHz to 28.7GHz, which covers X, Ku and K bands simultaneously. The new absorber has angular stability of incidence about 40 degrees for TE polarization and 30 degrees for TM polarization which is good compared to similar structures reported in the literature. The total thickness of the fabricated and measured Circuit Analogue (CA) absorber is 3.96mm. Furthermore, by changing the dimensions, the SMD loaded star-shaped absorber can be redesigned to work in lower or higher frequency bands with proper absorbing properties. This proposed structure which includes the number of unit cells, measured using the waveguide measurement method due to the simplicity and availability of the measurement method.**

Keywords— RCS Reduction, Frequency selective surface, FSS absorbers, resistor elements.

I. INTRODUCTION (*HEADING 1*)

Nowadays, RCS reduction is a very important issue for stealth aircrafts. The two main techniques for RCS reduction are shaping and using radar absorbing materials (RAM). By changing the shape, the scattered fields swerve from radar orientation [1]. Although this method is useful for monostatic radars, it leads to change more in target shape for bistatic radars; therefore, it causes aerodynamic problems.

Using electromagnetic absorbers with complex susceptibility and permeability solves aerodynamic problems, but it increases the weight of the aircrafts. An ideal absorber should be low profile, inexpensive, easy to build, stable to angle of incidence, and also have significant bandwidth. One solution to decrease the weight is to use Salisbury screen and Dallenbach layer. Salisbury screen is a resistive sheet mounted a quarter-wavelength from a metal sheet. As these sheets should be suspended in the air, they are not more applicable. In addition, manufacture of the resistive sheets is very Costly and needs particular technology. Using one layer structure results in narrowband response and it is good only for perpendicular incidence. Jaumann absorbers which implemented by cascading two or more resistive sheets with different resistances spaced each other a quarter-wavelength, result in wideband response. However, the whole structure becomes very heavy and bulk, so they cannot be located on movable parts of the target. Both Salisbury and Jaumann absorbers show real input admittance at their interface [2]. In five past decades, a lot of investigation has been attracted to periodic structures. Lossy frequency selective surfaces (FSS) are vastly used to fabricate thin and lightweight absorbers. Real admittance sheets in Salisbury and Jaumann absorbers can be replaced by complex admittance sheets including FSSs made of resistive materials. Such the surfaces are named circuit analog (CA) absorbers. The reactive part of the admittance obtained by FSS elements, can improve impedance matching and bandwidth. Since these structures have good bandwidth behavior and low return loss, they have been more attractive to researchers and engineers. Different CA absorbers have been used for RCS reduction such as square and cross elements [3], circular patch, double square loops [4], Fractal structures, multilayer square structures and spiral FSS instead of ground plane in patch antenna printed on resistive sheets. , also FSS are widely employed in antenna's radar cross section (RCS) reduction [5]. The number of layers is based on required bandwidth and absorption. The most important issue in such structures is scarce of resistive sheets and need of advanced fabrication technology.

Furthermore, the resistance quantity (Ω/m^2) has a key role in the frequency behavior of such structures and also the fabrication of a resistive sheet with desired quantity is expensive or sometimes impossible. Instead, the lossy FSS layer can be made by lumped or SMD resistors printed on copper or tantalum [6]. Such an absorber could be produced easily by available low price materials. So, the cost of the whole structure only depends on the number of SMD resistors which are employed. In [6] a CA absorber with a double square loop unit cell printed on FR4 layer loaded with 16 lumped resistors was presented. This absorber resulted in 126% relative bandwidth for normal incidence with -10dB reflectivity and absorption stability up to $\theta = 30^\circ$ for both TE and TM polarization.

This paper introduces a novel lossy FSS absorber made of a 2-D array of star-shape FSS unit cells loaded by 8 SMD resistors. The structure which has a thickness of only 3.96mm resulted in a broad bandwidth about 20GHz for reflectivity of -10dB. This novel absorber also shows good angular incidence stability up to 40° for TE and TM polarizations. Furthermore, by changing the dimensions, the SMD loaded star-shaped absorber can be redesigned to work in lower or higher frequency bands with proper absorbing properties. Finally the structure which includes a number of the unit cells,

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measured using the waveguide measurement method for measurement simplicity.

This paper is organized as follows. After the introduction, section II introduces the novel resistors loaded FSS printed on FR4 layer and dimensions and simulated frequency behavior are given. Section III discusses the structure features. Section IV describes the fabrication, measurement technique and results. Finally, the conclusion is represented in section V.

