Progress In Electromagnetics Research Letters, Vol. 13, 131–138, 2010

A NEW MINIATURIZED FRACTAL FREQUENCY SELECTIVE SURFACE WITH EXCELLENT ANGULAR STABILITY

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Abstract—A new miniaturized bandpass fractal frequency selective surface (FSS) with excellent angular stability performance is proposed. The miniaturization has been achieved by scheming out a symmetric fractal pattern of continuous slots from the surface of a square-shaped patch, in which each periodic cell consists of incurved slot resonator for reducing the cell size. Reduction in FSS size of up to 74% with respect to the conventional square loop aperture FSS operating at the same frequency of 3.3 GHz is obtained. Furthermore, results show excellent angular stability for both vertical and horizontal polarization at different incidence angles because of its fractal configuration. A prototype is fabricated, and the FSS measurement and simulation results are presented and discussed.

1. INTRODUCTION

FSS is an infinite 2D periodical array theoretically, usually printed on a dielectric substrate. FSS exhibits total reflection or transmission characteristic respectively in the neighborhood of the unit cell resonance. It has been used in many applications, such as radome, sub-reflectors of antenna [1–3] and superstrates above patch antenna to enhance the antenna directivity [4, 5], etc.

In practice, FSS is not infinite in extent and has finite size. In order to obtain the desired frequency response, the finite surface must include a large number of the constituting elements. For some applications, especially at low frequency, FSS of relatively small

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electrical dimension is highly desirable. Furthermore, the explosive growth recently in wireless security [6–8] has also increased the demands for FSS miniaturization techniques. For wireless security in buildings, FSS may be placed in the walls of the building to provide isolation, reduce interference between adjacent vicinities and protect people from electromagnetic radiation.

Several techniques [6–10] have been proposed to address these problems. In [6–10], the oblique incidence and polarization performance of the cross dipole FSS, the bandwidth enhancement using SIW (substrate integrated waveguide), and the effect of the building materials on FSS response have been investigated. However, the size reduction is not satisfactory, and the manufacture cost is higher (the structure is more complex).

In this paper, a small size FSS design with a symmetrical array of slots etched on the patch surface is presented. Results show that the proposed FSS is characterized by excellent angular stability and is more than 74% smaller compared to the traditional square loop aperture FSS operating at the same frequency. Moreover, different resonance responses can be obtained by changing substrate permittivity using a formula. Because of its stable performance and simple manufacturing procedures, the proposed FSS can be a good candidate for FSS miniaturization and other applications.

2. FSS DESIGN

Figure 1 shows the proposed miniaturized angularly stable fractal FSS. According to the MUNK theory [1], the square loop slot FSS presents resonant as long as the slot perimeter is on the order of resonant wavelength. Therefore, the incurved slots are designed to lengthen the resonant length for miniaturization. Rectangular loops in slot form are chosen for their dual polarized property and simplicity. The slots have their sides parallel to the edge of patch, lengths L_1, L_2, L_3, L_4, L_5 and width W. In practical application, various desired operation frequencies can be obtained by adjusting the length of slot and the permittivity of the dielectric substrate. Theoretically, the longer L_i ($i = 1 \sim 5$) means larger perimeter of the whole slot, which makes the resonant frequency lower. Symmetrical configuration is designed to get good frequency stability for both TE and TM polarizations at different oblique angles.

This symmetric square FSS patch has a periodicity of D. Practically, D must be small enough to avoid the appearance of grating

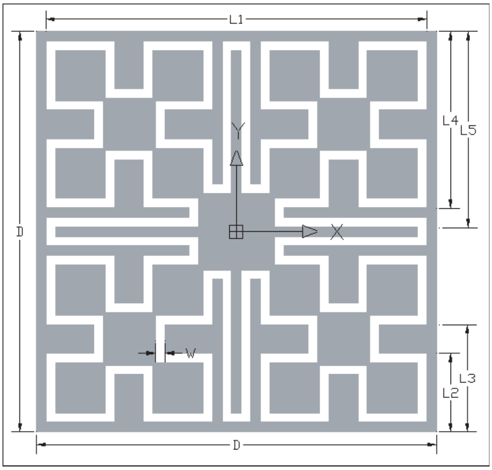


Figure 1. Unit cell configuration of the miniaturized FSS.

lobes according to the formula [11] bellow.

$$D < \frac{\lambda_o}{1 + \sin\theta_o} \tag{1}$$

where λ_o is the wavelength in vacuum, and θ_o is the incidence angle. It can be observed that D must be less than λ_o to make the grating lobe effect on frequency response negligible.

