A dual-band fractal FSS with SZ curve elements

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Abstract: A novel dual-band miniaturized frequency selective surface adopting fractal elements is proposed. The proposed structure is composed of interconnected four SZ curves of second generation. Such a design is to provide two pass-bands with stable performance, the first band resonates at S-band with a center frequency of 3.02 GHz and the second band is at C-band centered at 7.22 GHz. In addition, the compact structure employing the space filling curve can further reduce the size of the FSS. The dual-band FSS achieves better miniaturization compared with other single layer FSS in previous literature, the dimension of the unit cell is only 0.072λ × 0.072λ, where λ represents the free space wavelength at first resonant frequency. Furthermore, the proposed FSS exhibits great resonance stability for different polarizations and incidence angles. Both the simulation and measurement verify the stable performance of the FSS.

Keywords: frequency selective surface, dual band, miniaturization

Classification: Microwave and millimeter-wave devices, circuits, and modules

References


1 Introduction

Frequency selective surfaces (FSSs) are composed of periodic conducting patches or apertures perforated on a conducting plane. FSSs have widespread applications in the electromagnetic spectrum, such as radome design, microwave absorbers, infrared filters and antenna systems [1]. With the increasing requirements of multi-frequency communications, multiband and dual-polarization FSSs have aroused great interest of many researchers. Different design methods of multiband FSS can be found in many papers, which include single screen FSS with combined element method [2], multi-screen FSS cascaded method [3], genetic algorithm [4], fractal FSS [5], or several combination of above methods [6].

Designing FSSs with fractal elements is an attracting method on providing better performances compared with traditional structures [7]. Due to self-similarity of fractal generations, fractal structures can be used to realize multiband frequency response of FSSs, and they have the potential of space filling to reduce the element size, thus improving the angular stability and moving the working band away from the grating lobe. A amount of fractal elements have been applied to design FSSs in previous literatures, for example, the Sierpinski gasket dipole has been used to design dual-band FSS in [8], the Gosper pre-fractal elements have been exploited to design dual-band FSS in [9], and the Hilbert curve as one of the space-filling curves is applied to reduce the size of the FSS elements in [10].

FSSs adopting space-filling curves can fully utilize limited space to achieve miniaturization while realizing multiband, which is a competitive solution for designing FSSs. In this letter, a novel space-filling curve named as SZ curve is employed to design a miniaturized-element FSS with two pass-bands in S- and
C-band. The FSS element in slot form is connected by four symmetrical SZ curves of second iteration, symmetrical arrangement is designed to ensure dual-polarized characteristic. The unit cell of the FSS is only \( \frac{0.072\lambda}{C_{21}} \times \frac{0.072\lambda}{C_{21}} \), where \( \lambda \) represents the free space wavelength of the first resonant frequency. In addition, the designed FSS shows stable performance for oblique incidence and different polarizations. The simulated results and measured ones agree well, which proves the stable performance of the dual-band fractal FSS proposed.

2 The fractal FSS structure and its performances

The geometry of the newly proposed fractal element providing two pass-bands is shown in Fig. 1. The miniaturized aperture element is composed of four symmetrical fractal SZ curves of second generation, each second generation SZ curve is arranged by 90° rotation to its adjacent ones, finally they are linked together in the center, where the gray areas represent metallic structures, while the other areas represent slots. Such a symmetrical arrangement is to ensure stability for different polarizations. Fig. 2 presents the first and second generation of the SZ curve. Initially the iteration process of the SZ curve is started with an S shape curve, then are continually added tiny S-curves and Z-curves by 90 degrees. Such a growth rule makes the SZ curve eventually pass through the center of every grid, which lengthens the perimeter of the FSS element further improving the space utilization.

Each generation is composed of segments of length \( d_n \), where \( n \) represents the generation number, \( d_n \) and the side length \( l_n \) of the element are formulated by

\[
(3^n - 1) \times d_n = l_n
\]  

(1)

And \( d_n \) and the array period \( D \) of the designed FSS are related by

\[
d_n = \left(\frac{1}{3}\right)^n \times \frac{D}{2}
\]  

(2)

For the proposed FSS element that connects four second generation SE curves, considering fractal structure size and manufacturing requirements, setting the array period \( D = 7.2 \) mm, the gap width \( s = 0.2 \) mm, according to Eq. (1) and Eq. (2), the side width \( l_2 = (1 - (1/3)^2) \times D/2 = 3.2 \) mm, the strip width \( w = D/2 - l_2 - s = 0.2 \) mm.
Fractal FSSs can realize multiband characteristic due to self-similarity of structures. Usually, the number of FSS resonances increases with the fractal iteration. The fractal Sz curve of second generation can be utilized to achieve multiband, however, the frequency bands except the first band are generally unstable for oblique incidence. It can be ascertained that the second Sz curve element can provide a frequency band with great angular stability [11]. Therefore, in order to produce another resonance with stable performance, an improvement on the basis of original structure is proposed, the center cross patch is intentionally removed from the original structure, so that the four separate Sz curves are connected together to form a meandered aperture unit. It can be deduced that the miniaturized aperture units will provide another stable frequency band with respect to different incidence angels. Combined with the stable frequency band formed by the second generation Sz element, two pass-bands with great angular stability are obtained, which also have good independence of polarization because of the symmetry of the structure designed.

