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APPLICATION OF BIONICS IN FREQUENCY SELECTIVE SURFACE DESIGN AND ANTENNA RADAR CROSS SECTION REDUCTION

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Abstract—Bionics principle is applied to frequency selective surface (FSS) design in this paper. To authenticate the method, a novel bionic and miniaturized FSS is proposed by use of a model of alternate phyllotaxis. The simulated and measured results show that the proposed FSS has a much smaller size and maintains other FSS-related performances. To study the applications of the novel bionic FSS in practice, it is used for the ground plane of an antenna array to reduce the antenna radar cross section (RCS). Compared to a reference antenna, the antenna with bionic FSS has lower RCS and favorable radiation performance. Hence, applying bionics principle to FSS design and antenna RCS reduction is proved feasible, which will serve as a good candidate for the future design of FSS and antennas with or without a requirement of RCS control.

1. INTRODUCTION

Bionics has been successfully applied to various fields. The utilization of bionics in synthetic constructs is desirable because evolutionary pressure typically forces living organisms to become highly optimized and efficient. Biological methods and systems found in nature can be applied to the study and design of engineering systems and modern technology, from which the concept of bionics is derived. The author applied the bionics principle to antenna radar cross section (RCS) reduction in 2009 [1]. Many other bionic models have also been used to design other antennas [2, 3]. However, most of the antennas were designed just based on the appearance of biological structures. The functions of the bionic model and the antenna have almost

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no relationship. It is thought that the study of bionics should emphasize on implementing a function found in nature rather than just imitating biological structures. How the bionics shows its charm in electromagnetics is still an important topic worthy of further study.

Leaf plays important roles in the life of the plants. It should make full use of the limited space around the plants for photosynthesis. A reasonable leaf arrangement (phyllotaxis) on the plant stem will help the plants take advantage of the limited space. The basic phyllotactic patterns are opposite or alternate. With an opposite leaf arrangement, two leaves arise from the stem at the same level, on opposite sides of the stem. With an alternate pattern, each leaf arises at a different point on the stem. A perfect leaf arrangement can help the plants receive as much sunlight as possible in a smallest space.

FSSs have been widely treated as spatial filters to reflect totally or transmit electromagnetic waves in some specified frequency bands. FSS can be applied as antenna reflectors, radomes, electromagnetic band-gap materials and so on in the microwave and millimeter-wave regimes. Theoretically FSS should be an infinite array, but in practical applications FSS is finite. It is of great necessity that sufficient elements be used to keep the characteristics of infinite FSS. However, when the operation frequency is low, the element size will be so large that it is difficult to fill enough elements in a reasonable size. Hence miniaturization of FSS is of great significance [4–10].

FSS irradiated by electromagnetic waves is similar to leaf irradiated by sunlight. Space and efficiency are both strictly required by the leaf and the FSS. Thus, the leaf and the FSS are thought to have a similar function. In nature, alternate phyllotaxis is more common, as is shown in Fig. 1(a). This kind of arrangement will make sure that the plants receive the sunlight efficiently and save space significantly. Furthermore, the concept of bionics has been used in many applications widely and successfully. Therefore, there is a good reason to believe that the alternate phyllotaxis model can be applied to FSS design.

The aim of the present work is to describe a strategy to design a novel miniaturized FSS using a bionic structure, and prove the novel FSS valuable in practice. Thus, this paper is organized as follows. In Section 2, the procedure to design the miniaturized FSS element by use of the model of alternate phyllotaxis is addressed. The simulated and measured parametric analysis of the novel FSS is also given. In this section, the miniaturization of the FSS element is pivotal. To demonstrate the practical application of the novel FSS, it is used to reduce antenna RCS in Section 3. The traditional solid ground plane of an antenna array is replaced with the proposed FSS to obtain RCS reduction. In this section, antenna RCS reduction is crucial.