II. CIRCUIT ANALOG FSS ABSORBER STRUCTURE

A. *Equivalent circuit model and design procedure*

The equivalent circuit model for a star-Shaped FSS (ECM) is based on the theory proposed by [7], which developed the initial expression for periodic gratings. According to [7] the series RLC circuit model shown in Fig. 1 is equivalent to the patch. These equivalent lumped elements are in parallel to shorted transmission lines. The length of the transmission lines represents the thickness of the dielectric h2 and spacer h1 shown in Fig. 2 with corresponding characteristic impedances Z. To obtain the R, L and C values, the star can be considered as a loop multiplied by a correction factor. Once the element values were determined, the recursive relations [7] were employed to calculate the patch dimensions. Since, the relations are very complex for a star-shaped ring; first the dimensions are estimated, and then optimized using CST software.

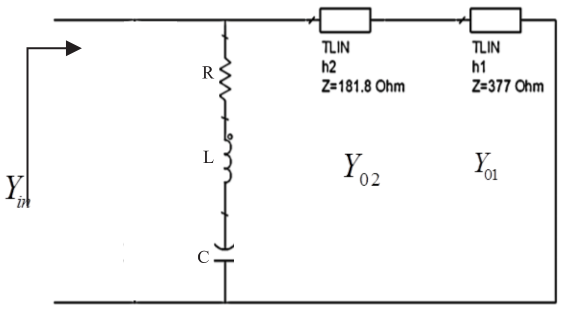


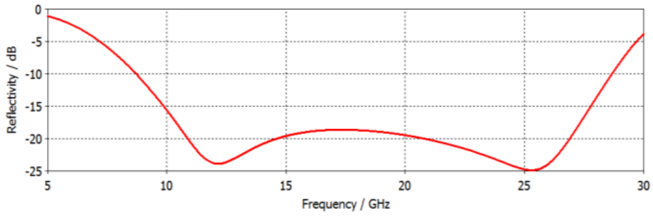
Fig.

Fig. 1. The equivalent circuit model of star-shaped FSS

B. *Geometry*

Fig. 2 shows the geometry of the star-shaped FSS unit cell loaded by 8 lumped resistors. The FSS unit cell should be mounted $\lambda/4$ from the ground plane. For physical strength, this space is usually filled by a foam with dielectric constant nearly equal to 1. Therefore, the height of the foam, h1 is a quarter-wavelength. The copper is simply available and more inexpensive than tantalum used in conventional absorbers, therefore in this work the star-patch has been printed on the copper layer over a FR4 substrate.

Physical dimensions of the CA absorber have been given in Table 1. The thicknesses of the metallic ground plane and top copper layer are 0.01mm and 0.017mm, respectively. Fig.3 illustrates the simulated reflectivity diagram of the final structure with 105Ω resistors. It should be noted that all simulations in this paper have been done using the commercial numerical software CST Studio Suit. As depicted in Fig. 3 the designed absorber has a wide 10-dB absorption bandwidth from 8.7GHz to 28.7GHz (107%) and covers X, Ku and K bands simultaneously. Meanwhile, the 15dB absorption bandwidth is about 97%.



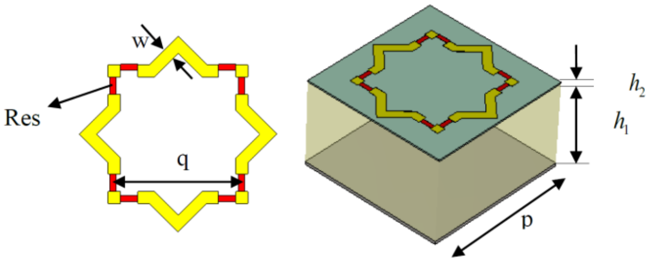


Fig. 2. Top view and perspective view of the resistor loaded star-shaped FSS absorber

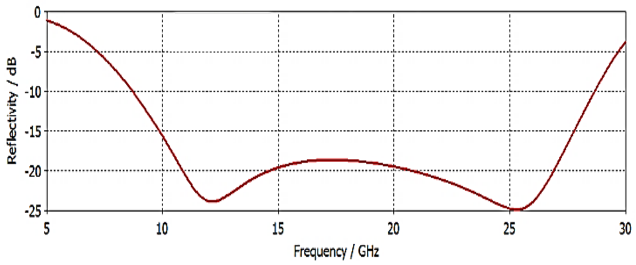


Fig. 3. Reflectivity diagram for designed CA absorbers

Table 1: Physical parameters of a unit cell of the proposed absorber

Parameter	Value
P	4.2mm
Q	2.8mm
h_1	3.68mm
h_2 (FR4 layer)	0.25mm
W	0.5mm
Frequency Bands	8.7GHz- 28.7GHz (X, Ku, K)

III. STRUCTURE FEATURES

A. *Angular stability*

One of the key properties of a microwave absorber is stability of reflectivity with respect to polarization and angle of incident variations. Simulations have been down to investigate these properties and the results have been shown in Fig. 4.