The detailed geometrical parameters of the proposed FSS shown in Figure 1 are listed in Table 1, where ε_r and h denote the permittivity and thickness of the dielectric substrate, respectively. All the surfaces discussed here are single layer.

Table 1. Geometrical parameters of the miniaturized FSS.

D (mm) 8.4	h (mm) 1.0	ε_r 2.65
L_1 (mm) 8.0	L_2 (mm) 1.65	L_3 (mm) 2.25
L_4 (mm) 3.7	L_5 (mm) 4.1	W (mm) 0.2

3. RESULTS AND DISCUSSION

The proposed FSS with the geometrical configuration presented in Figure 1 and Table 1 has been implemented, and its performance is tested by software and measured in a standard anechoic chamber. The sample used in the experiment is shown in Figure 2, which comprises 30×30 elements, and its dimension is $252 \times 252\,\text{mm}^2$. The simulated and measured results are presented and discussed bellow.

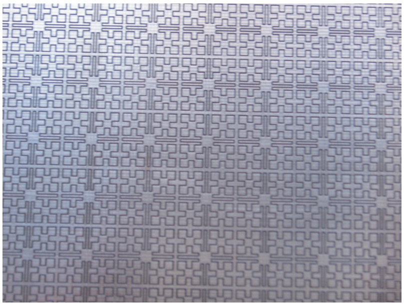


Figure 2. Photograph of the fabricated miniaturized FSS.

Table 2. Size comparison between miniaturized element and the conventional square loop element.

Element Type	Slot width (mm)	Resonant Frequency (GHz)	Periodicity (mm)	Element area (mm^2)
Miniaturized Element	0.2	3.3	8.4	70.56
Square loop Element	0.2	3.3	16.5	272.25

For comparison purposes, a reference FSS (the conventional square loop aperture FSS) operating at the same frequency of 3.3 GHz as the proposed FSS is also implemented, and its characteristics are measured. Figure 3 shows the comparison of transmission characteristic between the miniaturized FSS and reference FSS at oblique incidence of 60° for both TE and TM polarizations. Table 2 shows the dimension comparison between the miniaturized FSS and reference FSS.

As shown in Table 2 and Figure 3, for the same resonant frequency at 3.3 GHz, the proposed FSS has a periodicity of 8.4 mm (0.093 wavelength refers to resonant wavelength), whereas the conventional square loop aperture FSS has a periodicity of 16.5 mm (0.183 wavelength). Hence, a size reduction of approximately 74% $[(16.5^2 - 8.4^2)/16.5^2 \approx 74\%]$ is achieved by its lengthened slots of fractal structure. This is very encouraging. Furthermore, the $-3\,\text{dB}$

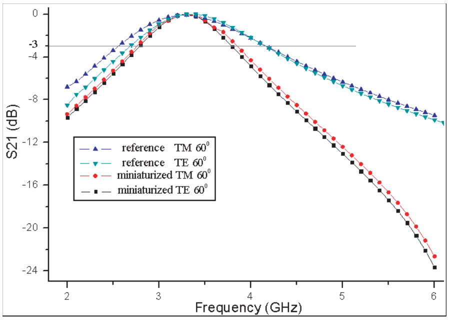
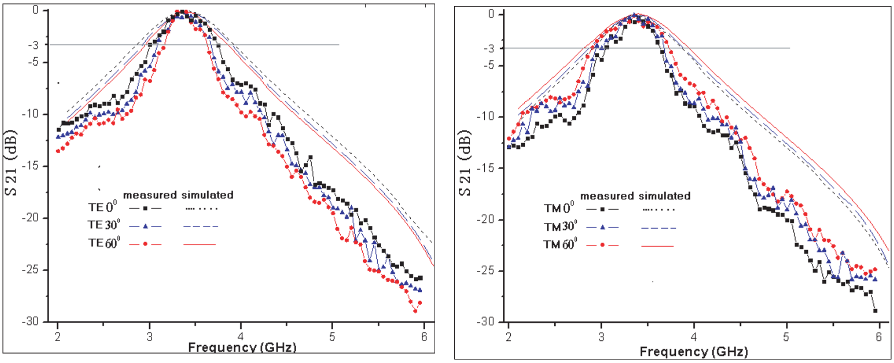


Figure 3. Transmission characteristics of the miniaturized FSS and the reference FSS for TE60° and TM60°.



