Design of a frequency selective surface element using Fibonacci series for invisible radome application

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Abstract:
In this paper, a novel Fibonacci FSS element is presented based on the golden ratio of nature's numbering system. A dual resonance is obtained using the combined effect of the Single square loop and Fibonacci element to generate passband characteristics. Then, a multilayered radome wall has been demonstrated by embedding the proposed FSS element in the dielectric skin. The radome structure shows better angular stability for a wide angle of an incident electromagnetic wave up to 60 degrees which is more desirable for radome application The proposed structure is found to show bandpass characteristics in the frequency range of 9.5-12.58 GHz with very good transmission efficiency (>90%).
Keywords— Conformal FSS, Fibonacci FSS, radome,

I. INTRODUCTION

The wide variety applications Frequency selective surfaces (FSSs) to reflect, transmit or absorb electromagnetic fields based on the frequency ranges, made them feasible for commercial, medical, industrial and aerospace applications [1]. The radome must be transparent to RF energy, hence the signal can exit, forms an echo and return to the radar. The operation of the radome will be prevented if the radome has a metal body. Earlier, composite radomes made of fibreglass served as transparent radomes. Yet the radome must be opaque to enemy radar, this can be achieved by a band-pass radome [2]. In this regard, a transparent radome configuration is presented with invisible characteristics at out of the band. For this purpose, to prevent reflection of the incoming power, frequency selective surfaces loaded with the lumped resistors are employed. To obtain the pass-band properties in lower frequencies, the convoluted slots are utilized [3]. A conformal thick-screen FSS radome for the reduced radar cross section (RCS) has been discussed in [4]. Recently, a Swastika-shaped metamaterial structure has been reported for radome application. Which includes a planar multilayered radome wall configuration with thick Arlon layer embedded with Swastika-shaped MTM FSS as the middle layer backed by two thin quartz-based laminations on each side [5]. However, the performance of the structure suffers at high incident angles and exhibits limited operating bandwidth. Also, the thickness of the structure is high, which increases the payload of aircraft.

In this paper, a novel bandpass FSS radome is proposed with broadband characteristics. Two FSS elements viz. single square loop and a Fibonacci element have been considered to generate two stop bands. The passband between two stopbands is thus employed to operate radome wall. As moving from the front end to back end of a conical radome, the surface becomes conformal. Hence, to make sure the working of the proposed structure for radome application, a conformal analysis has been performed. In addition, the structure shows a stable response at a higher angle of incidence for both TE and TM polarized EM wave. The analysis is performed with the help EM full-wave simulation tool CST Microwave Studio (CST MWS). Compared to the structure of other elements, the miniaturization characteristic of proposed FSS is superior to that the aforementioned elements exhibit. The design methodology, working of the proposed structure in both planar and conformal shape is explained in further sections.

II. DESIGN OF FSS ELEMENT

The main part of the structure design is Fibonacci FSS element. The element is inspired from nature's numbering system known as “Fibonacci numbers”. It can appear elsewhere in Nature, from the leaf arrangement in plants to the shell of the chambered Nautilus. A quick inspection shows that this sequence of numbers can go on infinitely. It begins with two 1’s and continues to get succeeding terms by adding, each time, the last two numbers to get the next number (i.e., 1 + 1 = 2, 1 + 2 = 3, 2 + 3 = 5, and so on). Moreover, there are no numbers in all of the mathematics as ubiquitous as the Fibonacci numbers. The design geometry will explore their relationship with the most beautiful ratio, known as the "golden ratio”. Here the Fibonacci numbers, when taken as quotients in consecutive pairs, approach the golden ratio [6]:
phi = 1.61803. . .
The Fibonacci spiral is shown in Fig. 1a. The spiral element is

