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Dual-Band Frequency Selective Surface With Compact Dimension and Low Frequency Ratio

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ABSTRACT In this paper, frequency selective surface (FSS) with low profile, miniaturized structure and closely located dual-band is proposed based on the fractal technology. The FSS is designed by etching the conductive pattern on a single layer substrate. Two fractal slots are designed to increase the spatial efficiency of the pattern and provide two isolated resonances. For the dual-band FSS, the miniaturization should work for both of the resonances to keep the frequency ratio. Therefore, the slots are convoluted as different principles and twisted with each other to keep the miniaturization and isolation. With the third-order fractal pattern, two pass-bands are achieved at 1.04 GHz and 1.49 GHz with the frequency ratio of 1.42. The dimension of the element is as compact as $0.039\lambda \times 0.039\lambda$ where λ is the wavelength of low frequency resonance. Moreover, benefiting from the miniaturized element, the angular stability is very good that the resonances keep stable when the incident angle increasing from 0° to 60° . In order to get insight of the mechanism of the proposed element, an equivalent circuit model is established and studied. A prototype is fabricated and all the proposed performances are verified by simulations and measurements.

INDEX TERMS Frequency selective surface, dual-band, miniaturization, low frequency ratio.

I. INTRODUCTION

Frequency selective surface (FSS) is a kind of periodic structures with arbitrary shapes, it can exhibit reflection or transmission characteristics at a certain frequency, which works as a spatial filter for the incident electromagnetic waves [1]. In recent years, FSS has caused extensive research for its widely applications in hybrid radomes, antenna sub-reflectors, absorbers, electromagnetic shields, etc. [2]–[8].

With the increasing demands of wireless communication and radar systems working on multiple transmission bands, multi-band FSS have attracted much attention, which can provide much more exact electrical windows in frequency domain [9]. Besides, as a common structural requirement, the dimension of the FSS element should be compact enough to arrange a sufficient number of elements in a finite space and to suppress the appearance grid lobes.

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Many miniaturization techniques for single resonance elements have been reported in recent years [10], [11].

However, most of these techniques could hardly work in the multi-resonance element. Since the multi-resonance is achieved by the resonant structures combining together inside the FSS element, the miniaturization should be effective for all of the resonant structures. Obviously much greater compactibility is required by the multi-band element than the single-band one. Moreover, in view of the isolation between the multi-resonance, the coupling between the resonant structures should also be taken into consideration. In order to solve these problems, several techniques are reported to achieve a high selective dual-band performance, such as convolution [12]–[17], 2.5-D [18], [19], 3D [20] and multi-layer [21] techniques.

In this paper, band-pass FSS with compact dimension and highly isolated dual resonances is proposed based on fractal technology. Different fractal principles are applied in element design. An equivalent circuit model (ECM) of the proposed FSS is established to get insight into the working mechanism.

The performances of the proposed FSS are verified by both simulations and measurements.

II. DESIGN AND MECHANISM

A. STRUCTURE AND PERFORMANCES

The geometry of the proposed FSS is shown in Fig. 1. The conductive pattern is etched on a FR-4 substrate with relative permittivity of 4.4, loss tangent of 0.02 and thickness of 0.8 mm.

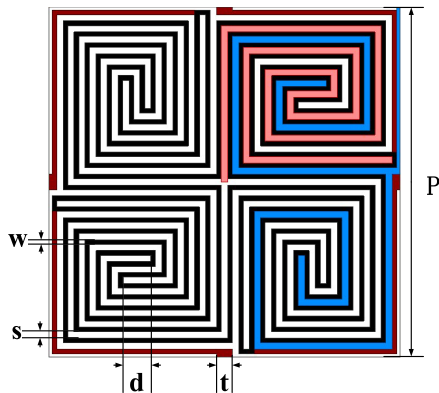


FIGURE 1. Geometry of the proposed FSS.

Based on the fractal technology, two different principles are applied in the convoluted slots: one is a spirally convoluted slot (SCS) in red color and the other is a branched spiral slot (BSS) in blue color. Consequently, the conductive pattern of the FSS element is divided into two stripes: one surrounds the SCS and the other connects the adjunct elements, which are marked in black and crimson colors respectively. The structural parameters of the proposed FSS are listed in TABLE 1.

TABLE 1. Structural parameters of the proposed FSS.