To demonstrate the resonant stability of the fractal FSS designed, the Sz curve FSS element is printed on one side of the F4B-2 substrate, whose dielectric constant $\varepsilon_r = 2.65$, loss tangent $\tan \delta = 0.002$, and thickness $h = 1$ mm. The Full-wave simulation is done by the HFSS. The transmittance is defined as

$$\text{Transmittance} = 20 \times \log_{10} \frac{|S_{21}^T|}{|S_{21}^I|}$$

Where $S_{21}^T$ and $S_{21}^I$ denote S-parameters with and without the FSS, respectively.

Fig. 3 shows the transmittance of the designed FSS as it is illuminated by a plane wave with different polarizations and incidence angles. It can be observed from Fig. 3 that the fractal FSS provides two pass-bands at S- and C-bands centered at 3.02 GHz and 7.22 GHz. As shown in Fig. 3(a), for TE-polarized wave, as the incidence angle is up to 45°, both of the frequency deviations are less than 1.7%, and the $-3 \, \text{dB}$ bandwidths of both bands decrease from 0.76 GHz to 0.55 GHz and from 0.38 GHz to 0.24 GHz respectively. From Fig. 3(b), for TM-polarized waves, there are less than 1.1% frequency deviations for both bands under oblique incidences, and the $-3 \, \text{dB}$ bandwidths increase from 0.78 GHz to 1.06 GHz and from 0.31 GHz to 0.49 GHz accordingly. Through the comparisons between Fig. 3(a) and Fig. 3(b), it can be obtained that the frequency deviations in both bands are less than 0.8% for two polarizations. Therefore, the proposed FSS
exhibits extremely stable resonance for different incidence angles and different polarizations.

![Graph](image)

**Fig. 3.** Transmittance of proposed FSS for different incident angles: (a) TE polarization. (b) TM polarization.

To prove the improved miniaturization performance of the single layer FSS proposed, the comparison results of the FSS structure proposed and other single layer structures are listed in detail in Table I. Obviously, it can be observed that the designed FSS shows better miniaturization characteristic.

**Table I.** Results of comparisons with other FSS structures

<table>
<thead>
<tr>
<th>Value of $\varepsilon_r$</th>
<th>FSS structure</th>
<th>Unit cell size</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>Structure in [5]</td>
<td>$0.133\lambda \times 0.133\lambda$</td>
</tr>
<tr>
<td></td>
<td>Structure proposed</td>
<td>$0.057\lambda \times 0.057\lambda$</td>
</tr>
<tr>
<td>3</td>
<td>Structure in [10]</td>
<td>$0.076\lambda \times 0.076\lambda$</td>
</tr>
<tr>
<td></td>
<td>Structure proposed</td>
<td>$0.069\lambda \times 0.069\lambda$</td>
</tr>
<tr>
<td>2.65</td>
<td>Structure in [12]</td>
<td>$0.092\lambda \times 0.092\lambda$</td>
</tr>
<tr>
<td></td>
<td>Structure in [13]</td>
<td>$0.077\lambda \times 0.077\lambda$</td>
</tr>
<tr>
<td></td>
<td>Structure proposed</td>
<td>$0.072\lambda \times 0.072\lambda$</td>
</tr>
</tbody>
</table>

3 Experimental results

To verify simulation results of the designed FSS, a prototype is fabricated and measured using the free-space measurement method. The dimension of the FSS prototype shown in Fig. 4 is $400 \text{ mm} \times 400 \text{ mm}$, containing $55 \times 55$ elements. The material of the substrate is F4B-2 same as the simulated one. The measurement is performed in a microwave anechoic chamber, the measurement system consists of vector network analyzer, transmitting and receiving antenna, turntable and so on. The prototype is placed on the turntable, and the incidence angle is controlled through the turntable. To calibrate the system, the measurement is accomplished in two steps: First, measuring the transmittance without the FSS; second, measuring the transmittance with the FSS. The comparisons between measured results and simulated ones are plotted in Fig. 5. It can be observed the measured resonant frequencies are centered around 3.02 GHz and 7.22 GHz respectively, agree well with the simulation results. The measured insertion losses at the first and second resonant frequencies are 0.35 and 0.6 dB, respectively. The measured results prove...
that the proposed FSS has stable frequency performance for both polarizations under oblique incidence angles. The minute deviations of the measured data and the simulated ones are mainly due to the losses of the substrate and edge diffraction scattering effect of the EM waves.

Fig. 4. Photograph of the fabricated FSS prototype.

Fig. 5. Simulated and measured transmittances of the proposed FSS: (a) TE polarization, (b) TM polarization.

4 Conclusion

In this letter, a novel dual-band frequency selective surface based on fractal SE curve elements is proposed. The proposed FSS provides two pass-bands with great angular stability, and the designed FSS has dual-polarized characteristic due to the symmetric structure designed. The deviations of both resonant frequencies are all less than 1.7% for both TE waves and TM waves under oblique incidence, the proposed FSS shows excellent polarization stability and angular stability. And due to space filling characteristic of the SZ curve, the proposed FSS shows better miniaturization performance with the unit cell size only $0.072\lambda \times 0.072\lambda$. Both the simulation and measurement validate the stable performance of the FSS proposed. The designed FSS with simple geometry is attractive for applications providing only limited space and requiring stable dual-band frequency response.

Acknowledgments

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