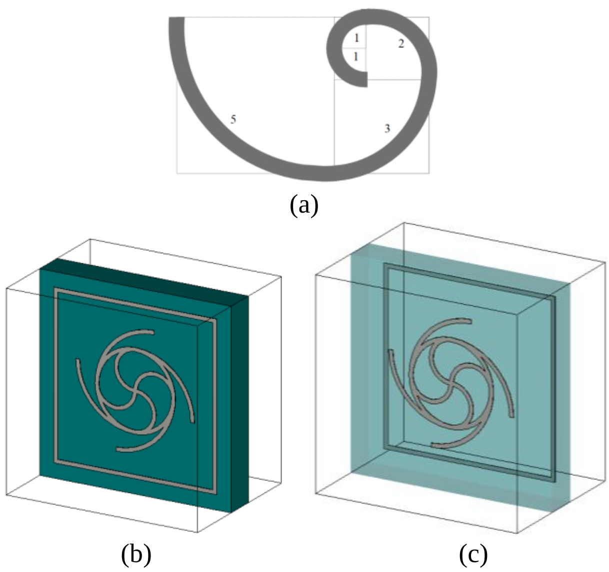


Figure 1 Design of FSS elements. (a) Fibnocci spiral, (b) Type- I, (c) Type- II.

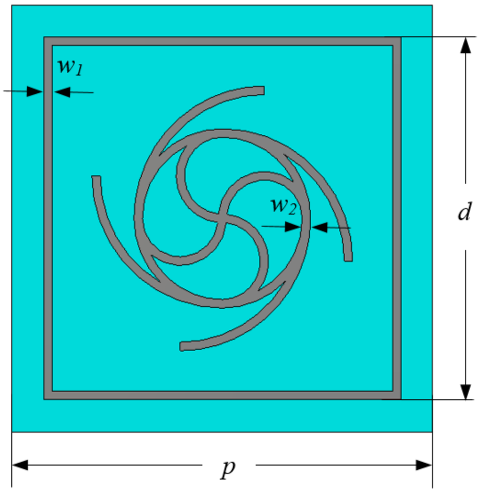


Figure 2 Unit cell of proposed FSS elements with notations.

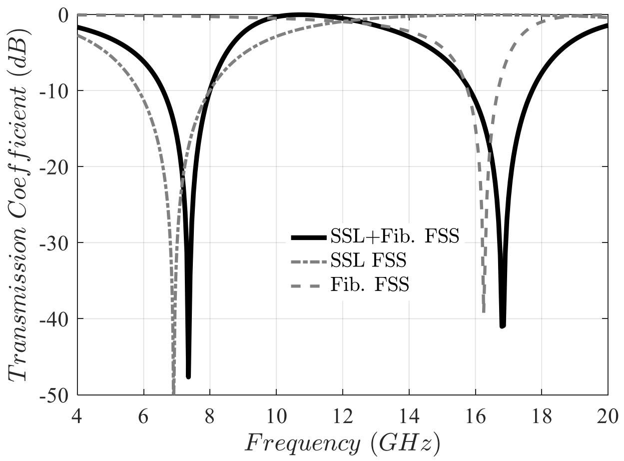
started with a ring radius of 1 mm and terminated at 5 mm. The FSS element using Fibonacci spiral is given in Fig. 1b-c.

The single spiral element is repeated four times with the rotation angle of 90 degrees from the centre of the structure, forms a centre connected FSS element. The element is enclosed by SSL FSS to generate dualband response. The performance of FSS element is analyzed in two types. In Type-I, Fibonacci and SSL FSS elements are placed on top of the substrate layer and in Type-II, SSL FSS is printed on the bottom side of the substrate by keeping Fibonacci FSS at top surface. As a result, a novel dual band FSS is formed. It can act as a band-pass filter in the frequency range of interest. In both cases, it shows a stable transmission response w.r.to the wide angle of incidence, thus efficient to the polarization because of the spiral shape. Here, Fibonacci FSS is having circular polarization and square loop element will work for linear polarization. The structure is designed to operate at around 11 GHz and Rogers 5880 substrate ($\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$ at 10 GHz) used as a dielectric substrate with a thickness of 1.57 mm. The conductive metal FSS layers are made of copper (conductivity of 5.8×10^7 S/m). The unit cell dimension is $0.36\lambda_0 \times 0.36\lambda_0$ and height of the substrate is $0.058\lambda_0$ where λ_0 refers to the free space wavelength.