Parameter	P	t	d	S	w	h
Value(mm)	11.2	0.5	0.9	0.2	0.15	0.8

The transmission and reflection coefficient curves of the proposed FSS under the normally incident TE and TM polarized waves are shown in Fig. 2. The resonant frequencies of 1.04 GHz and 1.49 GHz are achieved and the frequency ratio is about 1.43. Under the condition of $|S_{11}| < -10$ dB, the two pass-bands of the proposed FSS are from 0.87 GHz to 1.17 GHz and from 1.42 GHz to 1.63 GHz, respectively. The achieved fractional bandwidth of the pass-bands is 29.4% and 13.8%, respectively. The Maximum isolation between the pass-bands is as high as 15 dB. The compact FSS element of $0.039\lambda \times 0.039\lambda$ is obtained by using fractal technology, where λ is the free space wavelength at the lower resonance.

The polarization stability of the proposed FSS is studied and shown in Fig. 3 under the normally incident case. Due to

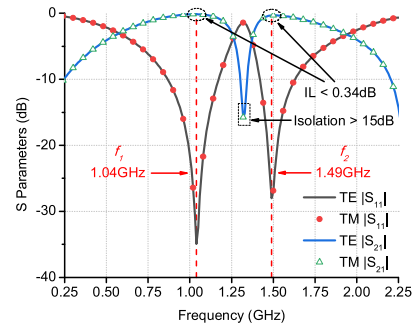


FIGURE 2. Frequency response of the proposed FSS.

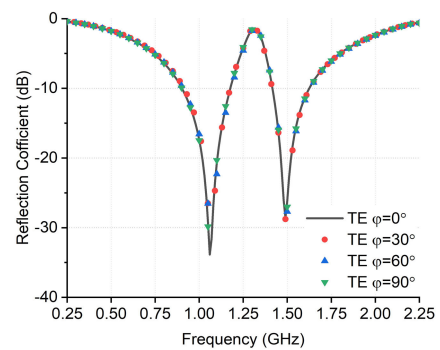


FIGURE 3. Reflection coefficient under various polarization.

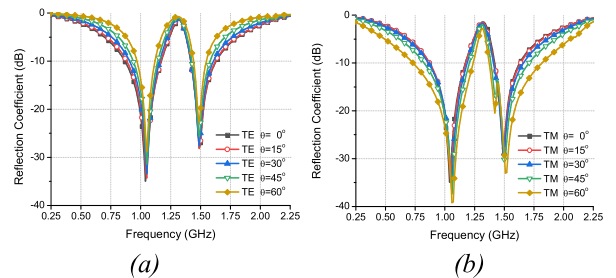


FIGURE 4. Reflection coefficient under various incident angles. (a) TE mode. (b) TM mode.

the centrosymmetric structure, only the results of the polarization angles between 0° and 90° are studied. Good coincidence is observed between the curves when the proposed FSS is normally illuminated. The frequency shifts are less than 10 MHz at both 1.04 GHz and 1.49 GHz.

B. METHOD AND MECHANISM

Fractal is a commonly used method to achieve multiple resonances because of its self-complementary characteristic. The number of the resonances and the frequency ratio are determined by the order and ratio of the fractal pattern. However, proper fractal ratio should be well designed to keep the isolation of the resonances. Otherwise, the multiple resonances will not lead to multiple bands, but a wideband.

In order to achieve two band-pass resonances, two fractal slots are designed to resonant at different frequencies.

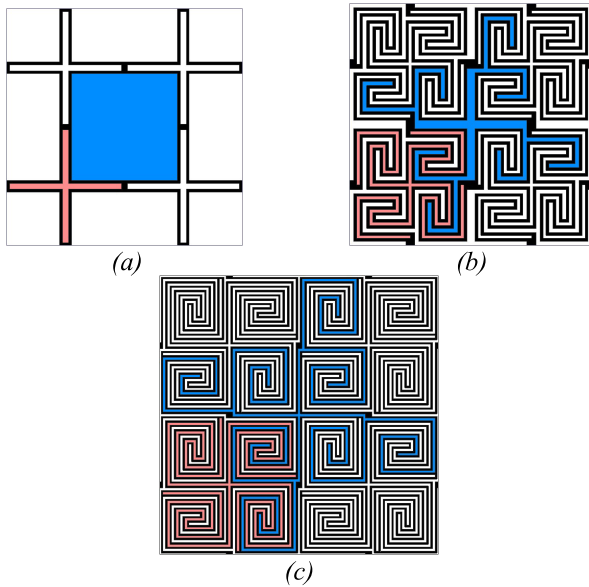


FIGURE 5. Evolution of the proposed FSS. (a) First-order pattern. (b) Second-order pattern. (c) Third-order pattern.