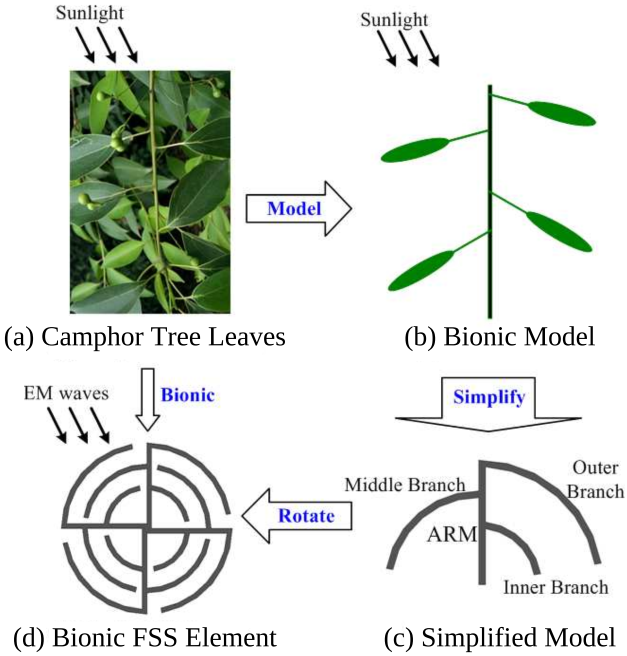
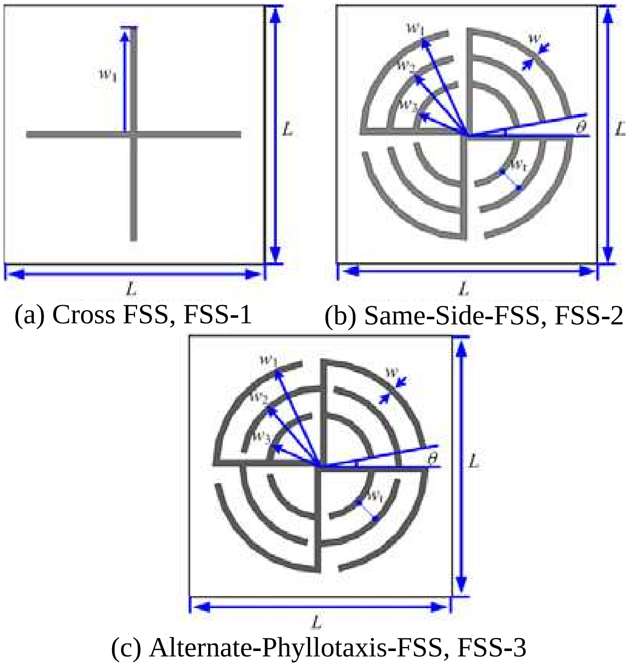


Figure 1. Design process of bionic FSS.

2. DESIGN PROCESS OF BIONIC FSS

Alternate phyllotaxis is common in nature. For instance, the camphor tree is one of the typical plants with alternate phyllotaxis. The design process of the proposed FSS will be described as follows. Firstly, as is shown in Figs. 1(a), 1(b), the leaf arrangement of the camphor tree is modeled according to the truth. Secondly, the bionic model is simplified further in Figs. 1(b), 1(c). As indicated in Fig. 1(c), three arc branches are arranged on the two sides of the arm alternately, which simulates the alternate phyllotaxis. In this way, one part of the FSS element is formed. The arm is then duplicated and rotated by 90°, 180°, 270°, respectively. Consequently, a bionic FSS element is obtained, as we can see in Figs. 1(c), 1(d). The alternate arc branches make full use of the space around.

To demonstrate the miniaturization of the bionic FSS, another two reference FSSs are given and shown in Fig. 2. The same-side-FSS (denoted as FSS-2) is designed to verify the superiority of the alternate-phyllotaxis-FSS (denoted as FSS-3). In fact, FSS-2 and FSS-3 are special variations of a cross FSS (denoted as FSS-1). The three



(a) Cross FSS, FSS-1 (b) Same-Side-FSS, FSS-2

(c) Alternate-Phyllotaxis-FSS, FSS-3

Figure 2. Elements of the three FSSs.

FSSs are printed on the same kind of FR-4 substrate with the relative dielectric constant of 4.4 and a size of 11 mm × 11 mm. The length of arm w_1 is 4.5 mm. The width of arm w is 0.25 mm. w_2 is 3.39 mm, w_3 is 2.28 mm, θ is 10°. The number of the branches n is 3. The distance w_t between two adjacent branches is 1.0 mm.

Using the commercial full-wave finite element method (FEM) simulator in HFSS, the transmission coefficients of the three FSSs are shown in Fig. 3. As shown in Fig. 3, the center frequency of FSS-3 is much lower than the others. With the same element size, the bionic FSS can operate at low frequencies. The center frequencies of the three FSSs are 10.4 GHz, 4.74 GHz, and 3.9 GHz, respectively. The electric sizes of the three elements are 0.381λ, 0.174λ, and 0.143λ, respectively. The results demonstrate the claimed miniaturization performance clearly. Although the electric size of the bionic FSS element may not be the smallest, the method of introducing bionics to FSS design is still of great value for our references. The electric size of the proposed FSS will become smaller after optimizing parameters, which will be shown as follows.

Next, we will analyze the influence of various parameters of FSS-3 on the transmission characteristics. The flare angle θ, the distance w_t, and the number of the branches n will be discussed respectively with the other parameters constant.