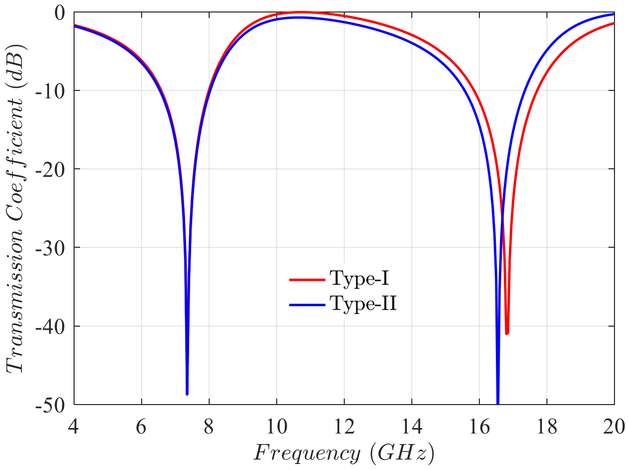
The structure is a resultant of two reflective FSS elements. The SSL FSS is designed to resonate at C-band and Fibonacci FSS is designed at resonating in Ku-band. Then, the two structures are combined to exhibits double resonance. As result, a wide passband is obtained in between two resonant bands which cover entire X-band regime. The evolution of proposed response is clearly depicted in Fig.3a. The bandpass characteristics of mentioned FSS element are depicted in Fig. 3b. At a normal incident angle, the Type-I structure shows a better than 1 dB (90%) passband in the range of 9.5-12.58 GHz with a relative bandwidth of 32.42%. Whereas, at 3dB(50%) bandwidth in the range of 8.85-14.04 GHz with 58.75% relative bandwidth. The second structure Type-II exhibits a better than 1 dB (90%) passband in the range of 9.8 – 11.55 GHz with a relative bandwidth of 17.85%. Whereas, at 3dB(50%) bandwidth in the range of 8.85-14.04 GHz with 51.68% relative bandwidth. Hence, it is believed that the realized bandpass characteristics of FSS element can make them a better candidate to use as a radome wall structure.

A. *Conformal Analysis*

In this section, the response of the same structure is analyzed in conformal shape by considering its potential applications in sub-reflectors and radome walls for EM cloaking [7]. EM cloaking is a method of hiding a target from EM wave impinge on it. This concept has found extensive applications in modern military aviation, as aircraft are required to be hidden from

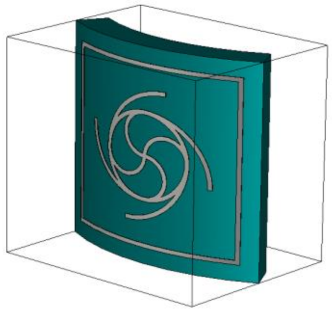


(a)



(b)

Figure 3 Transmission response of FSS element. (a) Evolution of dualband, (b) Type- I and Type- II



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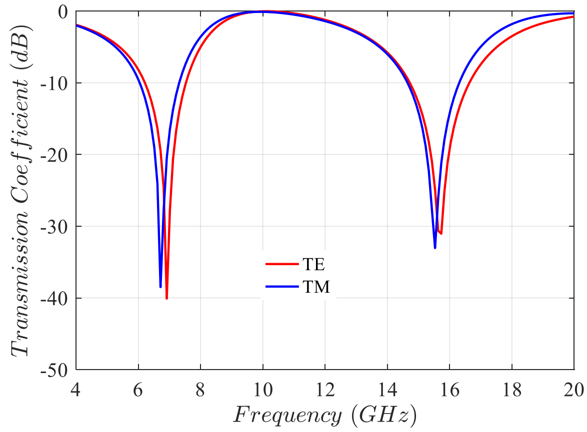


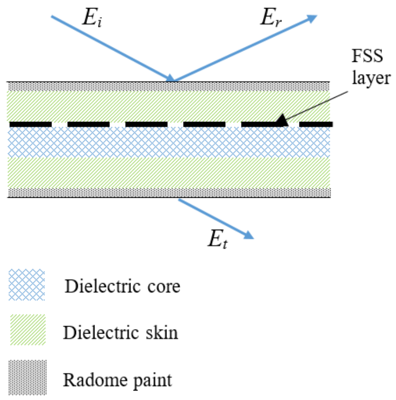
(b)

Figure 4 Conformal FSS, (a) Unit cell topology, (b) Transmission coefficient for TE and TM polarization.