(a) TE polarization (b) TM polarization

Figure 4. Simulated and measured transmission coefficients of the miniaturized FSS at different incidence angles for TE and TM polarization.

bandwidth of the miniaturized FSS is narrower compared with the reference FSS for both TE and TM polarizations at 60° incidence angle. For the same element, the TM bandwidth is wider than TE bandwidth. In practice, the reduced bandwidth means that better frequency selective performance for bandpass FSS can be achieved.

In practical application, FSS needs to be angularly stable especially when illuminated by wave with large incidence angle. Figure 4 shows the simulated and measured transmission coefficients of the proposed FSS at different incidence angles of 0°, 30°, and 60° for both TE and TM polarizations.

It is shown that the proposed FSS exhibits a stable resonant frequency at about 3.3 GHz as the angle of incident wave varying from 0 to 60 degrees, and there is no obvious shift of resonance frequency.

Compared with the TE polarization, there is no considerable change in the frequency response properties for TM polarization at different incidence angles, which lies on its configurable symmetry and self-similarity of fractal structure. It also can be observed that the TM -3 dB bandwidth gets wider with the increasing incidence angle while the TE bandwidth is reverse. The only resonance frequency in this frequency band (2–6 GHz) is 3.3 GHz. Even up to 6 GHz, there is no other resonance frequency, the undesirable grating lobes are eliminated according to Formula (1).

The largest discrepancy in the simulated and measured results for the proposed configuration is that the measured bandwidth is narrower than the simulated one, which can mostly be attributed to the following factors: (a) diffractions from the edge of the finite FSS panel (b) machining precision and the measured condition. In spite of these differences, the result shown in Figure 4 demonstrates that good frequency stability for both polarizations, and incidence angles can be obtained using the proposed structure.

Theoretically, the higher the dielectric permittivity is, the lower the frequency response presents. Active control of the center frequency for this proposed FSS can be achieved by loading the substrate with different dielectrics using the formula bellow.

$$f \approx \frac{f_o}{\sqrt{(1+\varepsilon_r)/2}} \tag{2}$$

where $f_0 = 4.4$ GHz is resonance frequency in vacuum. ε_r is relative permittivity, and f is the desired resonant frequency. Figure 5 presents the transmission characteristic using the calculated and simulated results for TE polarization at normal incidence angle. As shown, the

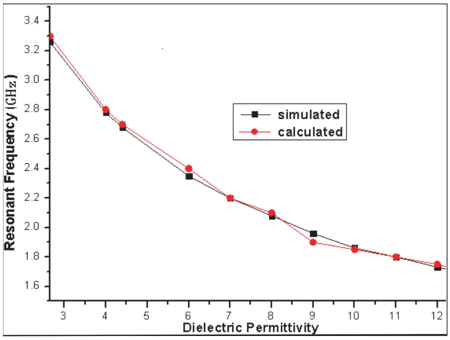


Figure 5. Calculated and simulated resonant frequency of the miniaturized FSS for different permittivity.

simulated results agree well with the calculated ones, which means that it is convenient to obtain a desired bandpass FSS at WLAN band (2.4–5.5 GHz) and S band (2–4 GHz) using this formula. This method can really lower the complexity and cost of fabrication for FSS working at lower frequency band.

4. CONCLUSION

A miniaturized bandpass FSS has been proposed in this paper. The size reduction is achieved by convoluted slots of fractal structure to lengthen the resonant length, and the area of this fractal FSS is reduced by 74% at the same operation frequency of 3.3 GHz, compared with the conventional square loop aperture FSS. Experimental and simulated results show that this miniaturized FSS is angularly stable for both polarizations (TE and TM) at different incident angles. Furthermore, results show that the structure can be tuned to provide variable resonant frequency using a formula for other desired transmission response.

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