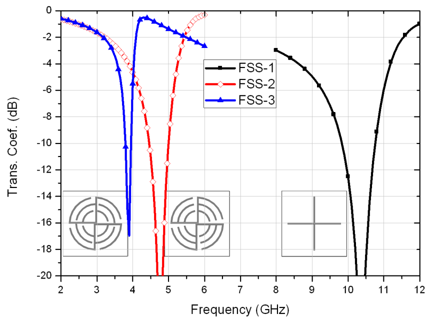


Figure 3. Simulated transmission coefficients of the three FSSs.

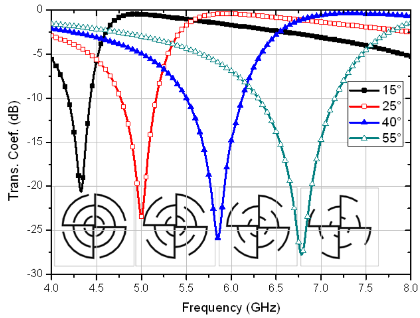


Figure 4. Frequency response of the bionic FSS with different θ.

2.1. Flare Angle θ

For the bionic FSS-3, miniaturization is realized through the arc branches filling the space. As the most important parameter, Fig. 4 shows the frequency response varying with the flare angle θ. As shown in Fig. 4, with the flare angle decreasing, the resonant frequency decreases. The smaller the flare angle is set, the lower resonant frequency we will get. When the flare angle is 90°, FSS-1 will appear.

2.2. Distance between arc Branches w_t

For the bionic FSS-3, another crucial factor of the space fill effect is the distance w_t between two adjacent branches. Fig. 5 shows the frequency response varying with w_t. As shown in Fig. 5, with the distance w_t decreasing, the resonant frequency decreases. Compared to the result shown in Fig. 3, a lower resonant frequency 3.5 GHz appears.

2.3. Number of the arc branches n

As another important parameter, Fig. 6 shows the frequency response varying with the number of the arc branches n. As shown in Fig. 6, with the number of the branches increasing, the resonant frequency decreases. But when $n \geq 3$, the resonant frequency no longer decreases. Adopting a small number can simplify the design. This is the reason why we chose $n = 3$.

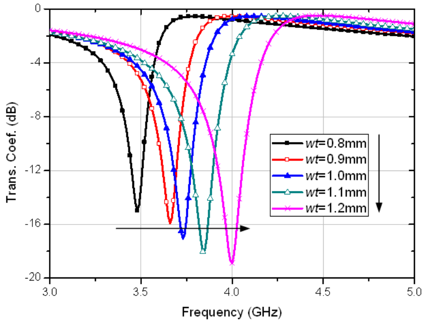


Figure 5. Frequency response of the bionic FSS with different w_t.

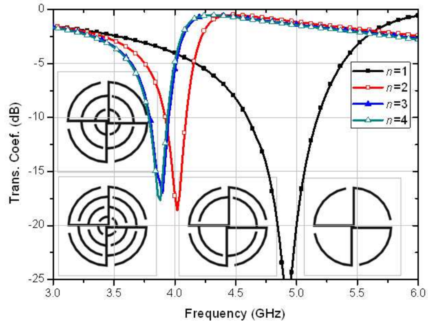


Figure 6. Frequency response of the bionic FSS with different n.

2.4. Different Polarization and Incident Angels

As is well known, the most important performance of FSS is insusceptibility to changes of polarization state, insensitivity of incidence angle and stability of bandwidth. These performances determine if the FSS can be used in practice or not. Hence, the proposed bionic FSS with 20×20 elements are fabricated and measured. Measurement is carried out using two double-ridge horn antennas operating at 2 to 6 GHz in a microwave anechoic chamber. Fig. 7 shows the measured transmission coefficients of the FSS-3 sample for different incident angles of the illuminated planar wave with TE- and TM-polarization, respectively. The transmission coefficient for normal incidence is also shown for comparison.

It can be seen that the measured central frequencies and band edges are nearly the same as those of the normal incidence case. This

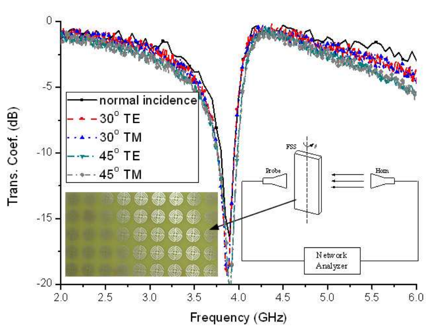


Figure 7. Measured transmission coefficients for the incident plane wave with different incident angles and polarization states.

indicates that the proposed FSS is insensitive to the incident angle of the illuminated wave.

All the results above show that the proposed FSS constructed by using a bionic model has excellent related performances. The proposed miniaturized-element FSS has great potential for practical applications with limited space. In order to investigate the performances of the proposed FSS in practice, FSS-3 will be used to reduce antenna RCS in next section.