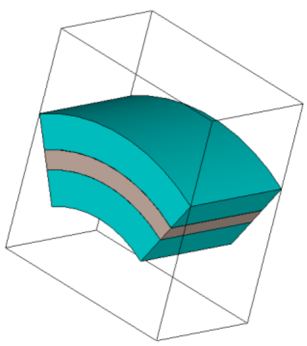
enemy's radar. Conformal shapes mostly dealt by aerospace domain and it leads to the requirement of conformal cloaking unit cells. From the results, it has been observed that the curvature of the unit cell affects the material properties. The conformal shape and transmission response of the structure is depicted in Fig.4a-b respectively. In general, the transmission response for a planar structure for TE and TM polarization is same at a normal angle of incidence. But in the case of conformal shape due to cylindrical bent, the transmission response slightly deviates at normal incidence.

III. Design and EM Performance Analysis of Proposed Radome Structure

In this section, a multilayered radome wall is designed by embedding proposed FSS element structure into dielectric layers. Proposed bandpass FSS element is embedded in the mid plane of a radome skin. Here, Rogers 4003C ($\varepsilon_r = 3.38$ and $\tan\delta = 0.0021$) layer of optimized thickness 2.75 mm has been chosen as dielectric skin and then a layer of anti-corrosion radome paint ($\varepsilon_r = 3.46$ and $\tan\delta = 0.068$) with 0.2 mm thickness is painted on either side of the skin. The simulation model of the structure is shown in Fig. 4a. The plane wave is excited from the top of the bounding box and passes through the structure as shown in Fig. 4c. To observe the behaviour of structure for oblique angle of incidence, the structure is simulated up to 60-degree incident angle for both TE and TM polarized waves. Thus, the transmission coefficient of the structure is computed and illustrated in Fig. 5. Of the results, it is evident that the structure of more stable for wide incident angles, which is the more desirable property of an airborne radome. It is known that the shape of a streamlined nose cone radome in ogive shape. The dimensions are, height is 1.4 m and base diameter as 0.69 m. At the broader dimension (at the base) the FSS element will act as almost planar structure.



(a)



(b)

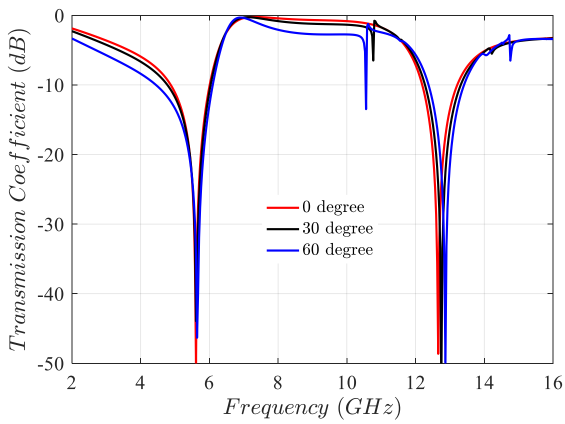
Figure 5 Design of FSS radome, (a) Planar, (b) Conformal

TABLE I. Optimized Design Parameters

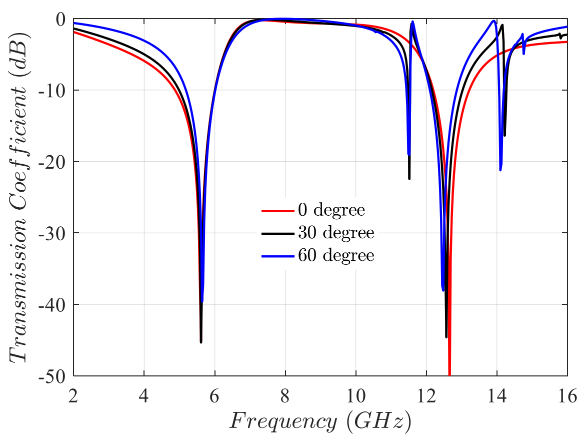
Parameter	Value (mm)
p	10
d	8.5
w_1	0.2
w_2	0.2
h	1.57
h_1	2.75
h_2	2.75

But, the diameter reduces as moving from base to the tip of the cone, where the FSS element will be conformal. Hence, it is more desired to examine the behaviour of FSS structure in conformal shape. For better performance analysis, it is assumed that the FSS element is located at the point where the diameter of the structure is 30 mm. By these considerations, the FSS along with dielectric walls is designed in conformal shape and simulated. The curved surface is shown in Fig. 5b.