As shown in Fig. 5(a), in the first-order pattern, the cross slots are located inside the cross rings and the square apertures are located between the cross rings, which are marked in red and blue colors, respectively.

By convoluting the elements, the spatial efficiency of the first-order pattern would be increased. However, to keep the isolation of the two resonances, the specific fractal principle should be followed. In this case, two different principles are followed in the convolution of the cross slots and square apertures. The second-order pattern is shown in Fig. 5(b), according to the self-similarity of the fractal structure, the blue parts is changed into a branched spiral slot and the red parts is changed into a spirally convoluted slot and further complementary to each other. In this way, the dual-resonant element is miniaturized and the isolation between resonances is also kept at the same time.

In order to get a low frequency ratio and further miniaturize the element, the third-order pattern is designed as the same principle above, which is shown in Fig. 5(c).

In the convolution of the slots, the coupling between the slots should be well controlled to increase the inductance of stripes and the capacitance in the slots, so that the effective electrical length of the resonant structures can be increased. As shown in Fig. 5, two kinds of slots are obtained based on different principles, the slots are spirally convoluted and twisted each other. In this way, the stripes are separated by each other and the coupling between them is reduced. In order to verify the effectiveness of the fractal principles, as shown in Fig. 6, the response of the third-order pattern is compared with that of a S-shaped convoluted pattern. Dual-band response is achieved by both patterns. However, the resonant frequencies and the frequency ratio of the third-order pattern is definitely lower than the S-shaped pattern.

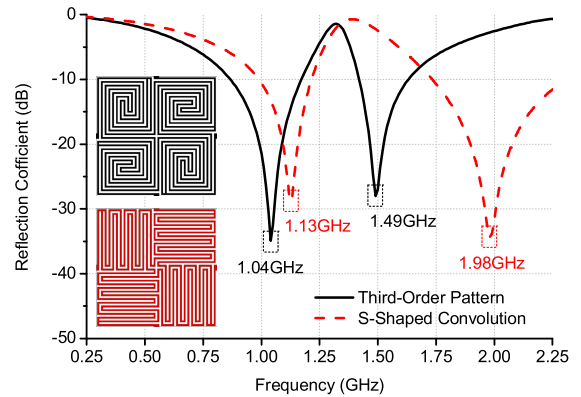


FIGURE 6. Frequency response of the third-order pattern and S-shaped convoluted pattern.

C. EQUIVALENT CIRCUIT MODEL

In order to get insight into the proposed FSS, the equivalent circuit model (ECM) is established by analyzing the surface current and E-field distributions under TE polarization.

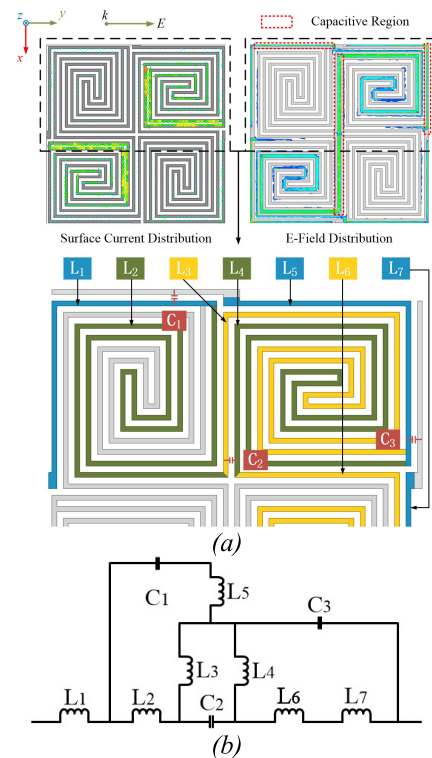


FIGURE 7. Construction of the Equivalent circuit model at 1.04 GHz. (a) Analysis on the current and E-field. (b) Equivalent circuit model.

The surface current and E-field distributions at 1.04 GHz is shown in Fig. 7(a). Due to the centrosymmetric structure of the element, half of the element is shown in the figures to discuss. On the conductive pattern, the capacitive regions are marked by the red dashed boxes and the inductive regions are indicated by different color.

The black metallic stripes which surround the SCS are described by the equivalent inductors of L2 to L4 and L6,

and the crimson stripes which connect the adjacent elements are described by L1, L5 and L7. It can be found that, on one hand, the surface current mainly surrounds the SCS, and the E-field distributes in the slot of SCS which could be expressed with C2. On the other hand, E-field observed in the slot of BSS could be expressed with C1 and C3. Obviously, the equivalent inductor is divided into several inductors by equivalent capacitors.