It is observed that the absorber has been shown acceptable -10dB reflectivity response for both polarizations for incident angles up to $\theta = 40^{\circ}$. Note that for TM polarization the frequency response shifts to right by increasing the angle of incidence.

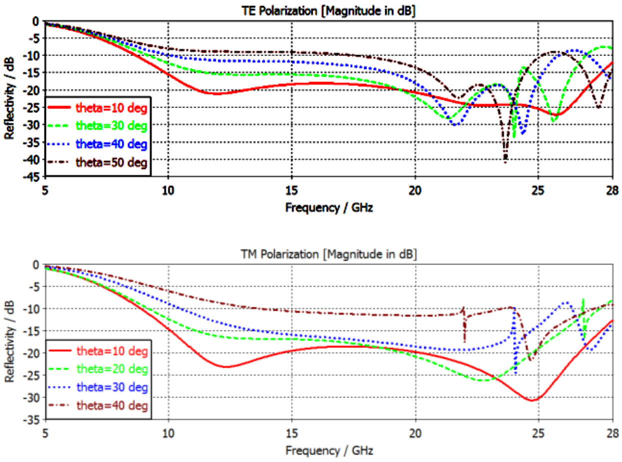


Fig. 4. The effect of incident angle on the reflectivity of the designed absorber for both TE and TM polarizations.

B. Design C-band absorber

As mentioned before it is possible to redesign the proposed absorber to change the working frequency band. In this subsection, another design is shown. The structure with parameters p=12, q=8, w=1.4, h_1=12.4, h_2=0.25 (mm) is used. The total thickness of the absorber is 12.7mm. The simulation results are depicted in Fig. 5.

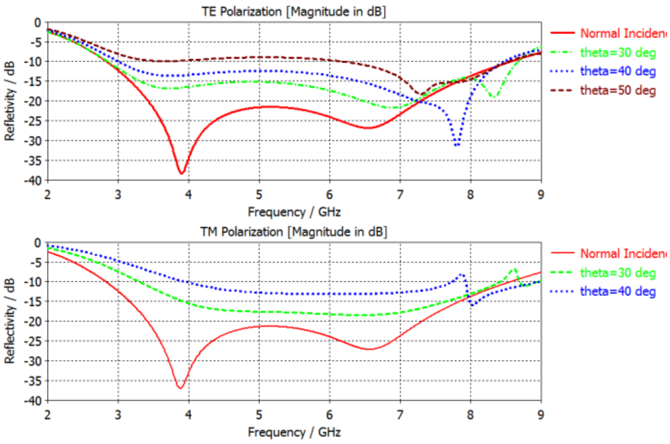


Fig. 5: Reflectivity diagram for C-band CA absorbers, TE and TM polarizations, normal and oblique incidence

As it is seen, the absorbing bandwidth is about 107% (from 2.8 to 8.6GHz) for -10dB reflectivity and about 72% for 20dB absorption. The angular stability of 40 degrees is observed for both the polarizations.

C. RCS reduction behavior

The RCS of a two dimensional target followed:

$$\sigma = \lim_{\rho\to\infty}\left(2\pi\rho\frac{S_s}{S_i}\right) \qquad (1)$$

Fig. 6 shows the monostatic RCS reduction of the proposed absorber at normal incidence. A 13-13 array of unitcells has been considered so that the total dimension of the structure under study was about 10λ at the center frequency. After the RCS has been calculated by CST software, its difference with respect to the RCS of a ground plane with the same size was obtained.

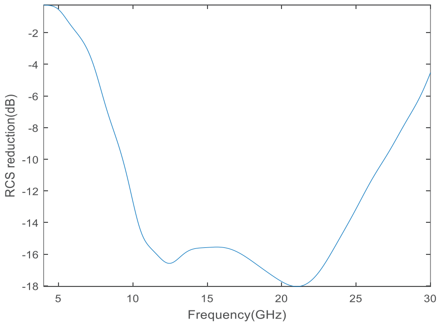


Fig. 6: Monostatic RCS reduction of star-shaped FSS at normal incident

IV. FABRICATION AND MEASUREMENTS

Fig. 7 shows the fabricated proposed absorber which includes two star-shaped FSS unit cells printed on FR4 substrate, each one loaded by 8 SMD resistors. The dimensions are the same as reported in Table 1 using 105Ω resistors. Different measurement methods are used to examine absorbers. To reduce cost and difficulties of the implementation, the waveguide method was employed [9]. In this method, two or more unit cells of the FSS structure are located on a foam spacer and inserted in a short-circuit waveguide. Usually in X-band, C-band and S-band measurements, The WR90, WR229 and WR284 are utilized, respectively.