The EM performance characteristics of proposed passband radome are analysed for wide incident angles in both planar and conformal shape. The 1dB and 3dB bandwidth of in two cases are summarized in Table II. The sharp surges are formed in the transmission response of analyzed planar and conformal structures (Fig. 6 and 7) at higher incident angles. It is mainly due to the instability of individual FSS elements due to second order modes. This can be avoided by suppressing higher modes. Moreover, the FSS element offers a higher degree of flexibility in terms of bandwidth. The desired bandwidth and resonances can be obtained by tuning the FSS elements. This model can be useful to design radome structures with the stable angular response with reduced outband RCS.



(a)



(b)

Figure 6 Transmission response of a planar radome structure at oblique incident angles. (a) TE, (b) TM

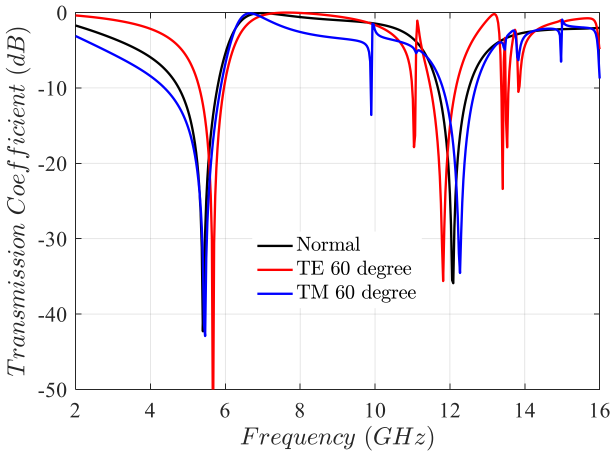


Figure 7 Transmission response of conformal FSS radome wall.

TABLE II. EM PERFORMANCE OF RADOME WALL STRUCTURE

BW (GHz) / Angle (deg)	1dB		3dB	
	Planar	**Conformal**	**Planar**	**conformal**
0	3.65	2.52	5.01	4.72
30	3.68	2.4	5.01	4.02
60	0.70	0.75	3.93	2.24

IV. CONCLUSION

A novel dual-band FSS element is presented with broadband characteristics. The proposed structure is found to show bandpass characteristics in the frequency range of 9.5-12.58 GHz with very good transmission efficiency (>90%). Further, a multilayered planar radome wall has been designed by embedding proposed FSS structure into a multi-layered dielectric layer, which showed very good bandpass response including stability w.r.t. the angle of incidence and polarization. In view of airborne radome applications, the conformal analysis has been performed on multilayered radome wall. In planar form, the structure has shown a very good bandpass characteristics from 6.75 – 10.40, whereas in the conformal form it has exhibited from 6.44 – 8.96 GHz.

REFERENCES

[1] B. A. Munk. *Frequency selective surfaces –Theory and design*, New York: Wiley, 2000.

[2] D. J. Kozakoff, *Analysis of Radome enclosed Antennas*, Artech House, Norwood, Mass, USA, 2009

[3] LIU Li-Guo, LI You-Quan, MENG Qing-Zhi, WU Wei-Wei, MO Jin-Jun, FU Yun-Q, YUAN Nai-Chang, “Design of an Invisible Radome by Frequency Selective Surfaces Loaded with Lumped Resistors,” *CHIN. PHYS. LETT*. Vol. 30, no. 6, pp. 064101–1-064101–4, 2013

[4] B. Q. Lin, F. Li, Q. R. Zheng and Y. S. Zen, "Design and Simulation of a Miniature Thick-Screen Frequency Selective Surface Radome," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, no. , pp. 1065-1068, 2009. doi: 10.1109/LAWP.2009.2032251

[5] B. Sangeetha, G. Gulati, R. U. Nair and S. Narayan, "Design of airborne radome using Swastika-shaped metamaterial-element based FSS," *IEEE Annual India Conference (INDICON)*, Bangalore, 2016, pp. 1-5.

[6] A. S. Posamentier, I. Lehmann, *The Fabulous Fibonacci Numbers*, by, 59 John Glenn Drive Amherst, New York 14228-2197

[7] M. Nauman, R. Saleem, A. K. Rashid and M. F. Shafique, "A Miniaturized Flexible Frequency Selective Surface for X-Band Applications," *IEEE Transactions on Electromagnetic Compatibility*, vol. 58, no. 2, pp. 419-428, April 2016.

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