Based on the study above, the ECM of the element at 1.04 GHz is constructed and shown in Fig. 7(b).

Through the same process, the equivalent capacitive and inductive regions could be found out according to the surface current and E-field distributions shown in Fig. 8(a). Because of the similarities between the resonances at 1.04 GHz and 1.49 GHz, an ECM shown in Fig. 8(b) could be constructed, which has the same principle but different circuit with the 1.04 GHz ECM.

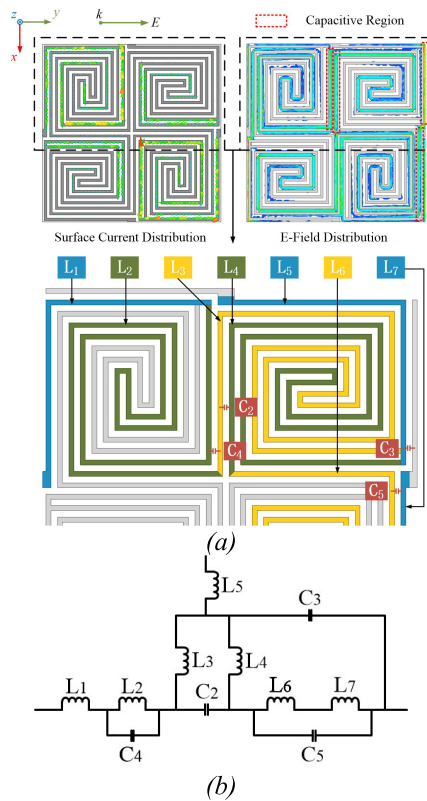


FIGURE 8. Construction of the Equivalent circuit model at 1.49 GHz. (a) Analysis on the current and E-field. (b) Equivalent circuit model.

Finally, combining the above analysis, the complete ECM of proposed FSS is shown in Fig. 9 (a). Through the curve-fitting method, the actual value of each lumped component is: $L_1 = 0.461\text{nH}$, $L_2 = 0.307\text{nH}$, $L_3 = 1.807\text{nH}$, $L_4 = 0.919\text{nH}$, $L_5 = 0.336\text{nH}$, $L_6 = 1.483\text{nH}$, $C_1 = 4.971\text{pF}$, $C_2 = 5.125\text{pF}$, $C_3 = 3.437\text{pF}$, $C_4 = 4.581\text{pF}$, $C_5 = 2.813\text{pF}$. It should be noted that L6 and L7 have been merged into one inductor. Fig 9(b) shows the S parameters comparison between the calculation result of the ECM in ADS and the

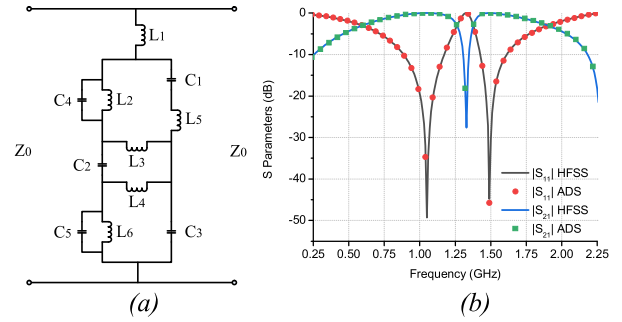


FIGURE 9. (a) Complete ECM of proposed FSS. ($L_1 = 0.461\text{nH}$, $L_2 = 0.307\text{nH}$, $L_3 = 1.807\text{nH}$, $L_4 = 0.919\text{nH}$, $L_5 = 0.336\text{nH}$, $L_6 = 1.483\text{nH}$, $C_1 = 4.971\text{pF}$, $C_2 = 5.125\text{pF}$, $C_3 = 3.437\text{pF}$, $C_4 = 4.581\text{pF}$, $C_5 = 2.813\text{pF}$). (b) Comparison between ADS and HFSS.

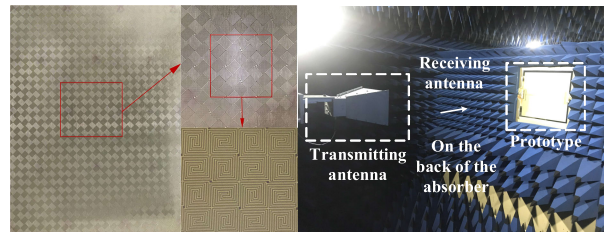


FIGURE 10. Photograph of measurement setup in microwave anechoic chamber.

TABLE 2. Comparison with the reported design.