3. ANTENNA RADAR CROSS SECTION REDUCTION

Antennas significantly contribute to the overall RCS signature of target objects such as naval ships and airborne vehicles [11–16]. The goal of reducing antenna RCS in this section is accomplished by replacing the solid ground plane of an antenna array with the proposed bionic FSS. The idea of replacing the ground plane of an antenna with a FSS to reduce the RCS dates back to 2003 when this concept was applied to a reflectarray [17]. The application of this principle is straightforward since the FSS behaves as a solid electric conductor for plane waves in its stop band. The idea is not novel, but it is still meaningful to the proof of the bionic FSS in practice.

The authors proposed a wideband printed dipole antenna in [18], which will be used as the antenna array element in this paper. An 1×4 dipole antenna array with a solid ground plane is designed to work at 3.9 GHz. 3.9 GHz is also the resonant frequency of FSS-3. A one to four power divider is employed for feed below the ground plane. This antenna array is fabricated and measured as a reference. The simulated and measured S_{11} of the reference array is shown in Fig. 8. After replacing the solid ground plane with the proposed bionic

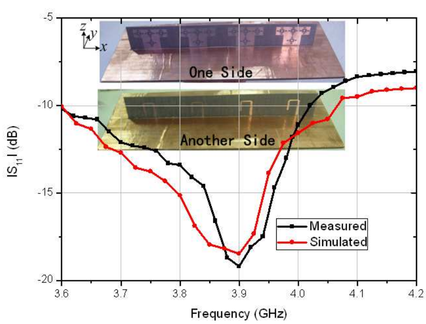


Figure 8. Simulated and measured S_{11} of the reference array.

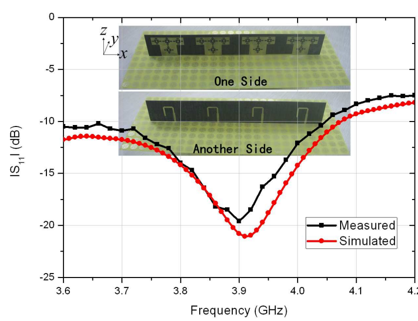


Figure 9. Simulated and measured S_{11} of the proposed array.

FSS, the proposed antenna array is obtained. It is also fabricated and measured. The results are shown in Fig. 9. As shown in Fig. 8 and Fig. 9, the simulated 10-dB bandwidths of the two antennas are 3.6–4.04 GHz and 3.6–4.07 GHz. The measured gain values of the two antennas are 10.68 dBi and 9.79 dBi. The results demonstrate that the two antennas have similar radiation performances.

Then the monostatic RCS of the two antennas terminated with matched loads are shown and compared in Figs. 10, 11. The incident electric field is parallel to x-axis. The incident wave directions are $\theta = 0°$ (normal) and $\theta = 30°$ (oblique). As is apparently indicated, the antenna with the bionic FSS is characterized by a remarkable RCS reduction within the transmission band of the FSS. And the RCS of the proposed antenna is smaller than that of the reference antenna in the whole band of 1–8 GHz.

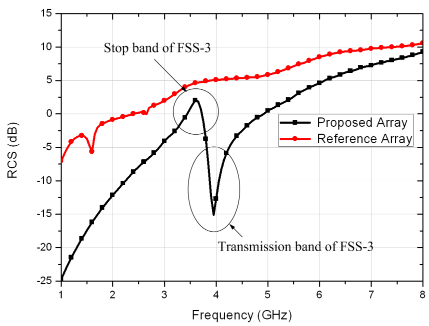


Figure 10. RCS comparison of the two antennas for a normal plane wave.

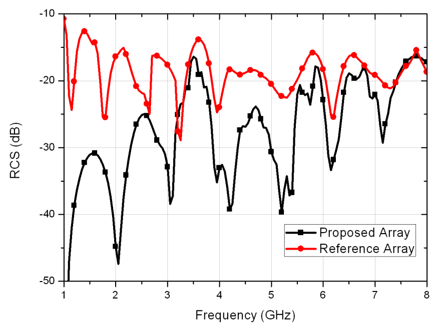


Figure 11. RCS comparison of the two antennas for an oblique plane wave.

It can be concluded from the results above that the proposed antenna has similar radiation performances yet much lower RCS compared to the reference antenna. Therefore, application of bionic FSS in antenna RCS reduction is proved to be feasible.

4. CONCLUSION

A novel bionic FSS and its application have been studied both theoretically and experimentally. The novel bionic structure performs better miniaturization. The proposed structure also shows excellent polarization stability and angle stability. Then the bionic FSS is used to reduce antenna RCS to prove its practical applications. Compared to a reference antenna, the antenna with bionic FSS has lower RCS and favorable radiation performance. Consequently, the technique of applying bionics principle to FSS design and antenna RCS reduction is valid. This paper provides a novel direction to the future design of FSSs and antennas with or without a requirement of RCS control.

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