In this work, the absorber has been designed for X-band; therefore, WR-90 was used to evaluate the performance. The return loss of the structure located in the appropriate waveguide was measured using vector network analyzer. Considering the fact that WR-90 waveguide can only support a single TE-mode, it is mandatory to provide the same condition in CST Studio (or HFSS) for comparing the experimental measurement results with the simulation results. This measurement setup has been shown in Fig. 8. The comparison between measurement and simulation results has been depicted in Fig. 9.

The experimental results are fairly close to the analysis. However, there are some discrepancies between the experimental results and the simulation results. These differences are due to the potential errors in the fabrication procedure. These errors are usually arisen from geometry of the samples (discrepancies in size and thickness). Another reason is the way of feeding the samples. Waveguide ports are employed in the simulations; however, coaxial cables are used in practice. Furthermore, using finite number of cells ruins periodic nature of the absorber and affect the experimental results. Also, another source of the errors can be attributed to SMD resistors.

Table 2. Comparison between proposed FSS and a number of good designs presented in articles

Ref.	Angular stability (degrees)	Thickness (mm)	Fractional Bandwidth (%)	Unit Cell of Structure
[9]	40	9	117	Salisbury resistive
[3]	30	2	92.2	Triple square
[6]	30	13.2	126	Double square
[10]	30	3	52	DSL loaded with 16 resistors
This paper	30-40	3.96	107	Star-Shaped FSS loaded with 8 resistors

Table 2 compares the proposed structure in this work with a number of good designs presented in the literatures. As shown in the table, the proposed star-shaped FSS has good angular stability along with high bandwidth. Also, this absorber has a small volume resulting from its small thickness. The remarkable advantage of our model with respect to [6] which shows high bandwidth behavior is due to using only 8 resistors per unit cell compared to 16 resistors per unit cell employed in [6]. As mentioned before the main cost of the whole CA absorber depends on the number of SMD resistors. As a result, the cost of the proposed structure is nearly half of the structure reported in [6].

Fig. 7. The fabricated star-shape resistor loaded CA absorber

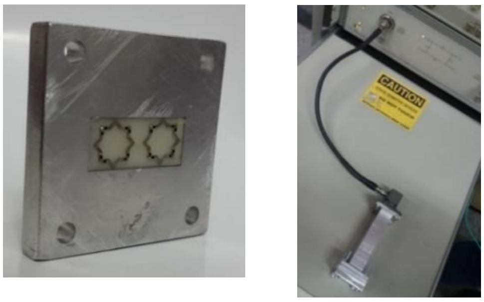


Fig. 8: The waveguide method measurement procedure (left) two unit cells of the lossy FSS absorber surrounded by waveguide, (right) Measurement setup.

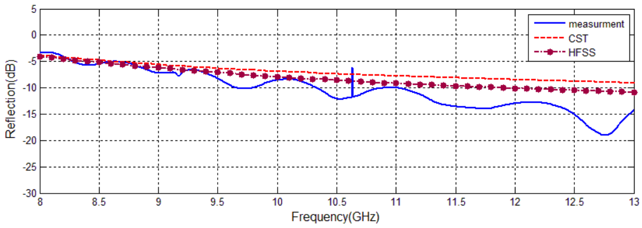


Fig. 9: The measurement and simulated return loss of proposed absorber in waveguide measurement method

V. CONCLUSION

In this paper, a new thin lossy FSS absorber which includes star-shaped unit cells loaded by SMD resistors was presented. The FSS unit cells were fabricated from copper instead of tantalum conventionally used in such structures. Copper and the FR4 substrate are simply available and inexpensive. Since, the whole cost of the proposed structure depends only on the number of SMD resistors; we tried to use only 8 resistors in each unit cell. The absorber was designed to work in wide frequency range of 8.7GHz - 28.7GHz. The proposed absorber with total thickness of 3.96mm was fabricated and the return loss behavior was measured by waveguide measurement technique.

The angular stability of the proposed structure was investigated by CST Studio Suit Software. It was shown that this absorber shows acceptable frequency response for -10dB reflectivity in both polarizations for incident angles up to $\theta = 40^{\circ}$. This novel proposed absorber can be redesigned for different absorption frequency bands by changing the unit cell physical dimensions. For example, a low frequency absorber was designed and its absorption bandwidth and angular stability were investigated. Simulations revealed this structure has 10dB absorption bandwidth about 107% (from 2.8 to 8.6GHz). Meanwhile, 20dB absorption bandwidth is about 72%. Also, the angular stability is up to 40 degrees with respect to both polarizations.

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