Ref	Resonant Frequency (GHz)	Dimension	Layers	Band Ratio
[12]	2.35, 3.05	0.065λ	1	1.29
[14]	3.4, 4.9	0.069λ	1	1.44
[15]	5.13, 8.85	0.113λ	1	1.73
[16]	1.57, 2.49	0.157λ	1	1.58
[17]	2.37, 5.29	0.273λ	1	2.23
[18]	2.3, 5.9	0.05λ	2	2.56
[19]	2.5, 3.5	0.082λ	2	1.4
[20]	5.46, 7.16	0.164λ	2	1.31
[21]	2.66, 5.04	0.059λ	2	1.89
Proposed FSS	1.04, 1.49	0.039λ	1	1.43

simulation result in HFSS, and that shows excellent coincidence in the band of 0.25 GHz - 2.25 GHz.

III. MEASUREMENT

A prototype with 1936 elements in a 44×44 arrays is manufactured and measured in an anechoic chamber as shown in Fig. 10. The FSS prototype was measured in a microwave

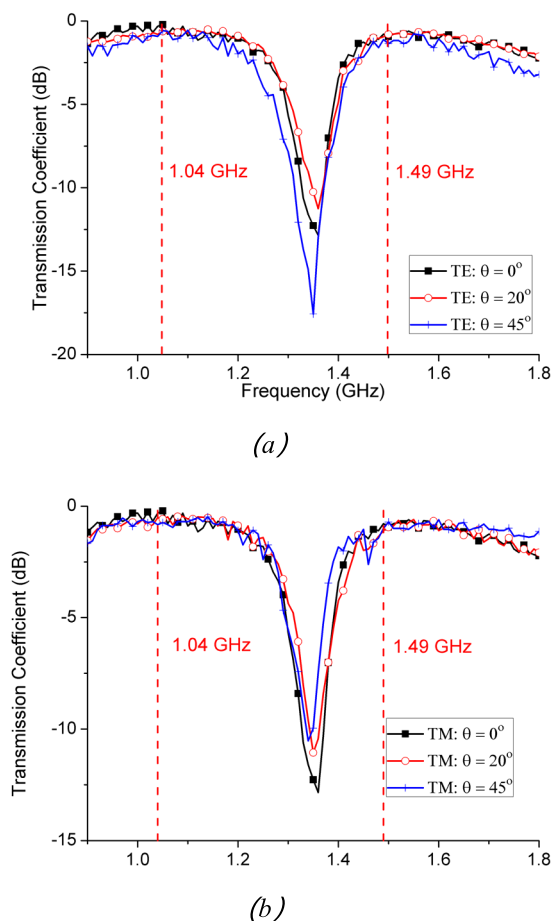


FIGURE 11. Measured transmission coefficient curves under various incident angles. (a) TE polarization. (b) TM polarization.

anechoic chamber which is equipped with two horn antennas and a vector network analyzer. Two horn antennas pointed toward each other are placed at both sides of the FSS prototype as transmitting and receiving antenna respectively. In order to ensure the accuracy of the measurement results, the distance between the prototype and the horns are calculated by the far field condition. For the sake of decrease the diffraction and unexpected reflections, the prototype is surrounded by a large pyramidal absorber screen.

The measured transmission coefficient curves under various incident angles for the TE and TM polarizations are shown in Fig.11 (a) - (b). Due to the diffraction in the measurement, the angular performance is discussed from 0° to 45° . Good coincidence is observed between the simulated and measured curves. The resonances keep stable at both the 1.04 GHz and 1.49 GHz resonant bands when the incident angle varies from 0° to 45° . The isolation between the pass-bands are as high as 12.5 dB under the normal incidence.

In order to illuminate the novelty of the proposed FSS, its performances are summarized and compared with the recently published researches in TABLE 2.

This comparison demonstrates better performances of miniaturization, frequency ratio, isolation and profile.

IV. CONCLUSION

FSS with compact structure, low profile and highly isolated dual-band is proposed in this paper. Fractal technology is used to reduce the dimension of the element. Novel convoluting principles are applied in the third-order pattern to achieve low frequency ratio and high isolation between the dual resonances. The ECM is established and studied and the performances are verified by both simulations and measurements.

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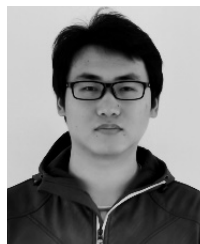
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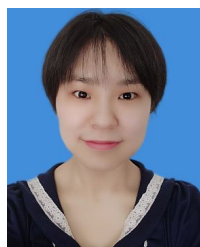


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